UNIVERSITY OF NAIROBI

DEPARTMENT OF ENVIRONMENTAL & BIOSYSTEMS ENGINEERING

SCHOOL OF ENGINEERING

INTEGRATED URBAN PLUVIAL FLOODING ANALYSIS AND MODELLING FOR NAIROBI WEST AND SOUTH C IN NAIROBI CITY

BY

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September 2018

DECLARATION

I, Simon Onyango Okoth, hereby declare that this MSC thesis is my original work. To the best of my knowledge, this work has not been presented for a degree in any other university.

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Simon Onyango Okoth Date

This thesis has been submitted for examination with our approval as supervisors.

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DEDICATION

To my beloved parents, particularly my father for their sacrifice. I wouldn't have been here were it not for them. I also dedicate this work to my children Ryan, Colleen, Myron, Basil, Howard and my beloved wife, Sarah for being patient during the study of this Master's Degree course.

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ABSTRACT

Flooding is one of the natural occurrences which have caused some of the most severe natural catastrophes in the world history including huge economic losses, fatalities and environment degradation. Urban pluvial flooding cases have increased due to urban densification, fast changing urban hydrology as well as inadequate urban drainage design especially for the combine storm-sewer systems. In Nairobi city, residents are at greater urban pluvial flooding risk as have been witnessed with a number of flood damages already experienced.

However, there are a number of tools that have been developed to help in analysing urban pluvial flooding risks and support sound planning to avert such catastrophes. The purpose of the study was to analyse and model urban pluvial flooding in Nairobi's South C and Nairobi West areas using Storm Water Management Model version 5.1(SWMM5.1) and demonstrate to city key stakeholders the applicability of SWMM 5.1 in analysing urban pluvial flooding for urban planning.

Three main datasets were used in the study including Geographic Information Systems (GIS) data, rainfall data disaggregated into 15-minutes events and the sewer network data. Other key parameters were drawn from existing literature. The EPA SWMM 5.1 was then used to simulate the response of two delineated sub-catchments to the rainfall event of 26th December 2012. Sensitivity analysis was applied to identify the relative influence of six selected model input parameters on the peak runoff. The results from both the RUNOFF and EXTRAN modules in the model showed significant flooding with the surface runoff registering 20.134 ha-m and over 81% of the manholes and conduits surcharging. The peak runoff was also found to be significantly responsive to variations in impervious manning's coefficient, N and % imperviousness parameters.

From the study, the pertinent parameters were identified through the literature review and the model run based on the identified pertinent parameters. From the results, the integrated SWMM5.1 model and GIS data processed by ArcGIS 10.1 was able to yield result confirming the flooding of 26th December 2018. It can therefore be concluded that SWMM model is a useful tool for simulating urban pluvial flooding and improving urban stormwater management. However, access to high resolution data especially the rainfall data is encouraged to enhance the precision of the model outputs.

This study, is therefore, an important illustration to the urban planners on the potential of integrating SWMM 5.1 model with GIS to analyse flooding risks an urban area get exposed to due to continued development and inadequate storm water management infrastructure. It can therefore be useful for influencing policy and improving the urban stormwater and drainage management for Kenya.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PICTIRES

LIST OF MAPS

ABREVIATIONS

ADF	Average daily flow
ADF_s	Average domestic flow
AoI	Area of interest
CN	Curve number
CSUD	Center for Sustainable Urban Development's
DCIA	Directly Connected Impervious Area
DEM	Digital Elevation Model
DWF	Dry Weather Flow
EPA	Environmental Protection Agency
FII	Flow Instability Index
FPC	Flow Per Capita
GIS	Geographical Information System
GLUE	Generalized Likelihood Uncertainty Estimation
iid	independent identically distributed
IMD_{max}	Initial Moisture Deficit
IPCC	Intergovernmental Panel on Climate Change
MOUSE	Model for Urban Sewers
PE	Population Equivalent
RBLM	Randomized Bartlett Lewis Model
RMC	Random Multiplicative Cascades
SCS	Soil Conservation Service
SSS	Separate Sewer System
SWMM5.1	Storm Water Management Model (Version 5.1)
ToC	Time of Concentration
TPE	Total population equivalent
WRI	World Resource Institute
WWF	Wet Weather Flow

NOTATIONS

Roman upper case letters

A_s	Surface area contributed by the conduits connected to the node
A_{store}	Surface area of the node itself,
C_{at}	Atmospheric conductance for water vapour
C_{can}	Canopy conductance
D	Pipe diameter
E	Trade Effluent Flow
ET_o	Evapotranspiration rate
$\mathrm{F}(t)$	Cumulative depth of the wetting front
G	Water consumption / head / day
H	Hydraulic head
H_n	Node's head
H_g	The ground elevation
I	Infiltration
K_h^*	Hydraulic conductivity
K_r	Net incoming shortwave radiation
L	Pipe length
L_c	The sub-catchment length.
L_r	Net incoming long-wave radiation
P	Population served
Q	Sub-catchment outflow
Q_d	Discharge flow
Q_f	Design full capacity of the downstream conduits.
Q_{in}	Total inflow discharge from the upstream conduits
Q_r	Surface runoff coming in to the manhole
Q_s	Surcharge quantity
R	Flow rate
R_a	Total incoming extraterrestrial radiation
R_0	Expected value of disaggregation
S	The slope,
S_{fx}	Friction slope
S_p	Parameter associated with watershed characteristics.

T_C	Temperature
T_R	Daily temperature range
V	Cross-sectional averaged flow velocity
W	Sub-catchment width
W_a	Relative humidity
W_g	Disaggregation weights

Roman lower case letters

c_a	Specific heat of the air
c_f	A coefficient generally written in terms of the Manning *n* or Chézy roughness factors.
d	Ponding depth (water depth)
d_p	Ground roughness (Depth of depression or retention)
e_a*	Saturation vapour pressure at the air temperature
f	Factor of friction,
f_{in}	Infiltration rate
f_c	(Asymptotic) infiltration rate for saturated ground
f_0	(Initial) infiltration rate for dry ground
g	Acceleration of gravity
$\Box_L$	Head loss resulting from friction
k	Infiltration constant
n	Manning's roughness coefficient
s_{bx} and s_{by}	Bed slopes on the *x* and *y* directions,
s_{fx} *s* and s_{fy} *s*	Friction slopes on the *x* and *y* directions.
t	Time
t_p	Time of ponding
t_w	Instant of the entire soil column becoming saturated
u and v	Velocity components in x and y directions
x	Distance in the flow direction

Greek letters

α	Velocity distribution coefficient
ρ_w	Density of water
ψ_f	Effective tension at the wetting front

$(\phi-\theta_0)$	Initial soil water deficit
Δ	Slope of the saturation-vapour-pressure vs. temperature curve at the air temperature
ρ_a	Density of air
ρ_w	Density of water
λ_v	Latent heat of vaporization
γ	Psychrometric constant

CHAPTER ONE

1 INTRODUCTION

1.1 Background

The significance of modelling urban flooding is continuously growing as a result of the ever-changing urban hydrological regime resulting from urbanization, changing climate and population growth. As urbanization intensifies, the magnitudes of pluvial flooding in many cities and towns across the world have also increased with catastrophic results. These floods more than often, result in wide-ranging damages characterized by unmatched economic damages, personal harm, deaths and social disturbance. Data collection and application in modelling is emerging as one way of enhancing flood preparedness and mitigation practice. This allows planners to understand and choose from a range of different systems optimal model to design effective control measures. The importance of modelling flooding in urban areas is to appreciate the drainage system performance for a given catchment, by considering accompanying physical parameters. In this context, several integrated modelling tools to analyse flooding have been developed to objectively evaluate the risks and propose effective remedial measures. Integrated modelling is the process of combining two or more physical aspects of different physiognomies and complexities to derive an integrated output that exhibits what the reality would have been. The swing towards integrated modelling emanates from the advances already made with regard to urban hydroinformatics and the need to apply these simulation advances and developments to model different stages of the complete water cycle optimally.

In the recent past, urban flooding has become one of the greatest sources of anxiety worldwide. Urban pluvial flooding is also contributing to this growing anxiety with the increased rate of urban development globally. Several authors have explained the many factors that contribute to urban pluvial flooding. Urban flooding may be due to various causes: overland flows on streets, flooding flows from rivers and overflows or surcharges from sewer networks (Kouyi, et al., 2011). The concept of urban pluvial flooding relates strongly to urban catchments in which the existing drainage systems are overwhelmed by the generated storm water due to high percentage of impervious areas and limited capacities. The development of impervious surface in the urban areas means reduced hydrologic cycle constituents, e.g. infiltration, evaporation and transpiration (or evapotranspiration) resulting in increased runoff volumes and peak flows from a storm event.

Urban flood risks and their impacts are expected to increase as urban development in flood prone areas continues and as rain intensity increases as a result of climate change while aging drainage infrastructures limit the drainage capacity in existing urban areas (Seyoum, et al., 2011). The combination of limited capacities of the cities' sewer systems which also double as principal drainage infrastructure, increased precipitation resulting from climate change and altered ecosystem due to increased urbanization result in urban pluvial flooding. The potential for evapotranspiration, water infiltration and recharge in urban catchments have consistently attenuated with the continued removal of vegetation, forestry and top soil cover and their replacement with impermeable surfaces thereby shifting the natural hydrology from an infiltration based cycle to a runoff-predominant cycle. The key contributor to stormwater runoff resulting in urban flooding is the urban imperviousness, also known as directly connected impervious area (DCIA). DCIA comprised of residential and commercial areas directly linked to the sewer network through conduits and other conveyance systems. In most of cities in the world, the drainage systems are combined in nature consisting of the sanitary sewer and the stormwater sewer conveyed to a common treatment plant. As rainfall magnitude increases, the stormwater runoff increases, causing sewer systems to surcharge which results in a combined sewer overflow (CSO) onto the streets and residential areas.

There are several evidences that the growing number of pluvial flooding incidences globally in urban areas have resulted remarkable destruction to societies' livelihoods, thus our attention should be focused on development and use of applicable tools for flood inundation modelling.

Nairobi city, since its establishment in late 1890s have steadily expanded as the Kenya's economic and industrial hub while offering gateway to East and Central African region thus drawing huge population from the rural areas of Kenya. This expansion is expected to increase flooding as the proportion of impervious area increase with no corresponding expansion in storm water drains. Urbanization in Nairobi has already heightened flooding in the city by restricting natural infiltration of waters into the ground as a result of ever increasing impervious surface on the ground due to buildings, pavements and roads.

The need to advance the understanding and management of urban pluvial flooding for flood resilience in our cities has grown (Oludare, et al., 2012). Urban pluvial flood management requires detailed information on what causes pluvial flooding, what the consequences are, how frequently flooding occurs, what locations are vulnerable for flooding and how climate change and urbanisation effect flooding (Spekkers, et al., 2011). With the current scientific advances, it has become common for Engineers to combine these factors that contribute to flooding through various methods to produce accurate information that can reliably be used for flood prevention and preparedness in a city. One of these methods that have emerged in the recent years for providing this important information is modelling. A model is a consistent representation or portrayal of a physical phenomenon as simplified reality, which can otherwise not be illustrated practically. To realistically model urban flooding processes, it is crucial to understand and represent dynamics of overland flow and subsurface flow i.e. interactions between surface flow network and the buried storm or combined drainage network systems (Boonya-aroonnet, 2008).

There are numerous different stormwater models for analysing stormwater and flooding at different spatial-temporal resolutions. Rainfall in urban areas, due to the rapidly changing urban hydrology are intense and rapid making high-resolution modelling the most exact method, even though it is normally not practicable for big geographical areas as formulation of the relevant parameters for input for stormwater models to simulate flooding of extensive geographical areas still remain a challenging task. The Storm Water Management Model (SWMM) is an urban modelling tool developed originally by the United States Environmental Protection Agency (EPA) (Ghosh, 2010). In recent years, SWMM5.1 has emerged as a popular tool for modelling urban flooding in many cities worldwide. Through integration of SWMM 5.1 model with Geographic Information System (GIS), the wearisome task of developing the SWMM5.1 data files can be overcome. GIS is a computer based application software that enables user to collect, stock, manage, analyse as well as represent spatially referenced data for decision making in a user-friendly format.

1.2 Problem Statement

Recent floods in Nairobi have caused considerable losses to various sectors in the city. These floods essentially results from rapid build-up of runoff from short but intense rainfall events due to factors such as the increased precipitation and enhanced impermeability with significant contribution also coming from sewer surcharge. The hydrologic and hydraulic interactions that has led to this type of flooding in sections of the city are usually complex and results from more than one physical system with different characteristics thus presenting major concerns to the city authorities, urban designers and managers during town planning. At the same time, the economic loss resulting from urban pluvial flooding is increasingly becoming a great concern to service providers including; transport, electricity, water and communication service providers, besides leading to losses lives and properties by families and the general public.

Some of flooding events include the December 2012, when heavy rains pounded Nairobi and its environs forcing residents to stay indoors after floods marooned their houses and rendered several roads impassable. There are many other flooding events that have had similar effects or even worse in Nairobi. Knowledge of the flooding behaviour in the city can significantly reduce human and financial damages caused by floods. Integrated modelling by use of both spatial-temporal parameters of a catchment and the physical features of the catchment is one way of improving the understanding of this complex flooding phenomenon and providing flood information to improve flood resilience and preparedness. This research is to analyse the risk of urban pluvial flooding occurrences in a selected area including inundation to inform the authorities for design of better flood risk management approaches.

1.3 Overall Research Objective

The broad objective of this study is to conduct an integrated urban pluvial flooding analysis and risk assessment of South C and Nairobi West areas using SWMM5.1 and GIS.

1.3.1 Specific Objectives

i. Identify pertinent modelling parameters influencing urban pluvial flooding.

ii. To integrate the parameters in (i) above in a multi-scale and multi-source data modelling framework for simulation of urban pluvial flooding.

1.4 Research Questions

i. What is the status of research work in urban pluvial flood modelling in Kenya?
ii. Does the sewer surcharges' resulting from storm exceedance significantly contribute to urban pluvial flooding in Nairobi?
iii. Have the increase in impermeable surface in Nairobi enhanced floods in the city?
iv. What are the uncertainties associated with modelling urban pluvial flooding using SWMM5.1 model?

1.5 Study Rationale

Cities and urban centres are places of greater human concentration due to their enhanced social and economic opportunities as well as being centers of communication. Multifaceted interfaces between the social mechanisms of cities and their local physical environments produce unique and dynamic human dominated ecosystems. This means there are several parties who have keen interests in natural occurrence of events including the outcomes of urban pluvial flood modelling.

National and Municipal authorities responsible for disaster risk management need to substantiate the budget they require from taxpayers to use in flood protection infrastructure.

At the same time, public and private businesses, properties' owners, housing corporations have critical interest in understanding whether their properties and businesses are secure on the basis of damage calculations thus enabling them to take decisions on value of insuring their properties or resorting investing in an alternative measures. This is also the case with insurance companies beginning to develop keen interest in the investment opportunities coming with provision of cover policies for disaster related damages including floods. Modelling is a perfect way of estimating flood damage and the flood scenarios from models to be used as justification for use of or plans to funds, inform policies and city regulations as well as, provision of sufficient risk analysis for flood management scenarios.

This research is aimed at demonstrating the application of SWMM 5.1 together with GIS as a method of analysing and simulating urban pluvial flooding scenarios for decision making and planning purposes by the city authorities. The research also attempts to provide potential for further studies in the area and trigger engineers to undertake the crucial role in identifying cost-effective innovative technologies that are appropriate for other cities in Kenya and the region, thus enriching the most critical scientific value of improving the understanding of resilience in relation to pluvial flooding.

1.6 Scope of Work

There are many reasons for developing and utilizing hydrological models including aspiration to simulate the hydrological processes that are not physically observable. This modelling exercise is to extend our understanding of the processes occurring that are not directly observable. The study focuses on Nairobi West area, which has been prone to regular flooding during rainy seasons. To achieve this research's first goal, extensive literature review regarding SWMM 5.1, its potential for integration with GIS and applicability was undertaken. The literature review also aided the understanding of the theoretical background and the identification of the pertinent parameters later used in the model to simulate the selected storm event. The process then proceeded to data collection based on the identified parameters for input into the model. A single event model run was undertaken and as it has become increasingly important to incorporate sensitivity and uncertainty analysis in the specification of our hydrological models in order to understand parameters whose variability are most effective in the modelled phenomenon, a sensitivity analysis methods were analysed and one method selected for the model and incorporated in the study process. Lastly, a detailed study report that summarizes the results of the existing conditions model was prepared with recommendation of areas for further research.

CHAPTER TWO

2 LITERATURE REVIEW

In the past, extreme rainfall have not been known to frequently occur, thus most municipalities and cities have not been considering the susceptibility of cities to pluvial flooding. However, the pattern and magnitude of occurrence of extreme precipitation is rapidly changing all over the world as marked by recent flooding events in major cities in the world. Flooding in urban areas is occurring with increasing frequency all over the world and is causing repeated damage that calls for improved management of floods (Simões, et al., 2011). The ongoing urbanization has continued to invade upon flood plains and other natural watercourses in cities. As this process of urbanisation continues, impermeable surfaces continues to steadily expand even on known major watercourses. The changing global climate and that of the urban microclimate is not helping the situation either. This therefore calls for improved and accurate flood modelling methods and approaches that ever before.

The dictionary definition of a flood is "An overflowing or irruption of a great body of water over land in a built up area not usually submerged (Wang, et al., 2008)." Looking back into the past few years, there has been a significant upsurge in the occurrence and severity of flood events that have been witnessed in many areas around the world. In addition, the extent, magnitude and frequency of urban pluvial flooding are likely to increase in the near future, given the increasing effects of climate change, the increased urbanisation and population growth (Ochoa , et al., 2012). These extreme events with a duration of up to several hours cause the urban storm water drainage system to be overloaded, either due to the intensity of the rain or due to runoff from urban green space which normally infiltrates into the ground (Kluck , et al., 2010). This noted rise in flood frequency and flooding intensity globally has posed key concerns in the world due to the increase of catastrophic flood situations.

2.1 Types of Flooding

There exists several forms of flooding which can be classifies in different categories depending on where they occur and the predominant causes. They include river or fluvial flooding, urban flooding, groundwater flooding, coastal flooding, flash flooding, and ponding or pluvial flooding. Coastal flooding results from a variety of causes including when storm surges and high winds coinciding with high tides. Fluvial flooding occurs from overland flow resulting from rainfall and natural erosion processes resulting in the formation of waterways which conglomerate and results major streams and afterwards rivers. When the equilibrium of flow is disturbed and the flow overwhelms the river capacity as it approach areas of low gradient during intense or extended storm, this type of flooding occurs. Fluvial flooding in river valleys happens mostly on flood plains or wash lands as a result of stream channels being exceeded by the flow capacity leading to spillage over the natural banks. Pluvial flooding are the results of surface runoff from localized heavy rain where the generated flow is beyond the capacity of the drainage network before discharging into a waterway or a drainage network and is usually accompanying high intensity storm events. Pluvial flooding mostly affects urban areas in a rather localized manner unlike the way river and coastal flooding affect wider areas. The flood water either fills natural or constructed surface storage or subsequently travels across the terrain through preferential pathways that create a surface flow network typically called the "major system," while the "minor system" refers to an underground sewer network. (Maksimović, et al., 2009). Any sort of urban infrastructure constructed in the catchment will aid the flooding process due to reduction in vegetative cover which reduces evapotranspiration while increases imperviousness resulting in reduced infiltration. Groundwater flooding results from the formation of springs that directly cause flooding within an area as a result of raised water table. This happens mainly in areas underlain by impermeable soil or rock and is a rare type of flooding even though it contributes to urban flooding. Flash flood is usually associated with violent storms falling over a short duration and over a small area with steep slopes. Other types of floods include, estuarine floods, snowmelt floods, ice-jam and debris-jam floods.

2.2 Urban Flooding

The most common phenomenon related to urbanization is the intensification of impervious ground surfaces as more and more areas that are built-up replace the natural vegetative cover and further disturb the original soil pattern of the areas. The resulting characteristic of the surface is directly connected impervious surfaces that reduce infiltration in the area. World over, there has been significant and rapid expansion of urban areas over the past two decades resulting in development of settlements along low-lying and flat areas that are prone to flooding. These developments have resulted in changes to the land coverage from vegetation to buildings and roads, which further causes a related alteration in the hydrologic regime of the basin. With the climate change also altering the local hydrological patterns of catchments, cities and towns are registering increased frequency and severity of flooding.

There have been many recent notable examples, including flooding in Brisbane in January 2011, widespread flooding in Thailand that inundated Bangkok during the 2011 monsoon season, and flash flooding caused by extreme rainfall in Beijing in July 2012 (Hammond, et al., 2015). Recently, severe flooding hit highly developed cities like Prague, Dresden, and several other cities (2002), Bern and several other cities (2005), New Orleans (2005), Copenhagen (2010, 2011, and 2014) and New York (2012), as well as areas like Queensland (2010), South-western England (2013–2014), and the French Riviera(2015) (Sörensen et al., 2016). Heavy floods visited Pakistan, India and China in the summer of 2010, Colombia from October to December 2010 and Australia during the austral summer 2010/11 (Kundzewicz *et al.* 2013). In 2011, severe floods were reported in Mozambique, Namibia, South Africa and Uganda in Africa; Brazil, Columbia, Mexico and the United States in the Americas; and Cambodia, China, India, Korea, Pakistan, the Philippines and Thailand in Asia, with fatalities in each flood exceeding 50 (over 1000 in the Phillippines and Colombia) and high material damage, in particular in the developed countries from the list above (Kundzewicz *et al.* 2013). The inadequacy of urban drainage infrastructure due to increased population has also contributed greatly to the increase in flooding in the urban areas.

2.3 Urban Pluvial Flooding

Pluvial flooding in urban areas is a phenomenon caused by an extreme rainfall event whereby the surface flooding is augmented by the sewer surcharge. Urban pluvial flooding occurs as a result of runoff from a short but intense storm surpasses the amount that a city's storm-sewerage transmission systems can convey normally in a combined sewer system. The surplus surface flow resulting from the storm therefore cannot be accommodated in the system anymore. At the same time, the surcharging storm-sewerage from the sewer systems adds to the surface flow exceedance. The definition of flooding given by European Standard EN 752 is "a condition where wastewater and/or surface water escapes from or cannot enter a drain or sewer system and either remains on the surface or enters buildings" (CEN, 1996). Many authors have also advanced the definition of urban pluvial flooding. Falconer defines urban pluvial flooding as "The result of rainfall-generated overland flow and ponding before the runoff enters any watercourse, drainage system or sewer, or cannot enter it because the network is full to capacity" (Falconer, et al., 2009) (Riel, 2011). In the context, of built up urban areas, urban pluvial flooding can therefore be said to be the surplus quantity of wastewater flowing in the highways and paths, depressions or on overland as a result of intense rainfall, reduced infiltration and overwhelmed drainage systems.

Urban development activities, which are characterised by demographic changes and increase of built-up areas thus reducing vegetative cover, have significantly altered the urban hydrologic behaviour. Urbanization and the resulting land-use change strongly affect the water cycle and runoff-processes in watersheds (Sikorska, et al., 2012). As a result, the severity and frequency of flooding have amplified at both basin and local levels, particularly in these fast urbanizing areas. The occurrence of urban pluvial flooding is a complex process that requires dedicated efforts to understand. During heavy storms pluvial flooding can take place even if flow in the sewer network capacity is with a free surface, i.e. the sewer network is not exceeded, if inlet capacity is insufficient to capture surface run-off (Maksimović, et al., 2009).

2.4 Factors Contributing to Urban Pluvial Flooding

2.4.1 Climate Change

Urban development increases flood risk in cities due to local changes in hydrological and hydrometeorological conditions that increase flood hazard, as well as to urban concentrations that increase the vulnerability (Huong & Pathirana, 2013). These modifications are direct consequences of climate change, which leads to increased global temperatures. Due to global warming, many subsystems of the global water cycle are likely to intensify, resulting in many regions, an increase of flood magnitude as well as flood frequency (Associated Programme on Flood Management, 2008). Nairobi city is no exception to this phenomenon as the microclimate of the city of Nairobi and its environs continues to significantly change as the city continues to rapidly grow. A large percentage of the city has been cleared of its natural vegetation to pave way for other development infrastructure. This has in itself affected the natural hydrological cycle around the city resulting in more rapid and intense downpours.

2.4.2 Effects of Urbanization

Urban areas always present some risk of flooding when rainfall occurs (Kamal-Chaoui & Alexis , 2009). Buildings, roads, infrastructure and other paved areas prevent rainfall from infiltrating into the soil – and so produce more runoff (Satterthwaite, 2008) (Kamal-Chaoui & Alexis , 2009). The main hydrologic parameters used to represent urbanisation conditions are: (a) impermeable area of the basin, understood here as consisting of every surface in which the precipitation contributes directly to stormwater network; (b) time of concentration (ToC) or velocity of flow through the basin (Campana & Tucci, 2001). Alteration to these parameters has effects on stormwater flow patterns. Urban development which is usually accompanied with not only compaction of the soil but also sealing off totally of the pores necessary for infiltration reduces the natural processes of hydrologic cycle thus aggravating overland flow. Increased urban population also means increased water consumption and hence wastewater production, which if not accompanied with expansion of wastewater systems will result in, exceeded capacities of the systems even from very short storm of medium intensity. All these changes of urban hydrology and their consequences of higher volume and increased peak flows within short durations cause the urban land to be inundated and affect the urban life and properties adversely (Amila, et al., 2011). The city of Nairobi has expanded rapidly over the past decade with rapid expansion of roads, residential and commercial structures resulting in a greater proportion of impervious area in the city. The effects of this enlarged impervious area have been quite evident with regular flooding in certain areas of the city.

2.4.3 Effects of Sewer Surcharge

Sewer systems can be classified as either separate sewer systems (SSS) or combined sewer systems (CSS). These sewer infrastructures are developed to manage wastewater from households, institutions and industries as well as storm water resulting from rainfall. A combined sewer system transports both sewerage and storm water all in the same conduits while in separate sewer system storm water is transported in a different pipe to that which conveys sewerage or wastewater. Combined sewer systems gathers both sewerage and storm water during rainfall and releases the mixture through conduits, forming composite branching network of sewer systems continuously sloping towards one end to transmit the storm-wastewater by gravity to a water body or treatment plant. These systems are often overwhelmed during wet weather flows forcing the mixture of sewerage and stormwater to flow overland causing floods. Distinct from flooding, the term 'surcharge' is defined as a 'condition in which wastewater and/or surface water is held under pressure within a gravity drain or sewer system, but does not escape to the surface to cause flooding (Schmitt, et al., 2004). Such flows especially in conduits are common under extreme heavy rainstorms in areas with under designed pipes. The combination of increasing population that leads to a change in the wastewater production patterns and the higher rates of stormwater to be conveyed result in a high risk of overloading the capacity of the system (EEA, 2001). The surface water failing to enter the drains coupled with the surcharging mixture of wastewater and stormwater results in enhanced surface flow with potential flood risks to the population. Nairobi with its aging sewer system is not spared the problems of sewer surcharges.

Picture 1a and 1b: Sewer surcharges on the streets after the conduit capacity is overwhelmed.

2.5 Urban Flooding and its Effects

The recent trend in urban flooding is emerging as one of the world's most common and feared global calamities. Urban flooding incidences have been growing in frequency and severity in the recent past and is expected to be on the rise as urban areas and cities continue to grow. Unlike in the past when the causes of floods were well known natural factors, the recent flooding occurrences particularly in urban areas have had much to do with urbanisation factors including alteration of urban hydrologic regimes. This has had several effects on the urban population including damaging the infrastructure and causing environmental health concerns from sewerage contamination. Moreover, street flooding as have been experienced usually hamper the operation of traffic and movement. Such occurrence has indirect effect on the welfare of the communities such as loss of time and business opportunities.

Cumulative damage due to pluvial flooding can be considerable, especially in lowland areas where this type of floods occurs relatively frequently (Santiago, et al., 2013). The effects of flooding vary, because of local physical, geographical, and meteorological conditions, and therefore, each situation requires individual responses (Smith, 2009). Direct flood destructions covers all varieties of loss to individuals and communities relating to human life, property, and the environment as well as the disruption of economic activities, social activities and invisible damages including foul smell or even health risk.


Picture 2a and 2b: Flooded residential area and road in Nairobi during an extreme rainfall event.

2.6 Urban pluvial flooding in Nairobi City

As Nairobi continues to grow, the city is being exposed more to a number of major flood hazards. The increase in extreme rainfall due to climate change combined with rapid urbanization and expansion of the city has definitely led to an increase in urban pluvial flooding in the city. There have been several short intensive rainfall events in Nairobi in the past years. A scrutiny of daily rainfall data from the Kenya Meteorological Department (KMD) reveals several of these heavy rainfall events have occur in April and December. The media and reports from various sources have highlighted the floods and their effects from these highly intensive downpours. One such events is the intense rainfall of December 26, 2012 night that displaced several people while also causing extensive damages to both public and private properties including death. Vast areas of Nairobi were affected including some of the most expansive slums such as Mukuru, Mathare-Area C, as well as other well-known settlements like Eastleigh, South C, Industrial Area, Pipeline, and Imara Daima and its surroundings. This particular flooding event isolated particular settlements leaving them stranded in flood filled houses without access to important basic services.

During this storm, many roads in the city and its environs were reported to be heavily flooded by the media and emergency response teams including the Kenya Read Cross. During the rains, the infrastructure was also not spared and extensive damages to the city roads as well as collapsing bridges we observed. Contaminated water flowing into residential areas was observed during the storm and even days after.

Picture 3a and 3b: People and a motorist in South C navigates through a flooded street on December 27, 2012 in Nairobi West area. Pictures from www.sabahionline.com/en

While fluvial flooding and inundating of the floodplain have been studied before in Kenya, urban pluvial flooding is emerging as a new areas of concern highlighting the need for scientific research in the area to develop sound and sustainable flood management systems and tools not only for the city but other towns in the country. This can be done through various methods including modelling which has become one of the most popular and sustainable flood management methods in the cities of developed countries. Few studies have been done on urban flooding with a combination of characteristics of surcharged sewer system and the surface runoff of the catchments. Physical processes such as the hydrological process, the hydraulics of the drainage system, the DEM, the drift interchange between the impervious surface and the sub-surface drainage structures are all involved in urban pluvial flooding. The level of reliability of simulated results for urban flood can be largely improved if high-accuracy and fine-resolution rainfall estimates are available (Wang, et al., 2012). However, this requires a very dense network of rainfall sensors and is usually not available due to limited budget and space (Wang, et al., 2012). In developing countries like Kenya, these networks of precipitation censors are limited and are of coarser resolution. At this point, the modellers should be able to consider a consistent urban flood model that has the capacity to integrate the linkage between the two systems namely hydrologic pattern and the hydraulic aspects of an area.

