MODELING OF RAINFALL-RUNOFF FOR A STORMWATER DRAIN IN ELDORET TOWN

BY

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DECLARATION

DECLARATION BY THE CANDIDATE

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DEDICATION

To my beloved wife Priscah C. Rutto and my entire family for their support and constant encouragement throughout the study period.

ABSTRACT

Flooding in Eldoret town has been experienced during heavy downpours resulting in loss of property, life, and interruption of transportation systems. The overall objective of the research was to evaluate different scenarios of surface imperviousness and rainfall amounts on runoff generation and the influence of low impact developments (LIDs) on the generated runoff in Eldoret town. The specific objectives were: to determine the study sub-catchment characteristics (area, slope, percent impervious, rainfall, outflow, from the catchment); to calibrate and validate SWMM5 model for rainfall-runoff simulation in Eldoret; to evaluate different scenarios of rainfall and imperviousness proportions on runoff generation and to determine the influence of infiltration trenches and bio-retention cells as low impact developments (LIDs) on the study sub-catchment on stormwater runoff. On methodology, rainfall was measured using rain gauge while discharge was measured using the current meter. Digital Elevation Model of the study area was also obtained and processed. Five scenarios for analysis were formulated as follows: Maximum measured daily rainfall and increasing percentage imperviousness in tens from the actual 25% to 75%; Average measured daily rainfall and increasing percentage imperviousness in tens from the actual 25% to 75%; Minimum measured rainfall and increasing percentage imperviousness in tens from the actual 25% to 75%; The historical daily highest rainfall recorded between 2009 and 2019 with increasing percentage imperviousness in tens from the actual 25% to 75%; Historical average daily maximum rainfall recorded between 2009 and 2019 with increasing percentage imperviousness in tens from actual 25% to 75%. LIDs on stormwater runoff were also evaluated. The results showed that the catchment drained an area of approximately 696.5 hectares with a total of 23 sub-catchments. The average slope was found to be 2.57% and the mean average imperviousness was 25.72%. The maximum 3-hr rainfall event observed during the study period was 32.4 mm which resulted in the maximum average discharge of $0.131m^3/s$ and resulted in overflow in the drain. The calibrated model had N-Imperv of 0.45, Dstore-Imperv of 2.5, and Dstore-Perv of 8. ISE values of 3.0 and 1.4 were observed for calibration and validation, respectively. NSE values of 0.97 and 0.99 were observed for calibration and validation, respectively. This meant that the model simulated well the rainfall-discharge relationship in the study area and can be used for engineering design purposes. Scenarios of percentage imperviousness and runoff indicated that impervious surfaces in urban areas are a determining factor in runoff generation and affects the average flow and total runoff positively. The results indicated a reduction of average runoff flow by 25% when infiltration trenches were used to an extent of 100% treatment of impervious area and a reduction in total runoff volume by 19.6%. Studied low impacts developments; bio-retention cells and infiltration trenches have an effect of reducing flow and total volume in the study area therefore can be used to control flooding. It was concluded that infiltration trenches are superior to bio-retention ponds in reducing flow and total runoff volume in the study area. Future study is required to calibrate the model for water quality analysis in the study area.

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ABBREVIATIONS

BRC	Bio-Retention Cell
GIS	Geographical Information System
IT	Infiltration Trench
KURA	Kenya Urban Roads Authority
LIDs	Low Impact Developments
SDGs	Sustainable Development Goals
SWMM	Storm Water Management Model
UNEP	United Nations Environmental Program

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Above all, I would like to thank the Almighty God for providing and protecting me from the beginning of this study to its completion.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

A flood can be described as overflowing of water over land not usually submerged. It is any high flow that overtops either natural or artificial embankments along a stream (Chow *et al*., 1988). The European Union Floods Directive (Directive 2007/60/EC) defines a flood as a covering by water of land not normally covered by water. Heavy rainfall causes rapid accumulation and release of runoff waters from upstream to downstream which quickly reaches a maximum and diminishes almost as rapidly (Ouma & Tateishi, 2014). Khan *et al.*, (2011) indicated that heavy rainfall is among the most recurring and devastating natural hazards, causing severe economic damage and impacting heavily on human lives throughout the world. Drainage channels inadequate maintenance and debris and solid waste disposal (Chang & Guo, 2006) into such drainage systems in developing countries may worsen the situation (APFM, 2012).

Floods have been experienced in countryside and urban areas of Kenya with floods being experienced during the rainy season specifically in Eldoret town. Ouma & Tateishi (2014) in their study observed that unplanned built-up area development for instance followed by encroachment of low lands for instance, clogging of drainage channels, river floods, as well as waterlogging among others contributes greatly to flooding phenomenon in Eldoret town. In addition, increasing population growth, poorly planned land-use practices have further aggravated the situation leading negative impact on the catchment's natural ecological and structural stability of the and over the years.

In Kenya, the design and construction of urban drainage structures and the system are done by Kenya Urban Roads Authority (KURA). In Eldoret town, the work is done through a partnership of KURA and Uasin-Gishu County Government. KURA has regional stations for the maintenance of constructed structures in use. Design and construction of new hydraulic structures or roads are done by the head office in Nairobi under the supervision of a manager from the design and construction department. This makes it difficult to obtain the design parameters considered and the blueprint used in the construction of water control and conveyance structure(s) in the town.

Estates contributing runoff to the study catchment include Kapsoya, Munyaka, Jerusalem, Hawaii, and Subaru. The estates are densely built up area presenting a high percentage of impervious surfaces. Although there is an extensive drainage system in these estates consisting of paved open conduits, the result is a short time of runoff to the peak which may lead to flooding in the lower regions of the catchment towards the exit. The floodwater has led to loss/damage of property, injury, and death as reported in August 2014, following a major storm that wreaked havoc in the town (Bwisa, 2014).

1.2 Statement of the Problem

A tributary to Sosiani River in Eldoret town, was originally covered with reeds but now it has been transformed to a drain (Bwisa, 2014. Development has led to the increase of areas with impervious surfaces in the area that used to be swampy. This has increased risk of flooding in the drain. It is expected, that with time, the impervious surface area will increase, resulting in increased discharge into the drain. Next to the bus stage, many houses and other properties risk flood damage in the areas of concern thus the need to determine the rainfall amounts and percentage of imperviousness that will result in drain flooding. Apart from the loss of property lives can also be lost as it was observed in 2014 (Bwisa, 2014).

Low Impact Developments (LID) technique is a comprehensive land use planning and design approach to mitigate urban impacts on the environment at the sub-catchment level (Martin-Mikle, *et al.*, 2015). Decreasing the percentage of runoff within the watershed is the primary focus which promots infiltration and decreases the surface runoff (Paterne, 2019) which in the process reduce the impact of urban development (Wong *et al.*, 2002).

Indeed floods are the leading hydro-meteorological disaster in East Africa, and in Kenya they are emerging as the most prevalent climatic disaster (RoK, 2007 and UN-ISDR, 2009). The prevalence rates stand at 27% and affect 5% of the population affected by disasters. UNEP (2009) observed that flood-related fatalities constitute a whopping 60% of disaster victims in Kenya. In the process of urbanization, hydrological processes are modified by replacing vegetated land cover with impervious surfaces and by extending the natural drainage network to include artificial ponds, ditches, and conduits laid on the ground and underground (Berthier *et al*., 2006; Xiao *et al*., 2007; Dow, 2007).

1.3 Justification of the Study

The number of people migrating to live in urban areas is ever increasing across the globe. The world urban population is projected to reach 70% of the world population by 2050 (OECD, 2011). In Kenya for instance, there is rapid urbanization with 20.4% of the people residing in urban areas in 2005, and by 2030 the proportion of Kenyan population living in urban areas is estimated to reach 60% people. Eldoret town is projected to house 584,782 people in 2030 (RoK, 2007).

With the increasing number of urban dwellers worldwide, the number of people at risk or vulnerable to flood disasters is likely to increase (Oludare *et al.,* 2012). Ouma and Tateishi, (2014), further notes that the probable for overflow fatalities and damages is increasing in many regions due to the social and economic development, which infer pressure on land-use.

When natural disasters occur in any magnitude, they can hinder the achievement of sustainable development Goals (Fritz *et al*., 2019). In flood disasters, there is the loss of lives, destruction of public utilities, and disruption in the smooth functioning of the system that renders fear and uncertainties among the populace (Adedeji *et al.,* 2012). As per study by Oludare *et al.* (2012), in urban areas, that contains vital infrastructure, the impact can be very high because the areas affected are densely populated.

There is a need to come up with justifiable cities that assurance the safety of people and property from tragedies like storms and resulting runoff. This calls for establishing measures to manage overflows in built-up areas (Crobeddu *et al.,* 2007). Modeling rainfall-runoff as was proposed in this study will inform flood control management in planning for future to have sustainable and safe Eldoret town regarding flood disasters, through flood forecasting (Blöschl *et al.*,2013), devising of stormwater controlling strategy (Chen & Adams, 2007) and drainage system design (Crobeddu *et al.,* 2007). Low impact developments (LIDs) are normally associated with fewer risks on damage to property and life.

