Integrated Urban Pluvial Flooding Analysis and Modelling for Nairobi West and South C in Nairobi City

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Abstract: ***Urban pluvial flooding cases have increased due to urban densification, fast changing urban hydrology as well as inadequate urban drainage design especially the combine storm-sewer systems. In Nairobi city, residents are at greater urban pluvial flooding risk as has been witnessed with a number of flood damages having already been 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. This 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 planners among other key stakeholders the applicability of SWMM 5.1 in analysing urban pluvial flooding to support 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 response of two delineated sub-catchments to the rainfall event of 26th December 2012 was then modelled and sensitivity analysis conducted to identify the relative influence of some model input parameters on the peak runoff. The results from the model showed significant flooding of 20.134 ha-m surface runoff and 81% of sewer system surcharging. The peak runoff was found to be significantly responsive to variations in Impervious N and % imperviousness parameters. The study demonstrated that SWMM5.1 model is a useful tool for simulating urban pluvial flooding and improving urban stormwater management***.

Keywords: Pluvial Flooding; Runoff; Sewer Surcharge; Disaggregation; and urbanisation.

1. Introduction

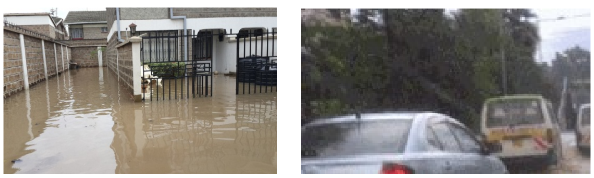
Flooding in urban areas is occurring with increasing frequency all over the world and is causing repeated damage that calls for improved management of floods [1]. In addition, the extent, magnitude and frequency of urban pluvial flooding are likely to increase in the near future, given the increasing effects of climate change, the increased urbanisation and population growth [2]. As a result, 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. Urbanization and the resulting land-use change strongly affect the water cycle and runoff-processes in watersheds [3]. Many authors have attempted to advance the definition of urban pluvial flooding. 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 [4]." Urban flooding may be due to various causes: overland flows on streets, flooding flows from rivers and overflows or surcharges from sewer networks [5]. 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 [6].

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

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" [7]. 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" [8] and [9]. 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 [10]. The 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 [11]. In other words, the potential for evapotranspiration, water infiltration and recharge in urban catchments which have consistently attenuated due the continued removal of vegetation, forestry and top soil cover and their subsequent replacement with impermeable surfaces have significantly shifted the natural hydrology from an infiltration based cycle to a runoff-predominant cycle. This, combined with limited capacity of cities' storm-sewer systems capacities, increased precipitation resulting from climate change and altered ecosystem due to increased urbanization, results in urban pluvial flooding. From this background, it can be concluded that 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.

A. Urban Flooding in Nairobi

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 areas increase due to population growth with no corresponding expansion in storm-sewer water management systems.



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

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 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. One such occurrence is the flooding event of 26th 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.

In this context, there is need to employ suitable modelling approaches to analyse and understand the flooding phenomenon in the city. An integrated modelling by use of both spatial-temporal parameters of a 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 analysed the urban pluvial flooding occurrence and the characteristics of a selected area including inundation to inform the authorities for design of better flood risk management approaches. It accomplishes this by undertaking an integrated analysis and modelling of urban flooding in Nairobi using the 26th December 2012 storm event. During this event, many areas in Nairobi were affected. The objectives were: (i) to identify pertinent modelling parameters influencing urban pluvial flooding; and (ii) to integrate the parameters in (i) above in a multi-scale and multi-source data modelling framework for simulation of urban pluvial flooding. This was done using Geographic Information System (GIS) and Storm Water Management Model (SWMM). The EPA SWMM is a dynamic rainfall-runoff simulation model that computes runoff quantity and quality from primarily urban areas [12]. The rationale for the study is drawn from the fact that many cities in developing countries are places of high population density and centers of infrastructure, investment, economic growth, networking, information and connectivity.

