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SCIENTIA ET LABORE

JOHANNESBURG

DETERMINING THE PARAMETERS FOR THE SIZING OF SEDIMENT TRAPS IN THE CITY OF JOHANNESBURG

Mankoe Francis Raliengoane

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.

Supervisor: Prof Anne Fitchett

The University of the Witwatersrand, Johannesburg

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Declaration

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

R.Mankoe

June 2024

Abstract

Urban land practices usually involve soil compaction and vegetation removal as cities expand and grow. This has led to increased flood peak flows and high stormwater runoff volumes associated with sediments, nutrients and other pollutants that load downstream water resources. To address these issues, there has been a growth of practices involving Sustainable Drainage Systems (SuDS) for managing stormwater runoff quantity and quality from urban areas. For example, this involves the application of attenuation ponds, and wetlands which temporarily store urban stormwater runoff, thereby reducing the sediment loads, pollutants, and release of peak flows to the downstream water resources at flow rates that mimic the pre-development flow patterns. This practice is gaining momentum in South African urban areas, which are supported by the policies and legislation set up by local authorities to address stormwater management. However, these stormwater application practices often do not perform according to their design capacities because they get filled with sediments and their effectiveness in attenuating peak flows is reduced. Therefore, it is important to reduce sediments coming into these structures by applying sediment traps and basins located at the head of such structures. The sediment trap's main function is to slow down the stormwater runoff and help in the reduction of sediments before stormwater runoff is discharged out of the construction site and other disturbed areas.

The City of Johannesburg Stormwater Management By-laws and Stormwater Design Manual have limited information for the management of sediment using sediment traps and basins and which parameters need to be considered when sizing sediment traps. Therefore, the main aim of the current research was to determine the parameters that should be considered when sizing sediment traps specifically for the city of Johannesburg. The following parameters: design rainfall, daily rainfall, catchment area, evaporation, land cover and land use, percentage of permeable and impermeable areas, topographical data, peak flow, runoff volume, catchment topography, soil types and infiltration characteristics, sediment particle size distribution, sediment settling velocity, sediment loading rate/yield were modelled through Personal Computer Stormwater Management Model (PCSWMM), ArcSWAT ArcGIS, and Excel Spreadsheet Models. Further, the sensitivity analysis was undertaken using different values of imperviousness and infiltration rates while observing peak flow and runoff volume changes in PCSWMM outputs.

Modelling in PCSWMM showed that peak flows and runoff volumes increased due to an increase in the values of the imperviousness used. However, the range of infiltration rates for the soils in both sub-catchments S22 and S23 did not change the peak flows and runoff volumes. Though it was not the scope of the current study, it was observed that higher infiltration rates than the ones that were determined from the sub-catchments S22 and S23 indeed reduced peak flows and runoff volumes. On the other hand, particle settling velocity showed that gravel particles took a short time to settle and required a smaller sediment trap

storage capacity. In comparison, silt particles took longer to settle and required a larger sediment trap storage capacity. Lastly, sediment yield from both sub-catchments S22 and S23 showed that sediment yield is driven by rainfall, whereby months with high rainfall had higher sediment yield than the months with low rainfall. It is therefore, concluded that the following parameters: design rainfall, daily rainfall, evaporation, land cover and land use, percentage of permeable and impermeable areas, topographical data, contributing catchment area, peak flow, runoff volume, catchment topography, soil types and infiltration characteristics, sediment particle size distribution, sediment settling velocity, sediment loading yield should be considered by the engineers, designers and planners when sizing sediment traps in the City of Johannesburg and possibly in other places as well.

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List of Acronyms and Abbreviations

Acronym / Abbreviation	Definition
BMPs	Best Management Practices
CHI	Computational Hydraulics International
CoJ	City of Johannesburg
DEA	Department of Environment Affairs
DEM	Digital Elevation Model
LID	Low Impact Development
MAE	Mean Annual Evaporation
masl	Meters above sea level
PCSWMM	Personal Computer Stormwater Management
SANRAL	South African Roads Agency Limited
SuDS	Sustainable Drainage Systems
SWAT	Soil and Water Assessment Tool
SWMM5	Stormwater Management Model Version 5
WR2012	South African Water Resources 2012 Study
WSUD	Water Sensitive Urban Design

List of Symbols

Symbol	Definition
A	Surface Area (m^2)
Ai	Impermeable area (%)
Ac	Contribution area (ha)
C	Cropping management factor
C	Constant (0.4 for spheres, 1 for typical sand grains)
d	Diameter of suspended particles (m)
g	Acceleration of gravity (m/s^2)
L	Length of the watercourse (km)
LS	Slope length and slope steepness factor
P	Erosion control practice factor
Q	Flow Rate (m^3/s)
R	Specific gravity in water (1.65 for silica sand)
S	Specific gravity of the suspended particle
$\boldsymbol{S_{av}}$	Average slope (m/m)
$\boldsymbol{V_S}/\boldsymbol{W_s}$	Settling Velocity (m/s)
V	Volume (m^3)
v	kinematic viscosity of the fluid
μ	kinematic viscosity in (m^2/s)

1 Introduction

1.1 Introduction to the Study

Urbanisation activities involve the removal of natural vegetation that facilitates the interception of rainfall, reduces the speed of surface runoff, and returns rainfall to the atmosphere through the evapotranspiration process. As a result, the surface runoff rate is increased and lag time is reduced in urban areas during storm events (Woods-Ballard *et al.*, 2007; Yazdi *et al.*, 2021). According to SANRAL (2013), urbanisation is believed to cause an increase in flood peaks by 20 to 50 percent when compared to natural conditions. Where there is industrial and high-density building development, the flood peaks may rise to 100 percent or more than that. The increase in runoff volumes and peak flow rates also cause streambed erosion leading to the transport of sediments and nutrients downstream into watercourses such as lakes, estuaries, and nearshore areas (Yazdi *et al.*, 2021; Haris *et al.*, 2016).

Furthermore, nutrients such as nitrogen and phosphorous carried in the stormwater runoff led to eutrophication and hypoxia in receiving watercourses (Yazdi *et al.*, 2021). Gauteng is no exception, as urbanisation and population growth have impacted the stormwater runoff, leaving many urban rivers badly degraded. The province's rivers are regarded as the most polluted rivers in the country, which has negatively affected water security (Dunsmore & de Groen, 2020).

Stormwater management problems in the City of Johannesburg (CoJ) include severe pollution, erosion, riverbank damage, and increasing flooding (Barnard *et al.*, 2019). A typical example of the stormwater problem in the City of Johannesburg would be a retention pond in Waterfall City that is losing its storage capacity due to sediment coming from construction activities and disturbed areas. Waterfall City is a fast-growing urban area composed of real estate developments, businesses and residential places. Also, many studies have indicated that the Jukskei River that drains Waterfall City is heavily polluted (Huizenga *et al.*, 2010). Runoff from the urban parts of the City of Johannesburg is contaminated with sediments, hydrocarbons, phosphates, pathogenic organisms, and a wide range of organic and inorganic compounds (Barnard et al., 2019). According to Aryal *et al.* (2010); Winston *et al.* (2023) the most common urban stormwater pollutants are total suspended solids, heavy metals, nutrients, hydrocarbons and bacteria.

Mostly, urban runoff contains a wide range of particulate matter from as small as 1µm to greater than 10,000µm (Aryal *et al.*, 2010), while Winston *et al.* (2023) adding that the particle sizes from urban road runoff have diameters from several nanometers to millimetres. Hence, particle size distribution is a vital parameter to be considered under pollutant removal by stormwater control measures that rely on settling-based treatment methods (Winston *et al.*, 2023).

There has been a growing interest worldwide in the management of stormwater runoff in a sustainable way (Armitage *et al.*, 2013). SuDS have been used internationally as stormwater Best Management Practices and the Gauteng Province has adapted to the use of SuDS for stormwater management (Dunsmore & de Groen, 2020). Moreover, urban stormwater runoff is managed through the construction of small earth dams. These include facilities such as retention ponds which remove sediments through gravitational settling (Suripin *et al*., 2020). Retention/detention ponds retard, attenuate and store runoff; hence they regulate and reduce peak flows/discharge to the downstream watercourses (SANRAL, 2013; Suripin *et al.*, 2020). Furthermore, retention ponds facilitate water quality treatment by trapping suspended sediments and the associated pollutants from stormwater runoff (Ahilan *et al.*, 2019; Yazdi *et al.*, 2021). Yazdi *et al.* (2021) indicate that the hydraulic residence time of the retention pond is the primary parameter in determining its treatment efficiency. Also, the water quality treatment of the retention pond is dependent on the contributing drainage area of the pond, design, and maintenance factors (Yazdi *et al.,* 2021).

However, as stormwater runoff passes through SuDS technologies, sediments settle and accumulate over time (Heal and Drain 2003). The accumulation of sediments reduces the storage capacity of SuDS technologies. Hence, the performance of SuDS in peak flow reduction and water quality improvement is then negatively impacted due to shortened residence time as storage is being filled with sediments. In addition, the reduction in the storage capacity of SuDS technologies can lead to flooding in urban catchments (Fox *et al.,* 2016; Al-Ani, 2018; Unal, 2018). Hence, this calls for the need to reduce sediments in stormwater runoff before it exit the construction sites and disturbed areas using sediment traps. The sediment trap's main function is to trap and treat stormwater runoff carrying sediments before it is discharged out of the construction site or other disturbed areas (Perez *et al.*, 2016). Sediment traps allow the suspended sediments to settle through the gravitational force by providing sufficient storage capacity and retention time (Perez *et al.*, 2016).

Therefore, sediment trap sizing is dependent on parameters such as particle size distribution, particle settling velocity and retention time. Furthermore, the design manuals such as Department of Planning and Local Government, (2010); Perez *et al.*, (2015); Perez *et al.*, (2016); Alabama Department of Transport, (2018); and Queensland Government, (2018) state that the storage capacity of the sediment trap should be sized based on the design flow rates, design rainfall, and sediment yield from the disturbed area. Moreover, Ferreira and Waygood, (2009) states that sediment traps are sized based on low-return period peak flows for flow reduction and trapping of sediments.

However, the Stormwater Design Manual for the City of Johannesburg (Barnard *et al.*, 2019) only indicates that construction sites should manage their sediment by using sediment control measures so that municipal drainage is protected against sediment. Moreover, stormwater facilities from the development site must transport the discharge to an appropriate sediment trap or sediment pond. There is no mention of the sizing of the sediment traps nor the parameters to be considered when sizing sediment traps in the City of Johannesburg.

The design manuals from other countries sized sediment traps based on design flow rates, design rainfall, particle size distribution, particle settling velocity, sediment yield and retention/detention time. However, the parameters from other countries' trap design manuals may not apply to the City of Johannesburg. Therefore, this study is set out to determine the parameters for sizing of sediment traps, specific to the City of Johannesburg through the vehicle of a case study of Waterfall City. The research involves the collection of data based on the parameters from Waterfall City, analysing and modelling it in Personal Computer Stormwater Management Model (PCSWMM), ArcSWAT ArcGIS, and Excel Spreadsheet programs. The results of the modelling activity will inform which parameters should be considered when sizing sediment traps in the City of Johannesburg. The findings of the current research can be added to documents such as the CoJ Stormwater Design Manual and the Gauteng Sustainable Drainage Systems Implementation Manual to facilitate sediment trap sizing.

1.2 Problem Statement

In the City of Johannesburg, the stormwater drainage and SuDS technologies are faced with the problem of sedimentation which reduces their storage capacity, and ability to treat and convey stormwater runoff effectively. An example of this can be seen in Figure 1-1 and Figure 1-2 from Waterfall City in the City of Johannesburg, where a retention pond is losing its storage capacity due to sediment emanating from a construction site nearby. Figure 1-1 and Figure 1-2 show the catchment before the construction and during the construction and how the storage of the retention pond has been filled with sediments.

Figure 1-1: Before construction took place on the North-western part of the retention pond in the year 2015

Figure 1-2: During construction on the North-western part of the retention pond in the year 2022

1.3 Research Objectives

Research Aim:

- Determine the parameters for sizing of sediment traps, specific to the City of Johannesburg.

Research Objective:

- Analyse different sources of data to determine which are most relevant for the sizing of sediment traps.
- To carry out modelling and sensitivity analysis of the parameters.

Research Question:

- What are the parameters that should be used when sizing sediment traps in the City of Johannesburg?

1.4 Structure of the Dissertation

The structure of this research is made up of the following chapters:

- Chapter 1: presents the introductory context of this research in terms of background, research objectives and structure of the research.

- Chapter 2: summarises the impact of urbanisation on runoff volume, peak flow, pollutants and the sources of sediments in urban areas. The typical urban stormwater management, as well as the sustainable stormwater management application in the City of Johannesburg. The chapter ends with the parameters for sizing sediment facilities, sediment trap efficiency, modelling software programs and a summary of the literature.

- Chapter 3: gives the background on Waterfall City's environmental characteristics, such as climatic conditions, geology, topography, vegetation cover, land use and land cover.

- Chapter 4: the chapter presents the methodology for the collection of data, analyses and modelling software packages.

- Chapter 5: presents the results of the modelling and a summary of the models used for peak flows, runoff volumes, particle size distributions and sediment yield.

- Chapter 6: presents the discussion of the findings from the models developed, the sensitivity analysis and parameters that should be considered for sizing of sediment traps in the City of Johannesburg.
- Chapter 7: presents the conclusion based on the findings of the research and recommendations for future research.

2 Literature Review

2.1 Introduction to Literature Review

This chapter presents the impacts of urbanisation which include an increase in runoff volumes and peak flows, as well as the sediment and pollutants transport in urban stormwater runoff that impact the downstream water resources. The chapter goes on to cover how stormwater in urban areas is managed sustainably through SuDS with examples in the City of Johannesburg. Moreover, the definition of sediment traps and their importance in capturing flows and sediment. Lastly, the chapter closes with an overview of the parameters considered when sizing sediment traps from different design manuals, modelling software programs and a summary of the literature.

2.2 Impacts of Urbanisation

Increase in Runoff Volume and Peak Flow

Development in urban areas removes permeable natural vegetation and replaces this with compacted soils and impervious surfaces which reduces soil infiltration and increases peak flows and runoff volumes (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013; Fletcher *et al.*, 2013). Blöschl (2022) and Miller and Hutchins (2017) indicated that conventional stormwater systems shorten the response time in the urban catchments. Figure 2-1 illustrates the pre- and post-development stormwater runoff hydrographs where the post-development hydrograph has high runoff quantity (volume), short response time, reduced recession time and high peak runoff rates which are both associated with flooding and channel erosion downstream of urban areas. In comparison, the pre-development hydrograph has a long response time, lower and less rapid peak flows, less runoff volume and gradual recession.

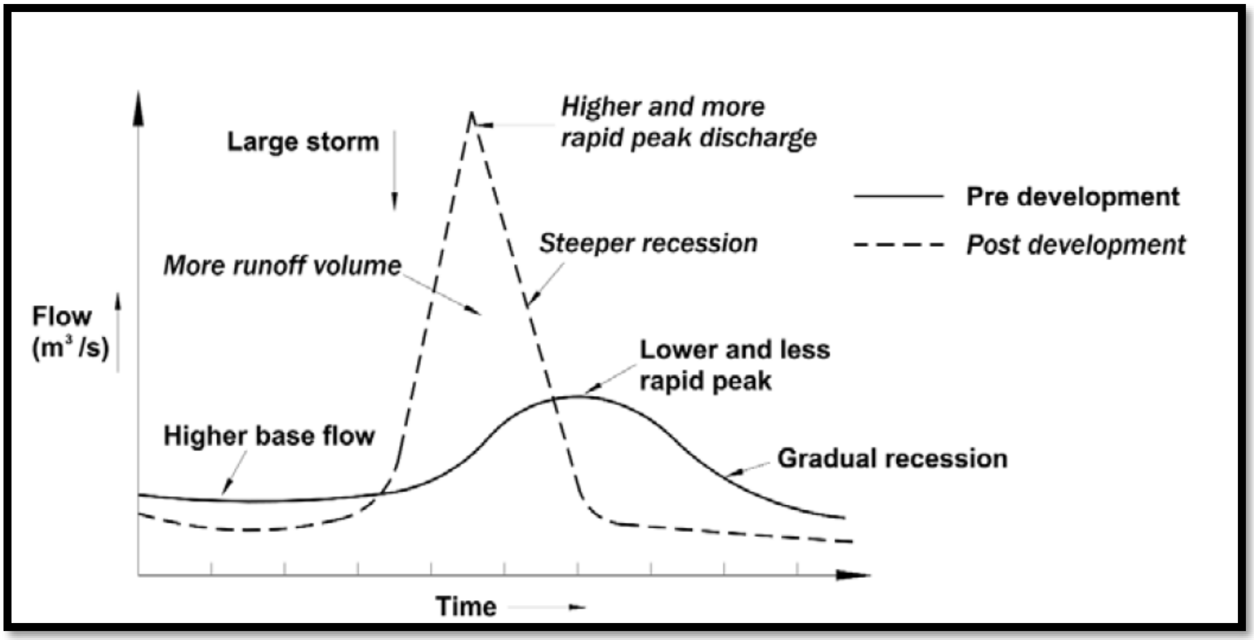


Figure 2-1: Pre- and post-development runoff hydrographs after a storm rainfall from an urban area (Woods-Ballard et al.*, 2007)*

Increase in Pollutants

The water cycle is classified as one of the most vital natural processes that support life and freshwater plays a central role in all aspects of our lives (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013). However, Woods-Ballard *et al.* (2007) and Armitage *et al.* (2013) states that pollution due to urbanisation has caused degradation in parts of the water cycle process which includes wetlands, rivers, and groundwater resources. Moreover, the runoff from urban areas is considered highly polluted thereby contaminating downstream receiving watercourses and damaging biodiversity (Armitage *et al.*, 2013).

The adverse effects of stormwater pollutants in the receiving water bodies are a function of several factors, for example, the nature and concentration of each pollutant, and the total load of the pollutants (Aryal *et al.*, 2010). High sediment concentration reduces the light penetration in streams and reservoirs, which leads to a decrease in activities such as the growth of photosynthetic organisms. Excess amount of sediment clogs the fish gills, smother habitats and harms other aquatic organisms (Burton *et al.*, 2000; Al-Ani, 2018; Zamanifard *et al.*, 2020). Also, through the monitoring of urban stormwater runoff, it has been found that the habitat and urban receiving watercourses are adversely impacted by the sediment load (Burton *et al.*, 2000; Al-Ani, 2018; Zamanifard *et al.*, 2020). The nutrients, pollutants, and coliform bacteria attach themselves to the finer sediment particles that are transported by stormwater runoff from the urban catchment. This impacts the downstream watercourses' biological, chemical, and physical integrity through eutrophication, toxication, and oxygen supply reduction (Ahilan *et al.*, 2019). The pollutants attached to sediments are released into the water body, where they may accumulate in plants and animal tissues and, lastly, enter the food chains (Dalu *et al.*, 2017). Moreover, an excessive amount of sediment has negative effects on recreational water use (Gu *et al.*, 2017). Also, an increase in sediment concentration increases the treatment costs of removing sediment for drinking water (Burton *et al.*, 2000; Fox *et al.*, 2016; Al-Ani, 2018; Perez *et al.*, 2019).

Sources of Sediments in Urban Areas

In urban areas, sediment and suspended solids emanate from asphalt or building erosion (erosion from construction sites), soils, sand, and silt (Aryal *et al.*, 2010). The study on the policy of sustainable environment by Ambali (2011) showed that land-clearing activities in Malaysia due to land development have caused soil erosion and river siltation leading to severe pollution of water. While, Barnard *et al.* (2019), indicated that the sources of sediments in streams and drainage systems in the City of Johannesburg include streambank erosion, erosion from poorly designed drainage systems, erosion from construction sites, runoff from paved surfaces carrying dust, grit, litter and discharge from sewage drainage systems. In addition, Winston *et al.* (2023), stipulated that anthropogenic sources of pollution from urban areas are brake pad wear, as well as vehicle fluids. Moreover, Russell *et al.* (2017) indicated that channel erosion is the major sediment source in urban catchments. Construction activities are associated with removing vegetation and other natural materials that hold soil particles together. Hence, this has led to surface areas and slopes exposed to erosive forces of wind and rain (Al-Ani, 2018).

Fox *et al.* (2016) indicated that the Conservation Effects Assessments Projects pointed out that sediment in streams resulted from excessive channel and bank erosion. Furthermore, the studies carried out in the United States also suggested that streambank erosion has the potential to yield 90-95% of sediments in the catchment (Fox *et al.*, 2016). Devereux *et al.* (2010) studied suspended sediment sources in an urban catchment, Northeast Branch Anacostia River, Maryland. The results of this study showed that the major sources of sediment in the Northeast Branch Anacostia River were from streambank erosion. Moreover, the study on bank-derived material dominates fluvial sediment in the suburban Chesapeake Bay watershed in the USA by Cashman *et al*. (2018) has indicated that bank-derived sediments were the major sources of the fine sediments in the Upper Difficult Run from 2008 to 2012.

2.2.1 Pre and Post-development Urban Stormwater Management

Figure 2-2 shows a typical example of pre- and post-development scenarios involving stormwater management. In pre-development environments, stormwater runoff flows naturally over the land, where some runoff infiltrates and recharges groundwater and evaporates. However, in the post-development environments, stormwater runoff is conveyed on hardened surfaces, gutters, pipe networks and concrete-lined channels and there is reduced infiltration into the groundwater (Yang *et al.*, 2020). The main goal of a conventional drainage system is to control runoff volume to avoid triggering floods in urban areas. Stormwater runoff is treated as a nuisance in the urban landscape; hence it is flushed out in a manner of "out of sight out of mind". Therefore, it is evident that the conventional drainage system has shortcomings when it comes to addressing the water quality, amenities and recreational benefits (Burns *et al.*, 2012).

Urban drainage systems designed with standard engineering practices are no longer considered best practices because they cannot restore post-development flows to natural flows (pre-development flows) and they do not comply with sustainable urban development (Fitchett, 2017; Bobbins *et al.*, 2019; Yang *et al.*, 2020). Moreover, conventional drainage systems can no longer accommodate the increase in flow peaks due to climate change-induced extreme rainfall events and the rapid rise of impervious surfaces in urban areas which makes it costly to expand the capacity of traditional/conventional stormwater infrastructure (Yang *et al.*, 2020). The normal practice of enlarging the urban drainage systems to carry high flood peaks is not economically viable. Therefore, to enhance the resilience of the urban drainage system, taking into consideration climate change and urbanisation, one should implement sustainable stormwater technologies for urban stormwater runoff conveyance and treatment.

According to Barnard *et al.* (2019), urban stormwater management is no longer centred around efficient drainage and flood management only, but it also includes the protection of natural resources. Stormwater drains are now used to convey stormwater runoff to designated treatment and reuse control points rather than being used as wastewater networks. Storing of stormwater runoff in retention/detention facilities is believed to reduce the frequency and range of downstream flooding, soil erosion, sedimentation and water pollution (SANRAL, 2013).

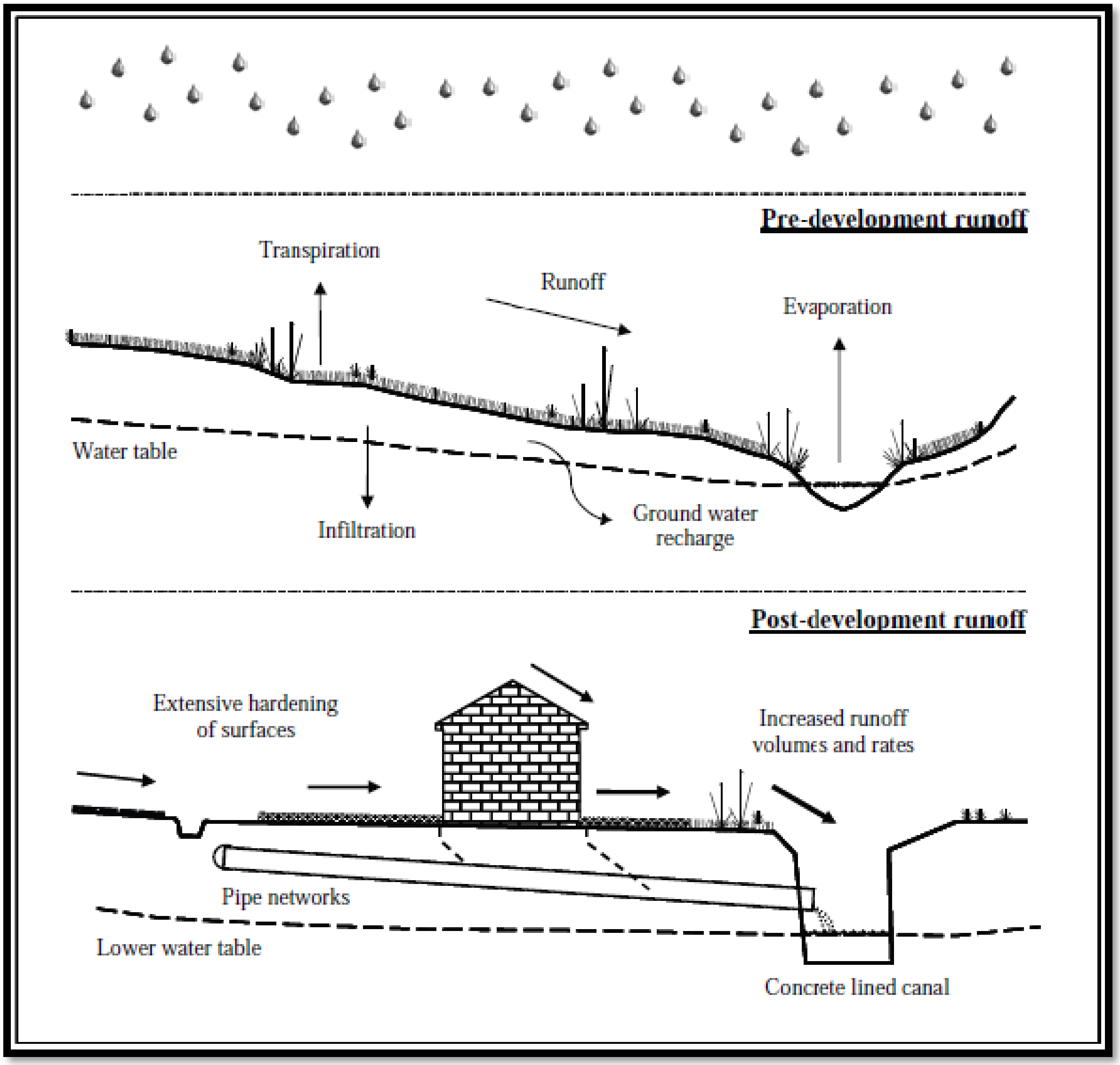


Figure 2-2: Typical example of pre- and post-development stormwater management involving a conventional drainage system (Armitage **et al.**, *2013)*

2.3 Sustainable Stormwater Management

The sustainable stormwater management technologies that are listed below work on minimising the impacts of urban stormwater runoff on downstream water resources. These technologies have been used in other developing countries such as Brazil and China, which are experiencing the same level of growth in their metropolitan areas as South Africa (Barnard *et al.*, 2019).

Recently, there has been more research carried out on the modelling of Low Impact Development (LID) for the management of urban stormwater runoff and many scholars are exploring the performance of LIDs in the management of surface runoff (Yang *et al.*, 2020; Saniei *et al.*, 2021). LIDs manage stormwater runoff by mimicking the pre-development hydrological conditions and enabling hydrological processes such as infiltration and evapotranspiration to take place in urban catchments (Yang *et al.*, 2020). In comparison to LIDs, conventional/traditional stormwater management mainly focuses on stormwater flow quantity management (Armitage *et al.*, 2013). Furthermore, the stormwater runoff is collected, channelized and quickly drained out of the urban areas to downstream watercourses without any treatment (Saniei *et al.*, 2021).