2.7 Urban Flooding Models

Rainfall- runoff correlation is a complex phenomenon to represent in the mathematical form (Rathod, et al., 2015). Rainfall–runoff models have been used to describe nonlinear hydrological processes, predict extreme events and assess the impacts of potential changes in future climates and/or land use (AghaKouchak, et al., 2013). Rainfall runoff processes involves many parameters which could either be physical features of the catchment being investigated or climatological parameters drawn from the climatic regime of the basin in which the catchment falls. Numerical simulations of urban floods are important when scientifically planning and designing urban drainage systems and providing efficient urban flood disaster control and management strategies (Fan, et al., 2017). In the real world system rainfall runoff process is influenced by each and every physical characteristics of catchment and to generalize all physical characteristics of the catchment is really a difficult task (Rathod, et al., 2015). The conception of modelling in hydrology is involved with relationships of water, climate, soil and land use (Jajarmizadeh , et al., 2012). There are many different types of deterministic catchment hydrology models designed to simulate time series of representative streamflow values (Hughes, 1995). In relation to urban flood modelling, the main hydrological model used focuses on rainfall-runoff simulation by factoring the behaviour and contribution of local storm drainage systems. Recently, an integrated approach of various models is commonly employed and the use of sophisticated hydraulic models as diagnostic, design and decision-support tools has become standard practice in water industry (Maksimović, et al., 2009).

2.8 Classification of Storm-Runoff Modelling Methods

A number of considerations including the physical principles pertinent to a model and the input parameters influences the classification of storm-runoff models. It can be classified as lumped and distributed model based on the model parameters as a function of space and time and deterministic and stochastic models based on the other criteria (Devi, et al., 2015). Deterministic model yields identical result for a solitary group of input parameter quantities while, dissimilar output results are realised for a solitary group of inputs in stochastic models. For same input parameters used in the model, deterministic models yield similar results. Unlike stochastic models which have some intrinsic arbitrariness, implying that ensembles of different results are obtained from the same set of input parameter values if initial conditions are maintained, deterministic models outputs are entirely determined by the parameter values together with the conditions at the start of the process. A stochastic model therefore, will always produce a different model response (Zoppou, 2001). Stochastic models are usually complex in nature but have one distinct advantage in that the uncertainty of a variable as per its distribution is entwined in the model. Physically-based models, empirical models and conceptual models are other ways of classification of models.

2.8.1 Empirical Models

These are observation oriented models which take only the information from the existing data without considering the features and processes of hydrological system and hence these models are also called data driven models (Devi, et al., 2015). Empirical models are normally mathematically simpler than their physical and conceptual counterparts, and reasonably good results can be quickly obtained by using techniques such as regression and neural networks (Aghakouchak & Habib, 2010). Unit hydrograph is an example of this method (Devi, et al., 2015). Its mathematical expressions are developed simultaneously by considering both the input and resulting temporal variability as opposed to catchment physical parameters with the model being valid only within the boundaries.

2.8.2 Conceptual Methods

These models describe hydrological processes holistically and are the most common methods in use. They are formulated by a number of conceptual elements, each of which is a simplified representation of one process element of the system being modelled (Abdolreza, 2006). The basic advantage of this form of modelling is that it reflects the thresholds present in hydrological systems, which otherwise cannot be adequately incorporated in a linear model (Gosain & Mani, 2009). It consists of a number of interconnected reservoirs, which represents the physical elements in a catchment in which they are recharged by rainfall, infiltration and percolation and are emptied by evaporation, runoff, drainage etc. (Devi, et al., 2015). Mathematically, the model is also simpler to apply which adds to the advantages of using the model. For a conceptual model to yield results for urban flooding, different parameters affecting different hydrologic and hydraulic processes in the catchment must be considered. Hence, assigning proper values to these parameters is very essential for obtaining accurate model results for the specific area being modelled (Gosain & Mani, 2009).

2.8.3 Physically Based Model

This is a mathematically idealized representation of the real phenomenon (Devi, et al., 2015). The physically-based modelling approach intends to derive the model equations from theory to the largest extent possible, while conceptual modelling employs higher-order laws derived largely from environmental data (Babel & Karssenberg, 2013). Parameters and state variables may be either directly measured in the field or reasonably assumed based on site characteristics (Aghakouchak & Habib, 2010). The use of fundamental hydrologic laws mainly derived from physics, which are expected to be valid in a wide range of conditions, renders them potentially applicable to a large diversity of current and future hydrological systems (Babel & Karssenberg, 2013). There is one important feature of physically based models which set them aside from the other two which is that they are not personalised to a specific sphere or field of simulation. In this regard, physically based models could be considered to reach, at the moment of their development, a relatively high degree of independence from observations (Babel & Karssenberg, 2013). Physical model can overcome many defects of the other two models because of the use of parameters having physical interpretation (Devi, et al., 2015). It can provide large amount of information even outside the boundary and can applied for a wide range of situations (Devi, et al., 2015).

2.9 Urban Flood Modelling

Depending on the hypothesis considered, one given model may be suitable for certain situations, but may not be applied to other conditions (Miguez & Canedo de Magalhães, 2010). Urban flood modelling often involves the use of computational techniques to simulate the spread of water onto a wide surface area that contains complex features (Ghimire, et al., 2013). To simulate the inundation of urban areas, the flow process in the inundation area is divided into two components, namely the surcharge and inundation components (Hsu, et al., 2000). Flood parameters such as inundation area, flood wave depth and flood duration can be simulated by several hydraulic and hydrologic models (Vozinaki, et al., 2012). Several models have been developed and applied for modelling urban waters following different approaches (Paz, et al., 2011). The hydrologic-hydraulic modelling procedure involves the dynamic linking of a pipe flow and a hydrologic modelling system to form an integrated tool for simulating total water movement in a catchment (Domingo, et al., 2010). Conventional modelling of overland flow assumes thin sheet flow over a plane surface with an area equivalent to the sub-catchment area (Maksimović, et al., 2009). Although this assumption can yield acceptable results, during heavy storms it may lead to false predictions because in flood vulnerable areas the actual flow pattern is significantly different from the simplified sheet flow (Maksimović, et al., 2009). It follows that reliable simulation of urban pluvial flooding require proper consideration of the relationship of the urban storm-runoff and drainage situation of the catchment and all the aspects of their complexities. The selection of a suitable model to apply will therefore be dictated by the prevailing characteristics of the study area, the purposes for which the study is being undertaken, the availability of relevant data for modelling, the availability of suitable tools for conducting the analysis, and the availability of other resources including human resources.

2.10 Types of Urban Modelling Tools

In the strive for understanding and reducing urban flooding many cities in the developed part of the world use computer-based solutions to manage local and minor flooding problems. Computer models for urban drainage networks are developed to imitate rainfall events. Many studies have been made on the subject of urban flooding and a few specific studies have been selected and published to exhibit different procedures when performing computer modelling of urban flooding. Some of the widely used modelling tools include: SIPSON-SIPSON is a 1D sewer network model that simultaneously solves continuity equations for network nodes, energy equations for nodes and pipe/channel ends, the complete Saint Venant Equations for flow in conduits and streets, and equations for other link types (pumps, weirs, etc.) (Chen, et al., 2016); The UIM is a 2D overland-flow model, that solves the non-inertia wave (diffusive wave) flow equations (Leandro, et al., 2009). MIKE STORM model which analyses 1D sewer network; MIKE 21which is an overland 2D flow model. XP-SWMM2D uses a combination of both the 1D XP-SWMM and 2D TUFLOW, to model the minor system, and the 2D TUFLOW to simulate flooding in both minor and the major system. SWWM is a free flood simulation software by the EPA. It can model both the sewer systems' surcharge and overland flow. Developed by WL / Delft Hydraulics, SOBEK is an integrated numerical modelling package used to simulate hydrodynamics of one-dimensional river/channel network and two-dimensional overland flow (Maynett, 2004). It is based on the 1D Saint Venant Equation and the 2D Shallow Water Equations, using an implicit scheme known as the Delft Scheme (Maynett, 2004). Most of these tools may require the support of GIS software for the surface network delineation based on DTM or DEM and fine-tuned based on cadastre, site reconnaissance and aerial photography.

Using software such as Model for Urban Sewers (MOUSE), InfoWorks and SWMM5.1it is possible to create computer models of the drainage or sewer system in order to understand the complex relation between rainfall and flooding (Mark et al., 2004).

2.11 U.S. EPA – SWMM5.1

There are numerous models capable of simulating urban water quantity and quality employing diverse approaches to handling the problem (Zoppou, 2001). However, there seem to be a number of deficiencies that are common to most of these models (Zoppou, 2001). SWMM is one of the commonly preferred modelling tool for simulation of dynamic stormwater-sewerage magnitude and level of contaminants in an urban catchment. SWMM5.1was first developed by EPA in 1971. Since then a number of upgrades have been done to the tool. The current version is one of the most refined stormwater analysis and drainage planning computer models currently available with the capability of simulating a number of flood components. During an urban flooding event where besides the run-off, there is substantial contribution to the overland flow by the surcharging sewers from the combined sewer flow. This combined sewer flow is often storm water mixed with dry weather flow (DWF) which is mainly the wastewater from households and other domestic and commercial establishments in the selected catchment and sub-catchment areas.

2.11.1 Wet Weather and Dry Weather Flows

In modelling pluvial flooding in an urban catchment, both the wet weather and dry weather flows are significant considerations. Dry weather flow refers to the wastewater flowing from premises without any storm water entering the system. It constitutes the average daily wastewater from households, industries and other commercial places that enters a treatment plant. Wet weather flow arises from that component of storm water runoff which enters the storm-sewer network to combine with the dry weather flow. Where a combination of both the wet and dry weather flows exceeds the size of the drainage network, surcharge occurs leading overflow of contaminated storm-sewer flow, the case in which we are interested in this study.

2.12 Spatial and Temporal Variability of Precipitation

Rainfall data for many hydrologic models especially in the urban areas are often essential at a finer scale than what is measured, such as hourly rather than daily.

However, rainfall data usually available for hydrological modelling are from daily records, which are much coarser for modelling phenomena like flooding. To address this issue, a number of different techniques for disaggregating and downscaling large-scale rainfall data to output small-scale resolutions for use in hydrologic models have been developed. These data transformation procedures from recorded coarse rainfall series to finer time series with the characteristic of the original data are collectively referred to as precipitation disaggregation methods. For urban flooding where runoff is rapid due to increased imperviousness, high resolution data is of great importance and this is a necessary step.

2.12.1 Rainfall Data Disaggregation Methods

A number of rainfall disaggregation methods have been developed which has made it easy to use recorded historical daily rainfall data to reproduce short-time step rainfall from coarse time steps records. Disaggregation of coarser rainfall data is a good way to preserve the necessary statistical properties of the original data, at the finer scale. The reproduced finer time-steps can then be used as input for SWMM5.1software for locations where only daily rainfall records are available. Various methods have been developed to disaggregate daily precipitation to hourly time series to make them usable for continuous hydrologic simulation (Gao, et al., 2012). Some of the rainfall disaggregation methods are highlighted below and they include; Uniform disaggregation, Random Multiplicative Cascades (RMC), Randomized Bartlett Lewis Model (RBLM), and Method of Fragments.

2.13 Digital Elevation Model – GIS

A GIS-embedded hydrological model, also known as a spatially based distributed hydrological model, can facilitate runoff management in both rural and urban catchments through enabling determination of the hydrological drainage network (Pourali, et al., 2014). Digital Elevation Model (DEM) is the digital representation of the land surface elevation with respect to any reference datum (Balasubramanian, 2017). Hydrologic applications of the DEM include groundwater modeling, estimation of the volume of proposed reservoirs, determining landslide probability, flood prone area mapping etc (Balasubramanian, 2017). Overland flow models are mainly depended on DEM, the advantage being that water is allowed to flow in any direction in the model, instead of flowing through a pre-set network. Since the DEM is an approximation to terrain characteristics, the accuracy of the topography and the related hydrological applications will depend on the quality of the DEMs, especially the characteristics such as slope analysis, river network density, flow path and the topographic index (Zhu, et al., 2013). The DEM gives information about the land elevation and requires detailed spot elevations. It is recommended for the intervals of the spot elevations to be in the range of 10-40 cm in order to obtain a good resolution and cover important details in the area (Mark et al., 2004).

2.14 Sensitivity Analysis and Understanding of the Model Uncertainties

Models are the primary way we have to estimate the multiple effects of alternative water resources system design and operating policies (Loucks, et al., 2005). Modelling real-world phenomena, especially when they are extreme, is generally plagued with errors arising from many approximations (Delenne, et al., 2012). This fact is held true as models are a simplified representation of reality and hence generate probability of failure which is inherently uncertain. Sensitivity analysis is the best method to investigate behaviours of simulated phenomenon. Uncertainties in model outputs as a result of inaccuracies in the input data as well as model structure are unavoidable and inherent elements in hydrological modelling. Understanding of the nature of model uncertainties or the parameters with significant contribution of uncertainty to a model is crucial for a model to be deemed applicable practice.

2.14.1 Sensitivity Analysis

There are always errors when measuring specific quantities or estimating parameter due to variances in in characteristics and behaviour of the catchment elements. Sensitivity Analysis (SA) investigates how the variation in the output of a numerical model can be attributed to variations of its input factors (Pianosi, et al., 2016). Within this broad definition, the type of approach, level of complexity and purposes of SA vary quite significantly depending on the modelling domain and the specific application aims (Pianosi, et al., 2016). In environmental applications, where models are often complex and simulations expensive, an acceptable trade-off has to be found between the need to obtain robust results and the need to limit computational cost (Sarrazin, et al., 2016). SA is an important element of judgement for the corroboration or falsification of the scientific hypotheses embedded into a model (Campolongo & Saltelli , 1997). Many different techniques have been proposed for performing uncertainty and sensitivity analyses on computer models for complex processes (Iman & Helton, 1988). Sensitivity of a parameter and model output can either be expressed quantitatively or qualitatively depending on the level of detail required and the application of the sensitivity results.

2.14.1.1 Sensitivity Analysis Methods

There exists a number of sensitivity analysis methods for models with different degree of accuracy and levels of application to a model contingent to model complexity and the desired accuracy. They range from simple methods for testing the basic effects of model parameters on the output of the model to complex methods integrate both the influence of variation in input parameters and the model response towards multi-scale input parameters. The table below summarises some of the common methods of sensitivity analysis.

Table 2-1 : Summary of sensitivity analysis methods

No.	Method	Description
1	Differential Sensitivity Analysis	Differential analysis of parameter sensitivity is based on partial differentiation of the model in aggregated form. It can be thought of as the propagation of uncertainties (Hamby, 1994). This method is simple and not suitable for multi-dimensional multi-parameters application.
2	One-at-a-Time Sensitivity Measures	This is a sensitivity analysis method that ranks the effect of varying one parameter repeatedly while holding the other parameters. This is simplest method to sensitivity analysis and can easily provide basis for qualitative conclusions.
3	Factorial Design	This is a type of stratified analysis where samples for each parameter are drawn and the model run for all the combinations of the selected samples. It is a hire order of the One-at-a-Time Sensitivity Measures requiring one to perform several runs thus resulting in lots of work. It, however has the potential of yielding highly accurate results.
4	The Sensitivity Index	A sensitivity index method is defined by an operation in which gives the magnitude of the relative sensitivity, in percentage, of the resulting output to the different parameters of the model. The steeper the gradient, the higher the sensitivity of results to changes in that parameter.
5	Subjective Sensitivity Analysis	This method of sensitivity analysis method which performed idiosyncratically (subjectively) by deciding on a selected number of parameters deemed to have influence over the output of the model. It is purely qualitative and is rather simple.

2.14.1.2 Uncertainties associated with hydrological models

Uncertainty of a model result is the measure of discrepancy of the result obtained by running the model due factors including inaccurate input parameters, model complexity, model structure, oversimplification of the model as well as lack of knowledge of the model parameters and outputs. Any modelling exercise involving measuring of parameter quantities and input of the same in a modelling tool weather complex or simple will be characterised by uncertainties. Uncertainties cannot be eliminated, and therefore it is necessary to understand their sources and consequences for model results (Geberemariam, 2015). In hydrological modelling which are dynamic in nature, uncertainty will result from a number of sources e.g. simplifications or approximations in the mathematical construct of the model giving rise to 'model uncertainty' and obscurity in selected values for the model parameters resulting in 'parameter uncertainty'. There are two types of uncertainties classified in the context of their nature which includes 1) Epistemic uncertainty and, 2) Stochastic uncertainty or ontological uncertainty.

Epistemic uncertainty is the scientific uncertainty in a model due to limited data and insufficient knowledge around the model components. On the other hand, stochastic uncertainty results from the probabilistic variability or randomness of the parameters and is irreducible, as the fundamental variables keep changing temporally and spatially. These challenges have resulted in the need for credible way of handling uncertainties including those linked with the nature of the models as well as those resulting from observations required for modelling. For example, the uncertainties associated with rainfall-runoff modelling could mainly result from the following sources; observational uncertainty, model uncertainty and parameter uncertainty.

2.15 Conclusion of the literation review

The literature review revealed that there are a number of models in existence that can be used for modelling flooding. It however provided the suitability of using of SWMM model for modelling urban pluvial flooding reinforcing the decision to choose the model for the research. The literature review further provided the critical analysis of the factors influencing urban pluvial flooding that lead to the analysis of key parameters critical for urban pluvial flooding. This chapter together with chapter 3 therefore proved crucial for identification the key parameters for the modelling exercise.

CHAPTER THREE

3 THEORETICAL FRAMEWORK

3.1 Urban Pluvial Flooding

Urban pluvial flooding primarily results from a combination hydrological, hydraulic and topographical characteristics of the particular urban catchment. This calls for an integrated approach to preparing of the model parameters and the actual modelling. In this study, two key applications were used in an integrated manner to analyse the pluvial flooding in the selected study area. The two applications SWMM version number 5.1 and ArcGIS version 10.1.

3.2 SWMM5.1

The EPA-SWMM is a dynamic rainfall-runoff simulation model that computes runoff quantity and quality from primarily urban areas (Gironás, et al., 2009). It is a computer model used to produce overland runoff hydrographs from catchments before the routing of the resulting runoff to a designated outfalls or outlets. SWMM was first developed by US Environmental Protection Agency in 1971. SWMM 5.1 is the latest series of the SWMM model application by EPA-USA. The choice of the SWMM 5.1 was influenced by its availability as a free ware, its suitability for application with single event rainfall data to for urban flooding analysis, as well as its robustness even where data is scarce to allow modeling from continuous process data.

SWMM5.1 has several features that can be grouped into two main categories based on the general flooding processes. The table below highlights both the hydrologic and hydraulic features of SWMM 5.1.

Table 3-1 : Common features modelled by SWMM

Hydrologic modelling features	Hydraulic modelling features
1) Spatially and time varying rainfall 2) Evaporation of standing surface water 3) Snow accumulation and melting 4) Interception from depression storage 5) Infiltration into soil layers 6) Percolation into shallow groundwater 7) Interflow between groundwater & channels 8) Nonlinear routing of overland flow	1) Handles drainage networks of any size 2) Accommodates various conduit shapes as well as irregular natural channels 3) Models pumps, regulators, storage units using flexible rule-based controls 4) Allows external inflows from runoff, groundwater, RDII, sanitary, DWF, and user-supplied time series 5) Models various flow regimes, such as backwater, surcharging, reverse flow, and surface ponding.

The above features are grouped in four main windows within the SWMM 5.1 including; the atmosphere window accounting for rainfall, the land surface window which is the plane intercepting rainfall and producing runoff, the transport window which directs flow arising from runoff to a grid of drainage systems, and the ground-water window which supports the transport window as well as receiving infiltration from the land surface window. The first three windows are very important to the floods analysis. The atmosphere window provides the precipitation data which is the water input into the catchment recorded within specific time-steps. The land surface window deals with features such as imperviousness/perviousness, evapotranspiration and infiltration aspects among others. The last major window of SWMM5.1 is the transport window which handles flow routing through a network of conduits and nodes or junctions.

3.2.1 Flow Routing

There are three routing methods for overland flow computation. These include the kinematic wave flow, the dynamic wave flow and the steady flow routings. The steady flow routing is often not considered when computing complex flows as it is merely a translation of a flow hydrograph. Therefore only the other two flow routing methods are mostly used in modelling using SWMM. Kinematic wave channel routing method is the most preferred method in many cases, although other methods may be acceptable based on prevailing situation. Computation of flooding including the effects of combined sewer overflow (CSO) will require a computation of both conduit and overland flow. SWMM5.1application has both the computational masks.

3.2.2 Surface and Subsurface Event Flows

Often, in intense storm events, flows may exceed the drainage systems capacities to convey the excess water. This excess water may cause temporary storage at certain nodes till the storm reduces to allow the system to convey the ponded water. The process of surface runoff occurs on saturated or impervious inclined surfaces eventually ending up in a depression where ponding takes place. Figure 3-1 illustrates how surface flow occurs. The intensity of the rainfall event is the precipitation input to the storm water volume on the surface of the plane; the output is a combination of the infiltration f and the runoff volume Q. If the ponding depth (d) increases above the ground roughness (d_p) or y_a and the surface tension's ability to restrict flow is surpassed, then surface runoff occurs.

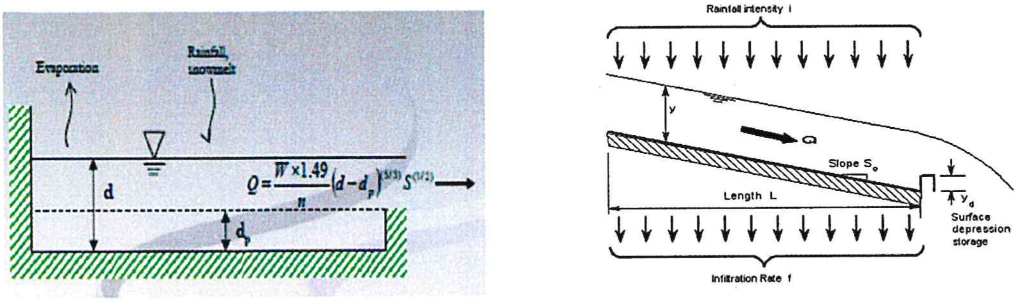


Figure 3-1a and b: Theoretical illustration of surface run-off in SWMM (Rossman 2010).

3.3 Modelling of Flow: The Governing Equations

In flow modelling using SWMM, two blocks are of critical importance i.e. RUNOFF and EXTRAN blocks. The RUNOFF block performs hydrologic simulation and its outputs are taken as input to the EXTRAN block, which routes the conduit flow in a storm sewer system using an explicit numerical solution of the Saint-Venant equations (Hsu, et al., 2000).

The hydraulics behind the flow dynamics of flooding are represented by particular equations used in hydraulic models for flood modelling. There are three types of flows that can occur in a flooding event and each is characterized by its own governing equations depending on the underlying assumptions and level of simplifications to define their applicability. The three types of flows include; gradually varying free surface flow which is a gravity driven flow of water under atmospheric pressure, pressurized flow which is the flow under pressure in a confined closed conduit and a combination of gradually varying free surface and pressurized flow.

3.4 The Gradually Varying Free Surface Flow

The general models used in many applications for to simulate flow apply the Navier-Stokes equations. In flows where the scale of horizontal flow is greater than that of vertical flow, the shallow water equations are used. The shallow water equations also known as Saint Venant equations are derived from the Navier-Stokes equations and are integrated over the flow depth. These are a set of partial differential equations which are usually nonlinear and time-dependent, used to describe the fluids' flow. The equations are articulated based on three conservation principles including conservation of mass-continuity equation, conservation of momentum equation of Newton's Second Law, and conservation of energy-first law of thermodynamics or energy equation. Saint

Venant equations defines gradually-varied unsteady flow with hydrostatic pressure distribution.

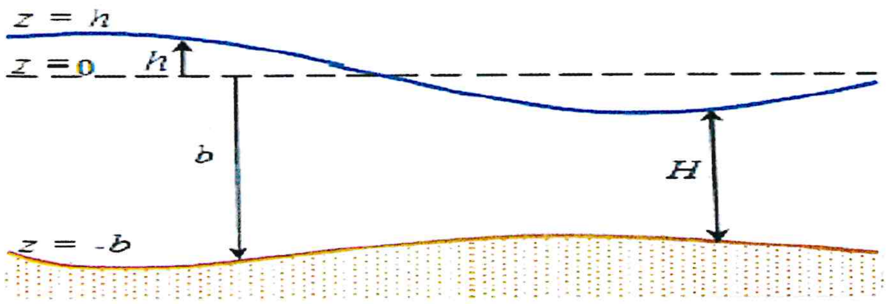


Figure 3-2 : overland flow parameters

From Figure 3-2;

$h = h(t,x,y)$ is the elevation (m) of the free surface relative to the datum, $b = b(x,y)$ is the bathymetry (m), measured positive downward from the datum and $H = H(t,x,y)$ is the total depth (m) of the water column. Note that $H = h(t,x,y) + b(x,y)$.

3.4.1 The 2D Saint Venant Equations

The shallow water equations, also widely known as the 2D Saint Venant equations, are formulated in a conventional form - as a function of the flow area and discharge or the non-conservative form i.e. functions of depth and velocities. The equation holds valid when Coriolis force, eddy losses, wind shear effect and atmospheric pressure are neglected. Depending on the problem being considered and numerical technique being used, it may be more appropriate to deal with one particular form of the equations than another. However, to provide for discontinuities such as a hydraulic jump, a strict processing of conservative equations is required.

3.4.2 1-Dimensional Flood Flows Continuity Equations

The modelling of open channel flow is based on mass and momentum equations with assumptions that flow is 1D, constant distribution of hydrostatic, the density of water constant, and the flow channel is considerably longer compared to the depth of flow. The continuity equations are given by:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(h\bar{u}) + \frac{\partial}{\partial y}(h\bar{v}) = 0 \quad \text{.......(1)}$$

And the momentum equation:

$$\frac{\partial(hu)}{\partial t}+\frac{\partial(hu^2)}{\partial x}+\frac{\partial(huv)}{\partial y}+gh\frac{\partial h}{\partial x}+gh(s_{fx}-s_{bx})=0 \quad (2)$$

$$\frac{\partial(hv)}{\partial t}+\frac{\partial(huv)}{\partial x}+\frac{\partial(hv^2)}{\partial y}+gh\frac{\partial h}{\partial x}+gh(s_{fy}-s_{by})=0 \quad (3)$$

Where: u and v = the velocity components on the x and y directions,

s_{bx} and s_{by} = the bed slopes on the x and y directions,

s_{fx} s and s_{fy} s = the friction slopes on the x and y directions.

The friction slopes are intended to provide for the effects of boundary friction and turbulence. Their description is rather empirical and developed for use with steady state flow.

The frictional slopes are given by:

$$s_{fx}=c_f u\sqrt{u^2+v^2} \quad (4)$$

and

$$s_{fy}=c_f v\sqrt{u^2+v^2}. \quad (5)$$

Where the coefficient c_f is generally written in terms of the Manning n or Chézy roughness factors.

The first term in Equations (2) and (3) caters for local accelerations, where the second and third terms caters for the convective acceleration. The fourth terms is the pressure forces and the last terms cates for the frictional forces.

3.5 Sewer Network Model

3.5.1 Closed Conduit Flow

Contrary to free-surface flow, closed-conduit flow happens in pipelines filled with water and is modelled using the principle of energy conservation. Based on the energy equation and neglecting energy losses, the following parameters should be equal when measured in between two points of a conduit. It is also important to consider the significance and evaluation of the frictional and local losses.

From Darcy-Weisbach's equation, the energy loss due to friction is given by:

$$h_L=f\frac{L}{D}\frac{V^2}{2g} \quad (6)$$

where

□$_L$ = head loss resulting from friction [m],

f = factor of friction,

L = pipe length [m],

D = pipe diameter [m],

V = cross-sectional averaged flow velocity [m/s],

g = acceleration of gravity [9.81 m/s^2].

Conduits are generally the hollow tubing that joins the drainage network at a given junction usually the manholes or pipe connection fittings among others. Key parameters of a conduit may include invert heights at the ends of the conduits, the length of the conduits, cross-sectional geometry and the Manning's roughness coefficient n. On the other hand, the parameters of the junction nodes includes the invert elevation and the invert-ground surface depth. In the transport window of SWMM tool, the most important output is the outflow (sewer flooding). Outflow in SWMM5.1is calculates as show in equation 7 below:

$$Q = \frac{W}{n}\left(d - d_p\right)^{5/3} S_o^{1/2} \quad \text{.........(7)}$$

where

Q = sub-catchment outflow [m^3/s],

W = sub-catchment width [m],

n = Manning's roughness coefficient [-],

d = water depth [m],

dp = depth of depression (retention) [m],

S = slope [%].

It is worth noting that SWMM assumes existence of uninterrupted water surface from the water height at the manhole and in the inbound and outbound connecting sewer pipes. The change in hydraulic head H at the node with respect to time can be expressed as (Rossman, 2010):

$$\frac{\partial H}{\partial t} = \frac{\sum Q}{Astore + \sum As} \quad \text{.....(8)}$$

Where: $Astore$ = the surface area of the node itself,

ΣAs = the surface area contributed by the conduits connected to the node, and

ΣQ = the net flow into the node (inflow – outflow). SWMM5.1 solves equations (6) through successive approximations method.

3.5.2 Surcharge Conditions

In SWMM 5.1, the conditions for surcharging is after all conduits joining a junction node are filled. Surcharge can also occur when the top of the water column at the junction is in between the ground surface and the crown of the uppermost incoming conduit. The flooding under these conditions are exceptional surcharge cases which happens when the ground surface falls below the hydraulic gradient line and there is loss of storm-sewer water from the junction on to the ground surface. The surcharge quantity is given by:

$$Q_s = Q_{in} + Q_r - Q_f, \quad \text{.....(9)}$$

Where: Q_{in} = the total inflow discharge from the upstream conduits,

Q_r = the surface runoff coming in to the manhole; and

Q_f = the design full capacity of the downstream conduits.

Flow continuity condition is applied as follows according to (Rossman , 2006):

$$\sum\left[Q + \frac{\partial Q}{\partial H}\Delta H_n\right] = 0 \quad \text{.....(10)}$$

Where: ΔH_n = the adjustment to the node's head that must be made to achieve flow continuity. Solving for ΔH yields:

$$\Delta H = \frac{-\sum Q}{\sum \partial Q/\partial H} \quad \text{.....(11)}$$

3.5.3 Model Linkage

The SWMM 5.1 uses the 1D sewer network model, which is already adequate to simulate most urban and suburban modeling as conveyance networks are closed pipes or contained open channels as well as hydrological runoff. When the capacity of the pipe network is exceeded, excess flow spills into the two-dimensional model domain from the manholes and is then routed using the Non-convective wave 2D overland flow model (Seyoum, et al., 2011). When $Q_{in} > Q_f$, the discharges Q_s of surcharged flows are introduced into the 2-D diffusive overland-flow model to simulate the surface inundation (Hsu, et al., 2000). Since the rainfall in the simulated areas and the runoff from upland areas has already been input into the RUNOFF block of SWMM 5.1, the only additional input to the 2-D diffusive overland-flow model is the surcharge flow from manholes and outlets of the storm sewer system (Hsu, et al., 2000). For the overland flow and the sewer system surcharge, the linking elements are the main features responsible for regulating the interacting discharges and thereby defining and constraining the extent of the flood inundation characterizing the interacting discharge between the surface and subsurface system (Hsu, et al., 2000).