2. Literature and Theoretical Framework

A. Literature

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 [13]. Cumulative damage due to pluvial flooding can be considerable, especially in lowland areas where this type of floods occurs relatively frequently [14]. The effects of flooding vary, because of local physical, geographical, and meteorological conditions, and therefore, each situation requires individual responses [15]. 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. This has resulted in the development of a number of interventions and urban flood risk management approaches including the emerging modelling methods.

1) Urban flooding modelling

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 [16]. The need to advance the understanding and management of urban pluvial flooding for flood resilience in our cities has grown [17]. 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 [18]. Rainfall runoff process involves many parameters which may either be physical features of the catchment or climatological parameter [19]. With the current scientific advances, it is 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 [20]. The conception of modelling in hydrology is involved with relationships of water, climate, soil and land use [21]. 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 [19]. 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, integrated approaches of various models are commonly employed and the use of sophisticated hydraulic models as diagnostic, design and decision-support tools has become standard practice in water industry [10].

Integrated modelling is the process of combining two or more physical aspects of different physiognomies and complexities to derive an integrated output that exhibits the reality that 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 to model different stages of the complete water cycle optimally.

2) Types of storm water models

Depending on the hypothesis considered, one given model may be suitable for certain situations, but may not be applied to other conditions [22]. 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 [23]. 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 [24]. Flood parameters such as inundation area, flood wave depth and flood duration can be simulated by several hydraulic and hydrologic models [25]. Several models have been developed and applied for modelling urban waters following different approaches [26]. 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 [27]. Conventional modelling of overland flow assumes thin sheet flow over a plane surface with an area equivalent to the sub-catchment area [10]. Although this assumption can yield acceptable results, 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 [10]. 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. 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.) [28]; The UIM is a 2D overland-flow model that solves the non-inertia wave (diffusive wave) flow equations [29]. 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, with 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 [30]. 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 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 [31].

3) U.S. EPA – SWMM5.1

There are numerous models capable of simulating urban water quantity and quality employing diverse approaches to handling the problem [32]. However, there seem to be a number of deficiencies that are common to most of these models [32]. SWMM is one of the commonly preferred modelling tool for simulation of dynamic stormwater-sewerage magnitude and level of contaminants in an urban catchment. The Storm Water Management Model (SWMM) is an urban modelling tool developed originally by the United States Environmental Protection Agency (EPA) [33]. 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. 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. On the other hand, 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. 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.

B. Theoretical Framework

SWMM5.1 has several features that can be grouped into two main categories based on the general flooding processes. The 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. 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 [24].

1) 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.

2) 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 [[24]].

There are three types of flows that can occur in a flooding event including; 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) Free surface flow

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. 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:

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

And the momentum equation:

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

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

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 $s_{fx} = c_f u\sqrt{u^2 + v^2}$ and $s_{fy} = c_f v\sqrt{u^2 + v^2}$ 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, while 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.

4) 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:

$$h_L = f\frac{L}{D}\frac{V^2}{2g} \ldots\ldots(4)$$

where

h_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 5 below:

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

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],

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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 [34]:

$$\frac{\partial H}{\partial t} = \frac{\sum Q}{Astore + \sum As} \quad \text{...(6)}$$

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.

5) 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 surcharge quantity is given by:

$Q_s = Q_{in} + Q_r - Q_f$, ...(7)

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 apply as follows according to [35]:

$$\sum \left[\mathrm{Q} + \mathrm{gA} \frac{\partial Q}{\partial H} \Delta H_n \right] = 0 \quad \text{...(8)}$$

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

$$\Delta \mathrm{H} = \frac{\sum Q}{\sum \partial Q / \partial H} \quad \text{...(9)}$$

6) Model Linkage

The SWMM 5.1 uses the 1D sewer network model, 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 [13]. 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 [24]. Since the rainfall in the simulated areas and the runoff from upland areas have 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 [24]. 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 characterizes the interacting discharge between the surface and subsurface system [24]. 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.

At the same time, a number of key catchment hydrologic and hydraulic behaviours are also linked to SWMM with different methodologies. These includes; evapotranspiration, infiltration and dry weather flow.

a) 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 [36]. Evapotranspiration is a key process of water balance and also an important element of energy balance [37]. 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 [38].

$$ET = \frac{\Delta(K_r - L_r) + \rho_a c_a C_{at} e_* a(1 - {}^{W_a}/_{100})}{\rho_w \lambda_\gamma \left[(\Delta - \gamma)(1 + {}^{C_{at}}/_{C_{can}})\right]} \quad \text{.........................(10)}$$

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].

$$ET_0 = 0.0023 R_a (T_c - 17.8) T_R^{0.50} \quad \text{...............................(11)}$$

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].

