The potential of green roofs in sustainable stormwater engineering in the eThekwini CBD

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted in fulfillment of the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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Arisha Sucheran

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ABSTRACT

Cities are facing serious problems relating to stormwater such as water scarcity, degraded waterways, increased flooding, and degradation of the quality of water. In response to these impacts, a number of sustainable urban drainage systems (SuDS) are being developed and implemented in many cities. In particular, green roofs boast an array of advantages, including their ability to delay and reduce stormwater runoff, and improve stormwater runoff quality. This study compares the water quality and quantity of green roofs with that of conventional roofs in the eThekwini region, and compiles a model using Personal Computer Storm Water Management Model (PCSWMM) to investigate the effect that incorporating the best performing green roof would have on stormwater flow rates and volumes for the region. In terms of water quality, the data analysis revealed significant variations in pollutant concentrations between the green roofs and the conventional roof. Metals such as arsenic, iron, and aluminium were found in high concentrations in green roof runoff. In terms of stormwater runoff quantity, the green roof systems proved to significantly reduce stormwater runoff flow rates and volumes. The highest retention rates were achieved for low intensity rainfall events, whilst the lowest was achieved for high intensity rainfall events. The implementation of green roofs within the eThekwini Central Business District (CBD) proved to be advantageous in reducing peak stormwater flow rates.

DEDICATION

Harder than saying Goodbye, is having never said Hello.

To my paternal grandfather, Sucheran (Sona) Budhu, I wish you could have been here in person to share in my achievements.

Thank you for guiding me.

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BOD	Biological Oxygen Demand
CBD	Central Business District
COD	Chemical Oxygen Demand
CSIR	Council for Scientific and Industrial Research
DWA	Department of Water Affairs
EIA	Environmental Impact Assessment
EPCPD	Environmental Planning and Climate Protection Department
GBCSA	Green Building Council of South Africa
GRPP	Green Roof Pilot Project
IDP	Integrated Development Plan
KZN	KwaZulu-Natal
LECA	Light Expanded Clay Aggregate
LID	Low Impact Development
MAP	Municipal Adaptation Plans
MCPP	Municipal Climate Protection Programme
NTU	Nephelometric Turbidity Unit
PCSWMM	Personal Computer Stormwater Management Model
SABS	South African Bureau of Standards
SANRAL	South African National Roads Agency
SANS	South African National Standards
SuDS	Sustainable Urban Drainage Systems
TSS	Total Suspended Solids

UNDESA	United Nations Department of Economic and Social Affairs
WHC	Water Holding Capacity
WSUD	Water Sensitive Urban Design

CHAPTER ONE: INTRODUCTION AND CONTEXT OF THE STUDY

1.1 Introduction

As a result of rapid economic growth, many cities have been experiencing increased urbanization which has now placed urban areas at the forefront of achieving global sustainability. Rapid urbanization has resulted in the construction of new developments which has increased the impermeable surfaces in urban areas, at the expense of vegetated areas. This has led to concerns in stormwater management as urban areas are increasingly prone to flood disasters and water pollution. For cities to become more sustainable, the infrastructure on which they rely must also become more productive, efficient and resilient. Green roofs are an example of green infrastructure, which uses vegetation, soil, and natural processes to manage water and create healthier urban environments. Green roofs have been proposed as an important means to increase the amount of vegetated area in densely built urban areas, and are of particular interest to urban stormwater management as they retain, detain and slowly release stormwater. This chapter forms the introductory chapter to the dissertation. The chapter commences with the rationale and context for the study. Thereafter, the aims, objectives and research questions for the study are presented. The outline of the dissertation is then provided, followed by a conclusion to the chapter.

1.2 Rationale for the study

In recent years, the phenomena of climate change and global warming have been in the spotlight, as the world has come to be educated about the negative impacts on the natural environment. Scientists have warned that the results of these phenomena could be drought, sea level rise, and extreme weather conditions. The urgency to implement environmental policies and practices arises from the realization that urbanization is taking place far more rapidly than the planning to deal with it is (Walsh et al., 2012). Major changes in land-use that resulted in a change in the natural landscape to a built-up urban environment have had disastrous consequences for urban ecosystems. In particular, inappropriate urban development has resulted in increased runoff and contaminant loads, and thus urban stormwater often results in significant deterioration of receiving freshwater systems due to pollution, unnatural flow regimes and habitat disturbance (Haskins, 2012).

Willuweit and O'Sullivan (2013) affirm that the global population is expected to increase to 9.2 billion by 2050. With the rapid rate of urbanization, the pressure on urban water demand will also escalate causing a stress on the current water systems. Cities around the world are facing severe stormwater-related issues such as water scarcity, degraded waterways, increased flooding, degradation of the quality of water bodies that receive surface run-off, due to the pollution load picked by rainwater run-off flooding, and ageing infrastructure (Ferguson et al., 2013; Papafotiou and Katsifarakis, 2015). These impacts are estimated to increase with climate change. Urban areas are further challenged by extensive impervious surfaces, damaged soils, and little room for green spaces or for stormwater management facilities. Conventional approaches fail to address the increase of storm runoff volumes and peak flow rates caused by urban development. The runoff overburdens the municipal wastewater treatment works and carry pollutants such as trash, bacteria and heavy metals into the receiving waters, and ultimately degrade the quality of the urban streams (Liu et al., 2014).

In response to these impacts, a number of sustainable urban drainage systems (SuDS) have been developed and implemented in many cities in the last three decades (Novotny et al. 2010). SuDS mimic the hydrological process that would have taken place, had the site are not been developed, by allowing stormwater to infiltrate, evaporate, run off, and/or be used on-site (Liu et al., 2014; Perales-Momparler et al., 2015). Water quality is defined as the chemical, physical and biological constituents of a specific water sample. Implementing SuDS allows for the filtration of stormwater runoff and therefore, the improvement of the quality of water entering our waterways and water sources. Examples of these SuDS include green roofs, rainwater harvesting, soakaways, permeable pavements, filter strips, swales, detention ponds, retention ponds, and constructed wetlands (Armitage et al., 2013).

Green roofs in particular, have the capability to filter stormwater through their soil and vegetation layers (Zhang et al., 2015). Green roofs are based on the idea that the green space consumed by the footprint of the building should be replaced. There are a number of environmental benefits associated with green roofs, namely stormwater management, lowering of building temperatures, insulating buildings, and positively contributing to human well-being (Oberndorfer et al., 2007; Vesuviano et al., 2014; Zhang et al., 2015). Green roofs are claimed to offer an array of advantages in terms of stormwater runoff, including their ability to temporarily and permanently store runoff, and improve runoff quality. Jarrett et al. (2006) stated that green roofs have the ability to hold approximately 45-55% of the annual volume of rain for a specific region, but that claim has been proven to depend on the amount of rain for every storm occurrence (Carter and Rasmussen, 2006; Moran et al., 2004; Teemusk and Mander, 2007; Hilten et al., 2008). During a rainfall event, stormwater runoff that travels through a green roof system can either be filtered or contaminated by the different plant types or by the constituents of the substrate layer. Studies have shown that green roofs can act as a filter for pollutants and have the capability of improving stormwater runoff quality (Vijayaraghavan and Joshi, 2014; Vijayaraghavan, 2016).

Green infrastructure within the South African context involves many green agendas but places more emphasis on the preservation of biodiversity within the country (Bobbins and Culwick, 2014). Implementing green roofs in South Africa has not been seen as a priority, with the only motivation for the implementation being the additional points allocated by the Green Building Council of South Africa (GBCSA) when a building is being assessed (Booysen, 2014). The poor integration of stormwater management with the rest of the urban water cycle results in South African municipalities not having a holistic approach covering all water services (Fisher-Jeffes and Armitage, 2012). Stormwater is often managed as a potential flood hazard and disposed of as rapidly as possible. This approach focuses on managing quantity and ignores the management of quality. It is against this background that the study seeks to analyse the potential of stormwater runoff from green roofs in enhancing water quality and improving stormwater attenuation.

1.3 Aim and objectives of the study

Aim of the study

The aim of this study is to analyse and compare the quality of stormwater runoff from the Green Roof Pilot Project at the eThekwini Municipality with that of freshwater body standards. The study also seeks to examine the effect of the Green Roof Pilot Project on stormwater runoff rates for the eThekwini Central Business District (CBD).

The objectives of the study are to:

- Analyse the quality of stormwater runoff data captured from the eThekwini Green Roof Pilot Project in terms of physical, chemical, microbiological and organic determinands, pertaining to stormwater discharging into freshwater ecosystems.
- Analyse the quantity of stormwater runoff from the eThekwini Green Roof Pilot Project in terms of retention as a percentage and the delay in peak flow rate.
- Compile a stormwater model using PCSWMM to investigate the effect that the best performing green roof would have on stormwater retention for the eThekwini CBD.

Research questions

The following research questions will be addressed by the study:

- Does the eThekwini Green Roof Pilot Project improve the quality of stormwater runoff in terms of physical, chemical, microbiological and organic determinands?
- Does the eThekwini Green Roof Pilot Project reduce the rate of stormwater runoff, and delay the peak flow rate?

1.4 Outline of the dissertation

The dissertation comprises five chapters. Chapter one provides an overview of the dissertation and presents an introduction to sustainable stormwater management and green roofs in urban areas. This chapter further examines the rationale and context for the research. The aims and objectives of the study, as well as the key research questions are also presented in this chapter. Chapter two provides a review of literature pertinent to the study. The literature review focuses on the impact of urbanization on urban stormwater, the challenges facing urban stormwater, and a synopsis of green roofs in terms of its structure, history, types and benefits. Literature on the role of green roofs in urban stormwater management with regard to quality and quantity is also presented. The chapter concludes with a section on green roofs and stormwater management within the South African context.

Chapter three embodies the research methods used in undertaking the study. An overview of the study area as a well as a detailed description of the Green Roof Pilot Project is offered in this chapter. The data collection methods and apparatus, as well as the methods used for data analysis in the study are explained. A comprehensive analysis of the data as well as discussions on the key findings are presented in chapter four. The content of this chapter includes analysis of runoff for water quality and quantity. The final chapter of the dissertation comprises the conclusion and recommendations of the study. Suggestions for future research on the role of green roofs in urban stormwater management are included in this chapter.

1.5 Conclusion

Stormwater management systems need to be improved to address the negative impacts on the hydrologic cycle that results from urbanization. By devising a stormwater management system that simulates the pre-development stormwater runoff, the negative impacts of urban stormwater can be effectively alleviated. Rooftops are typically unused, vacant areas that are impervious and contribute to the volume of stormwater runoff. Between 40-50% of impervious surface cover in urban areas is unused roof space (Mentens et al., 2006). The implementation of a stormwater control as a retrofit on vacant roofs could significantly reduce the impervious surface cover and help reduce stormwater runoff generation at the source.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Cities around the world are facing severe stormwater-related issues such as water scarcity, degraded waterways, flooding, changing demographics and an ageing infrastructure (Ferguson et al., 2013). Municipal stormwater managers now have to contemplate various management and engineering options that consider the environmental impacts in urban areas (Willuweit and O'Sullivan, 2013). The creation of more green spaces in urban areas is crucial for greener urbanization. Sustainable drainage systems (SuDS) are therefore now favoured, as they mimic the hydrological process that would have taken place, had the site not been developed (Perales-Momparler et al*.,* 2015). However, limited land space and the high land prices in urban areas has made the creation of green spaces rather expensive or virtually impossible (Berndtsson, 2010; Gambi et al., 2011; Bonoli et al., 2013). Given that 40 to 50% of impermeable spaces in urban areas consists of unused roof area (Dunnett and Kingsbury, 2008), green roofs are considered as an appropriate alternative towards sustainable urban stormwater.

The aim of this chapter is to present the literature review for the study. The chapter commences with a review of literature on urbanization, its impact on urban stormwater and the challenges facing urban stormwater. Literature on green roofs is then reviewed with a focus on its history, structure and benefits in terms of water quantity and quality. The chapter concludes with a section that examines literature on stormwater management and green roofs within the South African context.

2.2 Urbanization and urban stormwater

Globally, the urban population is rapidly increasing and urbanized areas are now expanding considerably in terms of space and density. In 2009, approximately 50% of the world's population (3.43 billion out of 6.83 billion) lived in urban areas. Projections indicate that by 2050, approximately 68.7% of the world's population will be residing in urban spaces (United Nations Department of Economic and Social Affairs, 2009). In Africa specifically, urbanization has grown at a rate of 3.9 per cent per year and this rate of growth is expected to continue until 2050. The population in urban areas in Africa has grown tenfold, from 44 million in 1965 to 412 million in 2010 (United Nations Department of Economic and Social Affairs, 2014).

Consequently, urban areas are now expanding considerably in terms of space and density which has given rise to buildings and new developments at the expense of urban green spaces (Getter and Rowe, 2006). The demands of the escalating urban population have therefore reduced the available land for green spaces in urban areas (Berghage et al., 2009; Palla et al., 2010; M'Ikiugu et al., 2014) which in turn has led to an increase in impervious surfaces. Urban areas now comprise large areas of impermeable, man-made hard surfaces such as roads, paving, roofs, etc. (Berghage et al., 2009; Stewart, 2010; Lamera et al., 2014; Samant, 2015). Urban green spaces are important for the natural and social makeup of a city and they play a significant role in sustainable urban development through environmental, social and economic benefits (Chiesura, 2004; Sanesi et al., 2006; Uy and Nakagoshi, 2008; Zhou and Wang, 2011; Tian et al., 2014).

The increase in urbanization and the subsequent increase in impervious surfaces has resulted in a number of negative impacts on city infrastructure and the environment. Such impacts include poor urban air quality, heat islands, and pervasive impervious surfaces that have led to plummeting groundwater levels and poor watershed health as "city expansion typically erodes the natural ability of the locale to perform its ecosystem services" (Ampin et al., 2015). The key environmental concern with urbanization, is the ability of the urban hydrological system to cope with the fluctuation in surface runoff. The urban water cycle has replaced the natural water cycle. This adds to water stress and water insecurity, and is expected to exert huge pressure on urban water management. In particular, stormwater infiltration is considerably reduced which results in increased surface runoff and a strain on existing stormwater infrastructure (Berndtsson, 2010).

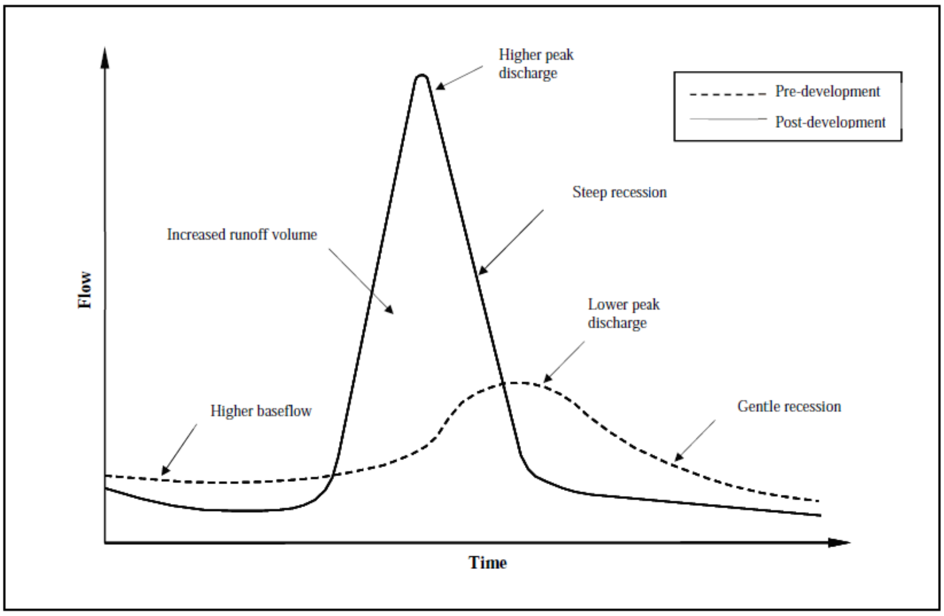


Figure 2.1: General pre-development and post-development stormwater runoff hydrographs

Source: Armitage et al. (2013)

Pre-development conditions result in minimal runoff. Precipitation is mainly infiltrated, evaporated and/or transpired. However, during post-development conditions, there is a substantial increase in runoff due to the impermeable surfaces. This significantly increases the likelihood of flooding and channel erosion downstream. Furthermore, reduced stormwater infiltration into the soil strata reduces aquifer recharge and decreases base flow discharges into receiving watercourses (Armitage et al., 2013). Figure 2.1 depicts the differences in the runoff volume and peak discharge rate for the pre-development and post-development scenarios.

Figure 2.2 compares the natural water cycle with that of the urban water cycle. With the natural water cycle, rains fall over areas of undisturbed soil. This water is then absorbed into the ground where it is stored on site and then cleansed through the soil and vegetation. With an increase in temperature, the water is extracted from the soil, through the plants, and into the air in order to regulate the climate and purify the surrounding air of pollutants (Pevzner, 2013). With heavy rainfalls in the urban water cycle, the water is unable to permeate as it should, and is unable to accumulate in the water table. Instead, the water moves rapidly over the paved surfaces and ends up in nearby waterways. This initial surge of stormwater runoff is called ‘first-flush’. The first flush contains large amounts of pollutants, chemicals and debris which can pose serious threats to wildlife, ecosystems and public health (Pevzner, 2013).

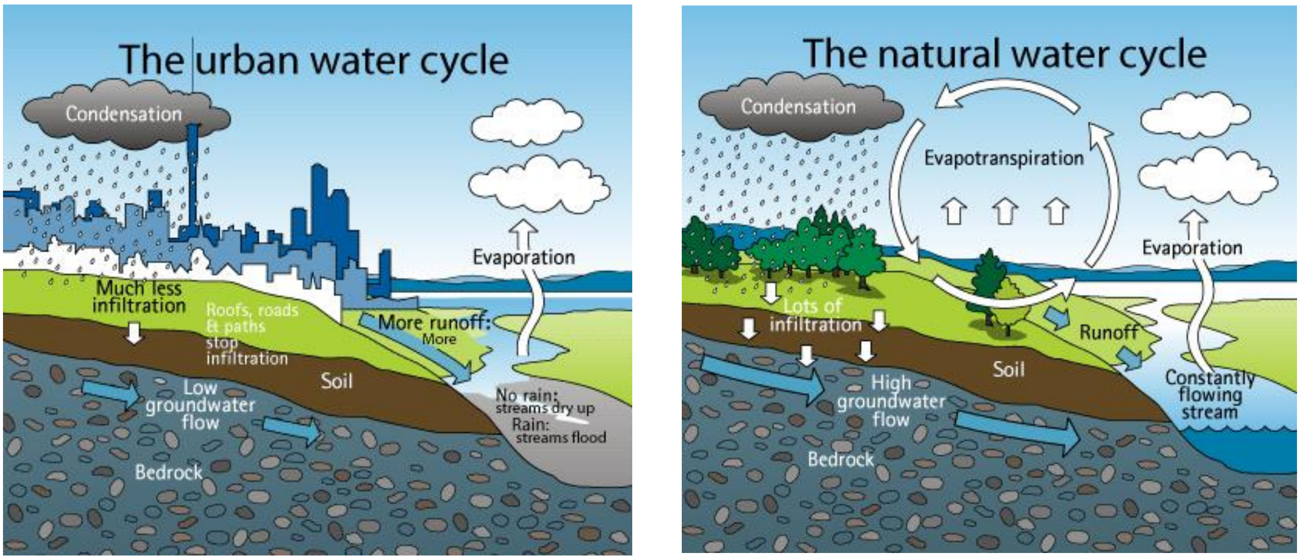


Figure 2. 2: The natural and urban water cycle

Source: Pevzner (2013)

The increase in impervious surfaces in urban areas has therefore reduced the ability of natural soil areas to absorb rain, resulting in an increase in the volume of water flowing into urban stormwater systems, which in turn leads to flooding (Oberndorfer et al., 2007; Edward and Stewart, 2009). Stormwater runoff is no longer able to infiltrate naturally in the soil, leading to changes in the ground-water balance (Bonoli et al., 2013). Figure 2.3 illustrates the relationship between the type of cover and the surface runoff. During a rainfall event, part of the water is absorbed by the ground and the rest flows along the surface as runoff. In vegetated areas where the ground is porous, approximately half of the water from rainfall infiltrates into the ground where it recharges as ground water. About 40% of this water returns into the atmosphere through evapotranspiration and the remaining 10% flows along the surface as runoff (Copeland, 2016). Evapotranspiration is the volume of water lost into the atmosphere through plant respiration and soil evaporation (Hui and Chu, 2009). However, in urbanized areas almost 40% of the land surface is impervious to rainfall which is unable to be absorbed by the ground and flows rapidly into sewers and then into rivers and streams. The US Environmental Protection Agency (EPA) (2003), estimates that, due to the impervious surface in urban areas, a city block will generate five times more runoff than a woodland area of the same size. Only 15% of rainfall in urban areas infiltrates into the ground as groundwater recharge. This increase in runoff in urban areas consequently increases the load of pollutants into streams, rivers and lakes (Samant, 2015; Copeland, 2016).

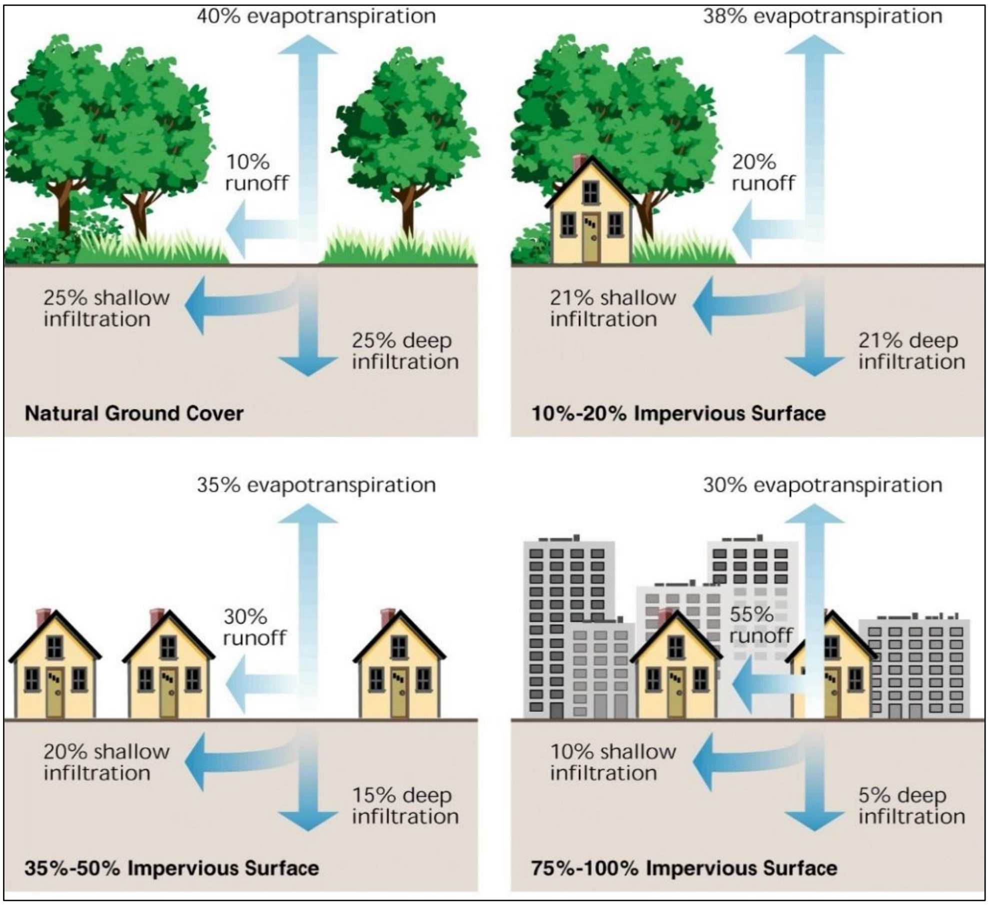


Figure 2. 3: Relationship between impervious cover and surface runoff

Source: The Federal Interagency Stream Restoration Working Group (2001)

Impervious cover in a watershed results in increased surface runoff, and therefore directly influences urban streams by dramatically increasing surface runoff during storm events. Depending on the degree of watershed impervious cover, the annual volume of stormwater runoff can increase by 2 to 16 times its pre-development rate, with proportional reductions in ground water recharge (Federal Interagency Stream Restoration Working Group, 2001).

Urbis Limited (2007) summarized the key problems associated with impermeable paved surface areas in urban areas as follows:

- Flooding

Rapid urbanization has created a strain on natural drainage systems in urban areas which cannot cope with the sudden surge of drainage water during rainstorms. This results in floods which cause significant disruption and financial damage to private and public property and infrastructure.

- Contamination of stormwater

As stormwater runs off impermeable surfaces, it picks up particulates, oil, grease, heavy metals, rubber and garbage from roads, driveways, car parks, pavements and roofs before it reaches storm drains.

- Sewage overflows

The sewage and stormwater systems in older urban areas are sometimes combined. This results in surges in stormwater that can cause an overspill of untreated sewage into public streets.

- Increase in water temperatures

The temperature of runoff from paved areas is higher than that of the surrounding natural drainage systems. This leads to a negative impact on aquatic plants and animals, and encourages algal blooms.

- Drop in local water tables

A large proportion of natural precipitation is discharged into the artificial drainage system, rather than infiltrating into the ground. This results in a drop in the local water tables which in turn makes it difficult for local vegetation to survive without artificial irrigation.

- Large investment in artificial drainage systems

There is a need to invest large sums of public money in stormwater infrastructure that is capable of coping with these runoff surges from impermeable urban surfaces.

Pavement and paved areas therefore reduce infiltration to groundwater, and increase the proportion of water going to surface overland flow. When surfaces are paved, vegetation that originally provided interception and evapotranspiration is removed, and natural depressions in the landscape, which normally detain up to 50% of the runoff, are eradicated. This substantially increases the volume and rate at which the runoff is delivered to the receiving water bodies, resulting in a greater recurrence of floods (Lang, 2010). In addition to exacerbating flooding, erosion and sedimentation, urban runoff is also high in pollutants such as pesticides and petroleum residues which harm wildlife habitats and contaminate drinking supplies, which poses a great challenge for urban stormwater systems.

2.3 The challenge for urban stormwater

Conventional urban stormwater systems have only one purpose, to transfer the water from one place to another via engineered systems which promote efficient and flood-protected land development, through drains, pipes and channels that enhance hydraulic efficiency. Traditionally, urban stormwater was considered a waste product in many countries instead of a precious resource, and its rapid conveyance and discharge contributes to the degradation of receiving waterways (Perales-Momparler et al., 2015).

Graham et al. (2012) highlight the following impacts of conventional drainage systems:

- Flooding

Piped drainage networks convey water far more quickly than natural processes. Flooding occurs where urban development increases the volume and rate of stormwater runoff, and the drainage systems cannot cope.

- Pollution

Surface water runoff is generally polluted with silt, oil and other contaminants which, when discharged into rivers, can harm wildlife and contaminate drinking water sources.

- Low flows in rivers and streams

Piped drainage prevents the natural percolation of rainfall into groundwater resources that support river flows. This can lead to the concentration of nitrates and phosphates in rivers and wetlands, causing an increase in algal blooms, harming wildlife and reducing amenity value.

Conventional approaches fail to address the increase in stormwater runoff volumes and peak flows caused by urban development. The runoff overburdens the municipal wastewater treatment works and carries pollutants such as trash, bacteria and heavy metals into the receiving water bodies that degrade the quality of the urban streams (Liu et al., 2014). There is now an urgent need to improve the management of surface water, especially to adapt to climate change, prevent flooding and protect waterways from pollution (Graham et al., 2012). Cities now face a huge challenge in managing stormwater and are exploring the use of innovative infrastructure in attaining sustainable stormwater management. The urgency to implement environmental policies and practices arises from the realisation that urbanisation is taking place far more rapidly than the planning to deal with it is (Walsh et al., 2012). These actions and their consequences on the environment and its resources, brings about the need for sustainable alternatives in urban planning.

The idea of sustainable development began in the 1990s and has led to rethinking of urban stormwater infrastructure (Berndtsson, 2010). Amongst other infrastructural methods, green roofs present a number of benefits depending upon regional climactic and infrastructural variables. Benedict and McMahon (2002) link sustainable development to green infrastructure, stating that green infrastructure ''is the ecological framework needed for environmental, social and economic sustainability.''

Recently, there has been a shift in identifying and utilizing cost effective, long term and environmentally-friendly infrastructure solutions, which has given rise to an increased interest in green infrastructure (UNEP, 2014). Green infrastructure is also known as Low Impact Development, and basically entails the use of natural landscapes to capture and treat rainfall where it falls. "Green infrastructure systems and practices use or mimic natural processes to infiltrate, evapo-transpire, and/or harvest stormwater on or near the site where it is generated" (Copeland, 2016:1), and are increasingly offering an opportunity for addressing the challenges related to water management. In particular, the green infrastructure approach refers to "the natural or semi-natural systems that provide services for water resources management with equivalent or similar benefits to conventional (built) "grey" water infrastructure" (UNEP, 2014:5). The increasing interest in green infrastructure is due to the need to improve water management as a result of the growing demand for freshwater and the impacts of climate change such as floods and droughts. Green infrastructure is therefore seen as an environmentally appropriate solution to water infrastructure solutions (UNEP, 2014).

New approaches to green infrastructure in stormwater management include the principles and applications of Sustainable Urban Drainage Systems (SuDS), Low Impact Development (LID) or Water Sensitive Urban Design (WSUD) (Palla et al., 2010). As human settlements expand, they begin to impact on the natural hydrological process. Figure 2.4 illustrates an urban catchment with traditional drainage. In urban areas, ditches are dug, fields are under-drained, streams straightened and rivers are embanked in order to quickly take water from the land to the sea. A number of watercourses running through urban areas are encased in large pipes beneath the ground. This has resulted in the natural water cycle being significantly disrupted, and landscapes and wildlife habitats being destroyed. Land that was once permeable is now impermeable, severely impeding groundwater recharge. As urbanization escalates, drains become increasingly overloaded and are unable to cope with heavy rainfall (Graham et al., 2012).

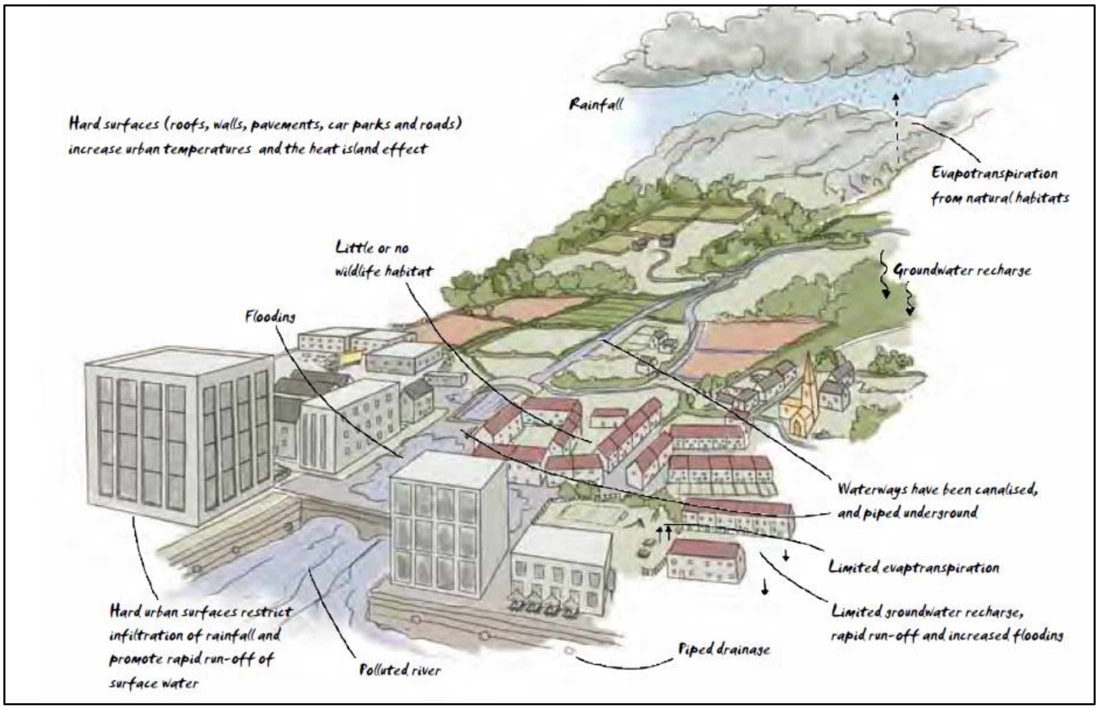


Figure 2. 4: Urban catchment with traditional drainage

Source: Graham et al. (2012)

Figure 2.5 on the other hand, depicts urban catchment with SuDS. Here, the natural processes of managing rainfall are mimicked by SuDS, using the landscape to control the flow and volume of surface water, reduce pollution and promote recharging of groundwater. The natural vegetation in SuDS helps to attenuate flows, trap pollutants, promote infiltration, enhance evapotranspiration and reduce the urban heat island effect.

Graham et al. (2012) summarizes the benefits of SuDS as to:

- manage volume and flow rates of runoff to reduce the downstream flow and destructive power of surface water, and reduce the risk of flooding;
- improve water quality by reducing pollution locally and downstream;
- encourage natural groundwater recharge to help maintain river and stream flows in periods of droughts;
- increase evapotranspiration and climate regulation in urban areas.

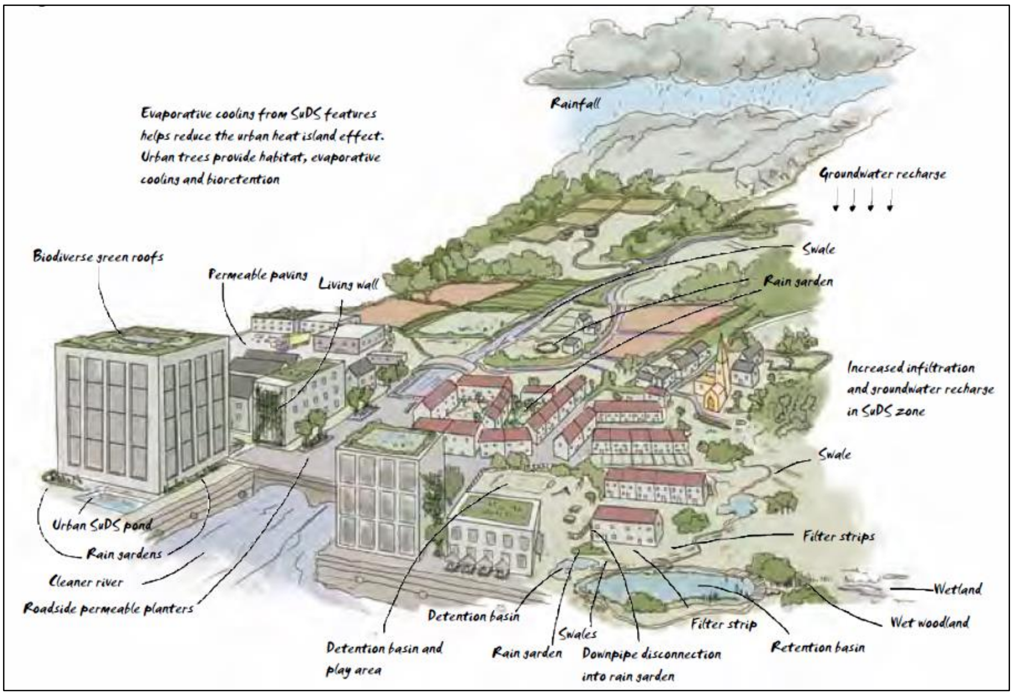


Figure 2. 5: Urban catchment with SuDS

Source: Graham et al. (2012)

SuDS are considered to be a ‘demand management technique that eliminates a portion of the stormwater entering municipal sewers or waterways”. Types of SuDS include green roofs, trees and tree boxes, rain gardens, vegetated swales, pocket wetlands, infiltration planters, vegetated median strips, curb extensions, permeable pavements, reforestation, and protection and enhancement of riparian buffers and floodplains (Copeland, 2016). In particular, green roofs are becoming increasingly popular in SuDS, and are regarded as a suitable technology as there is limited space to implement other types of stormwater controls in urban areas. Land values are often too high in urban areas to allocate much surface area to stormwater control devices. Through green roofs, the impervious area is decreased when planted roofs are installed on, or retrofitted to, buildings, as they contribute to the reduction of peak flow rates and runoff volumes collected by drainage systems (Berghage et al., 2009; Lamera et al., 2014). Moreover, green roofs are considered favorable for SuDS as they do not require any further land-take requirement apart from the footprint of the building (Stovins et al., 2007; Palla et al., 2008; United States EPA, 2009).

2.4 Green Roofs

Green roofs have been suggested as a means to reduce stormwater impacts due to their ability to detain stormwater (Berghage et al., 2009; Stewart, 2010; Samant, 2015). They offer a practical alternative for new construction and for retrofitting existing structures. The literature presents a number of definitions of green roofs. According to Urbis Limited (2007:7) a "green roof development involves the creation of vegetated space integrated structurally on top of a man made structure" and has become a "symbol of sustainable and green cities" (Shahidipour, 2014:104). A green roof is also defined as a flat or sloped rooftop that supports vegetation on a roof or deck designed to provide urban greening for buildings, people or the environment (Dvorak and Volder, 2010:197), while acting as a stormwater management system (Anderson, et al., 2010). Green roofs are also known as vegetated roofs, eco roofs, and living roofs and are viewed as "one way to reintroduce the foot prints of nature into urban environments where forests, grasslands and agricultural fields and other natural systems have been replaced with impervious surfaces in the form of buildings, roads, driveways, and parking lots" (Ampim et al., 2015:701).

In urban areas that experience high rainfall, the main focus of green roofs is on stormwater management. For example, by 2004 the city of Chicago realized that they could not manage the city's stormwater runoff on their own and therefore requested the cooperation of private developers to add sustainable features, such as green roofs, to the design of buildings (Semaan and Pearce, 2016). Chicago has a number of green roofs in its effort to become the greenest city in America (Urbis Limited, 2007) and to date Chicago has over 400 green roof projects in various stages of development

(UNEP, 2014). The Chicago City Hall (Figure 2.6) is an example of a retrofitted extensive green roof system. The City Hall green roof was amongst the first, and has now become an important site for research on green roofs. This green roof contains more than 150 varieties of trees, vines, grasses and shrubs for ongoing research in an effort to support government initiatives and incentives and address the urban heat island effect. The 1,900 m^2 roof on the Chicago City Hall has helped decrease stormwater runoff and improve urban air quality by reducing the urban heat island effect around the site (UNEP, 2014).

Figure 2. 6: Chicago City Hall green roof

Source: Klinkenborg, 2009

2.4.1 The development of contemporary green roofs

Initially developed for aesthetic purposes, green roofs are now being widely recognized for their beneficial impacts on urban drainage in countries such as Germany, Sweden, USA, UK, Japan and Singapore (Mentens et al., 2006; Berndtsson et al., 2006). The modern green roof originated at the turn of the 20th century in Germany, where vegetation was installed on roofs to reduce the damaging physical effects of solar radiation on the roof structure (Köhler et al., 2002). During the 1960s, green roof technology was widely researched in Germany and Switzerland.

The increasing environmental concern in the 1970s, especially in urban areas, set the platform for progressive environmental thought, policy, and technology in Germany. Due to its numerous environmental benefits, green roof technology was quickly adopted, and interdisciplinary research led to technical guidelines, the first volume of which was published in 1982 by the German Landscape, Research, Development and Construction Society (Gedge and Kadas, 2005). In the 1980s, installation of green roofs in Germany grew rapidly, at a rate of 15 to 20% per annum, from 1 million square meters in 1989 to approximately 10 million square meters of green roof by 1996 (Magill et al., 2011). This escalation in the development of green roofs in Germany was spurred by state legislation and government grants, and green roof coverage in Germany alone now increases by approximately 13.5 million square meters per year. Due to similar government support in Europe, green roofs have become an accepted characteristic of urban landscape in countries such as France, Austria, Norway, and Switzerland. In the past two decades, green roofs have advanced in countries such as Germany, Austria and Switzerland with 14% of flat roofs in Germany (13.5km^2) being green roofs, many of which have been promoted through financial incentives (Stovins et al., 2007; US EPA, 2009). Green roofs are also now becoming common in the United States (Magill et al., 2011), notably in Chicago, Portland and Atlanta. In Japan, green roofs are important for their evaporative cooling effect (Onmura et al., 2001), whilst in Sweden they are favored for aesthetics and urban stormwater runoff management (Bengtsson et al., 2005). Green roofs have now become a trend in a number of urban areas in an attempt to green cities, and as a means for addressing the urban heat island effect and reducing urban stormwater runoff (Berndtsson et al., 2009; UNEP, 2014).

2.4.2 The structure of green roofs

Green roofs are structurally engineered, designed and installed to alleviate the problems of urbanization. According to Mentens (2006), a green roof contains three key layers: a vegetation layer, a substrate layer and a drainage layer. According to Pevzner (2013) typical green roof material layers include:

- Waterproofing membrane which is required for all roof types.
- Drainage which ensures that water flows away from the roof.

- Root resistant fabric which is essential to ensure that the roots do not puncture the waterproof membrane.
- Soil medium which must be lightweight to reduce the roof load.
- Vegetation which is often low growing.

There are, however, variations to the structure of green roofs which are dependent on location and requirements. Typically, they comprise several components as indicated in Figure 2.7.