1.4 Objectives

1.4.1 General Objective

The main objective of the research was to evaluate different scenarios of surface imperviousness and rainfall amounts on runoff generation and the influence of low impact developments (LIDs) on the generated runoff.

1.4.2 Specific Objectives

The specific objectives were to;

i. Characterize the study sub-catchment in terms of area, slope, percentage impervious area, rainfall, and outflow from the catchment.
ii. Calibrate and validate the SWMM model for rainfall-runoff simulation in Eldoret.
iii. Evaluate the performance of different scenarios of rainfall and imperviousness proportions on runoff generation.
iv. Determine the influence of infiltration trenches and bio-retention cells as low impact developments (LID) on the study sub-catchment on stormwater runoff.

1.5 Research Questions

i. What are the catchment characteristics: Area, Slope, Percent Impervious, rainfall, and outflow from the catchment?
ii. Can rainfall-runoff simulation in Eldoret be performed using SWMM model?
iii. What are different scenarios of impervious area and rainfall one can consider for the catchment?
iv. What are the effects of infiltration trenches and bio-retention ponds as LID on stormwater runoffs?

1.6 Scope and Limitations of the Study

The catchment only covers estates which potentially contribute runoff that flows through the channel under study. These include sections or whole of; Kapsoya, Munyaka, Jerusalem, Hawaii, and Subaru. The area of interest is the drain at Bandaptai next to the bus stage. The study was limited to the investigation of the rainfall-runoff relationship in the study area using the Storm Water Management Model (SWMM) model version 5. The model can simulate both water quantity and quality in a given catchment. This study however focused on calibration and validation of the model for runoff simulation only.

CHAPTER TWO

LITERATURE REVIEW

2.1 Catchment Characteristics

Urban streamflow is a subject of great concern worldwide (Booth *et al*., 2014). Some regions worldwide have benefited from well managed urban stream flows while others have had problems associated with storm waters which lead to serious social-economic and ecological impacts (Walsh *et al*., 2005).

The processes which occur within a catchment form a complex system due to the multiple interacting processes. For instance, a river, or any flow in an area respond to some factors such as slope, rainfall intensity and amount, outflow, percent imperviousness among others (Bloschl *et al*., 2013). These complex interactions vary between catchments and through time depending on the antecedent conditions.

2.1.1 Catchment Area

A drainage basin forms the catchment area which is an area of land where precipitation collects and drains off into a common outlet, such as into a river, bay, or other body of water (Maidment & Morehouse, 2002; Ramaiah *et al.,* 2012). Topographically, each drainage basin is separated from adjacent basins by a perimeter and the drainage divide, (Gerard, 2014; Tambe, 2019) making up a succession of higher geographical features which include a ridge, hill or mountains forming a barrier.

The size of the catchment will help determine the amount of water reaching a river, as the larger the catchment, the greater the potential for flooding (Thomas & Nisbet, 2007). It is also determined based on the length and width of the drainage basin. The shape will contribute to the speed with which the runoff reaches a river. A long thin catchment will take longer to drain than a circular catchment (Legesse *et al.*, 2003).

Catchment area can be estimated by GIS software through watershed delineation from a Digital Elevation Model (DEM) which involves choosing a specific point usually referred to as the pour point and establishing the contour boundary all round that collects surface water and discharges through the pour point (Li, 2014). Each catchment is hydrologically independent and this uniqueness allows modeling of rainfall-runoff relationship and investigation of impact of development in the catchment.

2.1.2 Slope

Topography, generally plays a big part on how fast runoff will reach a river or delays (Meraj *et al.*, 2015). In steep mountainous areas, the rain that falls will reach the primary river in the drainage basin faster than flat or gently sloping areas (Antoine *et al.*, 2009). Topography can be responsible for a spatially heterogeneous pattern of precipitation in a river basin and one element that affects natural floods. Heavy orographic precipitation occurs frequently over windward areas.

The general effect of topography changes as per Masoudian & Theobald (2011) on flood parameters is the maximum flood discharge and time to peak. This is attributed to the slope (Meraj *et al.*, 2015). Masoudian & Theobald (2011) adds that the results of floods such as overflow hydrograph, the extreme discharge, and period to peak (Meraj *et al.*, 2015), means that land surface gradient must be well-thought-out for each sub-catchment. In the case of the terrestrial surface gradient increasing, the peak of the flood hydrograph goes up and to the left so that the rising limb will have been steeper, and it reverses in the case of land surface slope decreasing (Masoudian &

Theobald, 2011 and Meraj *et al.*, 2015). Accordingly, Johnson *et al.* (2011) added that when the catchment becomes flatter, the overflow hydrograph becomes flattered too. In other words, the concentration-period increases because of the reduction of land surface velocity. The average slope of a catchment area can be estimated by GIS software through the processing of a DEM (Li, 2014).

2.1.3 Soil Type

Soil type will help determine how much water is generated and reaches the river (Hutchins, 2012). Certain soil types such as sandy soils are very free-draining, and rainfall on sandy soil is likely to infiltrate into soil profile. Soils containing clay however, can be almost impervious, and consequently rainfall on clay soils will run off and contribute to flooding volumes (Schmocker-Fackel *et al.,* 2007). A study by Hutchins (2012) indicated that free-draining soils can become saturated on prolonged rainfall, summarizing that any further rainfall will reach the river rather than infiltrating into the soil profile. If the surface is impermeable the precipitation will create surface run-off (Schmocker-Fackel *et al.,* 2007) which will lead to a higher risk of flooding; if the ground is permeable, the precipitation will infiltrate into the soil profile (Hutchins, 2012).

2.1.4 Impervious Surfaces and Urbanization

Impermeable surfaces such as sidewalks, parking lots, roads and many others that are covered by water-resistant materials such as asphalt, concrete, brick, stone—and rooftops (Mentens, *et al.*, 2006), primarily found concentrated in an urban system.

Impermeable / impervious surfaces are an environmental apprehension because, with their construction, a chain of events is commenced that changes built-up air and water resources (Mentens, *et al.*, 2006). The pavement materials cover the soil surface, eradicating rainwater permeation and ordinary groundwater recharge (Heathcote, 2009). In an urban setup, the natural hydrological cycle is modified through the introduction of impervious surfaces and artificial flow paths, resulting in decreased infiltration and reduced water storage capacity (Hamel *et al.,* 2013; Golden and Hoghooghi 2017; Vogel *et al,* 2015). Urbanization continuously increases impervious land surfaces and this disrupts the water cycle, potentially resulting in higher runoff volume, more severe urban flooding, and lower water quality within associated drainage and waterway systems (Bellos & Tsakiris, 2015; Fletcher *et al.*, 2013; Quijano *et al.,* 2017). Barron *et al.* (2013), indicated that increase of urban impervious surfaces leads to a decrease in catchment evaporative losses. Dow & DeWalle, (2000) Salvadore *et al.*, (2015), Owuor *et al. (*2016) and (Litvak *et al. (*2017) added that evapotranspiration in built-up areas has multifaceted patterns associated with landscape heterogeneity and variations in the urban microclimate

Urban land use can contribute to the volume of water reaching the river, in a similar way to clay soils (Turner & Rabalais, 2003). The impervious surface cover is specifically known to lead to extreme disturbances in stream ecosystems, including shortening the time to flood peaks, increased flood flows, surge in bank-full discharges and higher surface runoff ((Moore & Palmer, 2005) cited in Nelson *et al.*, 2009; O'Driscoll *et al.,* 2010).

The impervious surface coverage increases with rising urbanization (Barnes *et al.*, 2001). Urban sub-watersheds have more impervious surface cover than the agricultural sub-watersheds (Jennings *et al.,* 2004). In countryside areas, the waterproof concealment may only be 1% or 2% (Kasanko *et al.,* 2006). On the contrary, uptown areas in urban coverage increase from about 10% in low-density portions to 50% in multi-family communities (Ackerman & Stein, 2008), above 70%

in industrial and commercial areas, and over 90% in local shopping centers and dense urban areas (Kasanko *et al.,* 2006). Increase in impervious area results in higher runoff generation due to minimum infiltration of water over the surface into the soil profile (O'Driscoll *et al.*, 2010).

Van de Voorde *et al. (*2009) has indicated that different methods have been anticipated for impervious surface mapping, several of which rely on existing land-use data sets, which indirectly can be used to estimate the water-resistant surface concealments. The subsidiary methods (Chormanski *et al.,* 2008), associate a percentage of impervious area with each land-use type. The disadvantage of this approach is lack of a consistent method for deriving the estimates and that there may be high inconsistency in the amount of imperviousness within the same land-use class (Chormanski *et al.*, 2008), therefore when mapping at a spatially more detailed level, a direct method is preferred.