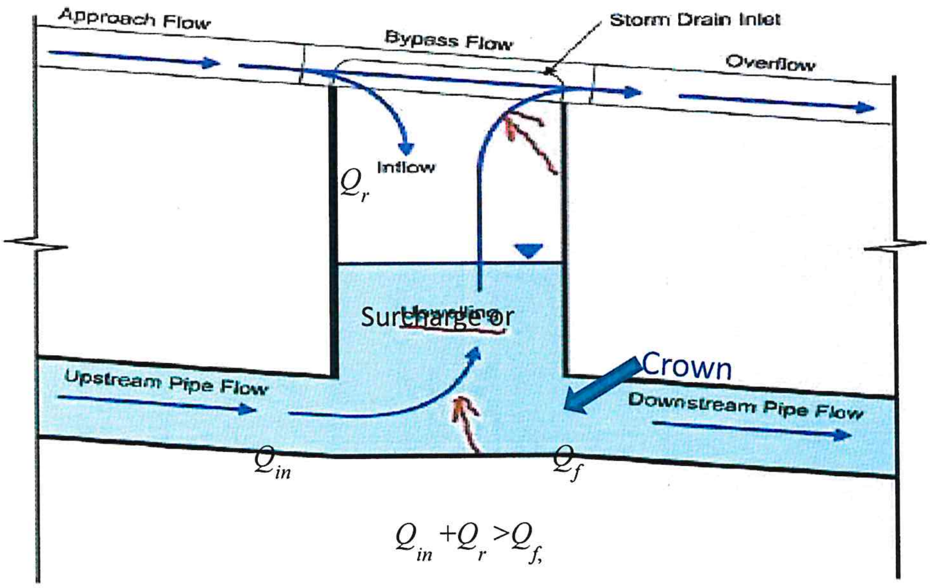


Figure 3-3 : model linkage.

The SWMM 5.1 model is designed with a modification such that the surcharged water doesn't return to the drainage system but flows on the ground surface to the receiving water body or treatment facility.

3.5.4 Evapotranspiration

Evapotranspiration (ET) is the loss of water to the atmosphere by the combined processes of evaporation from the soil and plant surface and transpiration from plants (Allen, et al., 1998). Evapotranspiration is a key process of water balance and also an important element of energy balance (Lingling, et al., 2013). Quantification of evapotranspiration can be done through measuring of associated parameters or by calculation, often using Penman-Monteith equation. The FAO Penman Monteith ETo is defined as the evapotranspiration rate from a reference surface not short of water (Jovanovic & Israel, 2012).

$$ET = \frac{\Delta(K_r - L_r) + \rho_a c_a C_{at} e_* \, a(1 - {}^{W_a}/_{100})}{\rho_w \lambda_\gamma \left[(\Delta - \gamma)(1 + {}^{C_{at}}/_{C_{can}})\right]} \quad \text{.........(12)}$$

where

ET = rate of evapotranspiration [mm/d],

Δ = gradient of saturation-vapour-pressure vs. temperature curve at the air temperature slope of the [mbar/°C],

K_r = net incoming shortwave radiation [kJ/m2/d],

L_r = net incoming long-wave radiation [kJ/m2/d],

ρ_a = density of air [kg/m3],

c_a = specific heat of the air [J/kg/°C],

C_{at} = atmospheric conductance for water vapour [mm/d],

$ea*$ = saturation vapour pressure at the air temperature [mbar],

W_a = relative humidity [%],

ρ_w = density of water [kg/m3],

λ_v = latent heat of vaporization [J/kg],

γ = psychrometric constant [mbar/°C],

C_{can} = canopy conductance [mm/d].

$$ET_0 = 0.0023 R_a (T_c - 17.8) T_R^{0.50} \quad \text{.........(13)}$$

where

ET_o = evapotranspiration rate [mm/d],

R_a = total incoming extra-terrestrial radiation [mm/d],

T_C = temperature [°C],

T_R = daily temperature range [°C].

3.5.4.1 Evapotranspiration on urban areas

For a significant number of urban hydrological issues, notably, water supply, water quality, groundwater recharge, saline intrusions, and flood runoff, knowledge of evapotranspiration (ET) rates is required (Grimmond & Oke, 1999). However, because little is known about the magnitude of urban ET rates and their spatial variability, broad assumptions have to be made in many applications (Grimmond & Oke, 1999).

Urbanisation increases catchment imperviousness which in turn increases runoff rate and linearly decreasing evapotranspiration as a result of reduced vegetation. Therefore, the evapotranspiration influence in urban catchments' water balance is fairly limited. The effect of evapotranspiration on stormwater modelling of rainfall events in urban catchments may remain almost negligible. In this study therefore, evapotranspiration will be neglected as it is assumed that the storm was a short intense downpour limiting potential evapotranspiration.

3.5.5 Infiltration

Infiltration occurs when water penetrates into the soil and has a critical influence on surface runoff during storm. This seepage water through the openings interspacing soil or other permeable medium can occur during dry or wet weather with water going into the combined sewer system. Urbanization results in reduction of permeable surface thereby reducing infiltration. This has the effect of increasing of runoff peak and volume. However, urban areas are hardly 100% impermeable hence some element of infiltration take place during a storm event. Numerous formulations, some entirely empirical and others theoretically based, have been proposed over the years in repeated attempts to express infiltration rate or cumulative infiltration as a function of time (Obiero, 1996). The three distinct infiltration methods used in SWMM are discussed below.

3.5.5.1 The Green-and-Ampt model

The Green-Ampt (GA) model is widely used in hydrologic studies as a simple, physically-based method to estimate infiltration processes (Chen, et al., 2015). The GA model is based on the assumption that the soil surface is continuously wetted by ponding water during infiltration, and the wetted and dry regions of the wetting domain are assumed to be separated by a sharp wetting front (Nie, et al., 2017). The GA model assumes that a sharp wetting front separates the soil profile into an upper saturated zone and a lower unsaturated zone (Nie, et al., 2017). This infiltration model was developed by Green and Ampt in 1911 and is regarded to be capable of providing a comprehensive and appreciative details of the process of infiltration as it can clearly provide a comprehensive infiltration trend until saturation occurs. It is therefore the approach that is highly preferred for modelling the infiltration process.

The time dependent governing equation for GA is given below:

$$f(t) = K_h^* \left[1 + \frac{|\psi_f|(\phi - \theta_o)}{F(t)}\right],\ t_p \leq t \leq t_w \ldots\ldots(14)$$

where

(t) = infiltration rate [cm s-1],

K_h^* = hydraulic conductivity [cm s-1],

ψ_f = effective tension at the wetting front [cm],

$(\phi - \theta_0)$ = initial soil water deficit [-],

$F(t)$ = cumulative depth of the wetting front [cm],

t_p = time of ponding, or the instant of the surface layer becoming saturated [s],

t_w = instant of the entire soil column becoming saturated [s].

3.5.5.2 Horton's Theory

Robert E. Horton is best known as the originator of the infiltration excess overland flow concept for storm hydrograph analysis and prediction, which, in conjunction with the unit hydrograph concept, provided the foundation for engineering hydrology for several decades (Beven, 2004). Horton's equation is one of the earliest and most popular empirical models for simulating infiltration (Ajayi , et al., 2016).

Horton's infiltration theory is built on the principle that the rate of infiltration is indirectly proportional to ground wetness. The wetter the ground becomes, the slower the rate of infiltration and thus continued storm event results in slower infiltration rate. The method is simple, useful for ungauged watersheds, and accounts for most runoff producing watershed characteristics as soil type, land use, surface condition, and antecedent moisture condition (Gabellani, et al., 2008). Although not necessarily representative of the actual physical behaviour of the soil the foregoing procedure can satisfactorily simulate the integrated' infiltration behaviour of the catchment elements (Bauer, 1974). Horton's Equation is the governing heuristic equation for infiltration and is given by:

$$(f - f_c) = (f_0 - f_c)e^{-kt} \ldots\ldots(15)$$

where,

f_{in} = infiltration rate

f_0 = (initial) infiltration rate for dry ground

f_c = (asymptotic) infiltration rate for saturated ground

k = infiltration constant

Horton's limitation is its assumption that the rate of rainfall is always higher than the rate of infiltration which is not usually the case.

3.5.5.3 The Curve Number method

Soil Conservation Services and Curve Number (SCS–CN) technique is one of the primogenital and simplest method for rainfall runoff modelling (Satheeshkumar, et al., 2017). The Curve Number method of estimating rainfall excess from rainfall penetration is extensively used in applied hydrology. Its development resulted from the realization of the need to obtain hydrologic data and to establish a simple procedure for estimating rates of runoff by the Soil Conservation Service (SCS).

The CN method has extensively been used to predict flood runoff depth where catchments are ungauged. The SCS-CN method deals with accumulated rainfall P and accumulated runoff Q corresponding to a rainfall (Michel, et al., 2005). Equation 16 shows the CN relationship. CN is easier to apply as it requires just one parameter (S_p) associated with the watershed characteristics. S_p is correlated to CN by the relationship:

$$CN = 1000/(10 + S_p) \qquad (16)$$

However, the CN method of infiltration modelling is most suitable for the rural catchments.

3.5.6 Dry Weather Flow (DWF)

Dry weather flow is the wastewater flow in a sewer network system during zero storm periods and is characterised by minimum infiltration as well as slow flow velocities. The slow flow during dry weather flow intensifies holding time if conduits and waterways are not designed correctly resulting in adverse sedimentation hence reducing the system capacity. This leads to increase in the frequency of surcharges even for low rainfall events. Therefore, it is essential to understand, for purposes of checking the hydraulic behaviour of the sewer network systems during periods without rainfall events, the dry weather flow dynamics to appropriately provide for the inflows during storm events.

A combined storm-sewer system is known to have additional capacity above what is provided for wastewater (sewage) to provide for storm conveyance during rainfall events. The design is ordinarily grounded on the capacity to treat multiples of DWF including population served expressed as water consumption / head / day (typically 150 litres), commercial wastewaters flow (litres) and infiltration.

Any increase in flow therefore, due to increase in population or to increased trade discharges, has the potential of resulting in overflows and so the risk of flooding thus endangering the welfare of the population. DWF being calculated using the formula below.

DWF = P G + I + E, ...(17)

where

P = Population served

G = Water consumption / head / day (typically 150 litres)

E = Trade Effluent Flow (litres)

I = Infiltration*

*Infiltration should be measured where possible using measured night time flows at the sewage works.

3.5.7 DWF Characteristics and Estimation

The average per capita flow during the dry period is calculated using the following equation:

$$FPC = \frac{ADF}{PE} \quad \text{......} (18)$$

Where

FPC is the Flow per capita.

ADF is the Average daily flow (m^3/day), and

PE is the Total population equivalent

The information that related to design sewerage systems are as follows:

$$ADF = FPC \times PE \quad \text{......} (19)$$

3.5.7.1 Base flows

Base flow estimates which is occasionally stated as "trickle flows" are flows not necessarily related directly to precipitation but may result from excess irrigation, wastewater return flows, groundwater recharge of streams, water system losses, and other urban water uses. These flows are sometimes seen in streams and even engineered channels during dry periods. Currently, for drainage basins, there are no known mechanisms for directly ascertaining their sources and quantifying them. This is often neglected in most of the analysis and will not be considered in this design.

3.6 Topographic Data for Urban Flood Modelling

The significance of the topographic data and their role in urban flood modelling cannot be underestimated as they provide the modeller with land surface and topography representation which influences surface flow. It is one of the most vital data sources for deriving variables and key parameters applied to urban flood modelling. Some of the most important topographical aspects used in the flood modelling include digital terrain model (DTM) and DEM. The most widely used DEMs for flood modelling applications are made of a collection of surface elevation values on a regular square grid. In this study, data from DEM sources was used to discretize the watershed into grid cells in the form of both the overland cells and channel cells through river network delineation by use of GIS.

3.7 Sub-catchments Slope

Catchments and sub-catchments slope is a parameter used to indicate the surface inclination of the areas. In SWMM5.1a sub-catchments is theoretically shown as a plane. Runoff is therefore perpendicularly directed towards the lower edge of the plane. In reality, sub-catchment slope and shape fluctuates within the sub-catchment, a common fact usually with huge diverse sub-catchments comparable to the likes of Nairobi West areas that is being studied. Thus, the best way to estimate the height term when deriving sub-catchment slopes was by DEM. The determination of the average slope of the sub-catchments using the equation below:

$$S = \frac{H_g}{L_c} \quad \text{.....(20)}$$

Where:

S = the slope,

H_g = the ground elevation and

L_c = the sub-catchment length.

3.8 Disaggregation of Rainfall Data

Rainfall disaggregation is the process of scaling down coarse resolution rainfall data into a finer temporal resolution for application in fine time series dependent modelling. Rainfall is intensity and quantities are variable over time and cannot be lumped when modelling hydronic behaviour of a catchment. This makes it necessary to disaggregate rainfall to improve historical data series to simulate finer course data series. Disaggregation concepts has further developed to a stage where it is now possible to perform a multi-level cascade down-scaling now referred to as multifractal down-scaling. Multi-fractional processing of the data has proven a potential method in hydrological modelling as it results in finer data series with mathematical and statistical resemblance of the storm variability pattern. The most widely used tool to simulate multifractal random processes is the framework of multiplicative random cascades (MRC) which was formalized by Mandelbrot [1974] (Paschalis, et al., 2012). They are stepwise split models, mathematically constructed for use to reflect sporadic and highly irregular behaviour especially of rainfall. The models highly rely on cascade weights whose careful and appropriate selection and distribution is of great significance. Based on the ease of application, the RMC was adopted for this study.

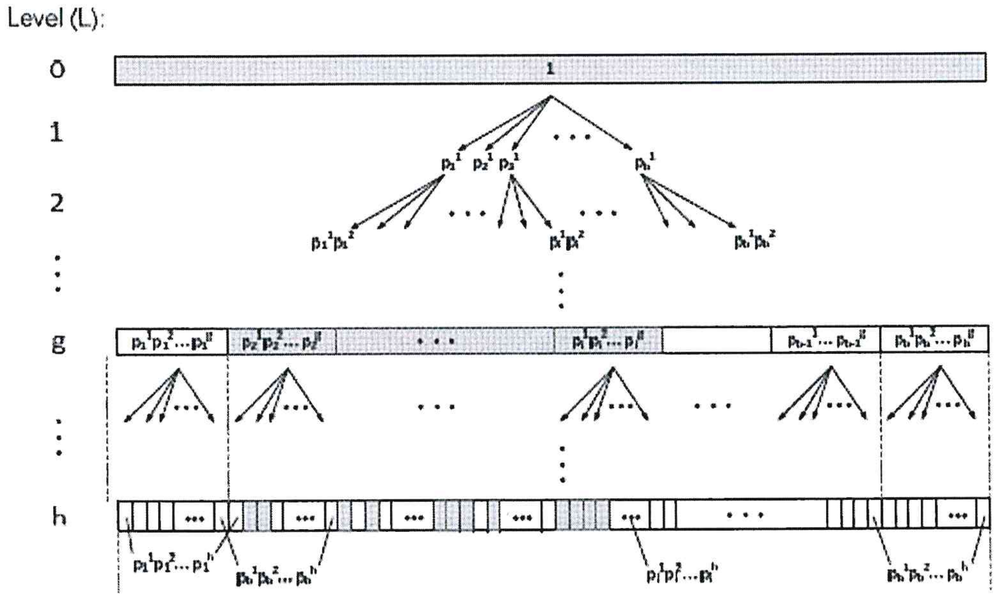


Figure 3-4 : Schematic diagram illustrating multiplicative cascade process and the associated mappings to rainfall sequences adapted from **(Wang, et al., 2010).**

The cascade weights are random variables which are assumed to be independent and identically distributed (iid) (Paschalis, et al., 2012).

3.8.1 Development of MRC

In urban areas, flooding is often a result of intense rainfall event occurring over a shorter duration of time. Whereas modelling of urban flooding will need the rainfall data of higher resolution, the meteorological stations often capture these data in lower resolutions. In Kenya for example, the publicly available rainfall data is in daily recordings. These types of data must then be transformed into the scale in which they can be used for modelling without losing properties of the original aggregated values.

In stochastic hydrology, a natural process $R(t)$, e.g. rainfall, is usually defined at continuous time t, but we observe or study it at discrete time as $R_j^{(\delta)}$, which is the average of $R(t)$ over a fixed time scale δ at discrete time steps j (= 1, 2, . . .), i.e. (Lombardo, et al., 2012):

$$R_j^{(\delta)} = \frac{1}{\delta}\int_{(j-1)\delta}^{j\delta} R(t)dt \quad (21)$$

Let $f\,\delta$ be a time scale larger than δ where f is a positive integer; for convenience δ will be omitted. Then, we can define the aggregated stochastic processes on that time scale, $Z_j^{(f)}$ (and relate it to the mean aggregated $R_j^{(f)}$) as (Lombardo, et al., 2012):

$$Z_j^{(f)} = \sum_{l=(j-1)f+1}^{jf} R_l = fR_j^{(f)} \quad (22)$$

e.g. $Z_1^{(f)} = R_1 + \ldots + R_f$ and $Z_2^{(f)} = R_{f+1} + \ldots + R_{2f}$ ....(23)

The disaggregation model following this approach is a simplified way of generating time-series through a logarithmic transformation of a step-by-step linear connection.

3.8.2 Multiplicative Random Cascade Model

The downscaling model in this study is based on a discrete multiplicative random cascade (MRC). Let $R_1^{(f)}$ be the mean rainfall intensity over time scale f (equation 22 above) at the time origin (j = 1); $R_1^{(f)}$ is assumed to be a random variable with mean μ_0 and variance σ_0^2 of a stochastic process, which we wish to be stationary. $R_1^{(f)}$ (for convenience $R_{1,0}$) is then distributed over b sub-scale steps of equal size $\Delta s = f/b$ (i.e. $R_j^{(\Delta s)}$, j = 1, 2, . . ., b). This is accomplished by multiplying $R_{1,0}$ by b different weights (one for each sub-scale step) *W, which are independent,* and identically distributed (iid) random variables (Lombardo, et al., 2012). The discrete random process at $\Delta s_k = b^{-k} f$ scale of aggregation is given by:

$$R_j^{(\Delta s_k)} = R_{j,k} = R_{1,0}\prod_{i=0}^{k} W_{g(i,j),i} \quad (24)$$

where j = 1, 2, . . ., b^k is the index of position in the series at level k; i is the index of the level of the cascade; $g(i, j)$ denotes a function which defines the position in the series at the level i, i.e. $g(i, j) = \frac{j}{b^{k-1}}$, which is a ceiling function. For $k = 0$ we have $W_{1,0} = 1$ (Lombardo, et al., 2012).

For a *canonical* cascade (another description of downscaling model) the values of the individual equal time steps at level k totals to the initial value at level 0 as shown in the equation 25 below.

$$\left\langle \frac{1}{b^k} \sum_{j=1}^{b^k} R_{j,k} \right\rangle = \langle R_0 \rangle \quad \ldots\ldots (25)$$

The expected value of $R_{j,k}$ (equation is given by):

$$\langle R_{j,k} \rangle = \langle R_k \rangle = \left\langle R_{1,0} \prod_{i=0}^{k} W_{g(i,j),i} \right\rangle \quad \ldots\ldots (26)$$

$$= \langle R_0 \rangle \prod_{i=0}^{k} \langle W_{g(i,j),i} \rangle = \langle R_0 \rangle \langle W \rangle^k = \mu_0 {\mu_W}^k \quad \ldots\ldots (27)$$

From the above two equations:

$$\frac{1}{b^k} \sum_{j=1}^{b^k} R_{j,k} = \langle R_0 \rangle, \qquad R_k = \mu_0, \quad \mu_0 {\mu_W}^k = \mu_0 \; and \; \mu_W = 1 \quad \ldots\ldots (28)$$

Consequently, W fulfil the form $\mu_W = 1$.

CHAPTER FOUR

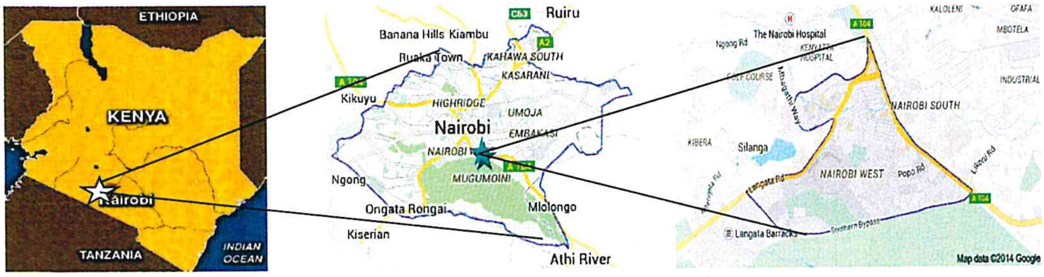
4 METHODOLOGY

The results of the study was expected to demonstrate how SWMM 5.1 and ArcGIS 10.1 can be used to model and analyse urban pluvial flooding and be used as a case for influencing decision support in strategic planning for urban storm water management. The flooding in the study catchment is influenced by two components including direct runoff from the storm and flows through the drainage system that induces inundation through surcharge. For this reason, a multi-step approach is required to ensure that all the components have the right data-sets for integration and modelling.

4.1 Study Area

Nairobi City, lying 36.59 degrees east of meridian and 1.19 degrees south of the Equator, is Kenya's capital, Eastern Africa. It has a varying altitude ranging from 1,600 to 1,850 metres above sea level with a temperate tropical climate. Generally, it has two distinct rainy seasons with the period running from April to June being the time of long rains while the months of November and December are usually characterised with short rainfall. The topography of the city slopes towards the eastern side which is generally flat from the uneven western side which is the highest. Nairobi city has an area of 689 km^2 a population of approximately 3.9 million people.

Nairobi city has been suffering from flooding over the past one decade due to heavy rainfall events. Urbanization, informal settlement, and more surface infrastructure than people need has resulted in impervious pavement which blocks the infiltration of rainfall/runoff through to groundwater. The area chosen for this study is Nairobi West, about 5.3 km South-East of the city from the city centre and is almost entirely urbanized with estates consisting of residential houses, commercial buildings, health centers, schools and other institutions including colleges, churches and mosques. The area has a population of 33,377 inhabitants according to the 2009 national census report occupying an area measuring approximately 1469.528 acre (5.94km). This gives a population density of 5,619 persons/km^2. The maps below indicates the study area location within Nairobi.



Map 1a, 1b and 1c: The location of the study area in Nairobi, Kenya.

4.2 The study process

The study process involved a number of sequential activities ranging from the literature review, software acquisition for modelling data collection and parameter estimation, analysis of the data including model simulation, interpretation of the simulation results discussion and reporting. The study was enabled through a number of data categories drawn from different sources, processed using different applications and subsequently fed into the SWMM5.1. The spatial data was first processed and analysis through ArcGIS 10.1 before being used with SWMM 5.1 to simulate the urban pluvial flooding of the area. The set of steps involved in order to model the flood situation in the area included literature review- to visualise the full extent of the gaps where this research fits, identification and acquisition of models and their softwares, data collection and parameterisation, data entry and model running, analysis of the model output and discussion of the results.

4.3 Identification of pertinent parameters for input in SWMM 5.1

In order to run the model and analyse the results for the specific objectives of this study, it was necessary to identify and input parameters. The identification of the pertinent model parameters was done through extensive review of literature on urban flooding modelling, critical analysis of the SWMM hydrologic and hydraulic components' features highlighted in table Table 4-1 according to the SWMM 5.1 Manual and the sub-catchment characteristics. Further breaking down of these features to specific properties associated with the catchments hydrologic and hydraulic features resulted in the individual parameters. The hydrologic parameters included storage (S-imperv), Impervious Manning's n (N-imperv), Pervious Manning's n (N-imperv), Sub-catchment area (A), sub-catchment width (W), percentage slope (% slope), disaggregated rainfall and the infiltration model. On the other hand, the hydraulic parameters identifies included junction invert elevations, maximum depth of junctions, length of conduits, conduits roughness coefficient, dry weather flow and conduits' shapes. These were the parameters processed through various methods including ArcGIS 10.1 for input in the SWMM 5.1 model thus yielding the results discussed here in this chapter. This process was further helped by the review of the theoretical framework dealt with in chapter 3 of this report.

4.3.1 Identification and Acquisition of Models and Support Softwares

The most preliminary activity was the identification and acquisition of the mandatory tools that would be required for simulate the flooding phenomenon in the area. As the study required key computer softwares suitable for modelling urban flooding given the urban flooding characteristics, an inventory of these applications was checked to help select the appropriate modelling tool.

4.3.2 Model Selection

This study applied the latest series of SWMM (version 5.1). The software is a freeware downloaded from the EPA website. It was found that SWMM5.1 would be ideal for modelling urban pluvial flooding as has been used in various design interventions in various cities Europe and America. The choice of SWMM5.1 for use to model the hydrodynamic of the area was also influenced by its availability as a free ware. In addition to the main tool which is the SWMM5.1, a large amount of geospatial data required GIS software hence the acquisition of ArcGIS 10.1 software.

4.3.3 Data Collection

The whole set of data including; sub-catchment areas components, precipitation, drainage systems components were extracted from various sources. In order to accurately integrate the GIS and the SWMM5.1in modelling, all the variables that should be accounted for in a flood system and the complexity of urban pluvial flooding due to interaction between hydrological processes (rainfall), and hydraulic processes (sewer surcharges) were considered. The data considered during data collection for parameterization included topographical data (slope data and land use data to define the pervious and impervious areas), precipitation data, evapotranspiration, area, width, sewer and other drainage data including the manholes in the study area.

4.3.3.1 GIS data

The GIS data for Nairobi, specifically for the study area for the year 2010 were collected from various sources including; DEM data with 5m-square spatial resolution to surface topography present from World Resource Institute (WRI) which produces data sets, charts, maps, infographics, and other visual resources. The watershed data was obtained from diva.GIS in form of hillshed-shapefiles for Kenya while the land use shapefiles and data was downloaded from Center for Sustainable Urban Development's (CSUD) Nairobi GIS maps and database.

The area of interest (AoI) for the study was digitized from the most updated google earth map. This AoI formed the larger catchment of Nairobi West and South C areas in which the study focused. This area was then used to clip the various features of interest including the sewer network system and the manholes that was provided for the entire of Central Nairobi, the pervious and impervious areas based on the land use shape files for Nairobi and the DEM.

4.3.3.2 The study area sewerage system

The sewer system data for the study area were obtained from the Engineering Department of Nairobi City Water and Sewerage Company (NCWSC). This data, which was in a GIS data format, covered the entire of the central region of Nairobi and was then sized by used of ArcGIS and included: the sewerage conduits network with their lengths, diameters, coordinates, materials from which they are made, and the manholes in the area with their invert levels.

4.3.3.3 Precipitation data

The rainfall (precipitation) data was acquired from the Kenya Meteorological Department (KMD). The data comprised 5-years duration daily rainfall recordings from January 2009 to December 2013 for three meteorological stations in Nairobi namely, Wilson Airport Meteorological Station, Dagoretti Corner Meteorological Station and Jomo Kenyatta International Airport Meteorological Station. These three neighbouring stations were chosen because of their relative proximity to the selected sub-catchments in the study area. Wilson Airport Meteorological Station is the closest station with a continuous period of record for precipitation data. It was not possible to get hourly or finer resolution data due to policy issues. Precipitation from these stations when compared showed a very low variability in rainfall in areas between the stations, almost insignificant. A precipitation file was created from these three stations from 1st January 2009 to 31st December 2013 (Appendix A). One particular heavy and continuous rainfall event of 26th December 2012 was of greater interest for this study. This particular storm caused loss of lives as well as a trail of destructions including forcing more than 500 families to abandon their homes and sleep in the cold night. Several roads in the city were flooded and this hindered the smooth flow of traffic (KMD, 2013).

The data type and the institutions from where the data was acquired are summarized and presented in table 4-1 below.

Table 4-2: Key data used in the simulation and analysis including their sources.

Data		**Type of data**	**Data Source**
Precipitation		Daily rainfall records for 5 years between January 2009 and December 2013.	Kenya Meteorological Department (KMD).
Sewerage network system	Manholes and pipes	Existing sewer system plan for Nairobi Central zone.	Nairobi City Water and Sewerage Company. (NCWSC)
	Dry Weather Flow	Estimation of dry weather flow from literature regarding population and PE.	Literature and Ministry of Water and Irrigation (MoWI) design manual.
Sub-catchment		Land use characteristics of Nairobi by 2010	Center for Sustainable Urban Development (CSUD)
GIS files		Digital cadastre for DEM analysis.	DIVA.GIS
		Othophotos from screen shots and exports.	Google Maps

4.3.4 Sub-catchments Parameterization

There are various parameters which are essential to flood modelling in general. However, there may be additional parameters for modelling urban pluvial flooding. The chosen SWMM5.1 required a wide range of parameters in order to come up with good model. While some of the parameters were straightforward, other parameters were derived through the processing geospatial data using other tools such as GIS and data disaggregation techniques. The rainfall data may require disaggregation in order to achieve a fine resolution data for use with SWMM5.1. The many and crucial parameters involved in the modelling were determined using different techniques and empirical formulas especially for the immeasurable hydrological components.

4.3.4.1 Entities used in EPA SWMM5.1

The key sub-catchment parameters for use in the EPA-SWMM5.1 are provided in detail in table 4-2 below:

Table 4-3: Sub-catchments parameters as defined in EPA-SWMM-5.1. Adapted from SWMM-5.0 Manual (Rossman, 2010).

Sub-catchment Properties	Input Values
Area	Area of the sub-catchment (e.g. rooftop area, the rain garden, rain barrel) (ha)
Width	Characteristic width of flow running over the sub-catchment (m)
Slope	Percent slope of the water surface flowing over the sub-catchment
Imperviousness	Percent of impervious area of the sub-catchment
Impervious N	Manning's factor n for the flow over the impervious area (dimensionless)
Pervious N	Manning's factor n for the flow over the pervious area (dimensionless)
Dstore-Imperv	Depth of depression storage on the impervious area (mm)
Dstore-Perv	Depth of depression storage on pervious area (mm)
% Zero-Imperv	Percent of the impervious area with no depression Storage.
Subarea Routing	Choice of internal routing of flow between pervious and impervious sub-areas (allows directing the flow between the pervious and impervious areas within a sub-catchment).
Percent Routed	Percent of the diverted flow toward a sub-area within a sub-catchment
Rain Gages	Refers to the rain gage where the rain intensity is defined over a time interval.
Outlet	Defines which node or sub-catchment is receiving the flow

The parameters associated with the above properties were estimated using different methodologies. The parameters included sub-catchment area, flow width, sub-catchment length, imperviousness, perviousness, sub-catchment slope, evapotranspiration, infiltration, manning's 'n' for various materials, the rain-gauge for the area, the sewer pipes attributes as well as the manholes.