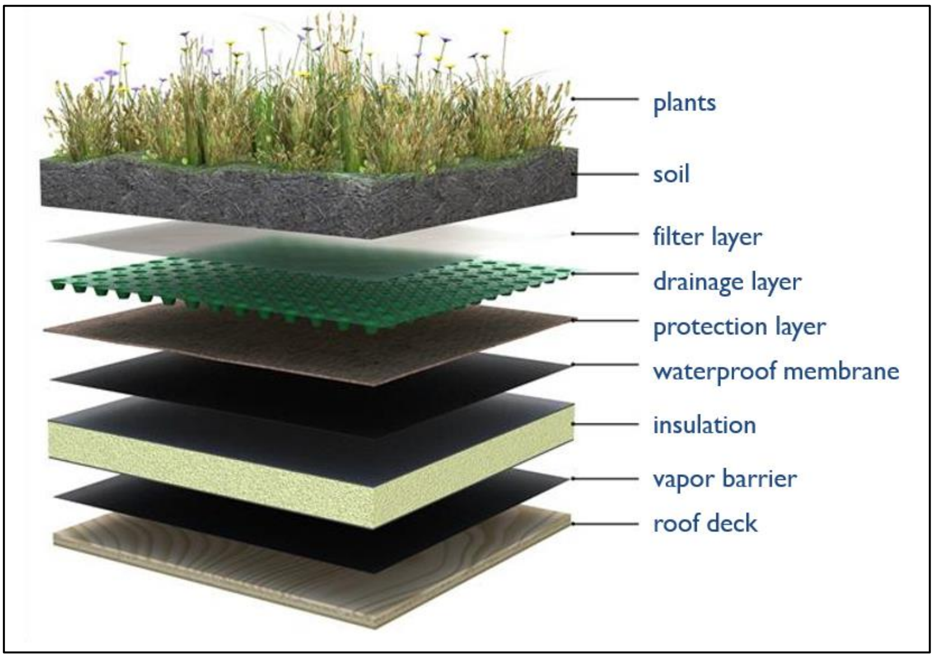


Figure 2. 7: Typical structure of green roofs

Source: Solaiman, 2016

- **Vegetation**

The uppermost layer of green roofs consists of vegetation which improve the quality of runoff, air quality and the thermal performance of green roofs (Dvorak and Volder, 2010; Rowe, 2011; Vijayaraghavan and Joshi, 2014). The type and condition of the plants determines the success and effectiveness of the green roof. Vegetation on rooftops must take into consideration the extreme environment of rooftops and therefore must be able to withstand drought conditions, survive with minimal nutrients, have good ground coverage, be of less maintenance, multiply rapidly and have short and soft roots (Hui and Chu, 2009; Vijayaraghavan, 2016). Plant size and selection depend on the depth of the roof overburden (growing media) and local climate, but almost always consist of winter-hardy, drought tolerant, perennial plants (Berghage et al., 2009).

- **Growth substrate**

The growth and performance of green roofs is directly influenced by the growth substrate, the purpose of which is to "anchor the plant, provide nutrients, and store water" (Magill et al., 2011:15). The growth medium provides a suitable rooting zone for vegetation, and is usually a low-density aggregate with high-water holding capability that provides effective drainage. Lamera et al. (2014) state that, because green roofs are located at the top of a building and are not connected to the natural ground, it is imperative that soils can drain and retain water simultaneously and that they are able to function even in very shallow systems. Water is stored by the substrate and then taken up by the plants from where it is returned to the atmosphere through transpiration and evaporation (Mentens et al., 2006; Onder, 2014). Hence, the choice of growth substrate is critical to the success of green roofs. The growth substrate of green roofs affects water quality improvement, peak flow reduction, thermal benefits and insulation. The characteristics of a green roof substrate include: low bulk density; high water holding capacity; high air filled porosity; high hydraulic conductivity; minimal leaching; high stability; good anchorage; and minimal organic content (Hui and Chu, 2009; Vijayaraghavan, 2016). Growth medium must also have low dry and wet bulk densities, as substrates constitute major load on roof structures (Ampim et al., 2015). It is therefore imperative to keep the weight of the substrate as low as possible. Therefore, heavy and unstable soils cannot be used in the green roof substrate. In order to reduce the weight of green roofs, the use of more than 80% of inorganic components in green roof substrate is suggested. Substrates must include nutrients to promote growth, and it is therefore necessary to include organic constituents to the growth substrate. Common organic constituents include peat, mulch and other composts (Vijayaraghavan et al., 2014; Nagase and Dunnet, 2012). Although organic constituents are necessary, they can contribute to the pollution of the stormwater runoff (Teemusk and Mander, 2007; Vijayaraghavan et al., 2012). Some studies have found heavy metals present in the stormwater runoff (Speak et al., 2014). Harper et al. (2015), also found that adding excessive amounts of nutrients to the media contributes to a higher pollutant concentration found in the stormwater runoff.

- **Filter layer**

The role of the filter layer in green roofs is to separate the growth substrate from the drainage layer in order to prevent soil media particles from clogging the drainage layer. Geotextile fabrics are generally used in green roofs as they are strong and able to withstand the loading from above (Wong and Jim, 2014; Vijayaraghavan and Rajah, 2015). Geotextile fabrics have small pores that enables water permeability and prevent soil water particles from entering the drainage layer. Moreover, the fabric acts as a root barrier membrane for soft and short plant roots (Vijayaraghavan, 2016).

- **Drainage layer**

The success of any green roof is highly dependent on the drainage layer. The drainage layer is an open, highly permeable material that quickly channels water off the roof. More specifically, the role of the drainage layer is to assist in the removal of excess water from the substrate to ensure an aerobic substrate condition and protects the waterproof membrane. Cost, construction requirements, vegetation type and the scale of the green roof are important factors in the selection of a suitable drainage layer (Hui and Chu, 2009; Vijayaraghavan, 2016). There are two types of drainage layers used in green roofs: modular panels and granular materials. Drainage modular panels comprise high strength plastic materials with compartments for storing water while allowing for the release of excess water. Drainage granular materials contain water holding capacity and large pore spaces to hold water such as light weight expanded clay aggregates, expanded shale, coarse gravel, stone chips and crushed brick (Wong and Jim, 2014; Vijayaraghavan et al., 2012).

- **Waterproofing layer and root barrier**

Even though waterproofing may not be a component of the actual green roof, it is essential during the installation of green roofs to prevent leaks. Green roofs have a high moisture content due to the wet soil and drainage layer. Furthermore, a leak detected in an operating green roof implies that all layers need to be removed to locate the leak. For intensive green roofs, root barriers are mandatory, whereas for extensive green roofs they are optional. See 2.4.3 for the distinction between intensive and extensive green roofs. The purpose of a root barrier is to ensure that the roots of plants do not penetrate from the upper layers of the green roof (Bianchini and Hewage, 2012). Root barriers are usually in the form of hard plastics or metal (copper) sheets.

Pevzner (2013:14) maintains that a green roof is “an extension of the existing roof involving a high-quality water proofing and root repellent system, a drainage system, filter cloth, a lightweight growing medium and plants”. This definition provides a basic guideline for green roofs, although green roofs may differ in structure. For example, although layers such as the waterproofing and root barrier must always be used, some green roof projects may require different levels of insulation, an installed irrigation system, different types and depths of growing mediums, or different species of vegetation suited to the specific conditions of the area (Palla et al., 2010; Graham et al., 2012; Shahidipour, 2014).

2.4.3 Types of Green Roofs

There are two major types of green roof: intensive and extensive. The differences between the two are defined by weight, type of plant species, irrigation needs, and the depth of growing medium (Fasnacht, n.d.; Mentens, et al., 2006; Pevzner, 2013; UNEP, 2014; Ampim et al., 2015).

- **Extensive green roof**

Extensive green roofs comprise a shallow substrate supporting low growing, drought tolerant plant species as depicted in Figure 2.8. They are not usually designed for human traffic apart from occasional maintenance. Functionally, extensive roofs are the most cost efficient, as they are much cheaper to install than intensive green roofs (Pevzner, 2013). They further provide maximum ground cover, with the entire rooftop surface covered with green roofing materials, growing substrate, and living plants. They are characterized by low weight, low capital cost, minimal maintenance and minimal technical expertise or practical experience required for installation and maintenance (Getter and Rowe, 2006; Mentens, 2006; Urbis Limited, 2007; Palla et al., 2010; Magill et al., 2011; UNEP, 2014; Samant, 2015).

Figure 2. 8: An extensive green roof in the district of Golzheim

Source: Holzmüller (2009)

- **Intensive green roof**

Figure 2.9 depicts an intensive green roof. Characteristics of intensive green roofs are: a deeper growing substrate; higher weight requirements; higher capital costs; a wider variety of plant species, such as small trees and other vegetation that require deeper soil; and greater maintenance requirements (Mentens, 2006; Urbis Limited, 2007; Dunnet and Kingsbury, 2008; Palla et al., 2010; Migall et al., 2011, Samant 2015). Intensive green roofs are often intended for human traffic, and they are often planned as fully usable landscapes, as they are characterized by their use as a 'garden' in much the same way as people would use a garden at ground level (Urbis Limited, 2007). Pevzner (2013) states that the higher costs, structural, and maintenance requirements of intensive green roofs make them less practical for retrofit applications.

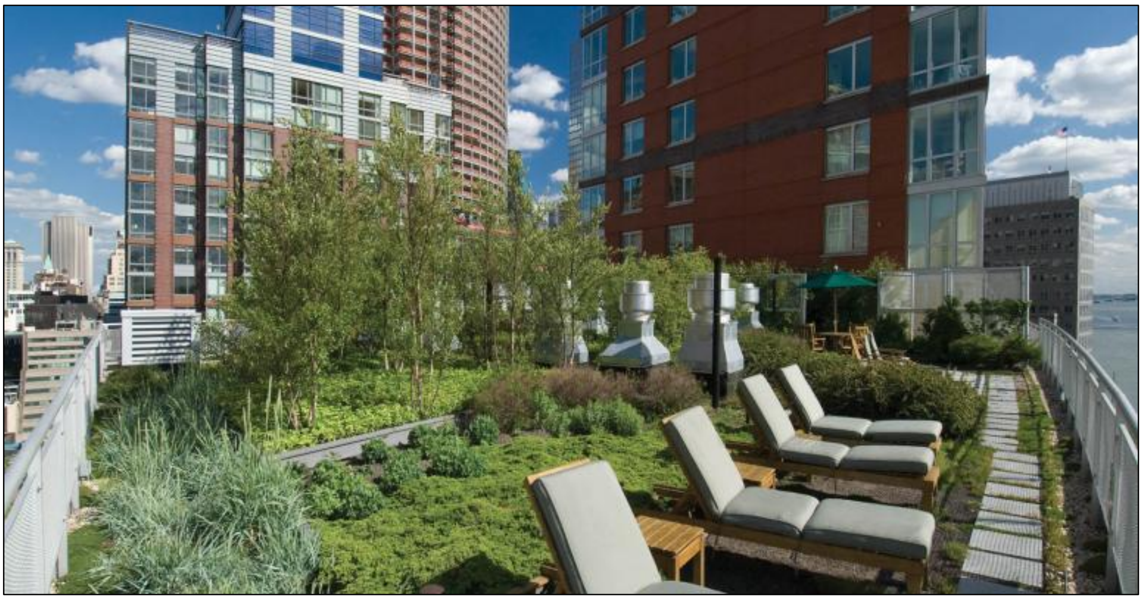


Figure 2. 9: An Intensive green roof at the Solaire building in New York

Source: Anderson (2015)

Wilkinson and Reed (2009) summarize the key differences between intensive and extensive roofs as follows in Table 2.1.

Table 2. 1: Differences between intensive and extensive green roofs

Extensive green roof	Intensive green roof
Shallow growing medium (<150 mm)	Deeper growing medium (>150 mm)
Lightweight structure to support roof	Heavier roof structure required
Requires minimum maintenance	More maintenance required
Lower capital cost	More expensive
Often inaccessible	Often accessible
Does not usually require irrigation	May require irrigation
Minimal structural implications for existing buildings	Likely structural implications for existing buildings

Source: Wilkinson and Reed (2009)

The elements of both intensive and extensive roofs can be combined into one roof top, termed ‘semi-intensive’ green roofs (Ampim et al., 2010). There is ambiguity in the literature in terms of the borderline between extensive and intensive green roofs. Generally, extensive green roofs have a low build-up height (80-150 mm), low load (from 80 kg/m^2) and low-growing plant types, and therefore have low care and maintenance. An intensive roof on the other hand has a higher build-up (250-500 mm), heavier load (300-600 kg/m^2), allows greater plant selection but also requires more maintenance.

2.4.4 *The benefits of green roofs*

The vegetated rooftops of building have yielded a number of environmental benefits as reported by several authors.

Table 2. 2: Review of literature on the benefits of green roofs

Benefits of green roofs	Authors
Stormwater management	• Mentens et al., 2006 • Getter et al. 2007, • UNEP, 2014 • Van Woert et al., 2005 • Bonoli et al., 2013 • Palla et al., 2010
Moderation of the urban heat island effect	• Kumar and Kaushik, 2005 • Jim and Hongming, 2010 • Jim, 2012 • Samant, 2015 • Fang, 2008 • Migall et al., 2011
Improved air quality	• Clark et al., 2008 • Currie and Bass, 2008
Increased biodiversity	• Clemants et al., 2006 • Pearce and Walters, 2012 • UNEP, 2014
Noise reduction	• Connellya and Hodgson, 2013 • Getter and Rowe, 2006 • Van Renterghem and Botteldooren, 2009
Energy efficiency	• Carter and Jackson, 2007 • Berardi et al., 2014
Aesthetic improvement	• Whittinghill and Rowe, 2011

Green roofs are widely promoted for energy savings in buildings as they are able to reduce building energy demand through improvement of the thermal performance of buildings. They are also considered as a practical tool to mitigate the urban heat island (UHI) effect (Saadatian et al., 2013; Hashemi et al., 2015). Green roofs are also reported to reduce noise pollution from urban areas through the provision of increased insulation on the green roof (Yang et al., 2012) and mitigate air pollution in urban centers (Yang et al., 2008). Green roofs can also be viewed as a tool to enhance the aesthetic appeal of any building by converting bland flat roofs into a more pleasant area to experience or view from other buildings, and “they can be utilizable and walkable, so it can constitute a green garden within the city” (Bonoli et al., 2013). Green roofs also aid in restoring biodiversity that has been lost due to urban development (Pearce and Walters, 2012). One of the most important benefits of green roofs is the ability to retain stormwater and delay peak flow, thereby reducing the risk of flooding (Mentens et al., 2006; Chen et al., 2015). Green roofs buffer acidic rain and theoretically retain pollutants, thereby improving quality stormwater runoff (Teemusk and Mander, 2007; Vijayaraghavan et al., 2012).

2.5 The role of green roofs in stormwater management

SuDs stormwater management techniques include storage reservoirs and ponds, constructed wetlands, and sand filters. These surface-area intensive technologies may be difficult to implement in dense urban centers (Mentens et al., 2006; Palla et al., 2008). The greening of rooftops has been asserted as a method to reduce the impacts of stormwater runoff by reducing the impervious surface within a developed area (Palla et al., 2008; Berghage et al., 2009). Green roofs are considered to be effective in urban storm-water management because they makes use of existing roof space and prevent runoff before it leaves the property. Due to their ability to retain stormwater, green roofs can mitigate the effects of impervious surface runoff (Oberndorfer et al., 2007). In particular, green roofs can play an important role in the quantity and quality of urban stormwater.

2.6 Green roofs and water quantity

It is argued that green roofs can contribute to an improvement in runoff water quantity compared to runoff from hard roofs (English Nature, 2003). This is due to the assumption that the total annual runoff from a vegetated roof is usually less than runoff volume from a hard surface, as a result of evapotranspiration (Bengtsson et al., 2005; Getter et al., 2007; Lamera et al., 2014). Compared to conventional roofs, green roofs alter stormwater runoff by reducing and delaying peak runoff, creating a time lag between peak flow from a hard roof and green roof for the same rain event (Berndtsson, 2010). This occurs because a proportion of the water volume is detained by the green roof. Of the detained water, part of it will drain and the other part will be retained. The water that is retained will either evaporate, be used by plants or transpire. This provides an opportunity to reduce and attenuate stormwater runoff at the source. They offer a higher level of water retention than a conventional rooftop during a rain event, reducing the peak flow rate from an area and therefore leading to a reduction of flood risks.

According to Mentens et al. (2006), the reduction in runoff peak consists of:

a) delaying the initial time of runoff due to the absorption of water in the green roof system;
b) reducing the total runoff by retaining part of the rainfall;
c) distributing the runoff over a longer time period through a relatively slow release of the excess water that is temporarily stored in the pores of the substrate.

Therefore, according to Lamera et al., (2014:989):

> Green roofs are designed to capture, temporarily retain and infiltrate storm water, promote evapotranspiration and harvest water at the source, encouraging in general, evaporation, evapotranspiration and the re-use of stormwater. Green roofs introduce natural processes of evapotranspiration and soil water retention into the urban environment, and this helps to protect streams and replicate the natural hydrologic cycle that existed prior to urbanization.

Figure 2.10 depicts the hydrological process of green roofs. According to Stovins et al. (2007:12), “during a storm event the key hydrological mechanisms operating within the green roof are the interception of rainfall by the plant layer, infiltration and storage in the substrate, and reservoir storage in the drainage layer”.

When rain water enters a green roof, portions of water will be absorbed by the growing substrate, retained in the pore spaces, be taken up by the vegetation and either stored in plant tissues or transpired back into the atmosphere (Nagase and Dunnet, 2012). The remaining water enters the drainage element. After all of the drainage space is utilized, the overflow will drain. The retained water inside green roof will evaporate or be used by plants, and parts of it will transpire. Typically, the retention potential of any green roof strongly depends on the type and depth of the growth medium, type of drainage element and its storage capacity, type of vegetation and coverage, volume of rain event and time of previous dry period, and slope of green roof. Growth medium usually plays a significant role in water retention of green roofs.

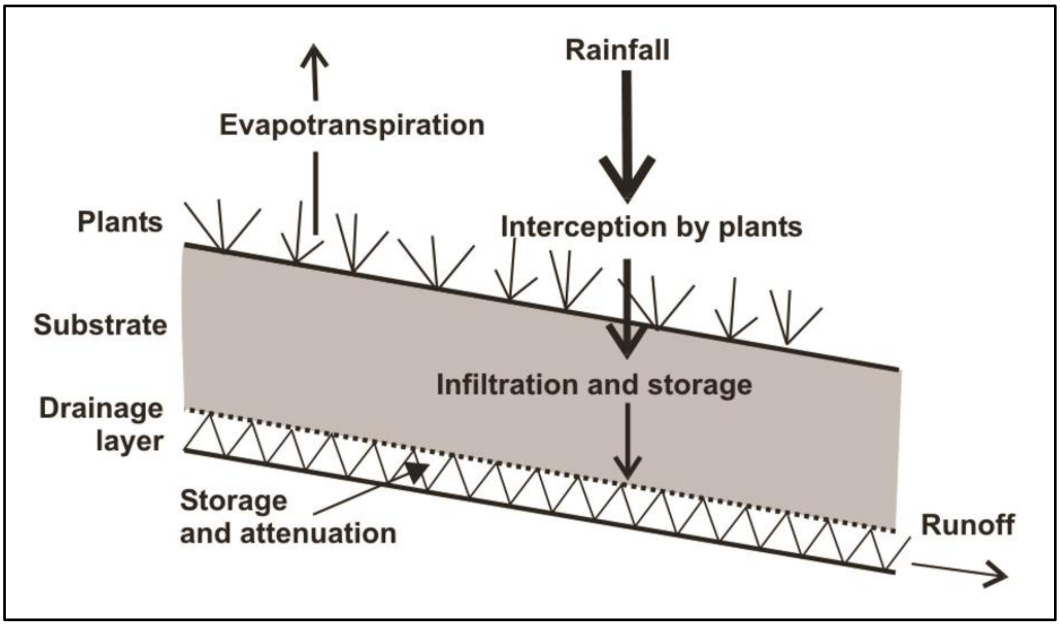


Figure 2. 10: Green roof hydrological processes

Stovins et al. (2007)

The most important benefit of green roofs is, therefore, its ability to hold stormwater and reduce flooding. Several studies confirm high levels of stormwater attenuation from green roofs and their ability to retain significant amounts of rainfall. In particular, green roofs can reduce storm water runoff in comparison to conventional roofs with volume retention in the order of 40–80% of the total rainfall volume and a decrease of 60–80% in runoff peak (Köhler et al., 2001; Liu, 2003; Moran et al., 2004; Bengtsson et al., 2005; Van Woert et al., 2005; Berghage et al. 2009).

Stovins et al. (2007) found that green roofs may be able to provide significant stormwater retention and attenuation in a UK climate with the average volume retention of 34% and the average peak reduction of 56.9%. According to Van Seters, et al. (2009), a study of green roofs at York University in Toronto revealed that the

green roof retained 63% more rainfall than the conventional roof. Samant (2015:74) claims that “gravel = 51% runoff while vegetated = 18% runoff”.
Kolb (2004) reported that green roofs reduced annual runoff by 45-70%, Moran et al. (2004) report 60% total rainfall retention and an 85% reduction in peak flow rate. In Portland, where “eco-roofs” must be irrigated for 3 months in the summer, Liptan (2003) suggested that a 10-35% volume reduction during the wet season and 65-100% volume reduction in the dry season can be achieved. Pevzner (2013) claims that a typical green roof absorbs, filters, retains and stores up to 75% of all annual precipitation that falls on it in most areas of the U.S. Simmons et al. (2008) found that the maximum run-off retention has been as high as 88% and 44% for medium and large rain events, respectively.

In terms of peak runoff rates, a monitoring project on green roof water quality and quantity of a 280 square meter green roof in Washington D.C. found that the roof retained approximately 75% of the total rainfall volume (29 in.) that fell over the ten-month period. This equated to preventing 104 144 liters of wastewater out of the city sewer system (Pevzner, 2013). Graham et al. (2012) claims that a 225m^2 green roof in Abbey Hive, London, stores 60% of annual rainfall in the substrate, plants and through evapotranspiration. Research undertaken by Palla et al. (2010) confirmed that the green roof system is able to significantly reduce stormwater runoff generation with retention scores of 40-80% of the total annual rainfall volume. According to Mentens (2006), a simulation for Brussels reveals that the use of extensive green roofs in only 10% of all roofs in a green urbanized area can reduce runoff by 2.7%. Berndtsson et al. (2006) demonstrated that an extensive green roof with a 30 mm (1.2 in.) substrate depth retained 49% of the annual rainfall.

In a study of green roofs in China, Zhang et al. (2015) reported that retention ranged from 35.5% to 100%, with an average retention of 77.2%. The retention varied with the rainfall intensity, with retention of nearly 94% for small rainfall events (<10.0 mm), >72% for medium rainfall events (10.0–24.9 mm), >67% for large rainfall events (25.0-49.9 mm) and nearly 39% for storm events (>50 mm). Gutteridge (2003) suggested that if 6% of the total roof area utilized green roof technology in Toronto, this would provide over 3.6 million cubic metres per year of stormwater retention capability. Deutsch et al. (2005) calculated that if 20% of all buildings in Washington, D.C., that could support a green roof had one, that they would add more than 71 million liters to the city's stormwater storage capacity and store approximately 958 million liters of rainwater in an average year. In many cities, roofs comprise approximately 40 to 50% of the impermeable urban surface area and therefore reducing the rate and volume of roof runoff can lead to improved stormwater management (Stovins et al., 2007).

Contrary to many of the findings stated above, a study in Johannesburg suggested that there was little or no reduction in the peak discharge from modular green roof systems (Singh, 2016). The research was conducted on modular green roof systems, using simulated rainfall events from a basic hydrology system found at the University of Witwatersrand's School of Civil and Environmental Engineering (Singh, 2016). After simulating a five-day rainfall pattern, typical of Johannesburg, the results indicated there was an increase in peak outflow from the modular systems (Singh, 2016). Singh (2016) suggested that the reason for these increased values was due to a number of characteristics relating to the modular systems, such as the high number of outflow holes, and the larger energy head created by the contained soil.

Green roofs also have the ability to delay peak flow, as depicted in Figure 2.11. Palla et al. (2010) attribute the delay between the time when rainfall starts and runoff begins to flow from the green roof to the time needed for the soil to start draining. Compared to the impervious roof, runoff continues to flow from the green roof for an extended period of time. This delay is due to the fact that water entering the green roof must first filter through the soil, drainage and filter layers before it can discharge from the roof. Hence, green roofs in stormwater control entail the retention of a portion of the rainfall, and delay and decrease the peak rate of runoff from the site (Berghage et al., 2009).

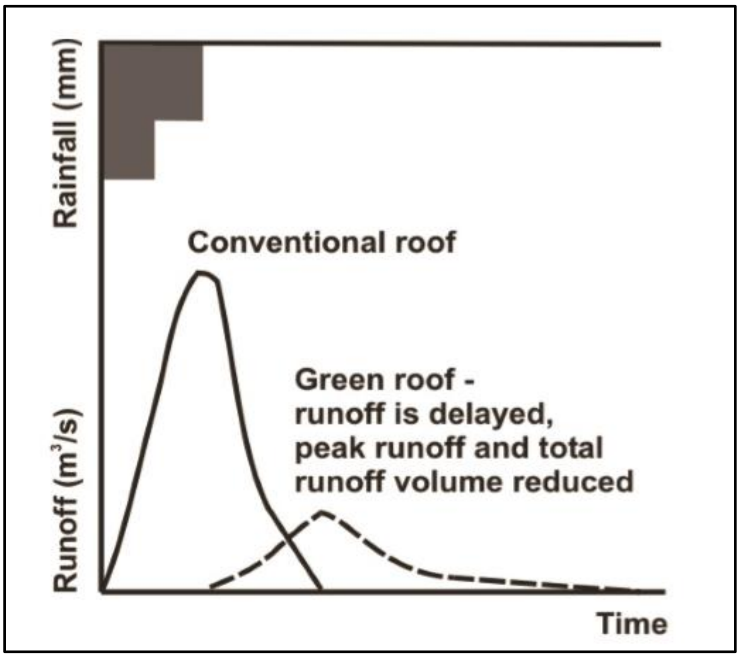


Figure 2. 11: Rainfall runoff response

Stovins et al. (2007:12)

Liu (2003) and Moran et al (2004) found that green roofs can delay runoff by 95 minutes to 4 hours compared to conventional roofs. “Stormwater is retained by the roof membrane and taken up by plants and then gradually released through evapotranspiration back into the atmosphere. Water loads, which saturate the roof membrane beyond its holding capacity, escape the roof laterally via the drainage membrane and then out via drain” (Migall et al., 2011: 25). A study conducted by Hathaway et al (2008) in North Carolina, indicated that the green roof in the study reduced average peak flows by more than 75% and delayed the commencement of outflow where in most cases, the green roof outflow began after several hours of continued rainfall. Razzaghmanesh and Beecham (2014) conducted a study on green roofs at the University of South Australia, Adelaide, and reported a runoff delay time of almost 3 hours for extensive roofs and up to 17 hours in intensive roofs.

Singh (2016) found that various types of modular green roof systems were able to delay the peak discharge by as much as 50%, during a study conducted in Johannesburg under simulated rainfall events.

2.6.1 Factors affecting water retention and runoff from green roofs

Depending on the slope, vegetation covers and depth of the substrate, local climate, rainfall patterns and rainfall intensities, green roofs can hold up to 100% of precipitation (Dunnet and Kingsbury, 2008; Getter et al., 2007; Carter and Rasmussen, 2006; Hilten et al., 2008; Carpenter and Kaluvakolanu, 2011; Nagase and Dunnett, 2012). According to Berndtsson (2010), the key factors that affect water retention and runoff from green roofs are:

- Green roof characteristics in terms of the number of layers and type of materials, soil thickness, soil type, vegetation cover, type of vegetation, slope/length of slope, roof position and roof age.
- Weather conditions such as length of preceding dry period, season/climate (air temperature, wind conditions, humidity), intensity and duration of the rain event.
- The type of green roof (intensive or extensive).

According to Mentens et al. (2006) studies from Germany from 1987 to 2003 showed that intensive green roofs reported annual runoff reduction of 85-65% of annual precipitation, and a median annual retention rate of 45% for extensive green roofs with substrate depths between 3 and 14 cm (Figure 2.12).

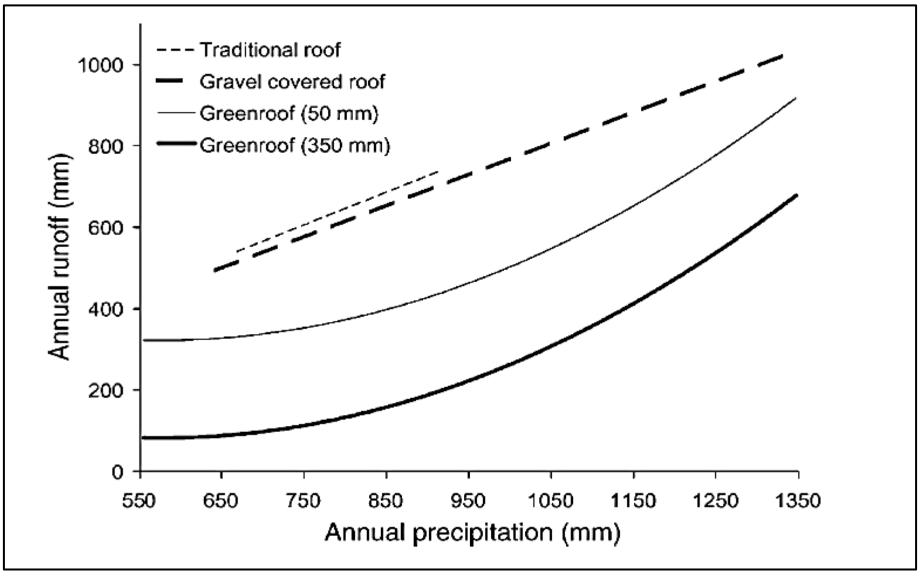


Figure 2. 12: Relationships between the annual runoff and annual rainfall for various roof types

Source: Mentens et al. (2006)

Several other studies have also investigated the relationship between green roof water retention and the intensity and size of a rain event. An inverse relationship between rainfall intensity and percentage of retention was reported by Carter and Rasmussen (2006). Small storms (<25.4mm) showed 88% retention, medium storms (25.4-76.2mm) yielded 54% retention and large storms (>76.2mm) had a 48% retention. Similar results were reported by Simmons et al. (2008) where small rain events (<10mm) were entirely retained by green roofs. For rain events of 12mm, the retention of the green roofs varied from 88% to 26% depending on the substrate and drainage type, whilst rain events of 28mm and 49mm showed retention of 43–8% and 44–13%, respectively. Carter and Rasmussen (2006) established that the peak discharge for small rain events was much lower from the vegetated roof than a conventional roof but this effect was much reduced for larger rain events. The runoff peaks from green roofs were found to be generally delayed compared to conventional roofs; 57% of peaks on a vegetated roof were delayed up to 10 min as compared with peaks from a conventional roof. Similar results were found by Simmons et al. (2008) and Van Woert et al. (2005) who observed 10 min runoff delays for vegetated roofs for heavy rains.

The water retention capacity of green roofs also depends on the season. Mentens et al. (2006) claimed that in Germany, a summer season with warmer temperatures results in higher evapotranspiration and the green roof retention capacity regenerates faster. In particular, season-wise runoff reductions were: 70% for the warm season, 49% for the in-between seasons, and 33% for the cold season.

Slope characteristics and media substrate depths were reported to influence levels of runoff from green roofs. Mentens et al (2006) confirm that the rainfall retention capability of green roofs on a yearly basis can range from 75% for intensive green roofs with a substrate of 150mm, to 45% for extensive green roofs with a median substrate of 100mm. Miller (1998) reported annual reductions of runoff of 38 - 54% and 38 - 45% for an 80mm deep media. A study of an extensive green roof in Korea by Lee et al (2015) demonstrates a 13.8 - 60.8% reduction in runoff for the total rainfall in the test period by retention and the evapotranspiration effect from the soil layer and vegetation layer. More specifically, there was a 42.8 - 60.8% reduction in runoff with 200mm soil depth and a 13.8 - 34.4% reduction in runoff with 150mm soil depth. Similarly, research from the Michigan State University revealed that from 83 rainfall events, 61% of the precipitation was retained by an extensive green roof with 25mm deep media and a 7.5mm thick water retention layer. The researchers further observed that the green roof reduced the peak runoff rate and delayed total runoff from the rooftop. This study concluded that shallower substrate depths and steeper roof slopes resulted in a greater stormwater runoff from the green roof (Durhman et al., 2004; Van Woert et al., 2005).

To quantify the impacts of various treatments on stormwater retention, Van Woert et al (2005) undertook studies of three simulated roof platforms with dimensions of 2.44 x 2.44m which were divided into three sections. The mean precipitation retention ranged from 48.7% for gravel test beds to 82.8% for vegetated test beds. Roof slope and green roof media depth also affected the magnitude of stormwater retention. A number of studies in North America recorded runoff retention during the growing season of at least 60% on roofs with gentle slopes (<10%) and growing medium depths of 60mm or more (Hutchinson et al., 2003; Rowe et al., 2003; Getter et al., 2007; Hathaway et al., 2008). Retention tends to decline to approximately 40% with a 20 to 40mm deep growing medium (Russell and Schickedantz, 2003).

2.7 Green roofs and water quality

While green roofs are observed to provide benefits in terms of stormwater quantity (Liu, 2003; Moran et al., 2004; Bengtsson et al., 2005; Van Woert et al., 2005; Carter and Rasmussen, 2006; Mentens et al., 2006; Getter et al., 2007; Hilten et al., 2008; Palla et al., 2008; Palla et al., 2010; Carpenter and Kaluvakolanu, 2011; Metselaar, 2012; Nagase and Dunnett, 2012), their role in influencing the quality of water has been debatable. Some studies cite an improvement in water quality (Berndtsson, 2006; Berghage, 2007) as green roofs help neutralize acidic rain and reduce the amount of pollutants (Van Seters et al., 2009; Vijayaraghavan et al., 2012), which results in the production of better quality stormwater runoff. Palla et al., (2008) found that green roofs are able to lower pollutant loads associated with the early stages of rainfall whilst Van Seters et al. (2009), in their study of runoff samples from an extensive green roof in Toronto, found that concentrations of most pollutants were lower in the runoff from the green roof relative to that from the conventional roof with the exception of Ca, Mg, and total P. This was attributed to leaching from unprotected metal surfaces around the roof.

Table 2. 3: Stormwater pollutants

<table>
<tr><th>Pollutant group</th><th>Pollutant</th><th>Source</th><th>Impacts</th></tr>
<tr><td>Nutrients</td><td>Nitrogen and phosphorous</td><td>• Fertilizers
• Organic waste
• Organic matter
• Septic tanks</td><td>• Excessive nutrients result in eutrophication.
• Commonly associated with algal plumes, reduced clarity resulting in decreased biodiversity.</td></tr>
<tr><td>Sediments</td><td>Suspended and settable solids</td><td>• Erosion of landscape.
• Erosion of construction sites.</td><td>• Increased turbidity and sedimentation.
• Smothering of aquatic plant and animal life.</td></tr>
<tr><td>Organic material</td><td>Plant litter</td><td>• Landscaping</td><td rowspan="5">• Increased nutrients and sediments.
• Public health risk.
• Contaminated recreational areas.
• Threats to downstream irrigation water and edible crops.</td></tr>
<tr><td>Pathogens</td><td>Bacteria, viruses and protozoa</td><td>• Failing sewer systems.
• Animal waste.</td></tr>
<tr><td>Hydrocarbons</td><td>Oils and grease</td><td>• Motor vehicle emissions and wear.
• Industrial processes and waste.</td></tr>
<tr><td>Metals</td><td>Lead, copper, zinc and others.</td><td>• Motor vehicle wear.
• Industrial leaks.
• Galvanized construction material.</td></tr>
<tr><td>Toxic chemicals</td><td>Pesticides and herbicides</td><td>• Agriculture
• Landscaping</td></tr>
</table>

Source: Krypo (2004); Minton (2002); Opher and Freidler (2010); Armitage et al. (2013)

Table 2.3 indicates the different types of pollutants that are typically found in stormwater runoff and their related impacts. The potential risks of each pollutant that may be present at a site need to be assessed. This is especially important in the case of pathogens where stormwater facilities are open to the general public.

Although green roofs can act as pollution adsorbents and filters, they can also potentially contribute to the degradation of the quality of receiving waters with pollutants released from soil, plants and fertilizers, and be a source of contaminants (Moran et al., 2004; Berndtsson et al., 2006; Teemusk and Mander, 2007; Berndtsson, 2010). Berghage et al. (2009) also confirmed that runoff from green roofs had a higher concentration of most nutrients. Therefore, studies on runoff quality from green roofs reveal contradictory results (Berndtsson, 2010; Vijayaraghavan and Joshi, 2014), as green roofs may have different effects on stormwater quality with the possibility of both filtration and contamination. Studies have also shown vast differences in green roof runoff quality as depicted in Table 2.4.

Table 2. 4: Nutrient concentrations in runoff from green roofs

Reference	Units	N-tot	NO_3-N	NH_4-N	P-tot	PO_4-P
Teemusk and Mander (2007)						
Precipitation	mg/l	0.6-1.3	0.18-0.09	<0.015-0.22	0.012-0.019	0.003-0.004
Rain runoff		1.2-2.1	0.42-0.8	0.12-0.33	0.026-0.09	0.006-0.066
Berndtsson et al. (2009) (average values)						
Precipitation	mg/l	2.65	1.03	1.08	0.04	0.02
Extensive roof runoff	mg/l	2.31	0.07	0.08	0.31	0.27
Intensive roof runoff	mg/l	0.59	0.11	0.15	0.01	0.00

Source: Adapted from Berndtsson (2010)

Moran et al. (2003) undertook a study of green roofs in Northern Carolina and found that although green roofs function as the best management practice for water retention and peak flow reduction, water quality data revealed higher contaminants and nutrient concentrations in the green roof runoff than those in the rainfall and control roof runoff. Common contaminants in urban stormwater runoff include heavy metals, petroleum hydrocarbons, pesticides, suspended solids, nutrients, and pathogenic micro-organisms.

Vijayaraghavan et al. (2012) observed that runoff comprises significant quantities of Na, K, Ca, Mg, NO_3 and PO_4. Forster and Knoche (1999), in a study of green roofs in Germany, found higher heavy metal concentrations in green roof runoff than in rainwater, however this was attributed to leaching from unprotected metal surfaces around the roof. Teemusk and Mander (2007) maintains that the slower the runoff rate, the higher the concentration of total N, NH_4-N and organic material (BOD and COD) in the runoff water.

2.7.1 Phosphorous

Generally, rainwater contains a small amount of phosphorous. Contamination of urban runoff with phosphorous may come from fertilizers, bird droppings and animal excreta. Artificial fertilizers are considered to be a major source of phosphorous in green roofs (Bliss et al., 2009). Several studies have concluded that green roofs are a source of phosphorous in runoff (Berndtsson et al., 2006; Teemusk and Mander, 2007; Hathaway et al., 2008; Berndtsson et al., 2009). Moreover, a number of studies reflect varying concentrations of phosphorous in green roof runoff (Berndtsson, 2010) ranging from 0.006mg/l (Teemusk and Mander, 2009) to 66.0mg/l (Vijayaraghavan et al., 2012). Teemusk and Mander (2007) reported concentrations ranging from 0.012 mg/l to 0.09 mg/l for a 1–2-year-old green roof. Others have reported higher concentrations of 0.23–0.45 mg/l (Van Seters et al., 2009), 0.6–1.5 mg/l (Moran et al., 2005), 0.31 mg/l (Berndtsson et al., 2009), 0.6–1.4 mg/l (Hathaway et al., 2008) and 2–3 mg/l (Bliss et al., 2009). Figure 2.13 indicates that concentration of phosphate phosphorus in green roof runoff was greater than that in precipitation in seven different studies.

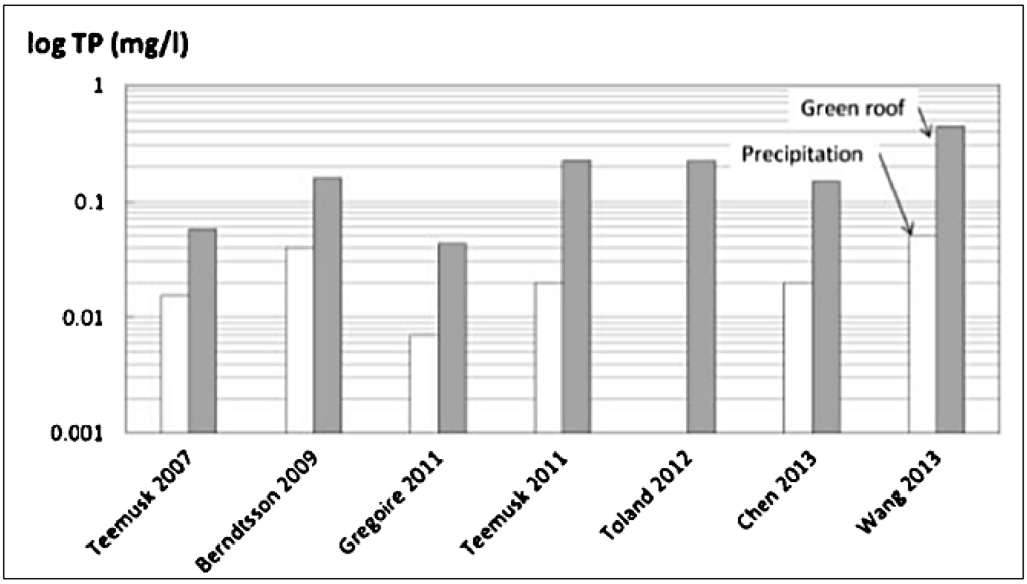


Figure 2. 13: Average concentration of total phosphorus in precipitation and green roof runoff

Source: Li and Babcock (2015)

Phosphorous was identified as a potential concern as green roof runoff concentrations were well above receiving water standards in North Carolina (Hathaway et al., 2008) and Oregon (Hutchinson et al., 2003). Berndtsson et al. (2006) undertook a study of green roofs in Sweden and also reported higher levels of phosphorus, which they attributed to fertilizer application. A study by Van Seters et al. (2009) on the green roof at York University in Toronto also found green roof loads of total phosphorus that were more than triple that of the conventional roof over the monitoring period and proved to be the main contaminant of concern in the green roof runoff. The source of phosphorous from green roof runoff is due to the fact that green roofs are made from soils rich in nutrients in the form of compost and green roofs are regularly fertilized (Teemusk and Mander, 2007; Moran et al., 2005; Bliss et al., 2009).