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 [39]. 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 [39]. In this study therefore, evapotranspiration will be neglected as it is assumed that the storm was a short intense downpour limiting potential evapotranspiration.

b) Infiltration

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 [40]. These includes three distinct infiltration methods used in SWMM namely the Horton's theory, Soil Conservation and Service Number (SCS-CN) and Green-and-Ampt model.

i. 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 [41]. Horton's equation is one of the earliest and most popular empirical models for simulating infiltration [42]. Horton's theory is based on the fact that infiltration is faster in dry ground, so as rain continues and the ground becomes wetter, the infiltration rate decreases. 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 [43]. 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 [44].

ii. 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 [[45]]. 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 22 shows the CN relationship. CN is easier to apply as it requires just one parameter (S_p) associated with the watershed characteristics. However, the CN method of infiltration modelling is most suitable for the rural catchments.

iii. 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 [46]. 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 [48]. The GA model assumes that a sharp wetting front separates the soil profile into an upper saturated zone and a lower unsaturated zone [48]. 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:

$$f(t) = K_h^* \left[1 + \frac{|\psi_f|(\phi - \theta_o)}{F(t)}\right],\ t_p \le t \le t_w \ldots\ldots\ldots\ldots\ldots(12)$$

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].

a) 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 system flow of sewage in the sewer network systems during periods without rainfall events needs to be understood in order to check.

A combined storm-sewer system is known to have a limit on the DWF of the influent sewage to provide for the 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.

i. DWF Characteristics and Estimation

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

$$FPC = \frac{ADF}{PE} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13)$$

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:

$$ADF = FPC \times PE \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

7) 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 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.

a) 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:

$$S = \frac{H_g}{L_c} \quad \text{.....(15)}$$

Where:
S = the slope,
H_g = the ground elevation and
L_c = the sub-catchment length.

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. Various methods have been developed to disaggregate daily precipitation to hourly time series to make them usable for continuous hydrologic simulation [49]. 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] [50]. They are stepwise split models, mathematically constructed for use to reflect sporadic and highly irregular behaviour especially of rainfall.

a) 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. [51]:

$$R_j^{(\delta)} = \frac{1}{\delta}\int_{(j-1)\delta}^{j\delta} R(t)dt \quad \text{.....(16)}$$

Let f_δ 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 [[51]]:

$$Z_j^{(f)} = \sum_{l=(j-1)f+1}^{jf} R_l = fR_j^{(f)} \quad \text{.....(17)}$$

e.g. $Z_1^{(f)} = R_1 + \ldots + R_f$ and $Z_2^{(f)} = R_{f+1} + \ldots + R_{2f}$ …(18)

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.

b) 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 29) 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 [51]. The discrete random process at $\Delta s_k = b^{-k} f$ scale of aggregation is given by:

$$R_j^{(\Delta s_k)} = R_{j,k} = R_{1,0}\prod_{i=0}^{k} W_{g(i,j),i} \quad \text{.....(19)}$$

where $j = 1, 2, \ldots, b^k$ 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 $W_{1,0} = 1$ [51]. 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 23 below:

$$\left\langle \frac{1}{b^k}\sum_{j=1}^{b^k} R_{j,k} \right\rangle = \langle R_0 \rangle \quad \text{.....(20)}$$

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

$$\langle R_{j,k}\rangle = \langle R_k\rangle = \left\langle R_{1,0}\prod_{i=0}^{k} W_{g(i,j),i}\right\rangle \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (21)$$

$$= \langle R_0\rangle \prod_{i=0}^{k} \langle W_{g(i,j),i}\rangle = \langle R_0\rangle \langle W\rangle^k = \mu_0 \mu_W{}^k \dots\dots\dots\dots\dots\dots\dots\dots (22)$$