Direct approaches involve ground inventorying and large-scale, ortho-rectified aerial photographs visual interpretation of which are the most reliable methods to map water-resistant surfaces (Canters *et al.* 2006; Chormanski *et al.*, 2008). Satellite imagery obtained from high-resolution sensors like Ikonos or Quickbird (Weng, 2012), offers an alternative for producing maps of surface imperviousness in absence of aerial photographs. To produce reliable information on the distribution of impervious surfaces, use of automated or semi-automated image interpretation methods may be requiredon the satellite imagery processing (Blaschke, 2010; Chormanski *et al.*, 2008).

In cases where the watershed is made up of various units, the percent impervious surface indicator is calculated by averaging the impervious surface areas across the total land area of the watershed (Shuster *et al., 2005*). This method was adopted for this study.

2.1.5 Precipitation

The rainfall distribution both in space and time directly affects the availability of freshwater, vital for sustaining life (NSTC 2004; Montaigne 2002). Extreme rainfall events associated with floods, landslides and hurricanes have significant socio-economic impacts on society (Futrel *et al.,* 2005; NRC 2010).

Precipitation has a significant influence on river flow. Climate change influence on river flow comes through its effects on precipitation and evaporation (Trenberth, 2011), although recent observations suggest that temperature and the amount of water in soil may also influence streamflow.

An annual flood is the most pervasive hydrological event in a catchment, the occurrences of which is generally as a result of relative to extreme precipitation. Excessive and intensive precipitation during the rainy season may induce a flood risk of different magnitudes, ranges, and durations over the mainstream and various tributaries (Marengo and Espinoza, 2016).

D'Alpaos *et al.* (2006) indicate that historically, explanations of precipitation have been an important focus of meteorology and engineering hydrology because water use such as irrigation for agriculture as an example. Administering freshwater supplies needs accurate and timely information of when, where, and how much it showers or snows (Hou, *et al.,* 2014).

Rainfall at a given location can be measured using surface-based instruments such as the rain gauge (Marengo and Espinoza, 2016). Large spatial and temporal variability of precipitation's intensity, occurrence and type, however, make straight and uniformly calibrated measurements difficult over great regions/oceans, and in such a case, global satellite-based rainfall approximation techniques are used (Hou, *et al.,* 2014). In the study, measurement of precipitation was done using a rain gauge.

2.1.6 Discharge from the Catchment

Discharge is the volumetric flow rate of water that is transported through a given cross-sectional area (D'Alpaos *et al.,* 2006). The catchment of a river above a certain location (Sawunyama *et al.,* 2006), is determined by the surface area of all land which drains toward the river from overhead that point.

The river's discharge at the outfall depends on the rainfall on the catchment (Loperfidoet *al.*, 2014) and the inflow or outflow of groundwater to or from the area, stream adjustments, as well as evapotranspiration and evaporation from the area's land and plant surfaces (Masih*et al.,* 2009).

Loperfido*et al.*, (2014) in their study adds that in storm hydrology, an important consideration is the record of how the discharge varies overtime after a precipitation event which is the stream's discharge hydrograph. The watercourse rises to a peak flow after each rainfall event and then falls in a slow recession (Pappenberger *et al.,* 2006). Peak flow is a factor of interest in flood studies because it parallels to the maximum water level reached through an event (Marchi *et al.*, 2010).

The relationship between the discharge in the stream at a given cross-section and the level of the stream is described using a rating curve. Average velocities and the cross-sectional area of the stream are measured for a given stream level (Leon *et al.*, 2006). The velocity and the area give the discharge at that cross-section. After measurements are made for several different levels, a rating table or rating curve may be developed

(Pappenberger *et al.,* 2006). Once rated (Chinn & Mason, 2016), the discharge in the stream may be assertained by measuring the level and determining the matching discharge from the rating curve. If a continuous level-recording device is placed at a rated cross-section, the stream's discharge may be continuously assertained (Marchi *et al.,* 2010).

2.1.7 Combine Effect of Biophysical Characteristics on Runoff and Discharge

Runoff is a function of precipitation's intensity, duration and coverage. High intensity rainfall results in more runoff and discharge and vise versa. The duration of rainfall is a determining factor of runoff generation because infiltration reduces over time as it rains. Longer duration rainfall is more likely to result in higher runoff and discharge generation. More area covered by a rainfall event also means more runoff will be collected and higher discharge will be recorded.

Size and shape of a catchment is a determinant factor in runoff and discharge generation. The larger the area of the catchment covered by rainfall the more the runoff/discharge generated. Shape of the catchment determines runoff and discharge generation in that a fan-shaped catchment area has a short period of resulting hydrograph hence higher peak flow, while an elongated catchment area has a longer period for a resulting hydrograph hence low runoff as some water has time to infiltrate.

Another factor that determines runoff and discharge generation is infiltration. The higher the value of infiltration rate, the lower the amount of runoff generated. Infiltration is affected by the nature of soil physical properties. The permeation rate (Mazaheri and Mahmoodabadi, 2012) is a function of permeability parameters and soil moisture which is closely related to the soil physical properties. Clay soil for instance results in more runoff/discharge generation because it has a low infiltration rate.

Slope of the catchment influence runoff and discharge generation from the catchment. Steep slope greatly reduce the time for infiltration to occur hence resulting in fast movement of water over the surface and hence more runoff and discharge generation. Time to peak is also shortened in sloppy catchments.

The information on the surface cover of a catchment is very significant due to its high connection with the runoff (Mazaheri and Mahmoodabadi, 2012). The higher the quantity of vegetation in a given catchment, the lower the amount of runoff and discharge generated (Braud, 2001). Vegetation slows the movement of water allowing time for infiltration and reducing the time of concentration. Impervious surfaces over the catchment on the other hand greatly reduce infiltration resulting in more runoff generation and increased discharge from the catchment (Miller, 2014).

2.2 Hydrological Models

Paterne, (2019) indicated that, there is an amplified use of computer-based models to investigate complex drainage systems and to manage stormwater. Hydrological models are used to simulate the processes and exchanges of water within a catchment (Marshall, 2014) and their simulation results can guide water resource management, hydroelectric power production, flood forecasts, and numerous other applications. These models normally reflect the major hydrological and hydraulic processes of urban stormwater processes and storage such as interception, infiltration, depression storage, overland flow, channel flow, and pipe flow.

Sidek *et al.,* (2016) added that the hydrological models can be used for both rainstorm incident modeling and continuous stimulation to effectively manage stormwater. They represent an important tool for the study of small, medium-sized, and large catchments/ basins (Legesse *et al.,* 2003). Jayasooriya and Ng,A (2014) reviewed models for green infrastructure (GI) which include low impact urban stormwater drainage and identified ten urban models mostly used in urban studies (Table 2.1).

Table 2.1: Urban Hydrological Models

Model	Primary use	References
RECARGA	To project and understand performances of bio retention, infiltration basins and rain gardens	(Atchison and Severson, 2004)
Program for Predicting Polluting Particle Passage through Pits, Puddles, & Ponds (P8 Urban Catchment Model)	To predict the generation and transportation of pollutants in urban runoff and design GI to achieve Total Suspended Solids Reduction	(Walker Jr. 1990)
EPA Stormwater Management Model (SWMM)	To plan, design and analysis of the performances of different GI in runoff quality improvement and quantity reduction	(Huber *et al.*, 1988; Rossman, 2010)
Water Environment Research Foundation(WERF) BMP and LID Whole Life Cycle Cost Modelling tools	To evaluate whole life cycle cost for GI practices	(Water Environment Research Foundation, 2009)
The Green Infrastructure Valuation Toolkit	To evaluate the environmental and economic benefit of GI in monetary terms	(Natural Economy Northwest, 2010)
Centre for Neighborhood Technology (CNT) Green Values National Stormwater Management Calculator	To compare GI cost, performance and benefits	(Center for Neighborhood Technology, 2009)
EPA System for Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN)	To develop implementation plans for flow and pollution control, evaluate cost effectiveness of GI	(Lai *et al.*, 2007)
Model for Urban Stormwater Improvement Conceptualization (MUSIC)	To evaluate GI practices in order to achieve stormwater quantity reduction, quality improvement and cost effectiveness	(Wong *et al.*, 2002)
Low Impact Development Rapid Assessment (LIDRA)	To study runoff cost reductions with GI	(Yu *et al.*, 2010)
WinSLAMM (Source Loading and Management Model for Windows)	To study the quality of urban runoff and the role of GI in runoff quality improvement	(Pitt and Voorhees, 2004)

Generally, hydrological models comprise parameters related to physical based characteristics of a river basin including soils, vegetation, land use, topography, percent imperviousness, and slope among others. The drainage basin is divided into units of areas interconnected by channels (Jacobson, 2011).

2.3 Storm Water Management Model

Storm Water Management Model (SWMM) version 5 was selected for this research due to its ability to model and simulate urban rainfall-runoff. SWMM model is the most widely used by researchers to model rainfall-runoff processes in urban areas (Li *et al*, 2016). This latest version is also able to model and simulate the effect of low impact developments (LIDs) on runoff (McCutcheon and Wride, 2013) an attribute that other hydrological models lack. According to Dietz (2007), cited in Jayasooriya and Nga (2014), engineers are using models like RECARGA, Win- SLAMM, and P8 to design LID technologies, although they may use other models such as SWMM for hydraulic routing on a site.