A study undertaken by Zhang et al. (2015) in China reported that the average total phosphorous concentration of the rainwater (0.035 mg/l) samples was significantly lower than that of the green roof runoff (0.113 mg/l), and asphalt roof runoff (0.091 mg/l). Teemusk and Mander (2007) however noted that concentrations of phosphate phosphorous were much less than the concentration of total phosphorous in green roof runoff. Gregoire and Clausen (2011) and Wang et al. (2013) on the other hand, reported no major differences in the amount of phosphorus in the runoff from green roofs and precipitation. Van Seters et al. (2009), who reported a significant decrease in phosphorus concentrations from the first to the second year of sampling, suggested that phosphorus is leached from the media over time, and that further decreases may be expected as the green roof ages. The reduction in phosphorous concentrations over time is attributed to a process of leaching whereby soil phosphorus is gradually flushed from the growing medium during the first few years of operation. This would suggest that phosphorus levels may have been even higher during the first year of operation, and that levels may continue to decline in the future (Van Seters et al., 2009).

Köhler et al. (2002) concluded that phosphate load reductions is highly dependent on water volume reduction within the green roof, the age of the green roof and fertilization routines. Berndtsson et al. (2009), in their study of green roofs in Japan and Sweden, found that the release of phosphorus was observed from the extensive green roof, most of it in the form of PO_4–P, and concluded that older, stable green roofs leach fewer nutrients than relatively new green roofs. Köhler et al. (2002) also reported a reduction of phosphate phosphorus over time: after a period of four years, the phosphate phosphorus load was reduced from 26% to 80%, due to vegetation development and time since fertilization.

2.7.2 Nitrogen

Nitrogen in soil is found as NO_3-N and NH_4-N. Excess nitrogen levels in natural water bodies can speed up the growth of algae and other aquatic plants, which leads to unpleasant odor and lowered dissolved oxygen levels from plant decay. Forms of nitrogen (ammonium), in combination with pH and temperature variations, can cause water quality problems and be toxic to marine life. This process consumes large amounts of oxygen in the water through eutrophication, and subsequently stresses or kills fish and other aquatic organisms when oxygen levels are reduced (Ahmed, 2011; Hashemi et al., 2015). Nitrogen concentrations from green roof runoff can be attributed to the type of soil, the age of the green roof, and the use of fertilizers on the roof (Berndtsson, 2010).

Studies on green roof nitrate concentration are contradictory, with runoff found in considerably different loads (Moran et al., 2004; Berndtsson, 2006; Teemusk and Mander, 2007; Berndtsson, 2010). Some studies have reported decreased total nitrogen in green roof runoff (Carpenter and Kaluvakolanu, 2011), some have shown unchanged concentrations (Gregoire and Clausen, 2011; Berndtsson et al., 2009), and others show increased nitrate and total nitrogen concentrations (Monterusso et al., 2005).

Berndtsson et al. (2006), in a study of green roofs in Sweden, found that the loads of nitrogen in green roof runoff were considerably less compared to that in precipitation. Teemusk and Mander (2007) reported similar concentrations of nitrogen in both green roof runoff and rainfall, even in heavy rainfall. Another study by Teemusk and Mander (2009) indicated that loads of nitrogen in green roof runoff was lower than that in rainfall. Zhang et al. (2015) reported an average pollutant load of NH_4^+-N (27.16 mg/m^2) in the green roof runoff which was significantly lower than asphalt roof runoff (42.23 mg/m^2), dry and wet deposition (48.57 mg/m^2) and rainwater (49.54 mg/m^2).

Gong et al (2014) reported that the maximum average concentration of total nitrogen was 2.80 mg/l, and the minimum concentration was 1.56 mg/l, which was 62.4% of the level of total nitrogen in the rainwater. Köhler et al. (2002) reported lower nitrate-nitrogen loads in green roof runoff, but that this is dependent upon water volume reduction. Morgan et al. (2011) maintained that green roof runoff resulted in nitrate concentrations of 3.0 to 70.3 ppm over a 15-month period.

Research undertaken by Van Seters et al. (2009) revealed high levels of nitrate, nitrite and ammonia in runoff from the conventional roof. Nitrate concentrations in green roof runoff were very low and the green roof may even act as a sink for nitrates. A considerable release of total nitrogen from green roofs was observed by Moran et al. (2005). Vijayaraghavan et al. (2012) also found that green roofs leach out some nutrients such as nitrate and phosphate in runoff. Zhang et al (2015) reported that the green roof increased the concentrations of total nitrogen, NH_4^+-N, NO_3^--N in stormwater runoff, which are believed to be released from the roof substrate. Berndtsson (2010) maintains that concentrations of nitrogen in green roof runoff can be attributed to the type of soil, the age of green roof and maintenance of the roof. Similarly, Teemusk and Mander (2007) also found that green roofs released more NH_4^+-N after heavy rain-storms.

For heavy rainfall, green roofs did not cause an increase of the concentration of total nitrogen which was similar in rainfall and green roof runoff (Teemusk and Mander, 2007). Different drainage and soil system revealed varying nitrate concentrations, with the shallowest systems showing the highest release (Monterusso et al., 2005). Berndtsson et al. (2009) found that nitrate-nitrogen is generally retained by the vegetation and the total nitrogen concentration for green roof runoff and precipitation are roughly the same, suggesting the roots may be releasing organic nitrogen.

According to Monterusso et al. (2005) the shallowest soil system produced the highest release of nitrates. High levels of nitrate-nitrogen were found to be dependent on plant type, with indigenous plants having lower releases and Sedum seed systems having the highest. This study agreed that the age of the green roof affected nitrogen concentrations, with decreased levels for older roofs. Retzlaff et al. (2008) reported significantly higher nitrate concentrations in green roofs regardless of their growth media. Berghage et al. (2009) found no significant differences between green and asphalt roofs for runoff nitrate concentrations.

2.7.3 pH

Anything that changes the chemical balance of waterways may be detrimental to aquatic plants and animals. pH is an indicator of this imbalance and improving water quality by buffering pH is one of the most important effects of green roofs. This is especially significant in areas where acid rain is prevalent because green roofs help to neutralize acid rain (Berghage et al., 2009; Bliss et al., 2009; Palla et al., 2010).

A study conducted by Berghage et al. (2009) found that green roofs increased the pH of runoff compared to flat asphalt roofs. The study results reported that the pH of runoff from the asphalt roofs ranged from 4 to 7, while runoff from the green roofs was consistently above 6.4. Zhang et al. (2015) conducted a study on the capacity of green roofs to reduce stormwater runoff and pollutants in a typical area of acid rain in China. The study identified the mean pH of rainfall as 5.61. However, the pH value increased to a mean value of 6.84 when the rain-water flowed through the green roof. Hence, the green roof has the potential to neutralize the local rainwater. Berghage et al. (2009) also emphasized that the increased pH was a benefit in an area of such acid precipitation.

Research undertaken on green roofs in Singapore by Vijayaraghavan et al. (2012) found that green roofs showed the potential to neutralize pH of runoff. Green roofs affect run off quality by increasing the pH values from between 5 and 6 (in rain water) to more than 7 and 8 (in green roof runoff water). Zhang et al. (2015) found that the average pH was significantly higher for the asphalt roof (pH 7.35) than for the green roof runoff (6.84). A study examining the effect of asphalt pavement on water quality, also found that the pH of the stormwater runoff had increased after passing over asphalt surface (Roseen et al., 2012). Similar results were found by Berndtsson et al. (2009) in their study of green roofs in Japan, and by Teemusk and Mander (2007) in their study of green roofs in Estonia.

The American Society of Landscape Architects analysed water quality data for the rainwater that ran off its test roof, which revealed that the runoff pH and temperature increased. Gnecco et al. (2013) in a study of a green roof in Italy found rainfall pH that was equal to 5.4 on average while pH values measured at the green roof outflow were 7.1 on average. Similar conclusions were made by Berndtsson et al. (2006), Teemusk and Mander (2007) and Bliss et al. (2009).

2.7.4 Suspended solids and turbidity

Suspended solids form the largest pollutant constituents in stormwater. The accumulation of suspended solids leads to negative impacts on the environment, including: increase in turbidity, making it difficult for aquatic ecosystem to function normally; decrease in light for photosynthesis; contamination of gills in fish and aquatic species; reduction in spawning of fish and general survival; increase in the transportation of heavy metals, phosphorous and other pollutants through waterways as they attach to the sediment particles and harm water quality (Ahmed, 2011). Suspended solids are defined as particles that cannot pass through a 2-micron filter (EPA Method 340). Total suspended solids (TSS) comprise clays, silts, fine organic debris and other suspended particulate matter. Suspended solids from discharges to water bodies also result in sediment build up, which can affect aquatic ecosystems (Harper, 2013).

Turbidity is one of the first measurements of water quality. This is a measurement of the amount of light that can pass through the water sample without being scattered by particles. Green roofs can increase suspended solids and turbidity after installation (Harper, 2013, Dong et al., 2014). Berghage et al. (2009) found that the most noticeable difference between runoff from green roofs and asphalt roofs was the turbidity of the water. Green roof runoff generally has a distinct yellow color, attributed to the green roof media. Berghage et al. (2009: 43) state that “color is a function of the organic components (humic acids), primarily compost incorporated in the media to enhance plant growth and establishment, and will likely decrease with time as the media ages”.

Morgan et al. (2011) found high TSS values (1050 to 250 mg/l) after the first watering event as compared to the second (300 to 75 mg/l) of a newly installed green roof. Gnecco (2013) reported that green roof substrate only slightly contributes to the delivery of solids into the drainage network. Berghage et al. (2009) observed that the runoff color varied with the storm event, namely that small rain events with less runoff resulted in the most colour. Turbidity ranged between 0.8 and 5.6 and was very similar between green roofs, media roofs and flat roofs (Berghage et al., 2009). Research by Morgan et al. (2011) revealed that the highest turbidity levels from the green roofs were evident during the first flush with turbidity values between approximately 550 to 120 NTU. There was a steep decline in the average turbidity thereafter with turbidity values of 150 to less than 50 NTU. Morgan et al. (2011) therefore concluded that TSS and turbidity decrease over time after installing green roofs. They further reported that the media cause the change in water quality more than the vegetation type. Dong et al. (2014) concurred with these other researchers in finding that green roofs reduced the turbidity value.

2.7.5 Heavy metals

Heavy metals are normally present in stormwater runoff, as a result of passing over polluted surfaces. They are not biodegradable and are therefore harmful to aquatic life. The following metals are usually measured for stormwater quality: zinc, cadmium, lead, copper, manganese, nickel, cobalt, vanadium, and chromium. Large proportions of these are found in stormwater, especially the runoff collected from roofs and street surfaces. The assessment of heavy metals in stormwater is very important due their toxicity for living organisms and the fact that heavy metals cannot be easily transformed or removed from water. The content of heavy metals in stormwater varies depending on site, rain intensity and rain duration (Hussain, 2010).

A number of studies indicate that there is no significant release of heavy metals from green roofs. Generally, the concentration the heavy metals in green roof runoff is far less than that from other urban runoff from hard surfaces. Berndtsson et al. (2006) claim that any concentration of heavy metals in green roof runoff usually corresponds to that of moderately polluted natural water. Results from research conducted by Zhang et al (2015) reveal that the average F^-, Cl^-, SO_4^{2-}, K^+, Ca^{2+}, and Si^{4+}

concentrations of the green roof runoff samples were considerably higher than those of the asphalt roof runoff. Copper (Cu) and zinc (Zn) have been the two metals most commonly found in green roof runoff (Köhler et al., 2002; Berndtsson et al., 2009; Berghage et al., 2009). In a study of a green roof in Italy, Gnecco et al. (2013) reported that the water quality data of Cu, Fe, and Zn confirmed that the concentration of heavy metals in green roof outflows was generally lower in comparison to urban impervious areas. The main sources affecting the runoff quality in traditional rooftops are metallic building elements (such as zinc cladding or rolled copper sheets) that contribute to water quality degradation, which may lead to concentration values in the region of 1 mg/l (Gnecco et al. 2013). The potential sources of heavy metals in storm water are degradation of roof material itself, atmospheric fallout, exhaust emissions, industrial activates, road surfaces, and de-icing compounds.

A study by Van Seters et al. (2009) on the green roof at York University in Toronto reported that higher detection frequencies of lead, nickel, cadmium, and beryllium were found in green roof samples whilst runoff from the conventional roofs revealed higher mean concentrations of copper, zinc and manganese. Forster and Knoche (1999), in a study of green roofs in Germany, found higher heavy metal concentrations in green roof runoff than in rainwater.

Research conducted on a green roof at the National University of Singapore by Vijayaraghavan et al. (2012), found that for conductivity and salinity, green roofs act as a source by increasing the concentration of ions in the runoff. Runoffs from green roofs were found to contain high concentrations of light metals such as Na, K, Ca and Mg. Release of heavy metals such as Fe, Cu and Al was also observed in green roofs on several instances. Gnecco et al. (2013) found that the green roof substrate was the main source of calcium and potassium. Gnecco et al. (2013) concluded that potassium behaves as a pollutant source in green roofs while zinc and copper was retained by the green roofs.

Gregoire and Clausen (2011) found that total nitrogen and $NO_3{}^{+}NO_2$–N concentrations were not significantly different between green roof runoff and precipitation. The green roof was a sink for Zn. The green roof acted as a sink for NH_3–N, Pb and Zn. The green roof was a source of $NO_3^+NO_2$–N, total phosphorous, PO_4–P, and Cu. The likely source of Cu was attributed to the type of fertilizer that was used.

2.7.6 Microbiological contaminants

Generally, stormwater harvested on green roofs has some level of fecal contamination, the main sources of which are animal feces, vegetation and air pollution. Factors that determine the microbiological quality of stormwater include: type of roof materials, roof contamination, rain intensity and the length of dry periods between rain events. Microbiological contamination tends to increase with the increased intervals between rainfalls events. Common indicators to assess the microbiological components of stormwater are fecal coliform, fecal streptococci and E. coli (Hussain, 2010).

2.7.7 Factors affecting green roof runoff quality

The differences in runoff quality as indicated by different studies are largely attributed to differences in green roof construction and maintenance. Other factors that affect green roof runoff quality are: type of material used in green roof construction (soil, drainage material or hard roof material), soil thickness, type of drainage, vegetation type, dynamics of precipitation; source of local pollution and physico-chemical properties of pollutants (Berndtsson, 2010); composition of the substrate; age of the green roof; and maintenance (Vijayaraghavan, 2016). In terms of the age of a green roof, Vijayaraghavan et al. (2014) and Rowe (2011) conclude that the quality of runoff in the first year of a green roof may not be representative of the runoff from a much older and established green roof.

A number of studies have focused on the runoff quality from green roofs and have shown that green roofs can filter and absorb pollutants (Berndtsson et al., 2006; Berndtsson et al., 2008; Ayata et al., 2011). However, in the long-term, green roofs can contribute to the deterioration of runoff water quality by releasing fertilizers regarded as pollutants (Berndtsson et al., 2006; Teemusk and Mander, 2007; Berndtsson, 2010). Moran et al. (2003) found that green roof systems have advantages and disadvantages in that they are best management practice for achieving water retention and peak flow reduction, but can result in high nutrient concentrations.

2.8 The situation in South Africa

South Africa is urbanizing rapidly (Figure 2.14), with estimates that 71.3% of South Africa's population will live in urban areas by 2030 and nearly 80% by 2050. The implication of this is detrimental on the natural environment and resources.

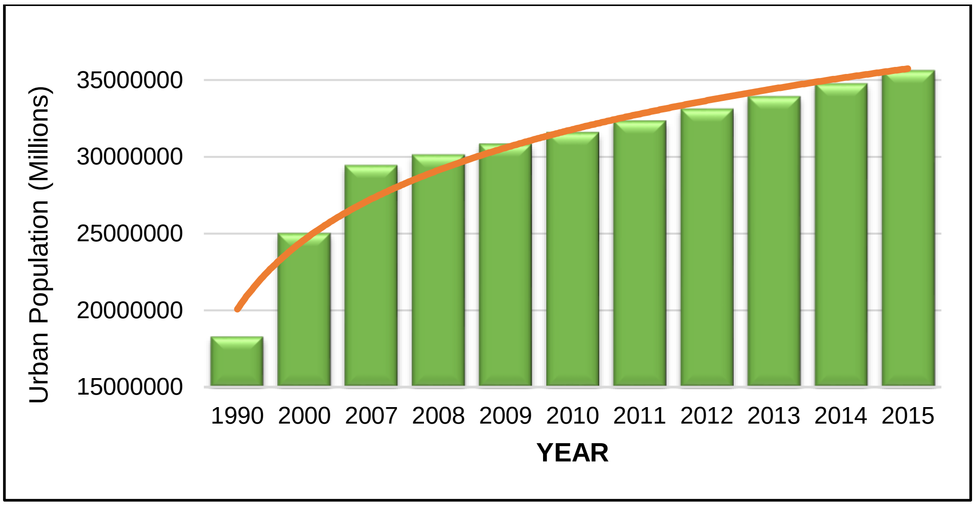


Figure 2. 14: Urban population in South Africa - 1990 to 2015

Source: World Bank Group (2016)

Prior to the 1994 democratic transition in South Africa, environmental management received very limited attention. After 1994, new local government structures led to a change in policy and legislative environment, with a specific environmental management mandate and focus (Roberts, 2008). This simultaneous incorporation of the environmental and development agendas has created a significant predicament for local government, which has led to increased tensions between the need to introduce environmental issues and concerns into planning and decision-making processes, and the need to expedite development to address the important socio-economic needs of the country. Environmental concerns were seen as being of less significance than development priorities in South Africa (Roberts, 2008).

2.8.1 Climate change and stormwater management in eThekwini

eThekwini is located on the east coast of South Africa in the Province of KwaZulu-Natal (KZN). The Municipality spans an area of approximately 2297km^2 and is home to approximately 3.5 million people (eThekwini Municipality, 2011). The municipality faces various social, economic, environmental and governance challenges and therefore strives to address these challenges, which mean meeting the needs of an ever increasing population.

Projections for climate in eThekwini include:

- An increase of 1.5–2.5 °C in mean annual temperature by 2045-2065.
- Rainfall is likely to increase slightly overall. Projected annual rainfall indicates increase in aggregated rainfall by 2065 with an increase of up to 500mm by 2100. This is likely to manifest as an increase in extreme rainfall events and stream flow intensity across the municipal area, with prolonged dry spells between rainfall events. The rainfall is projected to fall over shorter time periods, resulting in higher and faster stream flows. This will overburden the city's stormwater system resulting in floods. There is also likely to be an increase in the number of severe and tropical storms (Lewis, 2010).

Some of the effects of climate change on eThekwini include, amongst others:

- An increase in the frequency and intensity of floods and droughts;
- A decrease in water availability due to changed rainfall patterns and increased evaporation; this will affect subsistence dry land farmers the most.
- An increase in erosional capacity of river courses, resulting in the loss of more top soil, thus decreasing the agricultural value of land and increasing siltation in dams.
- Infrastructural damage as a result of extreme weather events causing flooding, affecting human well-being and safety as well as insurance costs;
- An increase in erosion of coastal areas due to sea-level rise (Environmental Planning and Climate Protection Department (EPCPD), 2009).

With the availability of water for Durban already a contentious issue due to the high hydro-climatic variability over time, and the need for assured water supplies based on the city's continued economic development and the sustainable livelihoods of its people, climate change is likely to add a further stressor to water availability and management in the city (Schulze et al., 2014). Schulze et al. (2014) argue that climate change is important to the eThekwini Municipality's water planners due to the following reasons:

- Water related infrastructure (e.g. dams, irrigation projects, inter-basin transfers, stormwater drains etc.) is typically a long term investment with a design life of 50 - 100 years, is very expensive, essentially irreversible once constructed and is designed to cope with currently (but not necessarily future) expected extremes of floods and droughts;
- Any changes in rainfall (be they up or down) are amplified in changes of hydrological responses;
- Climate change is not going to be experienced evenly throughout the municipality; and
- Climate change, within the bounds of Durban, does not occur on a "clean sheet" of pristine catchments, but is superimposed on land already impacted upon by human interventions (e.g. through urbanization, degradation, intensive sugarcane plantations) and on river channels equally impacted upon by humans (e.g. by dams, off-takes, return flows, environmental flows, inter-basin transfers, pollution), and all of this subject to strong socio-political as well as economic and historical footprints.

The eThekwini Municipality has recognized the impact that climate change will have on the long-term sustainability of the city and the quality of life of its residents. The Municipal Climate Protection Programme which aims to assist the municipality in adapting to and mitigating climate change was initiated in 2004, and began with the assessment of the likely impacts of climate change on Durban. This led to the development of Municipal Adaptation Plans. Developing and monitoring Municipal Adaptation Plans is one of the best ways to ensure that Durban is taking into consideration the impacts of climate change (Lewis, 2010/11). Municipal Adaptation Plans relating directly to stormwater and flooding are depicted in Table 2.5. Municipality sector plans have also been formulated and aimed at water management and climate change (Table 2.6).

Table 2. 5: eThekwini water sector adaptation interventions

Category	Impact	Intervention	Implementation of plan
Infrastructure Protection (New)	Flooding	Detailed analysis of latest rainfall/run-off projections and modelling of systems to be finalized.	• University of KwaZulu-Natal to finalize detailed analysis of level projections. • Water sector officials to work with researchers to understand the nature of and how to interpret results. • Expand municipality's rain gauge network by 30 gauges.
Infrastructure Protection (New)	Flooding	Revise rainfall data in line with latest projections (as of 30 September 2009) and review every 5 years.	• Coastal and Storm Water Catchment Management officials to commission revision of rainfall data for Durban based on projections as of 30 September 2009. • Revised report to be published on eThekwini Municipality website.
Infrastructure Protection (Existing)	Flooding	Protect and restore riparian vegetation so as to protect integrity of river banks and retain biological buffers against flooding.	Initiate a 'Working for Rivers' programme on a catchment by catchment basis.
Infrastructure Protection (New)	Flooding	Develop Master Drainage Plans for all river catchments within eThekwini municipal boundaries.	• Based on rainfall projections at 30 September 2009, revise 1:50 and 1:100yr flood lines to take revised rainfall and run-off data into account. • Identify priority areas for interventions to reduce risk.

Source: Lewis (2010/11)

It is anticipated that climate change will affect not only water supply, but also the demand for water, with projected changes in availability, timing and assurance of water supply. Changes will also affect the broader dynamics of the economy, including water scarcity, water-related disasters, spatial patterns of development and structural changes in economies. Durban's population is estimated to be growing by 150,000 people per year, and it is projected that it will take the city around 30 years to address water and sanitation backlogs (Sutherland and Lewis, 2012). There is a need to identify the impacts of climate change on nutrient and sediment transfer dynamics at a catchment level (Edwards and Withers, 2008), especially with regard to extreme rainfall events, which are highly relevant in Durban. A decline in water quality due to climate change will add pressure on water treatment plants, as well as potential issues with water courses which are used as direct water sources (Schulze et al. 2014).

Table 2. 6: Summary of eThekwini Municipality sector plans

Plan	Summary
• Water Conservation Guidelines • Green Landscaping Guidelines • Energy Efficiency Guidelines • Green Roof Guidelines	These guidelines were prepared through the Greening Durban 2010 Programme and subsequent work, an initiative aimed at ensuring that a positive environment legacy is achieved. • The Water Conservation Guidelines focus on daily management of water and ensures that water is used efficiently and effectively. • The Green Landscaping Guidelines provide information which is replicable to any landscaping project thereby creating an aesthetically pleasing, cost effective, functional, low maintenance and environmentally sound landscape. • The Energy Efficiency Guidelines provide information which can be used to stimulate wider implementation of intelligent building design thereby becoming more energy and resource efficient. • The Green Roof Guidelines provide recommendations on the creation of green roofs in Durban and their benefits in terms of addressing climate change and promoting biodiversity.
• Municipal Adaptation Plan, Health and Water	Durban already faces challenges associated with water availability and storms, but the nature and occurrence of these events is likely to change with altered climates. The impact of these direct, physical, climate risks have multiple, interlinked, secondary and tertiary effects including effects on social and institutional arrangements. Water availability and quality, and health (including food security) have been identified as potentially being critically affected by climate change in Durban. The institutions

	central to the responses to these challenges within the eThekwini Municipality are: • Water Sector Water and Sanitation (Coastal, Storm water and Catchment Management and Coastal Policy); • Health Sector Environmental Health (Clinical Health; • Social Development (food security); and • Communicable Disease Control.
• Durban Climate Change Strategy	eThekwini Municipality has developed as draft, a city-wide climate change adaptation and mitigation strategy through an inclusive and participatory process. The development of this strategy acknowledged that we live in a world with finite and diminishing natural resources, such that Durban needs to convert to a low carbon, green economy that prioritizes the sustainable use of ecosystem services whilst still overcoming the development challenges faced by the majority of Durban residents.

2.9 Conclusion

The global urban population is increasing at an alarming rate and urban areas are now expanding considerably in terms of space and density. Estimates indicate that by 2050, more than 65% of the world's population will be living in urban areas. The increase in urbanization and the subsequent increase in impervious surfaces have altered the ability of the urban hydrological system to cope with the fluctuation in surface runoff water. Conventional approaches fail to address the increases of storm runoff volume and peak flows caused by increasing urban development. Sustainable Drainage Systems (SuDS) are considered to be a solution to this challenge. Sustainable/green stormwater engineering and water sensitive urban design (WSUD) is an important element of SuDS. Green roofs are considered as favourable SuDS in urban areas. Green roofs are known to reduce the impacts of stormwater runoff by reducing the impervious surface within an urban area. In particular, green roofs can play an important role in the quantity and quality of urban stormwater. The urbanization rate within South Africa, and in particular, the eThekwini Municipality is causing a strain on natural resources. Despite the legislation in place to try to combat climate change and aim for more sustainable solutions, little has been developed and implemented by the eThekwini Municipality in terms of green roof infrastructure.

CHAPTER THREE: RESEARCH METHODS

3.1 Introduction

This chapter discusses the research methods adopted for this study. The chapter begins by providing an overview of the study area, the eThekwini municipality region, in terms of its key characteristics related to the study objectives. Thereafter, an in-depth description of the study site, the Green Roof Pilot Project of the eThekwini Municipality, is presented, highlighting its location, construction, structure, and objective. The chapter progresses to explain the research methods used in obtaining the data for the study as well as the data extraction and analysis procedures that were undertaken.

3.2 The eThekwini region

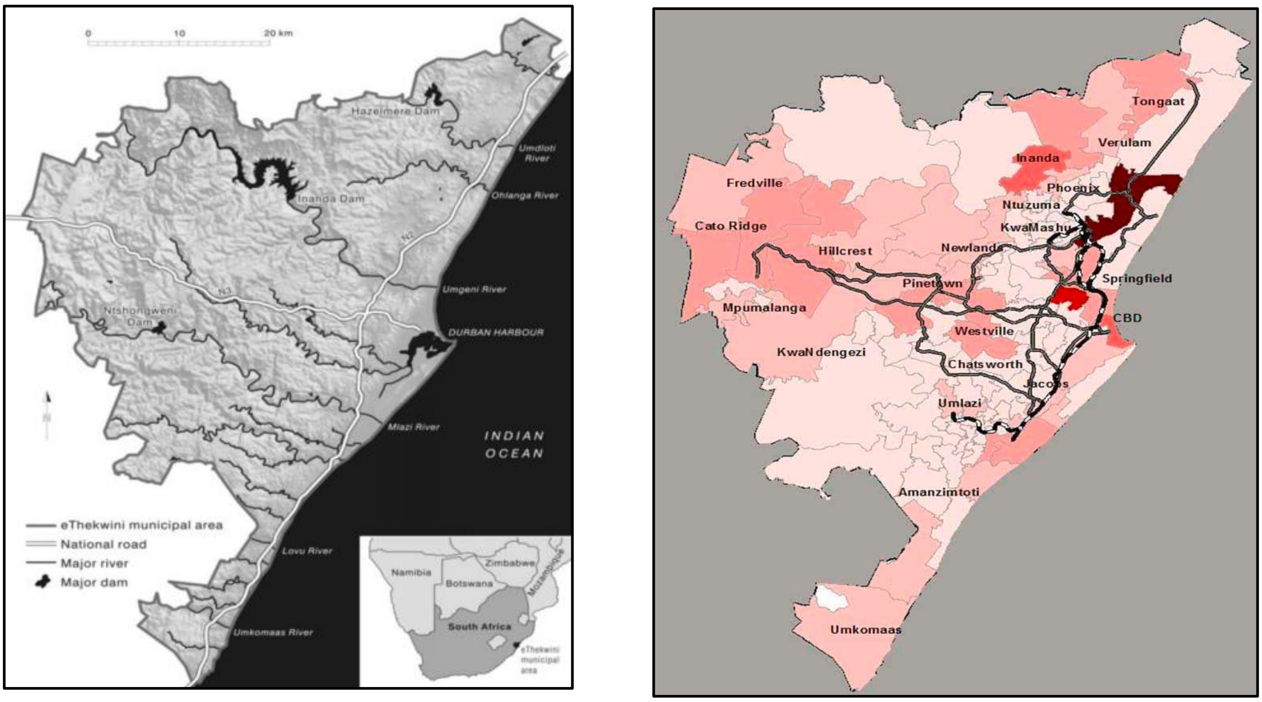


Figure 3. 1: Location of the eThekwini region

Source: Roberts (2009)

The eThekwini region, or Durban, is located on the south-eastern coast of South Africa, in the province of KwaZulu-Natal (KZN). The eThekwini region is 229,193 hectares (2292 km^2) and is bounded by the uTongati River in the north, the aMahlongwa River to the south, and the Indian Ocean to the east (Environmental

Planning and Climate Protection Department, 2014). The region covers approximately 98 km of coastline, along with 18 river catchments, 16 estuaries, and over 4,000 km of river. The main river that flows through city into the ocean is the Umgeni River (eThekwini Municipality, 2007). The population of eThekwini grew from 3.09 million to 3.45 million between 2001 and 2011, indicating an average annual growth rate of 1.13%, as depicted in Table 3.1. eThekwini's population is estimated to grow at a steady rate over the next few decades with a projected population size of between 4.1 and 4.5 million by 2035 (eThekwini Municipality, 2014).

Table 3. 1: eThekwini's historical population size and population projections

Year	Population	Annual growth rate
2001	3.090.000	Average annual growth of 1.13% (2001-2011)
2011	3.442.361	
2012	3.446.447	0.12%
2013	3.480.726	0.98%
2014	3.517.157	1.04%
2015	3.555.868	1.09%
2016	3.596.543	1.13%
2017	3.638.918	1.16%
2018	3.682.524	1.18%
2019	3.727.032	1.19%
2020	3.772.097	1.19%
2021	3.818.499	1.22%
2035	>4.000.000	

Source: eThekwini Municipality (2014)

Urban migration is contributing significantly to the population growth in eThekwini, with most migrants to the city coming from the province of KwaZulu-Natal (KZN). One of the major implications of population growth in the eThekwini region is new development that is transforming land along the urban periphery. In particular, the percentage of eThekwini land area that is transformed increased from 49% to 53% from 2008 to 2011 (Environmental Planning and Climate Protection Department, 2011/2012). This has led to a greater encroachment into natural habitats and reduction in biodiversity, and increased costs and capacity challenges to provide infrastructure services (World Bank Group, 2016).

3.2.1 *Climate/weather profile of eThekwini*

EThekwini has a mild and sub-tropical climate. Figure 3.2 reflects the average monthly minimum and maximum temperatures for the region. The maximum daytime temperature is 28°C during the months between January and March, while the minimum temperature during this period is 21°C. During the months from June to August, the maximum temperature reaches 23°C with the minimum being 11.5°C during this time.

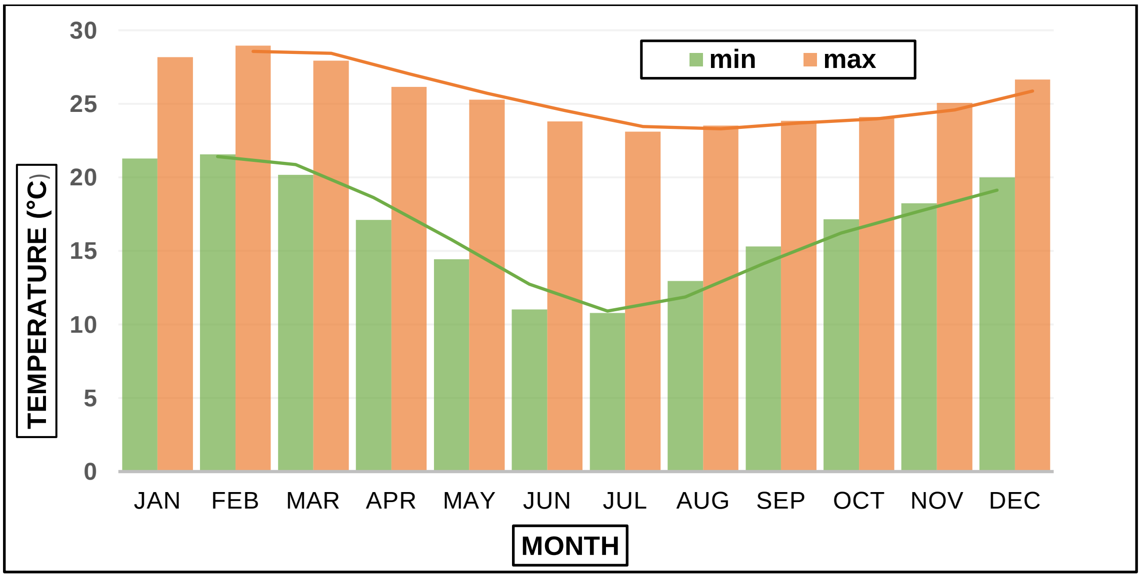


Figure 3. 2: Monthly minimum and maximum temperature for eThekwini (2005-2015)

Source: Adapted from the South African Weather Services (2016)

Figure 3.2 depicts the average yearly temperature from 2005 to 2015 for the eThekwini region.

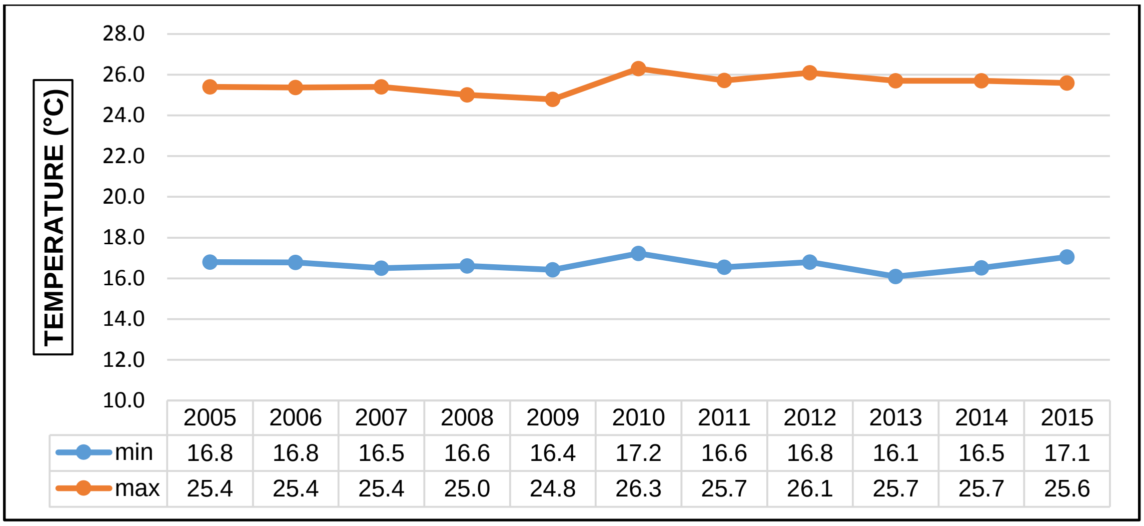


Figure 3. 3: Average yearly minimum and maximum temperatures for eThekwini
Source: Adapted from the South African Weather Services (2016)

Average monthly rainfall measures from 2001 to 2015 are depicted in Figure 3.4 and the average yearly rainfall measures from 2005 to 2015 are depicted in Figure 3.5. The data indicates that the least amount of rainfall measure is between May and August. August is the driest month for the eThekwini region, with an average precipitation of 31 mm. The summer period, from November to March, is the wettest season in the eThekwini region, with a high level of humidity. Summer months tend to be warm and wet, while the winter is dry, with the least occurrence of rain during the winter months.

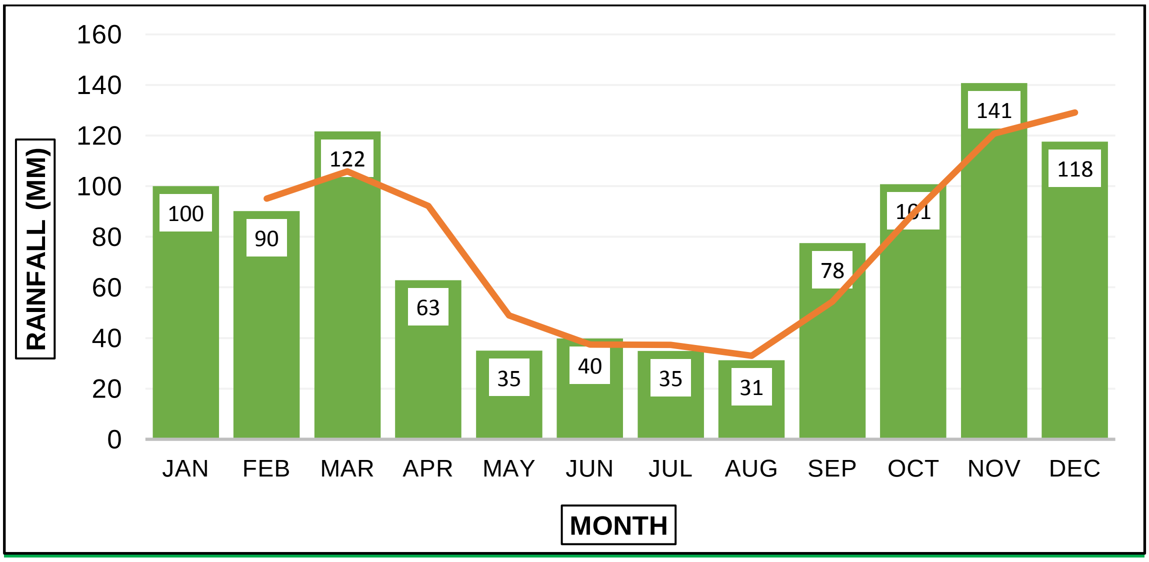


Figure 3. 4: Monthly average rainfall data (mm) for eThekwini
Source: South African Weather Services (2016)

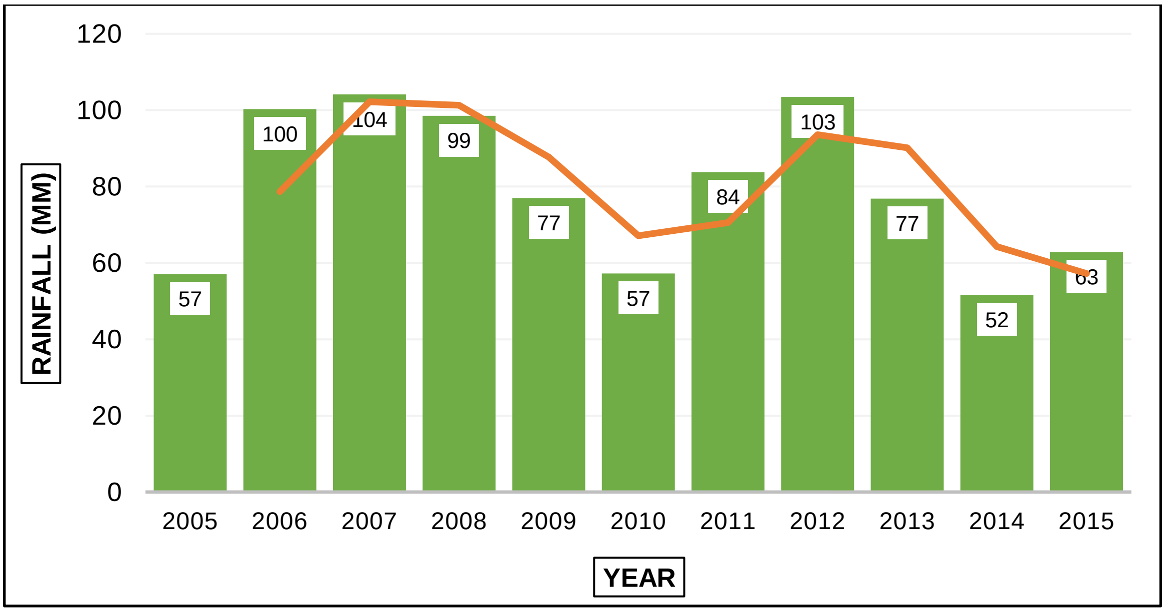


Figure 3. 5: Yearly average rainfall data (mm) for eThekwini (2005 to 2015)

Source: South African Weather Services (2016)

According to the Environmental Planning and Climate Protection Department (2014), the following changes in climate are projected for eThekwini:

- The average annual temperature increase is expected to be between 1.5°C and 2.5°C by 2065, and increase between 3°C and 5°C by 2100.
- Potential increase in aggregated rainfall by 2065, with an increase of up to 500 mm by 2100.
- The northern parts of the eThekwini Municipality are expected to experience increases of up to 20% in long duration (1 day and longer) rainfall.
- The outer west areas are predicted to experience increases in short duration rainfall, which may lead to localized increases of up to 30% in short term flooding.
- An estimated 30% to 100% increase in year-to-year rainfall variability.
- More intense rainfall events with increased erosive capacity.
- Increasing numbers of heat waves.
- Future sea level rise is expected to be greater than the current rate of 2.7 (+/- 0.05) mm/year.

This increased rainfall will generally be experienced through more intense storm events, resulting in more intense and frequent flooding. Due to this anticipated increase in rainfall variability and intensity, existing dams may be unable to capture and store sufficient water for drier months and years. In addition, the stability and health of watercourses and streams may be affected by the more frequent and intense flooding (Environmental Planning and Climate Protection Department, 2014). Therefore, the water supply systems in eThekwini are under considerable stress as a result of periods of drought, more intense rainfall events due to climate change, deterioration of water quality and catchments, lack of adequate bulk infrastructure, and rapid urban growth (eThekwini Municipality, 2012).

With regard to stormwater, the average rate and volume of stormwater runoff in eThekwini has increased due to the increase in the proportion of impervious surface area. The area lacks a city wide drainage system to slow the velocity and volume of storm water runoff and, as a result, flooding has been increasing with sea level rise and intensity of storm events. In terms of stormwater management, eThekwini has approximately 3700 km of stormwater pipes, 200km of culverts, and 50 km of canals (World Bank Group, 2016).