The term low impact development (LID) has been used in the United States of America and New Zealand to refer to attempts that are made to minimise the cost of stormwater management by considering a nature-based design (Fletcher *et al.*, 2015). LID aims to achieve natural hydrology through the site balance between post-development and pre-development runoff, infiltration, and evapotranspiration volumes. The application of LID has been on smaller-scale stormwater treatments and this includes bioretention systems, green roofs and swales which are located close to the sources of stormwater runoff (Fletcher *et al.*, 2015). The implementation of LIDs in the developing region of Tehran, Iran, Rashidi *et al.* (2017) found that runoff volumes were reduced from 33–70% and 22–54%, resulting from low to high rainfall intensities having 2-10 years return periods. Moreover, experiences from other countries have indicated that through the application of LIDs, flood damages were decreased and costs incurred for the implementation of flood control measures were reduced (Saniei *et al.*, 2021).

On the other hand, the term Water Sensitive Urban Design (WSUD) was first used in Australia and its objectives include managing water balance by taking into account the streamflow and groundwater, together with flood damage, maintaining and enhancing water quality which includes reduction of sediment in stormwater runoff, protection of riparian vegetation and minimisation of pollutant export to surface and ground waters, and to encourage water conservation which reduces importing of potable water supply through harvesting of stormwater and recycling wastewater (Fletcher *et al.*, 2015). Moreover, WSUD is described as an approach in urban planning and design aiming to reduce the hydrological impacts of urban development to closer environments. Some of the WSUD objectives include the reduction of stormwater runoff and peak flows coming from urban development through the application of detention measures at the local scale and the minimisation of impervious areas. WSUD forms the umbrella term for integrated urban water cycle management which involves water supply, sewage, and stormwater management (Fletcher *et al.*, 2015). According to Hotchkiss (2015), attenuation of runoff as a means to address urban stormwater runoff has become the standard practice in urban stormwater management worldwide. Retention/detention ponds and wetlands help in storing stormwater runoff during high peak flows and release it slowly, mimicking natural hydrological response. The retention/detention ponds and wetland facilities are fitted with outflow structures that release outflow peaks at a rate that matches or is closer to the pre-development flow rates. Figure 2-3 shows the runoff hydrographs from a catchment in pre-development, post-development and after the implementation of an attenuation pond.

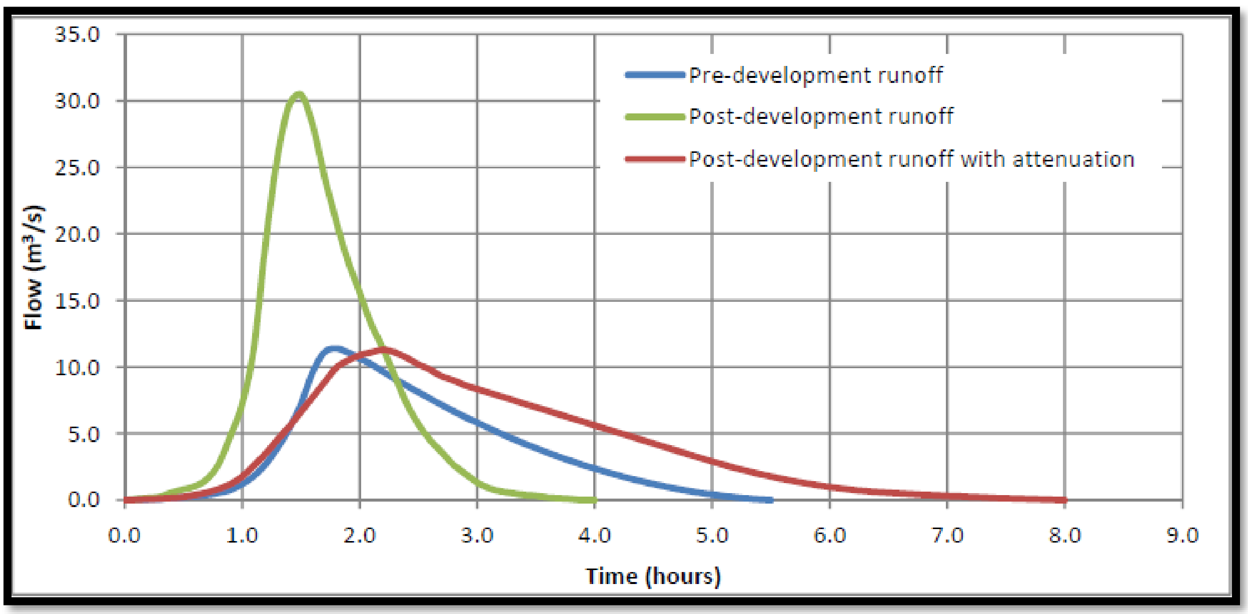


Figure 2-3: Hydrographs from a catchment in pre-, post- and post-development with attenuation structure (Hotchkiss, 2015)

From Figure 2-3, the post-development peak flow is much higher than the pre-development and the post-development with the implementation of the attenuation (retention/detention) structure. Furthermore, the post-development runoff hydrograph response is quicker (the response time is shortened). In comparison to the post-development hydrograph, the hydrograph after the implementation of the attenuation structure seems to match well with the pre-development hydrograph, which indicates that the high peak flow and the time to peak (response time) are both reduced.

Sustainable Urban Drainage Systems (SUDS) or Sustainable Drainage Systems (SuDS) have similar processes as the LID and WSUD. They were first used in the United Kingdom for the management of stormwater (Fletcher *et al.*, 2015). The practice of SuDS in the UK consists of several technologies and techniques that are used to convey stormwater and surface water in a manner that is regarded to be more sustainable when compared to conventional stormwater drainage systems. In Scotland, the SuDS technologies were used to improve water quality in receiving waters, as well as the conveyance of stormwater runoff from a variety of design storms for up to 200 years. England and Wales have used SuDS more for water quantity management than water quality control (Fletcher *et al.*, 2015). According to Woods-Ballard *et al.* (2007), SuDS that are properly designed, constructed and maintained well can mitigate the negative impacts of urban stormwater runoff to the receiving watercourses and are more sustainable than conventional drainage systems. Furthermore, SuDS are designed to manage surface water drainage in an integrated manner with the ideals of sustainable development. The main objectives of SuDS are to reduce the negative effects of development on urban stormwater runoff quantity and quality and thereby enhance amenities and maintain biodiversity (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013; Barnard et al., 2019).

The SuDS technologies and techniques are designed to manage stormwater runoff quantity and improve water quality, and amenities in an integrated manner as illustrated in Figure 2-4. Furthermore, SuDS systems preserve water quality, restore hydrological regimes and add recreational value to the landscape in the city. In contrast, conventional drainage systems treat stormwater as a nuisance in the landscape to be drained out of the city to downstream watercourses (Guptha *et al.*, 2022). They mimic as closely as possible the natural drainage systems, that existed there before development (Woods-Ballard *et al.*, 2007; Poleto and Tassi, 2012; Fletcher *et al.*, 2015). They achieve this through the application of a sequence of stormwater practices and technologies that work together to form a management/treatment train (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013; Fletcher *et al.*, 2015; Malulu, 2016), which facilitates in reduction of pollution, flow rates and runoff volume (Woods-Ballard *et al.*, 2007; Malulu, 2016). SuDS are applied to control runoff at the source, hence reducing the need for large flow attenuation and flow control structures at the catchment outlets. However, for better performance and to ensure the long-term effectiveness of SuDS technologies and techniques there must be pre-treatment before stormwater gets into SuDS, which involves removal of silt and sediment loads (Woods-Ballard *et al.*, 2007).

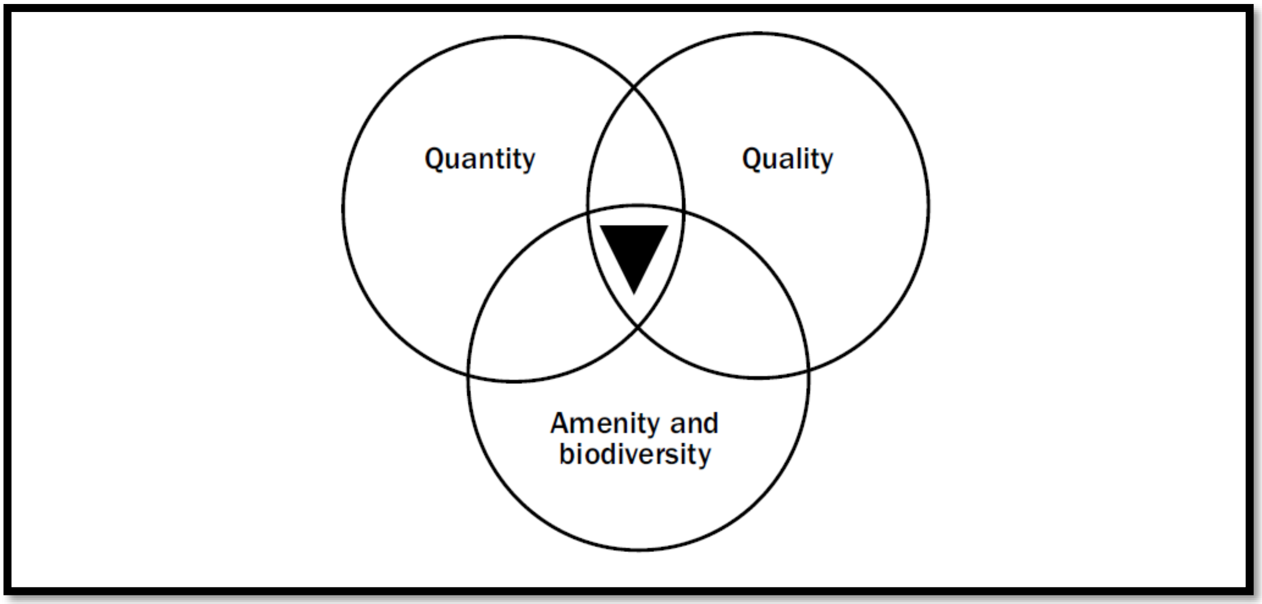


Figure 2-4: Sustainable drainage system objectives (Woods-Ballard et al., 2007)

2.3.1 The Typical Processes of SuDS

The typical example of processes in which SuDS integrates the quantity, quality management, enhancement of amenities and maintenance of biodiversity (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013) include the following:

- Slowing down and reducing the quantity of stormwater runoff coming from urban areas which then reduces the risk of flooding. This is achieved through harvesting, infiltrating, storing, slowing and conveyance of stormwater runoff.
- Reducing pollutants load in stormwater, such as the reduction of sediments in runoff to protect the water quality of downstream watercourses.
- SuDS contributes to enhancing green spaces in urban areas, linking other green places, and supporting local habitats and wildlife to grow and flourish. Also, local communities benefit through improvements in health, well-being and quality of life in general.

2.3.2 SuDS Treatment Train

SuDS manages stormwater runoff with the ideals of sustainable development using several sequential interventions that form a SuDS treatment train. The SuDS treatment train is an interconnected series of drainage systems to reduce pollution, flow rates and volumes of stormwater runoff (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013). The treatment train is made up of four interventions with each having a different combination of SuDS components for stormwater management (Armitage *et al.*, 2013). These treatment train interventions (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013) include:

1. Good housekeeping/prevention (meant to ensure that there is the minimisation of pollutant release).
2. Source control (managing stormwater runoff close to the source, and SuDS options that are used are green roofs, rainwater harvesting, permeable pavement and soakaways).
3. Site control/Local controls (managing stormwater in the local area and SuDS options which are used are bio-retention, filter strips, infiltration trenches, sand filters and swales).
4. Regional controls (managing stormwater runoff from multiple places and SuDS options which are used are retention ponds, constructed wetlands and detention ponds).

Figure 2-5 shows a typical example of a SuDS treatment or management train used for stormwater management. It is advised that stormwater should be managed within small sub-catchments close to the source rather than being conveyed to large systems at the catchment outlets (Woods-Ballard *et al.*, 2007).

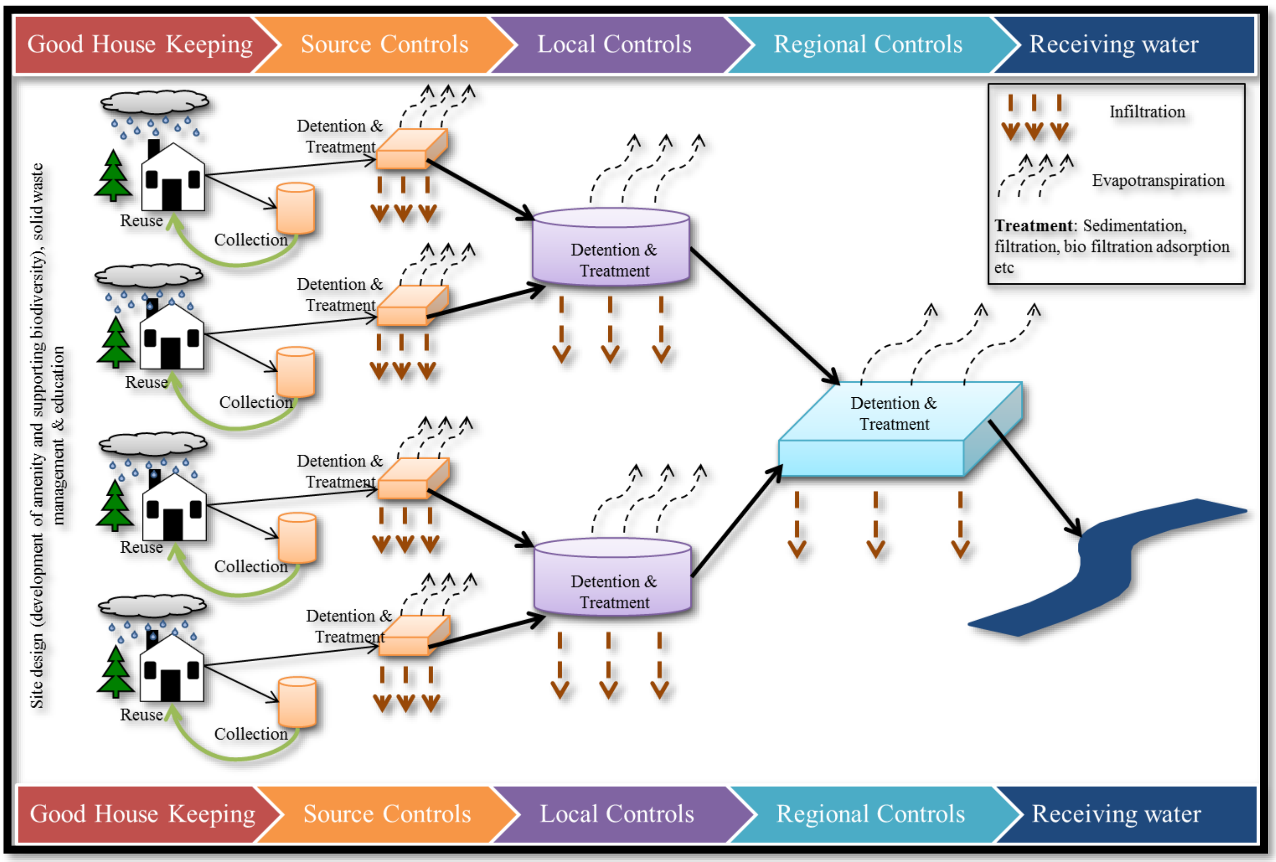


Figure 2-5: Typical example of a SuDS treatment train (Armitage et al., 2013)

2.3.3 SuDS Applications in the City of Johannesburg

Fitchett (2017) carried out a study using SuDS for the management of surface water in the Diesploot informal settlement, in Johannesburg, South Africa. The study's main aim was to reduce stagnant water in public spaces through SuDS interventions. The water quality results indicated that nitrate and phosphate concentrations were reduced by the permeable channels and soakaways that were implemented in the area. Another study was carried out by Seaton Thomson & Associates to rehabilitate the wetland located on the corner of Witkoppen Road and Cedar Road in Fourways. In addition to the rehabilitation of the wetland, the study added a SuDS treatment train consisting of bioswales and attenuation ponds. The bioswales and attenuation ponds were constructed to collect stormwater runoff from the residential development and attenuate and treat it before it flows into the wetland. The study successfully restored the wetland to its natural state with treated stormwater quality and reduced flows to downstream residents (Carden, 2018). Moreover, there was a study in 2021 on the implementation of bioswales for flood alleviation and water quality improvement in Diepsloot, Johannesburg. The results were positive where the initial baseline water samples indicated pollutant reduction in water (Mseleku, 2021). However, there are limited examples of SuDS in Johannesburg that involve stormwater design and due to this, there are some concerns that SuDS might be a problem in highveld conditions rather than a solution (Dunsmore & de Groen, 2020). Furthermore, some of the best practices that involve the use of infiltration systems in Johannesburg still need to be researched because of the steep terrain consisting of quartz and granite geology that limits groundwater recharge (Barnard *et al*., 2019).

2.3.4 Sediment Management in the City of Johannesburg

One of the objectives of the City of Johannesburg is to control the loading of sediment in the streams and rivers within the city (Barnard *et al.*, 2019). The main objective of the city is to restore the degraded streams, through new developments and re-developments in compliance with the objectives set out in the catchment management strategies. However, Barnard *et al.* (2019) stipulated that if the sediment loading guidelines are not available for river-specific standards, the current Catchment Management Plan and river objectives, and the South African river water quality guidelines may be used as the management objectives.

Table 2-1 shows the South African water quality guidelines for sediment loading in streams and rivers. Moreover, Barnard *et al.* (2019) has indicated that the turbidity of the rivers in the City of Johannesburg ranged between 10NTU and 30NTU during normal flow conditions, while flood conditions resulted in much higher turbidity values.

Table 2-1: South African water quality guidelines for sediment loads in rivers and streams (Barnard et al., 2019)

Source	Determinant	Unit	Limit	Comment
SA Water Quality Guidelines (DWA, 1996a)	TSS	mg/l	100 50	All aquatic ecosystems. Aquaculture, clear water fish species.
SA Water Quality Guidelines (DWA, 1996a)	Turbidity	NTU	25	Aquaculture, clear water fish species.

Therefore, Barnard *et al.* (2019) recommended that target discharge limits be determined considering the sensitivity of the receiving rivers and including any present strategic objectives set out for the stream. The setting of acceptable sediment discharge limits is expected to vary with location, within the municipality and during normal to flood flow conditions. During the compilation of the City of Johannesburg Stormwater Design Manual in 2019, it was stated that the acceptable sediment discharge limits were not yet set for the City of Johannesburg streams (Barnard et al., 2019). Therefore, due to the lack of sediment load discharge limits for the City of Johannesburg streams, the South African water quality guidelines shown in Table 2-1 for sediment load may be used as a guideline. However, the South African water quality guidelines for sediment load seem to be overly strict and difficult to achieve because turbidity before and after storm events varies and makes it unclear what the sediment loads would be during natural catchment conditions (Barnard *et al*., 2019). Moreover, it is recommended that further research on sediment loads across the City of Johannesburg streams is needed.

2.3.5 Stormwater Quantity Control in the City of Johannesburg

The City of Johannesburg Stormwater Management By-laws (City of Johannesburg, 2010) and Stormwater Design Manual (Barnard *et al*., 2019) stipulated that site runoff should not compromise the adjacent places to the development site and downstream properties which may include receiving stormwater networks and streams. Therefore, the acceptable discharge limits from a development site should be determined. These discharge limits are determined with consideration to the hydraulic capacity, structural stability and ecological and morphological sensitivity of the receiving system of the downstream drainage systems. In addition, the change in stormflow rates in drainage systems due to development should be indicated and a calculation of the likelihood of damage to the receiving watercourse downstream of the development be determined. Barnard *et al*. (2019), also recommended that for the design of stormwater quantity control structures, the estimation of peak stormwater runoff rates should be carried out using a hydrograph method of analysis that is approved by the Johannesburg Road Agency. The stormwater quantity control facilities are to be designed to meet the target stormwater runoff. Furthermore, the storage facility design is recommended to use routing calculation methods that are well known for the computation of the outflow hydrograph from the inflow hydrograph as well as the stage/storage characteristics of the storage facility. However, if the purpose of the basin is to reduce volumes or frequency of discharge, or the treatment of stormwater runoff water quality, then computation methods that are implemented in the design of the storage should consider infiltration, evaporation losses, and physical, chemical, and biological processes happening in the basin. The other recommendation made in the City of Johannesburg Stormwater Design Manual was that the post-development stormwater discharge rates should not be more than the pre-development flow rates for all ranges of recurrence intervals of any duration. The pre-and post-development discharge rates should be estimated for a range of recurrence intervals with a range of durations and the curves plotted to show that the post-development peaks are not higher than the pre-development peaks.

2.4 Stormwater Basins and Ponds

According to the Queensland Government (2018), the sediment basin's function is to slow water velocity and initiate the sedimentation of coarse and medium-sized sediment which are 125µm and larger. The coarse and medium-sized sediments usually settle at the bottom of the sediment basin where they need to be removed for a basin to maintain its storage to capture the subsequent sediment. In addition to sedimentation of coarse and medium sediments, Perez *et al.* (2015) stated that very fine soil particles such as clay and silt require longer detention times which are normally longer than the standard sediment basin treatment retention time. Therefore, chemical treatment using coagulants to assist in the binding of finer particles to provide flocculation may be used. Chemicals such as aluminium sulfate, calcium sulfate and polyacrylamide have been used as coagulants in the treatment of stormwater. Also, a natural substance such as chitosan is used as a coagulant (*Chitosan Flocculant Water Treatment*, 2024). Moreover, sediment basins can be used for water capturing, water reuse, and other benefits. Sediment basins can be used on their own or combined with other treatment systems. Working in a treatment train, sediment basins first remove coarse and medium sediment before stormwater runoff enters the downstream treatment system. The downstream systems deal with the removal of smaller-sized sediments, nutrients, and pesticides. The other benefit of sediment basins is the diverting of high-velocity flows from entering downstream systems and protecting them from scouring and resuspension of already-settled sediments (Perez *et al.*, 2019).

Apart from sediment basins, there are detention and retention ponds which are usually used for flood control and stormwater runoff treatment. They also facilitate the settling of suspended sediments and nutrients out of the stormwater runoff. Detention ponds are normally dry most of the time except after periods of rainfall. The main function of detention ponds is to hold the stormwater runoff and gradually release it over a time that is equal to the response time of the natural catchments. This helps to attenuate the post-development hydrograph to match the pre-development hydrograph. Detention ponds are mostly used in urban areas for the reduction of peak runoff, thereby decreasing flood damage (Laramie County Conservation District, 2016). On the other hand, retention ponds permanently store stormwater throughout. The permanent pool of water in the retention pond fluctuates in response to inflows from precipitation, stormwater inflow, and stormwater outflows. The main function of retention ponds is to store the stormwater runoff and release it very slowly over a prolonged time. Furthermore, a retention pond can also be used as a decorative feature, which can provide amenities and raise the property value. Retention ponds help in the biological treatment of water whereby the bacteria are allowed more time to feed on the pollutants. Also, plants take up and metabolise pollutants or nutrients and non-biological chemical processes can take place. Figure 2-6 shows the difference between a detention pond (a) and a retention pond (b).

(a) (b)

Figure 2-6: Detention (a) and retention (b) ponds (Myburgh, 2016)

According to Myburgh (2016), the important requirements for retention and detention ponds are:

- The sufficient storage of the ponds to capture and hold stormwater runoff.
- The outlet facility that limits the outflow from the ponds at a rate that matches or is not greater than the pre-development.

Myburgh (2016) further stipulated that the required storage capacity of the pond depends on the outlet or dewatering structure to ensure that the outlet structure can limit the routed post-development peak discharge to not exceed the pre-development discharge. Hence, the simultaneous and complementary sizing of both the storage volume and the outlet structure is a crucial design requirement in the planning and designing of stormwater facilities.

On the other hand, Suripin *et al*. (2020) stated that sediment basins work as retention and detention ponds through the retention and deposition of suspended sediment in the stormwater runoff. The flow velocity decreases when the stormwater runoff enters the sediment basin, where sufficient storage capacity and retention time are provided to enable sediment to settle at the bottom of the sediment basin (Perez *et al.*, 2016). However, the sedimentation is affected by factors such as geotechnical parameters, the type of outflow device, and hydrodynamic conditions. According to Al-Ani (2018), a typical sediment basin is made up of an impoundment, a riser, an outlet pipe, and an emergency spillway. Alabama Department of Transportation (ALDOT, 2002) sediment basin design includes baffles that separate the basin into different bays, a surface dewatering skimmer, and an auxiliary spillway. See examples of sediment basins in Figure 2-7.

Figure 2-7: Sediment basins (Department of Planning and Local Government, 2010)

2.5 Parameters for Sizing Sediment Facilities

According to Perez *et al.* (2016), the design parameters of sediment basins are not the same from one construction site to another but depend mainly on local hydrology and soil conditions. The following section discusses the parameters that impact the size of the sediment traps and basins from different manuals.

2.5.1 Design Rainfall, Design Flow Rate and Storage Volume

ALDOT and the United States Environmental Protection Agency (USEPA) design guidance require sizing of sediment basin volume to be based on 250m^3/ha of storage or volume of runoff resulting from the 2-year, 24-hour storm event (Perez *et al.*, 2015). Barnard *et al.* (2019) indicated that any erosion and sediment control facilities must be sized based on a 2-year recurrence interval design for storm events with a duration ranging from 0.25 hours to seven days. Moreover, the Department of Planning and Local Government (2010) requires that the sizing of the sedimentation basin be determined concerning the design flow of the 1-year Average Recurrence Interval (ARI). In Korea, the critical storm duration for a design return period is used in the design of detention basins (Park *et al.*, 2012). Larm and Alm (2014) found that it was common in Sweden to design flow detention basins using a rainfall duration of 10 minutes. However, this always resulted in insufficient detention volumes. Therefore, it was recommended that the rain duration and specific rainfall intensity be used to determine the sufficient detention volume.

Queensland, Australia recommended that the sediment basins should be designed to capture runoff volume resulting from 80% rainfall depth (Rowlands, 2019). Rowlands and Leinster (2015) carried out an analysis that indicated that was not the case. There was an implemented sediment basin sized according to the above recommended standards and it was able to treat only 34% of the annual runoff volume with the criteria of 50mg/L of TSS released. On the other hand, Rodak *et al.* (2020), stated that the design of stormwater control structures can be effective if their design is informed by the knowledge of the stormwater influent quantity. Ahilan *et al.* (2019) conducted a study using Personal Computer Storm Water Management Modelling, the designed pond had a rectangular shape (67m in length and 77m, in width) giving an area of 2400m^2 and a depth of 2.2m (resulting in a volume of 6,533m^3). The simulation results from the study indicated that the stormwater pond attenuation and sediment trapping were successful for frequent small (< 5-year) and medium (< 30-year) stormwater runoff events.

2.5.2 Sediment Basin Surface Area

Queensland Government (2018) indicated that several options can be used in sizing the sediment basins. The first option included a simple way of estimating the surface area of a sediment basin required based on the stormwater runoff flow rate and the settling velocity of the sediment in the stormwater runoff as indicated in Equation 1. The second option of sediment basin sizing was based on parameters such as turbulence, short-circuiting, and depth of the sediment basin.

$$A = \frac{Q}{V_S} \tag{1}$$

Where:

A = surface area of the sediment basin (m^2)

Q = flow rate (m^3/sec)

V_s = sediment settling velocity

Fileni *et al.* (2019) carried out a study on the application of LIDs in the Federal District of Brazil, located in a Savanna region for the mitigation of flooded areas, whereby the storage volume of the stormwater ponds was sized based on the percentage of the impermeable area and upstream area using Equation 2. The use of stormwater ponds that were implemented at the catchment outlet was able to reduce the peak flows by 86% and 84%. It should be noted that in Equation 2, there is no rainfall term, hence it would probably be applicable at a location with specific climate characteristics.

$$V = (4.705 * A_i) * A_C \tag{2}$$

Where:

V = volume (m^3)

Ai = impermeable area (%)

Ac = contribution area (ha)

The Auburn University Stormwater Research Facility (AU-SRF) designed and installed a large-scale sediment basin testing apparatus to evaluate its performance with reproducible results when used on highway construction projects. The designed and installed sediment basin had a total volume of $79m^3$. The basin was sized according to USEPA sizing criteria of $252m^3/ha$ while the flow and sediment loading rates were based on the local 2-year, 24-hour rainfall event (Schussler *et al.*, 2022). The research at AU-SRF encouraged Schussler *et al.* (2022) to conduct of field monitoring of single in-series and in-channel sediment basin design at the Iowa Department of Transportation (DOT). The study indicated that turbidity and TSS were not reduced by the basins. Then the researchers aimed to test the design improvement of in-channel basins, however, they were faced with constraints (Schussler *et al.*, 2022).