SWMM model has been used in various studies on stormwater quality and quantity. Cambez *et al.* (2008) successfully used the model for continuous modeling of stormwater hydraulics and quality in an urban area covering 110ha. Runoff quantity simulation has been demonstrated by Pathak and Chaudhari (2015) in a study where simulation of best management practices (BMPs) to reduce outflow from a catchment was done.

Gaborit*et al*. (2013) also applied SWMM5 in a study of improving the performance of stormwater incarceration basins by real-time control using rainfall forecasts. Many other studies involving the SWMM5 model have been done in different parts of the world (Bolognesi and Maglionico, 2010; Gülbaz and Kazezyilmaz-Alhan, 2012).

The Storm Water Management Model (SWMM) established by the United States Environmental Protection Agency is a physically-based, distributed, unsteady, continuous urban stormwater runoff quantity and quality model (Barco *et al.*, 2008). It is a full dynamic tendency simulation model (Gülbaz and Kazezyilmaz-Alhan, 2012) used for a single happening or long-term simulation of runoff extent and eminence, mainly from urban areas. The model uses a 1-D approach for dynamic wave routing producing the most theoretically accurate results (Ambrose *et al.*, 2009).

In 1971 SWMM was first developed and undergone several key upgrades later then, being used for planning, analysis, and design linked to stormwater runoff, sanitary sewers, combined sewers, and other drainage systems in urban areas, with many presentations in non-urban areas as well (McCutcheon & Wride, 2013). SWMM5 is the latest version which is a complete re-write of the previous release (SWMM4), running under Microsoft Windows (Cambez *et al.*, 2008) and providing an integrated environment for editing data, running hydrologic, hydraulic, and water quality simulations, and portraying the results (Ambrose *et al.,* 2009). The SWMM conceptualizes a drainage system as a series of aquatic and material movements between four main environmental partitions, namely:

(i) Atmosphere partition, from which rainfall falls and pollutants are placed onto the terrestrial surface compartment;

(ii) Land surface partition which is signified by sub-catchment objects;

(iii) Groundwater partition, which receives permeation from the land surface partition and transmissions a portion of this inflow to the carriage compartment; and

(iv) Transport partition, which contains a network of transmission, storage, guideline and treatment elements (Figure 2.1) (Pathak and Chaudhari, 2015). Not all compartments need to appear in a particular SWMM model (Batelaan *et al.*, 2007).

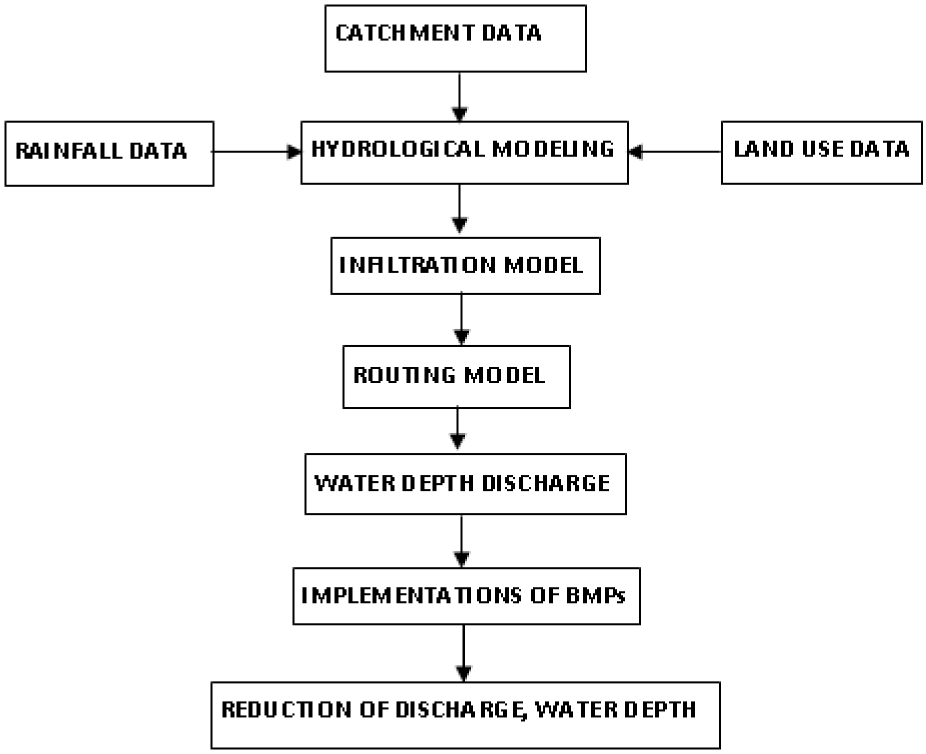


Figure 2.1: Conceptual Framework using SWMM

To model hydrological processes in the SWMM model, sub-catchments are divided into impervious and pervious areas and expressed as a percentage of the total drain area. Losses in impervious areas (Sun *et al.*, 2012) are only due to depression loading, while in permeable areas losses occur also due to infiltration (Cambez *et al*, 2008). Infiltration may be modeled through SCS Curve Number, Horton, or Green-Ampt method.

Hydrology requires daily rainfall data (hourly or fifteen minutes interval), daily evaporation rates, sub-catchment area, percent imperviousness, depression storage, and slope. Hydraulics requires conduit characteristics (shape, size, length, and slope), storage unit shape and size, weir/orifice type and dimensions, and pump curve data (Sun *et al.*, 2012).

SCS curve number method is designed for a single storm event. The start requirements for this method are the rainfall amount and curve number. The curve number is grounded on the zone's hydrologic soil collection, land use, conduct, hydrologic condition, and antecedent runoff condition. The SCS curve number (CN) method (USDA, 1986) is represented by the equation (2.1);

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

(2.1)

Where Q is runoff (mm), P is rainfall (mm), S is potential maximum retention after runoff begins (mm) and I_a is an initial abstraction (mm).

I_a is highly adjustable but generally is linked with soil and cover parameters. Through studies of many small farmed watersheds, I_a was found to be estimated by an empirical equation as expressed in equation (2.2):

$$I_a = 0.2S$$

(2.2)

S is connected to the soil and concealment conditions of the watershed through the CN. CN has a variety of 0 to 100, and S is related to CN by:

$$S = \frac{25400}{CN} - 254$$

(2.3)

The Horton infiltration model is based on the principle that infiltration capacity decreases exponentially with time from an initial maximum rate f_0 to a final constant rate f_c.

The Horton equation for infiltration (Horton, 1933) is given by equation (2.4) which shows the variation of the maximum infiltration capacity with time *t.*

$$f_t = f_c + (f_o - f_c)e^{-kt}$$

(2.4)

Where f_t (mm/hr) is the infiltration rate at time t, f_o (mm/hr) is the initial infiltration rate or maximum infiltration rate, f_c (mm/hr) is the constant or equilibrium infiltration rate after the soil has been saturated and k is the decay constant specific to the soil.

Green-and-Ampt Model (Rawls *et al.,* 1983); is based on the same values as the Richards Equation (Green and Ampt, 1911), but formulated differently and provides a *'more holistic and informative view of the infiltration process'* as per Dingman (1994). The model can nicely present the complete infiltration until surface ponding takes place (Dingman, 1994), and the infiltration capacity thereafter.

The underlying expectations of the Green-and-Ampt Model (Rawls *et al.,* 1983) included the vertical soil water-content outline to be originally standardized, and the wetting front to be considered as a separate discontinuity in that profile. The Green-and-Ampt equation is expressed as in equation (2.5) (Rawls *et al.,* 1983);

$$f = K(1 + \frac{\Delta\theta(\psi + D)}{F})$$

(2.5)

Where f is the infiltration rate (mm/hr), K is hydraulic conductivity, $\Delta\theta$ is the initial porosity of the soil, ψ is the absolute value of the initial suction head of the soil (mm), D is the depth of ponded water (mm), and F is the infiltrated volume of water (mm).

For a given soil, three parameters are needed to use the equation: K, $\Delta\theta$, and ψ.

Green-and-Ampt Model (Rawls *et al.,* 1983) is one of the greatest and widely used methods for modeling the infiltration process, and numerous other models and their extensions have been constructed on it (Dingman, 1994; Cambez *et al.,* 2008).
Surface runoff in pervious and impermeable fractions is given by the Manning's equation. SWMM allows for a explanation of additional characteristics and processes within the study area, namely those related to subsurface water in groundwater aquifers and snowfall and snowmelt phenomena (Cambez *et al.,* 2008; Cambez *et al.,* 2008).