As a consequence of equations (4) and (5):

$$\frac{1}{b^k}\sum_{j=1}^{b^k} R_{j,k} = \langle R_0\rangle, \qquad R_k = \mu_0, \quad \mu_0 \mu_W{}^k = \mu_0 \; and \; \mu_W = 1 \dots\dots\dots\dots (23)$$

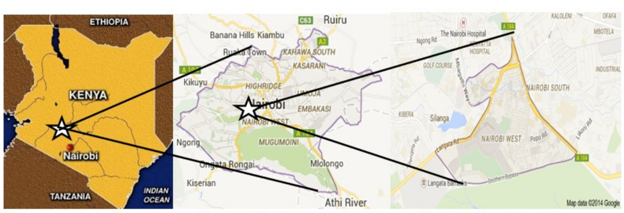
Thus, the weights W satisfy the condition $\mu_W = 1$.

3. Methodology

The results of the study was expected to demonstrate how SWMM 5.1 and GIS can be applied 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.

A. Study Area

Nairobi City, lying 1.19 degrees south of the Equator and 36.59 degrees east of meridian, is Kenya's capital, Eastern Africa. It has a varying altitude of between 1,600 and 1,850 metres above sea level with a temperate tropical climate. Generally, it has two distinct rainy seasons with the long rainy periods being between April and June while the short rains occurring in the months of November and December. 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. 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 1: The location of the study area in Nairobi, Kenya

B. 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 analysed through ArcGIS before being used with SWMM 5.1 to simulate the urban pluvial flooding of the area.

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. ArcGIS and SWMM 5.1 were identified as the most appropriate applications for the study.

2) 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.

a) GIS data

The most recent and updated GIS data for Nairobi and specifically for the study area were collected from various sources including; DEM data with 5m-square spatial resolution to surface topography from World Resource Institute (WRI). 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.

b) 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,

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coordinates, materials from which they are made, and the manholes in the area with their invert levels.

c) 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. A precipitation file was created from these three stations from 1st January 2009 to 31st December 2013. One particular heavy and continuous rainfall event of 26th December 2012 was of greater interest for this study as it caused a trail of destructions including forcing 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 [52].

3) 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 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.

a) Entities used in EPA SWMM5.1

The key sub-catchment parameters for use in the EPA-SWMM5.1 are provided in detail in table 3-1 below:

Table 3-1: Sub-catchments parameters as defined in EPA-SWMM-5.1. Adapted from SWMM-5.0 Manual [34]

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
% 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.
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

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) 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 area of study.

b) 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 rain-gauges (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. 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).

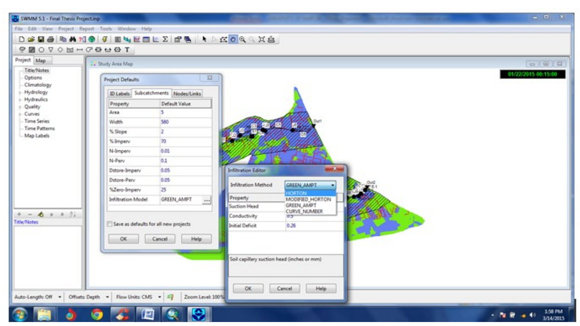

Figure 3-1: The setting of SWMM-5.1 defaults in preparation for sub-catchments data.

c) 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

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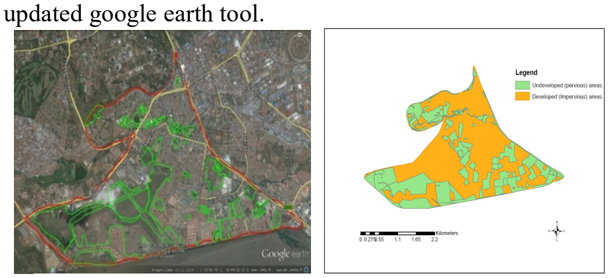
data for production of various map features such as DEM, impervious maps among others. The result of these individual analyses of the various sub-catchment properties were then used with SWMM5.1 model. The detail on this task is systematically explained the following subsections.

d) Precipitation and rainfall disaggregation

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. Random Multiplicative Cascades (RMC) model for rainfall data disaggregation was used to reproduce finer rainfall series. 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.