3.2.2 Water management in South Africa

With regard to water resources, South Africa is considered a water-scarce country (DWA, 2013). The adequate provision of water to the country's citizens is one of the most significant challenges facing the country. If a water crisis is to be averted, existing systems will need to be managed effectively (Muller et al., 2009), both in terms of quantity of resources as well as quality (Armitage et al. 2013). Future pressures on water resources are expected to arise from a growing (and urbanizing) population, development of new mines and power stations, forestry and irrigation development, as well as pressures resulting from poor water quality and management. Many of these pressures are specific to particular areas of South Africa as depicted in Figure 3.6.

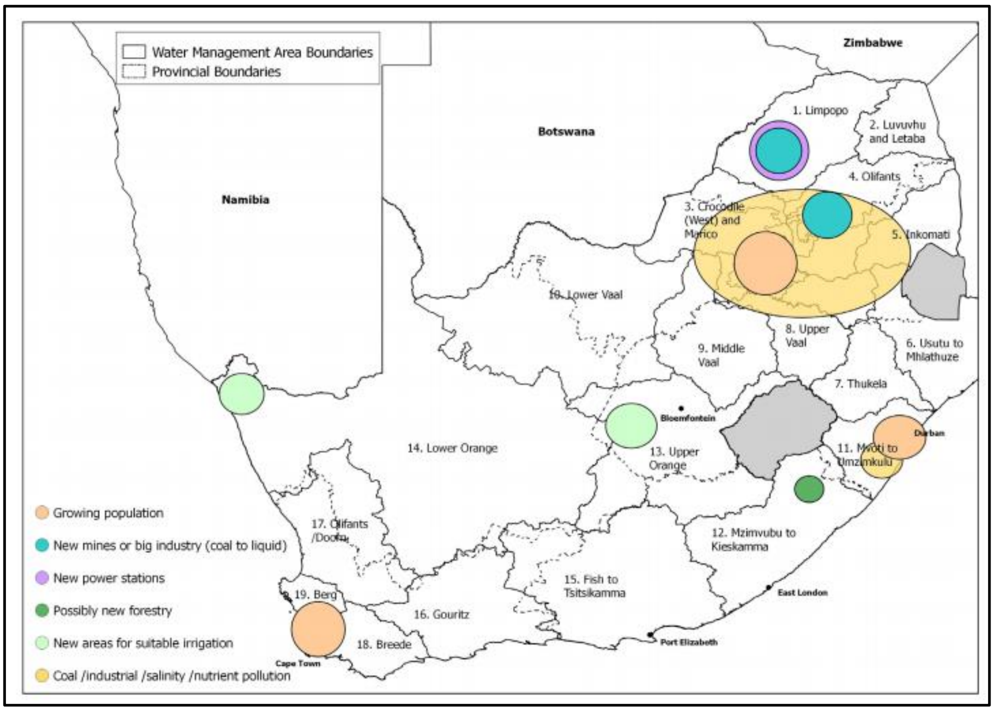


Figure 3. 6: Future possible pressures on the water resources due to possible developments in different sectors

Source: DWA (2011)

Moreover, South Africa is faced with water quality challenges which are mainly induced by human activity as well as natural causes. Table 3.2 indicates the trends that exists in South Africa with regard to water systems.

Table 3. 2: Trend analysis in South Africa per water feature

Indicator	Trend	Notes
Freshwater ecosystems	Deteriorating	More than half of river ecosystem types are threatened. Water is a scarce resource and rivers are stressed to meet development targets with the result that many of these systems are highly modified.
Water availability	Deteriorating	There is a rapidly increasing demand for water, yet a limited and fully allocated supply. Most catchments are already over-extracted and likely to enter into a negative water balance.
Water quality	Deteriorating	Increased salinity and pollution from agriculture, mining and urban runoff. Increasing sediment in water

		from poor land management and soil erosion. Water quality is a problem, particularly in urban areas where the effects are compounded.
Rainfall	Seasonal shifts	No real evidence exists of changes in rainfall over South Africa, but there are areas where significant changes in the characteristics of precipitation have occurred. These localized changes include more extreme wet and dry conditions.

Source: Department of Environmental Affairs (2016)

In response to water related environmental impacts, South Africa has formulated and adopted numerous acts, regulations, policies, guidelines and strategies which occur at the national level, which are summarized in Table 3.3.

Table 3. 3: Environmental legislation in South Africa pertaining to water management

Title	Objective
Environment Conservation Act 73 of 1989	Provides for the effective protection, control and utilization of the environment.
National Environmental Management Act (107 of 1998)	Provides for co-operative environmental governance based on the principles that everyone has the right to an environment that is not harmful to his or her health or well-being, and enabling the administration and enforcement of other environmental management laws. The Act requires that these principles be applied by municipalities, and used to undertake environmental impact assessments (EIAs) and to prepare Environmental Management Frameworks.
National Environmental Management: Biodiversity Act (10 of 2004):	Supports the conservation of plant and animal biodiversity, including the soil and water upon which it depends.
National Water Act (36 of 1998)	Promotes the protection, use, development, conservation, management, and control of water resources in a

	sustainable and equitable manner. The purpose of this Act is to ensure that the nation's water resources are protected, used, developed, conserved, managed and controlled in ways which take into account amongst other factors - • meeting the basic human needs of present and future generations; • promoting equitable access to water; • redressing the results of past racial and gender discrimination; • promoting the efficient, sustainable and beneficial use of water in the public interest; • facilitating social and economic development; providing for growing demand for water use; • protecting aquatic and associated ecosystems and their biological diversity; • reducing and preventing pollution and degradation of water resources; • meeting international obligations; • promoting dam safety; and • managing floods and droughts.
National Response to Climate Change White Paper (2012)	The National Response to Climate Change White Paper is the South African Government's response to the threat of climate change. It provides guidance in terms of policy development and implementation.
National Environmental Management: Integrated Coastal Management Bill (2008) (and amendments):	Supports integrated coastal and estuarine management system to promote conservation of the coastal environment, maintain natural coastal landscape and seascape attributes, and ensure that development and use of natural resources within the coastal zone is socially and economically justifiable and ecologically sustainable.
Marine Living Resources Act (18 of 1998)	Supports conservation of marine ecosystems.
National Framework for Sustainable Development (2008)	Purpose is to express the national vision for sustainable development and indicate strategic interventions to re-orientate South Africa's development path in a more sustainable manner.

National Strategy on Sustainable Development (2010)	The National Strategy on Sustainable Development builds on the National Framework for Sustainable Development and a number of existing initiatives by business, government, NGO's, academia and other key role players to address sustainability issues in South Africa. It is a forward-looking strategy that regards sustainable development as a long-term commitment that combines environmental protection, social equity and economic efficiency.
Environmental Impact Assessment Regulations (R1183 of 5 September 1997)	Procedures to be followed when an application has been lodged with the relevant authority to conduct a proposed activity, including preparation of a scoping report by an independent consultant, a 'full' environmental impact assessment and alternatives, and environmental issues identified in the scoping report.
SANS 10400-R: Stormwater Disposal	In August, 2012, the South African National Standards (SANS) released the publication of national regulations that pertain to stormwater management, entitled, 'SANS 10400-R: The Application of the National Building Regulations – Part R: Stormwater Disposal' (SABS Construction Standards, 2012). The document is heavily premised on 'hard', conventional urban drainage practices and there is no consideration given to SuDS options that are effective in the disposal of stormwater runoff from properties.
Drainage Manual (2006)	The 5th edition of the Drainage Manual was published by the South African National Roads Agency Limited (SANRAL) in 2006 (SANRAL, 2006). The manual was published as a guide to assist in meeting the challenges of stormwater drainage in urban environments. The manual is also premised on 'hard', conventional drainage practices, but provides useful equations and 'tools' that can be used to calculate drainage volume and flow characteristics for more sustainable forms of urban drainage.

3.2.3 Stormwater management in South Africa

Urban stormwater planning and design in South Africa concentrates on collecting runoff and channeling it to the closest watercourse, which usually has an impact on the environment through the resulting erosion, siltation and pollution. “Whilst some local authorities have gone to considerable lengths to reduce runoff peaks through the use of retention and detention ponds, very little attempt has been made to improve stormwater quality and almost no attempt has been made to treat stormwater as a resource” (Armitage et al., 2013:1-1).

Stormwater management in urban areas in South Africa is the responsibility of the local municipality. In many municipalities across the country, the management of stormwater has been separated from that of water and sanitation, with the former often being assigned to roads departments. This has resulted in stormwater being treated as ‘hazardous water’ that needs to be disposed of as rapidly as possible in order to prevent damage to road structures. This paradigm has resulted in the fragmented ‘silo-management’ of the different aspects of the urban water cycle. The National Water Services Act (RSA, 1997) highlights the role of municipalities in developing water services development plans. However, due to the fact that stormwater is considered a part of the provision of roads, it is seldom comprehensively dealt with in municipal water services development plans. The National Water Act (Schedule 1 (1a)) does allow for the collection and use of runoff from roofs which is a stormwater management tool. Therefore, in order to optimize the benefits of water services, it is essential that the urban water cycle be managed as a whole in the Water Services Development Plans (Armitage et al., 2013). In response to this, a number of local sustainable stormwater legislation has emerged (Table 3.4).

Table 3. 4: Local sustainable stormwater legislation

City	Legislation	Objective
City of Cape Town	Stormwater Management By-Law (2005)	The purpose of the by-law, as stated in the opening abstract of the by-law is to, "provide for the regulation of stormwater management in the area of the City of Cape Town, and to regulate activities which may have a detrimental effect on the development, operation and maintenance of the stormwater system."
	Management of Urban Stormwater Impacts Policy (2009)	This was the first policy to place value on stormwater in the context of the national water crisis and 'climate change'. The following is stated in the preamble; "Well- managed urban water bodies are valuable resources providing environmental and recreational services which require protection and enhancement. This is particularly important in the context of changing weather patterns and the associated local, national and international strategies targeting sustainability, climate and energy issues."
	Floodplain and River Corridor Management Policy (2009)	The Floodplain and River Corridor Management Policy (May 2009) is not directly associated with stormwater management; however it necessitates the importance of well managed and sustainable watercourses, and places significant value on the utility of stormwater runoff (Roads and Stormwater Department, 2009b).
City of Johannesburg	Stormwater management By-laws (2010)	The Draft by law is in response to the need to better manage stormwater.

eThekwini Municipality	Design manual: Guidelines and policy for the design of stormwater drainage and stormwater management systems.	Stormwater systems are designed on the basis that not more than 40% of the area of residential properties would be hardened. Any development in such areas in excess of a 40% limitation means that the developer must be held responsible to manage the excess runoff from such a site for the proportion of hardening.

Source: Armitage et al. (2013)

Whilst municipalities are responding to individual WSUD principles, there is a lack of coordination and integration across water and other related services. This is largely due to the lack of enabling policy, guidelines and capacity building on water sensitive approaches. “It is important that the profile of WSUD and SuDS is increased amongst the engineering fraternity, as well as with national and local government officials, planners, developers, etc.” (Armitage et al. 2013:ix). South African authorities have been mainly concerned with the management of flood risk. However, an increasing number of local authorities are adopting more advanced stormwater management approaches. Cape Town is considered to be the most advanced in the sustainable management of stormwater (Armitage et al., 2013). South Africa’s first Guidelines for Sustainable Drainage Systems have recently been published by the South African Water Research Commission (Armitage et al., 2013). Figure 3.7 highlights the SuDS options for South Africa, which includes green roofs.

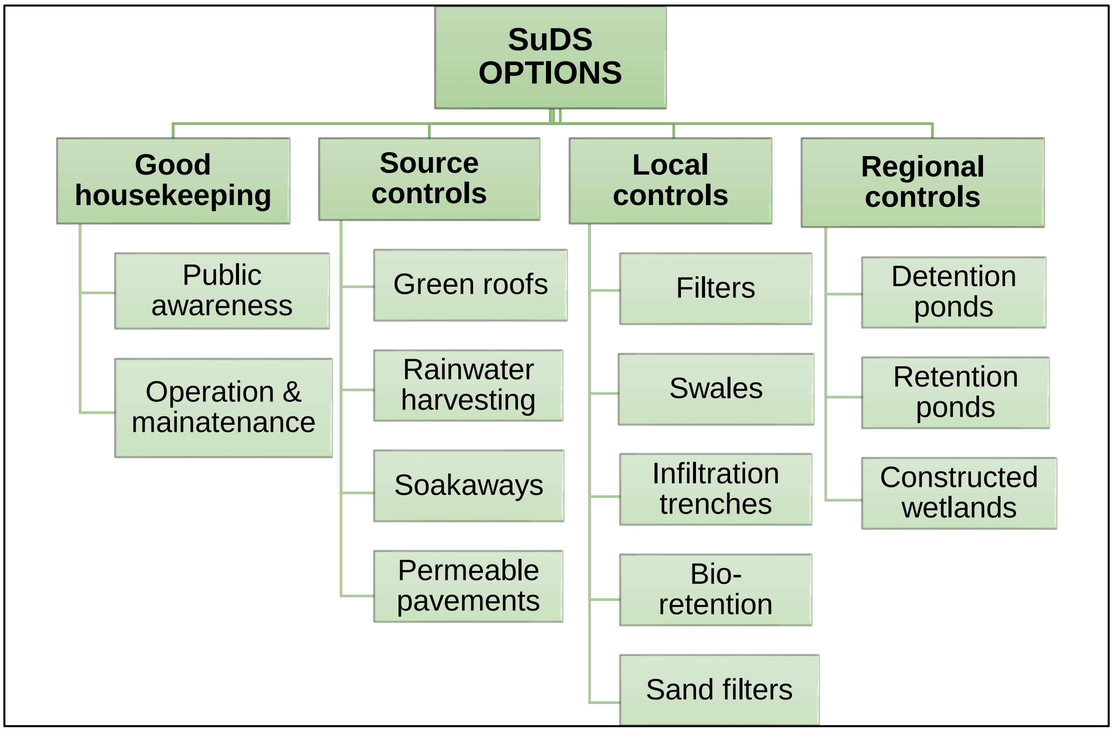


Figure 3. 7: South Africa SuDS Guidelines - Grouping of SuDS options

Source: Armitage et al. (2013)

3.2.4 eThekwini Municipality

The local government structure responsible for managing the city of Durban is known as the eThekwini Municipality. The city administration is led by the City Manager, supported by an executive management team of Deputy City Managers, each heading an administrative cluster. The eight administrative clusters are chiefly responsible for the city's services and infrastructure delivery in accordance with the city's overall Integrated Development Plan (IDP). The work and responsibilities of many units and associated departments have direct relevance to the planning, utilization and/or management of key environmental assets of the city, such as land and water. The municipality has undergone organizational transformation and, with its new model, the City Manager heads the city management structure (clusters), assisted by seven Deputy City Managers, Chief Strategy Officer, Chief Operations Officer and a Chief Audit Executive (eThekwini Municipality, 2011). These clusters and related units are depicted in Figure 3.8. The two units/departments primarily concerned with climate change and sustainable stormwater management and urban drainage are the Environmental Planning and Climate Protection Department and the Engineering Unit (eThekwini Municipality, 2011).

- **Environmental Planning and Climate Protection Department**

The Environmental Planning and Climate Protection Department is housed in the Economic Development and Planning Cluster within the Development Planning, Environmental and Management Unit. The objective of the Environmental Planning and Climate Protection Department is to conserve biodiversity and the ecosystem goods and services it provides for the benefit of present and future generations, and plan for adaptation to the impacts of climate change. The department is the contact point for climate change adaptation in the Municipality and provides relevant climate change information and expertise. This includes research into local level risks and impacts (environmental, social, and economic) and providing oversight and guidance in the implementation of the prioritized Municipal Adaptation Plans and the Durban Climate Change Strategy. In 2004, eThekwini Municipality initiated the Municipal Climate Protection Programme, which has resulted in the production of:

- Impact Assessment: The Climatic Future for Durban Report (2006) assessed the local impacts of climate change on the Municipality and proposed possible responses.
- Adaptation Planning: A Headline Adaptation Strategy (2006), which highlighted some of the key interventions required by the Municipality if it is to adapt successfully to inevitable climate change.
- Developing the Tool Box: the development of an Urban Integrated Assessment Framework (in progress) that will enable the simulation, evaluation and comparison of strategic plans and policies in the context of climate change.
- Mainstreaming: mainstreaming of climate change considerations into city planning and development and the creation of a Climate Protection Branch within the Environmental Planning and Climate Protection Department.

The Green Roof Pilot Project used in this study is an initiative of the Municipal Climate Protection Programme of the Environmental Planning and Climate Protection Department, in an effort to understand the benefits of green roofs, in terms of temperature regulation, storm water attenuation, inner city food production and biodiversity enhancement. The Green Roof Pilot Project is therefore a response to the higher temperatures and increase in the frequency and severity of floods and droughts that are expected as the result of climate change.

Cluster	Units
ECONOMIC DEVELOPMENT & PLANNING	• Development Planning, Environmental and Management Unit • Economic Development and Investment Promotion • Business Support, Tourism and Markets
HUMAN SETTLEMENTS, ENGINEERING & TRANSPORT	• Human Settlements • Engineering • eThekwini Transport Authority
COMMUNITY & EMERGENCY SERVICES	• Health • Security Management • Fire and Emergency • Safer Cities and ITRUMP • Disaster Management and Emergency Control • Parks, Recreation and Culture
GOVERNANCE & INTERNATIONAL RELATIONS	• International and Governance Relations • City Hall Administration and Secretariat • Communications • Sizakala Centres • Community Participation and Action Support
CORPORATE & HUMAN RESOURCE	• Human Resources • Skills Development • Management Services and Organisational Development • Occupational Health and Safety
FINANCE	• City Fleet • Expenditure • Real Estate • Revenue Management • Supply Chain Management • Internal Control and Business Systems • Finance Pensions and Major Project
TRADING SERVICES	• Electricity • Water and Sanitation • Cleansing and Solid Waste
CHIEF AUDIT EXECUTIVE	• City Integrity and Investigations • Chief Information Officer
CHIEF OPERATIONS OFFICER	• City Managers Support • Legal and Compliance • Performance, Monitoring and Evaluation • Area Based Management • Metropolitan Police
CHIEF STRATEGY OFFICER	• City Reg Growth & Development Strategy • Sustainable City Initiatives • Transformation Specialist • Programme Management Office • Programme Management

Figure 3. 8: eThekwini Municipality clusters and units

Source: eThekwini Municipality (2011)

- **Engineering Unit**

The Engineering Unit is housed in the Human Settlements, Engineering and Transportation Cluster (Figure 3.9). The Coastal Engineering, Stormwater and Catchment Management Department is responsible for managing flood risks to houses, industrial and commercial properties; improving water quality in the city's rivers, wetlands and receiving coastal waters by managing and monitoring developments; protecting and enhancing urban river corridors and wetlands as important natural features within the urban landscape; promoting multi-functional, sustainable use of river corridors and drainage systems; and maintaining a suitable beach width.

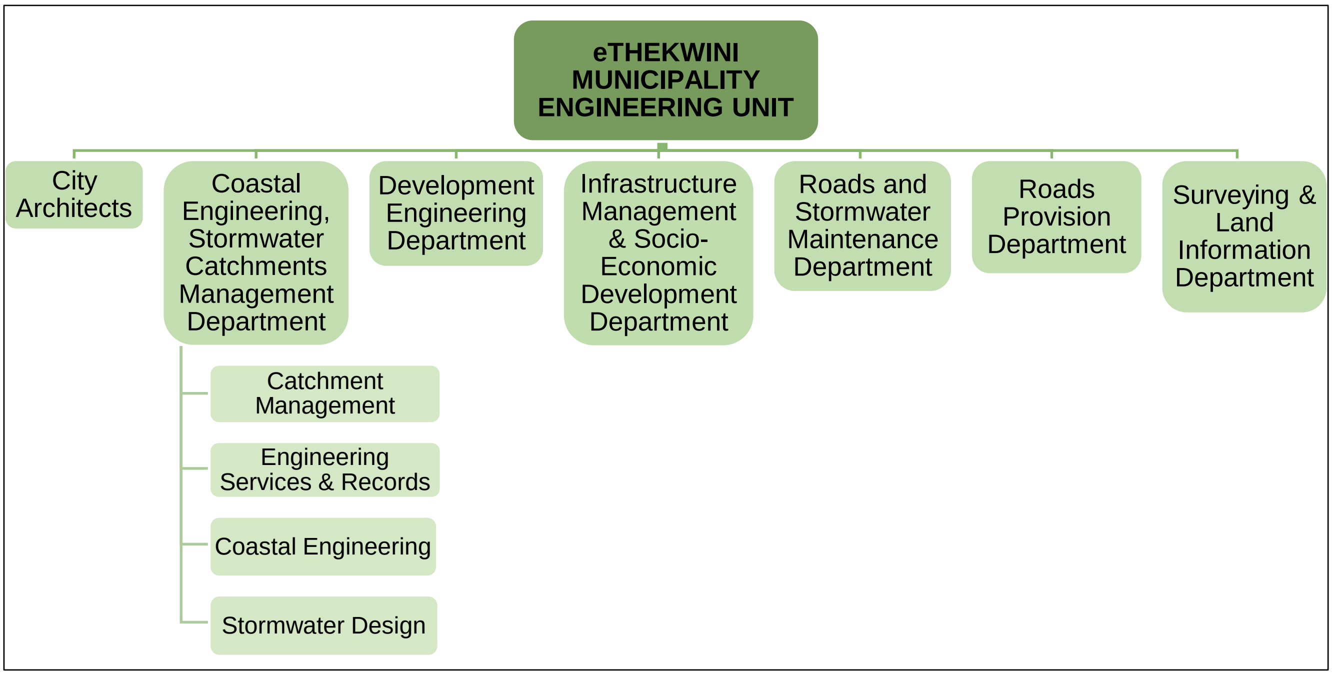


Figure 3. 9: eThekwini Municipality engineering unit departments

3.3 Study site: The Green Roof Pilot Project

The study experiment was conducted on the Green Roof Pilot Project under natural weather conditions. The Green Roof Pilot Project is part of the eThekwini Municipality's Municipal Climate Protection Programme. This programme was initiated by the eThekwini Municipality's Environmental Planning and Climate Protection Department where the eThekwini municipality launched the Green Roof Pilot Project on 22 May 2009. The aim of the project was to understand the city's resilience to climate change, based on projections of increased levels of surface run-off and flooding that result from the increase of non-permeable surfaces in the city, and to explore the extent to which green roof habitats can assist in reducing temperatures and stormwater run-off, thereby enhancing the city's adaptive capacity (Environmental Planning and Climate Protection Department, 2011). In particular, the Green Roof Pilot Project aimed to test green roofs in terms of their stormwater and temperature benefits (van Niekerk et al., 2011). The project site is the roof of a building within the eThekwini Municipality's Old Fort Complex. This particular roof was selected for the project due to the fact that it is flat, easily accessible, and located within a secure complex. Structural engineers confirmed that the roof is capable of withstanding the additional loading from the retrofitted green roof systems (Greenstone, 2009). The physical address of this Green Roof Pilot Project is 166 KE Masinga Road. Figure 3.10 illustrates the location of the study site.

Figure 3. 10: Location of the Green Roof Pilot Project in relation to the eThekwini region

Two adjoining flat topped roofs at the eThekwini Engineering Services building have been planted with twelve different varieties of vegetation. The roof used for Green Roof Pilot Project consists of two flat slabs on either side of a raised arch. Figure 3.11 illustrates the bare roof prior to the installation of any of the green roof systems.

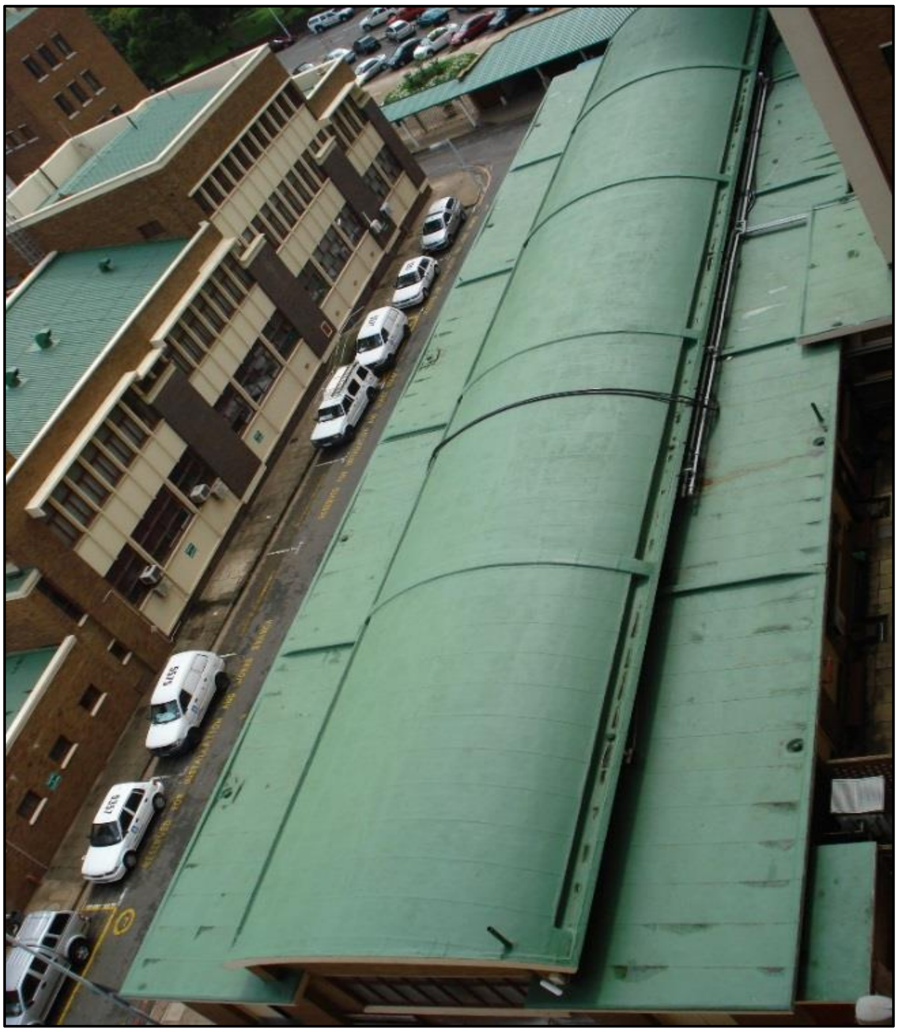


Figure 3. 11: Plan view of roof prior to green roof installation for the Green Roof Pilot Project

Source: Environmental Planning and Climate Protection Department (2008)

3.3.1 Loading analysis of the Green Roof Pilot Project

Considering that this was a retrofit project, a structural analysis of the roof was crucial in order to determine whether the roof was suitable to carry the loading of the green roof systems. A structural engineer established that the roof was able to withstand loading between 100-150kg/m^2 (van Niekerk et al., 2009). When considering the loading that results from a green roof system, the weight of a system that is completely water-logged and filled with the necessary plants, needs to be measured. During this process for the Green Roof Pilot Project, weights were recorded for varying substrate depths and plant types, which were put into modular boxes and then saturated with water (van Niekerk et al., 2009). The results are displayed in Table 3.5. The measured weight included a short range due to the use of different plant types, and hence varying weights. From the results, it was confirmed that the roof structure would be able to withstand the loading from the different chosen green roof systems (van Niekerk et al., 2009).

Table 3. 5: Loading analysis of substrates

Substrate Depth (cm)	Measured weight (kg)	Loading (kg/m^2)
7.5	15 – 25	80
10	30 – 40	85
20	40 – 50	90

Source: van Niekerk et al. (2009)

3.3.2 Design and construction of the Green Roof Pilot Project

The Green Roof Pilot Project comprises both modular and in-situ approaches to green roof installation, in an attempt to draw a comparison between the two, as well as a conventional control roof to use as a reference (Greenstone, 2009). The roof was subdivided into three portions, namely an in-situ green roof system, a modular green roof system and the control roof (van Niekerk et al., 2009). The total area allocated to the project is 550m^2, with each roof variation comprising approximately 50m^2 (Greenstone, 2010). The different sections are depicted in Figure 3.12. The dark green areas represent the in-situ systems, the light green areas represent the modular systems, and the red areas represent the control roofs (van Niekerk et al., 2009).

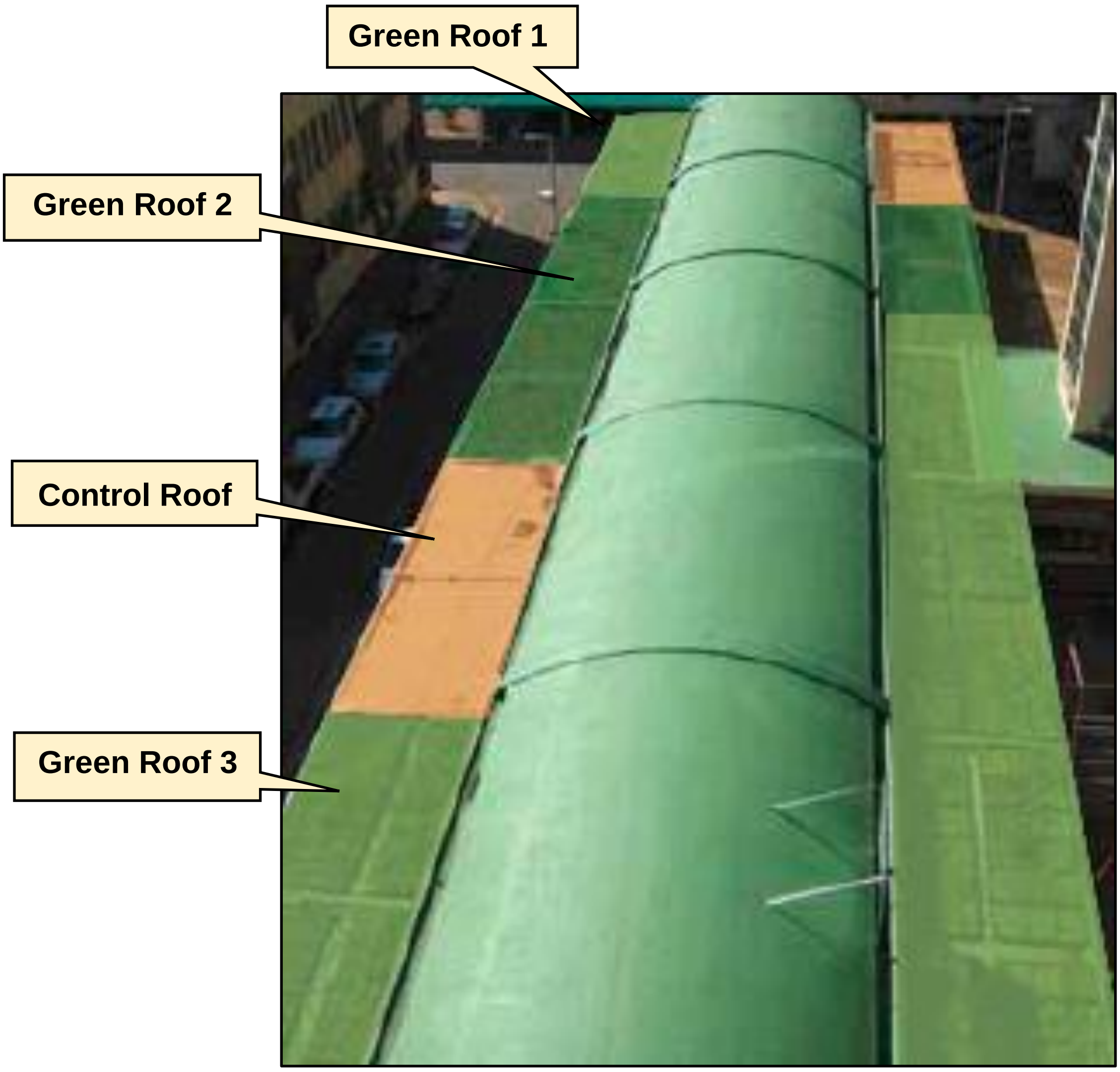
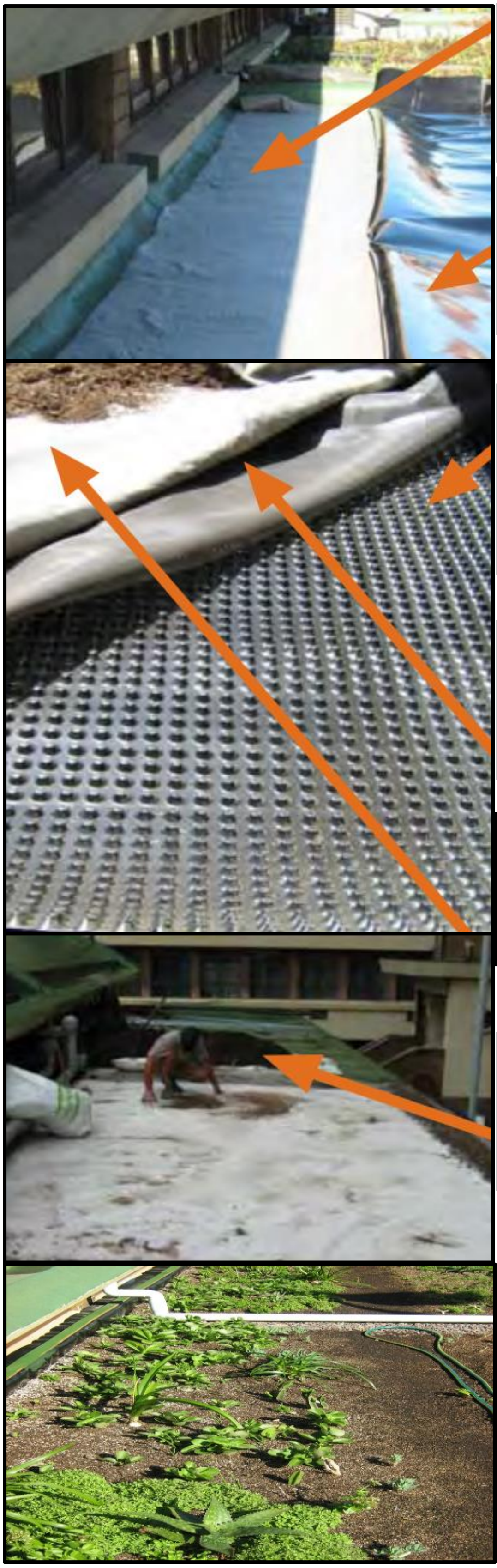


Figure 3. 12: Plan view of roof indicating initial demarcated areas

Source: van Niekerk et al. (2009)

The current arrangement is slightly different to the initial one, where only the green roof systems on the northern roof are being monitored for stormwater flow rates and there are no more modular systems on this side.

Figure 3.13 illustrates the actual construction of the in-situ green roof systems at the Green Roof Pilot Project in terms of the different layers and the materials used.



Layer 1: Protection layer
Purpose of this layer to protect the root barrier (i.e. layer 2) from being damaged or punctured by the existing roof.

Layer 2: Root barrier
Purpose of this layer to is to protect the existing roof from wandering roots which can cause structural damage.

Layer 3: Drainage layer
Purpose of this layer is to prevent oversaturation, ensure roots are well ventilated, and provide roots with extra space to grow.
Recommended: 7.5 mm PRO 600 GSM, LDPE Zip

Layer 4: Separation layer
Purpose of this layer to prevent the growing medium from entering and blocking the drainage layer.
Recommended - Geomesh BSP

Layer 5: Additional root barrier
Purpose of this layer is further protect the roof from wandering roots.
Recommended - Bidum A2 Geotextile Fabric.

Layer 6: Growing medium
The type of growing medium is also important as this provides plants with a nutrient base and space to grow.

Layer 7: Plants
It is important to note that conditions on a roof top are relatively unique and differ from those on the ground.

Figure 3. 13: Construction of the in-situ green roofs at the Green Roof Pilot Project

Source: van Niekerk et al. (2009)

The performance of the green roofs was monitored through: the placing of thermometers on the surfaces of and within the concrete layers; the placing of flow rate meters to facilitate the calculation of the flow rate and volume of stormwater that runs off each roof; the placing of rain gauges to record the actual rainfall data for a storm event; and the use of ecologists to monitor the growth patterns of the various vegetation types throughout the year, concentrating on the effects of extreme temperatures and the changing of seasons (Armitage et al., 2013).

3.3.3 Substrate Characteristics

Each green roof system that was installed comprised different substrate compositions of varying depths, which allowed for a range of nutrient components, drainage properties, and loading capacities (Greenstone, 2009). The purpose of the green roof substrate is to "anchor the plant, provide nutrients, and store water" (Magill et al., 2011:15). The substrate media provide a suitable rooting zone for vegetation, and is usually a low-density aggregate with high-water holding capability, and provides effective drainage. A range of locally available growing substrates, that were selected based on availability, were weighed for their dry weight as well as saturated weight in order to investigate their loading contributions (van Niekerk et al., 2009). The weights are tabulated in Table 3.6.

Table 3. 6: Substrate weight measurements of Green Roof Pilot Project

Substrate Name	Dry Weight (g/L)	Saturated Weight (g/L)
Perlite	174	461
Vermiculite	178	596
Potting mix	337	749
Compost	264	760
Ash	786	878
Light Expanded Clay Aggregate (LECA)	784	930
Crushed Brick	1200	1400
Berea red sand	1500	1800

Source: van Niekerk et al. (2009)

Perlite is a non-organic soil additive that is used to aerate the soil, and is small, round and white in appearance (World Seed Supply, 2010). Perlite retains water through its crannies amongst its many pores (World Seed Supply, 2010). Vermiculite is also a non-organic soil additive that is used to aerate the soil, but is yellow or brown in appearance (World Seed Supply, 2010). Vermiculite holds water, due to its sponge-like composition, and will therefore retain water until it is fully inundated (World Seed Supply, 2010). The test roof gardens comprised of wood ash which is proven to be highly beneficial to plant growth, due to the fact that after the wood has been burnt, important compounds such as calcium, magnesium and potassium are left behind (Savonen, 2007). Light expanded clay aggregate is defined as small, round balls of expanded clay (Everbright LECA, 2016). Advantages of using this in conjunction with growing media, are improved drainage and its ability to store water during drought periods (Everbright LECA, 2016). Crushed brick has been widely used as an additive to soils and growing media. This particular aggregate is very porous, giving it the advantage of being light in weight, and being able to store substantial volumes of water (Wildseed, 2016). Given that green roofs are being promoted to be constructed in urban areas, crushed brick is also an aggregate that can be easily sourced within a city environment (Wildseed, 2016).

The Green Roof Pilot Project substrates comprised different mixes as follows:

- Mixture A: 50% Light Expanded Clay Aggregate, 15% decomposed granite, 10% dark building sand, 10% fine decomposed compost, 10% vermiculite, and 5% perlite.
- Mixture B: 55% crushed brick, 23% decomposed granite, 11% fine decomposed compost, and 11% dark building sand.

Table 3.7 presents the mixture type and depth for each green roof system.

Table 3. 7: Properties of the Green Roof Pilot Project roof systems

Roof area	Substrate type	Substrate depth (cm)	Area (m^2)
Green roof 1	Mixture B	3	46.8
Green roof 2	Mixture A	10	43.6
Green roof 3	Mixture A	10	47.2

Source: van Niekerk et al. (2009)

3.4 Source of data for stormwater runoff quantity

Primary data was used in this study to ascertain the stormwater runoff quantity and attenuation of Green Roof pilot Project. The data used in this study was based on rainfall depths and stormwater runoff rates from the Green Roof Pilot Project that was collected between March 2017 and September 2017. This longitudinal, quantitative data includes rainfall depth measurements from the City Engineers building rain gauge and stormwater runoff flow rates from the Green Roof Pilot Project flow meters.

3.4.1 Data collection method and apparatus

The apparatus installed in the Green Roof Pilot Project to measure rainfall depth and stormwater runoff flow rates included a system of electronic tipping rain gauges, flow meters and data loggers. This system was able to measure the amount of stormwater runoff from the different areas of the project, and the rate of flow of the stormwater runoff (van Niekerk et al., 2009). Figure 3.14 illustrates the location of the various apparatus on the roof.