Prior to addressing sub-catchment-specific parameters, a number of general parameter settings exercises were undertaken. These included: (i) manually assigning to each sub-catchment the correct outlet node as provided by the sewer network data, (ii) were naming of the sub-catchments, (iii) setting of the routing of the flow from both the pervious and impervious portions of a sub-catchments directly to the outlet, and (iv) linking the two sub-catchments to the rain gage at Wilson Airport which is within the wider area of study.

4.3.4.2 Sub-catchment Properties

The selected area of interest for the study which was treated as one big catchment was divided into two sub-catchments based on the available sewer data, each with specific properties and parameters for input in SWMM5.1model. Before creating the sub-catchment, certain default elements are set in the new project started. These elements are grouped in three components including ID labels which are mainly the labelling process for the key elements that to be used in the simulation and focuses on the raingauges (Gauge), Junctions (J), Outfalls (Out), and Conduits (C). The second component is the sub-catchment where the default values are set for all the properties as detailed in table 4-3. The third and last component to be set was the nodes/links properties which includes node maximum depths, conduit roughness, node invert, node ponded area, conduit length, conduit geometry, flow units, force main equation (Darcy), links offsets, and routing method (kinematic).

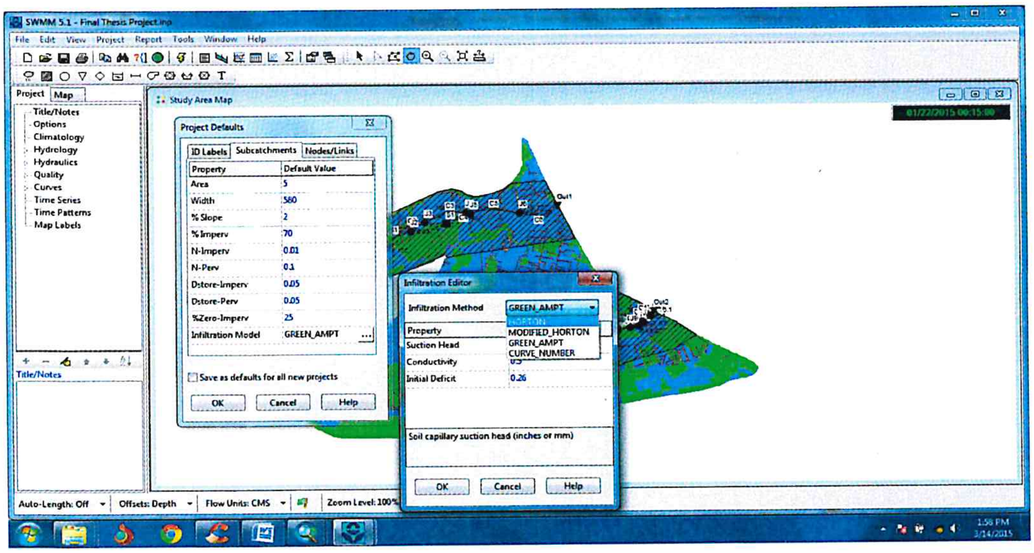


Figure 4-1: The setting of SWMM-5.1 defaults in preparation for sub-catchments data.

Table 4-4: The default values set for the SWMM-5.1 project for simulation and analysis.

ID Labels			Sub-catchments			Nodes/Links		
1	Raingauge	Gauge	1	Area	5	1	Node invert	0
2	Junction	J	2	Width	500	2	Node Max Depth	4
3	Outfall	Out	3	Slope	2	3	Node ponded area	0
4	Conduit	C	4	Imperviousness	70	4	Conduit length	400
			5	Impervious N	0.01	5	Conduit geometry	Circular
			6	Pervious N	0.1	6	Conduit roughness	0.01
			7	Dstore-Imperv	0.05	7	Flow unit	CMS
			8	Dstore-Perv	0.05	8	Link offset	Depth
			9	% Zero-Imperv	25	9	Routing method	Kinematic
			10	Infiltration model	Green-Ampt	10	Force main equation	Darcy-Waisbach

4.3.4.3 Data preparation for entry into SWMM5.1

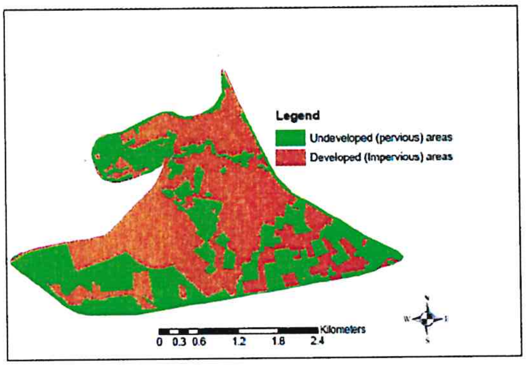
The input data used in the study comprised rainfall data, percent perviousness and imperviousness, percent average slope, area covered in square metres, length and widths of the sub-catchments, sewerage system networks data (including lengths, diameters, material and manholes with their invert elevations), the population density of the area, average water consumption in the city of Nairobi and GIS data for production of various map features such as DEM, impervious maps among others. The result of these individual analyses of the various sub-catchment properties were then used with SWMM5.1 model. The detail on this task is systematically explained the following subsections.

4.3.4.3.1 Precipitation

Although it was possible to acquire characteristic rain events for the Nairobi region it was not possible to get rain series for the same and through the assistance of the Weather Spark website, the characteristic rainfall event for 26th December 2012 and the storm duration was used to perform a data disaggregation. The recording was from Wilson Airport weather station where the nearest rain gauge is located approximately less than 2 km to the south west of sub-catchments but in the project area. The model was run with synthetic precipitation time series resulting from the disaggregation process.
The actual time of the storm was necessary for determining the specific wet weather duration for the day. This data, like the hourly rainfall data resolutions, could not be obtained from the Kenya Meteorological Department due to policy restrictions. However, the wet and zero precipitation hours over the 24-hours for that day was obtained from prediction of the day by WeatherSpark. Weatherspark is weather website displaying interactive weather graphs and information. It allows the user to skim through the entire history of any weather station on earth. The 94.5mm daily rainfall recorded was disaggregated to 15 minutes wet weather runoff time steps. Since daily rainfall in itself is considered to be of coarser time series, the rainfall data for this particular day was disaggregated into finer time series of 15 minutes resolution for use with SWMM5.1as per requirement. The disaggregation was performed using the simple cascade model to the fourth level leading to the 15 minutes rainfall resolution within a total duration of **6** hours for the simulation as predicted and recorded by the WeatherSpark.
With the exact rainfall durations and magnitude obtained from the Weather Spark, the 94.5mm rainfall for the day of interest was disaggregated. The original value of the daily record for the rainfall event of 26th December 2012 of 94.5mm was applied as the aggregated figure at the initial level of disaggregation. The complete set of parameters and their values for the model are summarized in Tables 4-4 to 4-11.

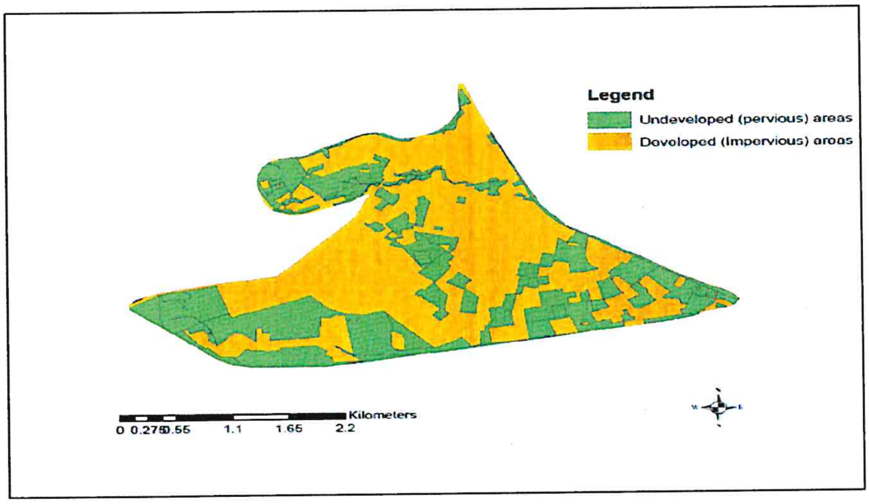
4.3.4.3.2 Impervious and pervious areas

The Orthophotos obtained from Google Earth was used to verify the estimated pervious and impervious areas of the selected sub-catchment areas. To estimate the percentage pervious and impervious areas of the project site, the most current land use layer for Nairobi city, obtained from the CSUD - Nairobi GIS maps and database was updated through digitization using the satellite map from the most updated google earth tool.



Map 2a and 2b: Digitizing pervious and impervious areas of the study area (Nairobi West and South C).

The area was generalized into developed (impervious) and undeveloped (pervious) areas. The red bordered area is the impervious area while the green bordered area illustrates the pervious areas. The intent here was to simplify the estimation of the overall average percentage of the pervious and the impervious areas of the selected sub-catchments. The impervious was considered to comprise of roofs, roads, paved areas and other establishments that disturbed the natural land cover of the study area while the areas that had the natural land cover and natural water courses and storage surfaces were considered pervious.



Map 3: The impervious areas of the study area

To estimate the imperviousness of the two sub-catchments, information on the current activities on the land as obtained from the SCUD topographic database and the othophotos from the google earth. Based on the digitised map of different forms of polygons, the surface area of the two sub-catchments were assumed generally to be either impervious or pervious. These included diverse varieties of buildings, parking lots, roads and streets which were depicted in the same database. The imperviousness parameter was determined by use of ArcGIS. On the other hand, within the sub-catchment, the unused land were grouped as pervious. Both the pervious and impervious areas of the sub-catchments were determined as percentages of the total sub-catchment area. In this study, from the estimation made from Map 3, the percent impervious was estimated to be 80% for the sub-catchment S_1 and 60% for sub-catchment S_2.

4.3.4.3.3 Infiltration

The Green-and-Ampt model was applied in the SWMM5.1to accommodate infiltration involving two important parameters dependent on the soil. These included the capillary suction head ψ and saturation hydraulic conductivity *K*. a third parameter of the infiltration considered was the initial infiltration model state defined by the initial moisture deficit (IMD_{max}). In the SWMM, the infiltration index is a default figure determined by the model after selection of Green-Ampt infiltration model in the sub-catchment settings.

4.3.4.3.4 Evapotranspiration in urban areas

As stated earlier in the literature review, the degree of soil imperviousness greatly affects the rate of evapotranspiration. As the imperviousness of an area rises, the degree of evapotranspiration linearly declines due to reduction in vegetation cover and reduced infiltration, which makes surface water to be held for shorter periods and to quickly flow into drainage paths in the sub-catchment. Therefore, when modelling storm water flooding in developed areas, the influence of evapotranspiration parameter is usually negligible and thus not considered.

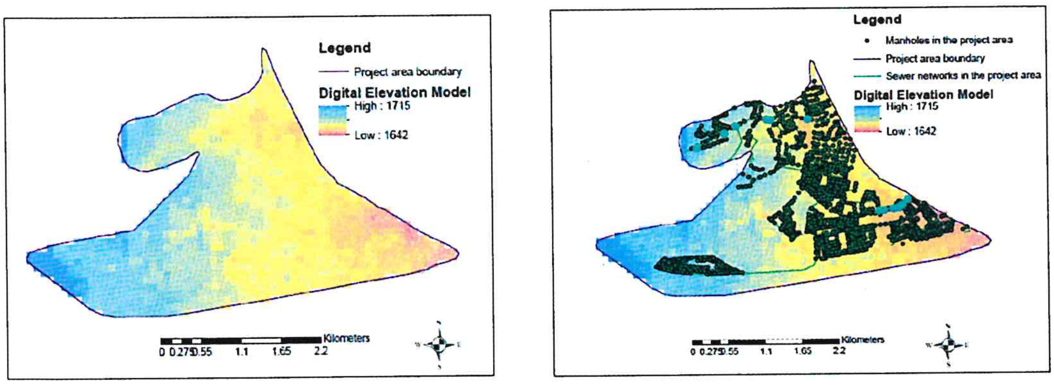
4.3.4.3.5 Area and flow width

One of the slightest tangible SWMM5.1parameters is the flow width. Flow width is the distinctive breadth of the surface over which the sheet flow runoff passes. Sub-catchment areas were calculated with the aid of SWMM5.1ruler, which has the capability to estimate both area and linear measurements. Likewise, the flow width parameter was also calculated in a more straightforward way using the ruler tool of the SWMM5.1. The sub-catchment areas having been created on the area map loaded from GIS bitmap with well-known coordinates, the estimation was merely a question of using the ruler tool to define appropriate flow widths (see figure 4-3). Using the ruler function of the SWMM5.1, the width of sub-catchment 1, S_1, was found to be 835.87m while that of sub-catchment 2, S_2, was found to be 703.30m.

4.3.4.3.6 Digital Elevation Model

The digital elevation data (DEM) files were downloaded from DIVA GIS website (diva.org) which obtains them from NASA's Shuttle Radar Topographic Mission (SRTM). USGS also provide data of up to approximately 90m resolution for free in their USGS ftp site among other platforms. DEM was part of the necessary model input and was provided through processing and analysis of DEM files downloaded with ArcGIS 10.1 by overlaying the DEM raster data on to the area of interest and clipping the DEM for the study area.

Using the Spatial Analyst Tool the downloaded DEM data was processed to produce contours before generating shaded relief image. The shaded relief features of the DEM and the contours clearly showed the difference in elevations as well as the depressions in the selected sub-catchment areas for the study. This shaded relief image was then overlaid with the sewer network data for the area and analysed for depressions positions and the network plan.



Map 4a and 4b: DEM details of the study area and the sewer system layout in the area.

4.3.4.3.7 Catchment and sub-catchment delineation

The catchment delineation of the sub-catchment areas was built upon both the topography and the comprehensive data of the sewer network system which also serve as a combined system for wastewater and storm water. To delineate the sub-catchment areas of interest and mark out the sub-catchment boundaries, the conduits and the manholes layers were overlaid on to the already processed DEM map with shaded relief showing high and points of the study area. The manholes with complete data i.e. Manhole invert levels and ground levels were then selected and given different symbology for ease of positioning (the blue dots in map 4b above represent manholes with complete data). This enabled the selection of the two sub-catchment areas of interest in the study area where data was complete. This reduced the study area from that of the originally defined study catchments of Nairobi West and South C.

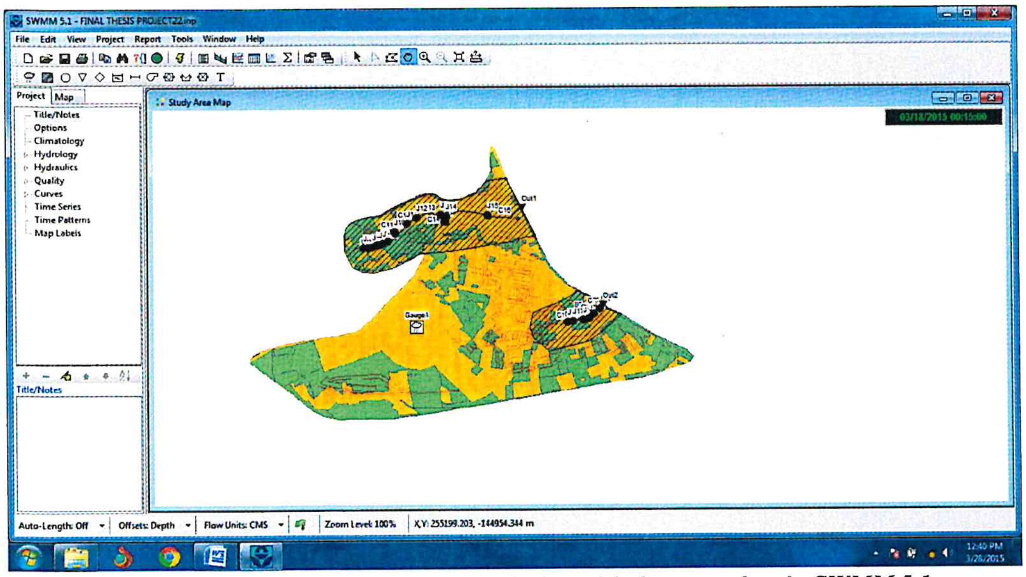


Figure 4-2: Sub-catchment demarcation and overlaying with the sewer data in SWMM 5.1.

The new geographic scope representing the original study area are shown in figure 4-3 because of the potential extreme flooding as indicated by the DEM map 4a above and the completeness of stormwater sewer system data. Therefore the two sub-catchments, all the sewer pipes had key attributes including diameters, lengths, and materials. The pipes were of concrete and varying diameters of between 150mm to 300mm with different lengths.

4.3.4.3.8 Slope

The length of the sub-catchment was also calculated using the ruler tool of the SWMM5.1model which then together with the difference in elevations between the start and end of the sub-catchment was used to calculate the slope. The length was measured along the overland sheet in the orientation of the direction of the sewer flow which drains to the outfall.

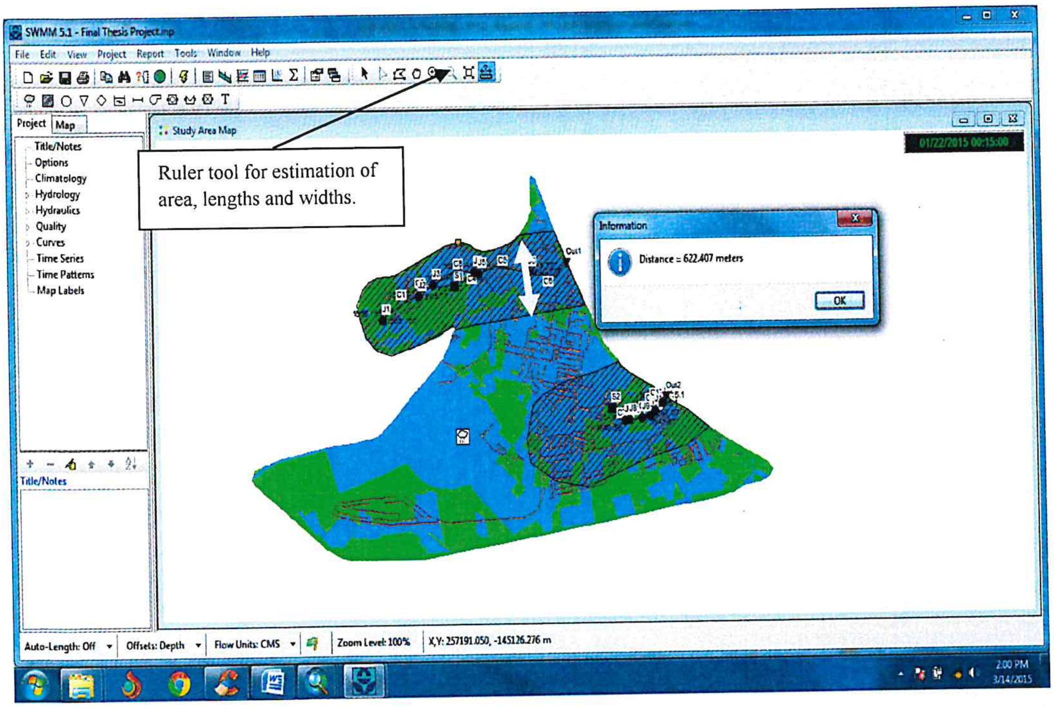
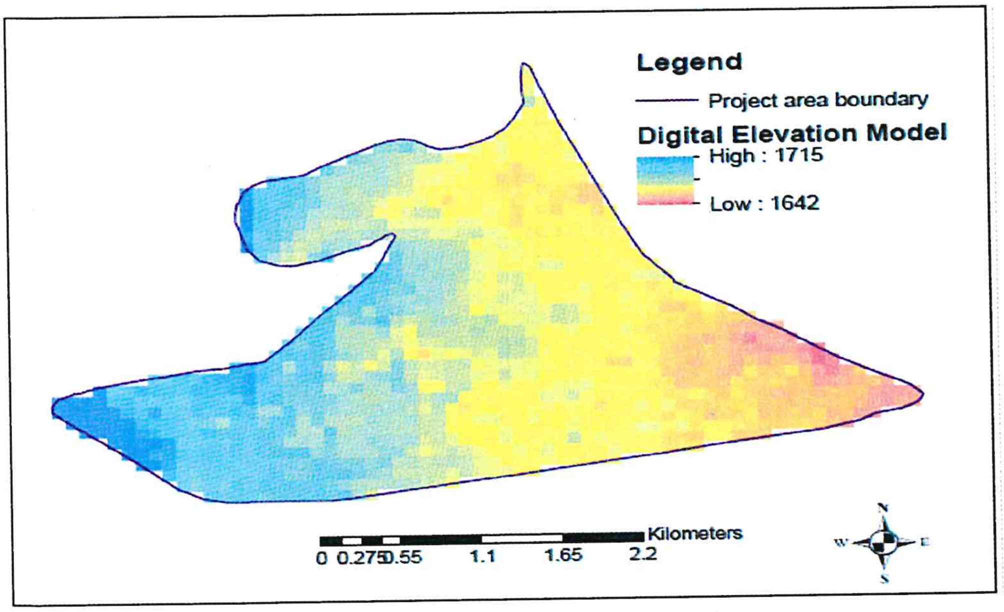


Figure 4-3: Estimation of sub-catchments area, lengths and widths using the ruler object of the SWMM-5.1

The slope of each sub-catchment was calculated by reading the highest point elevation and the lowest point elevation from the DEM map. Based on the DEM map and the resultant values of highest to lowest elevations, the average absolute rise was determined. The next step was to determine the catchment length which was achieved by use of the ruler tool (see figure 4-3). Using the catchment length and the heights determined from the DEM analysis, the slope parameter for the two sub-catchments were determine. The slope was found to be 0.5% for sub-catchment S_1 and 1.23% for sub-catchment S_2.



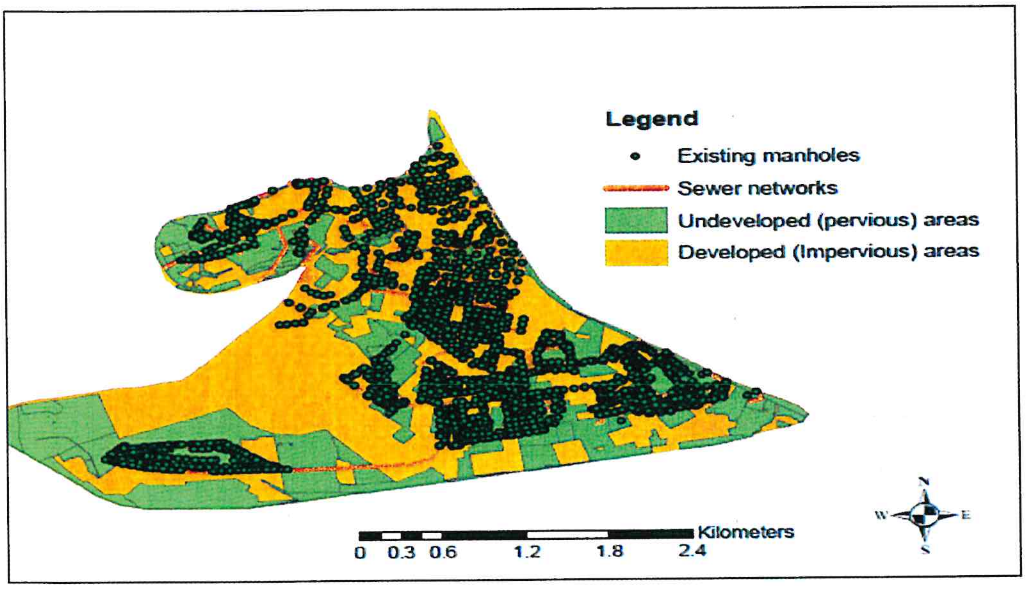
Map 5: The study area DEM details.

4.3.4.3.9 Manning's roughness coefficient *n* for overland flow

The roughness coefficient *n for* impervious areas of the two sub-catchments was estimated at *0.015*, being the value for old concrete surface that has slightly become rougher over time. Likewise, an *n* value of 0.3 was set for the pervious areas. This value was considered as a concession between the values for woods with light underbrush (0.40), thick grass (0.24) and small grass (0.15).

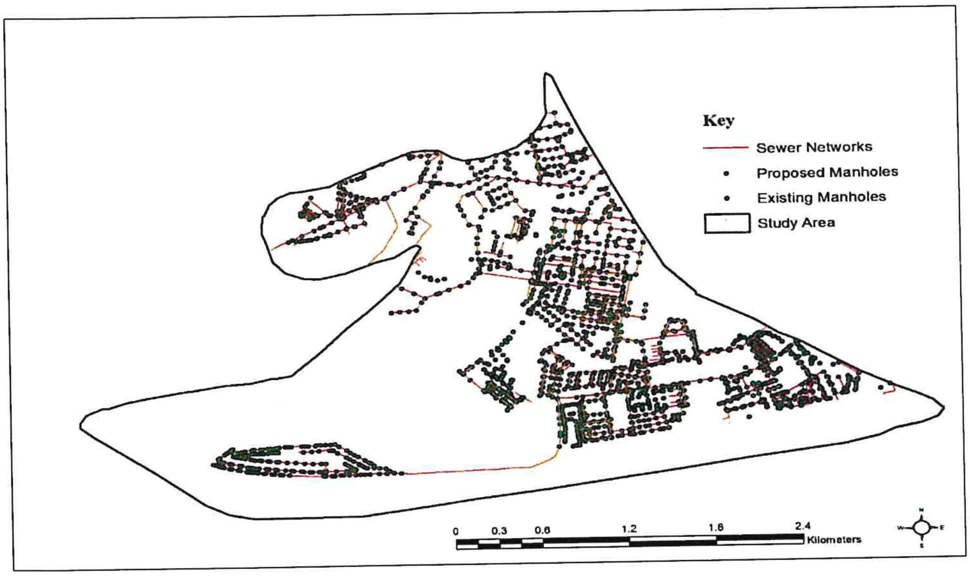
4.3.4.3.10 Sewer database

The city of Nairobi is hugely dependent on combined sewer system i.e. a system dealing with both the wastewater and storm water during rainfall events. Therefore the simulation of the flood behaviour in the selected project area needed analysis of both hydrologic as well as hydraulic characteristics of the area including the behaviour of the sewer system when there is extreme rainfall events in the area. The hydraulic behaviour of the combined sewer system for the two study sub-catchments was analysed for specific storms event of 26th December 2012 measuring 94.5mm. Surcharge is caused by the filling up of all pipes joining a node. A surcharge situation can also arise when the water surface at the node rises to a level below the crown of the uppermost joining conduit and the ground level. The added map which was first processed in ArcGIS and exported for utilization by SWMM5.1 in a BMP format had visual objects that were processed prior to importation into the SWMM5.1 including sub-catchment demarcations, links, nodes (junctions) and depressions.



Map 6: Sewer network and accompanying manholes positions in the study area.

The sewerage master data used for the SWMM5.1 model components in a GIS format comprised of a total of 642 sewer pipes (conduits) and 3,164 manholes. Each sewer conduit considered had data-set that included; x-y coordinates, both ends connection details, shape, junctions, as well as diameters while the manhole data included the invert elevation which was useful in verifying the slope. From the overlaid layers of the sewer network and the manholes, only the pipes that linked the manholes with complete data were considered. The table below contains the pipes details that were used in the SWMM 5.1. As a result of data sorting through ArcGIS 10.1, only 24 manholes and 22 conduits were found to fulfil the data detail required for SWMM 5.1 simulation. The pipe lengths were included in the data obtained from NCWSC. However, the pipe end elevations were estimated from the manholes ground level data provided by the NCWSC.



Map 7: Stormwater drainage network layout of the study area. Manholes are shown as dots and conduits as red lines.

Table 4-5: Sewer network system conduits' properties for sub-catchment 1 (S_1)

Conduit number	Diameter (m)	Length (m)	Measured length (SWMM5.1Ruler reading)(m)
C_1	0.225	271.28	31.164
C_2	0.225	271.28	16.699
C_3	0.225	271.28	33.505
C_4	0.225	271.28	42.661
C_5	0.225	271.28	18.709
C_6	0.225	271.28	41.671
C_7	0.225	271.28	49.969
C_8	0.225	66.31	148.401
C_9	0.225	127.46	20.599
C_{10}	0.225	121.67	142.151
C_{11}	0.225	138.665	109.390
C_{12}	0.600	324.21	235.804
C_{13}	0.600	80.23	51.147
C_{14}	0.600	569.48	397.453
C_{15}	0.600	533.31	357.672
$Outlet_1$	-		

Table 4-6: Sewer network system conduits' properties for sub-catchment 2 (S2)

Conduit number	**Diameter (m)**	**Length (m)**	**Measured length (SWMM5.1Ruler reading)(m)**
C_{16}	0.23	309.923	52.644
C_{17}	0.23	303.638	114.289
C_{18}	0.23	303.638	67.231
C_{19}	0.3	87.167	56.039
C_{20}	0.3	95.53	76.300
C_{21}	0.3	86.858	67.440
$Outlet_2$			

After determining the lengths and elevations of the conduits, the Manning's roughness coefficient *n* was determined from the pipe material for the conduits in the study area. Typically all the sewer network conduits in the two sub-catchments were of concrete pipes. Based on the SWMM5.1 User's Manual, the value of *n* ranging from 0.011 to 0.015 is applicable to the concrete material. However, many of the pipes were fairly old, hence rougher. Therefore, the value of *n used for all the pipes was* 0.014.

4.3.4.3.10.1System nodes (inlets, manholes, etc.)

The imported Bitmap from the ArcGIS had the sewer system with feature classes containing all the junctions, inlets, and outfalls with invert elevations. The tables 4-6 and 4-7 below summarises the properties of the system nodes for parameterisation.

Table 4-7: Sewer network system nodes' properties for sub-catchment 1 (S_1)

Junction number	Junction Ground level	Junction invert level from data	Estimated invert level for missing data	Depth
J_1	1667.616	1665.166	1665.166	2.450
J_2	1668.096	1666.000	1666.000	2.096
J_3	1667.963	1665.000	1665.000	2.963
J_4	1666.926	1664.240	1664.240	2.686
J_5	1666.673	1664.330	1664.330	2.343
J_6	1666.373	1664.000	1664.000	2.373
J_7	1666.072	1663.890	1663.890	2.182
J_8	1665.491	1663.110	1663.110	2.381
J_9	1662.915	1660.050	1660.050	2.865
J_{10}	1663.160	1660.770	1660.770	2.390
J_{11}	1663.080	1658.450	1658.450	4.630
J_{12}	1661.152	1659.000	1659.000	2.152
J_{13}	1657.661	1653.941	1653.941	3.720
J_{14}	1657.152	1653.362	1653.362	3.790
J_{15}	1655.377	1649.777	1649.777	5.600
$Outlet_1$	1649.000	1647.000	1647.000	2.777

Table 4-8: Sewer network system nodes' properties for sub-catchment 2 (S_2)

Junction number	Junction Ground level	Junction invert level from data	Estimated invert level for missing data	Depth
J_{16}	1649.680	1648.560	1648.560	1.120
J_{17}	1649.660	1648.070	1648.070	1.590
J_{18}	1649.590	1647.570	1647.570	2.020
J_{19}	1649.570	1647.070	1647.070	2.500
J_{20}	1648.240	1646.100	1646.100	2.140
J_{21}	1645.100	1642.240	1642.240	2.860
$Outlet_2$	1642.000	1640.000	1640.000	2.240

Overall, 43 points were included with two outfalls at the end of the two sub-catchments. Invert elevation and maximum depth were attributed to each of the junctions and outfalls. Invert height tells the elevation of the lowest of the manholes under consideration. As no data on this was available for the maximum depth, the maximum depth was set at 4m beneath the level of the bottommost conduits connecting to the junction node. The difference between the junction node invert and the ground level is what is referred to as maximum depth. The invert elevation of the two points taken to represent the sub-catchments drainage outfalls were assumed to be those of the height of the incoming conduit ends.