e) Impervious and pervious areas determination

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 and determined by use of ArcGIS. The yellow bordered area is the impervious area while the green bordered area illustrates the pervious areas. 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. 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. 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 2b, the percent impervious was estimated to be 80% for the sub-catchment S_1 and 60% for sub-catchment S_2.

ii. Infiltration and Evapotranspiration in urban areas

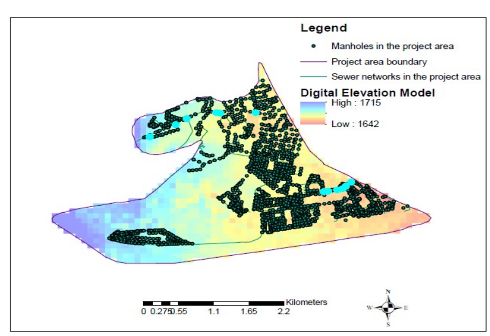
The Green-and-Ampt model was applied in the SWMM5.1to accommodate infiltration involving two important parameters dependent on the soil. These included the capillary suction head ψ and saturation hydraulic conductivity K. A third parameter of the infiltration considered was the initial infiltration model 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. Since the degree of soil imperviousness greatly affects the rate of evapotranspiration the influence of evapotranspiration parameter was considered negligible and thus not considered.

1) Area and flow width

Sub-catchment areas were calculated with the aid of SWMM5.1ruler, which has the capability to estimate both area and linear measurements. 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. Likewise, the flow width parameter was calculated in a more straightforward way using the ruler tool 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.

iii. DEM and the Sub-catchment Slope

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 [53]. Digital Elevation Model (DEM) is the digital representation of the land surface elevation with respect to any reference datum [54]. Hydrologic applications of the DEM include groundwater modeling, estimation of the volume of proposed reservoirs, determining landslide probability, flood prone area mapping etc [54]. 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 [55]. 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).



Map 3: DEM and sewer details of 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.

iv. The slopes of the sub-catchments

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. The length was measured along the overland sheet in the orientation of the direction of the sewer flow which drains to the outfall. 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.

C. 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. 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.

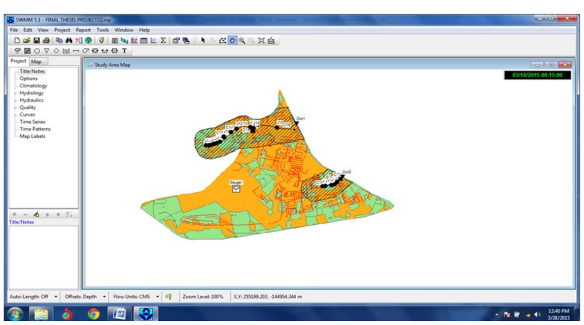


Figure 3-2: Sub-catchment demarcation and overlaying with the sewer data in SWMM 5.1.

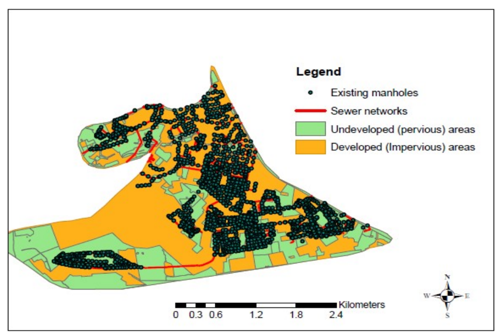
The new geographic scope representing the original study area are shown in figure 3-2 because of the potential extreme flooding as indicated by the DEM map 3 above and the completeness of stormwater sewer system data. Therefore, for the two sub-catchments, all the sewer pipes had key attributes including diameters, lengths, and materials. The pipes were of concrete and varying diameters of between 150mm to 300mm with different lengths.

1) 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 being a concession between the values for woods with light underbrush (0.40), thick grass (0.24) and small grass (0.15).

2) 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. 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 4: 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. As a result of data sorting through ArcGIS, only 24 manholes and 22 conduits were found to fulfil the data detail required for SWMM 5.1 simulation. However, the pipe end elevations were estimated from the manholes ground level data provided by the NCWSC. 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.

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 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.