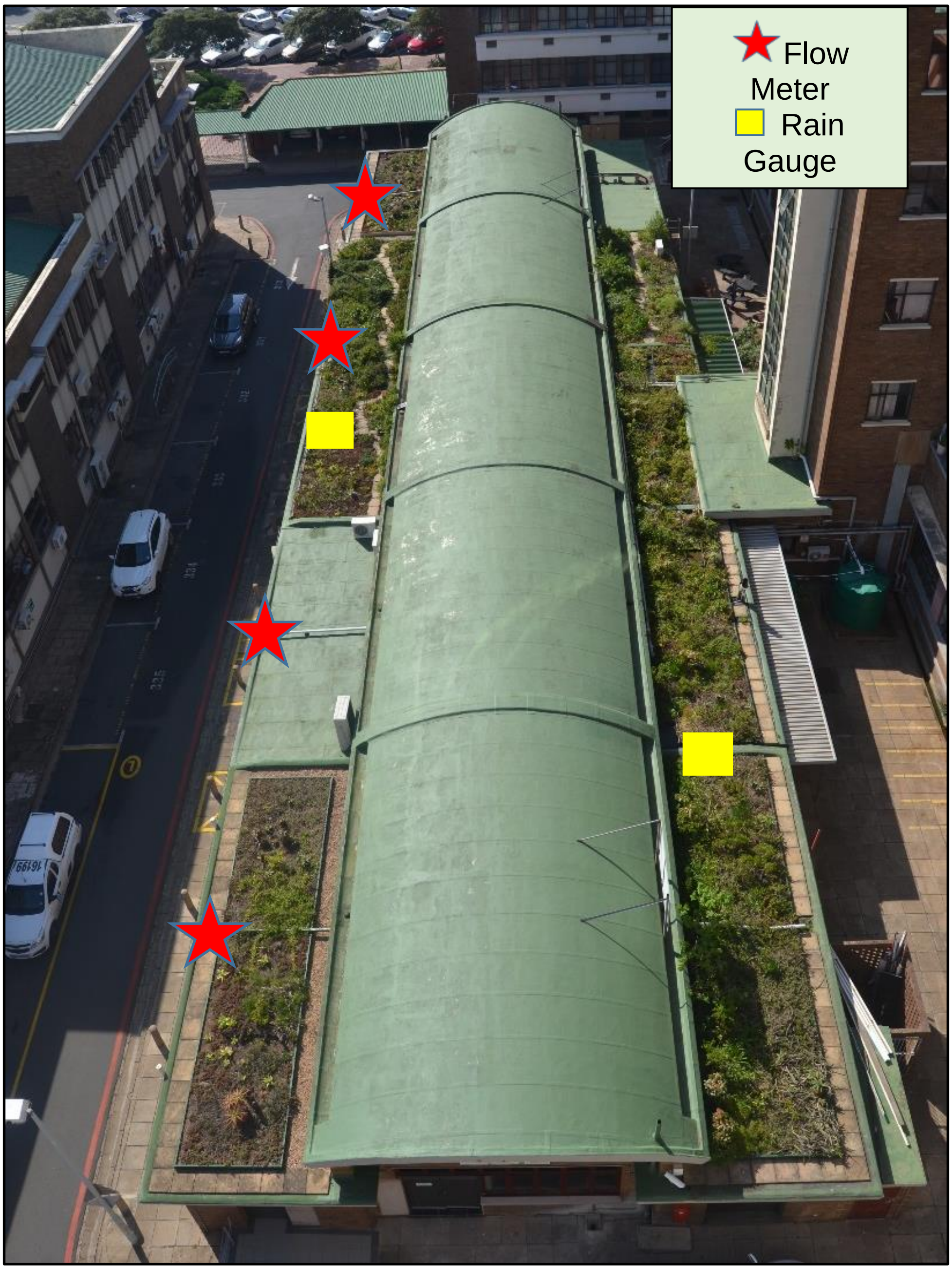


Figure 3. 14: Location of green roof monitoring apparatus on the Green Roof Pilot Project
(October 2016)

Rainfall data from the rain gauges on the green roofs seen in figure 3.10 proved to be unreliable. Therefore, data from the rain gauge on the City Engineer's Building was used for this study. This data has been calibrated against rainfall data provided by the South African Weather Services. The position of the rain gauge for the Green Roof Pilot Project is reflected in Figure 3.15.

Figure 3. 15: Position of rain gauge on the City Engineer's Building of the Green Roof Pilot Project

The installed rain gauge at the City Engineers Building is a tipping bucket rain gauge. A typical example is depicted in figure 3.16. The rain gauge contains a catchment area with an attached funnel leading down to two small buckets on either side of a see-saw, each with a holding capacity of 0.2mm (South African Weather Service, 2017). Rainfall is channeled to one bucket which tips over when full, and registers a signal to be recorded for the total measurement, allowing the other bucket to be available (South African Weather Service, 2017). This process is illustrated in figure 3.17.

Figure 3. 16: Typical tipping bucket rain gauge

Source: Akshar Electronics (2017)

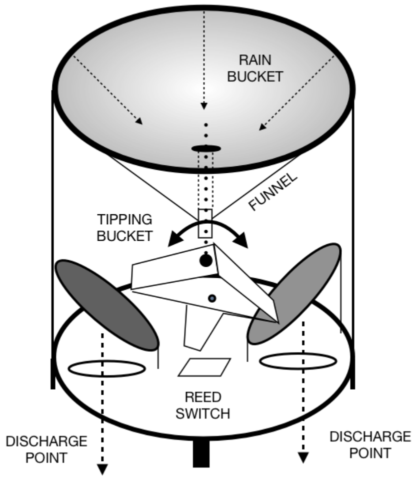


Figure 3. 17: Mechanics of a tipping bucket rain gauge
Source: Cliff Mass Weather and Climate Blog (2016)

In February 2017, new flow meters and data loggers were installed by the Durban based company Flowmetrix SA, due to the malfunction of the initial equipment installed in 2009. Figure 3.18 depicts the configuration of the new flow meters at the Green Roof Pilot Project.

Figure 3. 18: Configuration of flow meter device on the Green Roof Pilot Project

The new flow meter used in the project is a Sensus 420 Water Meter. The brass multi-jet meter measures flow rate, in liters per second (l/s), is resistant to bad water quality, and is sensitive to very low flow rates (Sensus, 2017). The flow meter unit is presented in more detail in Figures 3.19 and 3.20.

Figure 3. 19: Flow meter system used in the Green Roof Pilot Project

The flow and volume data can be retrieved from a web-based monitoring system called MyCity, in either a tabular or graphical format (Flowmetrix, 2015). This system is developed by the instrumentation services company, Flotron.

Figure 3. 20: Flow meter without housing

When monitoring green roofs for stormwater runoff, it is important to know the duration and intensity of each storm event. Rain gauges are typically used to measure the amount of rainfall over a particular period of time. In this study, the rain gauge was used to determine the amount of rainfall reaching the rooftop as well as the intensity of the rainfall. Coupled with the stormwater runoff data, this will show the effect the green roof has on reducing stormwater runoff and the delay in the peak flow rate.

3.4.2 Data analysis

Flow rate data from the loggers and rainfall data from the rain gauge was extracted from the raw data logs and modified into Microsoft Excel spreadsheets. The aim was to discover the most effective green roof in terms of the retention rate as a percentage, the delay in the peak flow rate, and the difference in the peak flow rate, all of which was compared to that of the control roof. The rain gauge measured rainfall in millimeters (mm), whilst stormwater runoff flow rates were measured in liters per second (l/s) per 15 minutes.

In order to illustrate the retention properties of each green roof, graphs of flow rate versus time were composed, using the control roof data to draw a comparison. The following steps were taken in the calculation of the retention rates:

1. The measurement of the actual rainfall depth that fell onto the roof was extracted from the rain gauge data. This measurement was recorded as having a mm unit.
2. This was multiplied by the area of each roof to calculate the actual rainfall that fell onto a specific roof. This value was divided by 1000 to get a m^3 unit.
3. The runoff volume was determined next by calculating the area under the flow rate vs. time graphs. This measurement was in liters and was therefore divided by 1000 to get a m^3 unit.
4. The retention rate formula explained below was then used to determine the retention rates for each roof.

The runoff retention rate from the Green Roof Pilot Project was calculated as:

$$\mathrm{RR} = \frac{(\mathrm{RV} - V)}{\mathrm{RV}} \times 100\%$$

$$\mathrm{RV} = R \times A$$

Where RR is the runoff retention rate (%); RV refers to the rainfall volume actually received by green roof (L); V is the runoff depth from the green roof (L); R is the actual rainfall volume (m); A is the area of green roof (m^2). RV is multiplied by a thousand to convert m^3 to L.

The different green roofs of the Green Roof Pilot Project were assessed according to different storm intensities. Based on the rainfall data for the entire study, the storms were categorised according to low, medium or high intensity. Comparisons of the retention rates were drawn for each storm category, as well as for the overall study. The retention rates were calculated using the formula mentioned above. This data was then used to formulate a stormwater runoff model for the best performing green roof in terms of retention rate.

3.4.3 Formulation of a stormwater runoff model

After identifying the most effective green roof system of the Green Roof Pilot Project, a stormwater model of eThekwini's Central Business District (CBD) was developed, using the Personal Computer Storm Water Management Model (PCSWMM) program. The initial Storm Water Management Model (SWMM), first developed in 1969-71 by the United States Environmental Protection Agency (USEPA) was one of the first such models. It has been continually maintained and updated and is perhaps the best known and most widely used of the available urban runoff quantity/quality models (Huber and Roesner, 2013). PCSWMM is an advanced stormwater modelling program and is used for the simulation of runoff quantity and quality, as well as the computation of dynamic rainfall-runoff for single events or long term continuous records (Kabbani, 2015). PCSWMM was selected for this study due to its special capabilities of having the Geographic Information System (GIS) engine that can handle the latest GIS data. The benefits of using the PCSWMM model for this study was also due to its dynamic hydraulic and hydrological modeling capabilities of simulating runoff quantity and quality in urban areas.

The purpose of the stormwater runoff model was to project the extent to which green roofs on buildings within the eThekwini CBD can reduce runoff flow rates. The steps in setting up the model involved, firstly, delineating the sub catchments within the eThekwini CBD district. This was done by using the contours and flow paths. Secondly, based on their land use, soil types, and slopes, characteristics were added to the sub catchments accordingly. Thereafter, rain characteristics were added to the sub catchments according to the eThekwini CBD's co-ordinates. The eThekwini Municipality utilizes the rainfall data from a report titled "The Estimation of Design Rainfall for Durban Unicity" (Smithers, 2002). The intensities from this report were then entered into a storm generator program, which created a storm event to be simulated.

The researcher added green roofs to the buildings within the chosen block (Figure 3.21) by means of PCSWMM's Low Impact Development controls. These controls include green infrastructure and best management practices such as swales, rain gardens, porous paving, rain barrels, green roofs, bio-retention cells, and infiltration trenches (James et al., 2012). Upon adding the green roof as a Low Impact Development control in the PCSWMM model, a number of characteristics were required. A summary of these characteristics are presented in Table 3.8.

Table 3. 8: Low Impact Development control parameters in PCSWMM model

Characteristic		**Source**
Surface		
Berm height (mm)	150	Measurement
Vegetation volume (fraction)	0.85	Measurement
Surface roughness (Manning's n)	0.1	ODOT, 2014
Surface slope (%)	1.0	Measurement
Soil		
Thickness (mm)	100	Van Niekerk et al. (2009)
Porosity (volume fraction)	0.376	PSWMM Support, 2016
Field capacity (volume fraction)	0.212	PSWMM Support, 2016
Wilting point (volume fraction)	0.142	PSWMM Support, 2016

Conductivity (mm/hr)	263	PSWMM Support, 2016
Conductivity slope	10	PSWMM Support, 2016
Suction head (mm)	194.74	PSWMM Support, 2016
Drainage Mat		
Thickness (mm)	7.5	Van Niekerk et al. (2009)
Void fraction	0.5	Van Niekerk et al. (2009)
Roughness (Manning's n)	0.01	ODOT, 2014

Figure 3. 21: eThekwini CBD Boundary

3.5 Stormwater runoff quality

Samples of the stormwater runoff from the different green roof systems on the Green Roof Pilot Project were collected to test their level of contaminants and pollutants. Although green roofs can act as pollution adsorbents and filters, they can also potentially contribute to the degradation of the quality of receiving waters with pollutants released from soil, plants and fertilizers and be a source of contaminants and nutrients (Moran et al., 2003; Berndtsson et al., 2006; Teemusk and Mander, 2007; Berndtsson, 2010).

3.5.1 Data collection and apparatus

Primary data comprised the raw data collected by the researcher for the investigation of the water quality. To assess the water quality from the runoff, five sets of stormwater runoff samples were collected from five different rain events between the period of March 2017 and September 2017. Stormwater runoff was collected from the three green roofs of the Green Roof Pilot Project and the one control roof. The stormwater runoff was collected in containers that were supplied by the Council for Scientific and Industrial Research (CSIR), who were also responsible for analyzing the samples. Details of the samples from the stormwater runoff from the five rainfall events are indicated in Table 3.9.

Table 3. 9: Details of water samples from stormwater runoff

Date	Collection Time
Monday, 24th April 2017	09:00
Friday, 12th May 2017	17:30
Sunday, 14th May 2017	12:30
Monday, 15th May 2017	21:30
Tuesday, 16th May 2017	09:30

The samples were collected at the base of the pipe connected to the flow meters. These pipes are also an extension of the roof gutter pipes. Both pipes are made from polyvinyl chloride (PVC). The containers were filled to the brim with no head space, as required by the CSIR.

Four sets of sample bottles were collected and analysed for each roof on each rainfall day. Each set consisted of:

- 1 x 2litre plastic bottle for inorganic analyses.
- 1 x 250ml glass bottle for sulphide analysis.
- 1 x 1litre glass bottle for soap, oil and grease analysis.
- 1 x 1litre glass bottle for surfactants analysis.
- 1 x 500ml sterilized plastic bottle for microbiological analyses.

All sets of samples were tested for the quality of stormwater runoff entering freshwater ecosystems. The tests focused on all physical, aesthetic, chemical, and microbiological determinants pertaining to stormwater runoff discharging into a freshwater ecosystem.

3.5.2 Data analysis

For all tests, the level of contaminants and pollutants were measured against the South African Water Quality Guidelines Volume 7 for Aquatic Ecosystems (Department of Water Affairs and Forestry, 1996). The guideline lists the determinands and corresponding target water quality range that should be achieved, in order for the water sample to be deemed acceptable for entering a freshwater aquatic ecosystem (Department of Water Affairs and Forestry, 1996). The target water quality ranges set out by the Guideline are tabulated in Table 3.10.

Table 3. 10: Target water quality ranges set by the South African Water Quality Guidelines Volume 7 for Aquatic Ecosystems

Constituent	Target Water Quality Range	Unit of measurement
Aluminium – pH < 6.5	≤ 5	µg/l
– pH > 6.5	≤ 10	µg/l
Ammonia	≤ 7	g/l
Arsenic	≤10	µg/l
Cadmium – in soft water	≤ 0.15	µg/l
Chlorine	≤ 0.2	µg/l
Chromium	≤ 7	µg/l

Copper – in soft water	≤ 0.3	µg/l
Cyanide	≤ 1	µg/l
Dissolved Oxygen	*80% - 120% of historic concentration	mg/l
Fluoride	≤ 750	µg/l
Iron	*≤ 10% of historic concentration	mg/l
Lead – soft water	≤ 0.2	µg/l
Manganese	≤ 180	µg/l
Mercury	≤ 0.04	g/l
Nitrogen	*≤ 15% of historic concentration	mg/l
pH	≥ 6 and ≤ 8 *≤ 5% of historic values or ≤ 0.5 pH units	pH units
Phenols	≤ 30	µg/l
Phosphorous	*≤ 15% of historic concentration	mg/l
Selenium	≤ 2	µg/l
Temperature	*≤ 10% of historic values or ≤ 2˚C	˚C
Total Dissolved Solids	*≤ 15% of historic concentration	mg/l
Total Suspended Solids	*≤ 10% of historic concentration	mg/l
Zinc	≤ 2	µg/l

Source: Department of Water Affairs and Forestry (1996)

Some of the constituents do not have a target water quality range set out in the South African Water Guidelines for Aquatic Ecosystems, but rather have a percentage limit in relation to their historic concentrations. This is because these constituents are site and time specific, implying that they do not have a set target value but rather a target value for different seasons and locations.

All sets of samples for water quality testing were handed over to the laboratory at the Council for Scientific and Industrial Research (CSIR) within 24 hours after collection, in order to accurately account for all the pollutants present. Details of the test results as received by the CSIR are evident in Appendix 1. The CSIR laboratory is equipped to test water samples for an extensive set of quality parameters and harmful impurities, including bacteria, viruses, minerals, chemicals and organic substances. The laboratory offers advanced testing and analytical facilities as well as specialized knowledge and technical services. The laboratory is accredited (ISO 17025) with the South African National Accreditation System which ensures that the analytical methods used by the laboratory, and the results achieved from the analyses, are traceable to international standards (CSIR, 2017). The researcher was unable to independently conduct tests due to inadequate apparatus available at the eThekwini Municipality's laboratory. The University of Witwatersrand does house a comprehensive water testing laboratory on campus. However, distance made it logistically difficult for the researcher to have conducted the tests at that particular premises.

The researcher proceeded to analyse the results from the CSIR, using Microsoft Excel to compile graphs for each determinand. A comparison was then drawn up between the test results and the target ranges set out by the South African Water Quality Guidelines. Another objective of the compilation of the graphs was to illustrate the difference in pollutant levels between the different green roof systems, as well as a comparison to the pollutant level of the control roof. Tests were not conducted on the rainwater before it fell on any of the roofs, therefore the researcher could not draw a comparison between the level of pollutants in the actual rainwater and the level of pollutants in the stormwater runoff from the green roofs as well as from the control roof.

3.6 Other sources of data

In addition to the data related to stormwater quality and stormwater quantity other sources of data for the study included interviews and secondary data.

3.6.1 Secondary data

Secondary data is information that has been collected for a purpose other than the current research study, but has some relevance and usefulness for the current research. The study incorporated various types of secondary data to gain further insight on the stormwater runoff quality and quantity from green roofs. Secondary data included, an extensive review of relevant literature using books and academic, peer reviewed journals, theses, conference proceedings and unpublished manuscripts on sustainable stormwater management and green roofs. The survey of literature facilitated the integration of information gathered with that of the primary data. The second source of documentation for the study was a review of relevant policy, legislation, development frameworks, guidelines on SUDS, stormwater management and green roofs, globally and in South Africa. Technical reports undertaken by research institutions and governmental departments were also utilized in the study. Statistical and archival data collected by various organizations was also used to supplement the primary data for the study. A major benefit of using secondary data such as this is that it has already been reviewed by authorities and suitably used elsewhere and much of the information has been accepted and approved for consumption by different users. Secondary data also provides a baseline with which to compare your primary data collection results. Secondary data was subjected to content analysis. Content analysis allowed the researcher to analyse large amounts of textual information through a conceptual analysis (Sekaran and Bougie, 2009).

3.7 Conclusion

This chapter provided an insight into the research design and research methods of the study. The study was conducted on the Green Roof Pilot Project under natural weather conditions. Primary data was used in this study to determine the stormwater runoff quantity and attenuation of Green Roof Pilot Project. The data was based on the rainfall and runoff rate from the project that was collected between March 2017 and September 2017. The aim was to discover the most effective roof (control and green roofs) in terms of reducing the volume, or slowing down the rate of stormwater runoff. In order to determine the level of contaminants and pollutants and general runoff quality, samples of the stormwater runoff from the different green roof systems on the Green Roof Pilot Project were collected. Tests were conducted for level of contaminants and pollutants. The tests focused on the determinands and their target water quality ranges as set out by in the South African Water Quality Guidelines for Aquatic Ecosystems by the Department of Water Affairs and Forestry. Interviews and secondary data was also used to illicit information about green roof stormwater runoff quality and quantity.

CHAPTER FOUR: RESULTS AND ANALYSIS

4.1 Introduction

The aim of this chapter is to present the research results and discuss the key findings of the study, and their implications. The data analysis commences with the presentation of results pertaining to the quality of stormwater runoff from the selected green roofs in the study. This data is compared with the quality of runoff from a conventional roof. The categories relating to quality of runoff include: physical and aesthetic determinands, chemical determinands, and microbiological determinands. The ensuing section focuses on stormwater runoff quantity of the green roofs, which is also compared to that of the conventional roof. The PCSWMM model has been used as a tool to show the effect of green roofs on stormwater runoff flow rates and quantity within the eThekwini CBD.

4.2 Analysis of Stormwater Quality

Stormwater runoff from the three different green roof systems, as well as the control roof was sampled and analysed for all determinands contributing to the quality of stormwater runoff entering freshwater aquatic systems within South Africa. Results were compared to the target water quality ranges set out by the South African Water Quality Guidelines for Aquatic Ecosystems, drafted by the Department of Water Affairs and Forestry in 1996.

Results below are represented graphically, and discussed in a comparative manner. Graphs with data which were represented by a hatched column as opposed to a solid column, indicate that this level was below the detection limit, and therefore could not be depicted as an actual value. Samples for testing were collected on five different days as depicted in Table 4.1.

Table 4. 1: Test days and rainfall information

	Date	Time	Peak rainfall in ten minutes	Day before	Time before collection
Test 1	24 April 2017	09:00	3.4mm	No rainfall	7hrs 10min
Test 2	12 May 2017	17:30	6.8mm	Light rainfall	10hrs 45min
Test 3	14 May 2017	12:30	1.4mm	Heavy rainfall	15hrs 50min
Test 4	15 May 2017	21:30	1.4mm	Heavy rainfall	1hr 25min
Test 5	16 May 2017	09:30	4mm	Heavy rainfall	2hrs 30min

4.2.1 Physical and Aesthetic Determinands

pH levels

Figure 4.1 shows the average pH levels obtained for each roof, from the 5 different tests. The control roof resulted in the lowest average pH level, whilst green roof 1 resulted in the highest. The average level of 5.882 from the conventional roof was the only result that did not fit between the target quality range of 6 – 8 pH units (Department of Water Affairs and Forestry, 1996).

In general, green roofs have been proven to reduce the acidity of stormwater runoff from between 5 and 6 in rainwater to between 7 and 8 in runoff from a green roof (Berndtsson, 2010). This correlated well with findings from this study, as the highest pH value came from green roof 1, whilst the lowest came from the control roof. This increase in the pH level indicates that green roofs have the ability to neutralize acid rain (Berndtsson, 2010; Vijayaraghavan and Joshi, 2014), and therefore protect the receiving water bodies from acidification (Beecham and Razzaghmanesh, 2015).

Test results indicated that green roof 1 proved to neutralize the runoff the most. Green roof 1 has a different substrate mix and thickness in comparison to the other two green roofs, and this can therefore be a possible reason as to why it produced a higher average pH level. Green roof 2 and green roof 3 had the same substrate mix and thickness, but varied in vegetation type and the amount of vegetation. This finding leads to the possibility that the diverse vegetation caused differing pH levels.

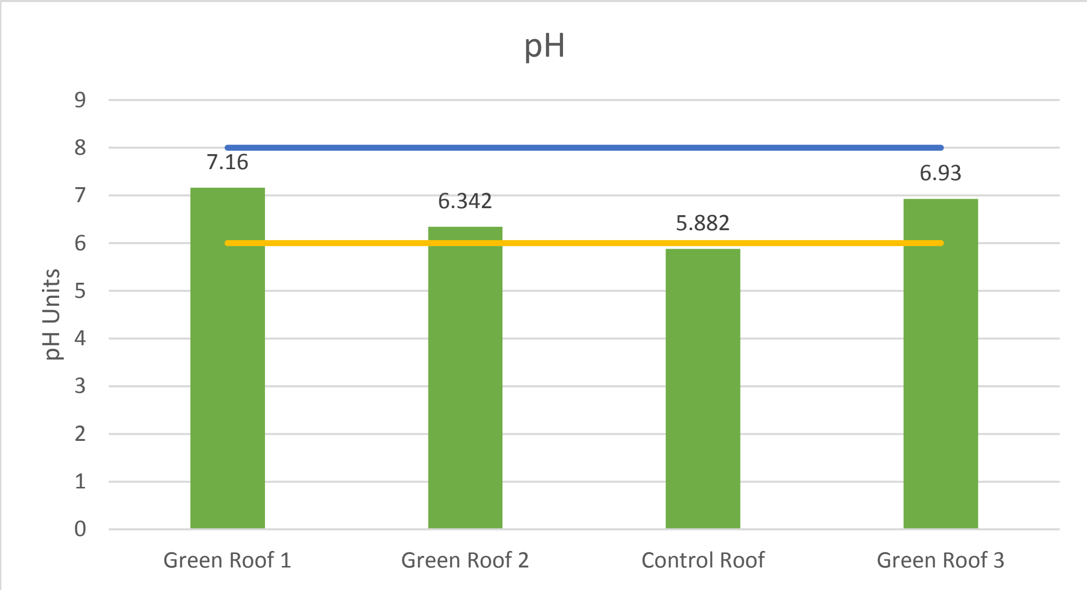


Figure 4. 1: Average levels of pH

Results obtained in this study are parallel to those obtained in other similar studies of an extensive green roof. A summary of these studies are presented in Table 4.2.

Table 4. 2: pH ranges obtained for different green roof systems

pH level (pH units)	Author/s
5 – 7	Beecham and Razzaghmanesh, 2015
6 – 8	Vijayaraghavan et al., 2012
7 - 8	Razzaghmanesh et al., 2014; Emilsson et al. 2007
6 – 9	Teemusk and Mander, 2007

Total Dissolved Solids (TDS)

Figure 4.2 displays the results of the average TDS found in the analysed stormwater runoff. The test results showed a range of 24 – 192.6mg/l. The lowest level came from the control roof, whilst the highest came from green roof 2.

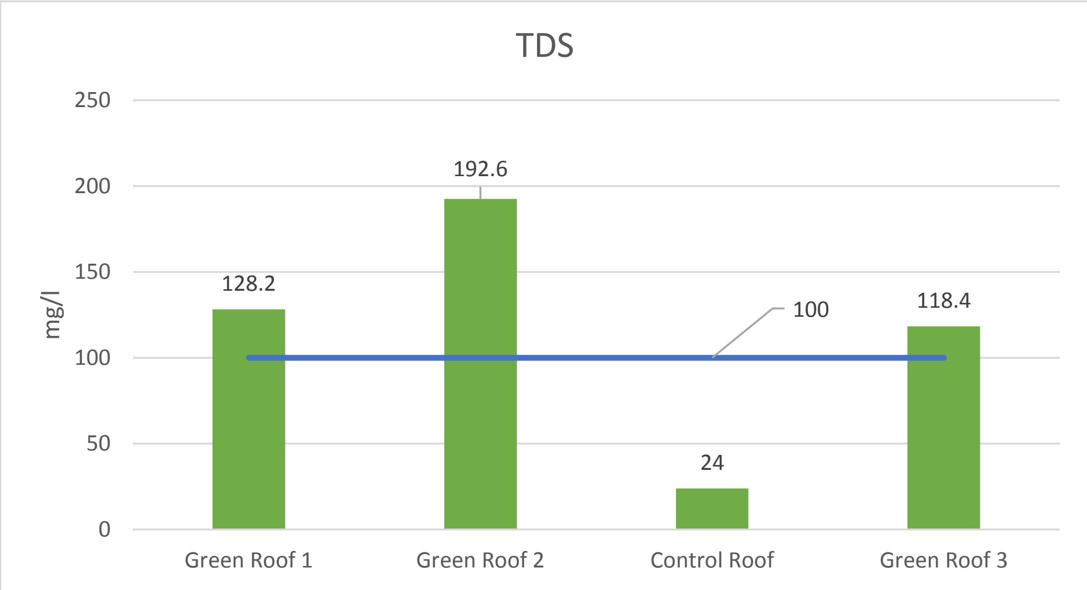


Figure 4. 2: Average levels of TDS

Green roof 3 contains a mix that comprises 10% dark building sand and 5% perlite. Vijayaraghavan and Raja (2014) showed that substrates with sand and perlite in the mixture, will have a lower TDS level. The results from green roof 3 at the eThekwini Green Roof Pilot Project are therefore consistent with their findings. Although green roofs 2 and 3 have the same substrate mixture and depth, green roof 2 produced runoff with a higher average TDS concentration. Therefore, this indicates that the plant type was possibly responsible for the difference in TDS levels.

<u>Total Suspended Solids (TSS)</u>

According to figure 4.3, stormwater runoff from the control roof contained the lowest average concentration of TSS. Amongst the green roof systems, green roof 2 produced the lowest concentration, and green roof 3 produced the highest concentration.

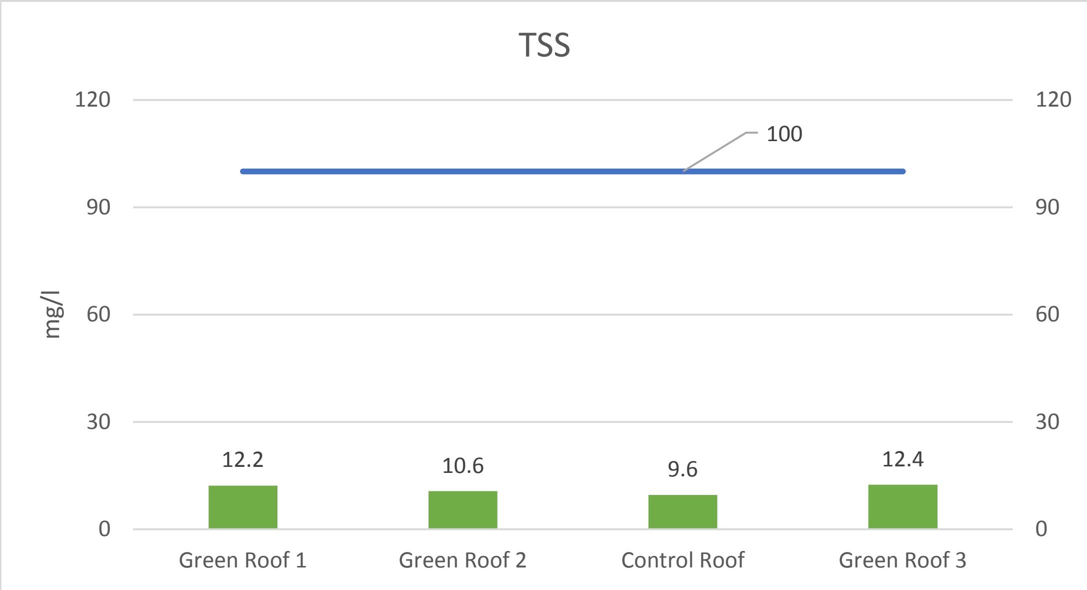


Figure 4. 3: Average levels of TSS

Results are inconsistent with findings by Zhang et al. (2015), who showed that the TSS levels in a green roof system are lower than that from a conventional roof. Studies propose that a common range of TSS from a green roof is 6mg/L to 482mg/L (Buccola and Spolek, 2011; De Cuyper et al., 2005; Morgan et al., 2011). From this study, all levels from the green roof systems agree with this finding.

Results of TSS levels in runoff from all the roof systems were found to below the target water quality minimum of 100mg/l (Department of Water Affairs and Forestry, 1996).

4.2.2 Chemical Determinands

Free Chlorine

All average levels of free chlorine were found to be above the target water quality range of 0.0002mg/l (Department of Water Affairs and Forestry, 1996). From figure 4.4, the control roof proved to have the lowest average concentration, from all the roof systems. The highest average concentration originated from green roof 2.

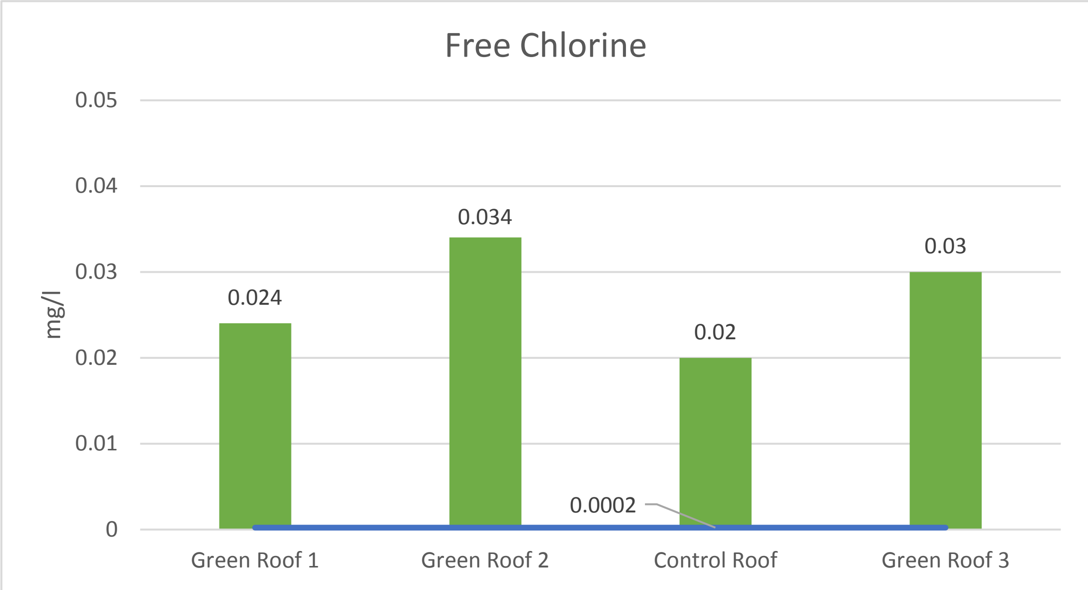


Figure 4. 4: Average levels of Free Chlorine

Zhang et al. (2015) found no significant difference in the chlorine concentrations originating from a green roof and a conventional roof. This is inconsistent with the findings from the eThekwini study, where a green roof 2 produced an average concentration almost 1.5 times that from the control roof.

<u>Nitrogen and Orthophosphates</u>

Combined nitrite and nitrate concentrations for the runoff from the various roofs in the study are shown in Figure 4.5. Based on average concentrations, the highest level came from runoff in green roof 1, and the lowest level came from runoff in the control roof.

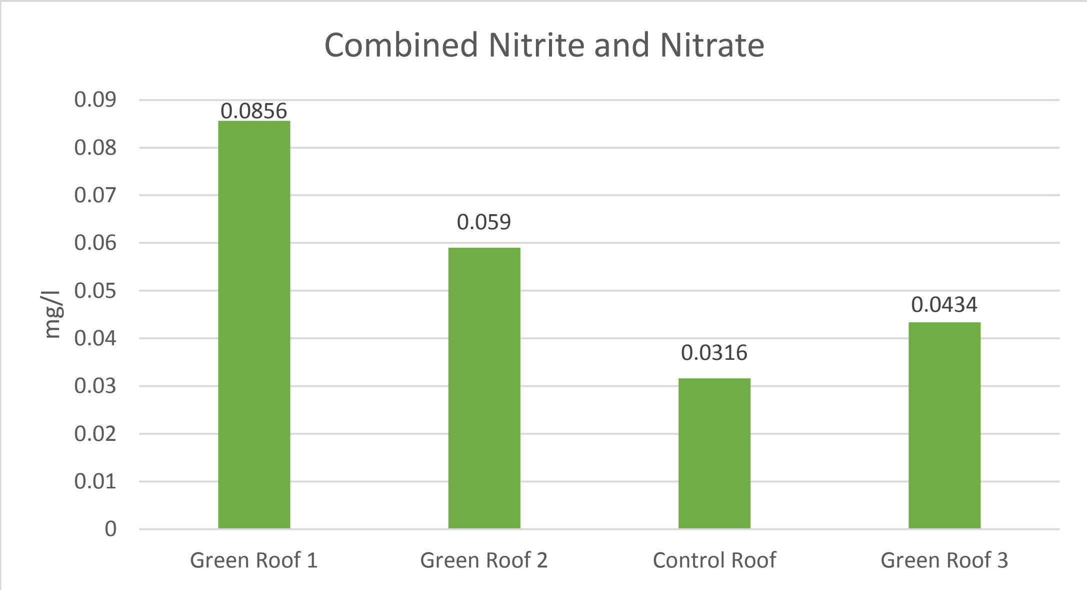


Figure 4. 5: Average levels of combined Nitrite and Nitrate

Amongst the green roof systems, green roof 1 produced the highest average concentration, and green roof 3 produced the lowest average concentration. The characteristic that sets green roof 1 apart from the other systems is the substrate mixture, and substrate thickness. This mixture contains 55% crushed brick, 23% decomposed granite, 11% compost and 11% building sand, and has a substrate thickness of 3cm.

Results were consistent with findings of similar studies whereby nitrate and nitrite concentrations were higher in green roof runoff than in runoff from a conventional roof (Zhang et al., 2015). The results therefore disagree with discoveries which suggest that green roofs have the ability to retain nitrogen (Berndtsson et al., 2009; Rowe, 2011; Speak et al., 2014).

Average ammonia concentrations for the study are illustrated in figure 4.6. As depicted, all test results were found to be below the maximum target water quality range value of 7000mg/l (Department of Water Affairs and Forestry, 1996).

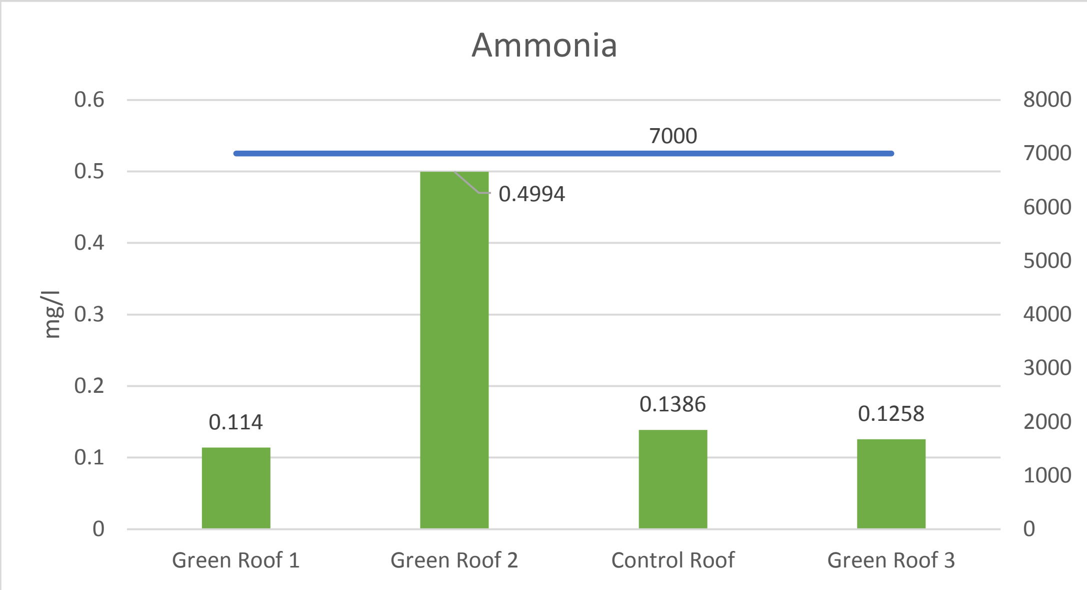


Figure 4. 6: Average levels of Ammonia

Runoff from green roof 1 resulted in the lowest average ammonia concentrations, and green roof 2 produced runoff with the highest average ammonia concentrations, between the green roof systems.

Green roofs 1 and 3 produced a similar average ammonia concentration, despite their substrate depths being different. Green roof 2 had the same substrate depth as green roof 3 but produced a result which was more than 4 times greater than the lowest result. Green roof 1 had a depth of 3cm, and green roofs 2 and 3 had a depth of 10cm. This finding indicates that the substrate depth alone does not dictate the amount of ammonia present in the stormwater runoff. The results from the eThekwini study are unaligned with findings by Beecham and Razzaghmanesh (2014), which showed that ammonia concentrations were higher in shallower depths of growing media.

Green roofs 1 and 3 both had vegetation that was similar in type and density. Green roof 2 consisted of very dense vegetation. Considering that green roofs 1 and 3 had similar average concentrations, and green roof 2 had a higher average concentration, the findings show that the vegetation type and density is a possible reason for these discrepancies.

Orthophosphate concentrations found in runoff from the control roof proved to remain at a constant level of 0.008mg/l over the 5 tests. Between the green roof systems, green roof 2 gave off the highest average concentration of orthophosphate, whereas green roof 1 produces the lowest average concentration of orthophosphate. Figure 4.7

shows that all the average results were found to be above the target water quality range of 0.00002mg/l – 0.00004mg/l (Hodgson et al., 2006).

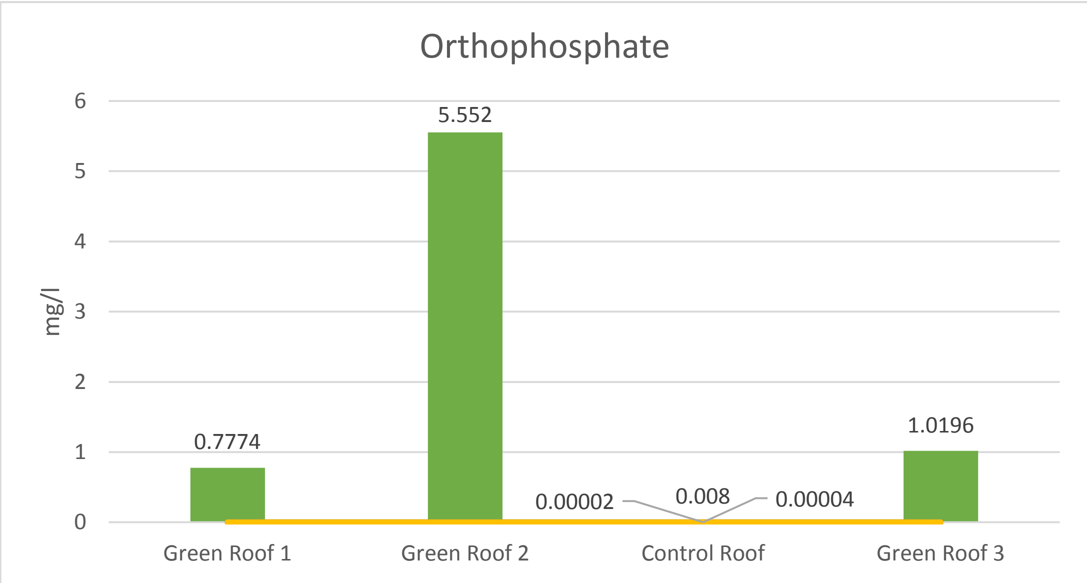


Figure 4. 7: Average levels of Orthophosphate

This results proved to be contradictory to findings made by Beecham and Razzaghmanesh (2014), which indicated that green roofs with lower plant density, produce runoff with higher orthophosphate concentrations. Green roof 2 has the highest plant density amongst the green roof types at the Green Roof Pilot Project, yet produced the highest average concentration of orthophosphate.

However, Beecham and Razzaghmanesh (2014) also found that green roofs with a crushed brick substrate gave off lower concentrations of orthophosphate in their stormwater runoff. Green roof 1 from the eThekwini study leached the lowest orthophosphate levels, with a substrate mixture consisting of 55% crushed brick, proving that this result was consistent with the findings made by Beecham and Razzaghmanesh (2014).

The eThekwini study results are also inconsistent with findings that argue that various green roof types reduce levels of nitrate and ammonia in stormwater runoff (Berndtsson et al., 2006). The study indicated that green roof systems increased the level of orthophosphate in stormwater runoff when compared to a control roof, which is consistent with findings from a study in Connecticut by Gregoire and Clausen (2011). An increase in orthophosphate levels could be due to the addition of fertilizer into the substrate media (Emilsson et al., 2007; Driscoll et al., 2015), or leaching from other mechanisms such as air-conditioning, which are housed on the green roof (Gregoire and Clausen, 2011). The former reason can be ruled out as eThekwini's Architecture Department has confirmed that no maintenance has taken place on any of the green roofs during 2017.