The hydrologic processes governing the drainage of stormwater out of a land unit are infiltration, evapotranspiration, and surface runoff. For the surface runoff, the sub-catchment surface is treated as a nonlinear reservoir where outflow only occurs when the depth of water over the catchment exceeds the maximum depression storage (Rossman, 2010). Outflow from a catchment is generated based on the modified manning equation expressed in equation (2.6);

$$Q = WCS^{\frac{1}{2}} \frac{(d - dp)^{\frac{5}{3}}}{n}$$

(2.6)

Where Q is outflow rate (length/time), W is sub-catchment width (length), C is 1.486 for English units and C = 1 for SI units, n is Manning's roughness coefficient, d is water depth (length), dp is the depth of depression storage (length) and S is the surface slope (%).

Flow routing in frequencies and pipes (Cambez *et al.*, 2008) is ruled by the preservation of mass and energy equations for progressively varied and unsteady flow Saint Venant equations (Zhang & Shen, 2007). The user decides on the popularization level of the equations: the steady flow routing; the kinematic wave routing; or the full dynamic wave routing (Cambez *et al.,* 2008).

Spatial variability in all of these processes is achieved by dividing a study area into a collection of smaller, homogeneous sub-catchment areas, each containing its fraction of pervious and impervious sub-areas (Beven, 2011).

2.4 Calibration and Validation of Hydrological Models

Almost all hydrologic models require calibration and validation to apply for studies in a particular catchment. The process begins by identification of calibration parameters that are sensitive to the model output. The process is termed sensitivity analysis and aims to identify the key parameters that affect model performance and play important roles in model parameterization, calibration, optimization, and uncertainty quantification (Song *et al.*, 2015). In hydrological modeling, sensitivity analysis is defined as the investigation of the response function that links the variation in the model outputs to changes in the input parameters, which allows the determination of the relative contributions of different uncertainty sources to the variation in outputs using qualitative or quantitative approaches under a given set of assumptions and objectives (Song *et al.*, 2015).

Sensitivity analysis is useful in providing the qualitative and quantitative indices needed to identify sensitive and non-sensitive parameters to efficiently and effectively identify the calibration parameter (Castaings *et al.,* 2009). Parameters can be analyzed in pairs or even more at a time but sensitivity analysis considering each parameter alone is more effective than considering more parameters at the same time (Song *et al.,* 2015).

The resulting identified parameters in sensitivity analysis are adjusted within a particular range to come up with calibrated parameter values for the model. Upon running simulations with the calibrated parameter values, model results should compare favorably with the observed data and consistent with watershed characteristics (Rosa *et al.,* 2015).

The calibration process requires a procedure to evaluate its success and the criterion of success has to be subjected to judgment adequacy (Paterne, 2019). Statistical indicators are used to measure the goodness of fit because their functions are more likely to produce a comparison between measured and modeled values (Rosa *et al.,* 2015). Examples of search statistical indicators include correlation coefficient, relative error (RE), the normalized objective function (NOF), coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), an index of agreement (d) (Mahajan *et al.*, 2017). Some of these indicators are selected to guide to an acceptable calibration.

The calibration is completed by validation where the outcomes are evaluated if they provide adequate information related to the need for the model (Paterne, 2019). The model validation aims to determine if the estimates achieved by the calibration are acceptable. For validation, the model is run with data of a period other than that used for calibration and the results are evaluated using the same statistical indicators (Palanisamy *et al.,* 2015).

Since the SWMM model was developed for United States conditions, it is necessary to calibrate and validate the model for application in areas outside the United States. Sensitivity analysis, uncertainty analysis, calibration, verification and validation, best design of sewer networks (Choi and Ball, 2002), and parameterization of EPA SWMM model has remained a concern by many scholars (Schoeneberger *et al.,* 2012; Kourtis *et al.,* 2017).

2.5 LID Controls and Flood Mitigation

Discharging stormwater as fast as possible is no longer a good option to manage it and doing things differently is now an essential requirement for managing surface water, especially when considering a changing climate and rapid urbanization (Schreier, 2014). Among the possible options, stormwater management in urban areas is becoming increasingly oriented to the use of low impact developments (LID), sustainable urban drainage systems (SUDS), water sensitive urban design (WSUD), best management practices (BMP), low impact urban design and development (LIUDD) or green infrastructure (GI) for effectively countering the effect of urban growth, wherein the stormwater is controlled at its source through detention, retention, infiltration, storage, retardation etc. (Charlesworth *et al.,* 2003, Elliott and Trowsdale, 2007; Kirby, 2005; Martin *et al.,* 2007; Peng *et al.,* 2017).

LID technique is a comprehensive land use planning and design approach to mitigate urban impacts on the environment at the sub-catchment level (Martin-Mikle, *et al.,* 2015). The chief focus is on decreasing the percentage of runoff within the watershed Charlesworth *et al.,* 2003) thus promoting infiltration and decreasing surface runoff

(Paterne, 2019) and in the process reduce the impression of urban development (Wong *et al.,* 2002).

LID techniques work by reducing runoff from localized impervious source areas (e.g., by using rain barrels, green roofs and porous pavement), by slowing and filtering overland water runoff, sediment, and pollutants before they reach the mainstream network (e.g., via grassed swales, rain gardens, and detention/retention ponds), and by slowing and filtering runoff in or adjacent to the mainstream network (e.g., protection and/or restoration of riparian buffers) (Craig *et al.,* 2008, Mayer *et al.,* 2007). The method aims to preserve and recreate the natural, pre-development characteristics of a site as closely as possible (Charlesworth *et al.,* 2003), even after development (Ciria, 2000), and reduce the impacts to an acceptable level by handling rainwater at its basis instead of discharging it into conservative drainage systems (Fleischmann, 2014).

LID devices include structural measures such as wetlands, ponds, swales, rainwater tanks, bio-retention devices, vegetated filter strips, and filter strips and can also include non-structural measures such as alternative layouts of roads and buildings to minimize imperviousness and to maximize the use of pervious soils and vegetation, contaminant source reduction, and programs of education to modify activities (Elliott & Trowsdale, 2007). Many design guidelines for such devices are now available (Ciria, 2000).

SWMM Model version 5 can model LIDs and gives eight options for the techniques; bio-retention ponds, green roofs, rain barrels, permeable pavements, vegetative swales, infiltration trenches, rain gardens and rooftops (Rossman, 2015).

2.5.1 Bio-retention ponds are depression areas built to collect and treat stormwater runoff. Water held in depression areas can permeate (Ciria, 2000) into the soil and recharge groundwater while evapotranspiration (Rossman, 2015) can decrease the quantity of water entering the stormwater system (Choe *et al.*, 2015).

2.5.2 Green roofs consist of thick soil with plants and trees on top of buildings, which absorb and hold precipitation that conventionally runs straight off of the roof (Rossman, 2015). Water is stored in the soil, and it is released back into the atmosphere through evapotranspiration by plants (Rowe, 2011).

2.5.3 Rain barrels collect and hold precipitation running off roofs. Infiltration happens slowly and water can be used for gardening, greenhouse watering, or other purposes (Ahiablame *et al., 2012*). Cisterns can reduce up to 100% of rooftop runoff, but become less effective for large storms because of capacity limitations.

2.5.4 Permeable pavements (Scholz, & Grabowiecki, 2007), have a surface with void spaces to allow the infiltration of stormwater into the underlying soil. They have the potential to substantially reduce runoff volume compared to conventional asphalt and concrete (Leroy *et al.*, 2016), including systems installed over clayey subgrade soils (Zimmerman *et al.*, 2010). Permeable pavements are designed to reduction peak runoff rates, reduce runoff quantity, and delay peak flows by promoting surface infiltration rates.

2.5.5 Vegetated swales are open channels designed to convey, treat and reduce stormwater runoff and usually consume about 5 to 15 percent of their contributing drainage area (Leroy *et al.*, 2016) and they have long been used for stormwater conveyance, particularly for roadway drainage. Longitudinal grades between 0.5 and 6% are allowable (Leroy *et al.*, 2016). This prevents ponding while providing residence time and preventing erosion (Leroy *et al.*, 2016). During the rainfall event, its rough surface consisting of vegetation could slow down the velocity of overland flow while conveying it to another location so that pollutants in particle phases would easily settle down and runoff could infiltrate to the soil (Martin-mikle *et al.*, 2015).

2.5.6 Infiltration trenches are narrow ditches filled with gravel that intercept runoff from upslope impervious areas (Brown & Borst, 2015), that provide storage volume and additional time for captured runoff to infiltrate into the native soil below.

2.5.7 Rain gardens are designed landscape sites that reduce the flow rate, total quantity, and pollutant load of runoff from impervious urban areas like roofs, driveways, walkways, and parking lots, and compacted lawn areas (Church, 2015). They rely on plants and natural or engineered soil medium to retain stormwater and increase the lag time of infiltration while remediating and filtering pollutants carried by urban runoff.

2.5.8 Rooftop disconnection (RD) is one of the simplest means of reducing stormwater from residential lots (Sample, 2013). RD takes roof runoff that has been collected in gutters and piped directly to streets, storm drains, and streams and redirects it away from impervious surfaces to landscaped areas.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Schematic Representation of Methodology

Materials and various methods were applied to achieve the study objectives. A summary of the process is presented in Figure 3.1.