3) 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. 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 3-2: Water consumption rates. Adopted from the Practice Manual for Water Supply in Kenya (Ministry of Water & Irrigation, 2005)

Consumer	Unit	Urban Areas		
		High class housing	Medium class housing	Low class housing
Individual connections	1/head/day	250	150	75
Without connections	1/head/day	-	-	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 3-3: DWF values for the two sub-catchments S_1 & S_2

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) 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.

D. 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.

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.

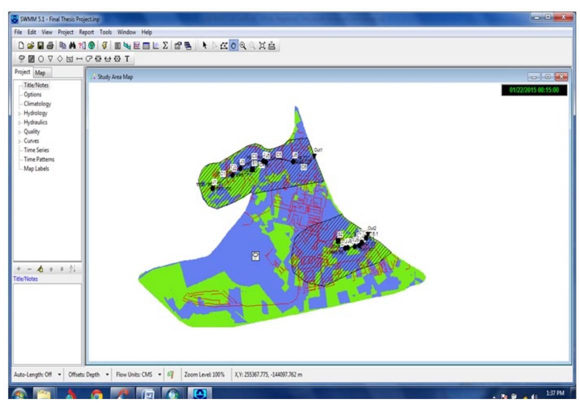


Figure 3-3: Screen view of the two sub-catchments created as guided by the topographical features of the area and the available sewer/manhole data.

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 3-4: Properties of the sub-catchment S_1 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 3-5: Properties of the sub-catchment S_2 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.

2) 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.

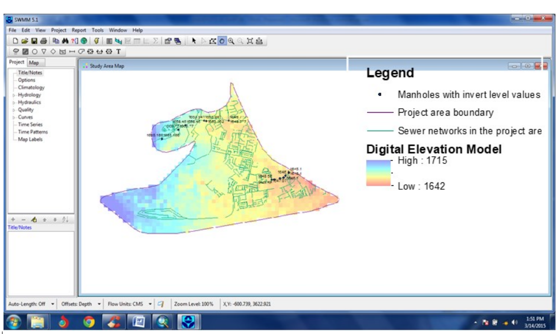


Figure 3-4: Screen view of SWMM-5.1 showing DEM details overlaid with sewer network & manholes.

As per the DEM, the sewer system's data and the manholes with ground elevation values as shown in the figure 3-5 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 invert elevations.

3) 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 doesn't 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) 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."

E. Sensitivity Analysis and Uncertainty Assessment

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 [56]. Many different techniques have been proposed for performing uncertainty and sensitivity analyses on computer models for complex processes [57]. Uncertainties cannot be eliminated, and therefore it is necessary to understand their sources and consequences for model results [58]. For the study, the sensitivity of the model and assessment of parameters with greater potential of resulting in uncertainty in the model output was done. 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. 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 8.4. 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.

A. 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 8.4, i.e. the runoff mass balance expressed in mm for depth or hectares-m for volume and the flow mass balance in m³, [see table 4-1]. 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 4-1: 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	

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.

Table 4-2: 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 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%.

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 to be 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.

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 199.581m^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).

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

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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 not accounted for, this cannot be considered absolutely accurate.

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 base flow parameters.

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 S_1 and 3.14mm for S_2 respectively as shown in table 4-2 and averaged as 2.112 mm in the mass balance summary in table 4-1. From this result, it can be seen that sub-catchment S_2 which was 60% impervious registered higher infiltration rates than sub-catchment S_1 which was 80% impervious.

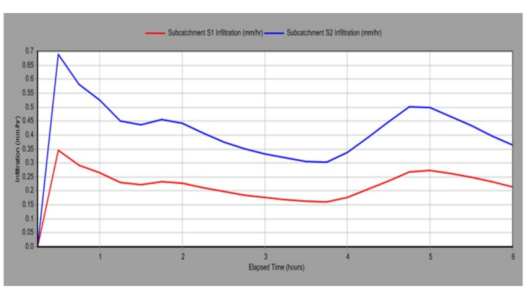

Figure 4-1: Comparative infiltration rate for the two sub-catchments S_1 and S_2

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 4-1 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 4-2].