According to Perez *et al.* (2016), the early design of sediment basin volumes was based on storage that captures the local 10-year, 24-hour rainfall events. However, a volume sizing factor (VSF) of $125m^3/ha$ of the contributing drainage area was used to simplify the hydrologic calculation and was thereafter adopted as guidance by several state agencies. USEPA then implemented the VSF guidance with the use of 7.62cm rainfall to represent a 2-year, 24-hour rainfall with an assumption that the event would result in 2.54cm of runoff that is proportional to 250m^3/ha of the contributing drainage area. This VSF was identified to be able to capture 90% of the rainfall events happening throughout each year. However, this VSF guidance was criticized because it could not provide adequate storage capacity to fully capture runoff from the 2-year, 24-hour rainfall events in many parts of the United States. It is evident as alluded to earlier in this section that the design parameters of sediment basins are not the same from one construction site to another but depend on local hydrology and soil conditions. To overcome this shortcoming, the USEPA updated its standards in 2008 by recommending that sediment basins be designed with enough storage for stormwater runoff generated from the 2-year, 24-hour rainfall events, or with a storage volume of 250m^3/ha. However, it should be noted that there is no agreed volume sizing factor for sediment basins with recommendations ranging from 125m^3/ha of the contributing drainage area to 250m^3/ha.

According to Perez *et al.* (2015) and Perez *et al.* (2016), the volume of the sediment basin must be sufficiently sized to provide enough storage for detaining sediment-laden stormwater runoff volumes generated by the rainfall events in the catchment and enabling suspended sediment time to settle from the runoff. Perez *et al.* (2015) further added that additional storage is required to store the volume of the settled sediments.

2.5.3 Catchment Area

Al-Ani (2018) and Perez *et al.* (2015) stipulated that the sediment basin's size depends on the size of the catchment area where stormwater runoff is generated. Therefore it was recommended that the maximum catchment area contributing flow to any sediment basin should be limited to 4.0ha (9.88 acres) with an absolute maximum catchment area of 405ha (1000 acres) (Alabama Soil and Water Conservation Committee, 2014; Perez *et al.*, 2015; Perez *et al.*, 2016).

2.5.4 Sediment Yield

The sediment basin is sized based on the sediment yield from the catchment (Al-Ani, 2018), which can be determined using the Modified Universal Soil Loss (MUSLE) Equation 3. Moreover, the sediment storage volume in high erodible soil areas should be sized to capture a two-month soil loss from disturbed areas in the catchment using the Modified Universal Soil Loss (MUSLE).

$$\boldsymbol{Y = 89.6(VQ_P)^{0.56}(K.LS.C.P)} \quad (3)$$

Where:

Y: Sediment yield per storm event (tonnes)

V: Runoff volume in a cubic meter

Q_P: Peak discharge in m^3/s

K: Soil erodibility factor

LS: Slope length and slope steepness factor

C: Cropping management factor

P: Erosion control practice factor

The Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE) and Modified Universal Soil Loss Equation (MUSLE) are the most used methods for soil erosion modelling. These empirical methods are applied globally because of their minimal data and computational requirements (Zhang *et al*., 2009). The main advantage of the MUSLE method over other methods is the ability to predict soil loss for individual storm events (Zhang *et al.*, 2009; Pretorius, 2016). Furthermore, the use of runoff as an independent factor in MUSLE for the modelling of erosion makes it an accurate soil erosion prediction method compared to USLE and RUSLE (Zhang *et al.*, 2009). However, MUSLE application in South Africa has been found to overestimate low measured values and underestimate higher measured values of soil erosion in the Mkabela catchments, Kwa-Zulu Natal (Pretorius, 2016).

2.5.5 Particle Settling Velocity and Retention Time

Department of Planning and Local Government (2010) stated that the sizing of the sediment basin is determined concerning the settling velocity of the selected sediment size. In comparison, Barnard *et al.* (2019) stipulated that when designing a sedimentation facility, one must consider the nature of the grading and specific gravity of the sediments and the retention time of the sedimentation treatment facility. Moreover, Perez *et al.* (2015), pointed out that sediment basin sizing is facilitated by Stokes Law through the determination of particle settling velocity (sedimentation rate). When it comes to the target sediment size, Department of Planning and Local Government (2010) recommended that 125µm (0.125mm) or larger sediment sizes should be considered for trapping because the literature on sediment analysis has shown that between 50-80% of sediment in urban stormwater runoff is composed of 125µm or larger sediment particles. The particle size and settling velocity may inform the corresponding sediment trap capacity required to settle out such particles. The settling velocity determines the settling time, i.e., the time required for a particular particle to settle out of suspension. The settling time is used to inform the retention time, which is a design parameter that must exceed the settling time. Stormwater runoff should be detained for sufficient time to enable suspended solids to settle down. The time required for sedimentation to occur is based on the particle size and nature of the soil. The Alabama Department of Transport (2002) retention time is usually 8 hours, while Gu *et al.* (2017) argued that the sufficient time for sedimentation is 24 hours. There are different retention times from one place to another. The different retention times are related to particle sedimentation and the flow rate hence they need to be determined in the project site.

Stokes Law expresses the force that drags the spherical objects during laminar flow conditions or at low Reynolds numbers (Suripin *et al.*, 2020). Moreover, Gulliver *et al.* (2010) stipulated that the fall velocity of small particles under quiescent conditions and spherical objects of Reynolds Number less than 1 is calculated using Stokes' Law Equation 4.

$$\boldsymbol{V_s} = \frac{\boldsymbol{g*(s-1)*d^2}}{\boldsymbol{18*\mu}} \qquad (4)$$

Where:

V_s = terminal velocity/particle fall velocity in (m/s)

g = acceleration due to gravity in (m/s^2)

d = diameter of suspended particles (m)

μ = kinematic viscosity in m^2/s

s = specific gravity of the suspended particle

Stokes' Law indicates that the rate at which the sediment particle sinks in water is dependent on the density and diameter of that particle, such that larger and denser soil particles fall faster than less dense and smaller soil particles when suspended in the water (Kroetsch and Wang, 2008; Gulliver *et al.*, 2010). Moreover, the viscosity of the water impacts the fall velocity of sediments whereby warm temperatures are associated with faster settling time (Gulliver *et al.*, 2010; Perez *et al.*, 2015). In addition, Ferguson and Church (2004) developed Equation 5 for the settling velocity of larger particles like sands. Equation 5 also behaves as Stokes' Law for sediment particles with smaller diameters.

$$\boldsymbol{V_s} = \frac{\boldsymbol{gRd^2}}{\boldsymbol{18v+(0.75CgRd^3)^{\frac{1}{2}}}} \qquad (5)$$

Where:

Vs = terminal settling velocity of the solid particle

g = gravitational acceleration

R = specific gravity in water (1.65 for silica sand)

C = constant (0.4 for spheres, 1 for typical sand grains)

d = diameter of the particle

v = kinematic viscosity of the fluid

Furthermore, Kroetsch and Wang (2008) stated that Stoke's Law can be used for small spherical particles of density (PS) and diameter (D), that settle in a liquid of density (PL), and viscosity (n), using Equation 6.

$$V_S = \frac{D^2 g(PS - PL)}{18 * n} \tag{6}$$

However, it should be noted that Equation 6 is based on assumptions which include: soils are assumed to be spherical; density ranges between 2.0 to 3.2Mg/m; and the water temperature should be constant during sedimentation (it is advised to use water at temperatures between 20 ^{0}Cand 30 ^{0}C). It is also assumed that sedimentation through the cylinder is not influenced by the cylinder walls (Kroetsch and Wang, 2008). Moreover, Zhiyao *et al.* (2008) conducted a study that produced Equation 7. The research objective was to produce an easy-to-apply formula for the determination of the settling velocity of natural sediment particles which applies to a wide range of Reynolds numbers from both Stokes and turbulent flow regimes. The research found that Equation 7 had a higher degree of prediction accuracy on the sediment settling velocity of natural sediment particles when compared to other previously published equations.

$$V_S = \frac{V}{d} d^3 \left(38.1 + 0.93\, d^{\frac{12}{7}}\right)^{-\frac{7}{8}} \tag{7}$$

Where:

V_s = settling velocity for single particles

d = particle diameter

v = fluid kinematic viscosity

2.5.6 Sediment Trap Efficiency

The performance of the sediment basin is determined through its trap efficiency factor, which is calculated as the ratio of the inflow sediment concentration to the settled sediment concentration in the pond (Ferreira and Waygood, 2009; Parsaie *et al.*, 2018; Suripin *et al.*, 2020). Perez et al. (2015) and Perez et al. (2016) stated that a sediment basin's efficiency at trapping sediment is affected by design factors such as basin size, geometry, energy dissipaters, chemical treatment, and dewatering methods. Moreover, storm events, soil characteristics, topography, upstream erosion, sediment control, and maintenance of the sediment basin have an impact on the performance of the basin. In addition, the location and construction of inlet and outlet structures, stormwater inflow volume, and settling time of the particle (Larm and Hallberg, 2008) have an impact on sediment basin trap efficiency. Gu *et al.* (2017) stated that currently, studies carried out on sediment in stormwater ponds have indicated a need to involve the modelling of sedimentation that will inform the design guide for municipalities working on strategies for improved sediment trap efficiency. Moreover, to improve the trap efficiency, one must consider the Best Management Practices design, including retention time, vegetation, physical particle characteristics, inflow, effluent, and sediment loading (Ferreira and Waygood, 2009). Also, the Alabama Department of Transport, (2002) recommended using coagulants to enhance the settling of finer particles.

Ferreira and Waygood (2009) further stated that silt trap efficiency at trapping sediments is related to the length-to-width ratio, geometry, and detention storage. Eckert *et al.* (2018) conducted a study which found that the nutrient and total suspended solids removal of the newly innovated wet detention pond was improved by the longitudinal interior baffle dike, which extended the flow path and increased the retention time. This study showed that making design improvements to the layout and geometry of stormwater ponds can significantly facilitate the reduction of nutrients and sediments from stormwater runoff. Furthermore, Perez *et al.* (2015) and Perez *et al.* (2016), added that the geometry of the sediment basin plays a major role in improving trap efficiency by affecting flow patterns and residence time. However, rectangular ponds with a length-to-width ratio of 4:1 and 3:1 L-shaped ponds were found to have poorer hydraulic efficiency. The recommended pond design criteria are a long length-to-width ratio of 4:1 to 5:1. McCaleb and McLaughlin (2008); and Perez *et al.* (2016) stated that to increase the performance of the pond, it is advised that the sediment basin should have a long length and narrow width (length-to-width ratio of 2:1). It is evident that different authors recommend a wide range of length-to-width ratios, hence it is wise to test this when designing sediment basins and traps.

On the other hand, Barnard *et al*. (2019) proposed the sediment trap target limits shown in Table 2-2. These sediment trap target limits are based on the settlement of different sizes of sediments using a combination of settlement and filtration methods. The trapping efficiency of the settlement facilities is for the design events, and it requires testing the system for a range of design hydrographs for different retention and attenuation facilities.

Table 2-2: Proposed interim trap efficiency of on-site sediment treatment facilities (Barnard et al., 2019)

Particle size	Category	Treatment	Trap Efficiency (per design storm event)			
		Primary(1) Secondary(2)	1.01 yr.	5 yr.	10 yr.	20 yr.
≥ 0.2mm	Gravel, coarse to fine sand	Settlement(1)	100%	100%	100%	90%
≥0.075mm	Fine sand	Settlement(1), filtration(2)	100%	100%	90%	65%
≥0.04mm	Coarse silt	Settlement(1), filtration(2)	100%	55%	35%	25%
≤0.04mm	Medium to fine silt & clay	Filtration(1), settlement(2)	50%	10%	_	_

2.5.7 *Introduction to Modelling*

Deterministic models used for urban water systems such as PCSWMM, are regarded as the most useful tools because of their ability to find solutions to problems (James, 2005). Moreover, the modelling exercise is driven by the design problem that needs to be answered by the end of the modelling process. These models are normally applied in engineering design, operations and planning. However, lately, there is more discussion around the interpretation of their outputs, which involves uncertainty and accuracy. Hence, this calls for the responsible use of models which include; sensitivity analysis, uncertainty, parameter optimisation, error analysis, validation, verification, discretisation, and model reliability. On the other hand, field data collected is important for the validation and calibration of the model. James (2005), also stated that continuous modelling using long records of data such as 50 and 100 years is considered reliable.

The modelling process starts with data collection, which is managed by conducting sensitivity analysis on the model to identify the processes that influence the model results. Therefore, quality control is essential while collecting data. The standards and procedures for data collection, analysis and presentation should be followed. The uncertainty of the field data is estimated to inform model performance whereby the observed data is processed to detect trends and calculation of statistical analyses such as mean, median, variance and correlation. Apart from input data, James (2005), stated that the connection between the drainage systems from the study site should be reproduced well in the model. This is termed model discretisation and it is known to carry important information in terms of drainage connectivity. Discretisation involves the demarcation of the catchment divide, marking of significant channels, and major hydrological components, and delineating of sub-catchments for each tributary and storage unit. Moreover, discretisation helps in the sequential pattern in the model, whereby stormwater runoff and pollutants are generated from the sub-catchments, and transported through the conveyance systems until they get to the catchment outlet. Hence, models that discritise the catchment into multiple sub-catchments are preferred over models that take a catchment as a single element.

2.5.8 Modelling Software Programs

There are tools and software programs used to facilitate the sizing of sediment basins and sediment traps using catchment parameters as input data. Donald *et al.* (2016) developed SEDspread, which is a hydrologic-based design tool that facilitates the proper sizing and configuration of sediment basins to capture stormwater runoff from construction sites and disturbed areas for the removal of sediment. SEDspread workbook sheet tool has three sediment basin sizing options which are regional-specific design criteria (125 or 250m^3/ha), volume sizing factor (2-year, 24-hour rainfall event), and manual input. A spreadsheet workbook contains eight worksheets, and it allows the designers to input site parameters to determine the required sediment basin geometry and volumes (capacity), surface skimmer sizing, sizing of the auxiliary spillway and baffles configuration. Furthermore, the outputs of the workbook for a designed basin have a stage-storage relationship plot and the dewatering schedules. The workbook has a summary sheet that shows the users a schematic of the designed basin, which is a piece of additional information to enhance communication between the designer and the construction personnel. This helps in the construction of the sediment basins as designed; it also allows designers to adequately design sediment basins using local hydrologic and soil conditions. This workbook was used in a case study to compare the actual designs of two sediment basins from local construction sites against the design carried out using the SEDspread volume sizing factor (2-year, 24-hour rainfall method). The case study indicated that the sediment basin was underdesigned for the 2-year, 24-hour rainfall event (Donald *et al.*, 2016).

Storm Water Management Model (SWMM) is another software program used for sizing LID and SuDS technologies. It is a dynamic rainfall-runoff simulation model developed by the Environmental Protection Agency (EPA). SWMM is used to simulate single events or long-term (continuous) runoff quantity and quality, mainly from urban catchments (Gironás *et al.*, 2009; Rossman, 2015). It has been a common model used by researchers to model urban stormwater flows at catchment scales (Rodak *et al.*, 2020). Runoff is generated from different times rainfall falling on multiple sub-catchment areas. The sub-catchment areas produce runoff and pollutant loads. The generated runoff is transported through a system of pipes, channels, storage/treatment devices, pumps, and regulators by the transport component of SWMM. Since SWMM's development by the EPA, it has been used worldwide to simulate hydrological processes and water quality management in urban catchments (Gironás *et al.*, 2009; Rossman, 2015; Li *et al.*, 2016). Some of the typical applications of SWMM include the design and sizing of drainage system components for flood control and the sizing of detention facilities and their parts for flood control and water quality protection (Gironás *et* *al.*, 2009; Rossman, 2015). In addition, SWMM uses flow routing methods, computing of water balances through the SCS surface runoff method, and determination of discharge flow rate at the catchment discharge point using Manning's equation (Fileni *et al.*, 2019). Moreover, it is a freely available model that is easy to use and accessible to hydrologists, engineers, and water resources management specialists (Gironás *et al.*, 2009).

On the other hand, Al-Ani (2018) conducted a study on urbanisation and sediment control which developed an intelligent system (Visual Basic Tool) to enable the engineers and decision-makers to design dry and wet sediment basins for application in Malaysian construction sites to capture and trap the sediments generated from construction activities. The developed system is regarded as being transparent and flexible software to use. It allows the users to carry out the design work with ease by reducing the consultation cost and time. The system can also be considered a training tool for engineers who have just started their careers to guide them with the design of sediment basins. Moreover, this system acts as a green technology because it minimizes environmental impacts. However, knowledge from other materials and information is still needed to be collected and inserted into the system.

2.6 Summary of Literature Review

Urban stormwater runoff carries sediments and pollutants to downstream water resources. The implementation of SuDS technologies helps in the management of stormwater runoff quality and quantity through the application of retention and detention ponds. Stormwater runoff is recognized as a resource instead of waste; hence, it is managed in a sustainable and integrated manner. However, for better performance and long-term efficiency of these SuDS technologies, sediment basins and traps are used to reduce sediment load before stormwater runoff is released from the development site.

The management objective of the City of Johannesburg is to control the loading of sediment in the streams and rivers within the city to protect the water resources and the aquatic life. Hence, the sediment facilities are sized based on design flow rates, rainfall intensity, particle size distribution, particle settling velocity, sediment yield and retention/detention times. However, it is stated that the design parameters are not the same from one construction site to another but depend on local hydrology and soil conditions. Moreover, studies have indicated the need to involve the modelling of sedimentation that will inform the design guide for municipalities.

There are a few tools and software programs used to facilitate the sizing of sediment basins, sediment traps and silt traps using catchment parameters as input data. These tools include SEDspread; a hydrologic-based design tool that facilitates the proper sizing and configuration of sediment basins to capture stormwater runoff from construction sites and disturbed areas for removal of sediment. PCSWMM is another software used for sizing LID and SuDS technologies.

It is clear from the literature that the parameters for sizing sediment traps are site-specific, many authors suggest different values of the parameters. However, the City of Johannesburg Stormwater Management By-Laws and Stormwater Design Manual have limited information on the parameters for sizing sediment traps. Hence, the main aim of the study is to determine the parameters for the sizing of sediment traps, specific to the City of Johannesburg.

3 Waterfall City

The literature review has described how urbanisation activities impact stormwater quality and quantity, as well as how SuDS technologies are used in the City of Johannesburg for stormwater management. However, SuDS technologies that are implemented in the City of Johannesburg are faced with the problem of sedimentation. To deal with sediment problems, other countries have developed design manuals with the parameters considered when sizing sediment traps. Therefore, Waterfall City in the City of Johannesburg was chosen as the case study, where stormwater and sediment transport programs were used for the determination of the parameters for sizing sediment traps, specific to the City of Johannesburg. Furthermore, Waterfall City was chosen as it is highly developed and urbanised, while the stormwater management consists of open channels and retention ponds. Also, as alluded to in the Section 1.1, there is a retention pond that is losing its storage capacity due to sediment coming from construction activities and disturbed areas. Hence, this calls for the implementation of the sediment trap at the head of these retention ponds.

The following section presents the location of the study site, its climatic conditions, geology, topography, land cover, land use and vegetation. Some of these physical parameters are also used as input data in the modelling programs.

3.1 Locality

Waterfall City is located on the northern side of the City of Johannesburg Metropolitan Municipality within administrative Region A, with central coordinates of 26°01'18.65" S and 28°06'00.15" E (see Figure 3-1). Waterfall City is a fast-growing, mixed-use, and real estate development with business, residential developments and lifestyle amenities and it covers an area of 2 200ha (Brill and Reboredo, 2019; Murray, 2015).

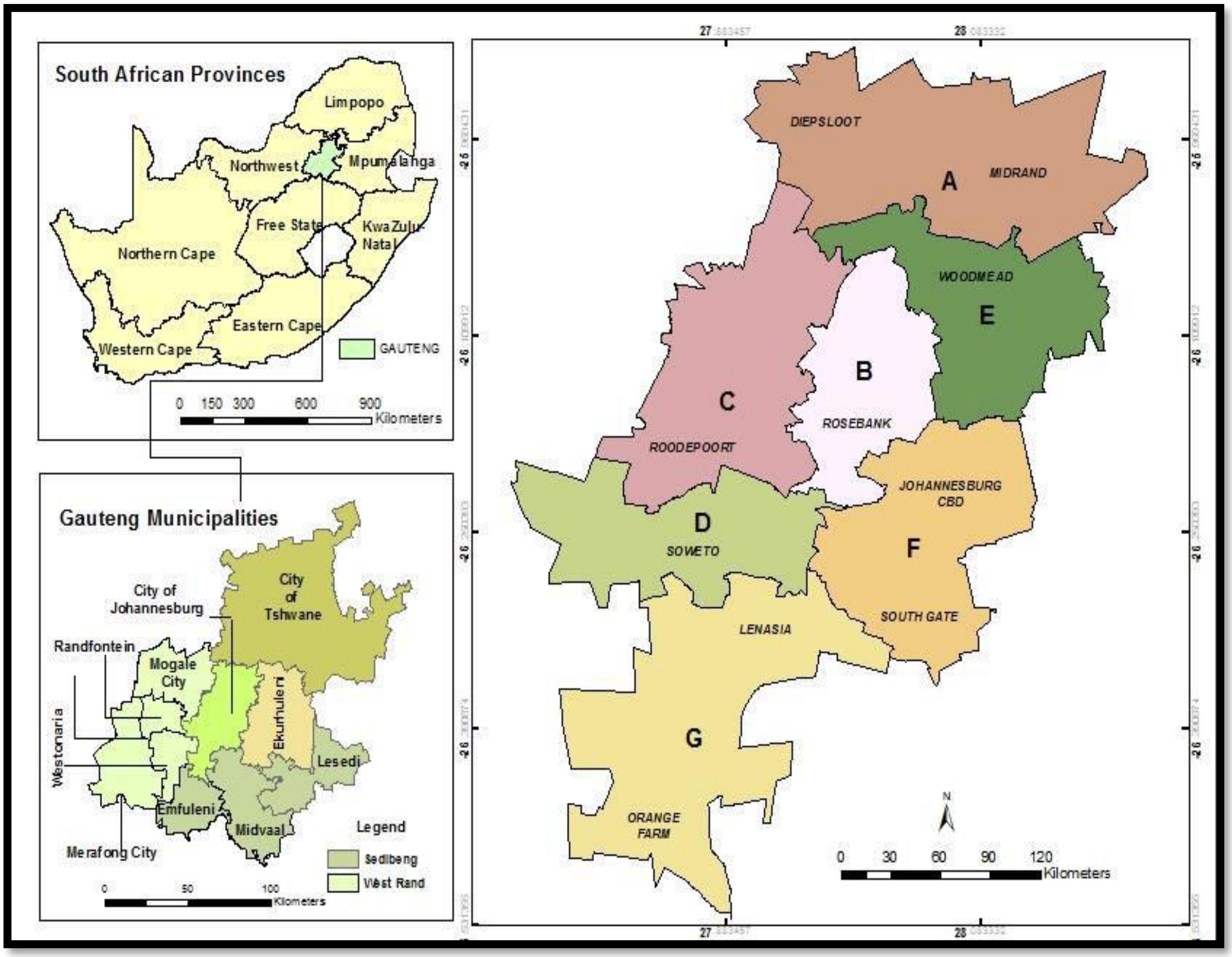


Figure 3-1: South African Provinces, Gauteng municipalities and administrative regions (Mabunda, 2021)

3.2 Climatic Conditions

Waterfall City falls within the summer rainfall zone, receiving annual rainfall ranging between 600 mm to 800 mm as shown in Figure 3-2 (Braun *et al.*, 2017; Mabunda, 2021). Waterfall City receives rainfall in the summer months and some occasional winter rains brought by frontal events. Precipitation is highest in the summer months with an average of 139mm per month, while winter experiences low to no rainfall at an average of 7mm around July. Rainfall in the summer months is often extremely intense, variable and accompanied by thunderstorms, lightning and hail (Mabunda, 2021). Rainfall-forming mechanisms in Waterfall City are associated with air masses moving from the northeast to the southeast that originates from the anticyclonic conditions of the Indian Ocean. The air masses rise as they pass over the Great Escarpment in Southern Africa moving towards Highveld, condensing, and resulting in thunderstorms in Johannesburg.

Waterfall City has an average annual temperature of 16.0 ^{0}C, with January being the hottest month at an average of 19.9 ^{0}C while June is the coldest month with the lowest average temperature of 10.0 ^{0}C (SAWS, no date). On the other hand, evaporation rates far exceed the precipitation rates in the study site and it is estimated that more than half of rainfall contributes to evapotranspiration (Jovanovic *et al.*, 2015; Mabunda, 2021).

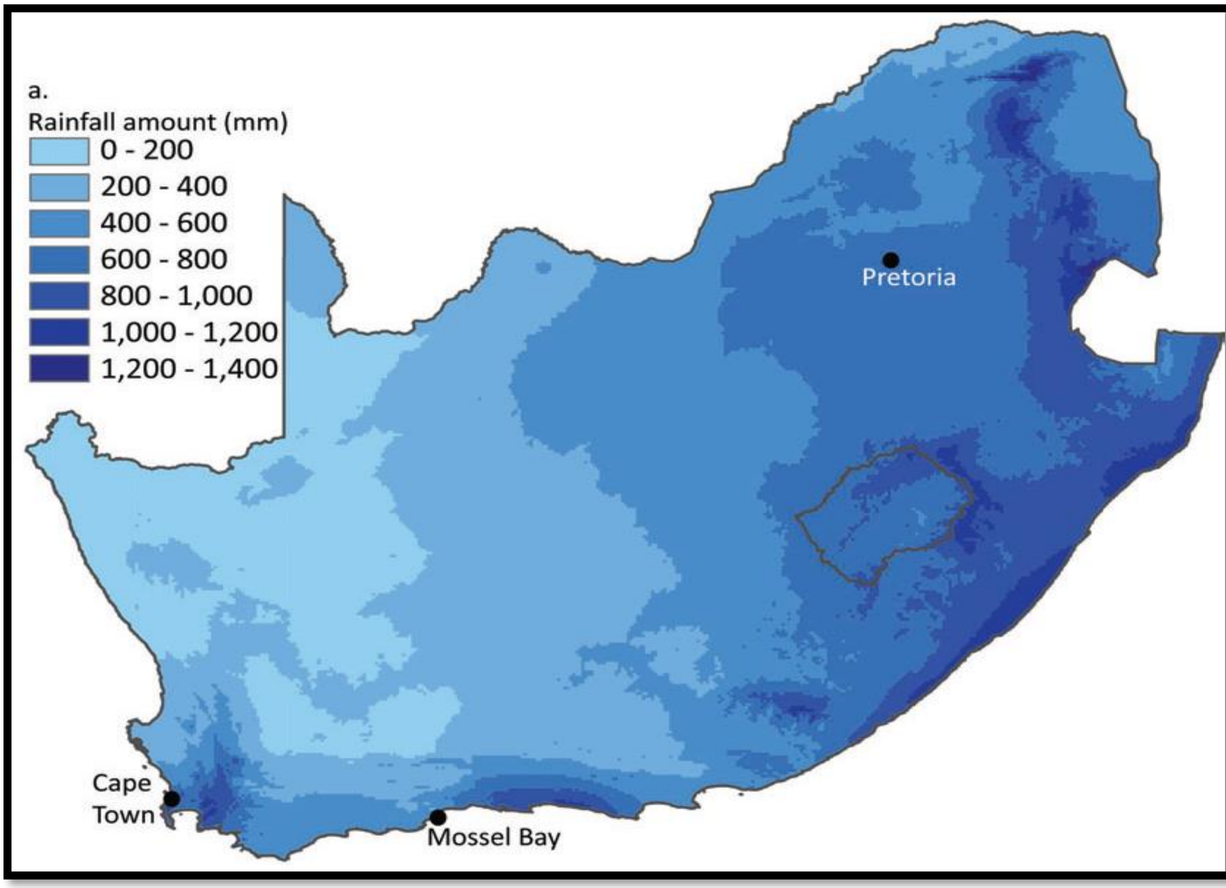


Figure 3-2: Annual rainfall map (Braun **et al.,** *2017)*

3.3 Geology

Johannesburg is made up of basement crystalline rocks of the Archean age which are mainly classified as meta-sedimentary, granitic and meta-volcanic rocks (Figure 3-3) (Abiye, 2011). Most of the granitic rocks are visible in the Granite Dome in the Midrand area (Abiye, 2011) while Halfway House Granite underlies Waterfall City (De Beer, 1986; Barnard et al., 2019).