Although roof 2 and roof 3 have the same soil mixture and depth, they recorded varying results for orthophosphate, ammonia, and nitrate. The difference in plant types may be the reason for this discrepancy, following a study by Aitkenhead-Peterson et al. (2011) that confirmed that different plant species in the same substrate showed varying nitrogen and phosphorous amounts in runoff. Varying concentrations of nitrogen have been proven to be a function of soil mixture, age of the green roof, maintenance practices, and the types of fertilizer used (Whittinghill et al., 2013; Carpenter et al., 2016; Gregoire and Clausen, 2011).

According to Moran et al. (2004), green roofs which are constructed with compost present in the substrate layer, will produce stormwater runoff containing high concentration levels of nitrogen and phosphorous. Although all the green roofs part of the eThekwini study did contain compost in their substrate layer, the results indicate that not all the nitrogen and phosphorous levels were elevated. This finding leads to the conclusion that other properties such as substrate depth, vegetation density, as well as vegetation type played a significant role in the concentrations of these determinands.

Fluoride

The average levels of fluoride for the 5 tests are displayed in Figure 4.8. When compared to the conventional roof, fluoride levels in runoff from the green roof systems were found to be significantly higher.

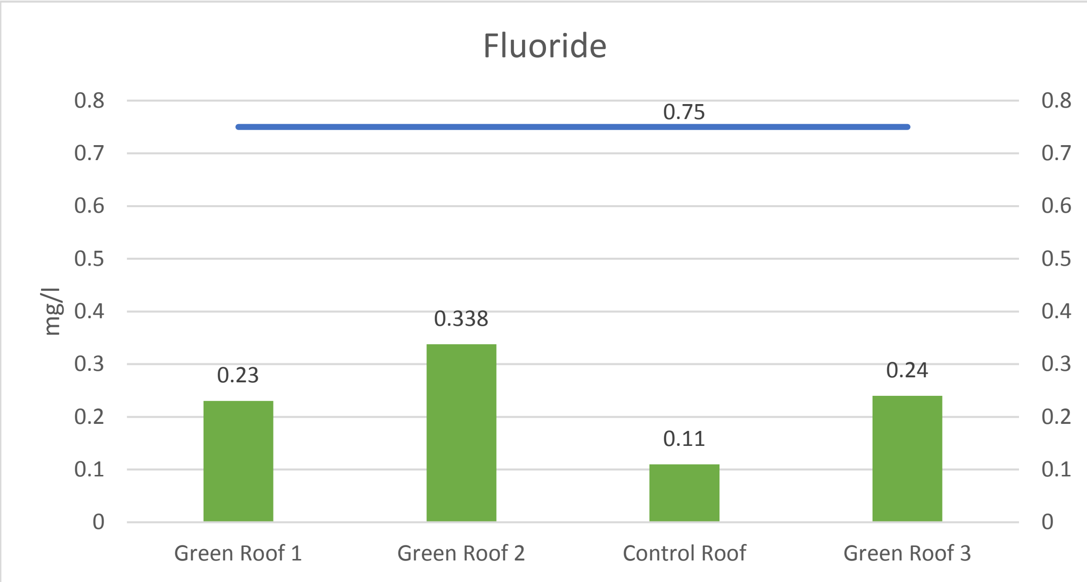


Figure 4. 8: Average levels of Fluoride

Green roof systems indicated average levels ranging from 0.23mg/l from green roof 1 to 0.338mg/l from green roof 2. Overall, the lowest average level of fluoride originated from the control roof, with a value of 0.11mg/l. All test results were found to be below the maximum target water quality level of 0.75mg/l (Department of Water Affairs and Forestry, 1996).

When average concentrations were compared amongst the green roofs, green roof 1 and green roof 3 obtained similar results, whereas green roof 2 produced a higher average concentration. This discrepancy could be a result of the higher volume of vegetation present on green roof 2, leading to the possibility that an increase in vegetation density could increases the concentration of fluoride in the stormwater runoff.

Contrary to results from a green roof measuring 4.1-5.6mg/L (Vijayaraghava et al., 2012), results from this study were fairly low. Zhang et al. (2015) showed that fluoride levels are greater in runoff from a green roof than from a conventional roof, which is consistent with results obtained in the eThekwini study.

Selenium

Selenium concentrations were all found to be below the maximum target water quality range of 2µg/l (Department of Water Affairs and Forestry, 1996). Amongst the green roof systems, green roof 2 produced the lowest average selenium concentration, whilst green roof 3 produced the highest. Figure 4.9 confirms that the control roof produced the lowest average concentration of selenium.

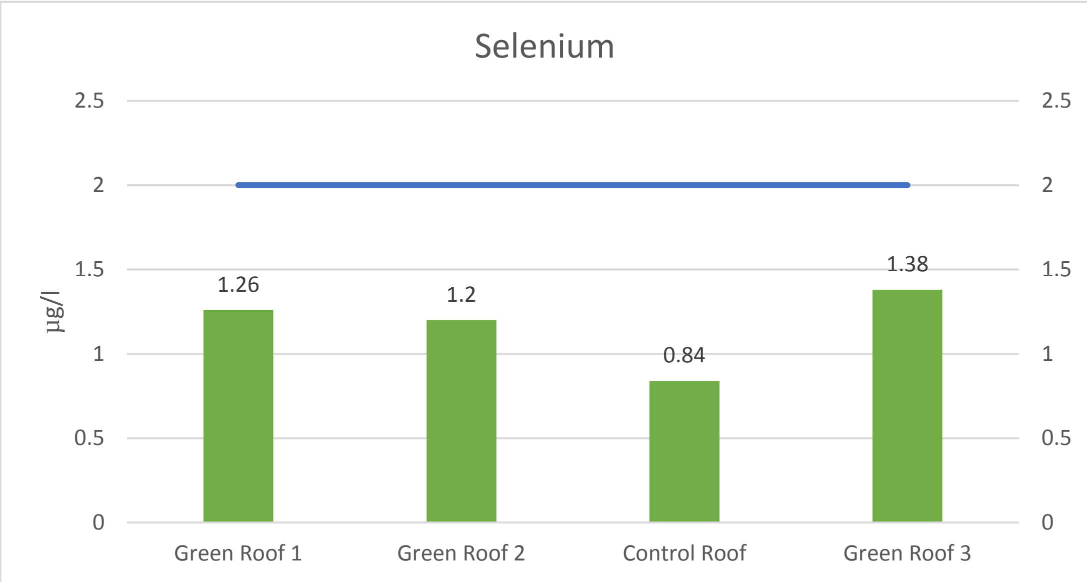


Figure 4. 9: Average levels of Selenium

Green roofs 2 and 3 contained the same substrate mixtures and depths, but different plant types and plant densities. A difference of 0.18µg/l is therefore more likely to be a result of the variation in plant type and density, rather than substrate composition or depth.

4.2.3 Metals

Arsenic

Figure 4.10 reflects the average levels of arsenic during the study. Average arsenic concentrations were found to range from 0.012mg/L to 0.106mg/L. Overall, green roof 2 produced the highest average, whilst green roof 1 produced the lowest average. All average levels recorded were found to be higher than the maximum target water quality range (Department of Water Affairs and Forestry, 1996).

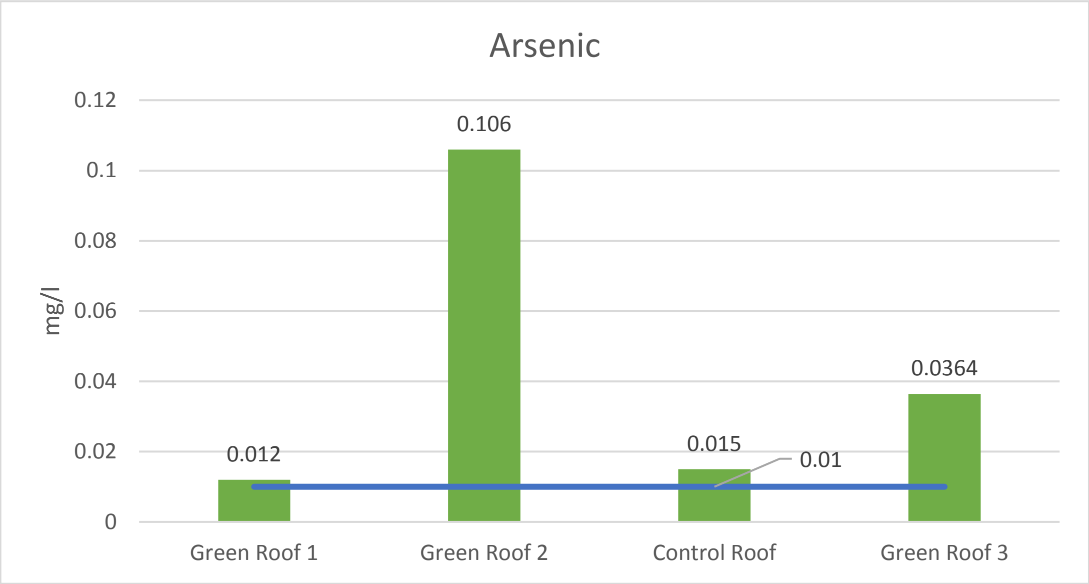


Figure 4. 10: Average levels of Arsenic

Once again, green roofs 2 and 3 show varying results despite having the same substrate depth and composition. This indicates that the different plant type and density could be responsible for the noticeable difference in the average arsenic concentration.

Copper

Figure 4.11 depicts the average levels of copper found in runoff from all roof types for the 5 tests. Levels were found to range from 0.0054mg/l from the control roof to 0.094mg/l from green roof 2. Between the green roof systems, green roof 1 produced stormwater runoff with the lowest level of copper, which measured 0.0174mg/l.

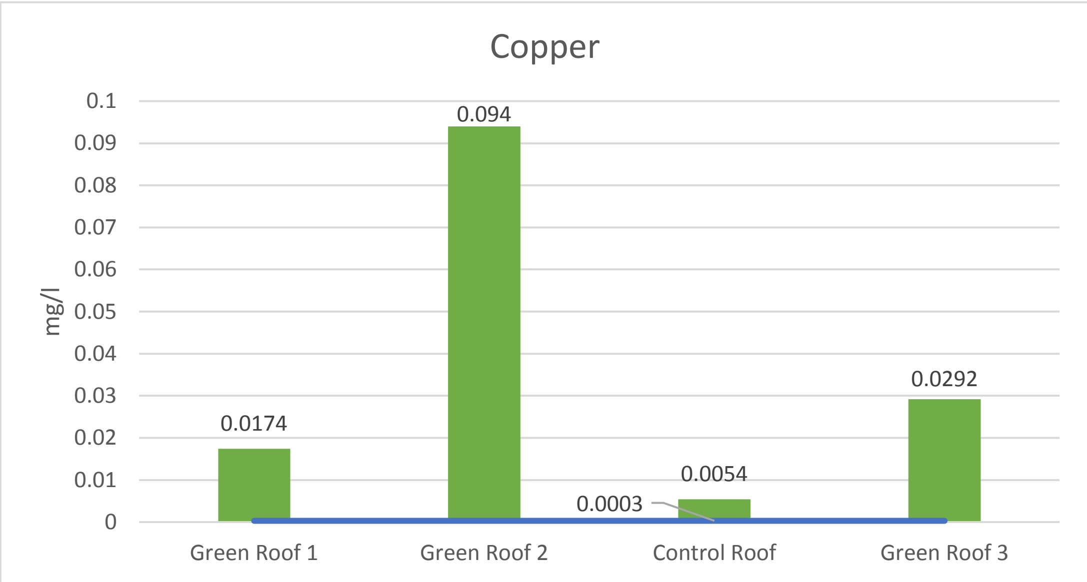


Figure 4. 11: Average levels of Copper

Results indicated considerably higher concentrations from the green roof systems than from the control roof. This result proved to be inconsistent with findings made by Zhang et al. (2015), which showed no substantial difference between the concentrations found in runoff from a conventional roof and a green roof. Differences in the green roof properties suggest that the type and density of vegetation present on green roof 2 resulted in the higher copper concentrations.

Iron

Figure 4.12 gives a representation of the iron concentrations obtained from the various tests. The control roof produced the lowest average iron concentrations, whereas green roof 2 produced the highest. The green roof with the lowest iron concentrations was green roof 1. As seen in previous results, the reason for the higher concentrations in green roof 2 could be a result of the vegetation types and density.

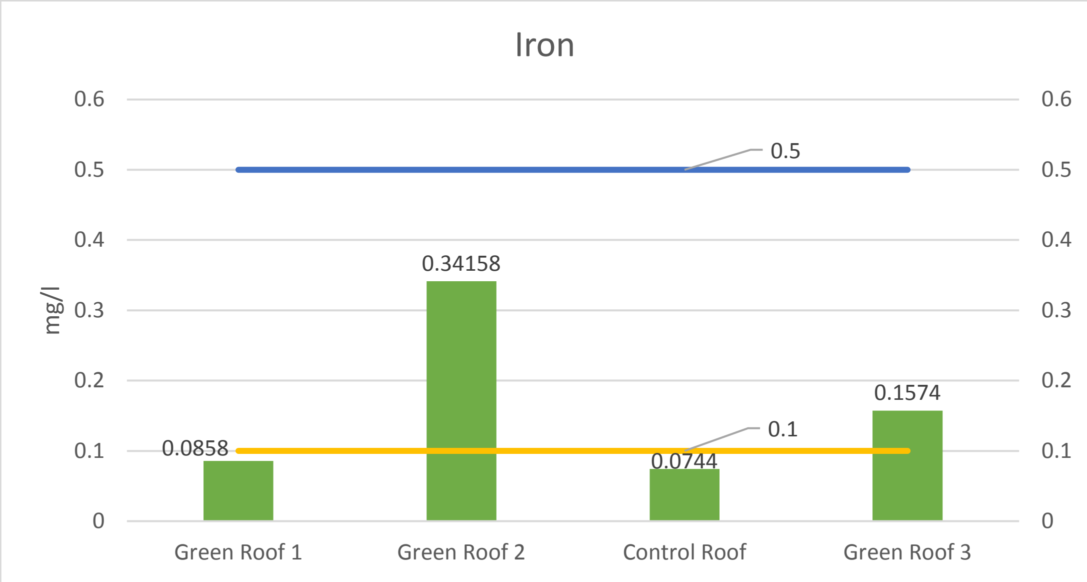


Figure 4. 12: Average levels of Iron

Hodgson et al. (2006) confirm that the target water quality range for iron for the Umgeni catchment is between 0.1mg/l and 0.5mg/l. Average results from green roof 1, green roof 3 and the control roof were found to be within these limits. Green roof 2 produced an average iron concentration that was higher than the target water quality maximum.

Manganese

Results for the concentration of manganese were all found to be below the maximum target water quality level of 0.18mg/l as seen in figure 4.13 (Department of Water Affairs and Forestry, 1996). Green roof 1 produced the lowest average concentration of manganese, and green roof 2 produced the highest average concentration.

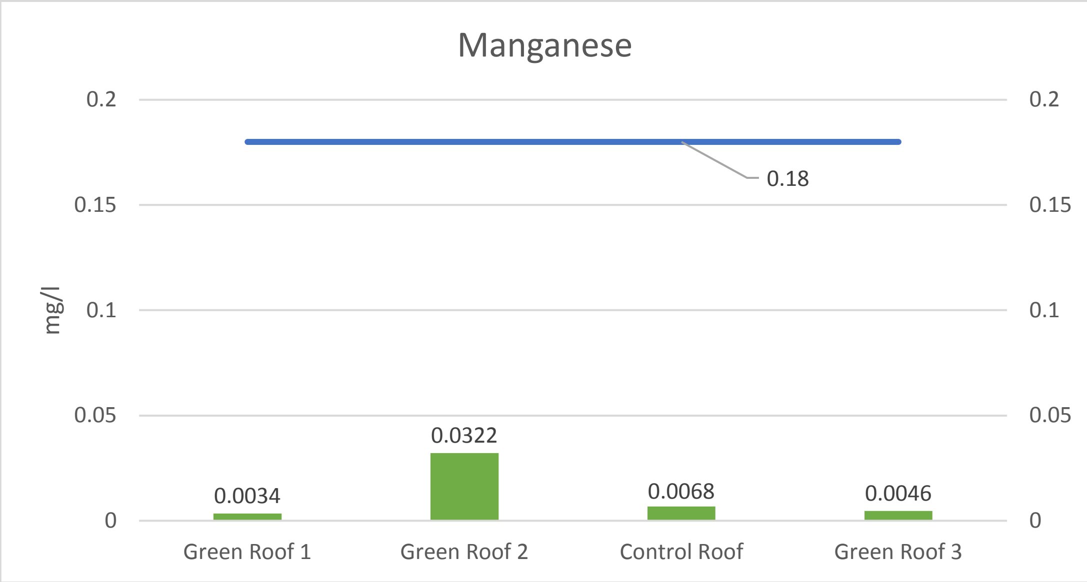


Figure 4. 13: Average levels of Manganese

Green roofs 1 and 3 showed a similar average level of manganese. The similarity between these roofs is the similar plant type and density. Green roof 2 varied drastically, and could be a result of its plant type and density. Findings from this study do not align with those made during previous research. Zhang at al. (2015) found no noticeable difference in the manganese levels found in runoff from a control roof and that from a green roof.

Aluminium

Average concentration levels of aluminium found in the different roof systems are shown in figure 4.14. All the results fall outside the target water quality range of 0.005mg/l – 0.01mg/l (Department of Water Affairs and Forestry, 1996).

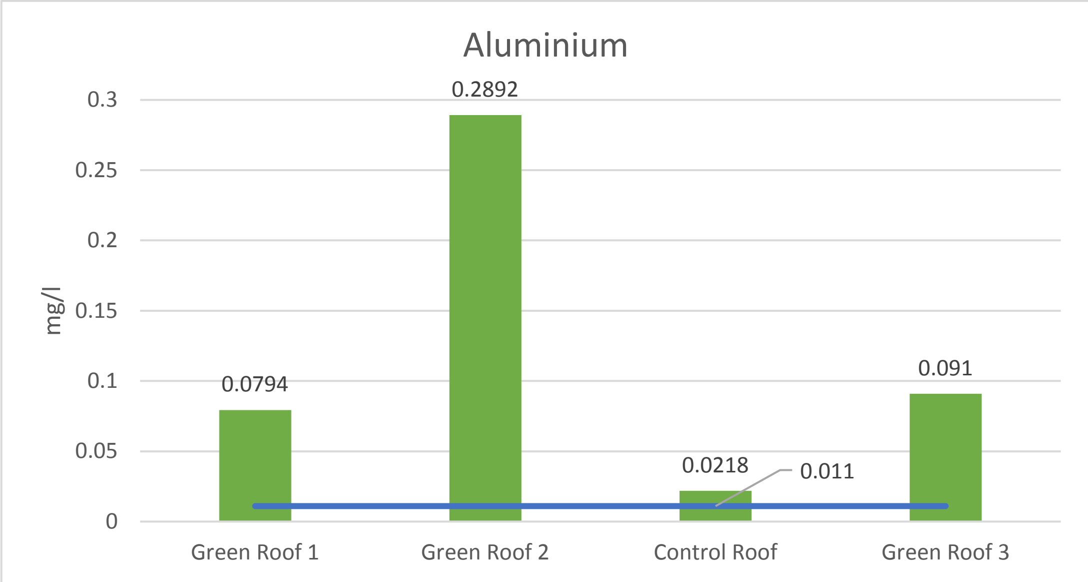


Figure 4. 14: Average levels of Aluminium

The lowest concentrations were found in runoff from the control roof, whereas the highest concentrations were found in runoff from green roof 2. Aluminium concentrations found in runoff from a green roof study in Singapore were between 0.13mg/l and 0.25mg/l (Vijayaraghava et al., 2012). Results from green roofs 1 and 3 agree with this finding, however the results from green roof 2 proved to have a higher average concentration. Vijayaraghavan and Raja (2014) found that substrates containing vermiculite produced stormwater runoff with a higher aluminium concentration level. Results from the eThekwini study agree with these findings.

Zinc

Average levels of zinc are presented in Figure 4.15. In the case of zinc, average concentration levels ranged from 0.002mg/l to 0.097mg/l. From the test results, it was established that all the resulting concentrations were greater than the maximum target water quality range of 0.002mg/l (Department of Water Affairs and Forestry, 1996), except for green roof 3 which showed 0.002mg/l.

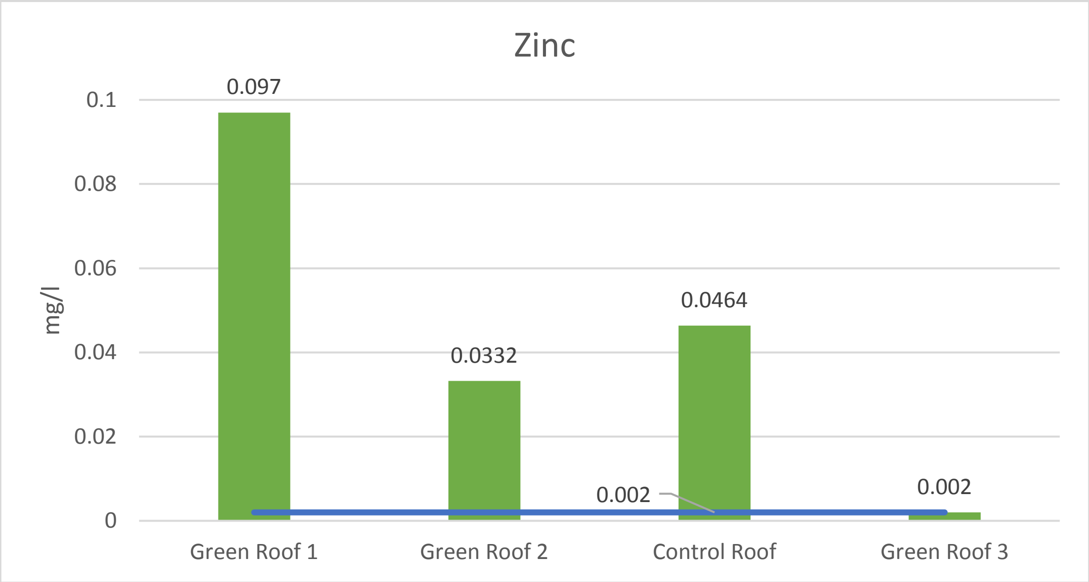


Figure 4. 15: Average levels of Zinc

Gregoire and Clausen (2011), claimed that a green roof acts as a sink for Zn, thereby reducing the amount present in runoff. Results from green roofs 1 and 3 from the eThekwini study are consistent with this finding. However, the average concentration from green roof 1 proved to be higher than that from the control roof, indicating that it acted as a source of zinc. Another conclusion from previous research stated that the zinc levels were not significantly different in the runoff from a green roof and a control roof (Zhang et al., 2015), which is also contradicted by the findings from this study.

Chromium

The graphical representation of resultant chromium concentrations indicates that all results were greater than the maximum target water quality range of 0.007mg/l (Department of Water Affairs and Forestry, 1996).

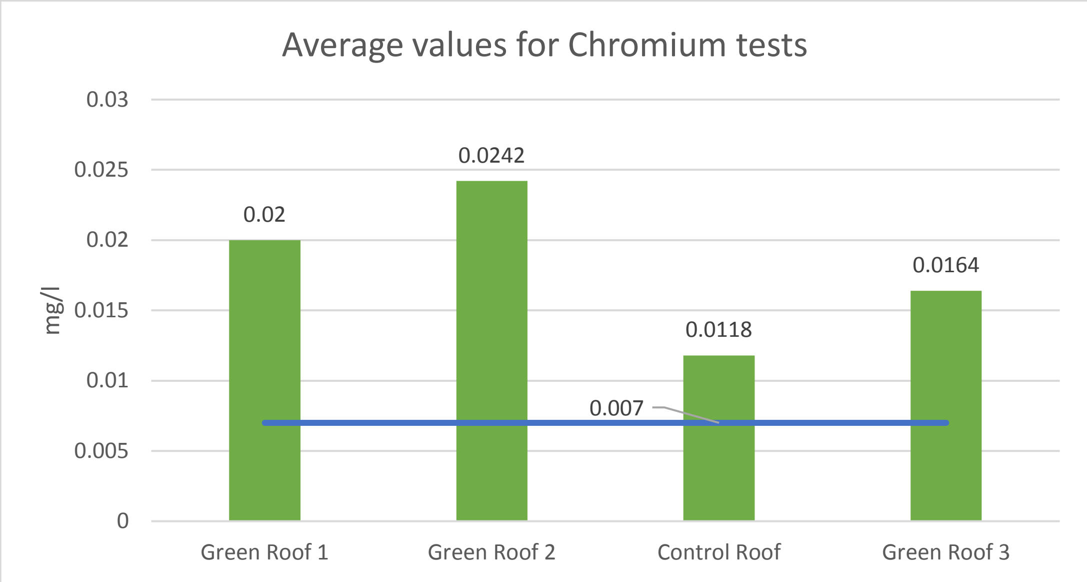


Figure 4. 16: Average levels of Chromium

4.2.3 Organic Determinands

<u>Phenols</u>

Outcomes of average concentrations of phenols from the stormwater runoff indicated that the control roof produced the lowest amount, and green roof 2 produced the highest amount. According to the Department of Water Affairs and Forestry (1996), the maximum target water quality range is 30µg/l. Figure 4.17 shows that the only result below this target was from the control roof.

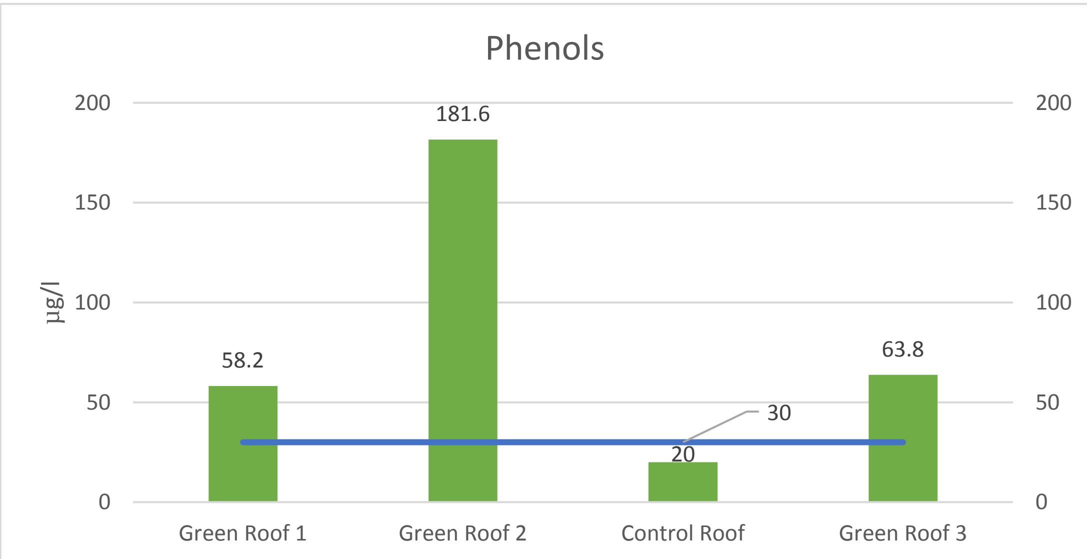


Figure 4. 17: Average levels of Phenols

Quality analysis summary

Results from tests for 17 pollutants were analysed. These results indicated that green roof 1 acted as a source for all pollutants except ammonia and manganese. Green roof 2 behaved as a source for all 17 pollutants, except zinc. The results also confirmed that green roof 2 acted as a source for all pollutants except ammonia, manganese and zinc.

Higher concentrations of free chlorine can hinder the growth rate, reduce reproductive activity, affect survival skills, upset the blood chemistry, and cause damage to gills in freshwater fish species (Department of Water Affairs and Forestry, 1996). Negative impacts also affect aquatic plant-life and phytoplankton (Department of Water Affairs and Forestry, 1996). Exposure to increased levels of arsenic could result in a reduction in growth and reproduction, and a reduction in migration behaviour in various aquatic organisms (Department of Water Affairs and Forestry, 1996). In higher concentrations, copper has been known to be responsible for brain damage in some mammals close to aquatic ecosystems (Department of Water Affairs and Forestry, 1996). Chromium can be especially harmful to mammals in terms of retarding bone repair (Department of Water Affairs and Forestry, 1996).

Table 4. 3: Average values for metals found in runoff from green roofs

Metal	Range (mg/l)	Authors	DWAF Range (mg/l)
Cu	0 – 0.75	Alsup et al., 2013; Alsup et al., 2010; Alsup et al., 2011; Buccola et al., 2008; Berndtsson et al., 2006; Berndtsson et al., 2008; Göbel et al., 2007; Gregoire and Clausen, 2011; Van Seters et al., 2009	0 – 0.0003
Mn	0 – 0.45	Alsup et al. (2010); Alsup et al. (2011); Berghage et al. (2009); Berndtsson et al. (2006); Berndtsson et al. (2008); Van Seters et al. (2009)	0 – 0.18
Zn	0.002 – 1.0536	Alsup et al., 2013; Alsup et al., 2010; Alsup et al., 2011; Berghage et al., 2009; Buccola et al., 2008; Berndtsson et al., 2006; Berndtsson et al., 2008; Berndtsson et al., 2009; Göbel et al., 2007; Gregoire and Clausen, 2011; Van Seters et al., 2009	0 – 0.02

Fe	0.7 – 831.6	Alsup et al. (2013); Alsup et al. (2010); Alsup et al. (2011); Berghage et al. (2009); Berndtsson et al. (2006); Berndtsson et al. (2008); Berndtsson et al. (2009); Van Seters et al. (2009)	0 – 0.1

Source: Whittinghill et al. (2016)

Phenols are known to cause an increase in respiratory rates, a reduction in growth, and imbalance in some fish species, as well as a reduction in the rate of photosynthesis in some aquatic plant species (Department of Water Affairs and Forestry, 1996).

Cu, Mn, and Zn values obtained from the study, were all consistent with the ranges in Table 4.3. Fe concentrations from the eThekwini study were found to be inconsistent with the values from Table 4.3. The analysis of results from the eThekwini study is presented in Table 4.4. Mason et al. (1999) maintain that a primary source of metals in the green roof runoff is atmospheric pollutants that are deposited onto the green roof. Although it has been proven that certain metals are present in higher quantities in runoff from a green roof than from a conventional roof, no study has confirmed that green roofs are a source of metal pollutants (Vijayaraghavan et al., 2012). Research by Beckett et al. (1998) and Hill (1971) show that vegetation act as a sink for pollutants, whereby the leaves and branches trap air pollutants.

Vijayaraghavan and Raja (2014) found that aluminium and iron concentrations in runoff from green roofs containing vermiculite were higher than in other substrate compositions. This is consistent with the eThekwini study, in which the highest levels of aluminium and iron were present in runoff from green roof 2, which consists of a substrate mixture containing 10% vermiculite.

Results from the study suggest that these green roof systems do not have the ability to filter pollutants out of stormwater runoff, but rather increase their concentrations as indicated in most test results.

Table 4. 4: Summary of stormwater quality results

	Unit	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3	Max Value	Min Value
TDS	mg/l	128.2	192.6	24	118.4	100	
TSS	mg/l	12.2	10.6	9.6	12.4		
Free Chlorine	mg/l	0.024	0.034	0.02	0.03	0.0002	
Nitrogen	mg/l	0.0856	0.059	0.0316	0.0434		
Ammonia	mg/l	0.114	0.4994	0.1386	0.1258	7000	
Orthophate	mg/l	0.7774	5.552	0.008	1.0196	0.00004	0.00002
Fluoride	mg/l	0.23	0.338	0.11	0.24	0.75	
Selenium	µg/l	1.26	1.2	0.84	1.38	2	
Arsenic	mg/l	0.012	0.106	0.015	0.0364	0.1	
Copper	mg/l	0.0174	0.094	0.0054	0.0292	0.0003	
Iron	mg/l	0.0858	0.34158	0.0744	0.1574	0.1	
Manganese	mg/l	0.0034	0.0322	0.0068	0.0046	0.18	
Aluminium	mg/l	0.0794	0.2892	0.0218	0.091	0.01	
Zinc	mg/l	0.097	0.0332	0.0464	0.002	0.02	
Lead	mg/l	0.0178	0.0268	0.0158	0.0158	0.0002	
Chromium	mg/l	0.02	0.0242	0.0118	0.0164	0.007	
Phenols	µg/l	58.2	181.6	20	63.8	30	

Key: - Acceptable - Unacceptable

4.3 Analysis of Stormwater Quantity

The following section focuses on the analysis of data that examined stormwater flow rates and volumes of the three different green roofs. This data is compared to that of the conventional roof. More specifically, this section focuses on overall green roof performance, retention behaviour in different rainfall intensities, and the PCSWMM model of the eThekwini CBD.

4.3.1 Retention behaviour, delay in peak flow rate, and difference in peak flow rate

Over the 7 month period from March 2017 to September 2017, a total of 20 rainfall events were monitored. Each event was analysed in terms of the retention rate, peak flow rate delay, and peak flow rate difference for the different roof systems. The peak rainfall intensities ranged from 0.4mm/hr to 3.4mm/hr. For the purpose of this study, the rainfall events were categorised according to intensity as done so in a previous study by Zhang et al. (2015). Low intensity meant 0 – 1.5mm/hr, moderate intensity meant 1.6 – 3mm/hr and high intensity meant 3mm/hr and above. Rainfall ranges of these values were used due to the rainfall intensity range of the study. The lowest rainfall intensity measured was 0.4mm/hr and the highest was 3.8mm/hr.

a. March 2017

Ten rainfall events were monitored on six different days during March 2017. The peak rainfall intensities ranged from 0.4mm/hr to 3.8mm/hr, with varying storm durations. Table 4.5 shows a summary of the rainfall event characteristics.

Table 4. 5: Characteristics for March rainfall events

	Peak Intensity	Duration (hh:mm)	Rainfall Before
9 March 2017 – Event 1	3.4mm/hr	01:00	None
9 March 2017 – Event 2	1.8mm/hr	03:45	Moderate
9 March 2017 – Event 3	0.6mm/hr	02:45	Light
10 March 2017 – Event 1	3.8mm/hr	04:30	Light
10 March 2017 – Event 2	0.8mm/hr	00:30	Moderate
10 March 2017 – Event 3	0.4mm/hr	05:05	Light
14 March 2017	1.2mm/hr	09:00	None
15 March 2017	0.6mm/hr	01:30	Light
19 March 2017	0.8mm/hr	01:15	None
24 March 2017	0.8mm/hr	05:15	None

Each event was analysed according to the retention, the peak flow rate delay, and the difference in peak flow rate, for each roof system.

- 9 March 2017 – Rainfall Event 1

The first rainfall event on 9 March 2017 that was monitored occurred from 00:15 to 01:15. Table 4.6 indicates a summary of the retention behaviour of the various roof systems during this time, and figure 4.18 displays the hydrograph created from the data collected.

Table 4. 6: Retention behaviour during rainfall event 1 on 9 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.198	0.33	0.33	0.198
Runoff Volume (m^3)	0.011	0	0.259	0.024
Retention (%)	94.41	100	21.53	87.95
Peak Flow Rate (l/s)	0.012	0	0.211	0.021
Time of Peak Flow Rate	01:15	-	01:00	01:15

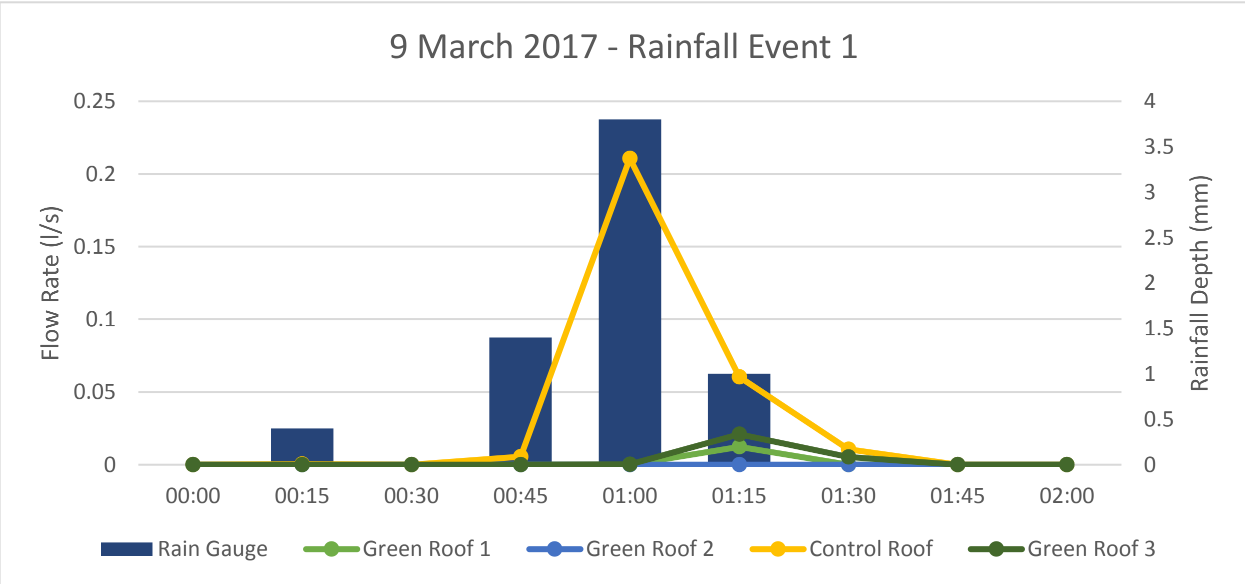


Figure 4. 18: Hydrograph for rainfall event 1 on 9 March 2017

Of the green roofs, green roof 2 proved to have the highest retention with 100%. The lowest retention rate for the green roofs came from green roof 3. Green roofs 2 and 3 had the same substrate depth and substrate mix, but different plant type and density. This leads to the conclusion that a green roof with denser vegetation can retain a higher volume of water, consistent with research by Berretta et al. (2014).

As depicted by the hydrograph, green roofs 1 and 3 experienced a 15 minute delay in their peak flow rates in relation to the control roof. The peak flow rate recorded for green roof 1 was 0.012l/s, and 0.021l/s for green roof 2. The control roof gave off a peak flow rate of 0.211l/s, indicating that the green roof systems were able to drastically reduce the peak flow rate for this particular rainfall event.

No flow data was recorded for green roof 2. This particular roofing system has the densest vegetation from all the systems, and different plant types in comparison to the other two green roofs. According to Nagase and Dunnet (2012) and Berghahge et al. (2007), the type of vegetation planted on a green roof can affect the retention capability, with certain plant types contributing as much as 40% of the roof's retention capability.

- 9 March 2017 – Rainfall Event 2

The next rainfall event also occurred on 9 March 2017 from 12:00 to 15:45. Table 4.7 shows the flow rate data collected during this rainfall event.

Table 4. 7: Retention and peak flow rate behaviour during rainfall event 2 on 9 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.449	0.419	0.411	0.453
Runoff Volume (m^3)	0.117	0	0.379	0.157
Retention (%)	73.92	100	7.82	65.31
Peak Flow Rate (l/s)	0.063	0	0.095	0.074

Time of Peak Flow Rate	14:30	-	14:15	14:15

Retention ranged from 7.82% for the control roof to 100% for green roof 2. The lowest retention of the green roofs came from green roof 3. Once again, the green roof with a thicker substrate layer and denser vegetation was able to retain more water.

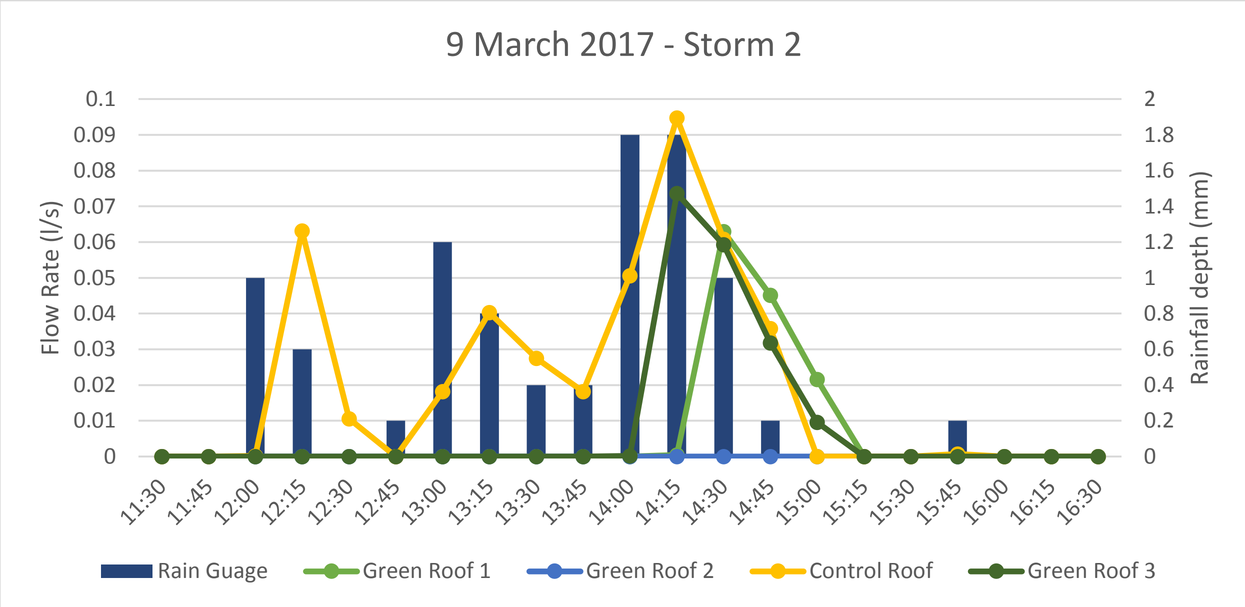


Figure 4. 19: Hydrograph for rainfall event 2 on 9 March 2017

Using the peak flow rate of the control roof as a proxy, green roof 3 experienced a peak flow rate at the same time. A reason for this occurrence could be the fact that this green roof was already partially saturated from the previous rainfall event. Green roof 1 delayed the peak flow rate by 15 minutes, and green roof 2 recorded no flow rate data for this rainfall event.

- 9 March 2017 – Rainfall Event 3

A third rainfall event was monitored on 9 March 2017. This event occurred from 18:45 to 21:15, and recorded a peak intensity of 0.6mm/hr. Table 4.8 summarizes the retention characteristics of the different roof systems for this event.