4.3.4.3.11 Dry Weather Flows

The total amount of sewerage flowing from the selected sewersheds within the sub-catchments was added using Dry *Weather Inflow window* into the SWMM 5.1 model. The assumption here was that each distinct sub-catchment in the model also represented distinct sewersheds. For simplicity, only daily dry weather inflows were added to the model as use of peak daily flows could have resulted in greater volume. It is therefore advisable, if a more accurate analysis is required, for the researcher to use diurnal time pattern to integrate the dry weather inflows holistically. The use of diurnal behaviour of the dry weather flow in modelling while integrating continuous rainfall records would enable a modeller to model the systems' dynamic performance for all events types. In this study the area was predominantly residential hence the average for domestic water consumption was used in the population equivalent equation. The per capita consumption averages were obtained from the ministry of Water and Irrigation, Kenya design manual as shown in the table below.

Table 4-9: Water consumption rates. Adopted from the Practice Manual for Water Supply in Kenya (Ministry of Water & Irrigation, 2005).

CONSUMER	UNIT	RURAL AREAS			URBAN AREAS		
		High potential	Medium potential	Low potential	High class housing	Medium class housing	Low class housing
People with individual connections	l/head/day	60	50	40	250	150	75
People without connections	l/head/day	20	15	10	-	-	20

The per capita domestic wastewater consumption rates vary between 250m^3/person/day for high class housing and 75m^3/person/day for low class housing. The average of this was used to calculate the dry weather flow for the two sub-catchments.

From the area and population, the population density for the area was calculated. The area of the wider Nairobi West which was the area of interest is 5.94km^2 and has a population of 33,377 people. This gave the population density of 5,619 persons/km^2. The population density was then used to calculate the populations for the selected sub-catchments.

Table 4-10 : DWF values for the two sub-catchments S1 and S2

Sub-catchment	Area (km^2)	Population density (persons/km^2)	Population (persons)	Average water consumption (m^3/person/day)	DWF (m^3/person/day)
S1	1.76	5,619	9,889	158	158
S2	0.7976	5,619	4,482	158	158

4.3.4.3.12 Sub-catchment Outlets

After the sewer conduits and junctions were entered in the model, the outlet nodes were then defined for the two sub-catchments. These were the nodes that received the storm water runoff generated by the sub-catchments together with the corresponding wastewater flows.

4.3.5 Integration of Model Parameters and Analysis

Simulation of urban pluvial flooding is a complicated exercise that requires several parameters processed and validated through different tools. In this study, GIS was used to process the topographical parameters of the sub-catchments including processing of percentage permeability of the sub-catchments, DEM, sub-catchment slope and delineation of the sub-catchment areas using the sewer system data available. These processed GIS based parameters were then imported into the SWMM 5.1 together with the hydrological data to simulate the urban pluvial flooding in the area. Other data integrated in the model was the dry weather flow values estimated through per capita water consumption and the population equivalent for the area.

4.3.5.1 Setting of the SWMM5.1for the input data

The setting up of the SWMM5.1 model started with specifying the default settings of options and object properties to be used in the model as a new project opened in the SWMM5.1.1. This allowed for importation of the area of interest through the back-dropping in order to create the sub-catchment areas. Also imported in the map of the area of interest was the sewer network with the selected manholes which had invert figures from the BMP map created using ArcGIS 10.1. These created base settings for the entry of the already obtained parameter values.

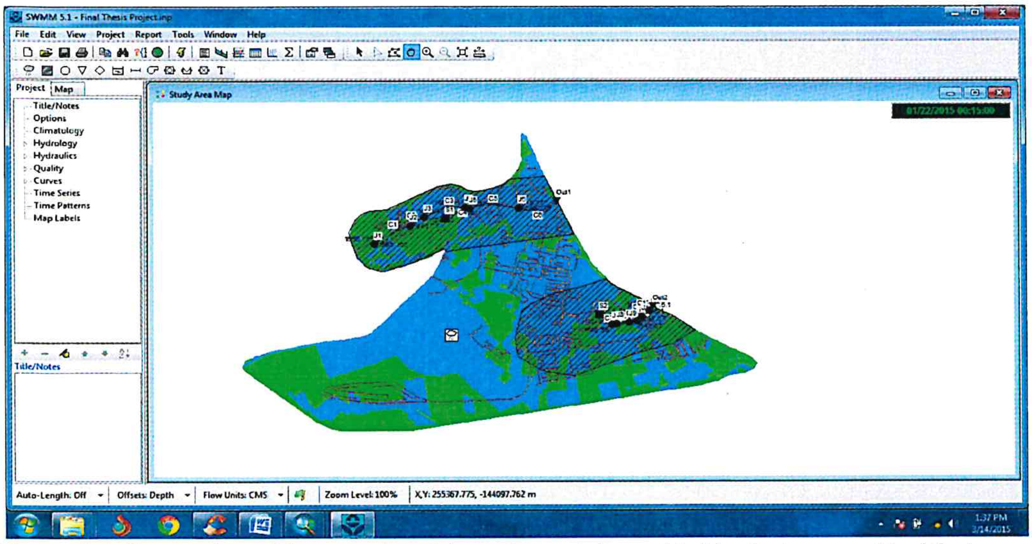


Figure 4-4: Screen view of the two sub-catchments created as guided by the topographical features of the area and the available sewer/manhole data.

Most of the parameters including lengths, widths, slope, area, imperviousness, manning's 'n', depression storage, infiltration and evapotranspiration were estimated using ArcGIS and literature. The two tables below details the parameter values that were used in the modelling of flooding in the two sub-catchments, S_1 and S_2.

Table 4-11: Properties of the sub-catchment S1 parametrised

No.	**Property**	**value**	**No.**	**Property**	**Value**
1	Area (ha)	176.066	7	Depression storage pervious areas	0.05
2	Width (m)	835.871	8	Depression storage impervious areas	0.05
3	Slope (%)	0.5	9	% impervious area without depression storage	20
4	Imperviousness (%)	80	10	% Routed	100
5	Roughness coefficient, impervious areas	0.014	11	Subarea routing	outlet
6	Roughness coefficient, pervious areas	0.15	12	Infiltration	Green-Ampt

Table 4-12: Properties of the sub-catchment S2 parametrised

No.	Property	value		Property	Value
1	Area (ha)	79.795	7	Depression storage pervious areas	0.05
2	Width (m)	703.302	8	Depression storage impervious areas	0.05
3	Slope (%)	1.23	9	% impervious area without depression storage	40
4	Imperviousness (%)	60	10	% Routed	100
5	Roughness coefficient, impervious areas	0.014	11	Subarea routing	outlet
6	Roughness coefficient, pervious areas	0.15	12	Infiltration	Green-Ampt

The parameterization of both the links and the nodes completed the work required to create the parameters required by the transport compartment of SWMM 5.1.

4.3.6 Data Input into the SWMM5.1

After the sub-catchment parameterization, the parameters identified were analysed to decide on how significant they are to urban pluvial flooding in areas of Nairobi West and South C with respect to the selected SWMM5.1.

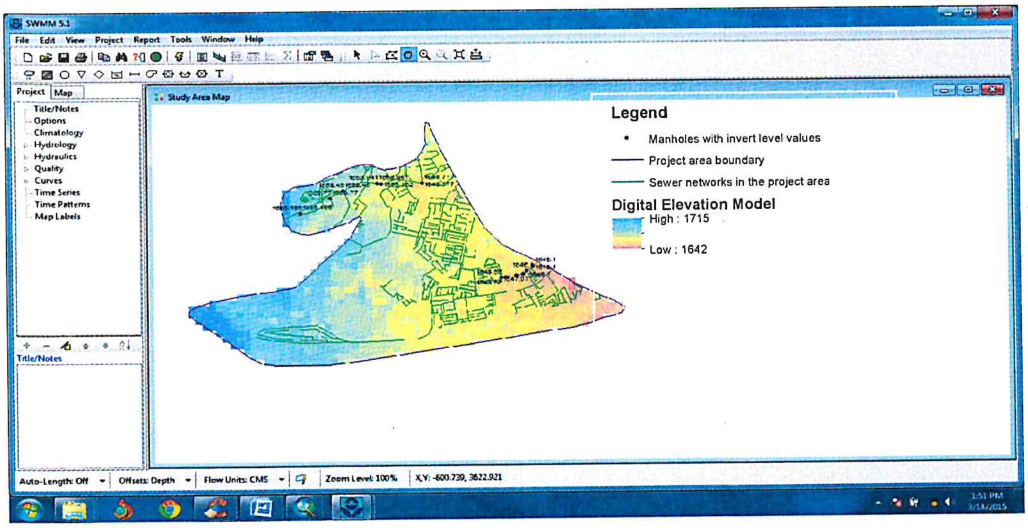


Figure 4-5: Screen view of SWMM-5.1 showing DEM details overlaid with sewer network & manholes.

As per the DEM, the sewer system's data and the manholes with ground elevation values as shown in the figure 4-5 above, the two sub-catchments were selected from the wider study area of Nairobi West for further parameterization and analysis. The two sub-catchments were created using the add sub-catchment tool in the SWMM5.1. It is worth noting that the sub-catchment areas were estimated with the idea that the SWMM5.1model is suitable for smaller sub-catchments usually not larger than 5km^2. Another consideration was that these areas had relatively complete data including conduits with distinct characteristics (diameters, length and material type) and manholes with ground level values as well as invert elevations.

4.3.7 Choosing the Kinematic Wave Method

SWMM5.1uses varying assumptions when calculating flow through channels and surfaces which are categorized into the three flow routing models discussed below. The simplest of the three flow routing models found in the SWMM5.1is the steady flow as it does not cater for flow to fluctuate spatial-temporally within a pipe. But in reality, the intensity of storm affects flow within conduits. This means that the model is of limited application to runoff analysis. The second flow routing model is the dynamic wave method which incorporates the most number of hydrologic factors to solve the Saint-Venant flow equations. This works most accurately when all or most of the data types are available. For this study, data on this property among others was prohibitively difficult to get hence not available. This allowed for the use of kinetic wave method for this work. Even though the kinematic wave method cannot evaluate flow in flooded conditions like the dynamic wave method, the focus of this study and its scope was a rainfall event that resulted in varied flows in an area which could be sufficiently predicted by the kinematic wave method. The choice of the kinetic wave method was therefore, influenced by the facts above.

4.3.8 Choosing the Green-Ampt Infiltration Method

The Green-Ampt method was chosen because of strong and realistic consideration of its ability to provide for water seepage through the soil of some degree of absorbency along a "wetted front."

4.4 Sensitivity Analysis and Uncertainty Assessment

The assessment of parameters with greater potential of resulting in uncertainty in the model output was done during the study. One-at-a-Time sensitivity measures method was preferred for estimating the model sensitivity using six selected parameters. It measured the response of the peak runoff against six selected parameters namely: sub-catchment area, flow width, sub-catchment slope, permeability, impervious N and Pervious N. The uncertainties associated with modelling urban pluvial flooding using SWMM5.1 based on the parameters used were also researched from the existing literature and qualitatively analysed.

4.5 Summary of Methodology

The flow chart below (figure 4-6) illustrates in summary, the whole process that led to the achievement of the integrated modelling and analysis of the urban pluvial flooding in the two sub-catchment areas. It outlines the stages from data collection, parameter identification and parameterisation, to the data entry and model run. It ends with the discussion and recommendations on the potential opportunities for application of the model in storm management and areas that needs further research.

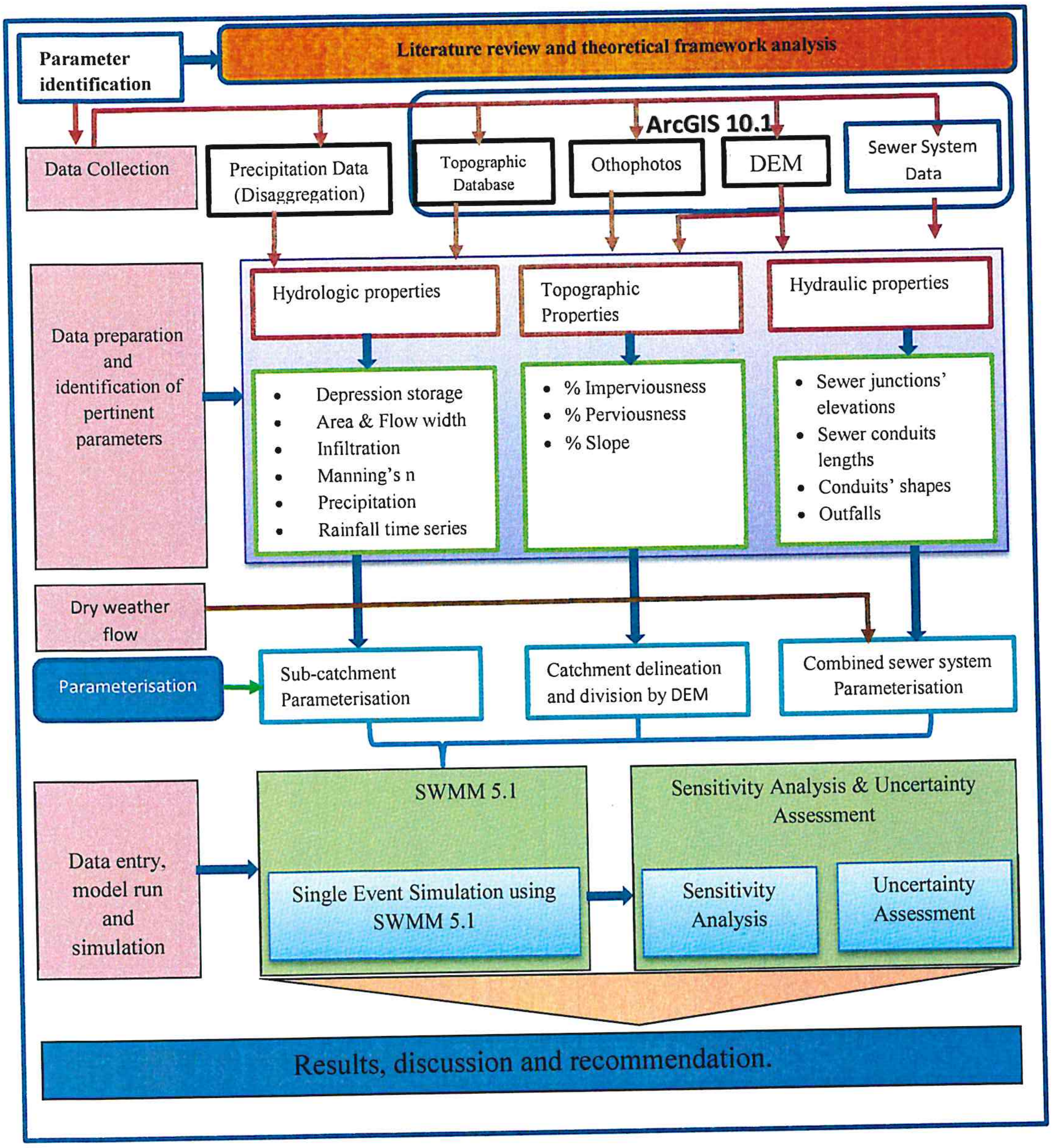


Figure 4-6: Flow process illustrating the methodology of the study.

CHAPTER FIVE

5 RESULTS AND DISCUSSION

One simulation with the estimated parameter values was run on the SWMM 5.1 model and another 30 simulations during the sensitivity analysis. After each run of the model, a status report for the simulation was extracted giving the overall behaviour of both the catchment surface runoff as well as the drainage network flows. From the status report obtained after running the model, it could be seen that the research provided several significant outcomes of integrated simulation of flooding and the strength of using SWMM 5.1 in studying urban pluvial flooding. The results of the simulation included outputs from both the RUNOFF and the EXTRAN modules as elaborated in the SWMM 5.1's Status Report in appendix F. The results of the simulation are presented in both tabular and graphical formats. The aspects analysed and discussed include the mass balance providing summery of result of various elements of both the surface runoff as well as the sewer network system, sub-catchment runoff summary, surcharge and flooding in the sewer systems, sensitivity analysis and a brief assessment of which parameters has potential of resulting in model uncertainty.

5.1 Result of the Mass Balance

Based on the mass balance equations inbuilt in the SWMM model, two distinct mass balance outputs were obtained in the status report as shown in the full status report in appendix F, i.e. the runoff mass balance expressed in mm for depth or hectares-m for volume and the flow mass balance in m^3, [see table 5-1]. The values in the mass balance summary table are average of the two sub-catchments of the study. The internal outflow is seen be 764.876m^3 during the entire storm.

Table 5-1: Mass balance scenario from the status report.

Flow Routing Continuity	**Volume (ha-m)**	**Volume (10^6 ltr)**		**Runoff Routing Continuity**	**Volume (ha-m)**	**Depth (mm)**
Dry Weather Inflow	56.703	567.034		Total Precipitation	23.710	92.667
Wet Weather Inflow	19.958	199.581		Final Surface Storage	3.105	12.134
External Outflow	0.117	1.174		Surface Runoff	20.134	78.689
Internal Outflow	76.487	764.876		Evaporation loss	0.000	0.000
Initial Stored Volume	0.043	0.429				
Final Stored Volume	0.008	0.081		Infiltration loss	0.540	2.112
Continuity Error (%)		0.119		Continuity Error (%)	-0.289	

Table 5-2 : Sub-catchment runoff summary

Sub-catchment	Total precipitation (mm)	Total infiltration (mm)	Total runoff (mm)	Total runoff (ha-m)	Peak runoff (mm)	Runoff Coefficient
S1	92.67	1.65	77.79	136.96	18.25	0.839
S2	92.67	3.14	80.67	64.37	9.49	0.871

The total precipitation of the runoff mass balance was 92.667mm, only 1.833mm less than the 94.5mm recorded by the rain-gauge at Wilson Airport and used during the disaggregation. The small and insignificant difference could have resulted from the complexity of the model as it was run. Based on the summarised mass balance report, the dry weather flow for the whole duration of storm was found to be 567.034m^3 while the wet weather inflow was found to be 199.581m^3. The total surface runoff from the simulation was found to be 78.689mm. The Infiltration Loss was found to be 2.112mm. However, the evaporation loss is was zero as it was found to be of negligible influence for short intense rainfall and so was not considered in the model. The final outflow at the two outfalls was found to be 1.174m^3. The final stored volume is just the sum of the storage in nodes together with the storage in links after all the nodes and links storage losses are considered was found to be 0.081m^3. The runoff continuity error was found to be -0.289% while that of the flow routing was found to be 0.119%.

5.1.1 Estimated Dry Weather Flow

Even though dry weather flow is usually a combination of domestic, industrial and commercial wastewater discharged into sewers systems without being affected by recent or current rain, in this case only the domestic waste water was considered. The model computed the dry weather flow as 567.034m^3. This flow significantly constituted an added input to sewer models of combined systems. As established later in the analysis of the nodes and conduits, there occurred bi-directional interchange of flow volume between the sewer system and the surface resulting in urban pluvial flooding. This parameter is significant if the sewer network capacities are to be adjusted as it will help the designers and planners to estimate the additional capacity of the network conduits and nodes required to cater for storm from an extreme precipitation. When an equal amount of runoff enters the system, the dry weather flow is then treated as a surcharge and combines with any extra amounts of runoff (wet weather flow) to cause urban pluvial flooding.

5.1.2 Modelled Wet Weather Flows

Wet weather flow includes a number of including surface water runoff from the previous overland flow entering the sewer system as well as groundwater flows that enter through defective junction joints, connections and/or manhole walls. In this study, only runoff was considered as the groundwater flow was not considered. The wet weather inflow was found to be $199.581 m^3$. This was exclusively rainfall derived inflow from the storm event and did not include any infiltrations. This is the amount of runoff that combined with the wet weather flow to cause flooding in the two sub-catchments. This confirmed that the storm event of the 26th December 2012 was in deed large enough to cause surface ponding and runoff. It can be seen that this amount of inflow is almost equal to the surface runoff in the mass balance table (table 4-1).

5.1.3 The Internal and External Outflows

Internal outflow occurs when there is surcharge that creates flooding within the sewer system. Surcharge is caused by full pipes joining a node. Results from all simulations showed that there was internal outflow (flooding) within the drainage network of 76.487 ha-m from a total of 76.604 ha-m during flow routing, representing 99.8% flooding during the storm. External outflow is the flow that leaves the system through Outfall nodes. During the simulation, the external outflows was found to be 0.117 ha-m. However, due to the fact that there were other connections feeding into the system that was not accounted for, this cannot be considered absolutely accurate.

5.1.4 Estimated Continuity Errors

Continuity error is the sum of the all outflow from the network divided by the sum of all of the inflow to the network and it indicates how much water was lost or gained in the routing of the inflows. The errors are quality assurance calculations performed by SWMM. In the model results the runoff continuity error was -0.289% indicating loss of water during runoff either laterally from the two sub-catchments or by evapotranspiration. Likewise, the model yielded 0.119% flow routing continuity error indicating that the combined storm sewer system gained inflows which could have mostly arose from interflows. Both the two continuity errors were less than +/-10% allowable range for the model to be considered numerically correct. It can be seen that the loss or gains during the runoff and by the combined sewer are extremely minimal hence insignificant. It was therefore not necessary to factor in the evapotranspiration as well as the baseflow parameters.

5.1.5 Surface Storage, Infiltration and Interflows

Surface storage is the variance between the aggregate precipitation and total runoff during a storm event and it is made up of subsurface leakage, transpiration, evaporation, infiltration as well as momentary surface or underground storage on the area when short periods are considered. The simulation resulted in 3.105 ha-m of the final surface storage. In addition, the simulation, as per the mass balance, separately resulted in the infiltration amount of 0.540 ha-m. Considering that the infiltration was computed separately by the model, the final surface storage results here therefore, only included possible transpiration, evaporation, subsurface leakage as well as underground storage or momentary surface. The infiltration amounts modelled were found to be 1.65mm for S1 and 3.14mm for S2 respectively as shown in table 5-2 and averaged as 2.112 mm in the mass balance summary in table 5-1. From this result, it can be seen that sub-catchment S2 which was 60% impervious registered higher infiltration rates than sub-catchment S1 which was 80% impervious.

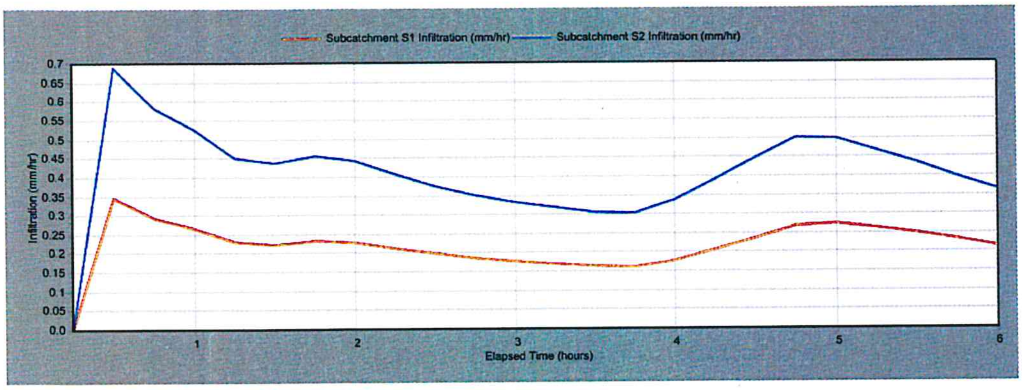


Figure 5-1Comparative infiltration rate for the two sub-catchments S_1 and S_2

The infiltration rate depends on the initial wetness of the soil in the period to the start of rainfall occurrence and thereafter the rate reduces with time. Figure 5-1 above shows the infiltration behaviour for the two sub-catchments over the period of the storm. During this time, part of the water in the unsaturated zones of the soil moved laterally becoming surface water later on down-stream through a phenomenon known as interflow. The Green Ampt infiltration index used in the model only considers infiltration in the upper soil layer leaving out the resultant sub-surface and ground water flows from interflows, an assumption based on the fact that urban catchments are extremely impervious and sub-surface flows are generally low or insignificant. However, throughout the storm, there could have been significant exchange of ground water from groundwater infiltration with the drainage system thus resulting in model uncertainty. It is also worth noting that there was a slight rise in the infiltration rate between the 4 and 5th hour of the event. This can be attributed to two reasons (1) the increase in the storm intensity during the period and (2) the period of low storm intensity between 2nd and 4th hours of the storm meant the soil saturation with water had reduced hence hire intake when heavy storm reoccurred [see figure 5-2].

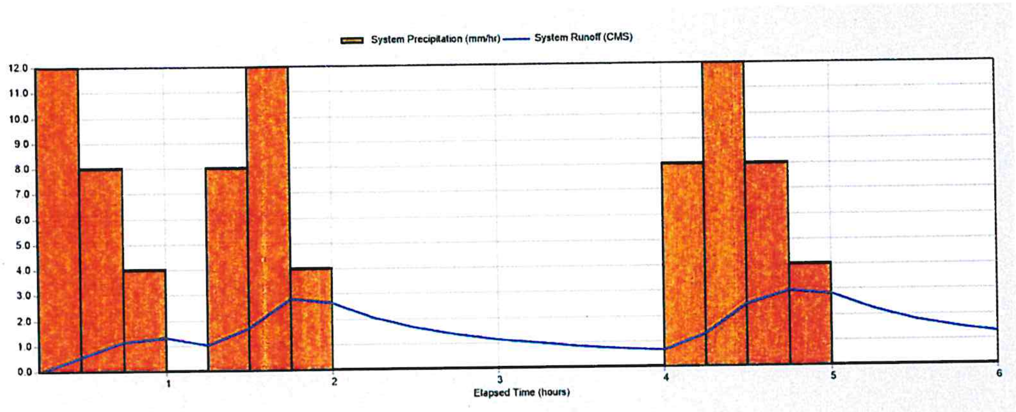


Figure 5-2 : System runoff against disaggregated precipitation

5.1.6 Modelled Surface Runoff

Surface runoff is ration of the precipitation, which is not absorbed by the soil into the ground sub-surface strata and is discharged in surface streams or into a drain like sewer among others. This is the difference between the total precipitation that lands on the surface over the entire storm period, infiltration loss, and the surface storage. It is also the amount of water entering the drainage system or conduit (inflow) at the downstream end of the modelled system.

The 26th December 2012 storm had a total rainfall of 23.710 ha-m (92.667 mm) over approximately 6 hours. The resulting surface runoff was found to be 20.134 ha-m. The direct surface runoff at the outlet of the two sub-catchments was approximated by assuming that the storm event exhibited a spatially homogeneous distribution throughout the downpour and lasted 6 hours.

5.1.7 Modelled Peak Runoff

The figure below illustrate the trend of the build-up of run off in the two sub-catchment areas S_1 and S_2 against the storm duration. The runoff was greatest at the 5th hour of the storm reaching 18.25 mm for S_1 and 9.49 mm for S_2. This could have been any hour during the storm but occurred in the 5th hour in this case based on the disaggregation that allocated more quantity of rainfall during the 5th hour. The figure below shows the behaviour of the runoff rate in the two sub-catchments.

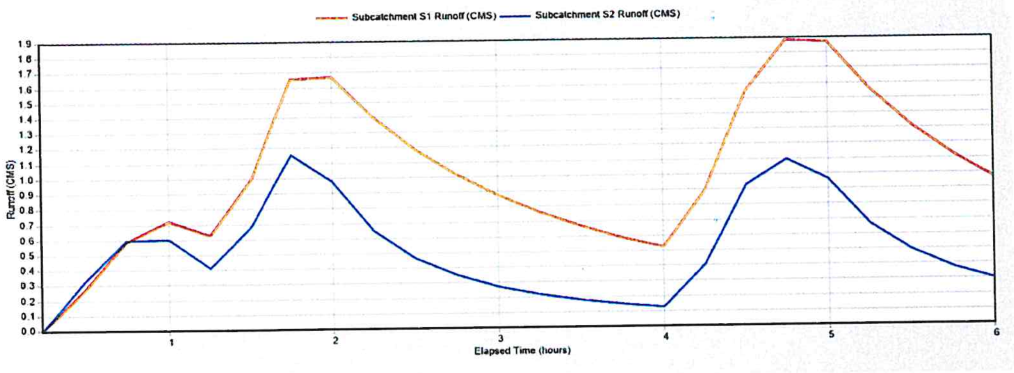


Figure 5-3 : Runoff pattern in the two sub-catchments S_1 and S_2

5.1.8 Estimated Runoff Coefficient

The runoff coefficient, C, characterises the combined effects of evaporation, infiltration, interception, and retention, all of which impact on the amount of runoff. It is the percentage of the total precipitation that that results in the total surface runoff amount after deducting the depression storage and interceptions. S_1 recorded runoff coefficient of 0.696 while S_2 had a runoff coefficient of 0.821. Since S_2 was more pervious (40% pervious) it was expected that the runoff coefficient of S_2 would be higher compared to that of S_1 as less imperviousness meant increased effects of infiltration, evaporation, retention, and interception by vegetation.

5.1.9 Flooding of the Sewer System

Flooding in the sewer systems was registered right from the start of the storm, steadily rising as the storm intensity increased and accordingly fluctuated with respect to storm intensity.