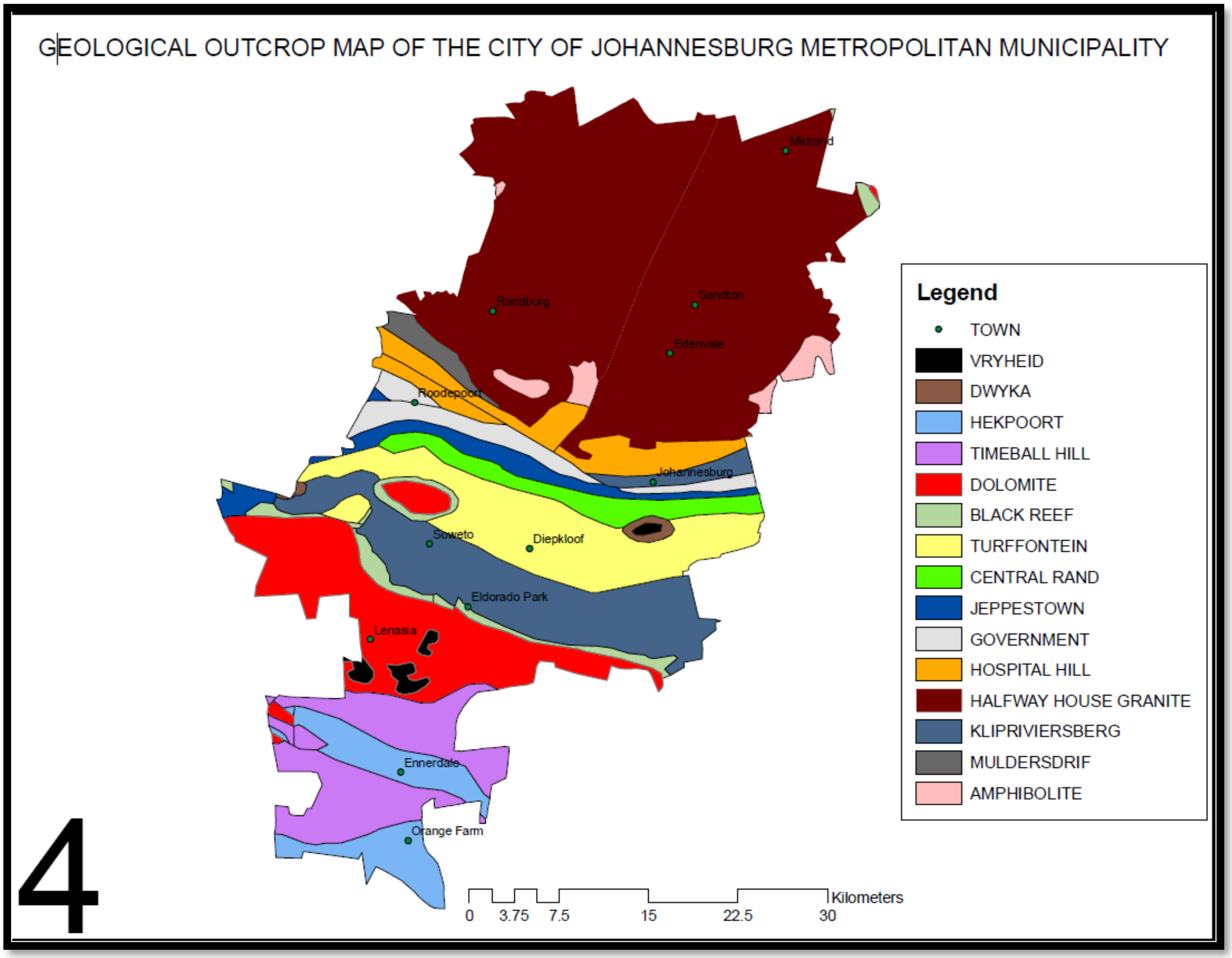


Figure 3-3: Geological map of the City of Johannesburg (Barnard et al., 2019)

3.4 Topography

Waterfall City catchment has a gently undulating topography between 1421m and 1513m (masl) (*Johannesburg topographic map, elevation, terrain*, 2001) which influences moderate stormwater runoff. Furthermore, Waterfall City is drained by the Jukskei River that follows in the westerly direction from the Central Business District of the City of Johannesburg.

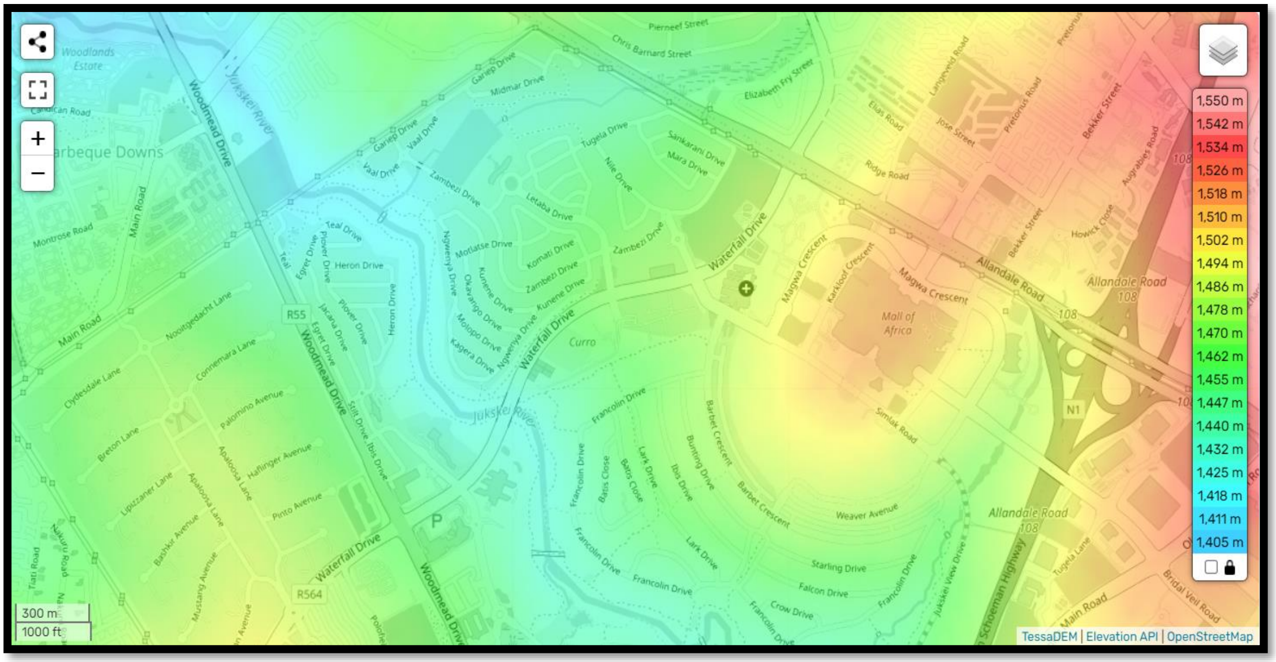


Figure 3-4: Waterfall topographical map (**Johannesburg topographic map, elevation, terrain*****, 2001)***

3.5 Land Cover, Vegetation and Land Use

Waterfall City land cover consists of agricultural land, bare land, forest, grasslands, urban areas, waterbodies, and wetlands (Dunsmore *et al.*, 2020). Land cover and land use are important factors determining human activities in certain areas, especially urban areas. The land cover and land use changes impact runoff volumes and peak discharges during storm events. Furthermore, De Roo *et al.* (2001) stated that the obvious effects of change in land cover and land use due to urbanisation are reductions in evapotranspiration, infiltration and an increase in surface runoff.

On the other hand, Waterfall City consist of Grassland Biome and some patches of Savanna Biome. The dense vegetation cover helps in reducing surface runoff flow velocity and facilitates in trapping of sediment particles (Olliver *et al.*, 2020).

4 Research Methodology

4.1 Introduction to Methodology

Research Question:

- What are the parameters that should be used when sizing sediment traps in the City of Johannesburg?

Approach to Methodology:

To answer the research question, the methodology started with the collection, analysis and preparation of design rainfall, 5-minute rainfall, daily rainfall, evaporation, digital elevation data, soil types and soil infiltration characteristics, impermeable and land cover data for use in the PCSWMM, ArcSWAT and Excel Spreadsheet modelling programs. The data was collected from Waterfall City within sub-catchments S22 and S23 during site visits and online data websites. Sub-catchments S22 and S23 found in Waterfall City form part of the already developed PCSWMM Model for the City of Johannesburg, See Figure 4-1. The City of Johannesburg Personal Computer Storm Water Management Model (PCSWMM) model developed by (Dunsmore et al, 2020) was used for modelling activity in the current study. The purpose of the PCSWMM modelling activity was to determine the change in the output peak flow and runoff volume due to variation of values of an input parameter, which would then indicate what parameters should be considered when sizing sediment traps in the City of Johannesburg. Furthermore, the sensitivity analysis was undertaken using various uncertain parameter values while observing flow rates and runoff volume changes in PCSWMM outputs. The uncertain parameters analysed in this study include infiltration rates and imperviousness. Moreover, the sensitivity analysis is to give the designer some insight into the system's response to variations in the values of uncertain parameters.

On the other hand, the soil samples were collected during the site visit. Thereafter, the particle size distribution of the collected soil samples was determined, as well as the particle settling velocity and time, which would inform the retention time and sediment trap storage capacity required to settle such sediments. Lastly, sediment yields from sub-catchments S22 and S23 were determined through the ArcSWAT modelling program. The sediment yield informs the storage capacity of sediment traps.

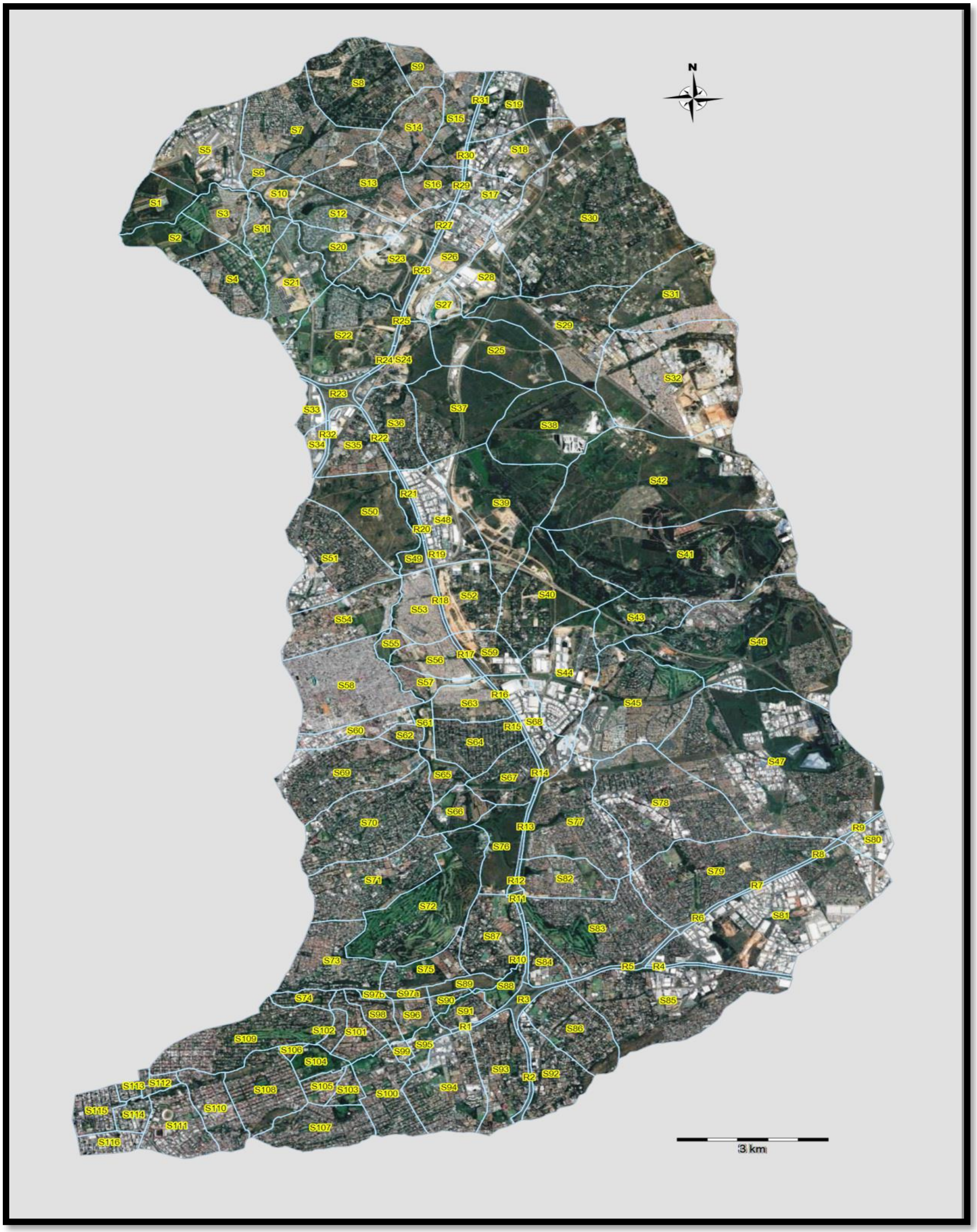


Figure 4-1: Sub-catchments layout (Dunsmore et al, 2020)

4.2 Description of Modelling Programs

PCSWMM

PCSWMM is a software developed by Computational Hydraulics International (CHI). It is based on the USEPA Storm Water Management Model (SWMM5). Moreover, in favour of using the PCSWMM modelling program in this study, it is a hydrological and hydraulic model used mostly in South Africa for the determination of peak flows, runoff volumes and flow hydrographs for urban stormwater system modelling. PCSWMM is widely used in South Africa which is evidenced by over 200 organisations that have registered for the software (Dunsmore *et al.*, 2020). Runoff in PCSWMM is calculated based on the catchment parameters impacting runoff such as slope, soil types, soil permeability, land use, land cover, urban and rural area percentage distributions, imperviousness, and curve number. The other function of PCSWMM that will be useful in this study is the sensitivity analysis and calibration tools that allow the comparison of output data in both graphical and numerical format for various values of input parameters.

ArcSWAT

The ArcSWAT ArcGIS extension is a graphical user interface based on the SWAT (Soil and Water Assessment Tool) model (Winchell *et al.*, 2013). The ArcSWAT interface can be added to function in QGIS and ArcGIS software. The SWAT model is defined as a river basin and catchment software program developed to predict the impacts of land management change practices, sediment, and agricultural chemicals on water resources. It is also described as a physically based model with computational efficiencies. It is a free and simple model that uses readily available data and can be used to predict long-term impacts on water resources. SWAT model was chosen in this study as it has a wide range of applications, such as the determination of sediment, nitrogen and phosphorus loading from various sources such as urban areas into water resources (Winchell *et al.*, 2013). The SWAT model can be applied to either single or several related hydrological catchments, whereby a bigger catchment is first divided into sub-catchments and further divided into hydrologic response units (HRU) in response to the land use and how soil is distributed in each sub-catchment.

Excel Spreadsheet Model

This is an Excel Spreadsheet model based on Ferguson and Church (2004) Equation for the determination of the particle settling velocity and sediment storage capacity based on the sediment particle size and settling time.

4.3 Data Collection, Analysis and Preparation

To carry out modelling activities, several datasets were collected, analysed and prepared for use in the PCSWMM, ArcSWAT and Excel Spreadsheet modelling programs.

The City of Johannesburg PCSWMM Model Calibration

Dunsmore et al, (2020) sourced flow records of the three gauging stations in the Jukskei River to facilitate the model calibration of the City of Johannesburg as shown in Figure 4-2. The current study attempted to obtain stream flow data from station A2H040 for calibration purposes, however, the stream flow data at this station ended in the 1990s. Due to a lack of recent stream flow data, the City of Johannesburg PCSWM model was not calibrated from its original set-up. It is argued that the absence of model calibration for this study will not affect the findings of this current study because the conclusions are based on the variations of input parameter values and the model peak flow and runoff volume outputs.

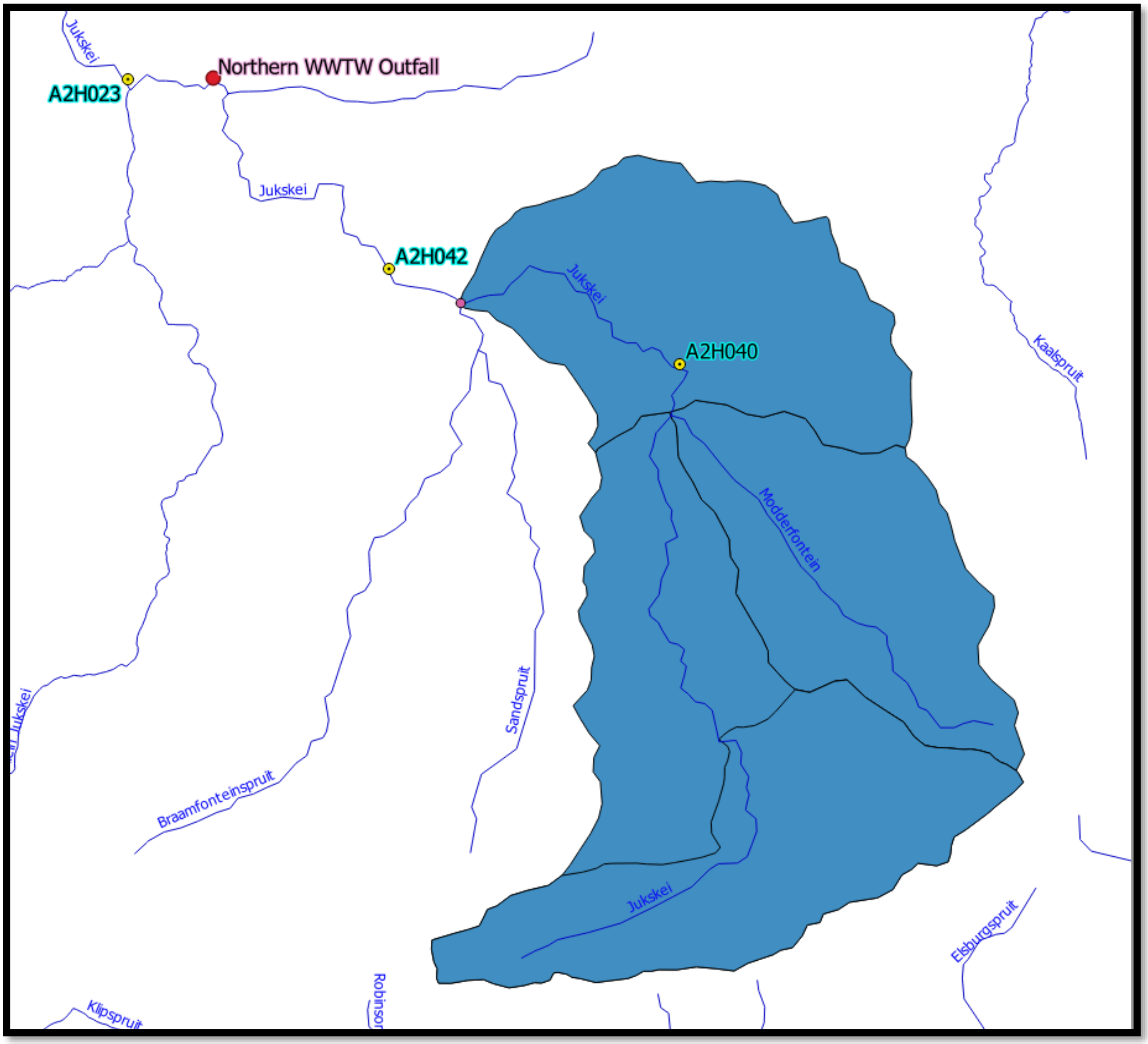


Figure 4-2: Department of Water and Sanitation flow gauging stations locations (Dunsmore et al, 2020)

4.3.1 PCSWMM Modelling Parameters

5-Minute Interval Rainfall

The study on Upper Jukskei Catchment Management Plan: Hydrological Model-Phase 1 Status Quo Model by (Dunsmore et al, 2020), identified the suitable South African Weather Stations for the City of Johannesburg. The stations which are close to Waterfall City are Leeukop and Grand Central as shown in Figure 4-3. The 5-minute rainfall data in the form of time series from Grand Central Station was provided by Fourth Element Consulting for the period 2003-2015 (Dunsmore et al., 2020).

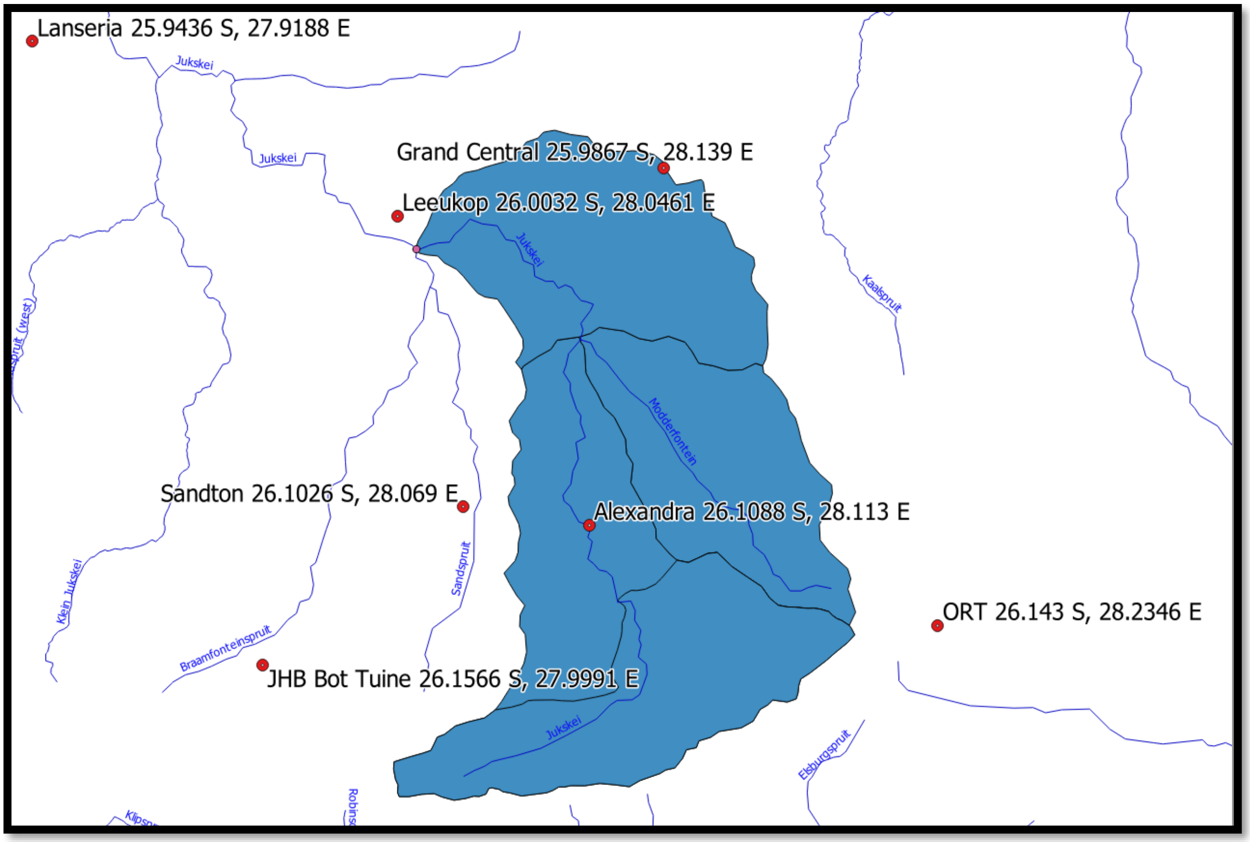


Figure 4-3: SAWS Weather station locations (Dunsmore et al. 2020)

Design Rainfall

Barnard *et al.*, (2019) recommended that design rainfall from Smithers and Schulze should be used for stormwater design in the City of Johannesburg. Furthermore, the Design Rainfall Estimation software is the recommended method for the determination of the point design rainfall in South Africa. The design rainfall depths for sub-catchments S22 and S23 in Waterfall City were obtained from the Design Rainfall Estimation software (Smithers and Schulze, 2003), shown in Figure 4-4. The software program enables the estimation of Depth Duration Frequency (DDF) for any given location within South Africa based on a statistical analysis of rainfall records for the six closest rainfall stations to the study site. The program caters for annual probabilities (frequencies) between 1:2-years, 1:5-years, 1:10-years, 1:20-years, 1:50-years, 1:100-years and 1:200-years return periods, for durations from 5 minutes to 7 days (SANRAL, 2013). To extract design rainfall data from Design Rainfall Estimation software, the coordinates or SAWS rainfall station number are used as the search method. In this current research, the centre coordinates of sub-catchments S22 and S23 were used to facilitate the search of the stations.

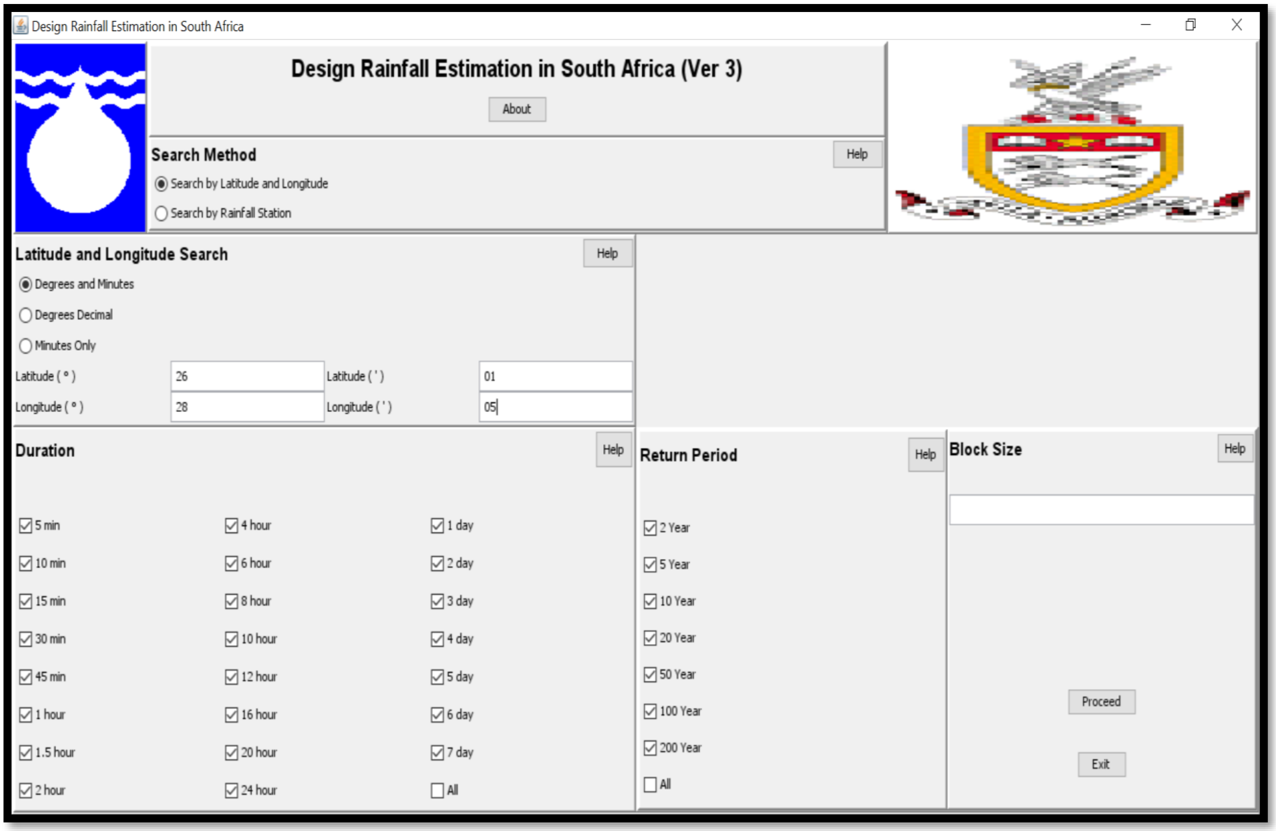


Figure 4-4: Design rainfall estimation software interface (Smithers and Schulze, 2003)

A summary of rainfall stations used in the calculation of design rainfall/storm depths for sub-catchments S22 and S23 in Waterfall City are shown in Table 4-1.