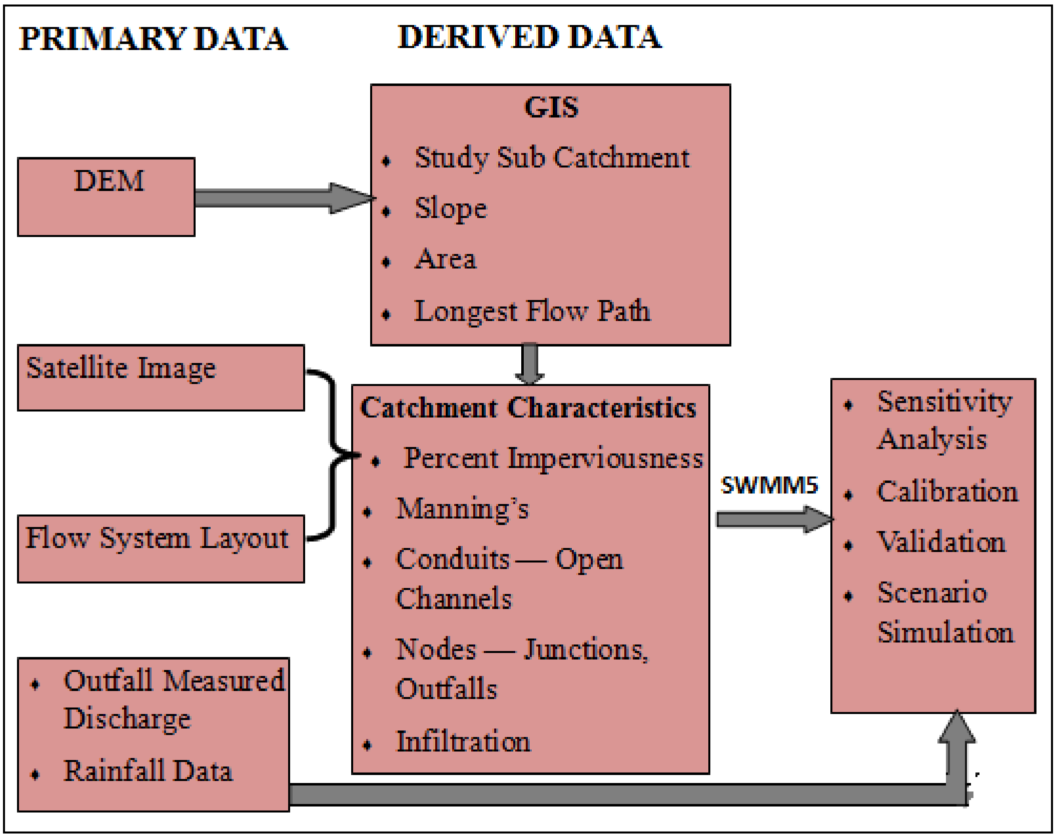


Figure 3.1: Flowchart of study methodology

Primary and secondary data were obtained during the study. Primary data was obtained majorly through measurement applying different techniques and equipment depending on the data required, while secondary data was obtained from various sources. Among the data measured include, channel parameters, rainfall amount, and discharge from the catchment at the outfall. Data acquired from secondary sources included historical rainfall data, DEM and captured Google earth image of the study area.

3.2 Study Area

3.2.1 Study Area Location

This study was conducted in Eldoret town. Uasin Gishu County is one of the 47 counties of Kenya, located in the former Rift Valley Province. It lies in the mid-west of the Rift Valley and covers an area of 3,345.2 sq km. It borders Kericho County to the south, Nandi County to the southwest, Kakamega County to the west, and Trans Nzoia County to the north. Other counties sharing borders with Uasin Gishu are Elgeyo Marakwet to the east and Baringo to the southeast.

Eldoret town is the county's administrative and commercial center which is Kenya’s fifth largest town and is about 311km from Nairobi city, the capital city of Kenya. It lies within latitude 0.26^{o}3’ N - 0.35^{o}34’ N and longitude 35.12^{o}21’ E - 35.20^{o}31’ E. Figure 3.2 shows the location of the study area, Eldoret Town and Uasin Gishu in Kenya. The study area is located between latitude 0^{o}31’0”N - 0^{o}32’0”N and longitude 35^{o}17’0”E - 35^{o}18’0”E with an approximated area of 696.5 ha.

Estates within Eldoret include Elgon View, Langas, Huruma, Kapsoya, Kahoya, West Indies, West, Kipkaren, Kimumu, Jerusalem, and Pioneer among many others (Mbwagwa, 2005). The northern part of Eldoret is marked by a steep slope. It is this slope and its influence on water velocity that contributes to runoff generation that has been reported to cause flooding towards River Sosiani. The focus was on the sub-basin covered by Kapsoya, Munyaka, Jerusalem, Hawaii, and Subaru which channels its water southwards across the town into River Sosiani.

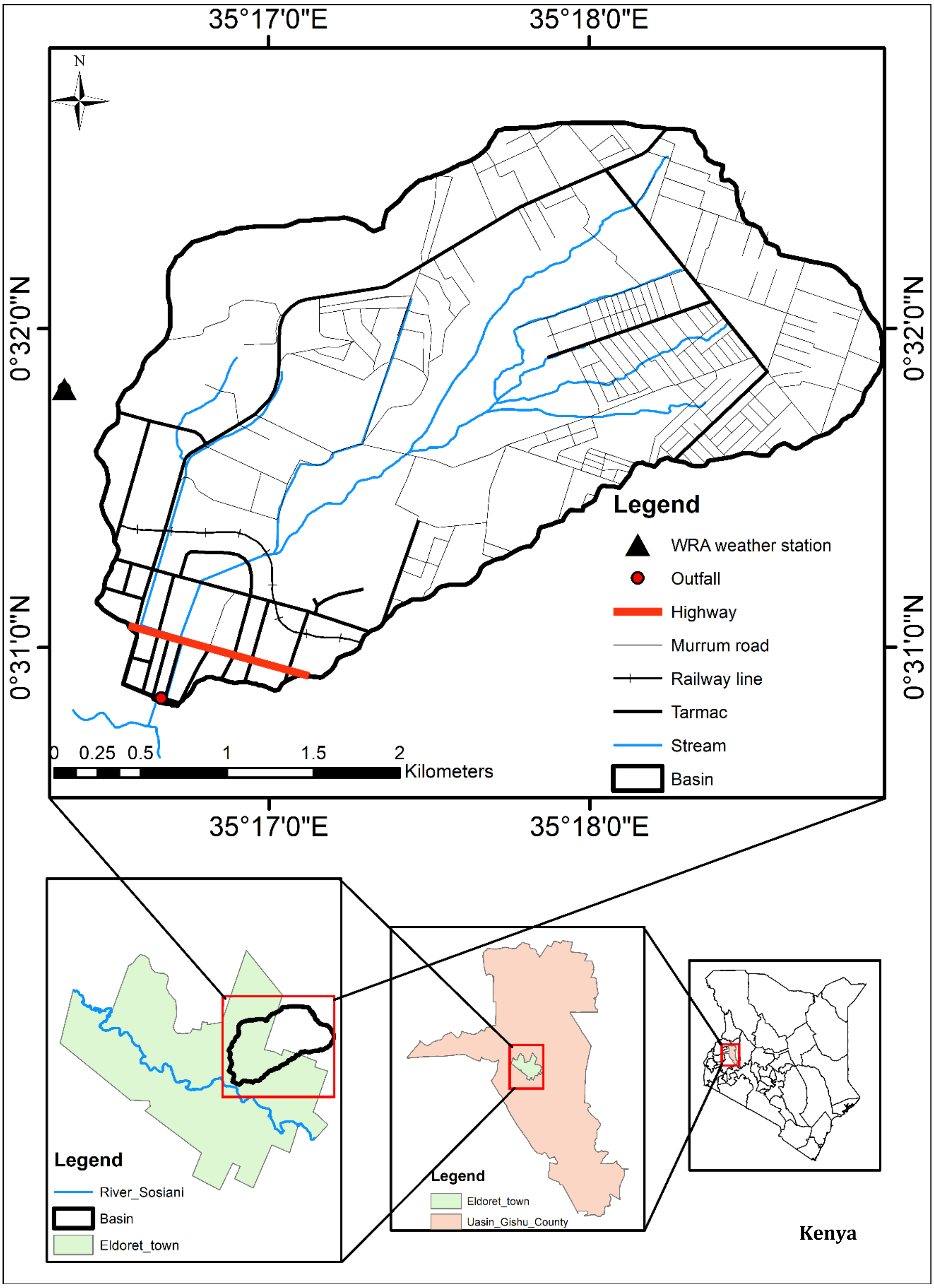


Figure 3.2: Map of the Study Area

3.2.2 Climate of the Area

Uasin Gishu is located on a plateau and has a cool and temperate climate. It has a temperature range of between 8.4^{0}C and 27^{0}C. The county has two rainy seasons with total annual rainfall varying from 900mm to 1,200mm (Kemboi & Jairus, 2018). The rainfall has a contributing effect to runoff generation in the study area.