Table 4. 8: Retention and peak flow rate behaviour during rainfall event 3 on 9 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.056	0.052	0.051	0.057
Runoff Volume (m^3)	0	0	0.03	0
Retention (%)	100	100	41.52	100
Peak Flow Rate (l/s)	0	0	0.0155	0
Time of Peak Flow Rate	-	-	21:00	-

From the summary, it is evident that the rain event was too light to record any flow rate data from the 3 green roofs. The control roof had a retention of 41.52%. A reason for such a result could be due to ponding because of a low intensity rainfall. Figure 4.20 gives a graphical representation of the behaviour of the different roofs.

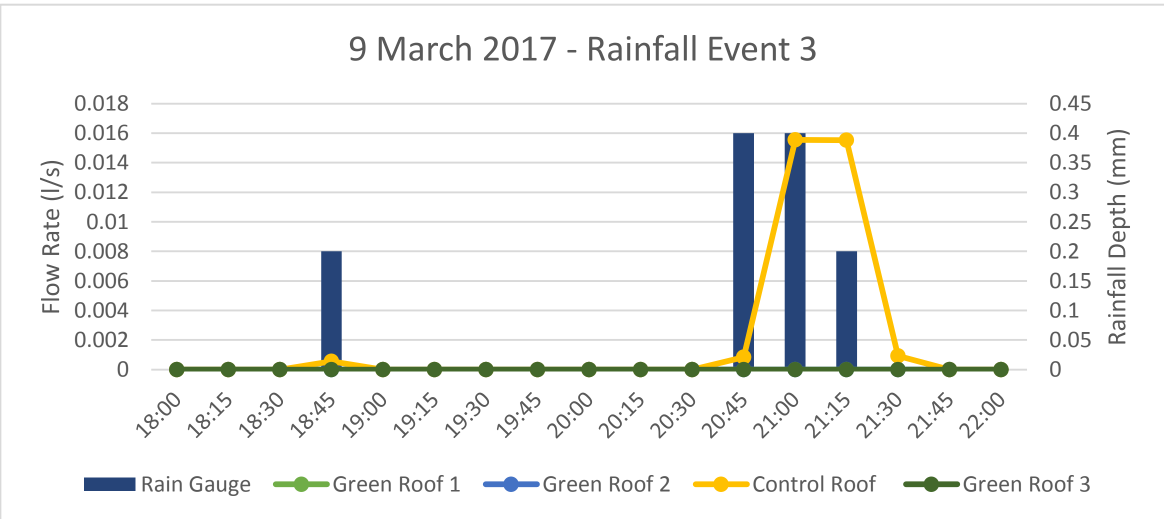


Figure 4. 20: Hydrograph for rainfall event 3 on 9 March 2017

- 10 March 2017 – Rainfall Event 1

The first rainfall event occurred from 00:15 to 04:45 and measured a peak intensity of 3.8mm/hr. Table 4.9 displays the retention for each roof during this occasion. A total rainfall depth of 8.4mm fell over the 4 hours and 30 minutes. Figure 4.21 also depicts the rainfall and flow rate pattern that was recorded.

Table 4. 9: Retention and peak flow rate behaviour during rainfall event 1 on 10 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.393	0.366	0.360	0.396
Runoff Volume (m^3)	0.240	0.076	0.264	0.232
Retention (%)	39.02	79.17	26.46	41.50
Peak Flow Rate (l/s)	0.158	0.029	0.197	0.138
Time of Peak Flow Rate	01:15	01:00	00:45	00:45

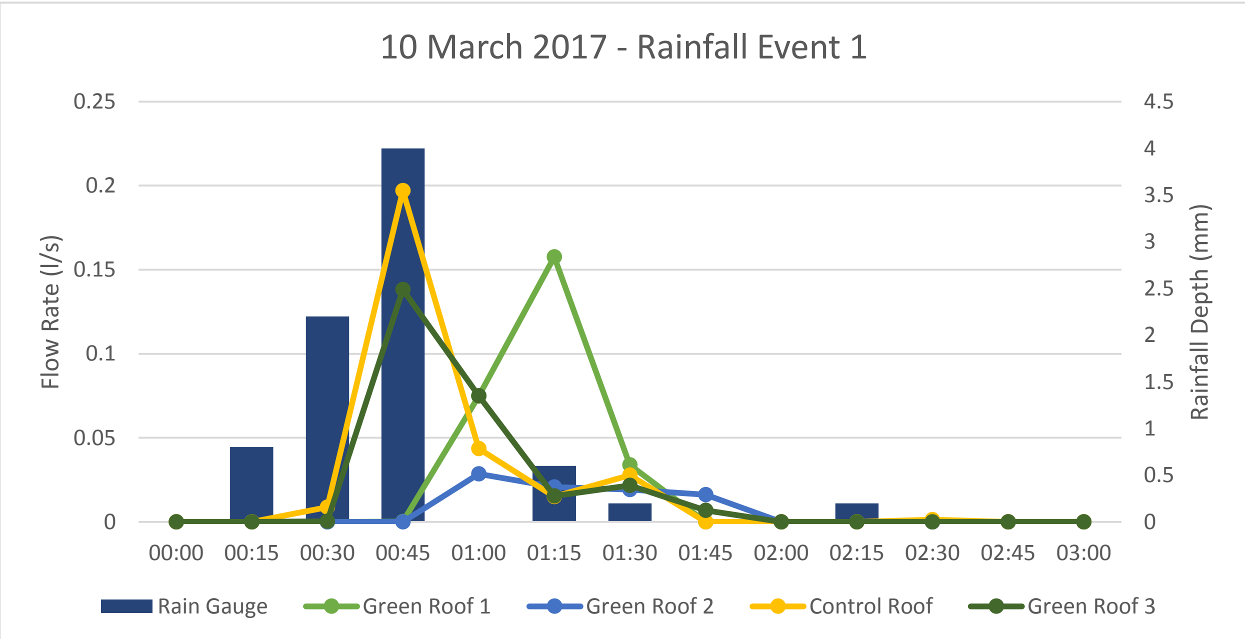


Figure 4. 21: Hydrograph for rainfall event 1 on 10 March 2017

During this rainfall, the green roof systems did not work as well as previously. One major difference was the fact that there were 3 rainfall events prior to the one under examination. This rainfall event also measured a higher peak intensity. A combination of these reasons could influence the saturation of the green roof, and therefore its ability to retain water. This is consistent with the findings of Stovin et al. (2007), and Lee et al. (2015), who state that the ability of a green roof to retain water is improved with an increase in the number of dry days prior to the rainfall event.

Amongst the green roof systems, green roof 1 demonstrated the lowest retention, and green roof 2 the highest. Green roof 1 had the shallowest substrate depth, and a different substrate mixture compared to the other two green roofs. The green roof with the highest vegetation density and deepest substrate performed the best in terms of retention. This situation was also noted in research from previous studies (Bengtsson et al., 2005; VanWoert et al., 2005; Mentens et al., 2006; Berndtsson, 2010; Zhang et al., 2015; Lee et al., 2015).

The peak flow rate for green roof 3 occurred at the same time in relation to the control roof. This showed that green roof 3 did not delay the peak flow rate for this occasion. Using the control roof as a proxy, green roof 1 delayed the peak flow rate by 15 minutes, and green roof 2 by 30 minutes. The biggest difference in peak flow rates was noticed between the control roof and green roof 2. The control roof measured a peak flow rate of 0.197l/s and green roof 2 measured 0.029l/s. Green roof 3 showed the highest peak flow rate amongst the green roof systems, measuring 0.138l/s.

- 10 March 2017 – Rainfall Event 2

A smaller rainfall event occurred on the same day from 15:00 to 15:30, with a peak rainfall intensity of 0.8mm/hr and rainfall depth of 1.8mm. As shown in table 4.10, the retention ranged from 30.19% from the control roof, to 100% from all the green roof systems.

Table 4. 10: Retention and peak flow rate behaviour during rainfall event 2 on 10 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.084	0.078	0.077	0.085
Runoff Volume (m^3)	0	0	0.054	0
Retention (%)	100	100	30.19	100
Peak Flow Rate (l/s)	0	0	0.059	0
Time of Peak Flow Rate	-	-	15:30	-

The data shows that the rainfall event was too light for any stormwater flow to leave the green roof systems.

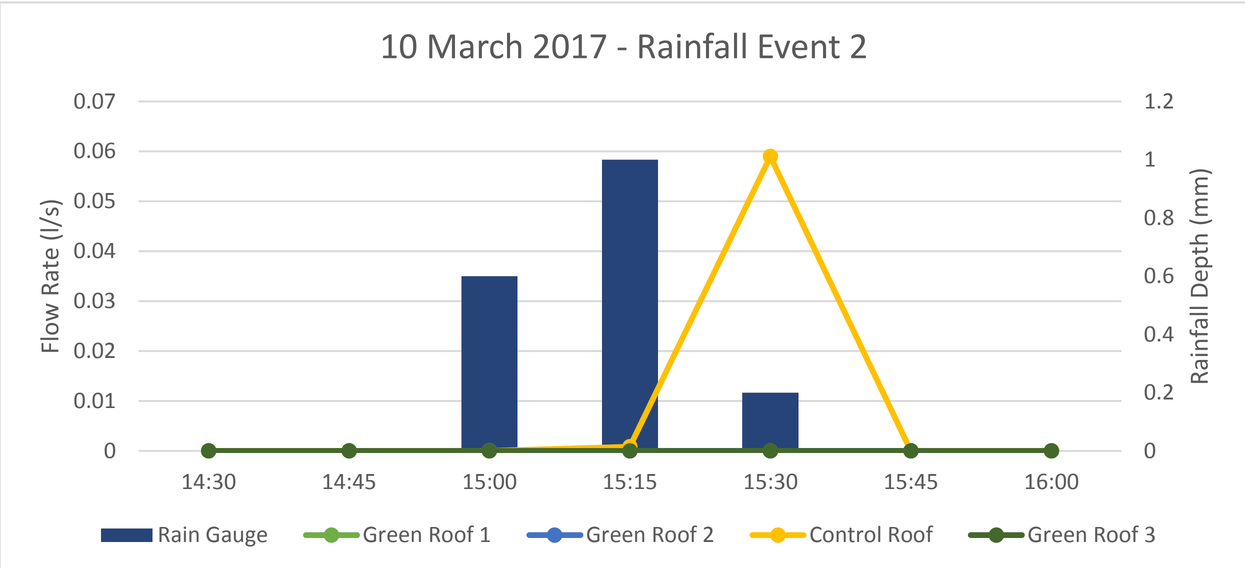


Figure 4. 22: Hydrograph for rainfall event 2 on 10 March 2017

- 10 March 2017 – Rainfall Event 3

This day saw another small rainfall event from 18:15 to 23:30. The event produced a peak rainfall intensity of 0.4mm/hr, and a rainfall depth of 1.2mm. Table 4.11 displays the retention and peak flow rate data.

Table 4. 11: Retention and peak flow rate behaviour during rainfall event 3 on 10 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.056	0.052	0.051	0.057
Runoff Volume (m^3)	0	0	0.054	0
Retention (%)	100	99.98	36.76	100
Peak Flow Rate (l/s)	0	0.009	0.032	0
Time of Peak Flow Rate	-	21:15	20:00	-

Both green roofs 1 and 3 produced no flow for this rain event, whilst green roof 2 produced a 99.98% retention rate. The control roof showed a retention of 36.76%. Green roofs 1 and 3 both have different substrate mixtures and depths, but have similar vegetation types. Green roofs 2 and 3 are identical in terms of substrate mixture and depth, but differ in vegetation type.

Figure 4.23 gives a graphical representation of the data, indicating that none of the roofs discharged any stormwater after 20:30, except the control roof at 23:30 which was minimal. This proved that a very low rainfall does not contribute to the runoff from a green roof system.

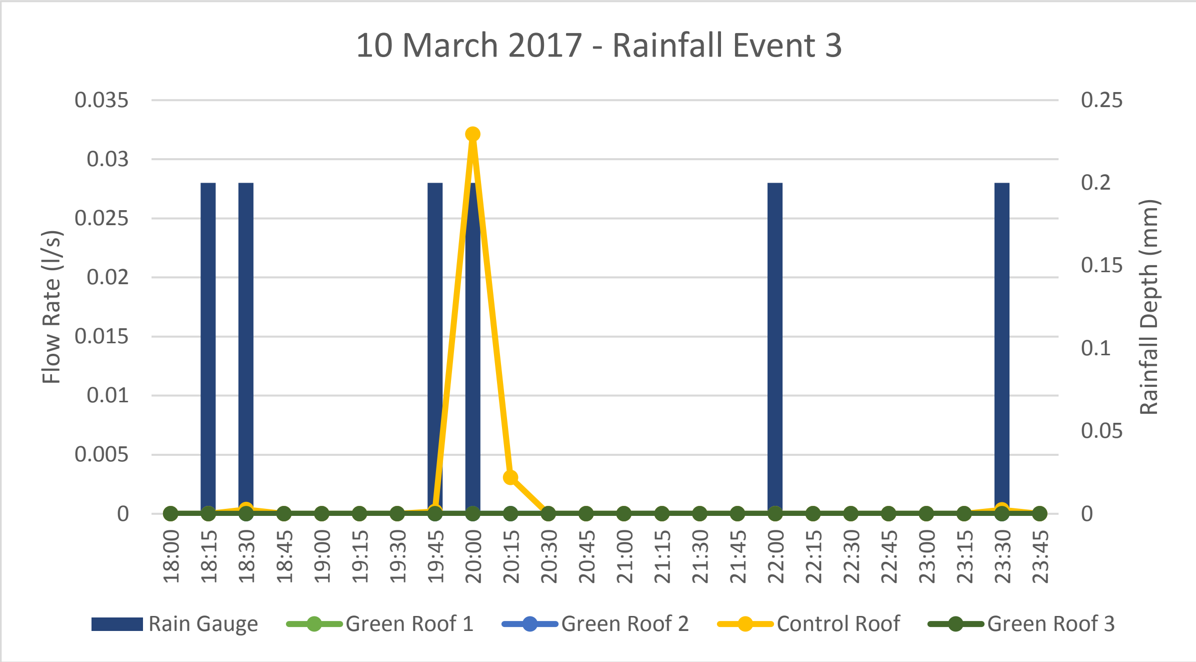


Figure 4. 23: Hydrograph for rainfall event 3 on 10 March 2017

- 14 March 2017

One rain event occurred on 14 March 2017, measuring a peak intensity of 1.2mm/hr and a rainfall depth of 8mm. Table 4.12 and figure 4.24 show the retention and peak flow rate behaviour. Green roof 2 achieved 100% retention, green roof 1 achieved 91.94% and green roof 3 achieved 66.83%. All three roofs performed significantly better than the control roof, which had 25.43% retention.

Green roof 3 did not have the shallowest substrate depth, therefore making this result inconsistent with the literature that asserts that a green roof with a shallower substrate depth has a lower retention rate (Bengtsson et al., 2005; VanWoert et al., 2005; Mentens et al., 2006; Berndtsson, 2010; Zhang et al., 2015). A major difference between green roofs 1 and 3 is the substrate composition. Green roof was constructed using a substrate consisting primarily of crushed brick, whilst green roof 3 was built using mainly LECA. As per table 3.3 of the research methods chapter, the constituents making up green roof 1 proved to have a significant difference in weight between dry and saturated measurements. This showed that those constituents with a bigger difference between dry and saturated weight, will have a higher water holding capacity, and therefore improve the retention capacity of the green roof.

When compared to the actual rainfall, green roof 3 delayed the peak flow rate by 15 minutes, and green roof 1 by 30 minutes. The greatest difference in peak flow rate when compared to the control came from green roof 2, as it measured no flow rate data for the rainfall event. Next was green roof 3, and the smallest difference achieved came from green roof 3.

Table 4. 12: Retention and peak flow rate behaviour during rainfall event on 14 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.374	0.349	0.342	0.378
Runoff Volume (m^3)	0.030	0	0.255	0.125
Retention (%)	91.94	100	25.43	66.83
Peak Flow Rate (l/s)	0.033	0	0.091	0.052
Time of Peak Flow Rate	05:30	-	05:00	05:15

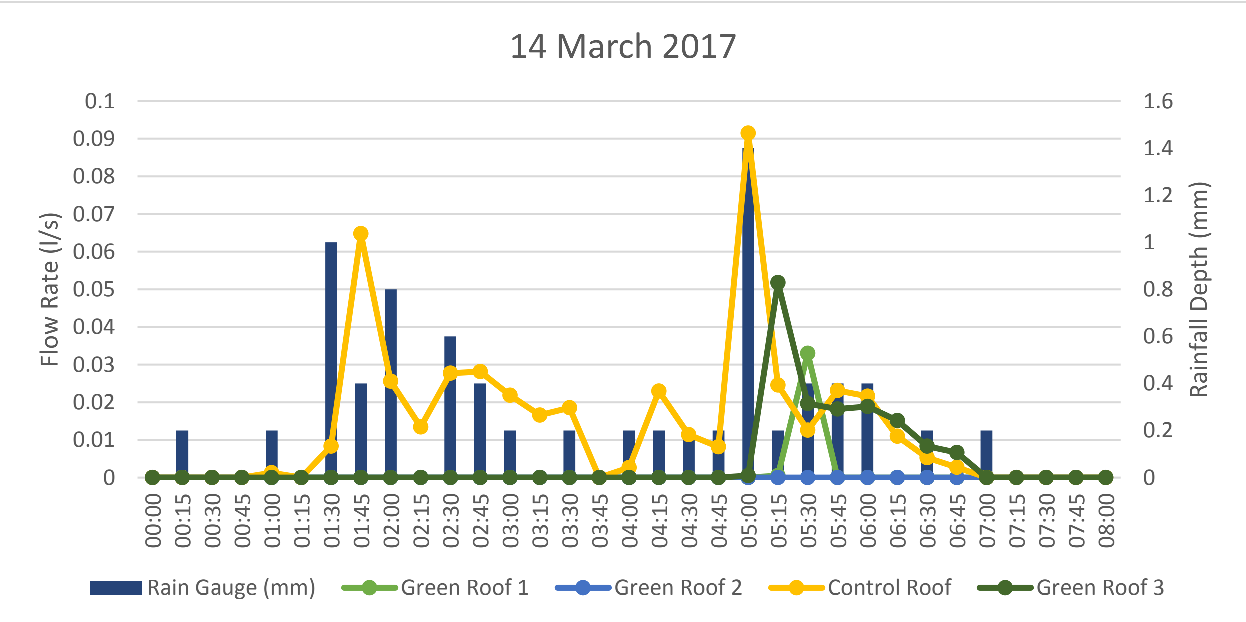


Figure 4. 24: Hydrograph for rainfall event on 14 March 2017

- 15 March 2017

This day experienced one rainfall event of low intensity measuring 0.6mm/hr, and a rainfall depth of 1mm. The entire event lasted an hour and 30 minutes. As seen in table 4.13, all the green roof systems did not produce any stormwater runoff. This indicates that under low intensity and short time periods, the green roofs can be completely effective and absorb all the rainfall.

Table 4. 13: Retention and peak flow rate behaviour during rainfall event on 15 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.047	0.044	0.043	0.047
Runoff Volume (m^3)	0	0	0.037	0
Retention (%)	100	100	13.68	100
Peak Flow Rate (l/s)	0	0	0.041	0
Time of Peak Flow Rate	-	-	20:30	-

- 19 March 2017

Another low intensity rainfall event occurred on 19 March 2017. The recorded rainfall depth was 1.6mm and peak rainfall intensity of 0.8mm/hr. As with the previous event, all three green roofs showed no record of stormwater runoff. The control roof showed a retention of 42.54% as per table 4.14. Again, these results showed the 100% absorption of rainfall by the green roofs.

Table 4. 14: Retention and peak flow rate behaviour during rainfall event on 19 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.075	0.070	0.068	0.076
Runoff Volume (m^3)	0	0	0.039	0
Retention (%)	100	100	42.54	100
Peak Flow Rate (l/s)	0	0	0.022	0
Time of Peak Flow Rate	-	-	10:15	-

- 24 March 2017

One rainfall event occurred on 24 March 2017 with a rainfall depth of 2.8mm and peak rainfall intensity of 0.8mm/hr, over a period of 5 hours and 15 minutes. This event was similar to that of 19 March 2017, but with a greater rainfall depth and longer duration. The green roofs reacted in the same way, with 100% retention from all three. The control roof reacted slightly differently in comparison with the previous event, with a lower retention of 9.58%. This indicates that during a rainfall event of a longer duration and higher rainfall depth, there will be more stormwater runoff from a control roof. The researcher reached the conclusion that more rainfall falling onto the control roof, meant that less water would be able to puddle. These results are tabulated in table 4.15.

Table 4. 15: Retention and peak flow rate behaviour during rainfall on 24 March 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.131	0.122	0.120	0.132
Runoff Volume (m^3)	0	0	0.108	0
Retention (%)	100	100	9.58	100
Peak Flow Rate (l/s)	0	0	0.038	0
Time of Peak Flow Rate	-	-	17:30	-

b. April 2017

Two rainfall events were examined over the course of April 2017, with peak rainfall intensities of 1.6mm/hr and 3.4mm/hr. Both rainfall events lasted over 8 hours, and experienced no prior rainfall. Table 4.16 highlights the properties of the events.

Table 4. 16: Properties for April rainfall events

	Peak Intensity	Duration (hh:mm)	Rainfall Before
6 – 7 April 2017	1.6mm/hr	10:30	None
24 April 2017	3.4mm/hr	08:30	None

- 6 – 7 April 2017

The rainfall began at 15:00 on 6 April 2017 and lasted until 01:30 on 7 April 2017. As shown in table 4.17, the retention amongst the green roof systems ranged from 71.81% for green roof 3 to 97.30% for green roof 2. The control roof had a retention of 12.18% for this event. This is slightly higher than that found by Mentens et al. (2006) of 27-81%.

Table 4. 17: Retention and peak flow rate behaviour during rainfall event on 6 – 7 April 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m³)	0.852	0.794	0.779	0.859
Runoff Volume (m³)	0.207	0.021	0.684	0.242
Retention (%)	75.70	97.30	12.18	71.81
Peak Flow Rate (l/s)	0.086	0.012	0.086	0.071
Time of Peak Flow Rate	01:00	01:30	00:30	01:00

Figure 4.25 depicts a graphical representation of the hydrograph for the rainfall event. The control roof achieved a peak flow rate of 0.086l/s at 00:30. Green roof 2 recorded the lowest peak flow rate. Green roof 2 also delayed the peak by the longest time, having achieved its peak flow rate at 01:30. All three green roof systems delayed the peak flow rate in comparison to the control roof, showing uniformity with previous studies, such as that by Stovin (2010) and Bengtsson et al. (2005) which proved that the peak flow delay is a key benefit of a green roof.

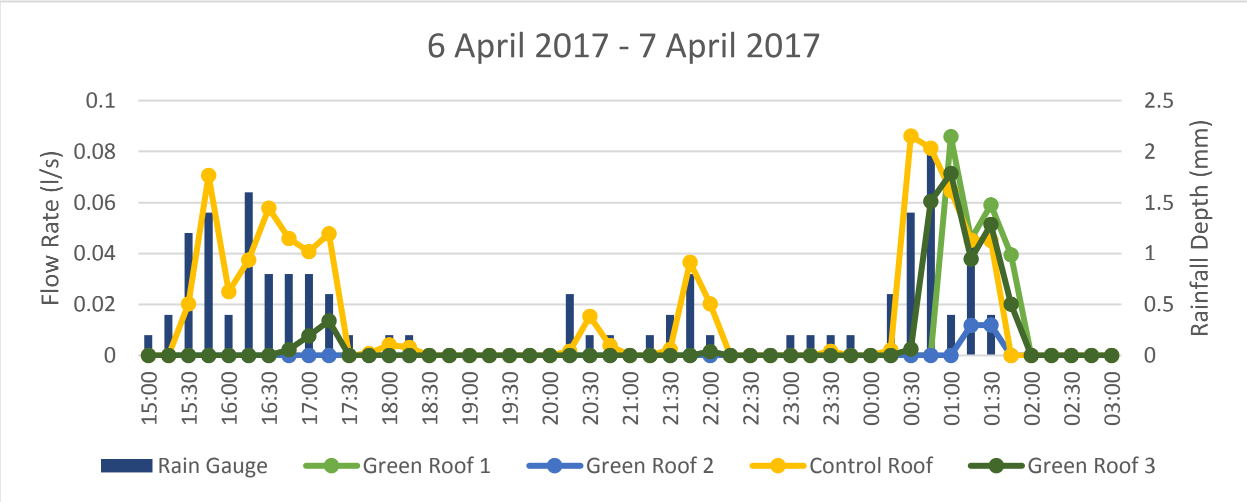


Figure 4. 25: Hydrograph for rainfall event on 6 – 7 April 2017

- 24 April 2017

A rainfall event with a peak intensity of 3.4mm/hr occurred over an 8.5 hour time period. The maximum retention achieved by any of the green roofs was 96.61% for green roof 2, and the lowest of 72.37% for green roof 3. Table 4.18 shows the behaviour of the different roofs.

According to figure 4.26, the peak flow rate was delayed by one hour by green roof 3, and by one hour and 15 minutes by green roofs 1 and 2. Green roofs 1 and 2 differ by substrate depth and mixture, and vegetation type and density. Green roof 1 has a substrate depth of 3cm, and mixture primarily consisting of crushed brick, as well as a lower density of vegetation, whereas green roof 2 has a substrate depth of 10cm, and a mixture containing mostly light expanded clay aggregate, as well as very dense vegetation. Berretta et al. (2014) argued that the evapotranspiration rate and ability of the plant species is directly proportional to the retention capability of the green roof system, and this could be a reason for the same peak flow rate delay from green roofs 1 and 2, despite their different substrate depths and compositions, when compared to the actual rainfall.

The green roof which reduced the peak flow rate by the largest degree was green roof 2. The control roof achieved a peak of 0.231l/s, whilst green roof 2 achieved a peak of 0.011l/s.

Table 4. 18: Retention and peak flow rate behaviour during rainfall event on 24 April 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.786	0.732	0.719	0.793
Runoff Volume (m^3)	0.119	0.025	0.648	0.219
Retention (%)	84.88	96.61	9.85	72.37
Peak Flow Rate (l/s)	0.061	0.011	0.231	0.065
Time of Peak Flow Rate	08:30	08:30	07:15	08:15

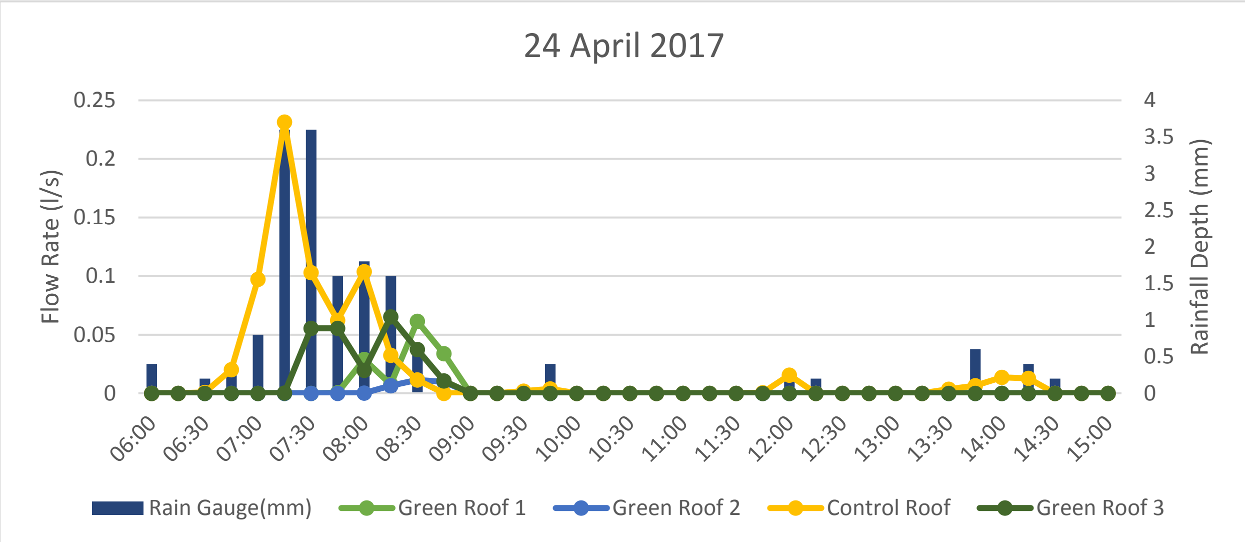


Figure 4. 26: Hydrograph for rainfall event on 24 April 2017

c. May 2017

The month of May 2017 witnessed 5 rainfall events in total, however a malfunction in equipment during the first few weeks of the month meant that only 2 events were monitored. These events occurred on 15 and 27 May 2017. The rainfall properties are highlighted in table 4.19.

Table 4. 19: Properties for May rainfall events

	Peak Intensity	Duration (hh:mm)	Rainfall Before
15 May 2017 – Event 1	0.8mm/hr	01:45	Heavy
15 May 2017 – Event 2	1.4mm/hr	03:30	Light
27 May 2017	0.6mm/hr	00:15	None

- 15 May 2017 – Rainfall Event 1

This rainfall event occurred after an intense rainfall that lasted 2 days (13 May 2017 – 15 May 2017). As seen in table 4.20 below, green roof 2 retained 100% of the rainfall. Green roof 2 attained a retention of 74.92%, and green roof 1, 50.19%.

Table 4. 20: Retention and peak flow rate behaviour during rainfall event 1 on 15 May 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.178	0.166	0.163	0.179
Runoff Volume (m^3)	0.089	0	0.173	0.045
Retention (%)	50.19	100	-6.40	74.92
Peak Flow Rate (l/s)	0.023	0	0.048	0.021
Time of Peak Flow Rate	16:00	-	16:00	16:30

The control roof showed a negative retention of -6.40%. This meant that amount of stormwater discharged was greater than the amount of rain that fell onto the roof. A reason for this occurrence could be because the rainfall from the previous storm, ponded on the roof, and therefore when this rainfall happened, it washed out the previous runoff as well as the runoff from this storm.

The retentions from green roofs 1 and 3 differ by more than 20%, which could be a result of the varying substrate depths and mixtures. Green roof 1 had a depth of 3cm, whilst green roof 3 had a depth of 10cm. As proposed by previous researchers, the substrate depth is one of the major contributors to the retention capacity of a green roof system (Bengtsson et al., 2005; VanWoert et al., 2005; Mentens et al., 2006; Berndtsson, 2010; Zhang et al., 2015).

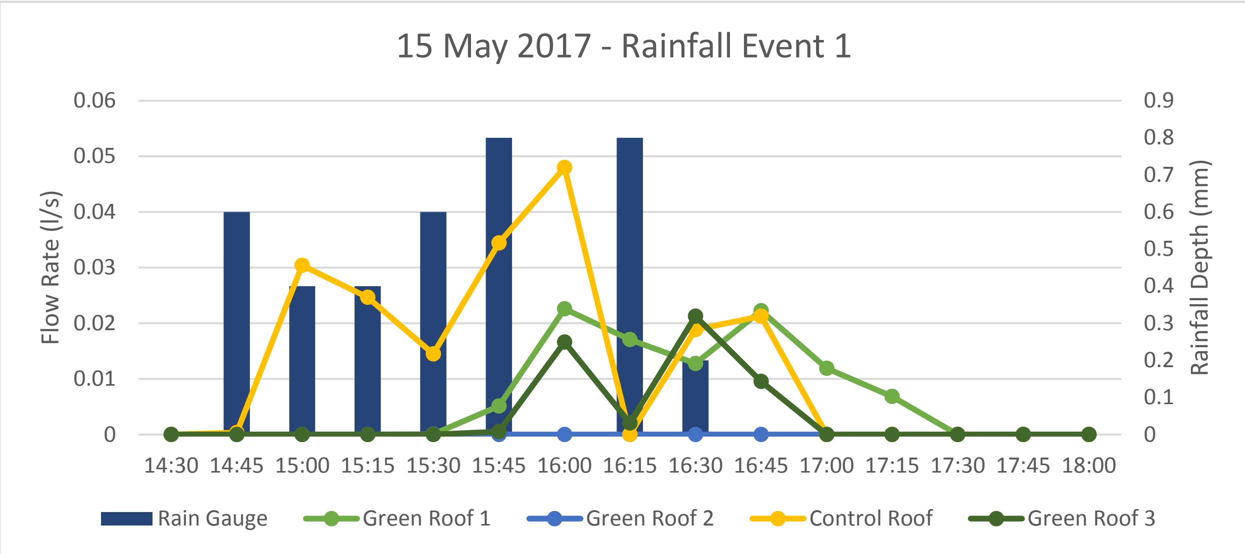


Figure 4. 27: Hydrograph for rainfall event on 15 May 2017

As depicted in figure 4.27, and using the control roof as a proxy, the peak flow rate for the control roof occurred at 16:00. The peak for green roof 1 also occurred at 16:00, showing that it did not cause any delay. Green roof 3 did delay the peak flow rate by 30 minutes. The most noticeable difference between peak flow rate measurements was between the control roof and green roof 2. Green roof 2 did not allow any stormwater to run off.

- 15 May 2017 – Rainfall Event 2

Table 4.21 shows the behaviour of the roof systems during the 3.5 hour rainfall, which produced a peak intensity of 1.4mm/hr.

Table 4. 21: Retention and peak flow rate behaviour during rainfall event 2 on 15 May 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.159	0.148	0.146	0.160
Runoff Volume (m^3)	0.064	0	0.119	0.050
Retention (%)	59.47	100	18.11	68.74
Peak Flow Rate (l/s)	0.031	0	0.078	0.023
Time of Peak Flow Rate	23:30	-	23:15	23:30

Once again, green roof 2 recorded no flow rate data indicating that it retained 100% of the rainfall. Green roof 3 attained 68.74% retention and green roof 1, 59.47%. Figure 4.28 provides a graphical representation of the behaviour of each roof.

From the graph, and in relation to the control roof, it is evident that peak flow rate was achieved at 23:15, whilst green roofs 1 and 3 achieved their peak flow rate at 23:30. Although green roof 2 had no stormwater runoff, green roof 3 managed to reduce the peak significantly, from 0.078l/s in the control roof to 0.023l/s. Green roof 1 produced a higher peak than green roof 2, which is possibly due to green roof 1 reaching saturation before green roof 2.

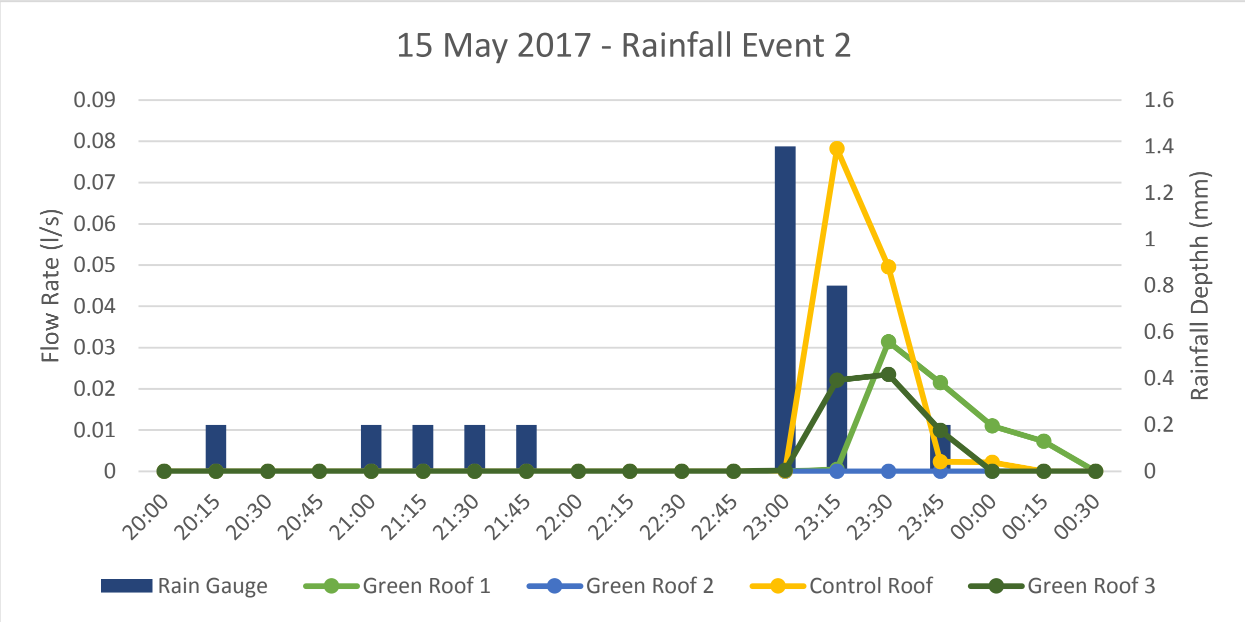


Figure 4. 28: Hydrograph for rainfall event 2 on 15 May 2017

- 27 May 2017

One rainfall event occurred on 27 May 2017 from 20:15 to 20:30. The event measured a peak rainfall intensity of 0.6mm/hr, and a total rainfall depth of 1mm. This was regarded as a low intensity storm over a short period of time. Table 4.22 gives insight to the retention and peak flow rate for each roof system under these conditions, and figure 4.29 presents the hydrograph created from the data collected.

The figure clearly indicates that none of the green roof systems discharged any stormwater during this rainfall event. The control roof retained16.25%.

Table 4. 22: Retention and peak flow rate behaviour during rainfall event 27 May 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.047	0.044	0.043	0.047
Runoff Volume (m^3)	0	0	0.036	0
Retention (%)	100	100	16.25	100

Peak Flow Rate (l/s)	0	0	0.040	0
Time of Peak Flow Rate	-	-	20:45	-

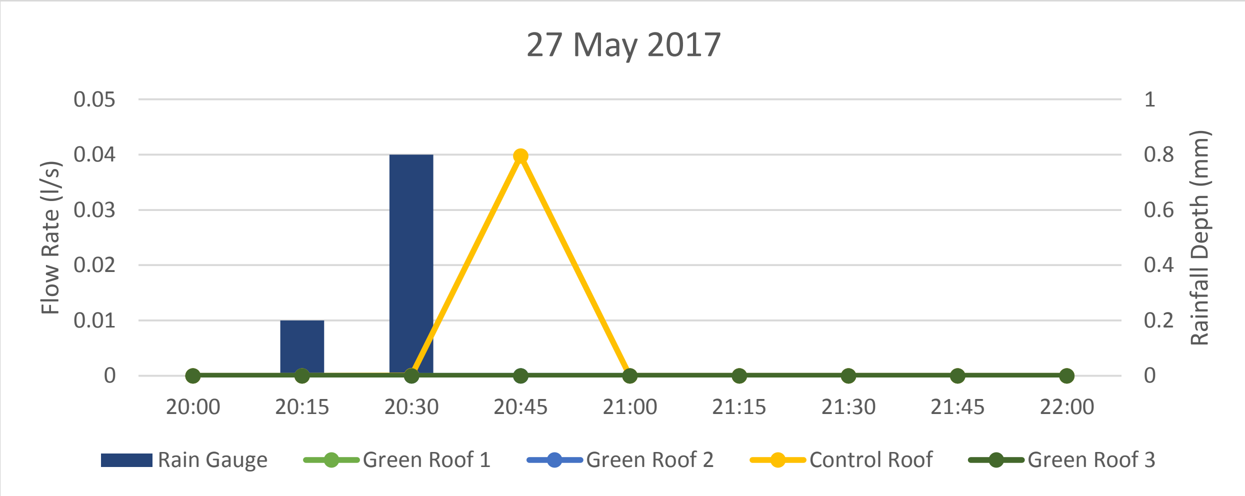


Figure 4. 29: Hydrograph for rainfall event on 27 May 2017

d. July 2017

Three rainfall events were monitored during the month of July. However, due to a malfunction in the flow meter equipment, reliable data could only be retrieved from two events. Both events occurred on 13 July 2017 as shown in table 4.23.

Table 4. 23: Properties for July rainfall events

	Peak Intensity	Duration (hh:mm)	Rainfall Before
13 July 2017 – Event 1	0.4mm/hr	04:00	None
13 July 2017 – Event 2	0.8mm/hr	00:15	Light

- 13 July 2017 – Rainfall Event 1

The first rainfall event lasted 4 hours, from 14:15 to 18:15, and recorded a peak rainfall intensity of 0.4mm/hr. This event was considered low intensity over a longer period of time than the previous one on 27 May 2017. The behaviour of the roofs in terms of retention rate and peak flow rate are presented in table 4.24.

Figure 4.30 presents the flow rate and rainfall data. Once again, all green roof systems had 100% retention, whilst the control roof achieved a 5.87% retention.

Table 4. 24: Retention and peak flow rate behaviour during rainfall event 1 on 13 July 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.075	0.070	0.068	0.076
Runoff Volume (m^3)	0	0	0.064	0
Retention (%)	100	100	5.87	100
Peak Flow Rate (l/s)	0	0	0.024	0
Time of Peak Flow Rate	-	-	18:30	-

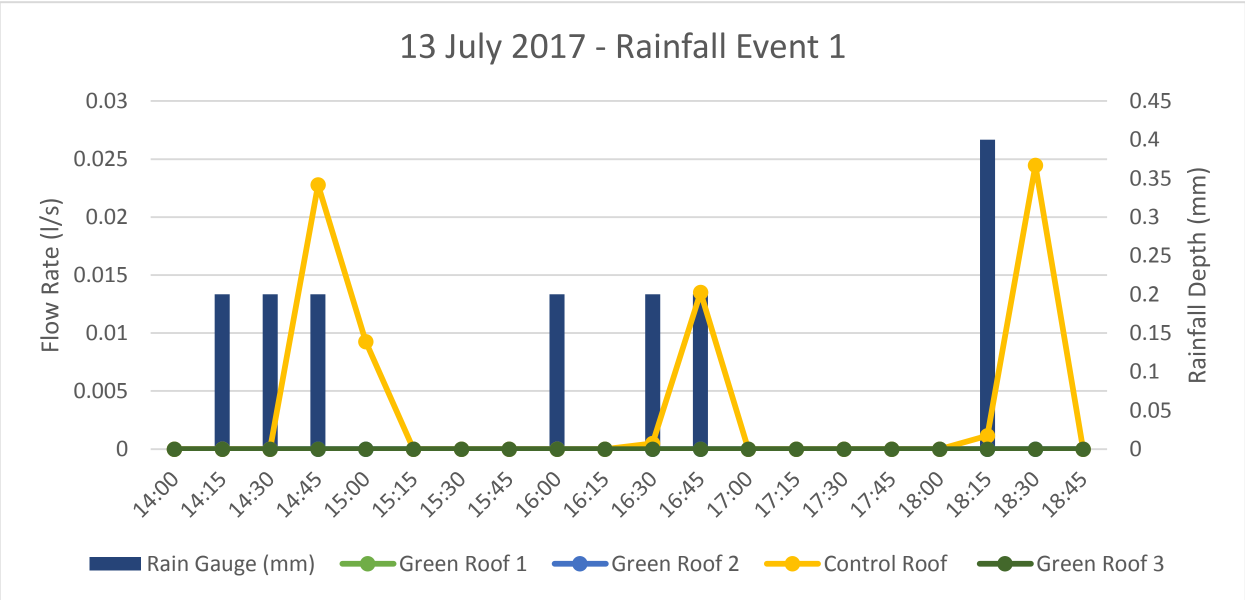


Figure 4. 30: Hydrograph for rainfall event 1 on 13 July 2017

- 13 July 2017 – Rainfall Event 2

The second rainfall event for 13 July 2017 occurred from 21:15 to 21:30, attaining a peak rainfall intensity of 0.8mm/hr. The retention and peak flow rates are shown in table 4.25. The control roof retained 54.32%. A similar event occurred on 27 May 2017, with the only exception of the peak rainfall intensity being slightly lower at 0.6mm/hr. However, in the May storm, 16.25% was retained by the control roof. A possible reason for this result is that the systems experienced a partial blockage during the rainfall event.