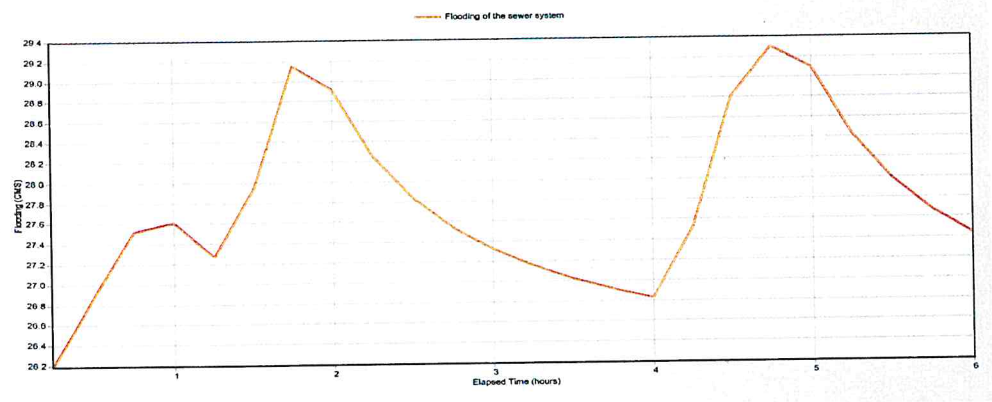


Figure 5-4 : Flooding in the sewer system

Table 5-3 : Summary of manholes and conduits flooding in the two sub-catchments S_1 and S_2

Sub catchment	Number of manholes						
	Total nodes	Surcharged nodes		Flooded nodes		Surcharged conduits	
		Absolute	Relative	Absolute	Relative	Absolute	Relative
S1	15	12	80%	9	60%	12	80%
S2	6	5	83%	3	50%	6	100%
S1&S2	21	17	81%	12	57%	18	86%

From the analysis of the sewer system results summarised in the table 5-3, it can be seen that 81% of the manholes surcharged of which flooding occurred in 57%. It can also be seen that 86% of the conduits surcharged. This result shows how extensive the surcharge was during the storm and its potential contribution to the pluvial flooding in the area.

The two flow profiles below illustrates how surcharging occurred in a number of manholes and conduits. The blue colouration denotes the level of storm-waste water in the conduits and the nodes. It is worth noting that it is normal for some of the surcharging especially for the nodes not to show in the profiles. In the two profiles representing the conduits and nodes status in the two sub-catchments, only junctions J1, J6, J7, J16 and J17 can be seen to have surcharged even though a number of manholes and conduits surcharges and flooded as analysed in sections 5.1.10 – 5.1.12 and their respective tables.

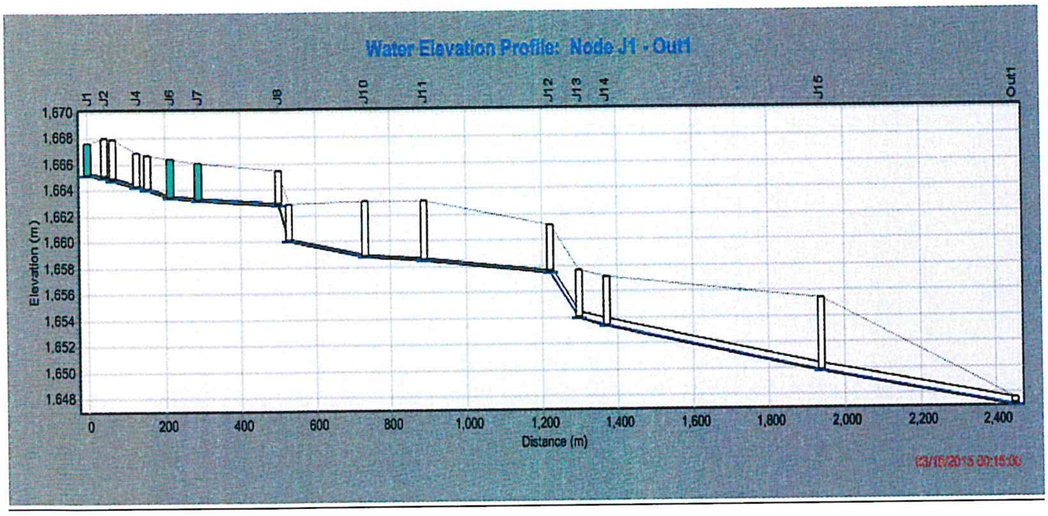


Figure 5-5 : flow profile in the conduits in sub-catchment S_1

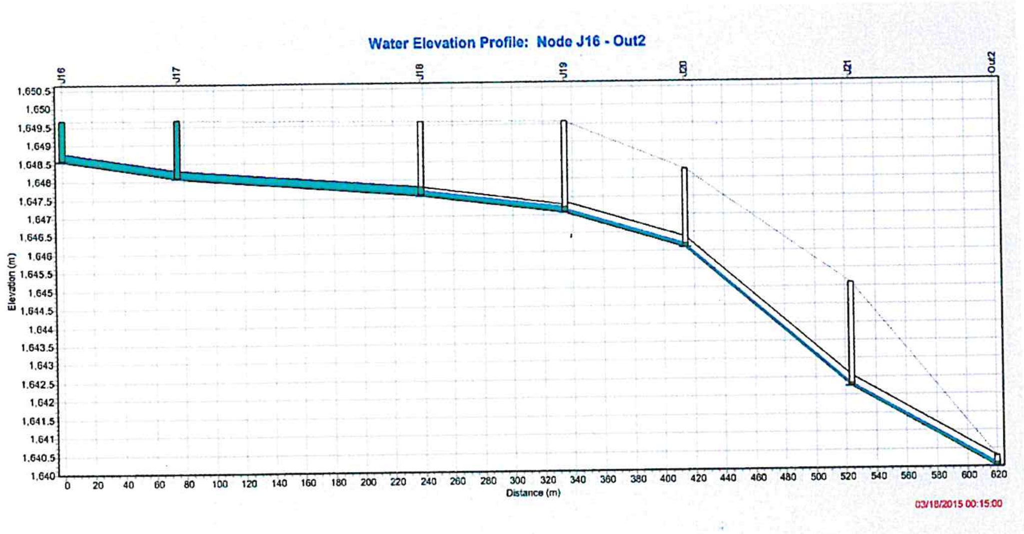


Figure 5-6 : flow profile in the conduits in sub-catchment S_2

5.1.10 Node Surcharge Summary

Based on the status report from the model, the node surcharge was recorded in 17 of the 21 junctions of the two sub-catchments where the combined storm-waste water rose above the top of the highest pipes linked to the junction nodes. Only 4 junctions namely J3, J5, J12 and J19 did not surcharge and are excluded from the status report. It was further observed from the status report that 12 of the 17 surcharged junctions reached maximum heights above the crown of the manholes while the remaining 5 junctions namely; J2, J8, J11, J18 and J20 surcharged to some minimum heights below the rim of the junction.

Table 5-4 : Summary of nodes surcharge for the two sub-catchments S1 and S2

Node	Hours Surcharged (hrs)	Maximum Height Above Crown (m)	Minimum Depth Below Rim (m)
J1	6.01	2.225	0.000
J2	6.01	0.000	2.871
J4	0.03	2.461	0.000
J6	6.01	2.757	0.000
J7	6.01	2.657	0.000
J8	6.01	0.000	2.456
J9	0.02	2.640	0.000
J10	0.09	4.165	0.000
J11	0.11	0.000	4.405
J13	0.02	3.120	0.000
J14	0.03	3.190	0.000
J15	0.05	5.000	0.000
J16	6.01	0.890	0.000
J17	6.01	1.360	0.000
J18	6.01	0.000	1.790
J20	0.01	0.000	1.840
J21	0.02	2.560	0.000

5.1.11 Node Flooding Summary

In the model, there was no ponding at the nodes. However, 12 junctions recorded flooding incidences with only junctions J2, J3, J5, J8, J11, J12, J18, J19 and J20 not flooding during the downpour.

Table 5-5 : Summary of nodes flooding the two sub-catchments S1 and S2

Node	Hours Flooded (hrs)	Maximum Rate (m^3/s)	Time of Maximum Occurrence (D H:M)	Total Flood Volume (10^6 ltr)	Maximum Ponded Volume
J1	6.00	19.899	0 04:45	410.830	0.000
J4	0.03	0.002	0 00:01	0.000	0.000
J6	6.01	0.022	0 00:01	0.076	0.000
J7	6.01	0.004	0 00:01	0.095	0.000
J9	0.02	0.013	0 00:00	0.001	0.000
J10	0.09	0.014	0 00:01	0.001	0.000
J13	0.02	0.123	0 00:00	0.007	0.000
J14	0.03	0.062	0 00:01	0.004	0.000
J15	0.05	0.050	0 00:02	0.005	0.000
J16	6.00	9.477	0 01:45	187.970	0.000
J17	6.01	0.011	0 00:01	0.243	0.000
J21	0.02	0.020	0 00:00	0.001	0.000

On the basis of table 5-3 containing the summary results of storm-sewer flooding and the two hydraulic gradients represented in figure 5-5 and 5-6, it is obvious, that the systems in both sub-catchments S_1 and S_2 cannot convey such a large amount of storm water without surface surcharge. It can clearly be seen that of the 21 manholes, 12 got flooded and further to that, J1 and j16 experienced flooding of quantities above 10 m³ which is a significant magnitude and measure of surcharge from a junction.

5.1.12 Conduit Surcharge Summary

The table below summarises the status of surcharging that occurred in the conduits analysed by the model during the storm. It details the duration during which particular conduits were full, the duration during which particular conduits were overloaded with water above the normal flow and the duration when the capacity of the conduits were overwhelmed.

Table 5-6 : Summary of conduits surcharge in the two sub-catchments S_1 and S_2

Conduit	Hours full			Hours Above Full – Normal Flow	Hours Capacity Limited
	Both Ends	Upstream	Downstream		
C1	6.01	6.01	6.01	6.01	6.01
C3	0.01	0.01	0.01	0.02	0.01
C4	0.01	0.02	0.01	0.03	0.02
C5	0.01	0.01	0.01	0.02	0.01
C6	6.01	6.01	6.01	6.01	6.01
C7	6.01	6.01	6.01	6.01	6.01
C9	0.01	0.01	0.02	0.01	0.01
C10	0.08	0.08	0.11	0.07	0.08
C11	0.01	0.01	0.01	0.07	0.01
C13	0.01	0.01	0.01	0.01	0.01
C14	0.02	0.02	0.03	0.03	0.02
C15	0.04	0.04	0.07	0.02	0.04
C16	6.01	6.01	6.01	6.01	6.01
C17	6.01	6.01	6.01	6.01	6.01
C18	0.01	0.01	0.01	0.01	0.01
C29	0.01	0.01	0.01	0.01	0.01
C20	0.01	0.01	0.01	0.01	0.01
C21	0.01	0.01	0.01	0.02	0.01

From the table above of conduit surcharge results, it can be seen that 18 of the 21 conduits under study were surcharged. Only conduits C2, C8 and C12 were not surcharged. All the 18 conduits that surcharged experience capacity inadequacy during the storm with conduits C1, C6, C7, C16 and C17 remaining full with limited capacity at both ends for the entire duration of the storm. This phenomenon could have resulted from the relative % slope of the conduit to the previous conduit before the junction of exit see the hydraulic gradient profiles in figures 5-5 and 5-6 as well as the conduits section of the status report in appendix F.

The overall analysis of the sewer network behaviour during the storm showed that a number conduits and junction nodes surcharged and flooded. Total amount of the internal outflow of 76.487 ha-m recorded from the flow routing continuity confirmed that there was a significant contribution to the total flooding that came from the surcharges and flooding of the junctions and conduits.

In general, the simulation results confirmed the flooding that occurred on the 26th December 2012 in Nairobi West and South C in the city of Nairobi. Further to this, the results of the analysis of the various aspects of urban pluvial flooding including surface run-off and sewer system surcharges during the event agreed with urban pluvial flooding process description advanced by (CEN, 1996), (Falconer, et al., 2009), (Riel, 2011) and (Maksimović, et al., 2009) in section in section 2.3.

5.1.13 Simulated Flow Instability Index (FII)

According to the modelling status report, conduit number C9, between J9 and J10 registered the highest flow instability index (FII) during the model run. FII tallies how many times the flow volume in a link is higher (or lower) than the flow volume in both the previous and subsequent periods. There was a significant water depth fluctuation noted in node 9 during the period of the storm. This could have resulted from the model numerical instability. However, numerical instabilities may well not be ostensible for modelling activities performed using courser time intervals to plot as they occur over short durations.

5.2 Sensitivity analysis

Since it was not possible to measure the principal parameters' attributes, calibration of the model could not be carried out. However, sensitivity analysis was used to at least check the extent to which varying of parameters was influencing the model and its results. The average parameter values as determined from estimation may not be as accurate as would be if they were measured. However the methods of estimation, considered documented values attributed to certain characteristics that have resulted from experiments used e.g. manning's coefficient and those resulting from consideration of the catchment area using the analysis scale factor are relatively correct. Tables 5-7 and 5-8 below shows the peak runoff values obtained when each parameter was varied while holding the others constant by 25%, 50%, 75%, 100%, 125% and

150% for sub-catchments S_1 and S_2. The two graphs below illustrates peak-runoff response to parameters during the sensitivity analysis.

Table 5-7 : Change of the peak runoff with variation in parameter value sub-catchment S1

Peak Runoff/Area	Peak Runoff/Width	Peak Runoff/Slope	Peak Runoff/ Impervious	Peak Runoff/ Imperv. N	Peak Runoff/ Perv. N
0.83	1.01	1.45	1.18	3.09	2.07
1.24	1.45	1.67	1.32	2.39	1.96
1.57	1.70	1.79	1.58	2.05	1.92
1.88	1.88	1.88	1.88	1.88	1.88
2.18	2.04	1.96	1.99	1.77	1.86
2.44	2.18	2.03	1.96	1.67	1.84

Table 5-8 : Change of the peak runoff with variation in parameter value sub-catchment S2

Peak Runoff/Area	Peak Runoff/Width	Peak Runoff/Slope	Peak Runoff/ Impervious	Peak Runoff/ Imperv. N	Peak Runoff/ Perv. N
0.47	0.65	0.86	0.62	1.54	1.42
0.82	1.00	1.09	0.9	1.42	1.26
0.97	1.19	1.26	1.12	1.35	1.2
1.32	1.32	1.32	1.32	1.32	1.32
1.52	1.43	1.37	1.49	1.08	1.13
1.66	1.51	1.42	1.51	1.02	1.11

For the two sub-catchments, sub-catchment area, Impervious N and Imperviousness parameters showed greater sensitivity, when the peak flow was analysed. This corroborated the conclusions of many other studies that have always found that variations in Impervious N and Imperviousness parameters have always had the greatest effect on model outputs. Khodashenas and Tajbakhsh (2016) in their study of East Eghbal catchment, located in the south and south-east of the Mashhad, the second crowded city in Iran, found that the peak runoff from the SWMM simulation conducted to be most sensitive to impervious area manning's roughness coefficient and sub-catchment width because of physical characteristics of the study area and presence of extensive sub-catchments. In a study conducted in Typical Mountainous, Low-Lying Urban Areas in China by Luan et al. (2017), the results showed that increasing the amount of impermeable area by 30% had the greatest influence on peak flow and was the most sensitive parameter of the model.

The sub-catchment slope had the least effect on the peak runoff, followed by the Pervious N then sub-catchment width. From the analysis, it was observed that increase in Impervious N and Pervious N resulted in a reduction in the peak runoff while increase in the rest of the parameters analysed elevates the runoff peak. Figures 5-7 and 5-8 below are graphical representations of comparative responses of the peak runoff to the variations in the different parameters.

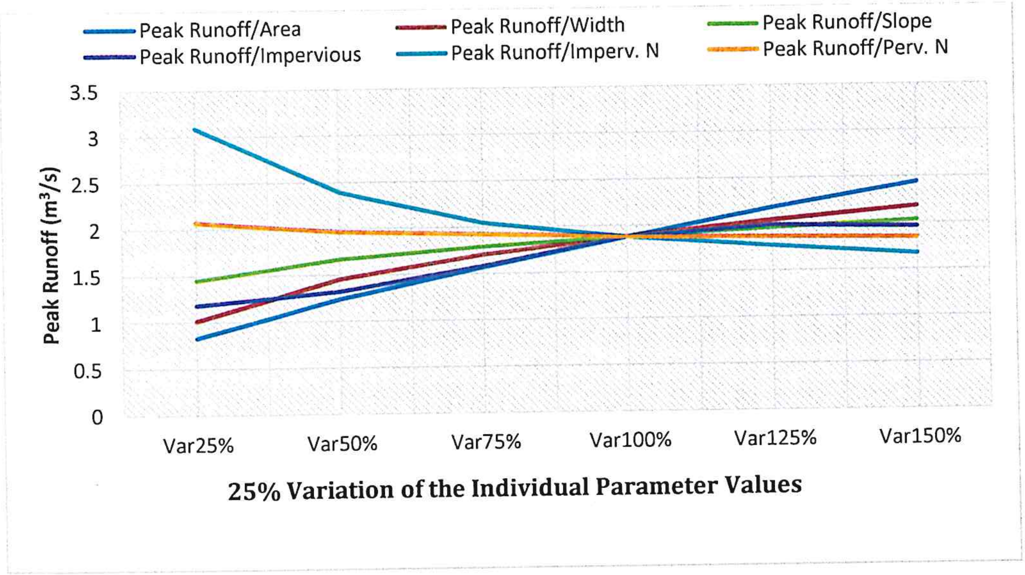


Figure 5-7 : Sensitivity of six parameters for sub-catchment S_1

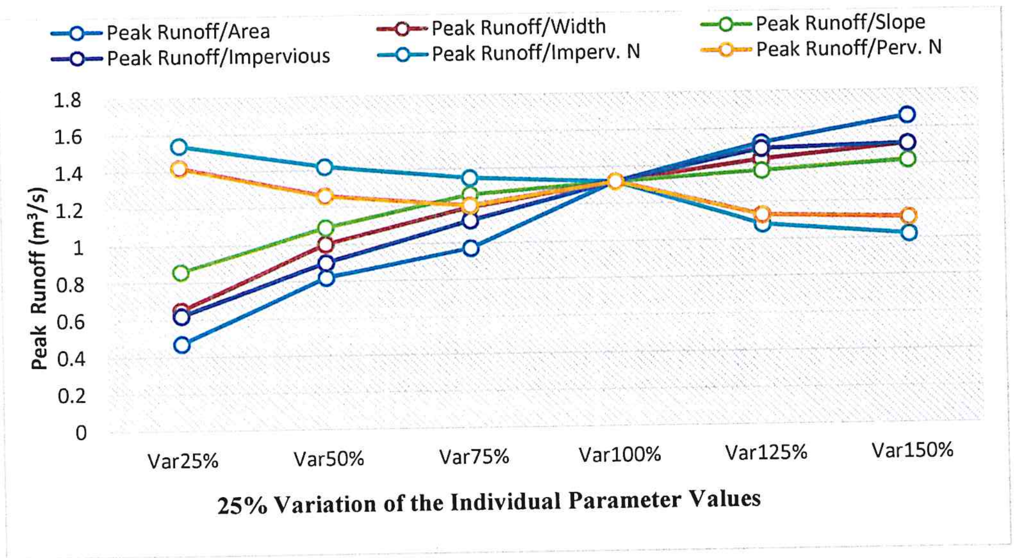


Figure 5-8 : Sensitivity of six parameters for sub-catchment S_1

Despite the fact that the sub-catchment areas and widths do not vary in the same watershed, the sensitivity of these two parameter was analysed to evaluate the possible errors of the assumption that their values were approximated. The sensitivity analysis is illustrated by the sets of tables 5-7 and 5-8 as well as graphs 5-7 and 5-8.

5.3 Uncertainties Associated with the Model

As dwelt upon in the literature review, most models of integrated water systems do inherently include all aspects of uncertainty that occur due to the uncertainties inherent to the modelled subsystems. In this study, a qualitative analysis of the possible influence of the accuracy of the data input in the model was done and discussed below.

5.3.1 Sewer Systems' Material Manning's n Value Uncertainties

During the modelling, Manning's n of 0.014 was used for all the pipes. This value was based on the conduit material which is rough concrete pipes. However, based on the age of the conduits, this figure could be greater, thus lowering the hydraulic size of the sewer pipes and amplifying the flooding quantities in the two sub-catchments. In other words, lower value for Manning's n means enhanced flow through the system and vice-versa hence Manning's n Roughness Coefficient, has been identified as a potential source for uncertainty in the model affecting the quantity of surcharge into the surface from the manholes.

5.3.2 Rainfall Data Accuracy

The rainfall data used SWMM5.1modelling of the two sub-catchments was disaggregated from the daily rainfall amounts recorded at the nearest rain-gauge to 15-minutes interval. The accuracy of this disaggregation could not be established as there were no records to validate the disaggregated data. While the disaggregation was only an estimate based on the precipitation for the day forecasted by for the 26th December 2017, the actual 15-minutes interval for the rainfall duration could have been shorter and intense or longer with zero precipitation intervals. SWMM models work best with rainfall data resolution of between 1-5 minutes and this could have been achieved by further disaggregating of the rainfall data. This would have called for an extended handling of extremely large amount of data through tiresome process which was not found necessary at this stage. Therefore, most likely, there could have been uncertainty in the flow discharges and hence the resulting runoff infiltration profiles as a result of rainfall input uncertainty. Improving precipitation inputs, through a validation process could have improve the performance of the urban flooding model significantly.

5.3.3 Spatial-temporal Variation of Rainfall Resolution

Given that urban catchments are highly impervious with the related drainage areas being small, the concentration times are normally short. This makes the urban catchments highly sensitive to the spatial and temporal inconsistency of precipitation. SWMM accounts for this spatial variability by the assignment of several gages to a particular sub-catchment. Since there was only one gauging station up-stream of the study area located almost at the upper boundary of the study area, for the two sub-catchments, there is a greater likelihood of spatial-temporal variation of rainfall related uncertainty in the model outputs and could have had a significant impact on the simulated flows.

5.3.4 Digital Elevation Model

The quality of DEM used under normal circumstances is not 100% accurate. In the case of highly urbanized area like the research area under consideration, the satellite information might have corresponded to the top of the buildings instead of the ground elevation. Lack of calibration of the DEM data definitely had an influence in the model runoff and peak runoff results.

5.3.5 Sub-catchment Network System

The selection of the two sub-catchments may be a major cause of uncertainty as other network components that are contributing to those considered were not being modelled at all. The model also assumed perfect operational conditions of the sewer network as it did not take into account any of the aging characteristics including disposals, in-growth of roots or damages. There was also inadequate sewer data for a larger portion of Nairobi West and South C. In general, only 24 manholes out of 3164 manholes had invert elevation data.

CHAPTER SIX

6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The study confirmed the flooding that was observed and in deed which occurred during the rainfall event of 26th December 2012. The two sub-catchments with complete data that were used to represent of the wider Nairobi West and South C areas of Nairobi exhibited flooding just as was observed during the said storm event. Based on the results obtained and the objectives of the study, the following conclusions can be drawn from the study:

1. There are significant and pertinent parameters that are prerequisite for SWMM modelling of rainfall-runoff event as was identified through critical analysis by literature review and the theoretical framework of the model sections.
2. It is evident from the study that there is sufficient potential of integration of GIS tools with SWMM5.1 to produce a model of acceptable applicability in urban pluvial flooding risk analysis and prediction by simulating different storm events and suggesting improvement for drainage systems for urbanising cities.
3. Studies from manholes demonstrated the model's applicability for urban planners to analyse the potential for systems to handle urban pluvial flooding and to use the results to design systems that will limit the flooding risks.
4. Results provided by the model in the mass balance summary reflected the correct urban water balance without significant bias.
5. Flooding problems established within the two sub-catchments studied showed that the drainage system should be improved, in some manner, to ease the surcharging of the sewer system in the area in order to reduce possible damage and health risks from contamination.
6. The qualitative uncertainty assessment and the simple sensitivity analysis of some of the parameters indicates that most complex hydrologic models with several input parameters do have inherent model uncertainties and sensitivities resulting from variations in pertinent parameters' values.

6.2 Recommendations

Based on the results of the study, the following recommendations can be suggested for implementation and follow-up:

1. The historical values of surface friction and the imperviousness estimation adopted from the literature and othophotos may have resulted in overestimation or underestimation of total amount of surface flows and surcharges runoff and hence the flooding. There is therefore the need to perform quantitative uncertainty analysis of individual ratings in a rigorous and individual way, including the deviation from the reference hydraulic regime to reduce the risk of under or overdesign of systems.
2. The urban development actors need to embrace the use of such tools which has the potential of giving more accurate scenarios as it integrates a number of key parameters with significant effect on urban flooding. To be assured of model output accuracy and validity for use in decision making, the urban authorities and other data resources holders must make considerable efforts to standardize data records to enhance data availability and credibility. This will enable researchers in urban flooding to conduct meaningful analysis of systems response to intense storm and the city planners to programme and implement sustainable urban development.
3. It necessary for the city authorities to re-survey the sewer system in the city to update the pertinent sewer network parameters particularly manhole ground and invert elevations for more accurate and comprehensive analysis and modelling using the this approach.
4. There was no data for calibration which remains very significant operation for improving the model quality. In this regard, the model should be subjected to further calibration using measured data from installed measuring apparatus.
5. With regard to opportunities for future studies, this work has revealed some interesting line of research that can be undertaken to holistically understand urban pluvial flooding and its effects. It would be worth furthering the study by experimenting the effects of using finer time resolutions of between 1 and 5 minutes with even smaller sub-catchments. This could also be done where fairly complete data is available and proper calibration is undertaken. In this study, historical data of coarser resolution was disaggregated into finer time steps of 15 minutes.

7 REFERENCES

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8 APPENDIXES

8.1 **Appendix A:** Monthly Rainfall Data

Year	Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual Total	Monthly Ave.
2009	Wilson	60.4	17.3	22.4	87.1	116.5	58.0	18.4	8.1	15.9	94.6	102.3	187.9	788.9	65.7
	Dagoretti	65.5	22.1	40.9	83.3	163.1	107.5	7	11.6	18.1	107.6	90.4	133.1	850.2	70.9
	JKIA	53.4	36.1	30.1	88.5	145.0	42.6	12.0	8.6	11.3	75.6	59.6	124.7	687.5	57.3
2010	Wilson	74.5	118.6	259.7	110.6	191.9	54.5	8.0	31.9	43.8	127.6	90.0	62.7	1173.8	97.8
	Dagoretti	76.1	109.3	212.4	161.3	359.7	43.7	9.5	43.5	37.9	109.2	120.9	77.1	1360.6	113.4
	JKIA	69.9	98.7	135.1	49.6	86.1	32.6	8.3	14.6	22.9	44.9	78.5	68.7	709.9	59.2
2011	Wilson	11.4	76.8	147.6	50.8	48.1	108.2	17.7	79.0	47.2	154.8	218.7	113.0	1073.3	89.4
	Dagoretti	15.2	127.81	131.53	473.11	260.31	134.8	15.7	49.8	50.6	142.6	173	141.2	1715.7	143.0
	JKIA	2.8	55.6	95.1	21.8	50.0	35.6	9.9	50.2	37.2	57.4	248.0	41.1	704.7	58.7
2012	Wilson	1.0	17.1	6.1	444.6	185.7	39.1	37.0	43.3	28.3	70.7	220.3	246.2	1339.5	111.6
	Dagoretti	1	11.9	8.5	473.1	260.3	32.2	15.6	93.6	18.7	72.8	289.32	283.02	1560.0	130.0
	JKIA	1	5.4	7.2	285.8	200.6	38.2	20.4	12.1	45.8	70.9	72.03	227.35	986.8	82.2
2013	Wilson	27.2	2.0	146.5	268.8	27.3	44.7	18.4	55.6	87.6	10.5	69.8	208.4	966.9	80.6
	Dagoretti	21.24	2.01	179.03	329.12	52.93	30.42	16.32	27.71	35.5	17	106.01	167	984.3	82.0
	JKIA	35.7	3.4	137.2	241.4	16.7	45.3	15.0	41.3	45.3	14.6	72.0	202.1	870.1	72.5

Table 8-1 : Rainfall data for three stations in Nairobi for the period between January 2009 – December 2013