Table 4-1: Rainfall station used for generating rainfall DDF

Station Name	SAWS	Distance	Record	Lat	Long	MAP	Altitude
	Number	(km)	(Years)	(−) (')	(−) (')	(mm)	(m)
SPRINGKELL	0476246_W	4.0	76	26 6	28 8	700	1562
JHB-RIEPEN	0476067_W	5.7	53	26 6	28 3	705	1660
SANDTON (POL)	0476093_W	6.5	81	26 3	28 3	646	1440
JHB-CYDNA (PUR)	0476098_W	6.5	31	26 8	28 4	754	1605
JHB-WAVERLY	0476128_W	13.1	58	26 8	28 4	754	1620
JHB-ROYAL GOLF CLUB	0476160_W	7.2	64	26 9	28 6	762	1637

From the design rainfall Table 4-1, the 24-hour duration of rainfall for 1:2-year and 1:5-year return periods for both sub-catchments S22 and S23 in Waterfall City are 60.3mm and 83.2mm respectively.

Table 4-2: Depth duration frequency

Duration	Return Periods (Years)						
(m/h/d)	2	5	10	20	50	100	200
5 m	8.6	11.9	14.4	17	20.8	24.1	27.6
10 m	12.4	17.2	20.8	24.6	30.1	34.8	39.9
15 m	15.4	21.3	25.7	30.5	37.4	43.1	49.5
30 m	19.7	27.2	32.9	39	47.8	55.2	63.3
45 m	22.8	31.4	38	45	55.1	63.7	73.1
1 h	25.2	34.8	42.1	49.8	61.1	70.5	80.9
1.5 h	29.1	40.2	48.6	57.5	70.5	81.4	93.4
2 h	32.2	44.5	53.8	63.7	78.1	90.1	103.4
4 h	38.4	53	64	75.8	92.9	107.3	123.2
6 h	42.5	58.7	70.9	84	102.9	118.9	136.4
8 h	45.7	63.1	76.3	90.3	110.7	127.8	146.7
10 h	48.3	66.7	80.7	95.5	117.1	135.2	155.2
12 h	50.6	69.9	84.5	100	122.6	141.6	162.4
16 h	54.4	75.1	90.8	107.5	131.8	152.2	174.7
20 h	57.6	79.5	96.1	113.7	139.4	161	184.8
24 h	60.3	83.2	100.6	119.1	146	168.6	193.4
1 d	52.2	72.1	87.1	103.1	126.5	146.1	167.6
2 d	64.3	88.7	107.3	126.9	155.7	179.8	206.3
3 d	72.6	100.2	121.1	143.3	175.8	203	232.9
4 d	78.9	108.9	131.6	155.8	191	220.6	253.1
5 d	84.1	116.1	140.4	166.2	203.8	235.3	270
6 d	88.7	122.4	148	175.2	214.8	248.1	284.6
7 d	92.7	128	154.8	183.2	224.6	259.4	297.6

Monthly Evaporation

Monthly evaporation data in the form of evaporation percentages were obtained from the Water Resources of South Africa (WR2012) website (Bailey and Pitman, 2015). The information is obtainable from the quaternary catchments in the Water Resources of South Africa, 2012 Study (WR2012) website. Waterfall City falls within the Limpopo Water Management Area (WMA), which is part of the former Crocodile West and Marico (WMA 3), quaternary catchment A21C and Evaporation Zone (3A). The S-pan evaporation data WR2005 Mean Annual Evaporation (MAE) from quaternary data spreadsheets was recorded as 1700mm. To get mean monthly evaporation values from January to December, the MAE (1700mm) was divided by 100% and then multiplied by the set of percentage evaporation values in Zone (3A) assigned to every month in South Africa and enclosed in Appendix A.

The mean monthly evaporation is presented in Table 4-3. From the monthly evaporation results below, it is clear that potential evaporation values are high in the summer months and low in the winter months.

Table 4-3: Monthly evaporation

Month	MAE WR90 (mm)	Pan Coefficient (WR90) %	Mean Evaporation (mm/month)
October	1700	11,52	196
November	1700	11,54	196
December	1700	11,86	202
January	1700	11,2	190
February	1700	9,2	156
March	1700	8,5	145
April	1700	6,38	108
May	1700	5,07	86
June	1700	3,99	68
July	1700	4,62	79
August	1700	6,78	115
September	1700	9,34	159

Terrain Data (Digital Elevation Model)

In this research, the digital elevation data was obtained from the developers of the City of Johannesburg PCSWMM model (Dunsmore *et al.*, 2020), who got it from the City of Johannesburg Corporate GIS (City of Johannesburg Corporate GIS, no date). The digital elevation data was then analysed in ArcMap 10.7.1 where the slopes of sub-catchments S22 and S23 were determined using Spatial Analyst Tools. Moreover, the digital elevation data was used to facilitate the delineation of the sub-catchments S22 and S23 areas in PCSWMM. Sub-catchment S22 has a slope of around 3%, while S23's slope is around 5% as shown in Figure 4-5.

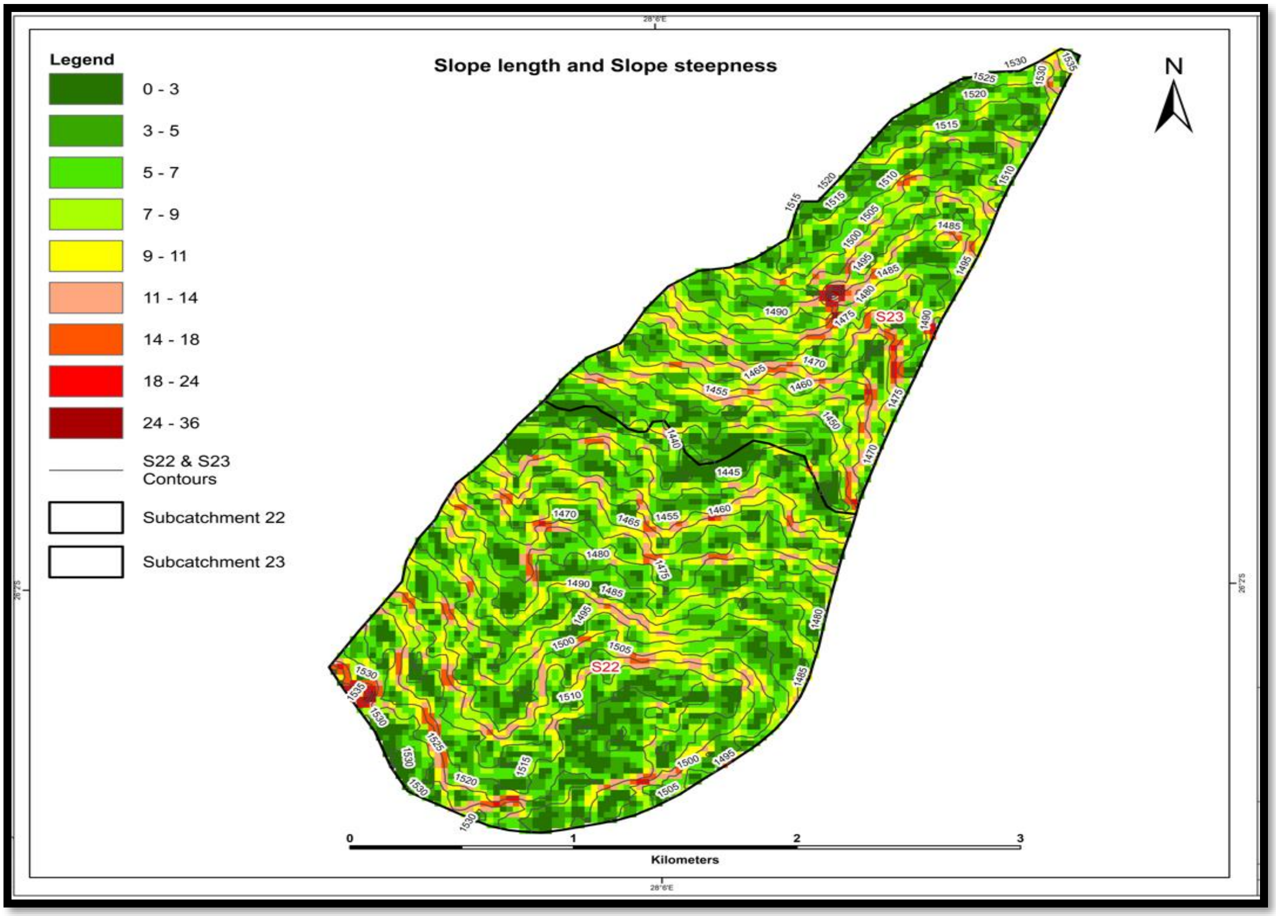


Figure 4-5: Slope in sub-catchments S22 and S23

Soil Types and Infiltration Characteristics

The soil infiltration parameters in sub-catchments S22 and S23 were previously determined by (Dunsmore *et al.*, 2020) using the Agricultural Research Council Institute for Soil, Climate and Water (ARC-ISCW, 2011) shown in Figure 4-6. The current study attempted to obtain updated soil data information for sub-catchments S22 and S23, however, that was not achieved due to a lack of recent data from the Agricultural Research Council Institute for Soil, Climate and Water. Table 4-4 shows that both sub-catchments S22 and S23 areas are composed of 56% Bb1 soils and 4% Bb2 soil types while Table 4-5 outlines the Green-Ampt Bb1 and Bb2 soil types parameters. On the other hand, the SCS hydrological soil groups were identified in this study for sub-catchments S22 and S23 using the SCS-SA Soil Groupings found in the SANRAL Manual (SANRAL, 2013). The soil for both sub-catchments S22 and S23 were identified as soil group B as shown in Figure 4-7. According to (SANRAL, 2013), soils in group B are associated with moderately low stormflow potential with moderate infiltration rates. Lastly, SANRAL (2013); Rossman & Huber (2016) have indicated that hydrologic soil group B has infiltration between 3.81mm/hr and 7.62mm/hr.

Figure 4-6: Sub-catchments S22 and S23 Soils

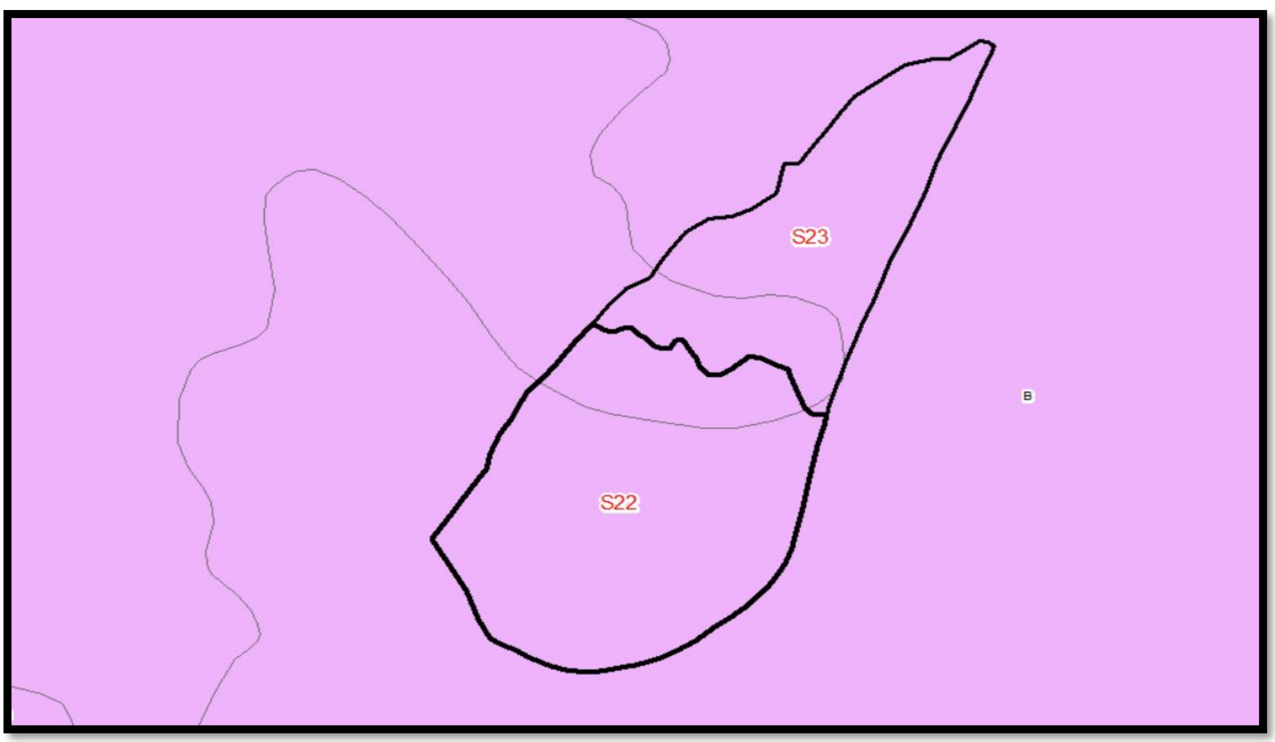


Figure 4-7: SCS-SA hydrological soil for sub-catchment S22 and S23

Table 4-4: Sub-catchment S22 and S23 soil types and characteristics (Dunsmore et al., 2020)

Soil type	% of catchment	Terrain unit	Depth (mm)	Horizon	Texture
Bb1	56	3	200-400	A	LmcoSa-SaLm
Bb2	4	3	200-400	A	LmcoSa-SaLm

Table 4-5: Green-Ampt parameters sub-catchments S22 and S23

Soil type	Suction head (mm)	Hydraulic conductivity (mm/hr)
Bb1 (sand and gravel)	85	20
Bb2 (sand)	85	20

Impermeable Areas and Land Cover

The data for determining the percentage of impervious areas for sub-catchments S22 and S23 was obtained from NASA's SEDAC global land survey impervious mapping project by De Colstoun *et al.* (2017). The data was downloaded from (http://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v1) and evaluated using zonal analysis in QGIS to determine the percent impermeability from each sub-catchment in the study area (Dunsmore et al., 2020). The Global Land Survey (GLS) from the Land satellites has global datasets at around 30m resolution to map global urbanisation. The dataset provides a fast and accurate measure of imperviousness in both catchments and sub-catchments. Furthermore, the Landsat spatial resolution is vital for accurately mapping urban features such as buildings, roads and parking lots (De Colstoun *et al.*, 2017). Figure 4-8 shows the percentage of impervious areas obtained from the NASA SEDAC global data set. The impervious percentage for sub-catchment S22 is around 12% while sub-catchment S23 is 15%. Moreover, the Department of Environmental Affairs website (https://egis.environment.gov.za/data_egis/accessed 15/04/2023) was visited to obtain the latest land cover data. However, there has been no updated land cover data since 2018, therefore the decision was made that the old land cover data which was used in the development of the City of Johannesburg PCSWMM model will be relied on in this study. It was observed that sub-catchment 22 is composed of grassland, forest, water bodies, bare surface, residential (formal), and recreational areas (urban). At the same time, sub-catchment 23 consists of grassland, bare surface, residential (formal), commercial and industrial, as shown in Figure 4-9. During the site visit on (23/09/2022) and (20/01/2023), it could be seen that both impervious and land cover have not changed much because of less development in both sub-catchments S22 and S23.

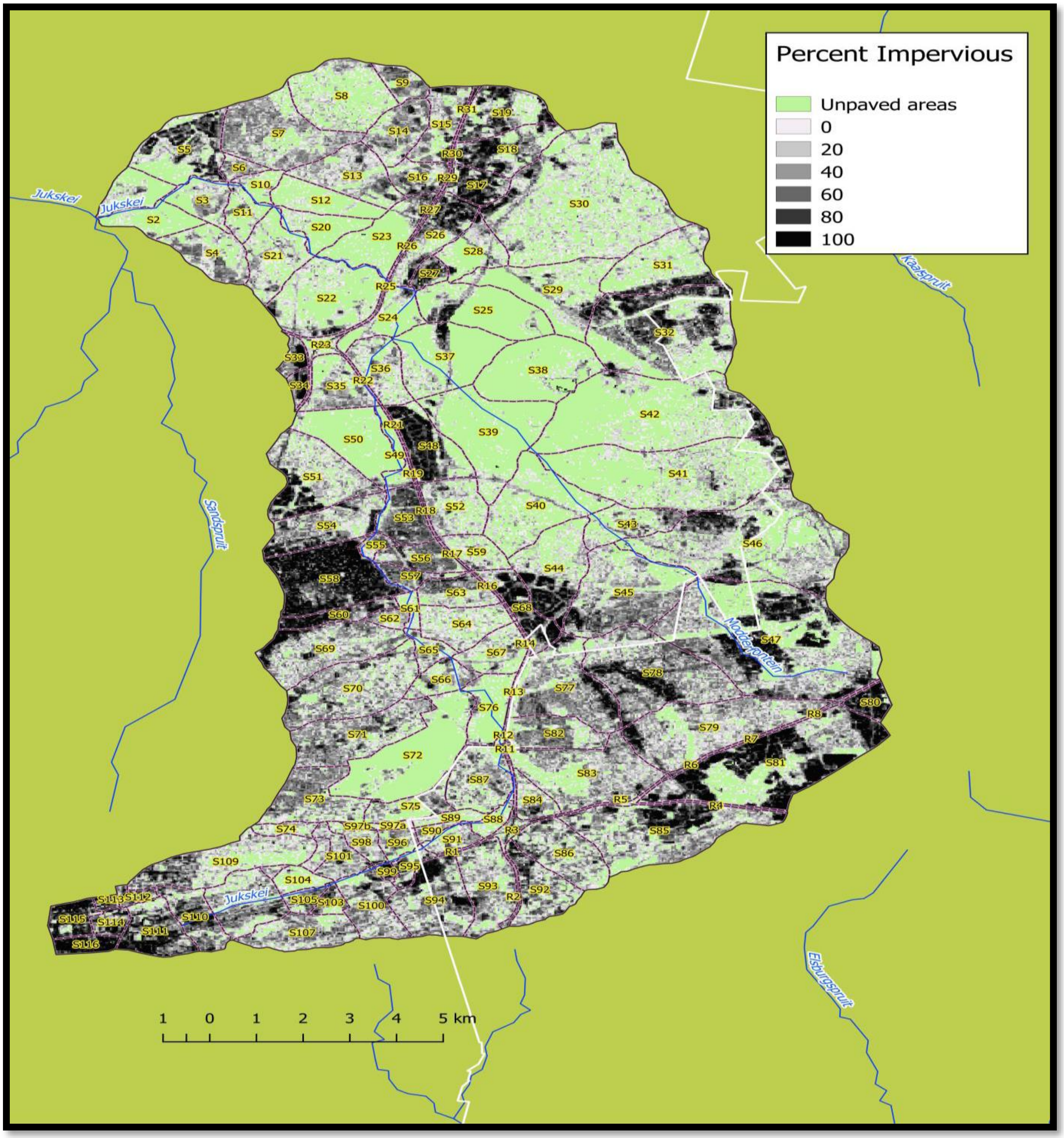


Figure 4-8: Impervious cover (Dunsmore et al., 2020)

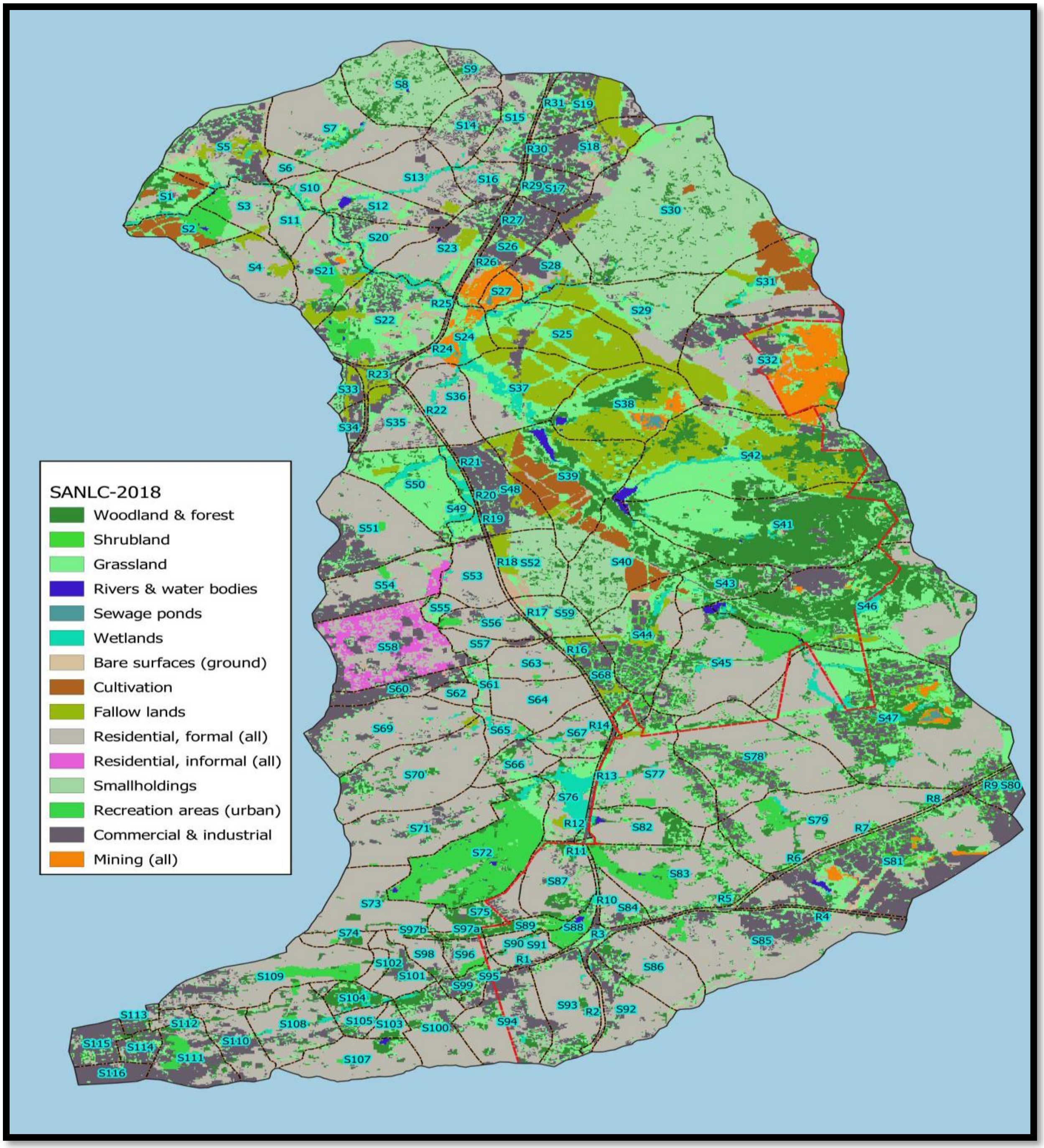


Figure 4-9: Sub-catchment land cover (Dunsmore et al., 2020)

4.3.1.1 PSCWMM Modelling Activity

Modelling Scenario 1:

- Sub-catchment S22 and S23: Design rainfall (RI 1:2yr), Green-Ampt
- Sub-catchment S22 and S23: Design rainfall (RI 1:5yr), Green-Ampt

The model input parameters are shown in Table 4-6. However, it should be noted that most of the input parameters from the City of Johannesburg PCSWMM model were left unchanged due to the lack of new data. Moreover, the input parameters were assumed to be correct from the previous model. Moreover, the new parameters that were used are listed in Table 4-7.

Table 4-6: PCSWMM input parameters

Parameters	Units	Sub-catchment 22	Sub-catchment 23
Rain Gage assigned to sub-catchment		G_Central-2003-2015	G_Central-2003-2015
Name of outlet		SU10	SU11
Area of sub-catchment	(ha)	362	220
Width of the overland flow path	(m)	1387	1086
Length of overland sheet flow	(m)	2609	2025
Average surface slope	(%)	3	5
Percent of impervious area	(%)	12	15
Manning’s N for impervious area		0.01	0.01
Manning’s N for the pervious area		0.1	0.1
Depth of depression storage on impervious area	(mm)	0.05	0.05
Depth of depression storage on pervious area	(mm)	0.05	0.05
Percent of the impervious area with no depression	(%)	25	25
Percent of runoff routed between sub-areas	(%)	100	100
Infiltration (soil capacity suction head)	(mm)	85	85
Infiltration (soil-saturated hydraulic conductivity)	(mm/hr)	20	20

Table 4-7: Updated parameters

Parameters	Units	Sub-catchment 22	Sub-catchment 23
Design Rainfall 1:2-year, 24-hours	mm	60.3	60.3
Design Rainfall 1:5-year, 24-hours	mm	83.2	83.2
Monthly evaporation	mm		
Soil infiltration rate	mm/h	3.8 and 7.6	3.8 and 7.6

4.3.1.2 Sensitivity Analysis

Modelling Scenario 2:

According to Rossman & Huber (2016) runoff volumes and peak flows are sensitive to surface runoff parameters such as imperviousness and infiltration rates. Hence in this study, the PCSWMM model was subjected to a sensitivity analysis using variation of infiltration rates and imperviousness values while observing the change in peak flows and runoff volumes at the outlets of sub-catchments S22 and S23. The imperviousness values used in the sensitivity analysis were chosen in such a way that they represent highly urbanised land use. Evaluation of the use of flood attenuation controls for the management of urban stormwater impacts in Cape Town study by (Hotchkiss, 2015) indicated that urban mixed land use can have as high as 85% imperviousness. On the other hand, the hydrologic soil group B having infiltration rates of 3.8mm/hr and 7.6mm/hr were used. The model was run by changing one parameter at a time while keeping other parameters constant.

The parameters used in the sensitivity analysis are shown in Table 4-8. Moreover, the modelling scenarios that were modelled are as follows:

- Test for the sensitivity of percentage imperviousness.
- Test for the sensitivity of infiltration rate.

Table 4-8: PCSWMM parameters for sensitivity analysis

Parameters	**Units**	**Sub-catchment 22**	**Sub-catchment 23**
Percent of impervious area	(%)	85	85
Infiltration rate (Horton)	(mm/hr)	3.8	3.8
Infiltration rate (Horton)	(mm/hr)	7.6	7.6

4.3.2 Excel Spreadsheet Modelling Parameters

Soil Sampling

Barnard *et al* (2019) stipulated that the design of stormwater management facilities for sediment management requires an understanding of site soils and geology. Hence, in this project, the geology of Waterfall City was reviewed to determine the gradings of soils derived from different rocks to get an idea of what gradings can be expected to be in the ponds. Apart from looking at the geology of Waterfall City, the researcher collected sediment samples from sub-catchments S22 sampling point 1 (26°1'52.68"S, 28°5'35.81"E) and sub-catchment S23 sampling point 2 (26°1'32.00" S, 28° 6'25.65" E) shown in Figure 4-10 for sediment particle size distribution determination and analysis. The sediment samples were dug using a shovel and collected in plastic bags. The samples were collected during a drier month (23/09/2022) and after rainfall events (20/01/2023). The samples during the drier months were collected from the inlet, middle and towards the outlet as the ponds were dry. On the contrary, after rainy months, the samples were only collected from the inlet and middle of the ponds because there was water towards the outlet and could not be reached for safety reasons. The samples were taken to the geotechnical laboratory at the University of the Witwatersrand for sediment particle size distribution and analysis.