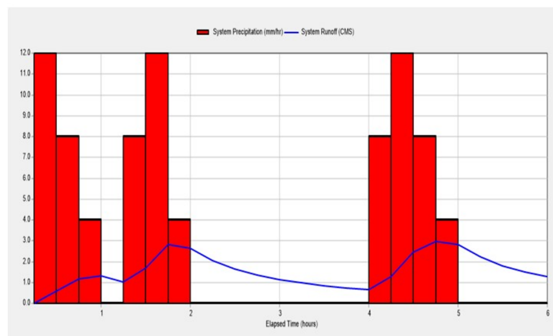

Figure 4-2: System runoff against disaggregated precipitation

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.

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. The figure below shows the behaviour of the runoff rate in the two sub-catchments.

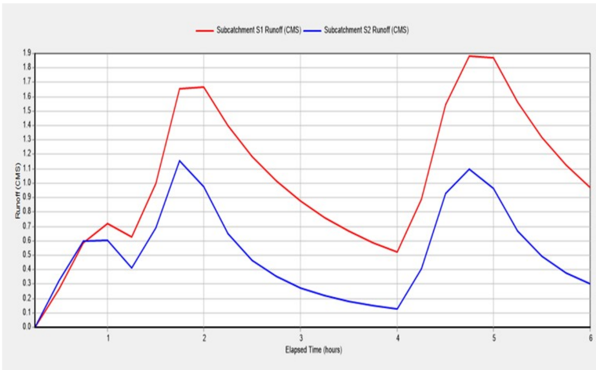

Figure 4-3: Runoff pattern in the two sub-catchments S_1 and S_2

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.

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.

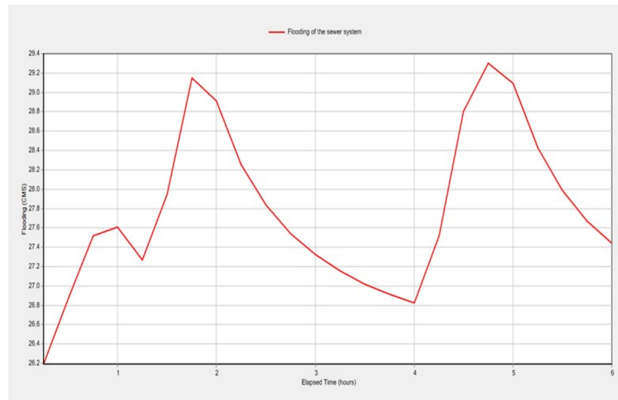

Figure 4-4: Flooding in the sewer system

Table 4-3 : 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 4-2, 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.

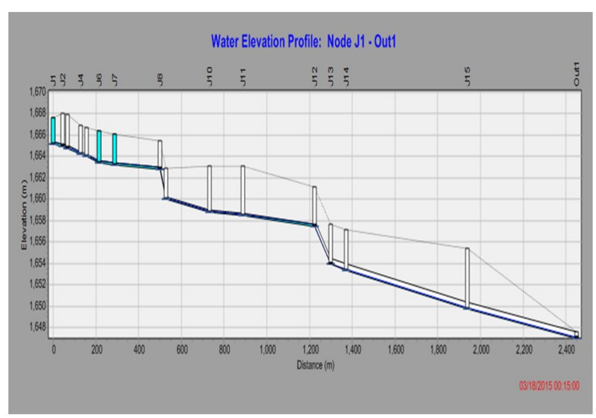

Figure 4-5 : flow profile in the conduits in sub-catchment S_1

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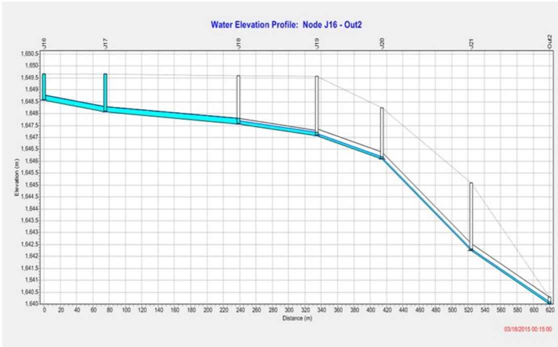

Figure 4-6 : flow profile in the conduits in sub-catchment S_2

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 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 surcharged to some minimum heights below the rim of the junction.