8.2 Appendix B: Daily Rainfall Data

				Day of the Month																															
Station_ID	Station_Name	Year	Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Tot Mo
9136130	WILSON	2009	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16.1	12.1	0	0	0	0	0	0	0	0	25.2	6	0	0	0	0	
9136130	WILSON	2009	2	0	0	0	0	0	5.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.1	1.1	0	0	0	0				
9136130	WILSON	2009	3	1.7	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	9.1	4.7	0	
9136130	WILSON	2009	4	0	0	0	0	3.1	2.2	0	0	0	0	0	6.1	1.1	0	0	0.4	0	0	13.5	6.2	5.7	0	0	0	0	30	14.8	0	0	0		
9136130	WILSON	2009	5	12.1	6.7	0.1	0	0.2	3.4	0	0	0.6	0	0	14	3	0	0.2	1.7	7.3	0	0	0	5.9	0	0	0	0	2.2	25.9	28.2	0	0	0	
9136130	WILSON	2009	6	0	7.1	0	0	0	2.7	0	0	0	0	0	0	0	9.6	0	2.1	0	0	0	0	0	0	0	0	1.9	0	0	0	28.6	0		
9136130	WILSON	2009	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11.4	0	0	0	0	0	0	0	
9136130	WILSON	2009	8	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9136130	WILSON	2009	9	0	1.3	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.6	0	0	0	0	0	0	0	2.2	0	0	0		
9136130	WILSON	2009	10	0	0	3.3	0	0	0	0	0	0	21.8	0	0	0	0	14.4	10.5	0	3.5	0.5	0	0	0	0.2	0	2.5	5.8	0	13.8	2	5.1	1.2	
9136130	WILSON	2009	11	10.1	4.4	0	4.8	3.9	0	0	0	2.1	0	0	0	0	3.8	0	1.9	28.3	14.3	0	0	0	0	3.6	10.3	0.6	0	2.4	0.4	0	0.4		
9136130	WILSON	2009	12	0	11.7	8.9	0	0	0	0	0	0	0.3	2	28	0.6	0	2.2	0	0	0	0	0	0	0.1	77.2	0	12.9	2.6	9.5	2.7	2.2	15	0	
9136130	WILSON	2010	1	0	34.4	8.2	0	0	0	1.8	4.7	23.9	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9136130	WILSON	2010	2	0	0	0	18.7	23.5	0	0	0	0	0	0	0	0	0	0	0	13.3	0	18.7	0.4	0	1.1	0	0	0	15.5	10	15.4				
9136130	WILSON	2010	3	1.1	32.4	0	0	0	0	18.2	1.5	0.4	0	0	0	0	0	0.9	0	0	0	0.6	27.9	0	0	31.2	85.1	0	0	1.1	0.3	15.2	31.8	9	
9136130	WILSON	2010	4	0.4	15.9	1.8	0	0	0.4	3.2	0	0	0	0	0	0	20	9.1	1.7	22.9	0	0	1.4	0	0	18.6	0	0	1.5	0	0	6.1	3.6		
9136130	WILSON	2010	5	0	0.3	0.5	3	12.6	0	0	0	22.6	5.2	42.8	0.3	15.6	25.5	0	17	38.9	1	0	0	0	0	0	0	0	0	0	1.6	0	0	0	
9136130	WILSON	2010	6	0	30	16.9	0	0	0.6	0	0	0.2	0	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0		
9136130	WILSON	2010	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	
9136130	WILSON	2010	8	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	16	3.4	0	0	0.3	0	0.6	1.3	1.6	0	0	0	
9136130	WILSON	2010	9	0	0	0.9	15.8	0	0	0	0	0	0	0	0	0	0	0	0	17.2	0	0	0	0	0	0	0	0	0	0	0.9	0	0		
9136130	WILSON	2010	10	0	0	0	0	32.7	0	0	0	0	0	0	0	3.1	0	0	0	0	0	0	0	0.2	33.5	29	0	18.5	0	0	0	0	0.6	0	
9136130	WILSON	2010	11	12.4	0.1	0.9	0.2	1.3	0	0.3	5.3	11.8	0.6	0	4.7	0	11.3	1.5	0.3	18.3	0	0	0	0	2.4	0	0	5	2.6	0	0	0	0		
9136130	WILSON	2010	12	0	0	0	0	21.8	0.5	7.4	0.4	0	8.3	TR	TR	0	0	0	0	0	0	0	0	0	0	0	0	0.4	11.8	0	0.1	0	0	0	
9136130	WILSON	2011	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.4	5	0	0	0	0	0	0	0	
9136130	WILSON	2011	2	0	0	0	0	0	0	0	0	0	0	0	0	34.1	16.4	24.3	0	0	0	0	0	0	0	0	0	0	0	0	0				
9136130	WILSON	2011	3	0	0	0	0	0	0	0	0	0	0	0	0	3.4	0	0	0	13	39.4	53.9	27.4	0	0	1.2	0	0	0	0.2	0	0	6.1	0	
9136130	WILSON	2011	4	0	18.8	5.6	0	0	0	0	0	0	2.5	0	0	0	0	8.8	0	0	0	0	0	0	0	0.8	0	0	0	0	10.1	0.2	0		
9136130	WILSON	2011	5	0.01	0.01	9.3	9	4.4	4.3	3.6	0.4	2.7	4.7	0	0	0	0	0	0	0	0	0	0	4.7	0	0	0.001	0	0	0	0	0	0	0	
9136130	WILSON	2011	6	0	0	0	0	0	0	0	0	0	7.8	5.1	2.1	0	2.4	0	0	0	0	1	0.3	0	0	0	0	3.3	72.2	0.2	0	0	7.8		
9136130	WILSON	2011	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	3.7	2	0	0	0	0	0	
9136130	WILSON	2011	8	0	0	0	0	0	0	0	0	0	1.1	0	0	61.6	0	8.1	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	
9136130	WILSON	2011	9	0	0	0.5	20.1	0.1	0	0	0	0.2	0	0.5	0	0	0	0	0	0	0	0	0	0	0	3.2	0	0	0	0	0	7.2	0.5	5.9	
9136130	WILSON	2011	10	5.9	0	0	0	0	0	0	0	0.8	3.4	1.8	0	6.9	10.7	0	1.7	0	0	1.1	1.1	1.3	0	10	6.7	0	1.5	66.5	22.6	0	2.8	0	
9136130	WILSON	2011	11	0	12.5	0	0	0	8.4	0	8.2	0	5.4	1.4	1.1	0	0.2	0.3	33.1	0.8	4	8.7	47.6	25.7	0	8.3	2.9	5	0	31.9	0	0.2	2		
9136130	WILSON	2011	12	19.4	20.2	0	9.4	0	0	0	0	0	0	0	0	0	0	0	0	11.2	0	0	0	0	0	0	0	28.6	11.7	0.5	0	0	0	0	
9136130	WILSON	2012	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9136130	WILSON	2012	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.5		0	0	0	0	0	0	0	9	1.6	0	tr			
9136130	WILSON	2012	3	0.5	0.8	0	1.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9136130	WILSON	2012	4	1.3	4.7	19.8	6.9	0.6	4.8	0		0	0	2.6	5.3		7.3	1.6	0	5.7	1.4	4.2	97.9	0	30.1	46.8	34.8	34.8	9.8	49.1	10.9	6.6	53.6		
9136130	WILSON	2012	5	6.6	2.9	60	26.7	33.9	30	0	1.2	0.6	0	0	0.2	tr	2.7	1.8	tr	1.5	tr	5.3	0	0	2.3	tr	TR	TR	2	tr	0.7	0	0	2.3	
9136130	WILSON	2012	6	0	0	0	0.2	0.2	1.9	1.3	0.6	0	0	0	0	0	0	0	0	0	tr	0	0	0	tr		28.9	0	0	0	0	0	0		
9136130	WILSON	2012	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	tr	0.0	tr	0.0	0.0	0.0	0.0	30.0	0.0	0.0	tr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9136130	WILSON	2012	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.2	0.0	0.8	0.0	0.0	0.0	0.0	0.0	tr	1.5	tr	0.4	tr	0.0	0.0	0.0	0.0	0.0	6.4	0.0	0.0	0.0	0.0	0.0	
9136130	WILSON	2012	9	0.0	0.0	0.4	0.0	0.0	0.0	tr	0.0	0.0	3.5	0.0	tr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.2	10.2	0.0	0.0	0.0	0.0	0.0		
9136130	WILSON	2012	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	tr	11.8	0.0	2.3	2.7	tr	8.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	6.3	0.0	0.0	29.5	0.0	0.0	0.0	tr	
9136130	WILSON	2012	11	1.5	101.9	4.9	5.6	0.0	7.9	5.8	29.3	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.4		17.0	0.0		
9136130	WILSON	2012	12	3.3	18.6	1.7	0.5	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	4.1	5.9	24.4	0.0	0.0	0.0	11.2	0.6	0.0	22.3	94.0	2.0	19.1	10.2	0.0	15.1	
9136130	WILSON	2013	1	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8	0.0	9.8	0.0	
9136130	WILSON	2013	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
9136130	WILSON	2013	3	0.0	0.0	0.0	2.5	7.9	0.2	8.1	4.0	0.0	0.0	0.0	1.0	7.8	9.8	0.0	0.0	0.0	0.0	35.2	1.4	0.0	0.0	0.0	0.0	0.0	0.0	28.4	2.8	0.0	3.0	31.4	
9136130	WILSON	2013	4	0.0	12.6	0.2	0.0	20.8	6.4	13.0	70.4	6.1	8.0	18.8	20.3	0.0	3.3	70.5	0.0	2.0	1.7	2.0	0.0	0.0	6.1	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.8		
9136130	WILSON	2013	5	0.0	0.0	0.0	0.4	16.7	0.6	0.0	2.4	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9136130	WILSON	2013	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.7	5.6	0.7	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
9136130	WILSON	2013	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.8	0.0	0.0	1.5	1.1	
9136130	WILSON	2013	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.3	30.3	0.0	5.6	1.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.1	
9136130	WILSON	2013	9	2.2	0.0	0.0	0.0	0.0	0.0	0.0	tr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	tr	51.0	1.5	tr	22.0	0.8	0.0	0.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0		
9136130	WILSON	2013	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
9136130	WILSON	2013	11	0.0	1.8	5.4	4.8	2.4	0.9	0.0	0.6	0.5	12.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	1.3	1.2	0.8	0.0	5.0	0.0	0.0	0.0	1.0	0.0	1.2	18.1	1.4		
9136130	WILSON	2013	12	4.6	0.0	0.0	1.0	56.0	0.0	0.0	8.8	10.9	16.7	46.5	2.9	47.7	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9136164	DAGORETTI	2009	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17.1	1.9	0	0	0	0	0	0	0	0	32.3	13.2	0	0	0	0	
9136164	DAGORETTI	2009	2	0	0	0	0	0	7	0	0	1.8	0	0	0	0	0	0	0	0	0	0	0	0	0	9.2	2.1	0	0	0	0				
9136164	DAGORETTI	2009	3	1.3	0	0	0	0	0	0	0	0	1.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5.8	19.5	6.9	1.6	
9136164	DAGORETTI	2009	4	0	0	0	0	18.4	2.4	0	0	0	0	0	5.7	0	0.7	0	0	0	0	20.7	5.9	6.3	0	0	0	0	13.5	5.7	0	0	0		
9136164	DAGORETTI	2009	5	4.1	3.5	0	0	1.5	7	0	0	11.4	0.7	0	19	18.7	8.7	0.8	2.9	16	0	0	0.4	1.5	0	0	0	0	9	43.2	7.5	2.2	0	0	
9136164	DAGORETTI	2009	6	0	2.5	0	0	0	1.5	0	0	0	0	0	0	0.6	16.9	0	5.5	0	0	0	0	0	0	0	0	0.5	0	0	0	74	0		
9136164	DAGORETTI	2009	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	
9136164	DAGORETTI	2009	8	0	0	0.1	0.8	0	0.6	0.2	0	0	0	0	0	0	0	0	0	0	0	1.5	0	0	0.1	0	0	0	0.3	0	0	0	0		
9136164	DAGORETTI	2009	9	0	1.9	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.5	0	0	0	0	0	0	0	1.1	0	0	0		
9136164	DAGORETTI	2009	10	0	0	19.5	0	0	0	0	0	1.8	0	0	0	0	6.8	12	15.2	0.7	8.8	0.7	0	0	0	0	0	2.5	1.6	0.1	19.8	3.1	5	0	
9136164	DAGORETTI	2009	11	6	4.7	0.1	5.2	14.6	0.1	0	0	4.8	0	0	0	0	4.4	0	7	18.8	8.7	0	0	0	0	1.8	1	0	0	1.4	0	0	0.8		
9136164	DAGORETTI	2009	12	1	4.7	8	0	0	0	0	0	1.2	0	7	40.5	0.6	0	0	0	0	0	0	0	0	0	26.6	1.8	20.3	0.9	1.1	5.7	0	1.7	0	
9136164	DAGORETTI	2010	1	1.6	13.1	3.2	0.3	0	0	2.8	9.3	44.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9136164	DAGORETTI	2010	2	0	0	0	7.4	0.5	1	0	0	0	0	0	0	0	0	0	0	16.5	0	10.5	2.9	0.2	0.2	0	0	0	22.5	31.5	14.1			0	
9136164	DAGORETTI	2010	3	2	11.5	0.6	16.2	0	2	17.1	1.6	0	0	0	0	0	0	0.3	0	0	0	0.2	23.1	0	0	0.7	37.8	1.3	0	3.9	23.5	37.2	30.4		
9136164	DAGORETTI	2010	4	10.8	35.8	4.1	0	1.1	0	14.3	0	0	0	8.2	4.7	0	16.9	9.3	3.5	14.1	0	0	0	0	0	23.8	0.5	0	0.3	0	0.5	5.2	4.2	0	
9136164	DAGORETTI	2010	5	8.7	1.9	4.6	11.6	4.1	0	0.4	0	86.3	50.3	61.4	0.4	20.3	17.4	0	43	33.1	8.5	0	0	0	0	0	0	0	0	0	2.7	0	0		
9136164	DAGORETTI	2010	6	0	5.9	13.4	1.5	0	14.6	0	0	1.5	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9136164	DAGORETTI	2010	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.4	1.1	0	0	0	0		
9136164	DAGORETTI	2010	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0.7	0	0	1.5	0	1.3	1.2	3.1	0.2	0	0.5	
9136164	DAGORETTI	2010	9	0	0	1.5	0	0	0	0	0	0	0	0	0	0	0	0	26.7	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0		
9136164	DAGORETTI	2010	10	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	53.1	12.4	0	10.4	0.6	0	0	0	0	0	
9136164	DAGORETTI	2010	11	31.4	0.5	0.9	0.4	0.6	0.3	0	9.7	10.5	9.9	0	2.2	0	6.1	1.8	5.6	19.1	0.2	0	0	0	0	0	0	4.7	1.2	4.8	0	0	0		
9136164	DAGORETTI	2010	12	0	0	0	0	0	4.3	5.6	7.6	0	22.2	3	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0.4	7.4	1.2	12.5	0	0	0	

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9136164	DAGORETTI	2011	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.5	7.6	1.1	0	0	0	0	0	0
9136164	DAGORETTI	2011	2	0	0	0	0	0	0	0	0	0	0	0	0	40	43	37.4	0	2.1	0.01	0	0	0	3.3	0	0	0	0	0	0			
9136164	DAGORETTI	2011	3	0	0	0	0	0	0	0	0	0	0	0	0	3.3	0	0	1.1	18.2	48.4	44	3.4	0	0	1.5	0	0.01	1	0	0.5	0.01	7.1	0.01
9136164	DAGORETTI	2011	4	4.8	35.5	29.1	9	0.5	1.7	6.5	0.2	0.3	0	1	2.2	1.1	8.3	18.8	0.9	3.8	4.2	0.01	76.2	0.1	13.9	29.7	59.8	19.6	14.9	74.7	10	35.9	6.4	
9136164	DAGORETTI	2011	5	20.5	2.3	40.3	41.1	28.7	14.7	0	3	2.6	0	1.4	27.9	7.5	1.5	1.2	4.6	2.8	9.9	29.2	0	0	1.5	0.01	1.8	2.7	0.9	1.9	0.5	0	0	6.8
9136164	DAGORETTI	2011	6	0	0	0	0.7	0	0	0	0	0	1.6	13.9	4.2	0	12.3	0.1	0	0	0	0.6	0.6	1.4	0	0	0	46.6	34.8	0	0	0	12	
9136164	DAGORETTI	2011	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	8.2	0.4	0	0	0	0	0
9136164	DAGORETTI	2011	8	0	0	0	0	0	0	0	0	0.2	2	0	0	22.8	0.1	16	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0
9136164	DAGORETTI	2011	9	0	0	0.1	22.1	1.1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	5.4	0	0	0	0	0	2.1	0	9.8
9136164	DAGORETTI	2011	10	9.8	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	3.6	1.2	0.0	6.4	7.0	0.0	2.5	0.0	0.0	0.1	2.5	0.5	0.0	3.0	0.0	0.0	5.6	47.8	38.2	3.0	0.0	0.0
9136164	DAGORETTI	2011	11	1.2	39.9	0	0	0	1.7	0	4.5	0	8.3	0.4	1.1	0	0.2	0.1	20.7	0.6	1.6	15.1	27.3	2.4	0.1	3.4	4.4	5.1	0	10.8	0.4	2.2	10.5	
9136164	DAGORETTI	2011	12	12.4	22.1	4.5	16	0	0	0	0	0	0	0	0	0.3	0	0	0	12.5	1.3	0	0	0	0	0	0	42.6	14.8	2.7	0	0	0	0
9136164	DAGORETTI	2012	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9136164	DAGORETTI	2012	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	tr	tr	1	0.3	tr	0	0	0	0	0	0	7.3	0.7	0	0.6		
9136164	DAGORETTI	2012	3	tr	tr	0.7	4.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9136164	DAGORETTI	2012	4	4.8	35.5	29.1	9	0.5	1.7	6.5	0.2	0.3	0	1	2.2	1.1	8.3	18.8	0.9	3.8	4.2	tr	76.2	0.1	13.9	29.7	59.8	19.6	14.9	74.7	10.0	35.9	6.4	
9136164	DAGORETTI	2012	5	20.5	2.3	40.3	41.1	28.7	14.7	0	3	2.6	0	1.4	27.9	7.5	1.5	1.2	4.6	2.8	9.9	29.2	0	0	1.5	tr	1.8	2.7	0.9	1.9	0.5	0	0	6.8
9136164	DAGORETTI	2012	6	0.4	0	2.5	0.6	0	0	4.6	1.5	TR	TR	0	0	0	0	tr	tr	0	0.6	0	0	0	0	3.5	9.5	3	0	0	0	0	0	
9136164	DAGORETTI	2012	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	tr	tr	tr	0.0	0.0	0.0	0.0	8.1	0.0	tr	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	tr	0.1	0.0	0.0
9136164	DAGORETTI	2012	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.7	0.1	tr	0.1	0.0	0.0	0.0	0.0	tr	31.0	0.1	6.0	tr	0.0	0.0
9136164	DAGORETTI	2012	9	0.0	0.0	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.2	tr	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.4	0.0	0.0	0.0	0.0	0.0	
9136164	DAGORETTI	2012	10	0.0	0.0	0.0	0.0	0.0	tr	0.0	0.0	0.0	7.4	0.1	2.1	6.5	2.8	12.7	tr	0.0	3.2	tr	0.0	0.0	0.0	0.0	1.3	0.0	0.0	25.7	0.0	0.0	0.0	1.0
9136164	DAGORETTI	2012	11	18.6	94.8	8.5	3.8	0.0	20.6	11.6	56.9	0.0	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	5.8	0.0	0.0	0.8	0.0	24.9	17.5	10.3	2.0	
9136164	DAGORETTI	2012	12	2.5	45.2	1.8	1.0	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	7.2	4.9	19.9	0.0	0.0	0.0	32.0	15.1	0.0	28.7	26.1	0.4	69.6	6.6	0.0	6.0
9136164	DAGORETTI	2013	1	0.0	2.1	0.0	0.0	0.0	4.6	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	8.5	0.9
9136164	DAGORETTI	2013	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
9136164	DAGORETTI	2013	3	0.0	0.0	0.0	0.0	0.5	0.0	4.8	1.5	0.0	0.0	0.0	0.0	17.2	15.6	0.0	0.0	0.0	0.4	17.9	2.5	0.0	0.0	0.0	0.0	0.0	0.1	54.1	2.0	2.8	23.2	33.4
9136164	DAGORETTI	2013	4	0.2	3.1	13.5	6.2	21.3	9.1.	22.8	40.0	12.3	19.5	16.1	36.8	0.1	1.9	59.2	6.6	16.0	10.9	0.4	3.2	0.0	27.7	0.0	0.0	0.0	5.1	2.2	0.0	0.0	0.0	
9136164	DAGORETTI	2013	5	0.3	0.3	0.0	2.3	12.0	1.1	1.9	0.7	0.1	0.0	29.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9136164	DAGORETTI	2013	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.7	0.6	1.2	0.0	0.0	0.7	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9136164	DAGORETTI	2013	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.2	0.0	0.0	0.1	0.0
9136164	DAGORETTI	2013	8	0.0	2.6	0.1	0.0	0.1	0.0	0.0	1.4	0.0	0.0	0.0	0.0	1.1	10.9	0.0	0.6	0.7	0.6	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1
9136164	DAGORETTI	2013	9	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.1		19.8	tr	0.0	1.4	0.6	0.0	0.0	0.0	0.0	0.0	0.0	
9136164	DAGORETTI	2013	10	0.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9136164	DAGORETTI	2013	11	0.0	2.5	8.1	3.0	0.0	2.1	0.0	0.0	11.4	12.1	4.3	0.0	0.0	0.0	0.0	2.1	0.0	14.7	6.7	1.1	0.0	1.5	0.0	0.0	0.7	1.9	0.0	0.9	19.9	2.0	
9136164	DAGORETTI	2013	12	1.2	0.0	0.0	2.5	40.4	0.0	0.4	14.6	10.9	12.3	52.8	0.7	17.1	1.5	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9136168	J.K.I.A.	2009	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12.5	19.4	0	0	0	0	0	0	0	0	17.8	2.7	0	0	0	0
9136168	J.K.I.A.	2009	2	0	0	0	0	0	7.6	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	24.6	0.4	0	0.5	0	0			
9136168	J.K.I.A.	2009	3	0	0	3.4	0	0	0	0	0	0	10.6	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.8	6.5	0
9136168	J.K.I.A.	2009	4	0	0	0	0	1	8	0	0	0	0	0	8.8	0	0	0	0	0	0	0	14.4	2.4	0	0	0	0	33	16.9	0	0	0	
9136168	J.K.I.A.	2009	5	0	22.2	0	0	0	3.9	0	0	0	0.2	0	1	8.9	0	0	0	0	0	0	0	21.6	0	0	0	0	28.3	24.9	29	0	0	0
9136168	J.K.I.A.	2009	6	8.6	18.9	0	2.9	0	3.6	0	0	0	0	0	0	0	0	0	2.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9136168	J.K.I.A.	2009	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0
9136168	J.K.I.A.	2009	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0	0	0	0	0	0	0
9136168	J.K.I.A.	2009	9	0	0.6	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9136168	J.K.I.A.	2009	10	0	0	4.8	0	0	0	0	0	2.2	0	0	0	0	0	17.2	15.2	2.5	2.9	0	0	0	0	0.5	0	1.6	0	1	3.8	0.4	7.5	6
9136168	J.K.I.A.	2009	11	11.2	3	0	0.2	5.2	0	0	0	0.8	0	0	0	0	0	0	0	12.4	4.3	0	0	0	0	2.8	3	0.4	0	3.4	1.9	0	0	
9136168	J.K.I.A.	2009	12	6.6	2	6.4	0.5	0	0	0	0	5.2	0.2	0.2	4.1	0	0	0	0	0	0	0	0	0	0	59.2	0	3	1.8	3.4	20.1	0	0	0
9136168	J.K.I.A.	2010	1	1.2	18.4	0.4	2	0	0	0	14.3	31.4	1	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9136168	J.K.I.A.	2010	2	0	0	0	17.2	1	1	0.4	0	0	0	0	0	0	0	0	0	0	0	50.1	0	4.2	14.5	0	0	0	0	0	8.3			
9136168	J.K.I.A.	2010	3	1.3	20.3	0	0	0	1.8	14	0	0	0	0	0	0	0	0.7	1.6	0	0	1	32.3	12.5	0	0	28.8	0	0	0	0	14.8	3	0
9136168	J.K.I.A.	2010	4	6.1	5.5	1.1	0.6	0	0	2.2	0	0	0	0	0	0	0	4.2	1.9	17.5	0	0	1.4	0	0	0	0	0	1.4	0	0	0	3.7	
9136168	J.K.I.A.	2010	5	1.1	0	0	0.3	8.1	0	0.3	0	0	12.2	19.1	3.7	6.9	10.8	0	0	16.6	0	0	0	0	0	0	0	0	0	0	2	0	0	0
9136168	J.K.I.A.	2010	6	0	3.5	19.9	0	0	3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9136168	J.K.I.A.	2010	7	tr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.5	0	0	0	0	0
9136168	J.K.I.A.	2010	8	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	2.9	1.8	0	0	0	0	0	0.2	1.2	0	0	0
9136168	J.K.I.A.	2010	9	0	0	3	3.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.6	5.9	0	0	
9136168	J.K.I.A.	2010	10	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17.5	0.6	0.4	1.4	0	0	0	0	0	0
9136168	J.K.I.A.	2010	11	15	2.3	3.2	0.5	1.5	0.7	0.6	12.9	6	0.2	0	5.9	0	6.6	0	0	5.1	0	0	0	0	0	0	0	2.3	3.7	1				
9136168	J.K.I.A.	2010	12	0	0	0	0	14	14.4	14.6	0	0.5	10.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	tr	1.8	tr	0	0	1
9136168	J.K.I.A.	2011	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.8	0	0	0	0	0	0	0	0	0
9136168	J.K.I.A.	2011	2	0	0	0	0	0	0	0	0	0	0	0	0	0.6	4	45	0	2	0	0	0	0	2	0	0	0	0	0	0			
9136168	J.K.I.A.	2011	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.4	37.6	23.1	8.4	0	0	0	0	0	1	0	1	0	13.6	0
9136168	J.K.I.A.	2011	4	0	7.2	8.4	0	0	0	0	0	0	0	0	0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0	0.8	0	0	0	
9136168	J.K.I.A.	2011	5	0.2	0	31.1	2.8	0.2	1.2	0	0	3.2	3.1	2.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
9136168	J.K.I.A.	2011	6	0	0	0	0	0	2.6	0	0	0	0	3.2	1.5	3	1.7	0	0	0	0	0	4.7	0	0	0	0	1.4	10.7	0	0	0	0.8	
9136168	J.K.I.A.	2011	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.5	1.4	0	0	0	0
9136168	J.K.I.A.	2011	8	0	0	0	0	0	0	0	0	0	2.2	0	0	33.6	0	4	0	0	0	0	0	0	2.4	0	0	0	0	0	0	0	0	0
9136168	J.K.I.A.	2011	9	0	0	3	13.3	0	0	0	0	0.3	0	0	3.8	0	0	0	0	0	0	0	0	0	0	2.6	0.2	0	0	0	0	3.9	0.7	0.4
9136168	J.K.I.A.	2011	10	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	2.0	0.0	15.2	8.0	0.1	0.5	0.0	0.0	0.0	0.0	0.0	0.0	6.8	1.5	0.0	1.0	0.4	7.0	0.2	0.4	0.0
9136168	J.K.I.A.	2011	11	0	36.9	0	0	0	13.3	0	2.8	0	0	2	2.7	1.4	0	8.1	30.1	2.9	4.4	2.7	87.9	20.1	0	1.8	4.3	7.2	0	8.4	0	0	0	
9136168	J.K.I.A.	2011	12	5.2	0.3	0	2.6	0.5	0	0	0	0	0	0	0	0	0	0	0	9.1	0	0	0	0	0	0	0	11	0.4	0	0			0
9136168	J.K.I.A.	2012	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9136168	J.K.I.A.	2012	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1		0		0	0	0	0	0	0	2.4	0	0	0		
9136168	J.K.I.A.	2012	3	0	4.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9136168	J.K.I.A.	2012	4	3.2	tr	10.3	26	6.2	10		0	0.6	0	0	5.6	6	2.6	1.6	0	6.6	27.4	10.5	26.3	0	23.8	3.2	73.6	23.5	7.5	4.7	1.2	0.0	1.4	
9136168	J.K.I.A.	2012	5	2.8	43.2	50.2	49.2	6.2	15	0	0	0.4	0	0	1	0	0	6.5	4.6	0.2	0.5	0	0	0	2.4	1.5	1.6	0	2	0.2	1	0	0	7.1
9136168	J.K.I.A.	2012	6	0.1	0	0.4	0.2	0	0	1.6	18.2	0	0	0	0	0	0	0		0	0	0	0	0	0	2.9	8.8	0	0	0	0	0	0	
9136168	J.K.I.A.	2012	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.2	0.0	tr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	tr	0.0	0.0
9136168	J.K.I.A.	2012	8	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	1.0	0.0		0.0	0.0	0.0	tr	tr	0.0	0.8	tr	0.0	0.0	0.0	0.0	0.0	0.5	0.0	1.3		0.0	0.0
9136168	J.K.I.A.	2012	9	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.6	0.0	tr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.2	3.0	0.0	0.0	0.0	0.0	0.0	
9136168	J.K.I.A.	2012	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	3.6	1.0	5.4	1.5	tr	3.6	0.0	0.0	0.0	0.0	tr	tr	0.0	0.0	24.4	0.0	0.0	14.2	0.0	0.0	0.0	0.2
9136168	J.K.I.A.	2012	11	3.2	17.0	2.1	7.0	0.0	0.2	2.5	0.7	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0	2.5	12.3	8.1		
9136168	J.K.I.A.	2012	12	4.0	20.1	0.6	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	5.3	15.5	0.0	0.0	3.6	3.2	0.0	0.0	9.3	119.3	3.0	4.9	17.5	0.0	6.0
9136168	J.K.I.A.	2013	1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	10.5	0.0	0.0	0.0	0.0	0.0	0.0	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	17.1	0.0
9136168	J.K.I.A.	2013	2	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
9136168	J.K.I.A.	2013	3	0.0	0.0	0.0	0.7	0.0	0.0	19.0	0.0	0.4	0.3	0.0	0.0	1.2	18.1	0.0	0.0	0.0	1.6	26.0	7.0	0.5	0.0	0.0	0.0	0.0	0.0	32.0	2.6	0.0	3.8	21.0
9136168	J.K.I.A.	2013	4	0.2	1.4	0.0	0.0	9.0	16.2	17.9	20.6	16.0	30.0	5.3	27.6	2.5	27.6	40.5	0.0	0.6	0.5	0.4	0.8	0.0	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0	
9136168	J.K.I.A.	2013	5	0.0	0.2	0.0	0.0	2.5	1.6	0.8	0.5	0.0	0.0	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0
9136168	J.K.I.A.	2013	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.6	21.8	1.5	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9136168	J.K.I.A.	2013	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0

[c]

9136168	J.K.I.A.	2013	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.6	0.0	7.0	0.0	0.4	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	
9136168	J.K.I.A.	2013	9	5.5	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	2.9	0.0	10.5	6.0	4.8	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0		
9136168	J.K.I.A.	2013	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0		
9136168	J.K.I.A.	2013	11	0.0	0.0	6.4	3.7	4.0	0.0	0.0	9.7	2.6	5.8	2.1	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.0	8.9	0.0	9.1	0.0	1.0	0.6	2.0	0.5	1.6	0.0	0.0		
9136168	J.K.I.A.	2013	12	4.7	0.0	0.0	8.4	46.8	0.0	0.4	13.4	16.9	20.6	13.9	0.0	61.1	1.9	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Table 8-2 : Daily Rainfall Recording from Three Selected Raingauges in Three Meteorological Stations in Nairobi

[d]

8.3 Appendix C: Sewer Network (Conduits) Parameterisation

Sub-catchment number	**Conduit number**	**Diameter (m)**	**Length (m)**
S1	C_1	0.225	271.28
	C_2	0.225	271.28
	C_3	0.225	271.28
	C_4	0.225	271.28
	C_5	0.225	271.28
	C_6	0.225	271.28
	C_7	0.225	271.28
	C_8	0.225	66.31
	C_9	0.225	127.46
	C_{10}	0.225	121.67
	C_{11}	0.225	138.665
	C_{12}	0.6	324.21
	C_{13}	0.6	80.23
	C_{14}	0.6	569.48
	C_{15}	0.6	533.31
	$Outlet_1$	-	
	C_{16}	0.23	309.923
	C_{17}	0.23	303.638
	C_{18}	0.23	303.638
	C_{19}	0.3	87.167
	C_{20}	0.3	95.53
	C_{21}	0.3	86.858
	$Outlet_2$		

Table 8-3 : Sewer conduits parameterisation

8.4 Appendix D: Sewer Network (Junctions) Parameterisation

Sub-catchment	Junction number	Junction Ground level	Junction invert level from data	Estimated invert level for missing data	Depth
S_1	J_1	1667.616	1665.166	1665.166	2.450
	J_2	1668.096	1666.000	1666.000	2.096
	J_3	1667.963	1665.000	1665.000	2.963
	J_4	1666.926	1664.240	1664.240	2.686
	J_5	1666.673	1664.330	1664.330	2.343
	J_6	1666.373	1664.000	1664.000	2.373
	J_7	1666.072	1663.890	1663.890	2.182
	J_8	1665.491	1663.110	1663.110	2.381
	J_9	1662.915	1660.050	1660.050	2.865
	J_{10}	1663.160	1660.770	1660.770	2.390
	J_{11}	1663.080	1658.450	1658.450	4.630
	J_{12}	1661.152	1659.000	1659.000	2.152
	J_{13}	1657.661	1653.941	1653.941	3.720
	J_{14}	1657.152	1653.362	1653.362	3.790
	J_{15}	1655.377	1649.777	1649.777	5.600
	$Outlet_1$				
S_2	J_{16}	1649.680	1648.560	1648.560	1.120
	J_{17}	1649.660	1648.070	1648.070	1.590
	J_{18}	1649.590	1647.570	1647.570	2.020
	J_{19}	1649.570	1647.070	1647.070	2.500
	J_{20}	1648.240	1646.100	1646.100	2.140
	J_{21}	1645.100	1642.240	1642.240	2.860
	$Outlet_2$				

Table 8-4 : Sewer junctions parameterisation

8.5 Appendix E: Domestic Water Consumption Rates by MoWI

Table 2.2: Consumption Rates

CONSUMER	UNIT	RURAL AREAS			URBAN AREAS		
		High potential	Medium potential	Low potential	High Class Housing	Medium Class Housing	Low Class Housing
People with individual connections	1/head/ day	60	50	40	250	150	75
People without connections	1/head/ day	20	15	10	-	-	20
Livestock unit	1/head/ day	50			-		
Boarding schools	1/head/ day	50					
Day schools with WC without WC	1/head/ day	25 5					
Hospitals Regional District other	1/bed/ day	400 200 100 } + 20 1 per outpatient and day (minimum 5000 1/day)					
Dispensary and Health Centre	1/day	5000					
Hotels High Class Medium Class Low Class	1/bed/ day	600 300 50					
Administrative offices	1/head/ day	25					
Bars	1/day	500					
Shops	1/day	100					
Unspecified industry	1/ha/day				20.000		
Coffee pulping factories	1/kg coffee	25 (when re-circulation of water is used).					