Figure 4-10: Soil sampling points

Particle Size Distribution

According to Kroetsch and Wang (2008), the commonly used methods for finer particle size analysis are the pipette and hydrometer methods while coarser soil particle analysis is determined through sieve analysis. However, in this study, only the sieve analysis methodology was carried out. The decision to use the sieve analysis method only was informed by the literature on sediment analysis which showed that between 50-80% of sediment in urban stormwater runoff is composed of 0.125mm or larger sediment particle sizes (Department of Planning and Local Government, 2010). Moreover, in favour of the sieve analysis method, it is suitable for soil classification in engineering works. However, the sieve analysis method has some shortcomings; Day, (1965) and Kroetsch and Wang (2008) have indicated that the chances of a particle passing through the sieve openings at any given time of sieve shaking are dependent on the properties of the sieve, the number of particles of that size, and the nature of the particle. Furthermore, Gee and Or, (2002) stated that the particle shape and sieve-opening shape affect the probability of the particles passing through the sieve. For example, a particle's shape might allow its passing through the sieve in one orientation, and this limits the chances of such particles passing through the sieve except if the shaking of the sieve is for longer periods. To overcome this problem, Gee and Or (2002) have recommended that since the sieve openings have different sizes, longer periods of sieve shaking should be done to enable all particles to have a chance to go through the largest possible openings and a careful standardisation of procedure should be applied for methodology reproducibility

Sieve Analysis

Apparatus

1. Sieves and pan (20cm diameter). Recommended ASTM sieve sizes No. 4 (4.76mm), No. 10 (2.00mm), No. 40 (0.42mm), and No. 200 (0.074mm).
2. Sieve brush.
3. Basins (500mL).
4. Balance (capacity 1000g; sensitivity 0.1g).
5. Mortar and rubber-tipped pestle.
6. Sieve shaker.

Sieve Analysis Procedure

The soil samples collected during dry and wet seasons from sub-catchments S22 and S23 were combined to make one soil sample. The soil samples from the two sites were combined because they came from the same geological formation and are a result of granite weathering as shown in Figure 3-3. The particle size distribution was determined using (ASTM D422-63, 2007) methodology.

Sediment Settling Velocity and Retention Time

After the particle size distribution, the sediment settling velocity was determined using Ferguson and Church (2004) Equation 5:

$$\boldsymbol{V_s = \frac{gRd^2}{18v+(0.75CgRd^3)^{\frac{1}{2}}}} \quad (5)$$

Where:

Vs = terminal settling velocity of the solid particle

g = gravitational acceleration

R = specific gravity in water (1.65 for silica sand)

C = constant (0.4 for spheres, 1 for typical sand grains)

d = diameter of the particle

v = kinematic viscosity of the fluid

From the settling velocity calculated, the time required for a particle to fall through a given height was calculated by dividing an assumed 1m depth of settling zone by the settling velocity. The assumed 1m depth of a sediment trap was adopted from (CSIR, 2019) which has a typical design of a detention pond with a wet pool zone depth of 1.5m – 2.5m. The calculated settling time informs the retention time required to settle out the sediments with different diameters through sediment traps.

After determining the settling time of the range of particle sizes from sub-catchments S22 and S23, an Excel Spreadsheet Model was used to determine the required sediment trap storage capacity for settling those different soil particle sizes. The Excel Spreadsheet Model determines the storage capacity by multiplying the settling time of the different particles with the stormwater flow rate. The input parameters for the calculation of sediment trap capacity are shown in Table 4-9, where 0.075mm diameter soil particle, 13.570m^3/sec inflow and 7.485m^3/sec outflow rates were used as a calculation example.

Table 4-9: Sediment trap storage capacity calculation

	CALCULATION SHEET - CAPACITY REQUIREMENTS			
Minimum particle size to be settled out		=	0.075	mm
Residence Time Required		=	223	sec
Inflow rate		=	13.57	m^3/s
Outflow rate		=	7.485	m^3/s
Capacity Required		=	1669	m^3

4.3.3 ArcSWAT Modelling Parameters

Digital Elevation Model/Topography

The topography of the catchment plays an important role in soil erosion. This is evidenced by high erosion from steep slopes while valley bottom or flat slopes experience low soil erosion and they act as a trap for sediment (Pretorius, 2016). The geoprocessing tool in ArcMap 10.7.1 was used for clipping the study area extended from the DEM. The LS factor map was generated in ArcMap 10.7.1 following the (Gwapedza *et al.*, 2018) methodology. It was determined in the Section 4.3 that sub-catchment S22 has a slope of 3%, while sub-catchment S23 has 5% slope. It is believed that the use of a DEM in GIS improves LS estimated while the higher DEM resolution improves the accuracy (Gwapedza *et al.*, 2021).

Land Use and Soil Data

The land use and soil data used here were collected, analysed and prepared in Section 4.3.1.

Rainfall data

Daily rainfall data was obtained from the South African Weather Services Station (0476031_W) Leeukop (MUN) for the period 2000-2022. Leeukop (0476031_W) (MUN) Weather Station is located on the northwestern side of sub-catchments S22 and S23 as shown in Figure 4-3. The rainfall data was analysed and plotted in Excel as shown in Figure 4-11.

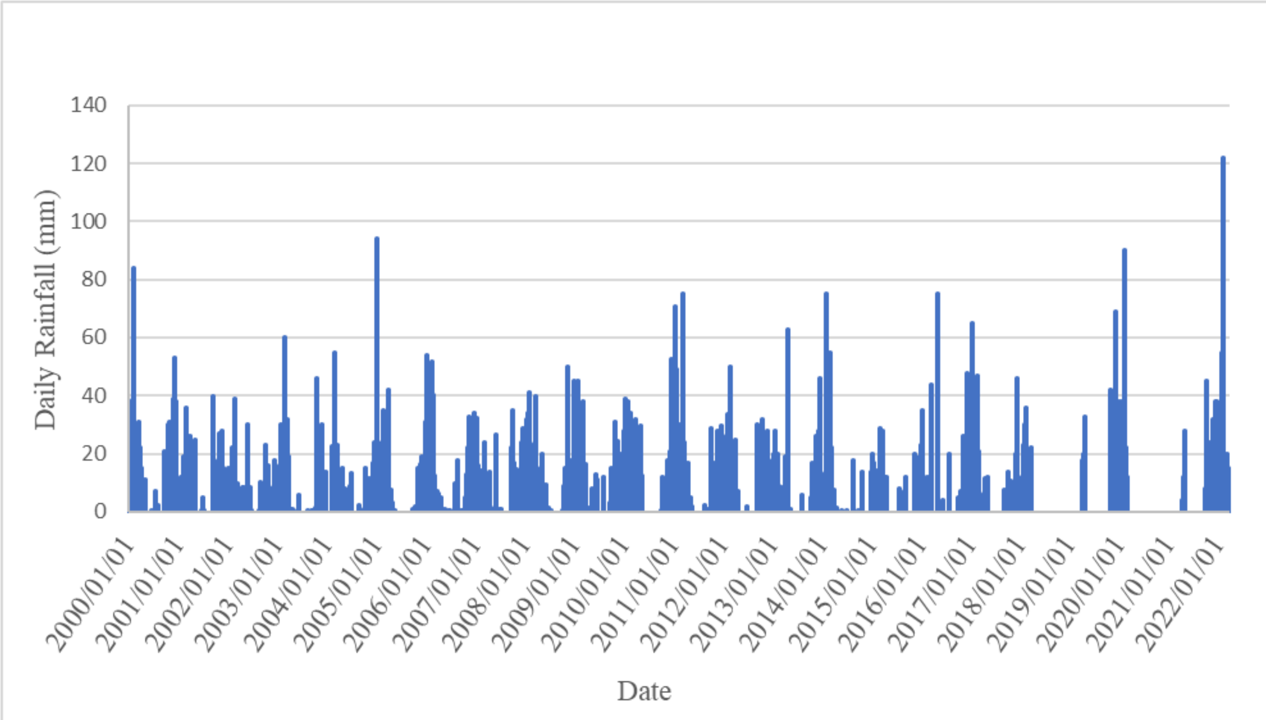


Figure 4-11: Leeukop daily rainfall analysis

4.3.3.1 ArcSWAT Modelling

The required ArcSWAT input datasets are the digital elevation model, land use, soil type, catchment slope and rainfall data. Rainfall and soil data were further filled into the ArcSWAT-based external spreadsheet database so it could be read by ArcSWAT. After the preparation of data, it was used in the Soil and Water Assessment Tool model (SWAT) (using ArcSWAT ArcGIS extension) in ArcMap 10.7.1 (Arnold *et al.*, 1998) for the determination of sediment yield from sub-catchments S22 and S23. ArcSWAT uses the Modified Universal Soil Loss (MUSLE) Equation 3 for the estimation of the sediment yield.

$$\boldsymbol{Y = 89.6(VQ_P)^{0.56}(K.LS.C.P)} \quad (3)$$

Where:

Y: Sediment yield per storm event (tonnes)

V: Runoff volume in a cubic meter

Q_P: Peak discharge in m^3/s

K: Soil erodibility factor

LS: Slope length and slope steepness factor

C: Cropping management factor

P: Erosion control practice factor

In this current research, the ArcSWAT ArcGIS extension was used to simulate sediment yield from sub-catchments S22 and S23 following the methodology/procedure by Winchell *et al.* (2013).

5 Results

5.1 PCSWMM Modelling Scenario 1

The results of modelling scenario 1 are shown in Table 5-1 and Table 5-2.

- Sub-catchment S22 and S23: Design rainfall of 5yr (83mm) and Green-Ampt infiltration method.

Table 5-1: Design rainfall of 5yr (83mm) and Green-Ampt infiltration method

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Total runoff volume from sub-catchments	(m^3*10^3)	41.5	32.7
Peak runoff rate from sub-catchments	m^3/sec	20	16.4

- Sub-catchment S22 and S23: Design rainfall of 2yr (60mm) and Green-Ampt infiltration method.

Table 5-2: Design rainfall of 2yr (60mm) and Green-Ampt infiltration method

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Total runoff volume from sub-catchments	(m^3*10^3)	24.6	18.9
Peak runoff rate from sub-catchments	m^3/sec	12.9	10.5

From Table 5-1 and Table 5-2 the following observations were noted:

- From both sub-catchments S22 and S23 an increase in recurrence interval from 2-year to 5-year, increased peak flows and runoff volumes as indicated in Figure 5-1 and Figure 5-2.

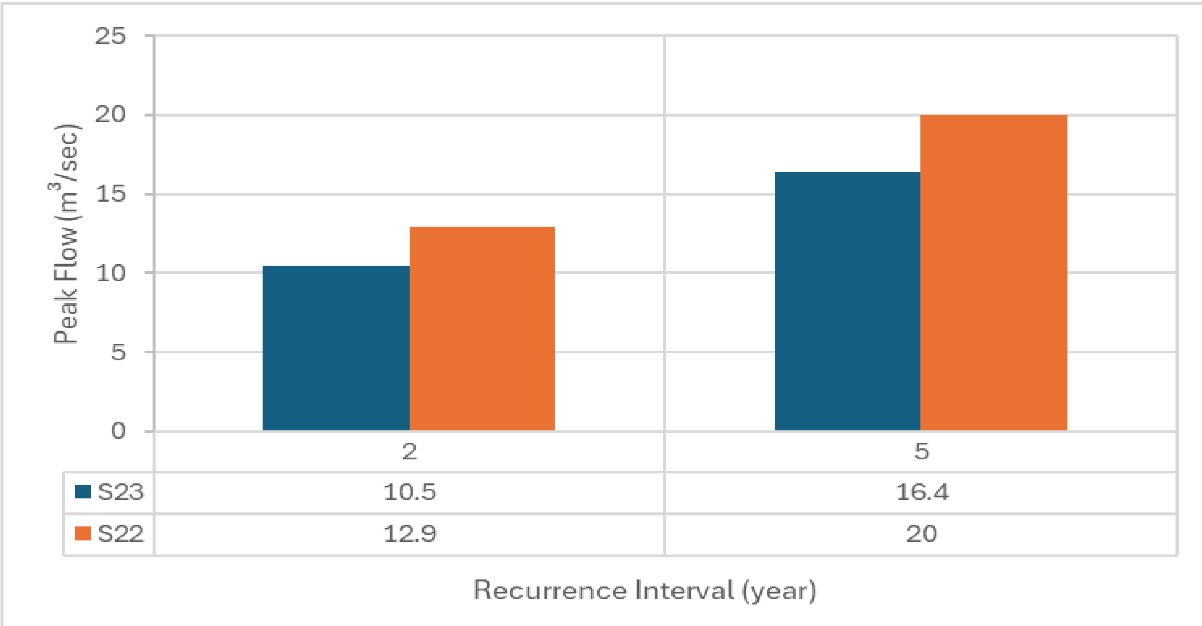


Figure 5-1: Recurrence interval vs peak flows

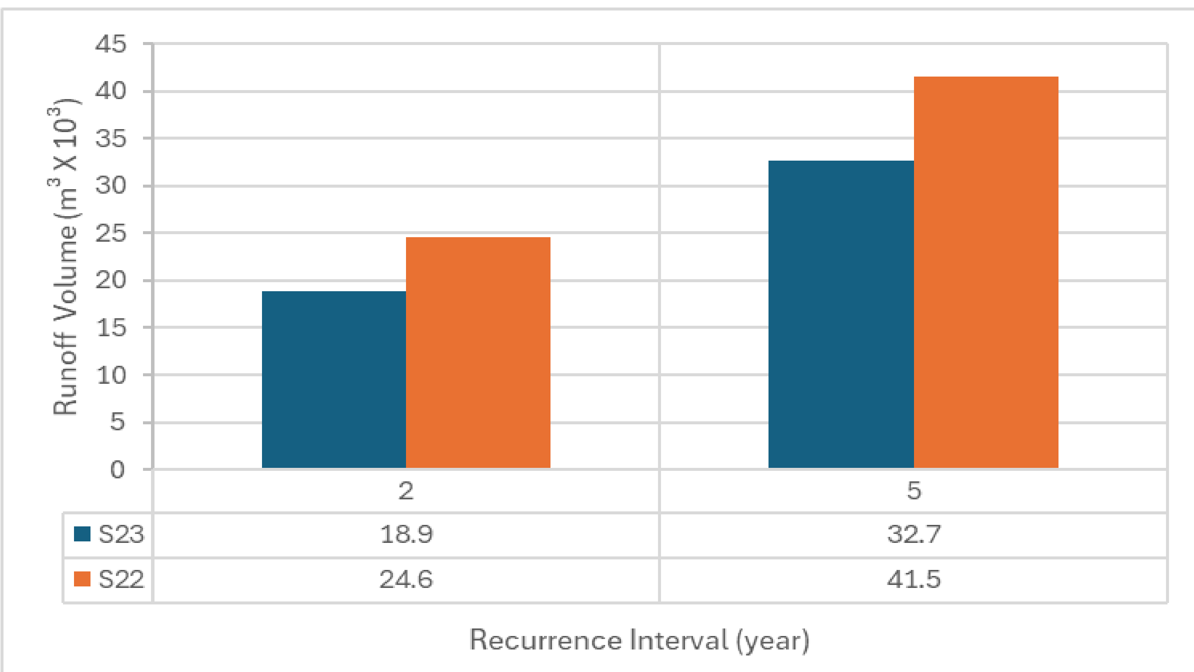


Figure 5-2: Recurrence interval vs Runoff volumes

5.2 PCSWMM Modelling Scenario 2

The results of the sensitivity analysis are shown in Table 5-3 and Table 5-4.

- Test for the sensitivity of 85% imperviousness from sub-catchments S22 and S23. The model was run with design rainfall of 5yr (83mm) and the Green-Ampt infiltration method.

Table 5-3: 85 % impervious area for 5yr RI in sub-catchments 22 and 23

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Total runoff volume from the sub-catchment	$(m^3 * 10^3)$	240.1	147.2
Peak runoff rate from the sub-catchment	m^3/sec	69.3	50.4

- Test for the sensitivity of 85% imperviousness from sub-catchments S22 and S23. The model was run with design rainfall of 2yr (60mm) and the Green-Ampt infiltration method.

Table 5-4: 85 % impervious area for 2yr RI in sub-catchments 22 and 23

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Total runoff volume from the sub-catchment	$(m^3 * 10^3)$	165.8	101.4
Peak runoff rate from the sub-catchment	m^3/sec	44.5	33.1

From Figure 5-3, Figure 5-4, Figure 5-5 and Figure 5-6, Figure 5-7, Figure 5-8, Figure 5-9, Figure 5-10 it is evident that runoff volumes and peak flows have increased when compared to the initial modelling of sub-catchments S22 and S23, which had 12% and 15% impervious areas respectively.

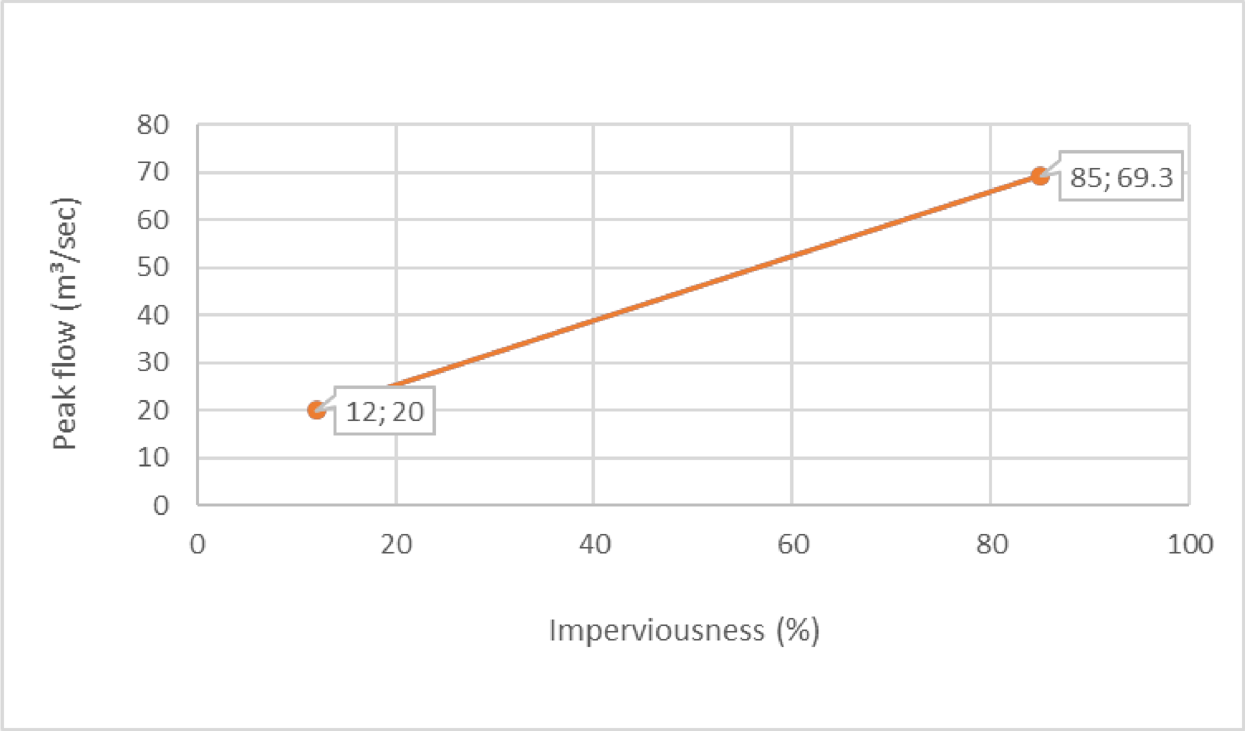


Figure 5-3: 12% and 85% impervious area vs peak flows from 5yr RI for sub-catchments 22

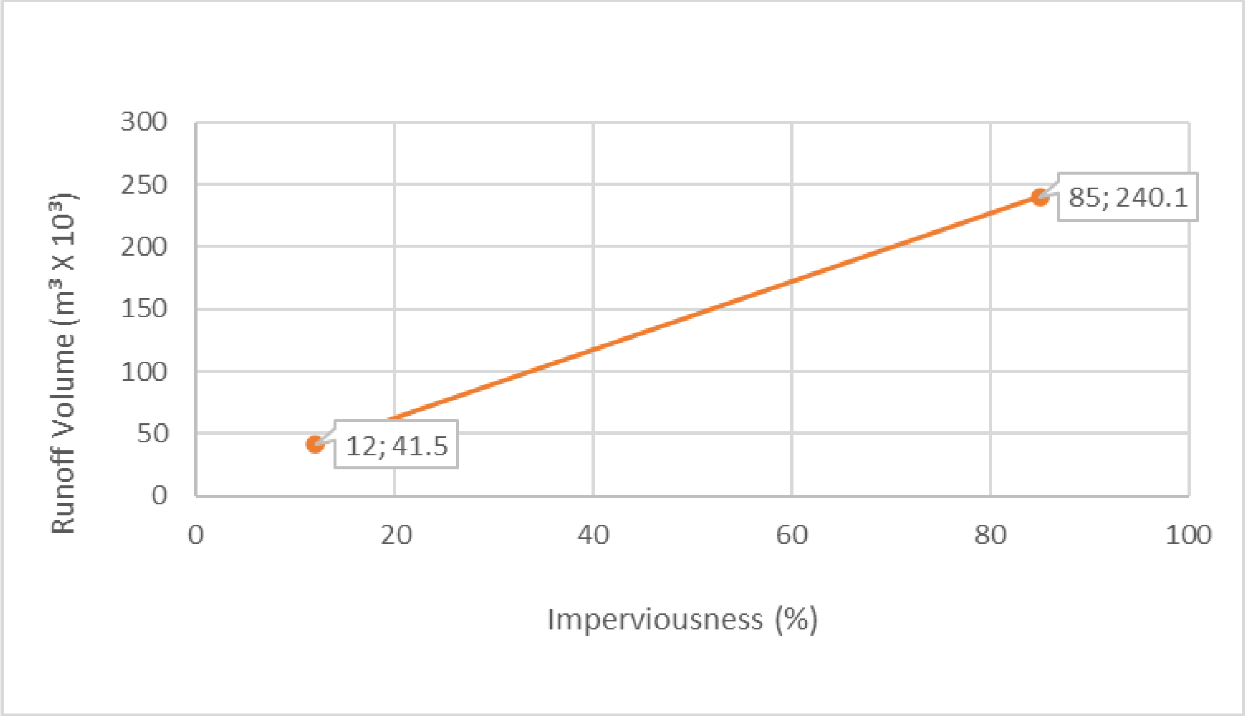


Figure 5-4: 12% and 85% impervious area vs runoff volumes from 5yr RI for sub-catchments 22

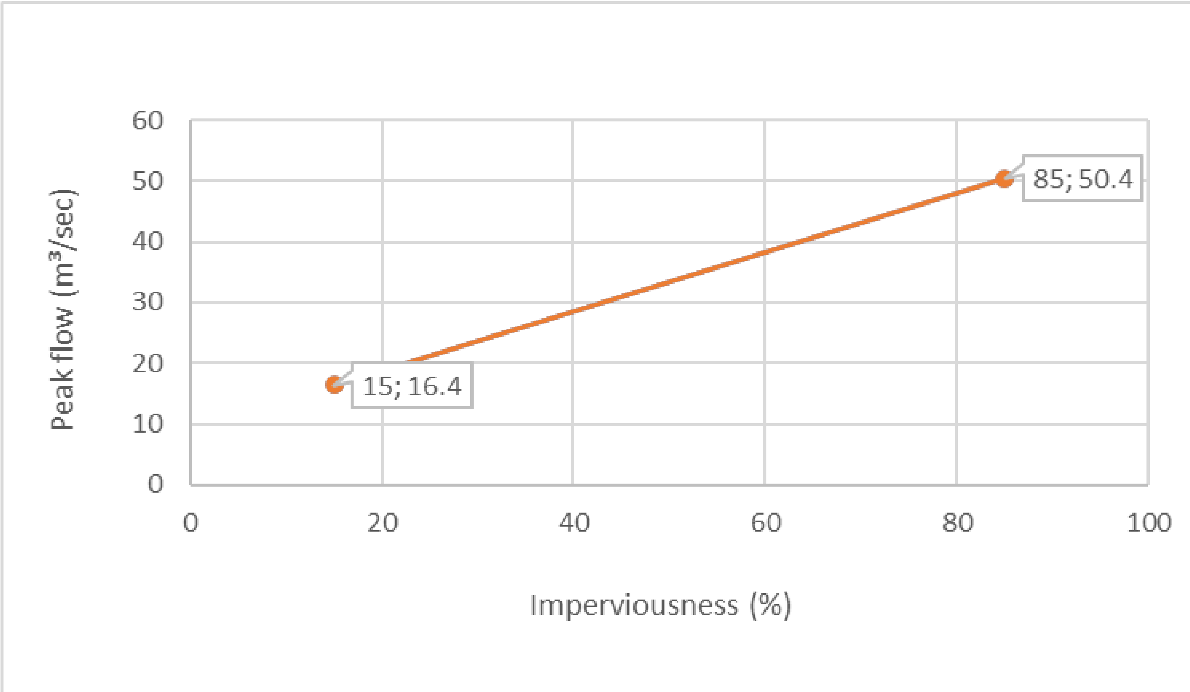


Figure 5-5: 15% and 85% impervious area vs peak flows from 5yr RI for sub-catchments 23

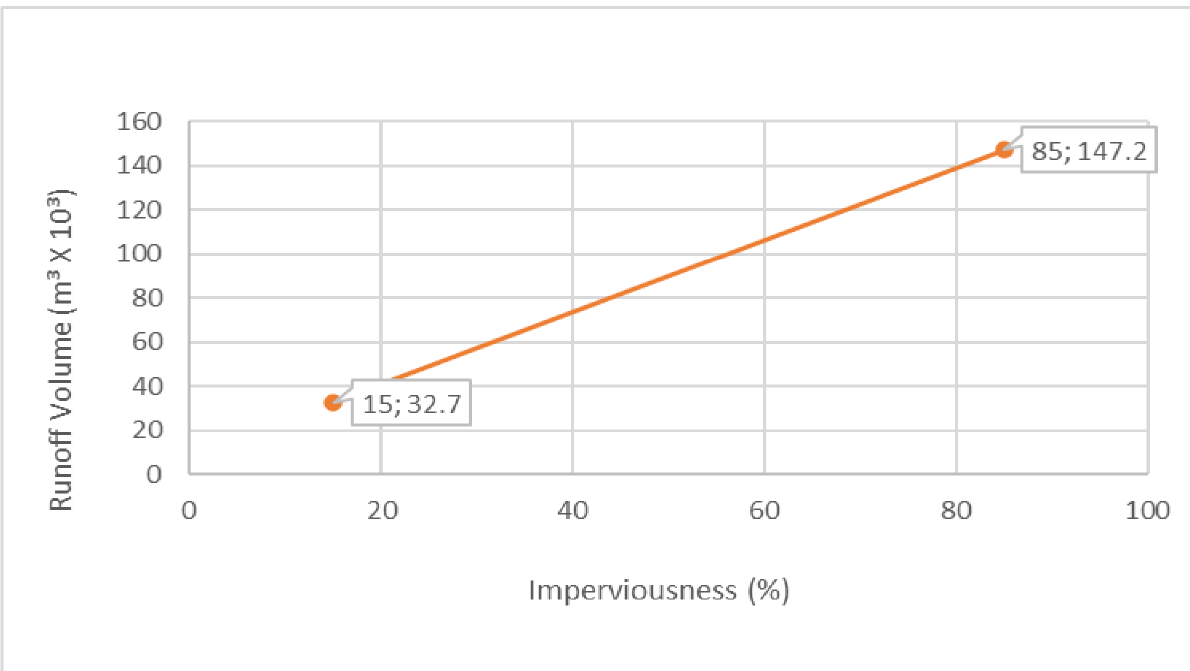


Figure 5-6: 15% and 85% impervious area vs runoff volumes from 5yr RI for sub-catchments 23