11) Node Flooding Summary

In the model, there was no ponding at the nodes. However, 12 junctions recorded flooding incidences with only 9 not flooding during the downpour. On the basis of analysed storm water sewer flow and the two hydraulic gradients represented in figure 4-5 and 4-6, 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, 17. Of all the flooded manholes, two junctions experienced flooding of quantities above 10 m³.

12) Conduit Surcharge Summary

The conduit surcharge results, indicated that 18 of the 21 conduits under study were surcharged and all the 18 conduits that surcharged experienced capacity inadequacy during the storm. Five of the conduits remained 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 4-5 and 4-6 as well as the link summary of the status report.

From the overall analysis of the sewer network behaviour during the storm in which a number of junctions and conduits surcharged and flooded. It can be confirmed the flooding that occurred during the rainfall event of 26th December 2012, even the two sub-catchments were only representative of the wider Nairobi West and South C areas of Nairobi. Total amount of the internal outflow of 76.487 ha-m recorded which in deed is the total flooding from the flow routing continuity were as a result of the surcharges and flooding of the junctions and conduits.

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.

B. 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.

The two graphs below illustrates peak-runoff response to parameters during the sensitivity analysis.

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 [59] 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. [60], 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. 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 two graphs 4-7 and 4-8.

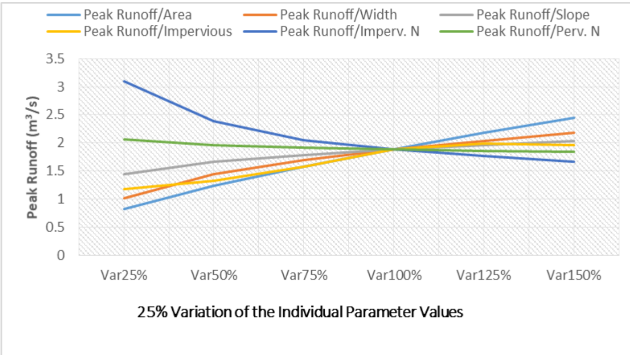

Figure 4-7: Sensitivity of six parameters for sub-catchment S_1

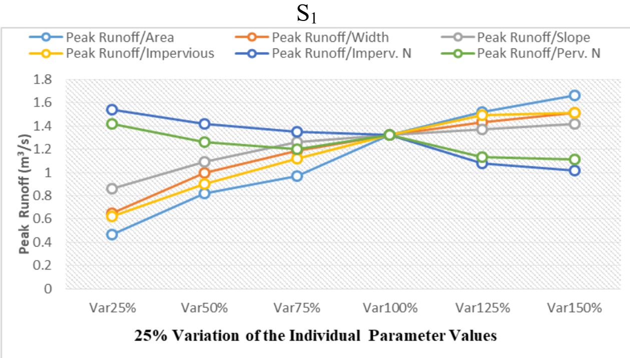

Figure 4-8: Sensitivity of six parameters for sub-catchment S_1

C. 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.

1) Manning's n Value Uncertainties

The Manning's n value used during the modelling exercise was of .015 which was selected based on the conduit material which is rough concrete pipes. However, based on the age of the conduits, this figure could be higher, reducing the hydraulic size of the sewer system and increasing the amount of flooding in the area. The lower the Manning's n value, the greater the volume of water that will flow through pipe 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.

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. 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.

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.

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) 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

5. Conclusion and Recommendations

A. Conclusion

Based on the results obtained and the objectives of the study, the following conclusions can be drawn from the study:

1) 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 for use in urban pluvial flooding mitigation design.
2) 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.
3) Results provided by the model in the mass balance summary reflected the correct urban water balance without significant bias.

4) 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.
5) 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.

B. 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 systems under or overdesign.

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) With regard to opportunities for future studies, this work has revealed numerous lines of research that can be undertaken to holistically understand urban pluvial flooding and its effects.

4) 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.

5) Finally, with regard to the potential environmental pollution, this study can be furthered using the SWMM 5.1 to estimate the pollutants flow during the storm as it has been proved that a significant amounts of sewer wastewater surcharged and flooded the area.

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