Table 8-5 : Water consumption rates as per the Ministry of Water and Irrigation, Kenya.

8.6 Appendix F: SWMM 5.1 Status Report

EPA STORM WATER MANAGEMENT MODEL - VERSION 5.1 (Build 5.1.007)

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NOTE: The summary statistics displayed in this report are

based on results found at every computational time step,

not just on results from each reporting time step.

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Analysis Options

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Flow Units .... CMS

Process Models:

Rainfall/Runoff .... YES

RDII .... NO

Snowmelt .... NO

Groundwater .... NO

Flow Routing .... YES

Ponding Allowed .... YES

Water Quality .... NO

Infiltration Method ...... GREEN_AMPT

Flow Routing Method ...... KINWAVE

Starting Date MAR-18-2015 00:00:00

Ending Date MAR-18-2015 06:00:00

Antecedent Dry Days 0.0

Report Time Step 00:15:00

Wet Time Step 00:05:00

Dry Time Step 01:00:00

Routing Time Step .... 30.00 sec

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Element Count

****

Number of rain gages 1

Number of subcatchments ... 2

Number of nodes 23

Number of links 21

Number of pollutants 0

Number of land uses 0

****

Raingage Summary

****

Name	Data Source	Data Type	Recording Interval
Gauge1	26-12-2012Event	VOLUME	15 min.

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Subcatchment Summary

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Name	Area	Width	%Imperv	%Slope	Rain Gage	Outlet
S1	176.07	835.87	80.00	0.5000	Gauge1	J1
S2	79.80	703.30	60.00	1.2300	Gauge1	J16

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Node Summary

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Name	Type	Invert Elev.	Max. Depth	Ponded Area	External Inflow
J1	JUNCTION	1665.17	2.45	0.0	Yes
J2	JUNCTION	1665.00	3.10	0.0	
J3	JUNCTION	1664.80	3.16	0.0	
J4	JUNCTION	1664.24	2.69	0.0	
J5	JUNCTION	1664.01	2.66	0.0	
J6	JUNCTION	1663.39	2.98	0.0	
J7	JUNCTION	1663.19	2.88	0.0	
J8	JUNCTION	1662.81	2.68	0.0	
J9	JUNCTION	1660.05	2.87	0.0	
J10	JUNCTION	1658.77	4.39	0.0	
J11	JUNCTION	1658.45	4.63	0.0	
J12	JUNCTION	1657.50	3.65	0.0	
J13	JUNCTION	1653.94	3.72	0.0	
J14	JUNCTION	1653.36	3.79	0.0	
J15	JUNCTION	1649.78	5.60	0.0	
J16	JUNCTION	1648.56	1.12	0.0	Yes
J17	JUNCTION	1648.07	1.59	0.0	
J18	JUNCTION	1647.57	2.02	0.0	
J19	JUNCTION	1647.07	2.50	0.0	
J20	JUNCTION	1646.10	2.14	0.0	
J21	JUNCTION	1642.24	2.86	0.0	
Out1	OUTFALL	1647.00	0.60	0.0	
Out2	OUTFALL	1640.00	0.30	0.0	

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Link Summary

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Name	From Node	To Node	Type	Length	%Slope	Roughness
C1	J1	J2	CONDUIT	44.5	0.3729	0.0140
C2	J2	J3	CONDUIT	23.9	0.8384	0.0140
C4	J3	J4	CONDUIT	60.9	0.9189	0.0140
C5	J4	J5	CONDUIT	26.7	0.8606	0.0140
C6	J5	J6	CONDUIT	59.5	1.0415	0.0140
C7	J6	J7	CONDUIT	71.4	0.2802	0.0140
C8	J7	J8	CONDUIT	212.0	0.1792	0.0140
C9	J8	J9	CONDUIT	29.4	9.4207	0.0140
C10	J9	J10	CONDUIT	203.1	0.6303	0.0140
C11	J10	J11	CONDUIT	156.3	0.2048	0.0140
C12	J11	J12	CONDUIT	336.9	0.2820	0.0140
C13	J12	J13	CONDUIT	73.1	4.8767	0.0140
C14	J13	J14	CONDUIT	73.1	0.7924	0.0140
C15	J14	J15	CONDUIT	567.8	0.6314	0.0140
C16	J15	Out1	CONDUIT	511.0	0.5435	0.0140
C17	J16	J17	CONDUIT	75.2	0.6516	0.0140
C18	J17	J18	CONDUIT	163.3	0.3062	0.0140
C19	J18	J19	CONDUIT	96.0	0.5206	0.0140
C20	J19	J20	CONDUIT	80.1	1.2117	0.0140
C21	J20	J21	CONDUIT	109.0	3.5435	0.0140
C22	J21	Out2	CONDUIT	96.3	2.3257	0.0140

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Cross Section Summary

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Conduit	Shape	Full Depth	Full Area	Hyd. Rad.	Max. Width	No. of Barrels	Full Flow
C1	CIRCULAR	0.23	0.04	0.06	0.23	1	0.03
C2	CIRCULAR	0.23	0.04	0.06	0.23	1	0.04
C4	CIRCULAR	0.23	0.04	0.06	0.23	1	0.04
C5	CIRCULAR	0.23	0.04	0.06	0.23	1	0.04
C6	CIRCULAR	0.23	0.04	0.06	0.23	1	0.04
C7	CIRCULAR	0.23	0.04	0.06	0.23	1	0.02
C8	CIRCULAR	0.23	0.04	0.06	0.23	1	0.02
C9	CIRCULAR	0.23	0.04	0.06	0.23	1	0.13
C10	CIRCULAR	0.23	0.04	0.06	0.23	1	0.03
C11	CIRCULAR	0.23	0.04	0.06	0.23	1	0.02
C12	CIRCULAR	0.23	0.04	0.06	0.23	1	0.02
C13	CIRCULAR	0.60	0.28	0.15	0.60	1	1.26
C14	CIRCULAR	0.60	0.28	0.15	0.60	1	0.51
C15	CIRCULAR	0.60	0.28	0.15	0.60	1	0.45
C16	CIRCULAR	0.60	0.28	0.15	0.60	1	0.42
C17	CIRCULAR	0.23	0.04	0.06	0.23	1	0.04
C18	CIRCULAR	0.23	0.04	0.06	0.23	1	0.02
C19	CIRCULAR	0.23	0.04	0.06	0.23	1	0.03
C20	CIRCULAR	0.30	0.07	0.07	0.30	1	0.10
C21	CIRCULAR	0.30	0.07	0.07	0.30	1	0.17
C22	CIRCULAR	0.30	0.07	0.07	0.30	1	0.14

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Control Actions Taken

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**************************	Volume	Depth
Runoff Quantity Continuity	hectare-m	mm
**************************	---------	-------
Total Precipitation	23.710	92.667
Evaporation Loss	0.000	0.000
Infiltration Loss	0.540	2.112
Surface Runoff	20.134	78.689
Final Surface Storage	3.105	12.134
Continuity Error (%)		-0.289

**************************	Volume	Volume
Flow Routing Continuity	hectare-m	10^6 ltr
**************************	---------	---------
Dry Weather Inflow	56.703	567.034
Wet Weather Inflow	19.958	199.581
Groundwater Inflow	0.000	0.000
RDII Inflow	0.000	0.000
External Inflow	0.000	0.000
External Outflow	0.117	1.174
Internal Outflow	76.487	764.876
Evaporation Loss	0.000	0.000
Exfiltration Loss	0.000	0.000
Initial Stored Volume	0.043	0.429
Final Stored Volume	0.008	0.081
Continuity Error (%)	0.119	

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Highest Flow Instability Indexes

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Link C9 (1)

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Routing Time Step Summary

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Minimum Time Step : 30.00 sec

Average Time Step : 30.00 sec

Maximum Time Step : 30.00 sec

Percent in Steady State : 0.00

Average Iterations per Step : 1.04

Percent Not Converging : 0.00

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Subcatchment Runoff Summary

****

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff CMS	Runoff Coeff
S1	92.67	0.00	0.00	1.65	77.79	136.96	18.25	0.839
S2	92.67	0.00	0.00	3.14	80.67	64.37	9.49	0.871

****

Node Depth Summary

****

Node	Type	Average Depth Meters	Maximum Depth Meters	Maximum HGL Meters	Time of Max Occurrence days hr:min
J1	JUNCTION	2.45	2.45	1667.62	0 00:01
J2	JUNCTION	0.23	0.23	1665.23	0 00:00
J3	JUNCTION	0.13	0.18	1664.98	0 00:00
J4	JUNCTION	0.14	2.69	1666.93	0 00:00
J5	JUNCTION	0.13	0.22	1664.23	0 00:00
J6	JUNCTION	2.98	2.98	1666.37	0 00:00
J7	JUNCTION	2.88	2.88	1666.07	0 00:00
J8	JUNCTION	0.23	0.23	1663.04	0 00:00
J9	JUNCTION	0.12	2.87	1662.92	0 00:00
J10	JUNCTION	0.24	4.39	1663.16	0 00:00
J11	JUNCTION	0.17	0.23	1658.68	0 00:00
J12	JUNCTION	0.15	0.23	1657.72	0 00:00
J13	JUNCTION	0.09	3.72	1657.66	0 00:00
J14	JUNCTION	0.10	3.79	1657.15	0 00:00
J15	JUNCTION	0.13	5.60	1655.38	0 00:00
J16	JUNCTION	1.12	1.12	1649.68	0 00:01
J17	JUNCTION	1.59	1.59	1649.66	0 00:00
J18	JUNCTION	0.23	0.23	1647.80	0 00:00
J19	JUNCTION	0.15	0.23	1647.30	0 00:00
J20	JUNCTION	0.10	0.30	1646.40	0 00:00
J21	JUNCTION	0.09	2.86	1645.10	0 00:00
Out1	OUTFALL	0.10	0.60	1647.60	0 00:00
Out2	OUTFALL	0.09	0.30	1640.30	0 00:00

****

Node Inflow Summary

Node	Type	Maximum Lateral Inflow CMS	Maximum Total Inflow CMS	Time of Max Occurrence days hr:min	Lateral Inflow Volume 10^6 ltr	Total Inflow Volume 10^6 ltr	Flow Balance Error Percent
J1	JUNCTION	36.289	36.289	0 03:15	526	526	0.060
J2	JUNCTION	0.000	0.025	0 00:00	0	0.821	0.000
J3	JUNCTION	0.000	0.038	0 00:00	0	0.821	0.000
J4	JUNCTION	0.000	0.042	0 00:01	0	0.822	0.000
J5	JUNCTION	0.000	0.041	0 00:01	0	0.822	0.000
J6	JUNCTION	0.000	0.045	0 00:01	0	0.823	0.006
J7	JUNCTION	0.000	0.022	0 00:00	0	0.748	0.009
J8	JUNCTION	0.000	0.018	0 00:00	0	0.652	0.000
J9	JUNCTION	0.000	0.059	0 00:00	0	0.653	0.000
J10	JUNCTION	0.000	0.033	0 00:00	0	0.654	0.000
J11	JUNCTION	0.000	0.020	0 00:08	0	0.653	0.000
J12	JUNCTION	0.000	0.024	0 00:01	0	0.656	0.000
J13	JUNCTION	0.000	0.754	0 00:00	0	0.677	0.000
J14	JUNCTION	0.000	0.523	0 00:01	0	0.689	0.000
J15	JUNCTION	0.000	0.487	0 00:02	0	0.791	0.000
J16	JUNCTION	17.689	17.689	0 03:00	241	241	0.058
J17	JUNCTION	0.000	0.036	0 00:00	0	0.894	0.019
J18	JUNCTION	0.000	0.024	0 00:00	0	0.652	0.000
J19	JUNCTION	0.000	0.033	0 00:01	0	0.653	0.000
J20	JUNCTION	0.000	0.099	0 00:00	0	0.656	0.000
J21	JUNCTION	0.000	0.177	0 00:00	0	0.663	0.000
Out1	OUTFALL	0.000	0.453	0 00:04	0	0.902	0.000
Out2	OUTFALL	0.000	0.137	0 00:00	0	0.666	0.000

****

Node Surcharge Summary

****

Surcharging occurs when water rises above the top of the highest conduit.

Node	Type	Hours Surcharged	Max. Height Above Crown Meters	Min. Depth Below Rim Meters
J1	JUNCTION	6.01	2.225	0.000
J2	JUNCTION	6.01	0.000	2.871
J4	JUNCTION	0.03	2.461	0.000
J6	JUNCTION	6.01	2.757	0.000
J7	JUNCTION	6.01	2.657	0.000
J8	JUNCTION	6.01	0.000	2.456
J9	JUNCTION	0.02	2.640	0.000
J10	JUNCTION	0.09	4.165	0.000
J11	JUNCTION	0.11	0.000	4.405
J13	JUNCTION	0.02	3.120	0.000
J14	JUNCTION	0.03	3.190	0.000
J15	JUNCTION	0.05	5.000	0.000
J16	JUNCTION	6.01	0.890	0.000
J17	JUNCTION	6.01	1.360	0.000
J18	JUNCTION	6.01	0.000	1.790
J20	JUNCTION	0.01	0.000	1.840
J21	JUNCTION	0.02	2.560	0.000

****

Node Flooding Summary

Flooding refers to all water that overflows a node, whether it ponds or not.

Node	Hours Flooded	Maximum Rate CMS	Time of Max Occurrence days hr:min	Total Flood Volume 10^6 ltr	Maximum Ponded Volume 1000 m3
J1	6.00	36.260	0 03:15	524.736	0.000
J4	0.03	0.002	0 00:01	0.000	0.000
J6	6.01	0.022	0 00:01	0.076	0.000
J7	6.01	0.004	0 00:01	0.095	0.000
J9	0.02	0.013	0 00:00	0.001	0.000
J10	0.09	0.014	0 00:01	0.001	0.000
J13	0.02	0.123	0 00:00	0.007	0.000
J14	0.03	0.062	0 00:01	0.004	0.000
J15	0.05	0.050	0 00:02	0.005	0.000
J16	6.00	17.646	0 03:00	240.161	0.000
J17	6.01	0.011	0 00:01	0.243	0.000
J21	0.02	0.020	0 00:00	0.001	0.000

****

Outfall Loading Summary

Outfall Node	Flow Freq Pcnt	Avg Flow CMS	Max Flow CMS	Total Volume 10^6 ltr
Out1	100.00	0.029	0.453	0.902
Out2	100.00	0.025	0.137	0.666
System	100.00	0.054	0.557	1.568

****

Link Flow Summary

****

Link	Type	Maximum |Flow| CMS	Time of Max Occurrence days hr:min	Maximum |Veloc| m/sec	Max/ Full Flow	Max/ Full Depth
C1	CONDUIT	0.025	0 00:00	0.64	1.00	1.00
C2	CONDUIT	0.038	0 00:00	1.26	0.99	0.70
C4	CONDUIT	0.042	0 00:01	1.36	1.05	0.89
C5	CONDUIT	0.041	0 00:01	1.21	1.06	0.99
C6	CONDUIT	0.045	0 00:01	1.35	1.05	0.89
C7	CONDUIT	0.022	0 00:00	0.56	1.00	1.00
C8	CONDUIT	0.018	0 00:00	0.44	1.00	1.00
C9	CONDUIT	0.059	0 00:00	4.52	0.46	0.36
C10	CONDUIT	0.033	0 00:00	1.25	1.00	1.00
C11	CONDUIT	0.020	0 00:08	0.57	1.08	1.00
C12	CONDUIT	0.024	0 00:01	0.69	1.08	0.85
C13	CONDUIT	0.754	0 00:00	9.48	0.60	0.32
C14	CONDUIT	0.523	0 00:01	4.57	1.03	1.00
C15	CONDUIT	0.487	0 00:02	3.26	1.07	1.00
C16	CONDUIT	0.453	0 00:04	2.30	1.08	1.00
C17	CONDUIT	0.036	0 00:00	0.86	1.00	1.00
C18	CONDUIT	0.024	0 00:00	0.59	1.00	1.00
C19	CONDUIT	0.033	0 00:01	0.98	1.03	0.83
C20	CONDUIT	0.099	0 00:00	1.88	1.00	0.70
C21	CONDUIT	0.177	0 00:00	3.24	1.05	0.76
C22	CONDUIT	0.137	0 00:00	2.70	1.00	1.00

****

Conduit Surcharge Summary

****

Conduit	Hours Full: Both Ends	Hours Full: Upstream	Hours Full: Dnstream	Hours Above Full Normal Flow	Hours Capacity Limited
C1	6.01	6.01	6.01	6.01	6.01
C4	0.01	0.01	0.01	0.02	0.01
C5	0.01	0.02	0.01	0.03	0.02
C6	0.01	0.01	0.01	0.02	0.01
C7	6.01	6.01	6.01	6.01	6.01
C8	6.01	6.01	6.01	0.01	6.01
C10	0.01	0.01	0.02	0.01	0.01
C11	0.08	0.08	0.11	0.07	0.08
C12	0.01	0.01	0.01	0.07	0.01
C14	0.01	0.01	0.01	0.01	0.01
C15	0.02	0.02	0.03	0.03	0.02
C16	0.04	0.04	0.07	0.02	0.04
C17	6.01	6.01	6.01	6.01	6.01
C18	6.01	6.01	6.01	6.01	6.01
C19	0.01	0.01	0.01	0.01	0.01
C20	0.01	0.01	0.01	0.01	0.01
C21	0.01	0.01	0.01	0.01	0.01
C22	0.01	0.01	0.02	0.02	0.01

Analysis begun on: Mon Aug 14 16:00:38 2017

Analysis ended on: Mon Aug 14 16:00:39 2017

Total elapsed time: 00:00:01

8.7 Appendix G: Sewer system data acquisition approval letter

NAIROBI CITY WATER & SEWERAGE COMPANY LTD.

KAMPALA RD, P. O. Box 30656-00100, Nairobi, Kenya
Tel: +254 20 3988598/000 5013598/000
Fax: +254 20 552126
Email: info@nairobiwater.co.ke
www.nairobiwater.co.ke

NAIROBI WATER
Improving Reliability

NCWSC/HR/TRG.13/VOL.1/38/SM

4th December, 2013

Water Services Trust Fund, Kenya
Po Box 49699-00100
Tel:+254- 20-2729017/8/9
Fax: +254-20-2724357
Email:info@wstf.go.ke
Nairobi, Kenya

Att: Mr. Paul Atwa

Dear Sir,

RE: RESEARCH PROJECT IN MODELING OF URBAN FLOODING IN NAIROBI

Reference is made to your letter dated 27th August, 2013 requesting Nairobi City Water & Sewerage Company for authority to enable **Mr.Simon Onyango Okoth, Admission Number F56/74481/2012** to carry out the above research project to complete his Masters degree in Environmental Engineering at the University of Nairobi.

We are glad to inform you that permission has been granted for Mr. Simon to carry out the above mentioned research subject to the following conditions:

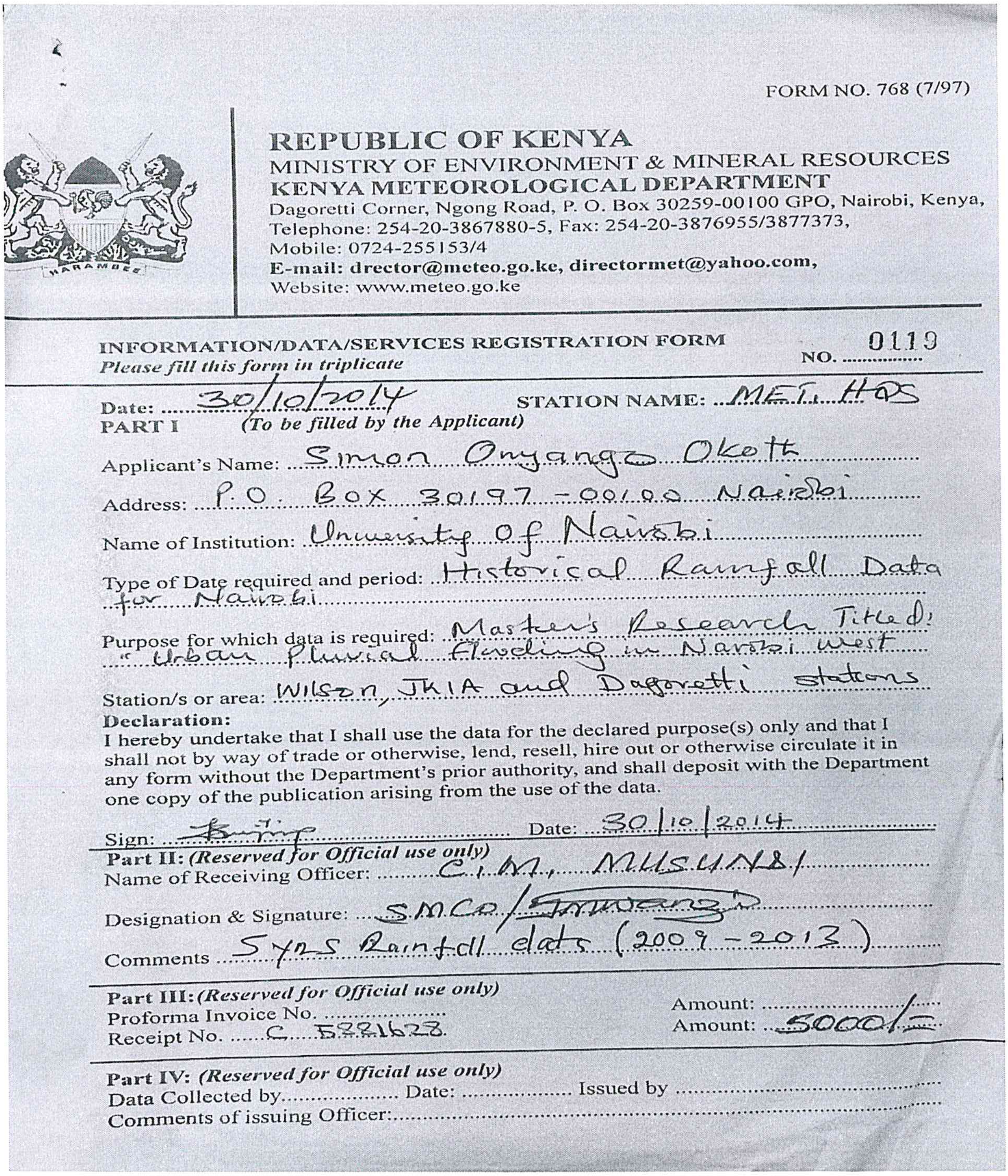
- That the Nairobi City Water and Sewerage Company Limited shall not be held responsible for any injury/ loss suffered during the period Mr. Simon will be collecting the data.
- That he will not qualify for any salary /allowances during the research period
- That the data so collected/created will not be used to malign the name of the Company in any manner whatsoever
- That the research will be used for (and limited to) academic purposes only
- That his activities will not in any way interfere with routine operations of the Departments/Sections where the research will be conducted.
- That he will not take photographs of the Company's facilities without written authority from the Managing Director, Nairobi City Water and Sewerage Company Ltd
- That he will be required to submit a Copy of his report to the Managing Director (through this Office), Nairobi City Water and Sewerage Company on Completion of his research.

If these Conditions are acceptable, kindly advise the Student to report to the **Environment and Compliance Manager** who will accord him the necessary support.

Rose Kariuki - Mwaura
Human Resource Manager

Figure 8-1 : Letter of approval for data acquisition by NCWSC.

8.8 Appendix H: Meteorological data acquisition approval



FORM NO. 768 (7/97)

REPUBLIC OF KENYA
MINISTRY OF ENVIRONMENT & MINERAL RESOURCES
KENYA METEOROLOGICAL DEPARTMENT
Dagoretti Corner, Ngong Road, P. O. Box 30259-00100 GPO, Nairobi, Kenya,
Telephone: 254-20-3867880-5, Fax: 254-20-3876955/3877373,
Mobile: 0724-255153/4
E-mail: drector@meteo.go.ke, directormet@yahoo.com,
Website: www.meteo.go.ke

HARAMBEE

INFORMATION/DATA/SERVICES REGISTRATION FORM NO. 0119
Please fill this form in triplicate

Date: 30/10/2014 STATION NAME: MET. HQS
PART I *(To be filled by the Applicant)*

Applicant's Name: Simon Onyango Okoth
Address: P.O. Box 30197 -00100 Nairobi
Name of Institution: University of Nairobi
Type of Date required and period: Historical Rainfall Data for Nairobi
Purpose for which data is required: Master's Research Titled: " Urban Pluvial flooding in Nairobi West
Station/s or area: Wilson, JKIA and Dagoretti stations

Declaration:
I hereby undertake that I shall use the data for the declared purpose(s) only and that I shall not by way of trade or otherwise, lend, resell, hire out or otherwise circulate it in any form without the Department's prior authority, and shall deposit with the Department one copy of the publication arising from the use of the data.

Sign: [signature] Date: 30/10/2014

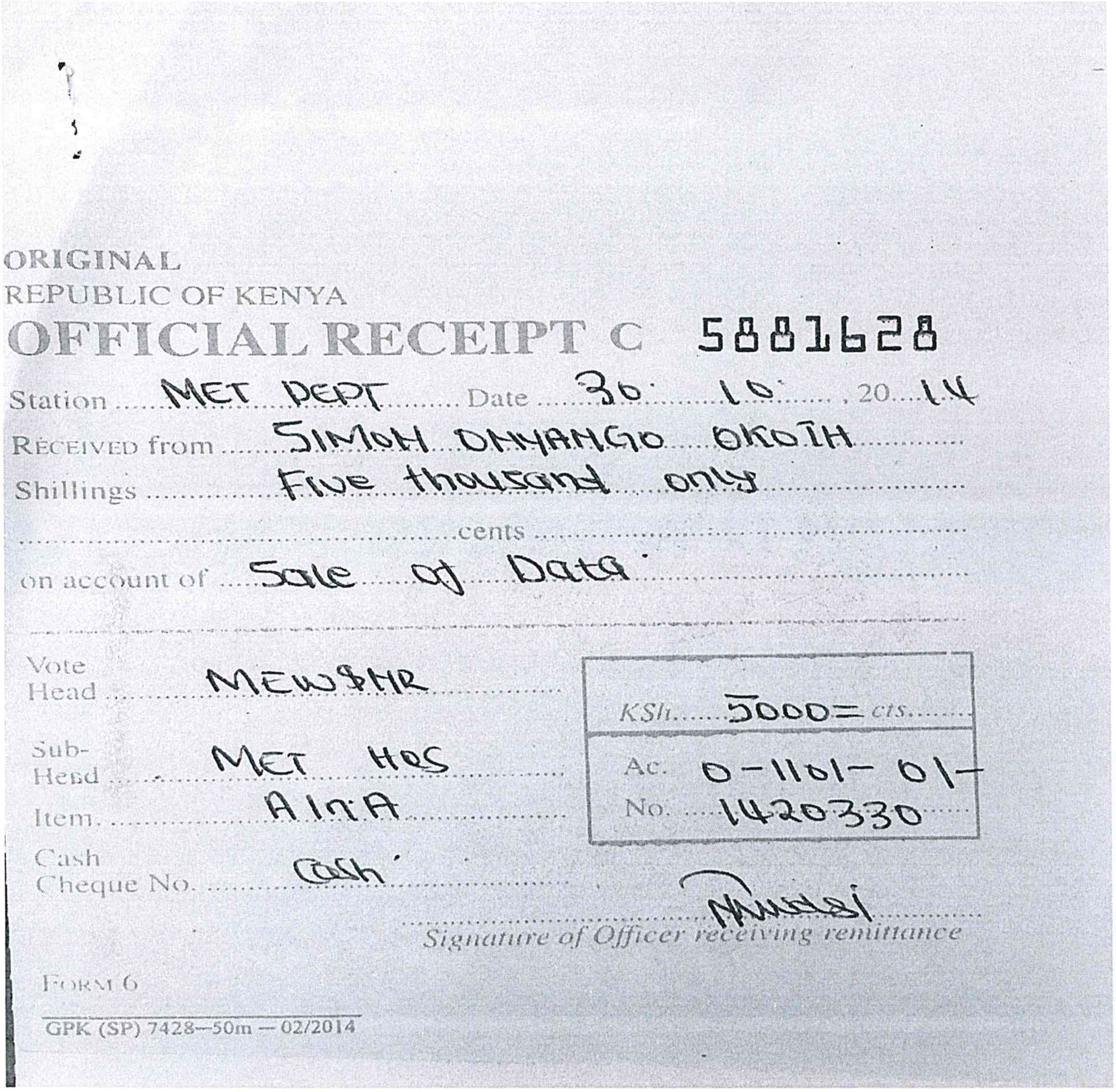
Part II: *(Reserved for Official use only)*
Name of Receiving Officer: C.I.M. MUSUNDI
Designation & Signature: S.M.C.O / [signature]
Comments: 5 yrs Rainfall data (2009 - 2013)

Part III: *(Reserved for Official use only)*
Proforma Invoice No. ....
Receipt No. C 5881628.
Amount: ....
Amount: 5000/=

Part IV: *(Reserved for Official use only)*
Data Collected by.................. Date: .... Issued by ....
Comments of issuing Officer:..................

Figure 8-2 : Meteorological data acquisition approval

8.9 Appendix I: Meteorological data acquisition receipt



ORIGINAL
REPUBLIC OF KENYA
OFFICIAL RECEIPT C 5881628

Station MET DEPT Date 30. 10. 20 14

RECEIVED from SIMON ONYANGO OKOTH

Shillings Five thousand only

cents

on account of Sale of Data

Vote Head MEW&NR	KSh. 5000= cts.
Sub-Head MET HQS	Ac. 0-1101-01-
Item. A1nA	No. 1420330

Cash Cheque No. Cash

Signature of Officer receiving remittance

FORM 6

GPK (SP) 7428—50m — 02/2014

Figure 8-3 : Data purchase receipt

turnitin

Digital Receipt

This receipt acknowledges that Turnitin received your paper. Below you will find the receipt information regarding your submission.

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Word count:	24,496
Character count:	135,618
Submission date:	06-Sep-2018 09:08AM (UTC+0300)
Submission ID:	916919884

2nd Oct 2018

Final Thesis Report

by Simon Okoth

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02 octo 2018