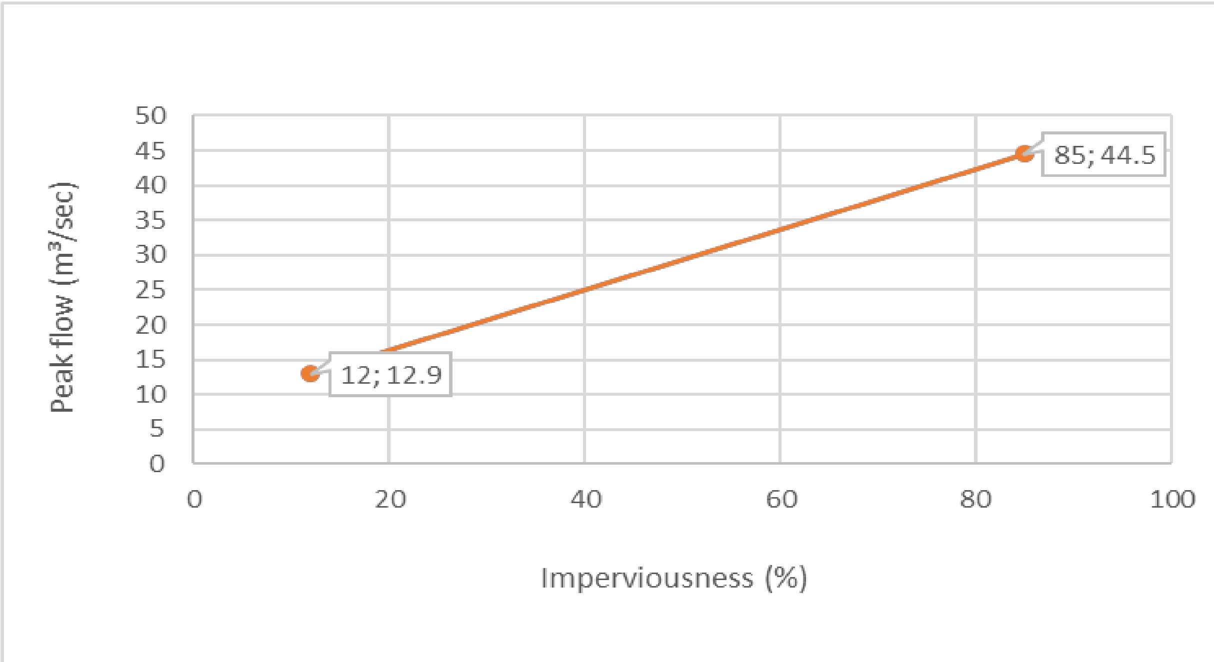


Figure 5-7: 12% and 85% impervious area vs peak flows from 2yr RI for sub-catchments 22

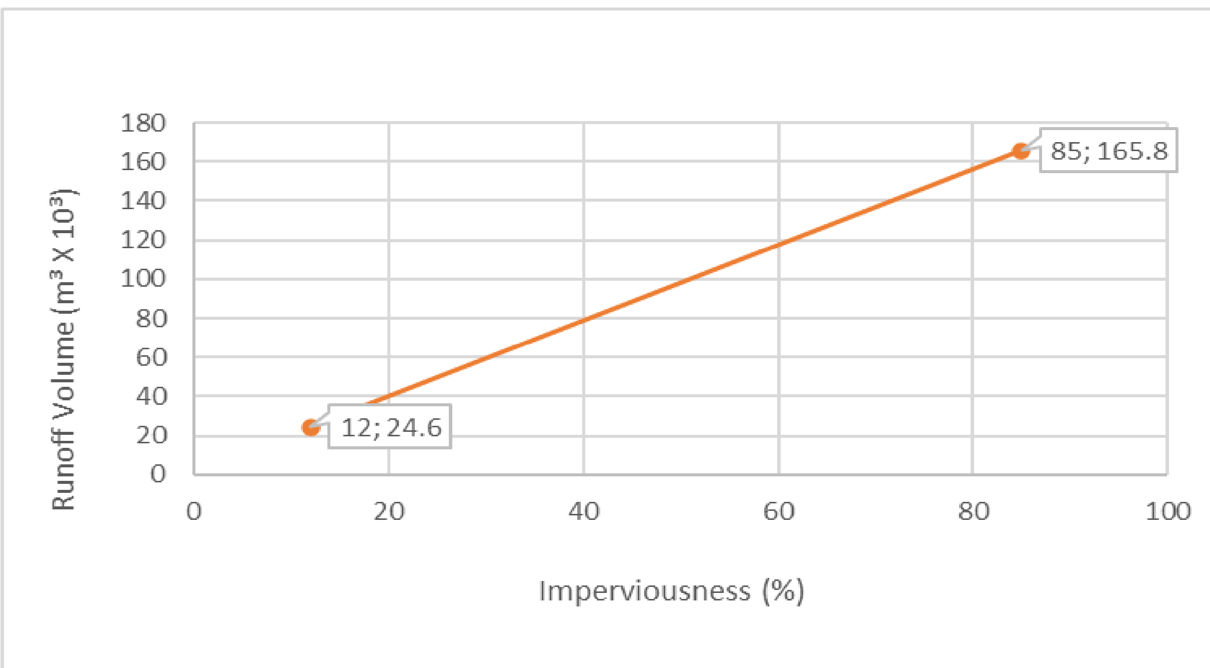


Figure 5-8: 12% and 85% impervious area vs runoff volumes from 2yr RI for sub-catchments 22

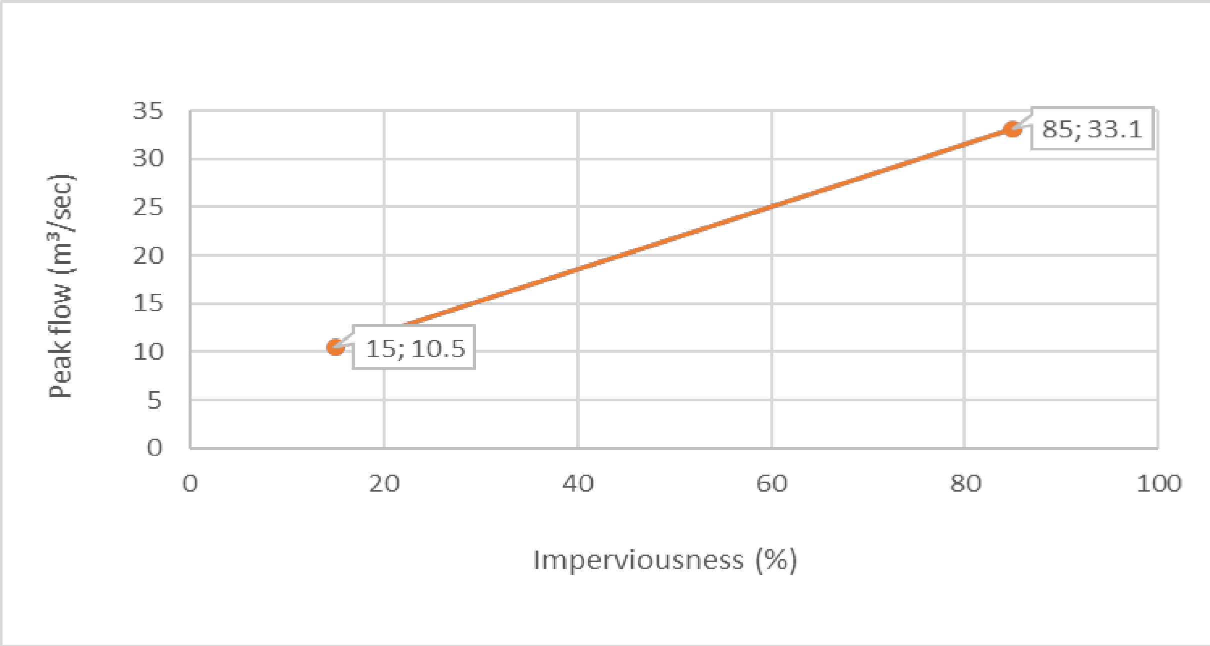


Figure 5-9: 15% and 85% impervious area vs peak flows from 2yr RI for sub-catchments 23

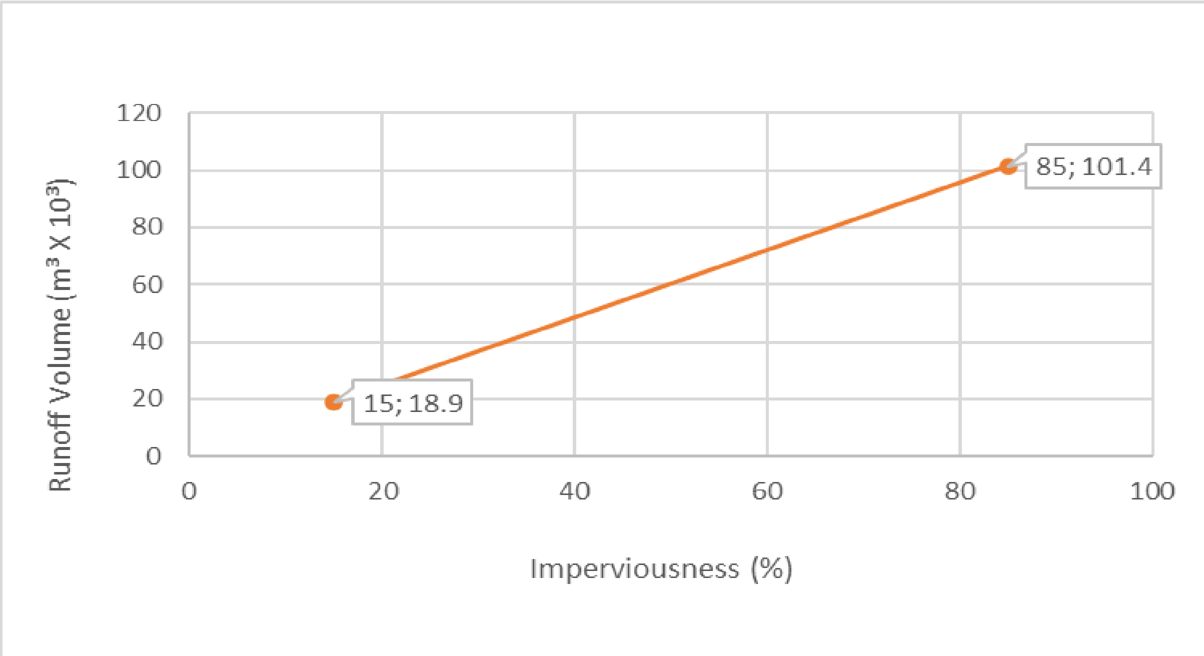


Figure 5-10: 15% and 85% impervious area vs runoff volumes from 2yr RI for sub-catchments 23

- Test for the sensitivity of infiltration rate.

The sensitivity modelling was carried out using the hydrologic soil group B having infiltration rates of 3.8mm/hr and 7.6mm/hr for sub-catchments S22 and S23. The model was run with design rainfall of 2yr (60mm), 5yr (83mm) and the Horton infiltration method.

From Table 5-5,Table 5-6,Table 5-7 and Table 5-8, it can be seen that the infiltration rates of 3.8 mm/hr and 7.6 mm/hr for sub-catchments S22 and S23 gave the same peak flows and runoff volumes.

- Test for the sensitivity of 3.8mm/hr infiltration rate in sub-catchments S22 and S23. The model was run with design rainfall of 5yr (83mm) and Horton infiltration method.

Table 5-5: 3.8 mm/hr soil infiltration rate for 5yr RI in sub-catchments 22 and 23

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Total runoff volume from the sub-catchment	(m^3*10^3)	229.2	145
Peak runoff rate from the sub-catchment	m^3/sec	28.6	24.4

- Test for the sensitivity of 7.6mm/hr infiltration rate in sub-catchments S22 and S23. The model was run with design rainfall of 5yr (83mm) and Horton infiltration method.

Table 5-6: 7.6 mm/hr soil infiltration rate for 5yr RI in sub-catchments 22 and 23

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Total runoff volume from the sub-catchment	(m^3*10^3)	229.2	145
Peak runoff rate from the sub-catchment	m^3/sec	28.6	24.4

- Test for the sensitivity of 3.8mm/hr infiltration rate in sub-catchments S22 and S23. The model was run with design rainfall of 2yr (60mm) and Horton infiltration method.

Table 5-7: 3.8 mm/hr soil infiltration rate for 2yr RI in sub-catchments 22 and 23

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Total runoff volume from the sub-catchment	(m^3*10^3)	151.8	97.6
Peak runoff rate from the sub-catchment	m^3/sec	18.4	15.8

- Test for the sensitivity of 7.6mm/hr infiltration rate in sub-catchments S22 and S23. The model was run with design rainfall of 2yr (60mm) and Horton infiltration method.

Table 5-8: 7.6 mm/hr soil infiltration rate for 2yr RI in sub-catchments 22 and 23

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Total runoff volume from the sub-catchment	$(m^3 * 10^3)$	151.8	97.6
Peak runoff rate from the sub-catchment	m^3/sec	18.4	15.8

5.2.1 Summary of PCSWMM Modelling

- An increase in recurrence interval from 2yr to 5yr, increased peak flows and runoff volumes.
- From the sensitivity analysis in PCSWMM, it is evident that as impervious areas percentage cover increases from 12%, 15%, and 85%, this increased peak flows and runoff volumes from sub-catchments S22 and S23.
- The infiltration rates of 3.8mm/hr and 7.6mm/hr for sub-catchments S22 resulted in similar values of peak flows and runoff volumes. The same trend of similar values of peak flows and runoff volumes is observed using infiltration rates of 3.8mm/hr and 7.6mm/hr for sub-catchments S23.

5.3 Sediments

Table 5-9 shows sieve analysis results of the soil samples from sub-catchments S22 and S23. The results in Table 5-9 show that the soil sample consists of 8.34% silt, 77.8% sand and 7.4% gravel. The soil sample also contains 6.42% of soil particles that passed sieve 200 and collected in the pan. On the other hand, Figure 5-11 shows the particle size distribution curve. From the particle size distribution curve, it is clear that soil samples from sub-catchments S22 and S23 are poorly graded, having only fine, medium and coarse sand soil particles.

Table 5-9: Sieve analysis

Sieve Number	Soil Type	Sieve Opening (mm)	Mass of Sieve (g)	Mass of sieve + soil (g)	Mass of soil retained on each sieve (g)	Percent of Soil Retained On each sieve (%)	Percent Finer (%) Passing
4	Gravel	4.75	451.5	472.9	21.4	4.28	95.72
10	Gravel	2.36	417.7	433.3	15.6	3.12	92.60
20	Sand	0.850	429.3	559.2	129.9	25.98	66.62
40	Sand	0.425	333.6	482.2	148.6	29.72	36.90
60	Sand	0.300	328.0	374.2	46.2	9.24	27.66
100	Sand	0.150	471.5	535.8	64.3	12.86	14.80
200	Silt	0.075	495.1	536.8	41.7	8.34	6.46
Pan					32.1	6.42	
Total soil mass (g)					499.8		

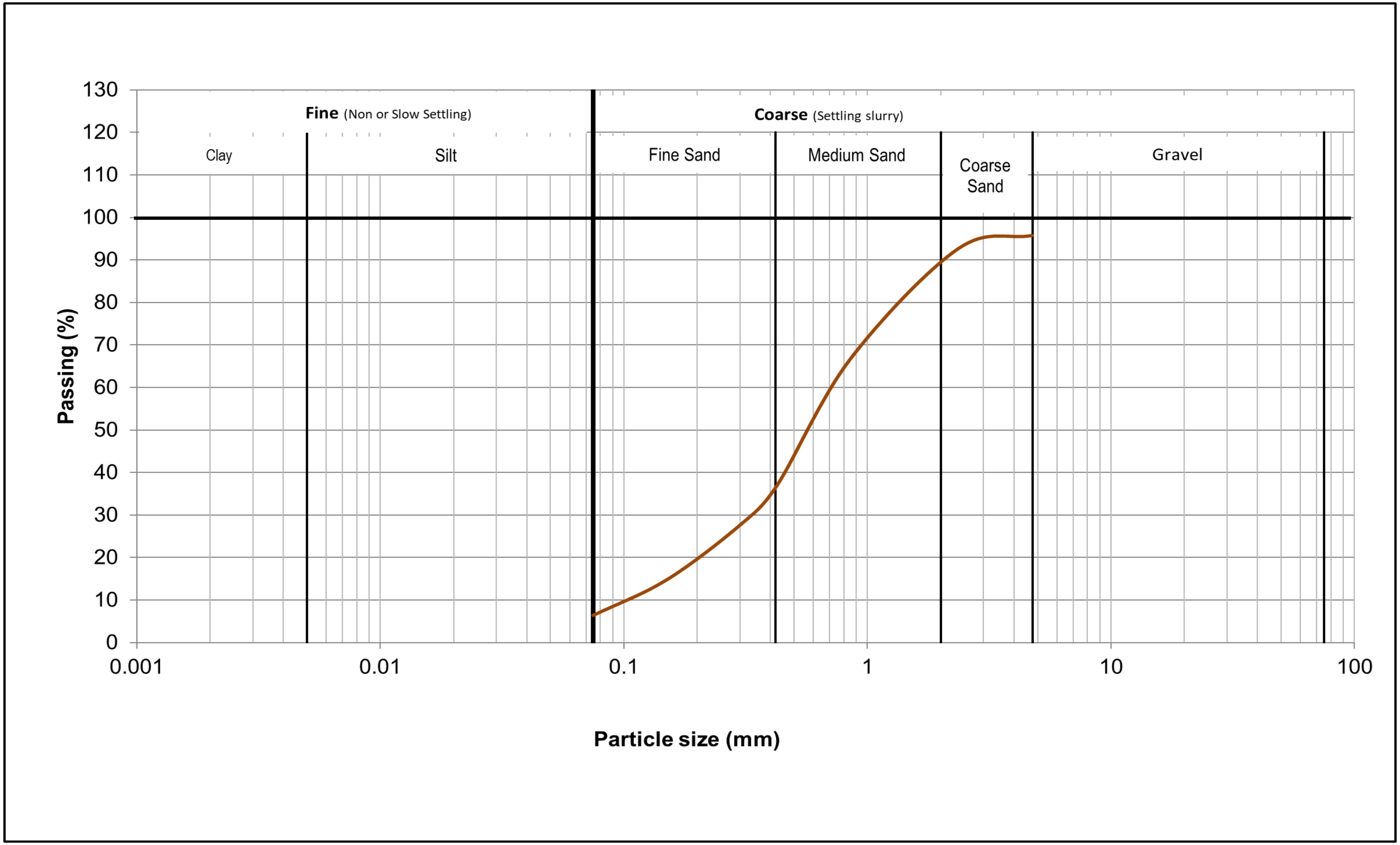


Figure 5-11: Particle size distribution of soil samples from sub-catchments S22 and S23

5.4 Settling Time

After determining the particle size distribution of the soils from sub-catchments S22 and S23, the particle settling velocity and settling time were then determined as shown in Table 5-10. Larger-diameter and denser soil particles (gravel) fall faster than less dense and smaller-diameter soil particles (silt).

Table 5-10: Fall velocity and settling time

	INPUT SHEET - SEDIMENTATION				
Gravity, g		9.81	m/s^2		
Specific Gravity in water, R		1.65			
Constant, C =		1			
Kinematic viscosity of water, ν		1.00E-06	m^2/s		
Dynamic viscosity of water, μ		0.001	N.s/m^2		
	CALCULATION SHEET - SETTLING TIME				
	Particle Size	Depth	Ferguson & Church	Depth	Settling
			Falling velocity	Settling Zone	Time
	(mm)	m	m/s	m	(sec)
Gravel	4.75		3.15E-01	1	3
	2.36		2.16E-01	1	5
Sand					
	0.85		1.12E-01	1	9
	0.425	1	6.02E-02	1	17
	0.3	1	4.03E-02	1	25
	0.15	1	1.49E-02	1	67
Silt	0.075	1	4.49E-03	1	223

The results of the sediment particle size and storage capacity are shown in Table 5-11 and plotted in Figure 5-12. Large sediment trap storage capacities are required for the sedimentation of less dense and smaller-diameter soil particles (silt) while denser and large-diameter soil particles (gravel) require small sediment trap storage capacities.

Table 5-11: Capacity of sediment trap corresponding to the particle sizes

	Particle Size	Sediment Trap Storage Capacities Required
Soil Gradings	(mm)	(m^3)
Gravel	4.75	24
	3.35	35
Sand	0.85	67
	0.425	124
	0.3	186
	0.15	502
Silt	0.075	1669

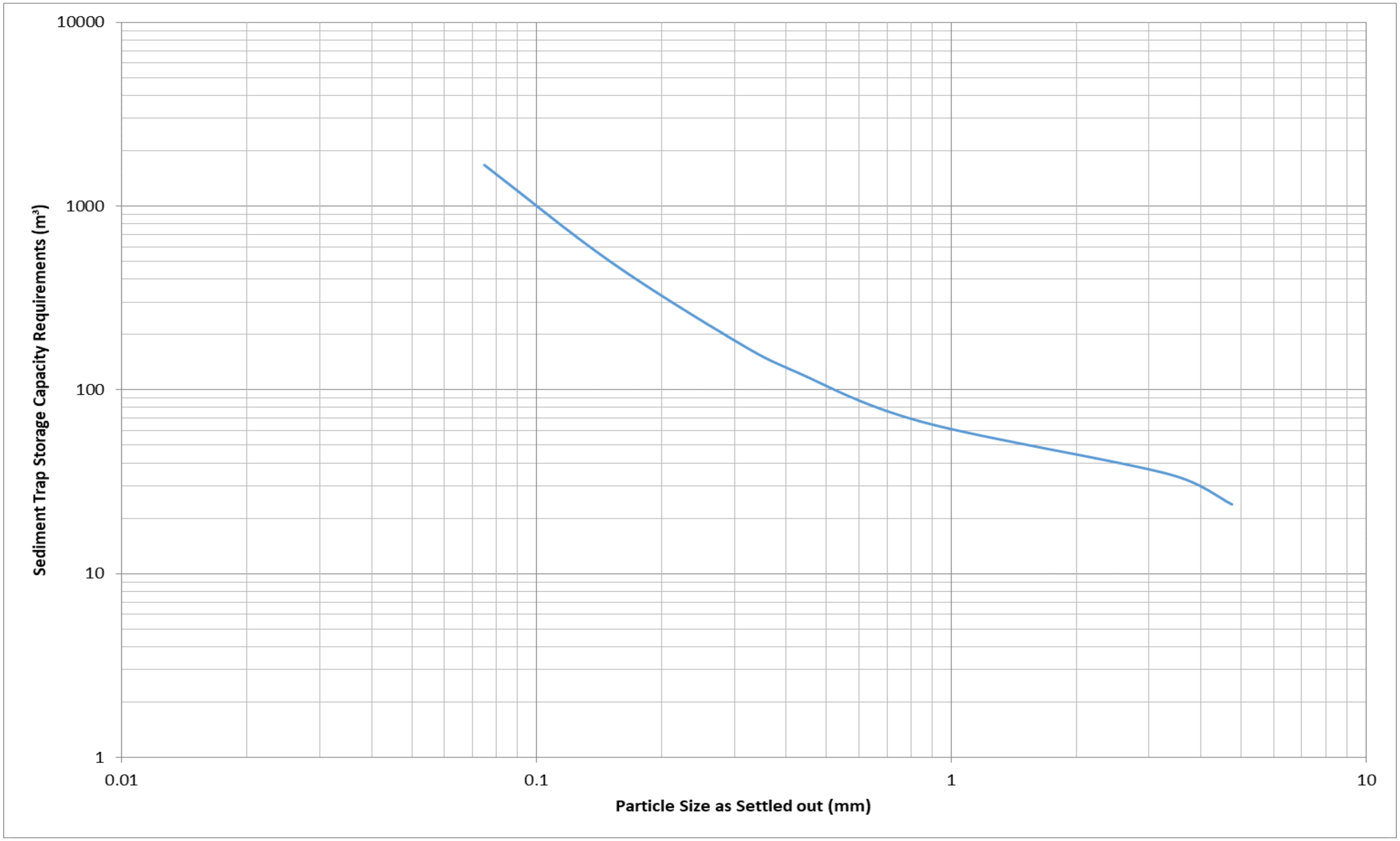


Figure 5-12: Particle size vs. capacity required for settling

5.4.1 *Summary of Sediment and Storage Capacity*

- The results show that the soil samples from sub-catchments S22 and S23 consist of 8.34% silt, 77.8% sand and 7.4% gravel. The soil sample also contains 6.42% of soil particles that passed sieve 200 and collected in the pan.
- Sediment particles with smaller diameters (silt) and less dense require a longer time to settle, while larger diameter and denser soil particles (gravel and sand) take a short time to settle.
- High sediment trap storage capacities are required to settle small diameter and less dense soil particles such as silt while larger and denser (gravel) soil particles require smaller sediment trap storage capacities.

5.5 *Sediment Yield*

Sediment yield was determined for sub-catchments S22 and S23 using ArcSWAT ArcGIS extension, and the results are shown in Table 5-12. The simulation period was from 01/01/2022 to 31/12/2022 and results were printed in monthly time series. It is seen that from both sub-catchments S22 and S23, there is high sediment yield during the months with high rainfall which are from January, February, March, April, and May. In comparison, there is low sediment yield in the months of low rainfall, which are June, July, and August. Sediment yield from sub-catchment S22 ranges from 0.05 to 6.25 ton/ha/month while in sub-catchment S23 sediment yield was from 0.18 to 5.37 ton/ha/month.

Table 5-12: ArcSWAT sediment yield

Unit Time (Months)	Sub-catchment 22	Sub-catchment 23
Units	Tonnes/hectares/month	Tonnes/hectares/month
January	0.91	0.97
February	6.25	5.37
March	5.29	5.09
April	1.40	1.95
May	0.52	1.25
June	0.06	0.46
July	0.07	0.68
August	0.07	0.55
September	0.43	1.37
October	0.05	0.18
November	0.27	0.84
December	0.56	1.57

5.5.1 *Summary of Sediment Yield*

- Sediment yield is high in months with high rainfall and less in drier months.
- Sub-catchment S22 sediment yield ranged from 0.05 to 6.25 ton/ha/month while in sub-catchment S23 sediment yield ranged between 0.18 to 5.37 ton/ha/month.

6 Discussion of finding

6.1 *Climate Characteristics*

The design rainfall data for the 2-year and 5-year return periods with 24-hour duration were determined as 60.3mm and 83.2mm respectively. From the PCSWMM model results, it is evident that peak flows and runoff volumes from both sub-catchments S22 and S23 increased due to an increase in recurrence intervals from the 2-year to 5-year. From the literature, Barnard et al. (2019), recommended that any erosion and sediment control facilities must be sized based on a 2-year recurrence interval of storm events with a duration ranging from 0.25 hours to seven days. Furthermore, Perez *et al.* (2015), recommended that sediment basins should be sized based on stormwater runoff resulting from the 2-year, 24-hour storm event. At the same time, the United States Environmental Protection Agency (USEPA) sizing criteria are also based on a 2-year, 24-hour rainfall event. In addition, Larm and Alm (2014), stated that the storage capacity of sediment traps should be based on rain duration and specific rainfall intensity. Based on the literature summary on rainfall parameters above, it can be seen that there is no agreed standard on which design rainfall must be used when designing sediment traps. However, based on the results of the current research, it is advised that the designers of sediment traps in the City of Johannesburg should analyse and use a 2-year and 5-year design rainfall with 24-hour duration. The design rainfall should be sourced from Design Rainfall Estimation software (Smithers and Schulze, 2003).

Evaporation data analysed for this study showed that potential evaporation values are high in the summer months and low in the winter months. The high temperatures in summer mean that high volumes of water will be lost due to evaporation, while low temperatures in winter evaporate less water from the sediment traps. Hence this will impact the storage capacity of the sediment trap. Therefore, designers should ensure that potential evaporation data is collected and analysed from the study site as it impacts the sediment sediment trap storage capacity. On the other hand, Barnard et al. (2019) stated that the evaporation of the study site should be considered as it impacts the site and stormwater systems implemented. It is therefore advised that evaporation values to use for the study site should be obtained from the Water Resources of South Africa (WR2012) website (Bailey and Pitman, 2015).