3.2.3 Geology

The geological formation of the area belongs to the Tertiary Volcanic of the middle and upper tertiary age. The soils are primarily of two types, namely red to strong-brown friable clays with laterite horizon and grey mottled clays (Simiyu, 2012). These features drive the river water chemistry (Kemboi & Jairus, 2018), dictating the species that can effectively create themselves and the levels of productivity.

3.2.4 Soils

Soils are chiefly of volcanic origin and tend to be friable, well-drained, and in some cases shallow (Kemboi & Jairus, 2018). Those on central plains are mainly derived from lacustrine deposits and volcanic ashes. Having developed on residues, the soils tend to be dark brown, deep, and poorly drained and slightly calcareous to saline (Simiyu, 2012). The soil type dictate the amount of water that can infiltrate into the soil profile during a rainfall event.

3.2.5 Population

Uasin Gishu County is home to 1,163,186 people as per the 2019 Kenya National Bureau of Statistics census report, representing 49.9% male and 50.1% female. It is largely a cosmopolitan region, with immigrants bringing different cultural practices. This has resulted in population growing rapidly hence increased settlement with high potential of runoff generation during rainfall events. The indigenous population is sports oriented owing to the friendly environment although with immigration they have diversified their practices investing in infrastructure development in the town for business activities which may result in increased runoff generation.

3.2.6 Infrastructural Developments

The county has relatively well-established infrastructure including Kenya's third international airport that handles large amounts of cargo from the Middle East. The airport allows the county to grow and expand the export market. It has a broad industrial base particularly in and around Eldoret town. The development of infrastructure in the town leads to increase in buildup areas resulting in increase in impervious surfaces.

3.2.7 Economic Activities

The economy is dominated by agriculture and is one of the largest contributors to food security in Kenya. Wheat, maize, and dairy are the leading farming activities. Various food crops also do well in the highly arable land (Kemboi & Jairus, 2018).

Many institutions among them the University of Eldoret, Moi University Campuses, Eldoret International Airport, Moi Teaching, and Referral Hospital are located within the town. Major industries within Eldoret town include textiles, wheat, pyrethrum, beverages and corn processing. The town is set to further develop with upcoming industries in its surrounding. Development of the various institutions within the study area has resulted to conversion of pervious surfaces to impervious surfaces that contribute to runoff generation when it rains.

3.3 Study Sub Catchment Characteristics

3.3.1. Area

To determine the area of the study sub-catchment, it was necessary to process a digital elevation model (DEM) to perform an estimation of the area. A DEM for 2014 was downloaded from earth explorer 2019 from United States Geological Survey's Earth Explorer site (http://earthexplorer.usgs.gov/) defined by attributes contained in Table 3.1. This is an open-source data download service. The digital elevation model has a resolution of 1-ARC SEC (30m×30m) in ASCII Grid format. The DEM was used with an assumption of minimum disturbance on the shape of land between 2014 and 2019.

Table 3.1: Digital elevation model attributes

Data Set Attribute	Attribute Value
Entity ID	SRTM1N00E035V3
Acquisition Date	11/02/2000
Publication Date	23/09/2014
Resolution	1-ARC
Path/Row	169/060

The study sub-catchment was obtained through DEM delineation in ArcGIS 10.2.2 toolbox under hydrology. The gauging point at Bandaptai in Eldoret was selected as the outfall of the catchment. This process resulted in the definition of the basin (study sub-catchment) that drains its water through the outfall of the sub-catchment (Gauging point). The area computation tool was then used in ArcGIS 10.2.2 environment to determine the area of the study sub-catchment.

To cater for spatial variability, the study sub-catchment was subdivided into 23 smaller homogenous sub-basins. Subdivisions were done in ArcGIS by presenting additional pour points along the watercourses within the catchment based on the stormwater system layout and flow accumulation grid (Simiyu, 2012). The area of each sub-basin was also determined. The width of each sub-basin was estimated by dividing the area of a basin by its longest flow path. Sub catchment editor in SWMM was used to enter the area and width of each sub-basin.

3.3.2. Slope

Study sub-catchment polygon which had been obtained during delineation to determine the area was used to clip DEM for the sub-catchment. The downloaded area of interest DEM was loaded as the input feature, a process which resulted in obtaining a DEM for the study sub-catchment. From the study area DEM, elevations were obtained and it's from here that slope was determined. The slope was computed in percentage using the surface tool under spatial analyst extension in Arc map 10.2.2.Software. The slope in percentage was then classified into three classes namely flat (0-5), gentle slope (between 5 and 10), and moderate slope (ranging from 10 to 15). Sub catchment editor in SWMM was used to enter slope.

3.3.3. Percentage Imperviousness

The determination of percentage imperviousness for each sub-catchment was done using the grid method. A shapefile of the study area sub-catchment indicating the sub-basins was loaded onto Google Earth software; which was able to provide an April 2019 image of the area of interest. The sub-basins were marked as S1 to S23. Each sub-basin was zoomed in to fit the computer screen and printed upon which 1cm grids were drawn over and the grid method applied through close observation and calculation to obtain the percentage impervious area for each sub-basin. Impervious areas include developed areas that could allow very low water infiltration to take place.

The weighted percentage proportion of each sub-basin as expressed in respect to its size and proportion to the entire area was determined. These percentages were then summed up to come up with the percentage imperviousness of the entire study sub-catchment. Sub catchment editor in SWMM was used to enter the percentage imperviousness of each sub-basin.

3.3.4. Rainfall and Discharge through the Outfall

Rainfall and discharge from the study sub-catchment were measured and recorded for six events. Runoff discharge was measured at the catchment outlet which formed the gauging point (Figure 3.1). Both parameters were measured and recorded at intervals of 30 min from the start of the rainfall event to the end, although discharge was further measured up to an hour after the end of the rainfall event.

Historical rainfall data was collected from the Water Resources Authority yard in Eldoret town which is located a kilometer to the west from the study area sub-catchment (Figure 3.1). This data was necessary for analysis to obtain rainfall trend in the study area. The analysis gave results of year-round daily average for 11 years between 2009 and 2019, as well as yearly daily minimum and maximum amount of rainfall recorded. The time series tool in the SWMM model allowed input of measured rainfall data and rain gauge tool provided an interface to read the data in the time series.

Discharge through the outfall of the study area was measured by the current meter method. Data was collected per rainfall event from the start to the stop of the event.

This was recorded in intervals of 30 min throughout the rainfall event to one hour after the rainfall event. A total of six events were measured.

3.3.5. Storm Water System Layout

Junctions and Conduits parameters were obtained through study area DEM analysis and ground measurement. These included the invert elevation of the junctions and maximum depth. A total of 19 junctions were considered for modeling.

Conduit parameters determined included conduit maximum depth, length, shape, and slope dimensions. Manning's roughness coefficient was also determined and was estimated based on the conduit lining and applying guidelines provided in the SWMM manual.

The conduits were trapezoidal; therefore depth, bottom width, and top width were measured using a tape measure, while side slopes were determined through calculation after measurement. The hydraulics tool in the SWMM model was used to input both junctions and conduits parameters.

3.4 Calibration and Validation of SWMM Model

The calibration processes started by the establishment of the most sensitive parameters for the catchment area. This sensitivity analysis was to help identify key parameters for calibration. This was done by running a simulation and comparing the results with observed flow. Three events were used in calibration.

Sensitive parameters that were used for calibration of the model for application in Eldoret were found to be; Manning's roughness coefficient for the impervious area (N-IMPERV), Manning's roughness coefficient for the pervious area (N-PERV), Depth of depression storage on the impervious area (Dstore-Imperv), Depth of depression storage on the pervious area (D-store-Perv).

Model validation was done using the input parameters that were resulting in the calibration development. Validation is done to confirm the model's ability to simulate events after calibration. To carry out validation, three events were used.

Model efficiency for both calibration and validation was evaluated using four measures of fitness namely; Nash–Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2), Integral Square Error (ISE) and Root Mean Square Error (RMSE).

3.4.1 Coefficient of Determination

The coefficient of determination R^2 is defined as the squared value of the coefficient of correlation (Krause *et al.*, 2005). The range of R^2 lies between 0 and 1 which defines how much of the practical distribution is explained by the forecast. A value of zero means no correlation at all; whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation (Wu *et al.*, 2013). The coefficient of determination is a measure that determines how certain one can be in making predictions from a modeled hydrograph. R^2 is calculated using equation 3.1.

$$R^2 = \frac{\sum_1^N O_i M_i - \frac{\left(\sum_1^N O_i\right)\left(\sum_1^N M_i\right)}{N}}{\sqrt{\left(\sum_1^N O_i{}^2 - \frac{\left(\sum_1^N O_i\right)^2}{N}\right)\left(\sum_1^N M_i{}^2 - \frac{\left(\sum_1^N M_i\right)^2}{N}\right)}} \quad (3.1)$$

Where:

O_i = observed hydrograph value at time i,

M_i = modeled hydrograph value at time i, and

N = number of hydrograph values.