Table 4. 25: Retention and peak flow rate behaviour during rainfall event 2 on 13 July 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.037	0.035	0.034	0.038
Runoff Volume (m^3)	0	0	0.016	0
Retention (%)	100	100	54.32	100
Peak Flow Rate (l/s)	0	0	0.015	0
Time of Peak Flow Rate	-	-	21:45	-

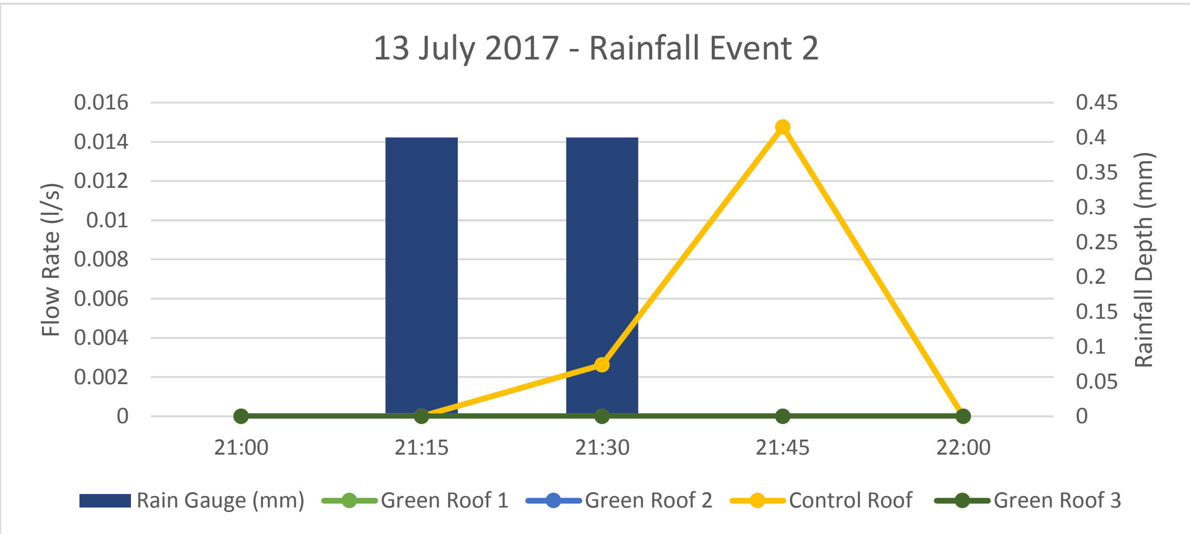


Figure 4. 31: Hydrograph for rainfall event 2 on 13 July 2017

e. August 2017

As identified in table 4.26, the one event monitored on 17 -18 August 2017 attained a peak rainfall intensity of 1.0mm/hr and lasted for 11 hours. There was no prior rainfall for 8 days.

Table 4. 26: Properties for August rainfall events

	Peak Intensity	Duration (hh:mm)	Rainfall Before
17 – 18 August 2017	1.0mm/hr	11:00	None

- 17 – 18 August 2017

The rainfall event began on 17 August 2017 at 20:00 and continued through to 18 August 2017 at 07:00. Table 4.27 below summarizes the retention and peak flow rate for each of the green roofs, as well as the control roof. It was found that all retention figures from the green roofs were higher than that from the control roof. Following table 4.27, figure 4.32 depicts the hydrograph created from the flow meter, as well as the rainfall data.

Table 4. 27: Retention and peak flow rate behaviour during rainfall event on 17 – 18 August 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	1.076	1.003	0.984	1.086
Runoff Volume (m^3)	0.462	0	0.958	0.219
Retention (%)	57.09	100	2.72	79.84
Peak Flow Rate (l/s)	0.054	0	0.071	0.042
Time of Peak Flow Rate	01:15	-	01:00	01:15

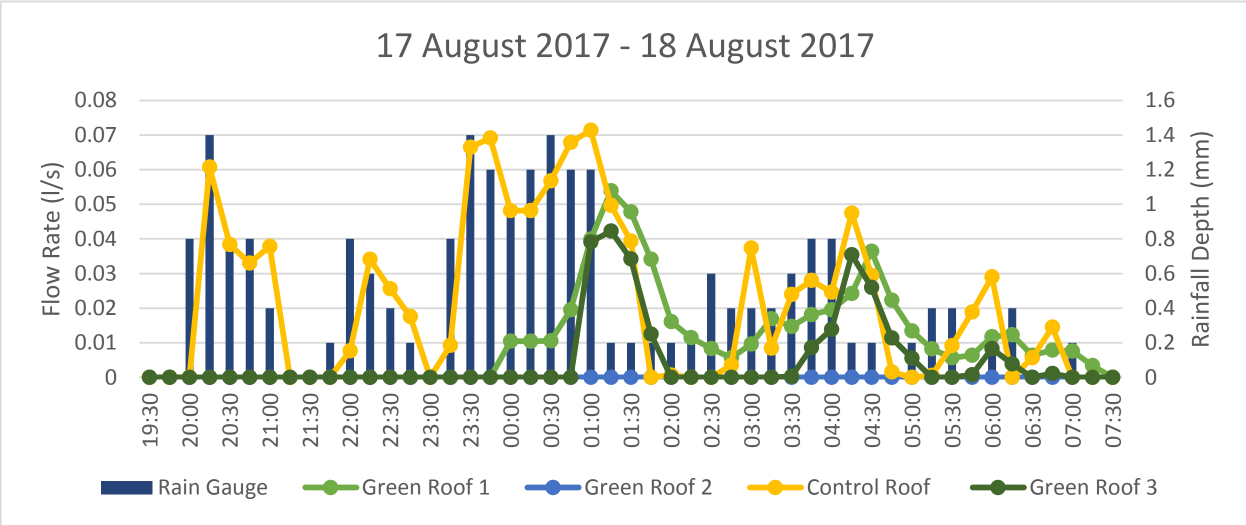


Figure 4. 32: Hydrograph for rainfall event on 17 – 18 August 2017

Green roof 2 achieved the highest retention with 100%, green roof 3 achieved 79.84%, and green roof 1 achieved 57.09%. Both green roofs 2 and 3 had the same substrate mixture and substrate depth of 10cm. The main difference between green roofs 2 and 3 was the type and amount of vegetation present on each roof. This supports the theory by Razzaghmanesh and Beecham (2014), that a green roof with a denser vegetative layer will have a higher retention rate.

Green roof 1 was constructed using a 3cm layer of a different substrate mixture, but similar vegetation to green roof 3. The difference in retention between green roof 3 and green roof 1 was 22.75%, with the former having the higher rate. The data shows that a deeper substrate layer leads to a higher retention rate during a rainfall event with similar properties. It has been confirmed by previous research that the depth of the growing media affects the retention capacity of the green roof (Bengtsson et al., 2005; VanWoert et al., 2005; Mentens et al., 2006; Berndtsson, 2010; Zhang et al., 2015). A study conducted by Beecham and Razzaghmanesh (2015) also suggested that intensive green roof systems outperform extensive green roof systems in terms of retention capacity, indicating that a deeper substrate layer would have a higher retention capacity.

The peak flow rate for the control roof, green roof 1, and green roof 3 occurred at 01:00, 01:15, and 01:15, respectively. Green roofs 1 and 3 were able to delay the peak flow rate by 15 minutes in relation to the control roof. The greatest difference between peak flow rate measurements was found to be between the control roof and green roof 2, as this green roof system did not allow any stormwater runoff to be discharged. The control roof had a peak flow rate of 0.071l/s, green roof 1 0.050l/s, and green roof 3 0.042l/s.

f. September 2017

Data for two rainfall events during September 2017 is presented in table 4.28. The event that occurred on 23 September 2017 experienced no prior rainfall in the previous 5 days, and the event that occurred on 26 September 2017 experienced a prior rainfall of high intensity measuring 6.0mm/hr on 25 September 2017, which could not be analysed because of a malfunction in the flow meter equipment.

Table 4. 28: Properties for September rainfall events

	Peak Intensity	Duration (hh:mm)	Rainfall Before
23 September	1.2mm/hr	05:15	None
26 September	0.4mm/hr	03:45	Medium

- 23 September 2017

This day experienced a rainfall with a peak intensity of 1.2mm/hr and total duration of 5 hours and 15 minutes. A summary of the retention behaviour and rainfall pattern is shown in table 4.29.

Table 4. 29: Retention and peak flow rate behaviour during rainfall event on 23 September 2017

	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3
Rainfall Volume (m^3)	0.515	0.480	0.471	0.519
Runoff Volume (m^3)	0	0	0.378	0.007
Retention (%)	100	100	19.73	98.64
Peak Flow Rate (l/s)	0	0	0.066	0.008
Time of Peak Flow Rate	-	-	16:00	17:45

Green roofs 1 and 2 both achieved a retention of 100%, whilst green roof 3 attained 98.64%. Green roofs 2 and 3 have the same substrate mixture and thickness, but varying vegetation types and density.

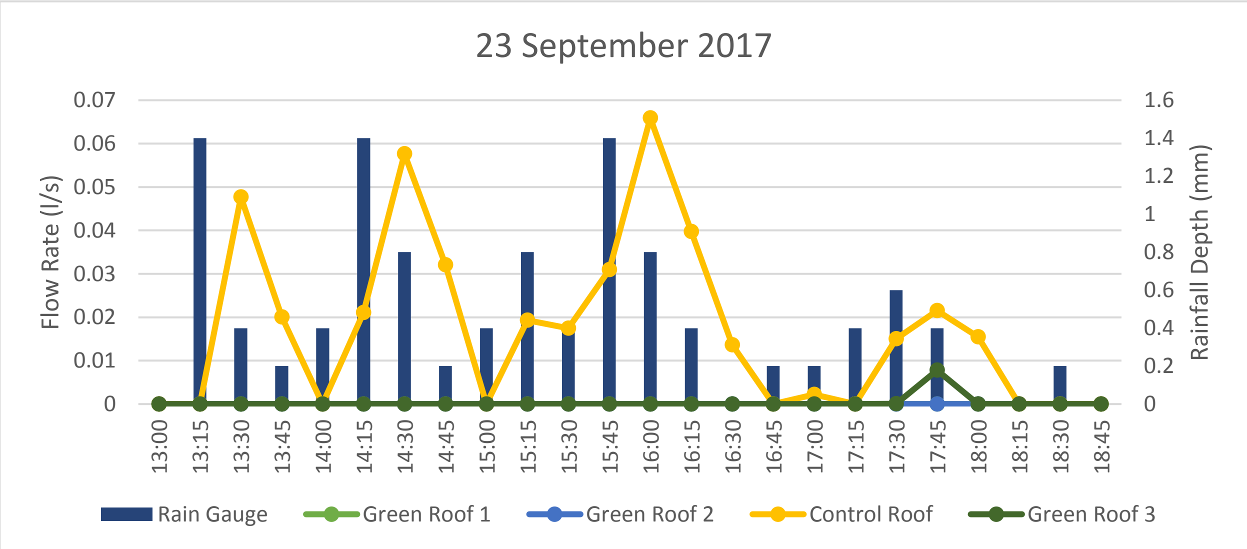


Figure 4. 33: Hydrograph for rainfall event on 23 September 2017

Figure 4.33 illustrates the hydrograph created from the flow rate data. A peak flow rate of 0.066l/s at 16:00 was recorded for the control roof, and a peak flow rate of 0.008l/s at 17:45 was recorded for green roof 3. This shows that the green roof systems delayed, as well as reduced, the peak flow rate significantly for this rainfall event, in relation to the control roof.

- 26 September 2017

A 0.4mm/hr peak intensity rainfall lasting 3 hours and 45 minutes occurred on 26 September 2017. Table 4.30 shows the retention and peak flow rate achieved by each roof system. As observed, all green roof systems achieved a 100% retention rate, whilst the control roof achieved 8.63% retention.

Table 4. 30: Retention and peak flow rate behaviour during rainfall event on 26 September 2017

	Green Roof 1	**Green Roof 2**	**Control Roof**	**Green Roof 3**
Rainfall Volume (m^3)	0.150	0.140	0.137	0.151
Runoff Volume (m^3)	0	0	0.125	0
Retention (%)	100	100	8.63	100
Peak Flow Rate (l/s)	0	0	0.024	0
Time of Peak Flow Rate	-	-	03:30	-

Figure 4.34 shows that the peak flow rate for the control roof, measuring 0.024l/s occurred at 03:30.

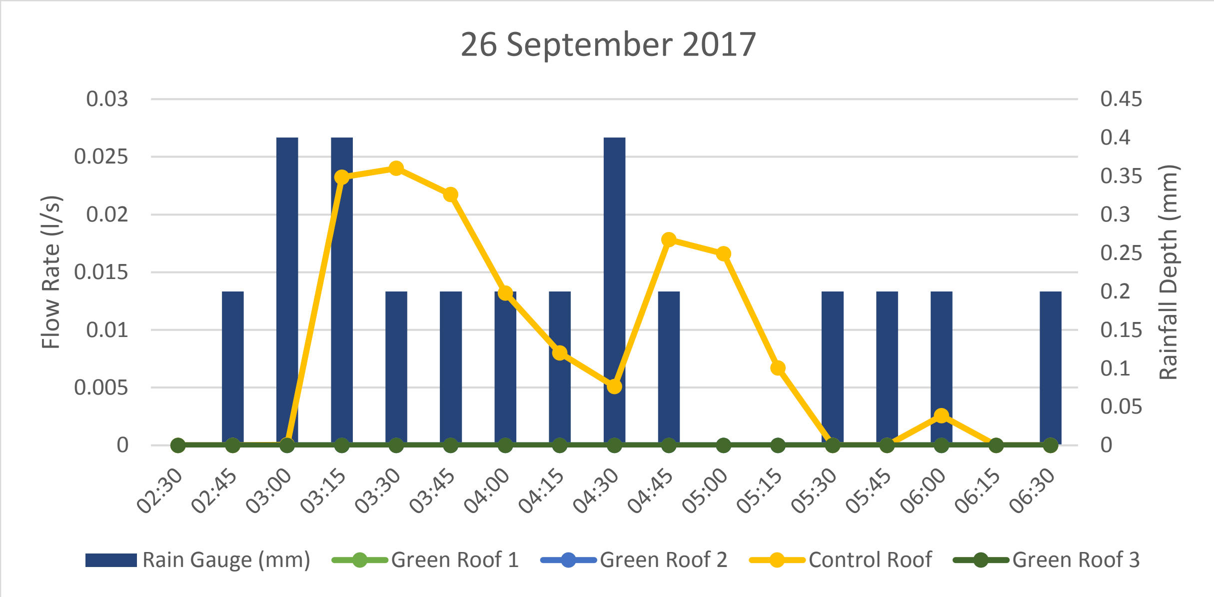


Figure 4. 34: Hydrograph for rainfall event on 26 September 2017

Quantity analysis summary

Table 4.31 provides a summary of the quantitative data for the entire study. Rainfall intensity, rainfall depth, rainfall duration, ADWP, and the retention rates for each roof are displayed to give a holistic view on the study.

Table 4.32 indicates the average retention for each roof system, for the different rainfall intensity categories. For low intensity rainfall, an average retention of 90.579 – 99.999% was achieved. For moderate intensity rainfall, the green roofs achieved an average retention of 68.56 – 98.65%. For high intensity rainfall, an average retention of 67.27 – 91.93% was achieved. This observation is parallel with a conclusion made by Harper et al. (2015), indicating that an increase in storm size meant a decrease in retention capacity.

	Rainfall Intensity (mm/hr)	Rainfall Depth (mm)	Rainfall Duration (hh:mm)	ADWP	Green Roof 1	Green Roof 2	Green Roof 3
09/03/17 Event 1	3.4	6.6	01:00	> 5 days	94.41	100	87.95
09/03/17 Event 2	1.8	9.6	03:45	10 hours	73.92	100	65.31
09/03/17 Event 3	0.6	1.2	02:45	2 hours	100	100	100
10/03/17 Event 1	3.8	8.4	04:30	3 hours	39.02	79.17	41.50
10/03/17 Event 2	0.8	1.8	00:30	2 hours	100	100	100
10/03/17 Event 3	0.4	1.2	05:05	3 hours	100	99.98	100
14/03/17	1.2	8	09:00	3 days	91.94	100	66.83
15/03/17	0.6	1	01:30	1.5 days	100	100	100
19/03/17	0.8	1.6	01:15	3.5 days	100	100	100
24/03/17	0.8	2.8	05:15	5.5 days	100	100	100
06/04/17 07/04/17	1.6	18.2	10:30	12 days	75.70	97.30	71.81
24/04/17	3.4	16.8	08:30	13 days	84.88	96.61	72.37
15/05/17 Event 1	0.8	3.8	01:45	4 hours	50.19	100	74.92
15/05/17 Event 2	1.4	3.4	03:30	4 hours	59.47	100	68.74
27/05/17	0.6	1	00:15	9.5 days	100	100	100
13/07/17 Event 1	0.4	1.6	04:00	13 days	100	100	100
13/07/17 Event 2	0.8	0.8	00:15	13.5 days	100	100	100
17/08/17 18/08/17	1.0	23	11:00	8 days	57.09	100	79.84
23/09/17	1.2	11	05:15	5 days	100	100	98.64
26/09/17	0.4	3.2	03:45	18 hours	100	100	100

Table 4. 31: Summary of rainfall and retention data

Green roof 1 and 3 have similar vegetation types and density, but the data shows a difference in the retention. This finding confirms that the constituents of the substrate layer and the vegetation type will affect the retention capacity of a green roof system. The main constituent of the mixture used in green roof 1 is LECA. Therefore this finding is inconsistent with the research conducted by De-Ville et al. (2017) which proved that as a green roof with a LECA substrate ages, the LECA develops a higher WHC. Another reason for the higher retention rate in green roof 1 could be the varying plant types and their rate of evapotranspiration. Plant types that are more prone to water uptake and an increased evapotranspiration rate, will increase the rate of retention for the green roof system (Berretta et al., 2014).

Table 4. 32: Average retention per rainfall category for the green roofs

	Green Roof 1	Green Roof 2	Green Roof 3
Low Intensity	90.58	99.999	92.60
Moderate Intensity	74.81	98.65	68.56
High Intensity	72.77	91.93	67.27
Overall	86.33	98.65	86.40

Table 4.32 also indicates that green roof 1 achieved the lowest average retention rate throughout the study, followed by green roof 3 and then green roof 2. The average retention rates achieved by the green roofs for this study were significantly higher than those reported by previous studies as identified in table 4.33.

Table 4. 33: Average retention for green roofs in previous studies

Average Retention (%)	Reference
34	Hathaway et al., 2008
51.4	Gregoire and Clausen, 2011
66	Nawaz et al., 2015
60	Harper et al., 2015
13.8 – 34.4	Lee et al., 2015

Although green roofs 2 and 3 had the same substrate depth and mixture, they differed in terms of their plant type and plant density. Green roof 2 had a much greater vegetation density, as well as larger plant types and achieved the highest average retention percentage for the study. Green roof 3 had a lower vegetation density, made up of smaller type of plant life. Therefore, the reason for the higher retention percentages achieved by green roof 2 were due to a higher vegetation density and the type of vegetation planted on it. This conclusion is parallel to findings in previous studies proving a proportional relationship between retention capacity, and vegetation density and type (Nagase and Dunnett, 2012; Berghage et al., 2007; Berndtsson, 2010; Harper et al., 2015).

Six findings were inconsistent with this research, namely from the storms which occurred on 9 March 2017 (first two events), 14 March 2017, 6-7 April 2017, 24 April 2017 and 23 September 2017. The data showed that the green roof with a deeper substrate and denser volume of vegetation, resulted in a lower retention percentage than the green roof with a shallower substrate. A possible explanation for this is that the green roofs reached saturation and then mimicked the characteristics of the control roof, resulting in an excess amount of runoff.

In terms of delaying the peak flow rate, it is apparent that green roof 2 had the biggest effect in delaying the peak flow rate. The main component of the growing medium in green roof 2 was LECA, which is known to have a high water holding capacity (WHC). This result is therefore well aligned with findings by Vijayaraghavan and Joshi (2014), which proved a bigger delay in runoff in substrates with a higher WHC. From the analysed rainfall events, at least one of the green roofs were able to delay the peak flow rate. During certain events, some green roof systems recorded no flow data, which suggested that all the rainwater had been absorbed by the green roof. In the instances where flow data was recorded, the green roof systems managed to delay the peak flow rate by up to 105 minutes. These results are consistent with findings which proved that green roofs have the ability to delay the peak flow rate as it passes through the soil media to the drainage layer (Chen et al., 2015; Lee et al., 2015; Stovin, 2010; Razzaghmanesh and Beecham, 2014).

Low Intensity Rainfall

For the category of rainfall ranging from 0 – 1.5mm/hr, most of the retention for the green roof systems was above 98%. Exceptions to this finding occurred during events on 14 March 2017, 15 May 2017, and 17-18 August 2017. On 14 March 2017, the recorded rainfall intensity was 1.2mm/hr over a 9 hour period, resulting in 8mm of rain. This result could have been achieved due to the prolonged duration of the storm.

On 15 May 2017, during the first rainfall event, green roofs 1 and 3 displayed retention of 50.19% and 74.92%, respectively, which could have been a result of the rainfall event the day before which measured a peak intensity of 3.4mm/hr and resulted in 148.6mm of rain. Event two saw the retention increase in green roof 1, but decrease in green roof 3. This event had a higher peak intensity, longer duration, but slightly lower rainfall depth. A partial blockage to the outlet of the stormwater runoff system could be a reason for this anomaly.

The event that took place over 17-18 August 2017, had an intensity of 1mm/hr, 11 hour duration, and rainfall depth of 23mm. The longer rainfall duration and increased rainfall depth may have contributed to the reduced retention from green roofs 1 and 3.

Moderate Intensity Rainfall

Two events within this category were identified, and occurred on 9 March 2017 during event 2, and over 6-7 April. The properties of the former were an intensity of 1.8mm/hr lasting 3 hours and 45 minutes, and resulting in 9.6mm of rain. During this event, retention was 73.92% for green roof 1, 100% for green roof 2 and 65.31% for green roof 3. The second moderate intensity rainfall was an intensity of 1.6mm/hr and lasted 10 hours and 30 minutes, with a rainfall depth of 18.2mm. During this event, retention was 75.70% for green roof 1, 97.30% for green roof 2 and 71.81% for green roof 3. Between event 1 and event 2, the retention in green roofs 1 and 3 increased, whilst the retention in green roof 2 decreased. The durations and rainfall depths were significantly different for the two events, whilst the rainfall intensity differed slightly.

Results from green roofs 1 and 3 are consistent with research by Harper et al. (2015), which shows that a storm of lower intensity will result in a higher retention.

High Intensity Rainfall

For a peak rainfall intensity of over 3mm/hr, three different rainfall events were identified over the study period. For these events, green roof 2 retained the most rainfall, followed by green roof 1, and the least effective was green roof 3. Despite confirmation from previous studies which argued for a proportional relationship between substrate depth and retention capability (Bengtsson et al., 2005; VanWoert et al., 2005; Mentens et al., 2006; Berndtsson, 2010; Zhang et al., 2015), this result indicated that green roof 3, with the shallower substrate depth had better retention rate than green roof 1, with a deeper substrate. This suggests that substrate mixture, vegetation type and vegetation density, have an effect on the retention and not just the thickness of the substrate layer.

For green roof 2, 100% retention was achieved on 9 March 2017 during event 1, followed by 79.17% retention on 10 March 2017 during event 1, and 96.61% retention on 24 April 2017. The main differences between the three events was the rainfall duration and rainfall depth. There was also a slight difference in the rainfall intensity.

Table 4. 34: Behaviour of green roof 2 during high intensity rainfall

	Retention (%)	Rainfall Depth (mm)	Rainfall Duration (hh:mm)	Rainfall Intensity (mm/hr)
09/03/17 Event 1	100	6.6	01:00	3.4
10/03/17 Event 1	79.17	8.4	04:30	3.8
24/04/17	96.61	16.8	08:30	3.4

As seen in table 4.34, green roof 2 did not follow the pattern in terms of rainfall depth and rainfall duration. A higher retention was produced during the shorter rainfall event with the lower rainfall depth. However, the second highest retention did not occur during the second shortest rainfall event, as the pattern would suggest. The pattern did follow the rainfall intensity as there was a higher retention achieved during the two 3.4mm/hr rainfall events in comparison to the 3.8mm/hr rainfall event.

Green roof 3 had the lowest retention of the high intensity rainfall events, the lowest of which occurred during the event with the second longest duration and second highest rainfall depth. This did not indicate a linear relationship. The other difference that would affect the retention rate was the Antecedent Dry Weather Period (ADWP). Although the third event in this category had the longest duration and the highest rainfall depth, there was no prior rainfall. In conclusion, during high rainfall intensity, the retention capability of green roof 2 was mostly controlled by the ADWP.

4.3.7 PCSWMM model of the eThekwini CBD

This section will investigate the effects of implementing more green roofs, similar to the composition of green roof 2, within the eThekwini CBD, on stormwater peak and average flow rates, and volumes. Green roof 2 was the best performing green roof in terms of stormwater retention and would therefore be expected to have the greatest impact in the modelling that follows in this section.

A random block was chosen within the CBD to run the model on. Two scenarios were compiled as follows:

- A base model with the existing stormwater infrastructure.
- A model with green roofs installed on all the flat-roofed buildings within the block.

The results that follow are from simulations of each of these models for different rainfall intensities based on 1 in 2, 1 in 5, 1 in 10, 1 in 20, and 1 in 50 year storms.

Scenario 1: Base model with the existing stormwater infrastructure

The first model was compiled based on the existing stormwater infrastructure as observed in Figure 4.35.

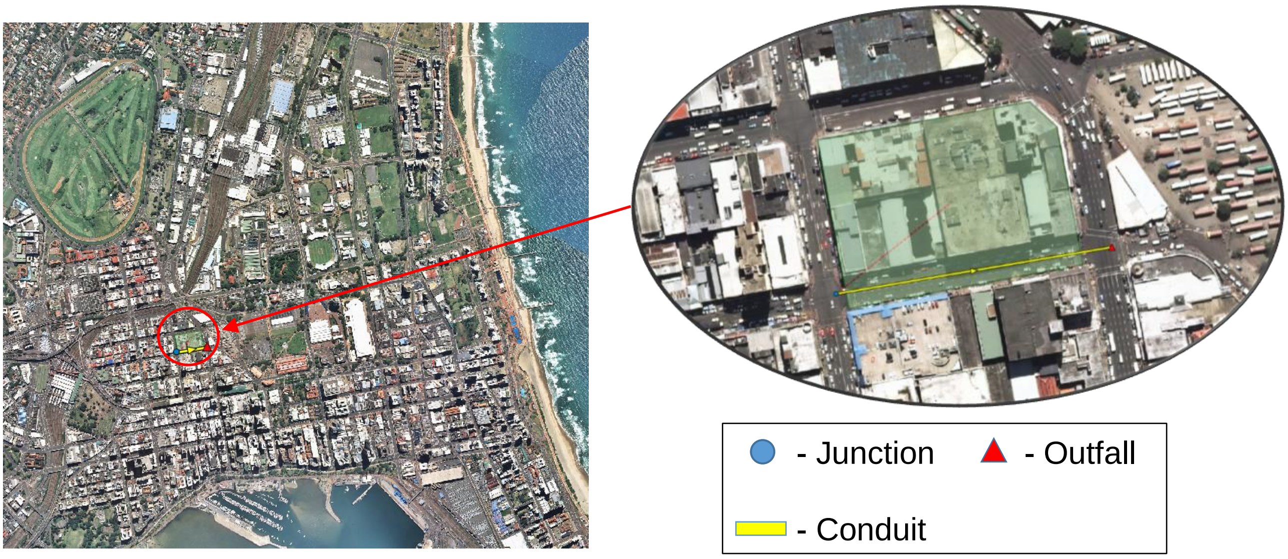


Figure 4. 35: Base model compiled in PCSWMM

The results of the base model were analysed based on peak flow. Table 4.35 gives an indication of the peak flows at the outfall and inlet for different storm intensities, measured in m^3/s. For all storm events, the values ranged from $0.308 m^3/s$ to $1.049 m^3/s$ at the outfall, and $0.313 m^3/s$ to $1.063 m^3/s$ at the inlet.

Table 4. 35: Peak flow rates (m3/s) from the base model

	Outfall	Inlet
1 in 2 year	0.308	0.313
1 in 5 year	0.492	0.5
1 in 10 year	0.639	0.649
1 in 20 year	0.803	0.814
1 in 50 year	1.049	1.063

Scenario 2: A model of the eThekwini CBD block with green roofs installed on all the buildings

In this scenario, green roofs similar to green roof 2 were assumed to be installed on the buildings within the block. The adapted model was analysed based on peak flow rates, as shown in Table 4.36. For most of the storm events, the peak flow rate decreased when compared to the base model.

Table 4. 36: Peak flow rates (m3/s) from the green roof model

	Outfall	Inlet
1 in 2 year	0.185	0.193
1 in 5 year	0.263	0.27
1 in 10 year	0.322	0.331
1 in 20 year	0.387	0.398
1 in 50 year	0.679	0.682

PCSWMM model summary

When compared to the base model, peak flow rates from the green roof model decreased by over 40% for all storm intensities. Table 4.37 gives an indication of these differences.

Table 4. 37: Comparison of the peak flow rates (m3/s) from the base model and green roof model

	Outfall			Inlet		
	Base Model	Green Roof Model	Difference (%)	Base Model	Green Roof Model	Difference (%)
1 in 2 year	0.308	0.185	60.065	0.313	0.193	61.661
1 in 5 year	0.492	0.263	53.455	0.5	0.27	54.000
1 in 10 year	0.639	0.322	50.391	0.649	0.331	51.002
1 in 20 year	0.803	0.387	48.194	0.814	0.398	48.894
1 in 50 year	1.049	0.679	64.728	1.063	0.682	64.158

For return periods 1 in 2, 1 in 5, 1 in 10, and 1 in 20 year, the percentage difference decreased with an in increase in the return period.

A break in the pattern occurred during the simulation of the 1 in 50 year return period, when the percentage difference increased and was the highest at both the outfall and the inlet. This indicates that green roofs performed the best in terms of stormwater management during the highest storm intensity. This particular result is inconsistent with findings by Harper et al. (2015), who showed that an increase in storm intensity meant a decrease in retention capacity. Assumptions made in the compilation of the PCSWMM model may be a reason for this discrepancy. The aforementioned assumptions include the absorption rate of the ground coverage type, and the dimensions of the inlet chamber to the stormwater system.

4.4 Conclusion

This chapter provided an overview of the analysis of stormwater runoff quality and quantity from the Green Roof Pilot Project. In terms of water quality, the data analysis revealed significant variations in pollutant concentrations between the green roofs and the conventional roof. While some pollutants were found in higher concentrations in green roof runoff, other pollutants were significantly higher in runoff from the conventional roof. Metals that were found in high concentrations in green roof runoff were iron, copper, arsenic, aluminium, barium and manganese. In terms of stormwater runoff quantity, the green roof systems proved to significantly reduce stormwater runoff volumes. The highest retention rates were achieved for low intensity rainfall events, whilst the lowest were achieved for high intensity rainfall events.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The aim of this chapter is to summarise the results and findings of the study, and provide recommendations where necessary. The chapter will first address the quality aspect of the study, in terms of the determinands that increased, and the determinands that decreased in concentration in green roof runoff. Secondly, the chapter will explore the quantity aspect of the study, in terms of the retention percentages achieved by the different green roof systems, and the results from the PCSWMM model of the eThekwini CBD.

5.2. Objective 1: Quality analysis of stormwater runoff from the eThekwini Green Roof Pilot Project, in terms of physical, chemical, microbiological and organic determinands

The following sections explore the effects that the green roof systems at the eThekwini Green Roof Pilot Project had on various determinands, with regards to the tests that were done for stormwater quality discharging into freshwater ecosystems.

5.2.1 Determinands that increased in concentration in green roof runoff

Results from the tests indicated that most pollutants had increased in concentration after passing through the various green roof systems, in comparison to the readings obtained from the control roof. Physical and aesthetic determinands which showed an increased level in runoff from all green roof systems were TDS and TSS. Chemical determinands which increased in concentration comprised free chlorine, nitrogen, orthophosphate, fluoride, selenium, arsenic, copper, iron, aluminium, lead, and chromium. Results indicated that levels of ammonia and manganese increased for tests done on green roof 2 only. Zinc results showed that levels increased for green roof 1 only. Lastly, the organic determinand which increased in concentration after passing through all green roof system was Phenols.

An increase in concentration of these pollutants in a freshwater ecosystem can affect aquatic life by hindering their growth rate, reducing their reproductive activity, damaging their gills, reducing their migration behaviour, and increasing their respiratory rates. Plant life can be affected by a reduction in the rate of photosynthesis. An increase in concentration levels of copper in particular, can lead to brain damage of mammals close to the ecosystem (Department of Water Affairs and Forestry, 1996).

5.2.2 Determinands that decreased in concentration in green roof runoff

The only results that decreased in comparison to the control roof were that of ammonia and manganese for green roof 2, and zinc for green roof 1. This indicates that green roof 2 acted as a sink for ammonia and manganese, and green roof 1 acted as a sink for zinc. Green roof 2 differed from the other green roof systems in terms of vegetation type and density, leading to the proposition that the type of plants used in green roof 2 can decrease the ammonia and manganese concentrations in stormwater runoff. The main characteristics that were different in green roof 1 were the substrate depth and the substrate mix. A substrate depth of 3cm and a substrate mix of primarily crushed brick and granite, are two possible reasons for the decrease in the zinc concentration found in the stormwater runoff from green roof 1.

Having lower concentration levels of these determinands in stormwater runoff would be an added benefit for any green roof system. Increased levels of ammonia in freshwater ecosystems have been known to affect aquatic life by increasing their breathing rate, reducing their hatching success, and causing detrimental changes to the tissue of their kidneys, liver and gills. Ammonia also increases eutrophication within an ecosystem (Department of Water Affairs and Forestry, 1996). Manganese has the ability to disturb the central nervous system of the different animal species, and elevated zinc levels have resulted in the gills being covered in mucus containing an impenetrable substance (Department of Water Affairs and Forestry, 1996).

5.3 Objective 2: Analysis of stormwater runoff from the eThekwini Green Roof Pilot Project in terms of retention as a percentage

The ensuing section highlights the key findings from the analysis of the data collected for the Green Roof Pilot Project, in terms of flow rates, rainfall intensities, and retention rates.

5.3.1 Retention behaviour in different rainfall intensities

The green roof systems achieved a higher retention percentage during low intensity rainfall events, and a lower retention percentage during rainfall events of high intensity. This suggested that an inverse relationship exists between rainfall intensity and retention rate. The average retention ranged from 90.579% to 99.999% for low intensity rainfall events, 68.56% to 98.65% for moderate intensity rainfall events, and 67.27% to 91.93% for high intensity rainfall events. Green roof retention percentages achieved in this study were higher when compared to the retention achieved in previous studies. The data showed that a number of factors affected the retention of a green roof, such as substrate type, substrate depth, plant species, plant coverage, rainfall intensity, and the dry period length. The average retention percentage from roofs with a thicker substrate were found to be higher than from roofs with a thinner substrate layer. Results indicated that two roofs with the same substrate mix and depth exhibited varying retentions. This suggested that the plant species and coverage did affect the percentage of retention. The roof with the higher vegetation density resulted in a higher retention than the roof with a less dense vegetation cover. During longer dry period spells, the green roofs proved to perform better as opposed to during rainfall events with a shorter prior dry period spell.

5.3.2 Delay of the peak flow rate

Green roof 2 proved to have the best influence on delaying the peak flow rate. Results from green roof 3 indicated that this green roof system had the least influence on delaying the peak flow rate of stormwater runoff. Findings made by Vijayaraghavan and Joshi (2014) showed that a substrate possessing a high WHC resulted in a higher time delay in the peak flow rate. This finding is parallel with the results from this study as green roof 2 contained 50% LECA in its substrate layer, which is known to have a high WHC. Data from all storm events analysed suggested that there was always a delay in the peak flow rate by a green roof system. These results therefore agree with findings made in previous studies which confirm that one benefit of green roofs is their ability to delay the peak flow rate of stormwater runoff (Chen et al., 2015; Lee et al., 2015; Stovin, 2010; Razzaghmanesh and Beecham, 2014).

5.3.3 Overall green roof performance

The green roof with the best overall retention average was green roof 2. The average retention percentage over the six month period was found to be 98.65%. The average retention for all the green roof types over the study period ranged from 86.33% to 98.65%. The poorest performing green roof was green roof 1. The average retention of the conventional roof was found to be 19.84%. Results from the green roof systems were significantly higher than this, showing that green roofs have the potential to increase the retention of stormwater runoff. Green roof runoff percentages achieved from the Green Roof Pilot Project data were considered high, when compared to results from previous studies. A possible explanation for this could be the position of the building which houses the Green Roof Pilot Project. The building is single storey, and is surrounded by two buildings which are significantly taller, thereby affecting the rainfall onto the study site.

5.4 Objective 3: Investigation of the effects that incorporating the best performing green roof would have on stormwater retention within the eThekwini CBD, using a PCSWMM model.

This segment focuses on the results obtained from the PCSWMM model after incorporating green roofs similar to green roof 2 from the Green Roof Pilot Project, within the eThekwini CBD. Two models were compiled, namely a base model of the existing stormwater infrastructure, and a model with green roofs on the buildings within the specified block of the eThekwini CBD.

The results of this modelling showed that the implementation of the green roof system within the eThekwini CBD, would reduce the peak flow rate of stormwater discharge by at least 40%. Consistent results from the stormwater quantity analysis in objective 2 allowed for five return periods to be analysed, ranging from 1 in 2 year to 1 in 50 year storm events. Results from these models indicated that the percentage difference between the base model peak flow and the green roof model peak flow decreased with an increase in return period. Simplistically, the green roof had a greater benefit during smaller storm events. However, the results for the 1 in 50 year return period did not follow this pattern, and indicated an increased benefit in terms of peak flow rates as opposed to the results obtained for the 1 in 20 year return period. The results showed that the implementation of the green roof systems were increasingly beneficial with higher intensity storms, except in the case of the 1 in 50 year storm. This conclusion could be a result of assumptions made in the compilation of the PCSWMM model. The finding also leads to the supposition that the green roof system actually may increase the percentage differences for storm events greater than a 1 in 50 year.

5.5 Limitations

Some conclusions could not be made due to various limitations that the researcher was faced with. These limitations included:

- Malfunctions in apparatus. During certain periods of the study, the flow meters did not record data. This was either due to a malfunction in the loggers which could not send data to the reporting system, or due to the tampering of the apparatus by member of the public. Unfortunately, the apparatus was attached to a part of the building that can be accessed by anyone.
- Inconsistent monitoring of the data. It was evident that the data had not been monitored consistently, as malfunctions in certain apparatus were not picked up on time. This led to lost data during storm events.
- Lack of relevant green roof data or research within the South African context. During the literature review, and discussion phases of the study, the researcher noticed many gaps in green roof literature, specifically within the South African context, making it difficult to draw a comparison to the Green Roof Pilot Project.
- Insufficient research on plant types and their effect on stormwater retention.
- Assumptions made in the PCSWMM model. Certain assumptions needed to be made when compiling the model.

5.6 Recommendations

In terms of quality, green roofs should not be perceived as an instrument for improving the quality of stormwater runoff. The green roof systems proved to act more as a source for pollutants, than as a sink.

With regards to stormwater runoff quantities, green roofs have shown significant benefits in terms of reducing flow rates, and increasing retention capabilities. Targeted investigations into substrate mixes and plant types should be conducted in order to understand and achieve the optimum retention abilities of a green roof system.

Within the eThekwini CBD, green roofs should be considered as a tool for reducing peak and average flow rates, as well as reducing stormwater runoff volumes. In this way, green roofs can be used as a means of flood mitigation. Interviews with management from the Coastal, Stormwater and Catchment Management, indicated their willingness to adopt green roofs as a stormwater management control measure. Interviews also revealed that the biggest issue with the lack of green infrastructure within the eThekwini municipality, was the lack of policies and legislation from governmental departments higher up in the hierarchy. This issue allows room for research, education and implementation of green roofs in a South African context.

5.7 Conclusion

The key findings, limitations, and recommendations were highlighted in this chapter. In terms of drinking water quality, green roofs should not be used as a tool for improving water quality. In terms of stormwater runoff quantities, the findings in this study and many others conclude that green roofs can and should be used as a means of reducing stormwater runoff rates, and increasing stormwater retention, especially within urban environments. Results from the PCSWMM model suggested that implementing more green roofs within the eThekwini CBD could reduce peak and average runoff flow rates, as well as reduce stormwater runoff volumes from the eThekwini CBD.

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