6.2 *Physical Catchment Characteristics*

6.2.1 *Imperviousness Areas*

The sensitivity analysis modelling in PCSWMM showed the significant effects of imperviousness on peak flows and runoff volumes. It is clear from Table 6-1 (5-yr RI) and Table 6-2 (2-yr RI) that peak flows and runoff volumes increased due to the percentage of imperviousness increase from 12% (S22), 15% (S23) to 85% (both sub-catchments S22 and S23). From Table 6-1 (5-yr RI) sub-catchment S22 runoff volume increased by 478% from (12-85)% imperviousness, while runoff rate increased by 246% from (12-85)% imperviousness. The same trend is evident from sub-catchment S23 where runoff volume increased by 350% from (12-85)% imperviousness, while runoff rate increased by 207% from (12-85)% imperviousness. In comparison, from Table 6-2 (2-yr RI) sub-catchment S22 runoff volume increased by 574% from (12-85)% imperviousness, while runoff rate increased by 245% from (12-85)% imperviousness. The same trend is evident from sub-catchment S23 where runoff volume increased by 436% from (12-85)% imperviousness, while runoff rate increased by 215% from (12-85)% imperviousness. This finding shows that peak flows and runoff volumes are sensitive to imperviousness, hence imperviousness should be accurately determined and analysed from the study site for use in sediment trap sizing.

Table 6-1: Design rainfall of 5yr and imperviousness impact on peak flows and runoff volumes

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Imperviousness Percentage change		(12-85)%	(15-85)%
Total runoff volume from sub-catchments	(m^3*10^3)	(240.1-41.5) +478%	(147.2-32.7) +350%
Peak runoff rate from sub-catchments	m^3/sec	(69.3-20) +246%	(50.4-16.4) +207

Table 6-2: Design rainfall of 2yr and imperviousness impact on peak flows and runoff volumes

Outputs	Units	Sub-catchment 22	Sub-catchment 23
Imperviousness Percentage change		(12-85)%	(15-85)%
Total runoff volume from sub-catchments	(m^3*10^3)	(165.8-24.6) +574%	(101.4-18.9) +436%
Peak runoff rate from sub-catchments	m^3/sec	(44.5-12.9) +245%	(33.1-10.5) +215

The national land cover dataset is obtainable from the Department of Environment Affairs (https://egis.environment.gov.za/data_egis/). Also, the Global Man-made Impervious Surface (GMIS) Dataset can be sourced from (http://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v). The better source of data from the two datasets is the Global Man-made Impervious Surface (GMIS) as it has a 30m resolution which helps to map global urbanization. The 30 m resolution helps in accurate mapping of urban features such as buildings, roads and parking lots (De Colstoun *et al.*, 2017).

6.2.2 Infiltration Rate

The hydrological soils from sub-catchments S22 and S23 were determined to be Group B soils. These soils have moderately low stormflow potential with moderate infiltration rates (SANRAL, 2013). The soil depths in this group are said to be shallow with infiltration rates between 3.81mm/hr and 7.62mm//h. The sensitivity analysis results have shown that both 3.81mm/hr and 7.62mm//h infiltration rates gave the same peak flows and runoff volumes from sub-catchments S22 and S23. However, even though it is out of the current research scope, it was determined that high infiltration rates decrease peak flows and runoff volumes. From the literature, the Australian Department of Planning and Local Government (2010) regards the assessment and interpretation of site conditions such as soil properties of the site as a vital part of the design of sediment basins. Moreover, Al-Ani (2018) stated that sediment basins are sized based on the information of soil type. Therefore, it is recommended that engineers and designers involved with sediment trap sizing determine the soil types and their characteristics such as soil infiltration when sizing sediment traps. The soil classification methodology that is used by SANRAL (2013), should be relied on in the soil classification process. Also, soil data information is obtainable from the Agricultural Research Council Institute for Soil, Climate and Water (ISCW) (ARC-ISCW, 2011).

6.2.3 Sediment Particle Size, Settling Time and Sediment Storage

From Table 6-3, it is seen that as gravel particle size decreased from 4.75mm to 3.35mm the particle settling time increased from (3sec – 5sec) while the storage capacity increased from (24 – 35) m^3 with an increase of 46% storage capacity. From gravel particle size of 4.75mm to 0.85mm of sand, the particle settling time increased from (3sec – 9sec) while the storage capacity increased from (24 – 67) m^3 with an increase of 179% storage capacity. From gravel particle size of 4.75mm to 0.425mm of sand, the particle settling time increased from (3sec – 17sec), while the storage capacity increased from (24 – 124) m^3 with an increase of 417% storage capacity. From gravel particle size of 4.75mm to 0.3mm of sand, the particle settling time increased from (3sec – 25sec) while the storage capacity increased from (24 – 186) m^3 with an increase of 675% storage capacity. From gravel particle size of 4.75mm to 0.15mm of sand, the particle settling time increased from (3sec – 67sec) while the storage capacity increased from (24 – 502) m^3 with an increase of 1992% storage capacity. Lastly, from gravel particle size of 4.75mm to 0.075mm of silt, the particle settling time increased from (3sec – 223sec) while the storage capacity increased from (24 – 1669) m^3 with an increase of 6854% storage capacity. From these findings, it is evident that the longer the particle takes to settle, the larger the storage capacity required to settle such a particle. In comparison, the shorter the settling time of the particle, the smaller the sediment trap storage capacity required. These findings support the literature that stated that fine soil particles such as silt require longer retention time, normally longer than the standard sediment basin treatment conditions (Perez *et al*., 2015). Moreover, the Alabama Department of Transport (2002), stated that the retention time for sedimentation is usually 8 hours, while Gu *et al.* (2017) argued that the sufficient time for sedimentation is 24 hours. On the other hand, sediment traps are meant to treat coarse and medium-sized sediment that is normally 0.125mm and larger, while finer particles can be treated further in sediment traps using chemical coagulants (Queensland Government, 2018). The Australian Department of Planning and Local Government (2010); Barnard et al. (2019); and Queensland Government (2018) recommended that the sizing of the sedimentation basin be determined concerning the selected particle sizes and their settling velocity. It is, therefore, recommended from the results of this research that engineers or designers carry out a detailed analysis of particle size distribution, determine the settling velocity of the particle size in the study site and lastly determine the sediment trap storage capacity required to settle the target sediment particles.

Table 6-3: Percentage of sediment trap storage capacity increase

	Particle Size	Settling Time	Capacity Required	Sediment Storage Capacity Increase
Soil Gradings	(mm)	Seconds	(m^3)	%
Gravel	4.75	3	24	0
	3.35	5	35	46
Sand	0.85	9	67	179
	0.425	17	124	417
	0.3	25	186	675
	0.15	67	502	1992
Silt	0.075	223	1669	6854

6.3 ArcSWAT Sediment Yield

The modelling results have shown that sediment yield is directly related to rainfall, whereby months with high rainfall yielded high sediment loads while months with low rainfall yielded low sediment loads. The results further showed that sediment yield from sub-catchment S22 ranged from 0.05 to 6.25 ton/ha/month while in sub-catchment S23 sediment yield ranged from 0.18 ton/ha/month to 5.37 to/ha/month. These findings inform on the loading rate of sediment that is expected to come into the sediment traps, hence it is vital that sediment yield from the project site is accurately determined to inform the sediment storage capacity. On the other hand, the daily rainfall used in the ArcSWAT model should be sourced from the South African Weather Services Station that is in proximity to the study site. The designer can extract results from the ArcSWAT in a monthly time step and see how much of the sediment would have collected in a year and therefore design the sediment trap accordingly. The Australian Department of Planning and Local Government (2010) recommended that sediment traps be sufficiently sized to prevent the frequent need for sediment removal. Moreover, Rodak *et al.* (2020) stated that the design of stormwater control structures can be effective if their design is informed by the knowledge of the sediment loading rate. In addition, the United States Environmental Protection Agency (USEPA) recommended that sediment traps should be sized based on sediment loading rates from the local 2-year, 24-hour rainfall event (Schussler *et al.*, 2022). Moreover, Al-Ani (2018) stated that sediment storage volume in highly erodible soil areas should be sized to capture a two-month soil loss from disturbed areas in the catchment using the Modified Universal Soil Loss (MUSLE).

6.4 Parameters to be Considered when Sizing Sediment Traps in the City of Johannesburg

The findings of this study recommend that the following parameters should be considered when sizing sediment traps in the City of Johannesburg.

- Design rainfall.
- Daily rainfall.
- Evaporation.
- Land cover and land use.
- Percentage of permeable and impermeable areas.
- Topographical data.
- Contributing catchment area.
- Peak flow.
- Runoff volume.
- Soil types and infiltration characteristics.
- Sediment particle size distribution.
- Sediment settling velocity.
- Sediment loading rate/yield.

Collection of Data for the Parameters

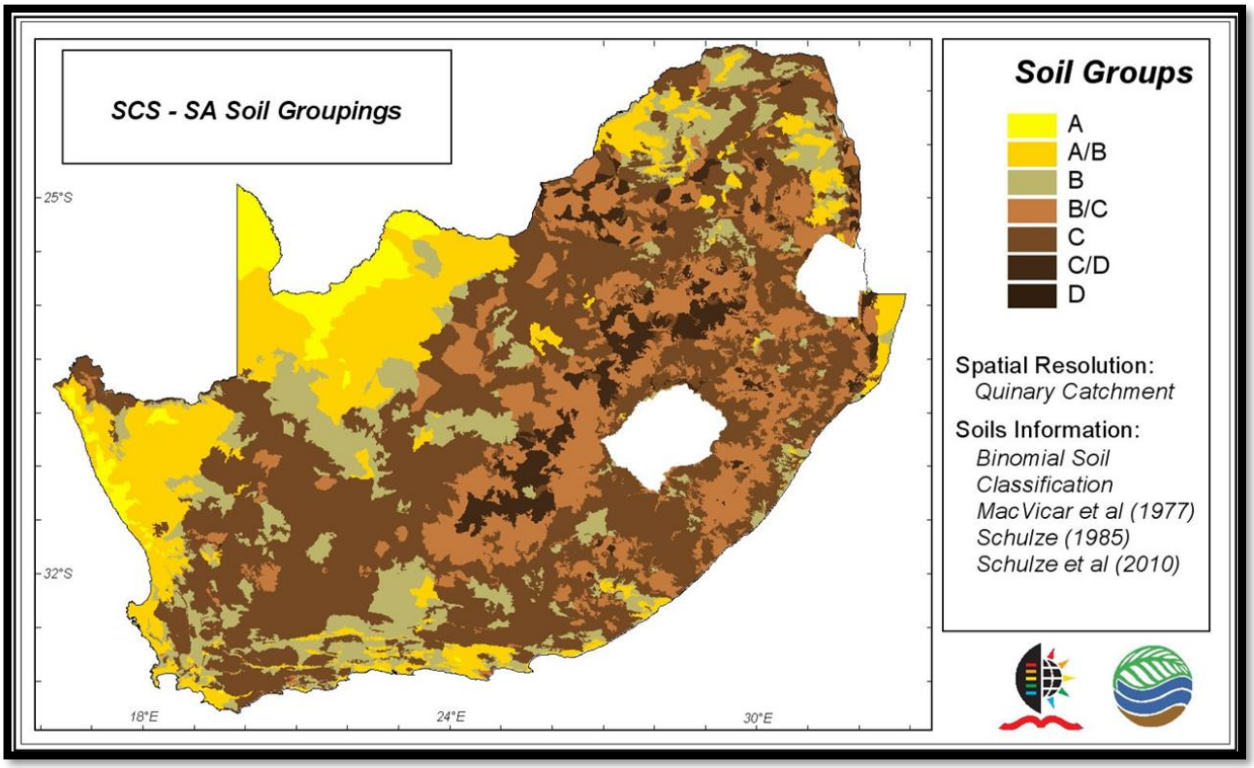
After the identification of the design parameters, the step that follows is the collection of data for each parameter.

- Daily rainfall, and 5-minute interval rainfall data are sourced from the South African Weather Services.
- Design rainfall for the site should be obtained from Design Rainfall Estimation Software (Smithers and Schulze, 2003). The program caters for annual probabilities (frequencies) between 1:2-years, 1:5-years, 1:10-years, 1:20-years, 1:50-years, 1:100-years and 1:200-years return periods, for durations from 5 minutes to 7 days (SANRAL, 2013) for any place in South Africa.
- Monthly evaporation data in the form of evaporation percentages is obtainable from the Water Resources of South Africa (WR2012) website https://waterresourceswr2012.co.za/ (Bailey and Pitman, 2015).
- Land cover and land use, percentage of permeable and impermeable areas data is obtainable from Global Man-made Impervious Surface & Settlement Extent from Landsat. NASA's SEDAC1 (http://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v1/).
- The national land cover dataset for South Africa is obtainable from the Department of Environment Affairs (https://egis.environment.gov.za/data_egis/).
- For catchment area delineation, the digital elevation model or terrain data can be obtained from the City of Johannesburg's Corporate GIS.
- Soil data information in South Africa is obtainable from the Agricultural Research Council Institute for Soil, Climate and Water (ISCW) (ARC-ISCW, 2011).
- The hydrological soil types and soil properties such as infiltration rates can be determined using the SANRAL Drainage Manual (SANRAL, 2013) and Storm Water Management Model Reference Manual (Rossman & Huber, 2016).
- Soil samples for particle size distribution should be collected from the study site, also the geological formation of the study area should be determined.

Data Analysis

- Rainfall should be analysed and patched where there is missing data to get a long record of rainfall as it is recommended for a better understanding of the hydrological characteristics of the site.
- The mean monthly evaporation is determined by multiplying the mean annual precipitation with the conversion factor and dividing by 100%.

- The percentage of permeable and impermeable areas data is evaluated using zonal analysis in QGIS to determine the percentage of impermeability from each sub-catchment in the study area. Also, the imperviousness can be mapped using Google Earth Pro.
- Land use and land cover for the study site can be determined using ArcGIS or QGIS.
- The contributing catchment area is delineated in PCSWMM using a digital elevation model or terrain data. Furthermore, the slope of the catchment can be determined in ArcMap using Spatial Analyst Tools.
- For the determination of hydrological soil data, the (SANRAL, 2013) methodology uses the figure attached below.



- The particle size distribution of the soil samples in the study area should be determined using sieve analysis and hydrometer methodology.
- The particle settling velocity should be determined using Equation 5 below.

$$\boldsymbol{V_s} = \frac{\boldsymbol{gRd^2}}{\boldsymbol{18v + (0.75CgRd^3)^{\frac{1}{2}}}} \quad (5)$$

Where:

Vs = terminal settling velocity of the solid particle

g = gravitational acceleration

R = specific gravity in water (1.65 for silica sand)

C = constant (0.4 for spheres, 1 for typical sand grains)

d = diameter of the particle

v = kinematic viscosity of the fluid

- After the determination of particle settling velocity, the settling time is evaluated using the sediment trap depth. The sediment trap depth is then divided by the settling velocity to get the settling time or retention time.

Modelling

- **PCSWMM** is a suitable modelling program for urban stormwater and it also enables the sensitivity performance.
- **ArcSWAT**-modelling for the determination of sediment yield, the ArcSWAT model is highly recommended as it gives sediment yield in different time steps such as daily, monthly, and annually.

7 Conclusion

No work has been done in the City of Johannesburg on sediment basins and trap sizing design. The City of Johannesburg Stormwater Design Manual only stipulated that construction sites should manage their sediment by using sediment control measures to protect municipal drainage against sediment. Moreover, the development sites are recommended to direct their discharge to an appropriate sediment trap or sediment pond. It is evident from the literature that there is little guidance in the City of Johannesburg on the sizing of the sediment traps nor the parameters that one should consider when sizing sediment traps.

The purpose of this study was to determine the parameters for sizing sediment traps, specific to the City of Johannesburg through the vehicle of a case study of Waterfall City. This was achieved by reviewing existing literature from local and international manuals on the design of sediment basins and traps, sizing sediment basins and traps and parameters considered when sizing sediment basins and traps. It was identified that several sediment basin and trap design manuals considered design flow rates, design rainfall, particle size distribution, particle settling velocity, sediment yield and retention/detention time when sizing sediment traps. After the identification of the above-listed parameters from other manuals, it was then that the data and information based on those parameters were collected from Waterfall City in sub-catchments S22 and S23. The data was analysed and prepared for modelling in Personal Computer Stormwater Management

Model (PCSWMM), ArcSWAT ArcGIS, and Excel Spreadsheet programs. The modelling was carried out using PCSWMM while observing the peak flows and runoff volumes from the model outputs. The soil samples were modelled using Sieve Analysis, Scientific Formulas and Excel Spreadsheet Models while sediment loading was modelled using ArcSWAT ArcGIS.

The modelling in PCSWMM involved scenario 1 and scenario 2. Scenario 1 involved modelling using current parameter values while scenario 2 involved sensitivity analysis using different values of the imperviousness and infiltration rates. The sensitivity analysis was performed by changing one factor at a time while keeping all other factors constant. After each model run, the resulting peak flow and runoff volume were compared.

Key Findings from PCSWMM:

PCSWMM Modelling Scenario 1:

- Sub-catchment S22 and S23: Design rainfall of 5yr (83mm) and Green-Ampt infiltration method.
- Sub-catchment S22 and S23: Design rainfall of 2yr (60mm) and Green-Ampt infiltration method.

From both sub-catchments S22 and S23 an increase in recurrence interval from 2-year to 5-year increased peak flows and runoff volumes.

PCSWMM Modelling Scenario 2:

- Test for the sensitivity of 85% imperviousness from sub-catchments S22 and S23. The model was run with design rainfall of 5yr (83mm) and the Green-Ampt infiltration method.
- Test for the sensitivity of 85% imperviousness from sub-catchments S22 and S23. The model was run with design rainfall of 2yr (60mm) and the Green-Ampt infiltration method.

The results showed that runoff volume and peak flow increased as a result of an increase in imperviousness from 12% and 15% to 85%. This suggests that designers should accurately analyse the imperviousness when sizing sediment traps. Moreover, imperviousness is one of the parameters that should be considered when sizing sediment traps.

Test for the Sensitivity of Infiltration Rate:

- Test for the sensitivity of 3.8mm/hr infiltration rate in sub-catchments S22 and S23. The model was run with design rainfall of 5yr (83mm) and Horton infiltration method.
- Test for the sensitivity of 7.6mm/hr infiltration rate in sub-catchments S22 and S23. The model was run with design rainfall of 5 yr (83mm) and Horton infiltration method.

- Test for the sensitivity of 3.8mm/hr infiltration rate in sub-catchments S22 and S23. The model was run with design rainfall of 2yr (60mm) and Horton infiltration method.
- Test for the sensitivity of 7.6mm/hr infiltration rate in sub-catchments S22 and S23. The model was run with design rainfall of 2 yr (mm) and Horton infiltration method.

The infiltration rates of 3.8mm/hr and 7.6mm/hr for sub-catchments S22 and S23 gave similar peak flows and runoff volumes. The results showed infiltration as not a sensitive parameter. However, it should be noted that the range of infiltration rates used was low and high infiltration rates indeed decreased peak flows and runoff volumes. Hence, it is one of the parameters that should be accurately determined and analysed when sizing sediment traps.

Particle Size Distribution and Settling Time:

- The results from particle size distribution, particle settling velocity and particle settling time have shown that denser soil particles (gravel) took a short time to settle and required smaller sediment trap capacities. In comparison, less dense soil particles (silt) took longer to settle and required larger sediment trap storage capacities. Therefore, sediment trap designers in the City of Johannesburg should accurately analyse the particle size distribution of the soil in the project site to be informed of the particle sizes, settling velocity and time to able to determine the storage capacity that will be sufficient to facilitate sedimentation of the chosen soil particle sizes.

Sediment Yield

- The results showed that sediment yield is associated with high rainfall, hence rainfall data should be analysed accurately when determining sediment yield in ArcSWAT. Moreover, these results have indicated that sediment yield is one of the parameters that should be determined to inform the sediment trap storage capacity.

From the results of the modelling activities carried out in this study, it is therefore, concluded that the following parameters: design rainfall, daily rainfall, evaporation, land cover and land use, percentage of permeable and impermeable areas, topographical data, contributing catchment area, peak flow, runoff volume, catchment topography, soil types and infiltration characteristics, sediment particle size distribution, sediment settling velocity, sediment loading/yield should be considered by the engineers, designers and planners when sizing sediment traps in the City of Johannesburg and possibly in other places as well.

7.1 Recommendations for Future Research

This study focused specifically on determining the parameters for sizing sediment traps without looking at the actual sizing of sediment traps, the design of the sediment trap structure and their design features for the City of Johannesburg.

- It is therefore recommended that future studies focus on the investigation of sediment loads across the City of Johannesburg streams.
- Future studies should focus on the sizing and design of the sediment trap structure.
- The implementation and testing of the sediment trap performance in reducing sediments at the head of conventional drainage systems and SuDS technologies for the management of sediments in the City of Johannesburg.
- Development of sediment trap design manual for the City of Johannesburg.
- The economic evaluation of sediment trap implementation in the City of Johannesburg.

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APPENDIX A: MONTHLY EVAPORATION AS A PERCENTAGE OF MAE FOR EVAPORATION ZONES

Evap Zone	OCT	NOVE	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1A	11.13	10.49	10.70	10.26	8.81	8.65	6.96	6.02	4.84	5.38	7.31	9.45
1B	10.46	10.03	10.68	10.43	8.49	8.49	6.94	6.55	5.40	6.08	7.42	9.03
1C	11.08	10.29	10.96	11.00	9.15	8.89	6.89	5.72	4.65	5.04	7.02	9.31
1D	11.60	10.78	10.78	10.72	8.64	8.45	6.63	5.63	4.65	5.23	7.03	9.56
2A	11.16	11.21	11.59	11.08	8.90	8.38	6.58	5.50	4.48	5.03	6.94	9.15
2B	11.15	11.01	11.35	11.10	9.03	8.61	6.57	5.44	4.56	5.05	6.93	9.20
3A	11.52	11.54	11.86	11.20	9.20	8.50	6.38	5.07	3.99	4.62	6.78	9.34
3B	10.92	10.37	11.28	11.70	8.93	8.66	6.83	5.81	4.78	5.30	7.02	9.40
4A	10.78	10.17	11.20	11.00	9.17	9.05	6.96	5.86	4.76	5.21	6.90	8.94
5A	9.50	9.48	10.77	11.28	9.67	9.49	7.20	6.28	5.16	5.57	7.05	8.55
6A	9.63	11.72	13.66	13.74	10.87	9.27	6.50	4.78	3.66	3.94	5.22	7.01
6B	10.02	11.56	12.87	12.65	9.90	8.91	6.60	5.24	4.27	4.69	5.71	7.58
7A	10.07	11.90	13.71	13.60	10.45	9.02	6.30	4.54	3.45	3.99	5.44	7.53
8A	11.47	12.08	12.53	11.78	8.93	8.22	6.13	4.88	3.87	4.51	6.54	9.06
9A	11.14	12.09	12.59	11.89	9.10	8.13	6.15	4.88	3.99	4.64	6.50	8.90
9B	10.96	12.05	13.16	12.75	9.87	8.47	6.06	4.68	3.59	4.20	5.83	8.38
10A	11.11	11.46	11.87	11.48	8.98	8.13	6.33	5.28	4.17	4.91	6.97	9.31
11A	10.97	11.39	12.37	12.23	9.86	8.96	6.55	4.94	3.78	4.22	6.12	8.61
12A	10.85	10.88	11.71	11.36	9.37	8.76	6.62	5.37	4.36	4.71	6.83	9.18
13A	9.79	10.19	10.91	10.98	9.39	9.09	7.07	5.88	4.94	5.54	7.15	9.08
13B	10.35	10.20	11.00	10.87	9.38	8.94	6.88	5.85	4.82	5.29	7.26	9.16
14A	9.50	11.22	12.82	13.06	10.99	10.30	7.40	4.96	3.74	3.66	5.12	7.23
14B	9.58	11.40	12.32	12.66	10.23	9.57	6.92	5.41	4.76	4.52	5.55	7.12
15A	9.21	11.38	13.37	14.22	11.48	10.38	6.69	4.63	3.47	3.62	4.77	6.78
15B	9.22	12.03	14.48	14.94	11.98	10.36	6.24	4.08	2.80	3.18	4.44	6.25
16A	9.84	12.07	14.13	14.40	10.97	9.56	6.23	4.25	3.11	3.48	4.89	7.08

17A	10.19	12.43	14.64	14.41	10.67	8.89	5.91	4.12	2.99	3.38	5.05	7.32
17B	10.30	11.94	13.88	13.96	11.19	9.28	6.10	4.26	2.97	3.53	5.08	7.51
18A	10.32	11.61	13.46	13.07	9.83	8.54	6.08	4.78	3.77	4.44	6.10	8.00
19A	10.59	11.93	13.51	12.83	10.05	8.94	6.21	4.48	3.47	4.01	5.82	8.16
19B	10.52	12.36	14.06	13.62	10.44	8.62	6.10	4.29	3.23	3.62	5.30	7.84
19C	10.68	12.05	13.81	13.51	10.15	8.81	5.94	4.37	3.16	3.74	5.52	8.26
20A	10.61	12.17	13.81	13.19	10.09	8.66	6.00	4.34	3.37	3.86	5.75	8.15
20B	10.83	11.69	13.48	12.72	9.86	8.56	5.94	4.64	3.50	4.09	6.00	8.69
21A	9.93	10.38	11.07	10.76	9.36	9.01	7.25	6.00	5.06	5.56	7.17	8.45
21B	10.23	9.39	9.77	9.57	8.02	7.93	7.00	6.88	5.64	6.45	9.01	10.11
21C	10.16	10.21	11.37	11.19	9.50	8.93	6.93	5.70	4.82	5.29	7.26	8.64
22A	8.95	10.36	11.63	12.05	10.33	10.01	7.22	5.83	4.79	5.17	6.18	7.48
22B	10.66	9.75	10.78	10.63	8.84	8.76	6.67	6.03	5.16	5.63	7.90	9.19
22C	9.22	10.24	11.71	12.46	10.73	10.13	7.12	5.63	4.40	4.67	6.10	7.59
23A	9.19	11.46	14.11	14.78	12.40	11.16	7.05	4.34	2.94	2.96	3.83	5.78
23B	8.67	12.08	14.83	15.09	12.45	11.51	7.06	4.00	2.62	2.55	3.57	5.57
23C	8.76	12.23	14.38	14.73	12.43	10.86	6.76	3.90	3.00	3.32	3.90	5.73
23D	8.77	12.40	15.47	16.12	13.44	11.29	6.12	3.24	2.40	2.21	3.24	5.30
23E	9.65	12.36	14.98	14.98	11.88	9.81	6.36	3.91	2.69	2.94	4.09	6.36
24A	9.31	11.56	13.89	14.21	11.62	10.18	6.77	4.51	3.30	3.50	4.68	6.47
24B	9.21	10.91	13.29	12.96	10.16	8.77	6.59	5.41	4.95	5.06	5.92	6.77
24C	9.19	11.10	13.74	13.97	11.09	9.72	6.91	4.85	3.95	3.94	4.87	6.67
25A	9.73	11.36	13.67	13.60	10.57	9.02	6.30	4.78	3.88	4.27	5.62	7.20
26A	9.51	11.23	13.45	13.79	11.06	9.54	6.92	4.88	3.54	3.83	5.23	7.02
27A	9.96	11.37	13.38	14.21	10.45	9.07	6.28	4.81	3.61	4.09	6.05	7.86
28A	9.75	11.15	13.07	12.96	10.49	9.05	6.53	4.86	3.99	4.41	5.92	7.61
28B	10.06	11.43	13.07	13.97	10.46	9.25	6.81	4.96	3.66	4.09	5.52	7.52
28C	9.24	9.56	10.92	13.60	8.77	8.28	6.82	6.36	6.04	6.91	7.78	8.51

28D	9.58	10.89	12.43	13.79	10.17	9.19	6.73	5.31	4.65	4.66	6.18	7.81
29A	10.32	11.20	12.03	11.61	9.58	8.82	6.46	5.10	4.31	4.85	6.99	8.73
29B	10.06	10.82	12.60	12.62	10.20	8.97	6.82	4.77	3.82	4.43	6.49	8.40
30A	9.39	9.65	10.56	10.42	9.37	9.26	7.58	6.40	5.60	5.99	7.24	8.47
30B	9.47	9.57	11.27	10.69	9.41	9.62	7.23	6.03	5.14	5.78	7.41	8.36
30C	8.70	8.76	11.18	12.02	10.41	9.95	7.71	6.34	4.74	5.24	7.22	7.73