3.4.2 Nash–Sutcliffe Efficiency

The Nash–Sutcliffe Efficiency, NSE, is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation (Wu *et al.*, 2013).

The range of E lies between 1 and −∞. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model (Shamsi & Koran, 2017). Table 3.2 shows NSE ratings for model calibration and application (Shamsi& Koran, 2017). NSE is calculated using equation 3.2.

$$\boldsymbol{NSE = 1 - \frac{\sum_{i=1}^{N}(M_i - O_i)^2}{\sum_{i=1}^{N}((O_i - O)^2}}$$

(3.2)

Where:

O_i = observed hydrograph value at time *i*,

M_i = modeled hydrograph value at time *i*,

N = number of hydrograph values, and

O = mean of observed values.

Table 3.2: NSE goodness of Fit Ratings

NSE Range	Calibration Rating	Model Application
0.5 to 1.0	Excellent	Planning, Preliminary Design, Final Design
0.4 to 0.49	Very good	Planning, Preliminary Design, Final Design
0.3 to 0.39	Good	Planning, Preliminary Design
0.2 to 0.29	Fair	Planning
<0.2	Poor	Screening

3.4.3 Integral Square Error

The integral square error, ISE, integrates the square of the error over time. ISE magnifies large errors more than smaller ones since the square of a large error is much bigger. ISE as per Shamsi and Ciucci, (2013) has a good measure of goodness-of-fit between observed and modeled hydrographs Table 3.3 provides calibration ratings and model applications for different ISE ranges (Shamsi & Koran, 2017). ISE is calculated using equation 3.3.

$$ISE = \frac{\left(\sum_{i=1}^{N}(O_i - M_i)^2\right)^{\frac{1}{2}}}{\sum_{i=1}^{N} O_i} \times 100 \qquad (3.3)$$

Where:

Oi = observed hydrograph value at time i,

Mi = modeled hydrograph value at time i, and

N = number of hydrograph values.

Table 3.3: ISE Goodness of Fit Ratings

ISE Range	Calibration Rating	Model Application
0 to 3	Excellent	Planning, Preliminary Design, Final Design
3.1 to 6	Very good	Planning, Preliminary Design, Final Design
6.1 to 10	Good	Planning, Preliminary Design
10.1 to 25	Fair	Planning
<25	Poor	Screening

3.4.4 Root Mean Square Error

Root Mean Square Error is a frequently used degree of the differences between observed and modeled values (Simiyu, 2012). It characterizes the sample standard deviation of the differences between modeled and observed values (Shamsi & Koran, 2017). The RMSE serves to aggregate the magnitudes of the errors in predictions into a single measure of predictive power (Shamsi & Koran, 2017). ISE is calculated using equation 3.4.

$$RMSE = \sqrt{\sum_{i=1}^{N}(\frac{(O_i - M_i)^2}{N})} \qquad (3.4)$$

Where:

Oi = observed hydrograph value at time *i*,

Mi = modeled hydrograph value at time *i*, and

N = number of hydrograph values.

3.5 Scenarios of Rainfall and Surface Imperviousness on Runoff Generation

The scenarios for analysis were formulated as indicated in Table 3.4. Impervious area percentage was increased in tens from 25% to 75%. The measured rainfall events and historical rainfall events were used.

Table 3.4: Scenarios of Rainfall and Impervious Area Proportions

Scenario	Description
Scenario 1	Maximum measured daily rainfall and increasing percentage imperviousness in tens from the actual 25% to 75%
Scenario 2	Average measured daily rainfall and increasing percentage imperviousness in tens from the actual 25% to 75%
Scenario 3	Minimum measured rainfall and increasing percentage imperviousness in tens from the actual 25% to 75%
Scenario 4	The historical daily highest rainfall recorded between 2009 and 2019 with increasing percentage imperviousness in tens from the actual 25% to 75%
Scenario 5	Historical average daily maximum rainfall recorded between 2009 and 2019 with increasing percentage imperviousness in tens from actual 25% to 75%

3.6 Influence of Low Impact Developments on Stormwater Runoff

Assuming continuous development and increase in impervious area by 30% of the total area (the currently estimated imperviousness is 25.72%), 55% imperviousness was set for the study sub-catchment to run simulations. The model was run without LIDs and with three scenarios of LIDs. The scenarios were formulated as shown in Table 3.5. Maximum recorded daily rainfall observed between 2009 and 2019 was applied to perform this evaluation. The rainfall amount was 72.78 mm. Infiltration trenches and bio-retention cells were considered for modeling of LIDs due to the current percentage imperviousness of the study area which can allow for their development. The rest of the LIDs in SWMM model as described in section 2.5 can be applied where the percentage imperviousness is high due to development of buildup areas and there is limited space.

Table 3.5: Scenarios of LID Treatments

Scenario	**Description**
Control	Simulation run without LID treatment
Scenario 1	Infiltration trenches (IT) used to an extent of 100% of impervious area
Scenario 2	Bio Retention Cells (BRC) used to an extent of 100% of impervious area
Scenario 3	A mixture of infiltration trenches and bio-retention cells, each used to an extent of 50% of the impervious area

CHAPTER FOUR

RESULTS

4.1 Sub Catchment Characteristics

4.1.1 Area

The DEM analyses indicated that the outfall of the study sub-catchment drains an estimated area of 696.5 hectares (Figure 4.1). The study area is located between latitude $0^{o}31'0''$N - $0^{o}32'0''$N and longitude $35^{o}17'0''$E - $35^{o}18'0''$E. The Time of Concentration for the catchment was 7.78Min.

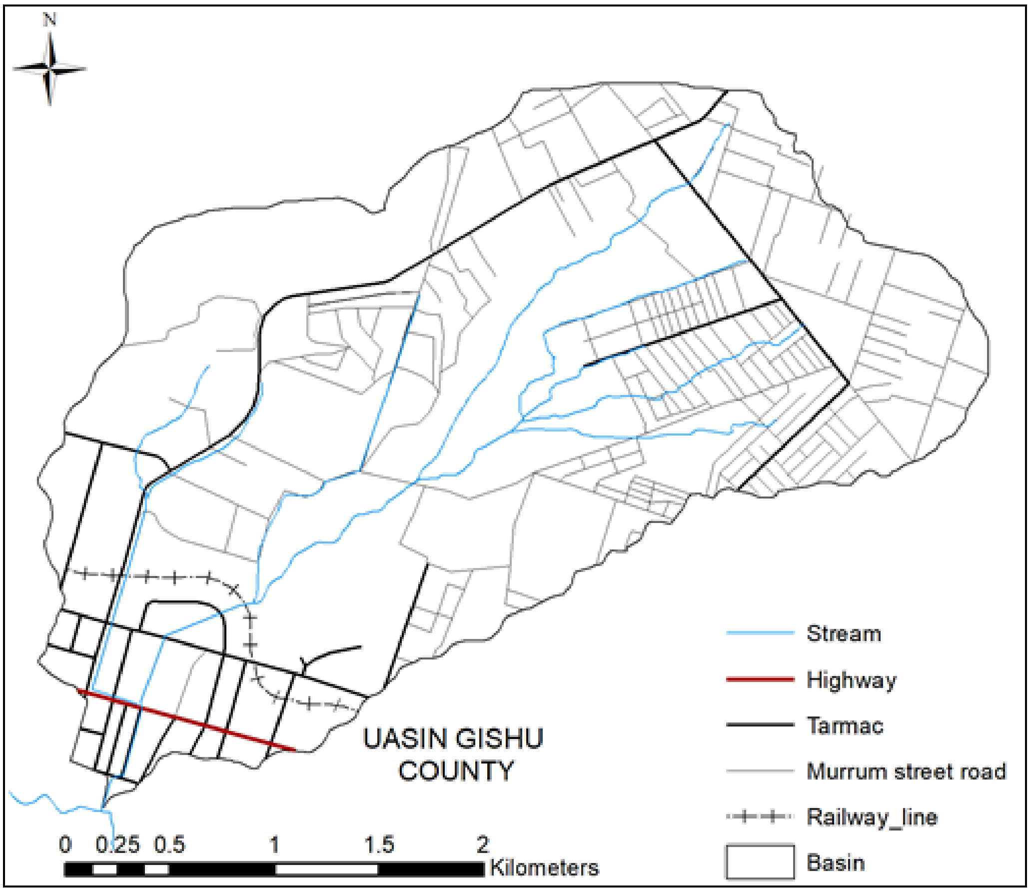


Figure 4.1: Catchment Map Showing Various Attributes of the Study Area

The study sub-catchment sub-division resulted in 23 sub-basins that form the drainage of the sub-catchment. The size of each resulting sub-basin is indicated in Table 4.1, as well as slope, width, and percentage of impervious surfaces. Each sub-catchment was assigned to an outlet node in the drainage network that would collect all resulting runoff. Figure 4.2 indicates the sub-basins, junctions, and conduits within the study sub-catchment.

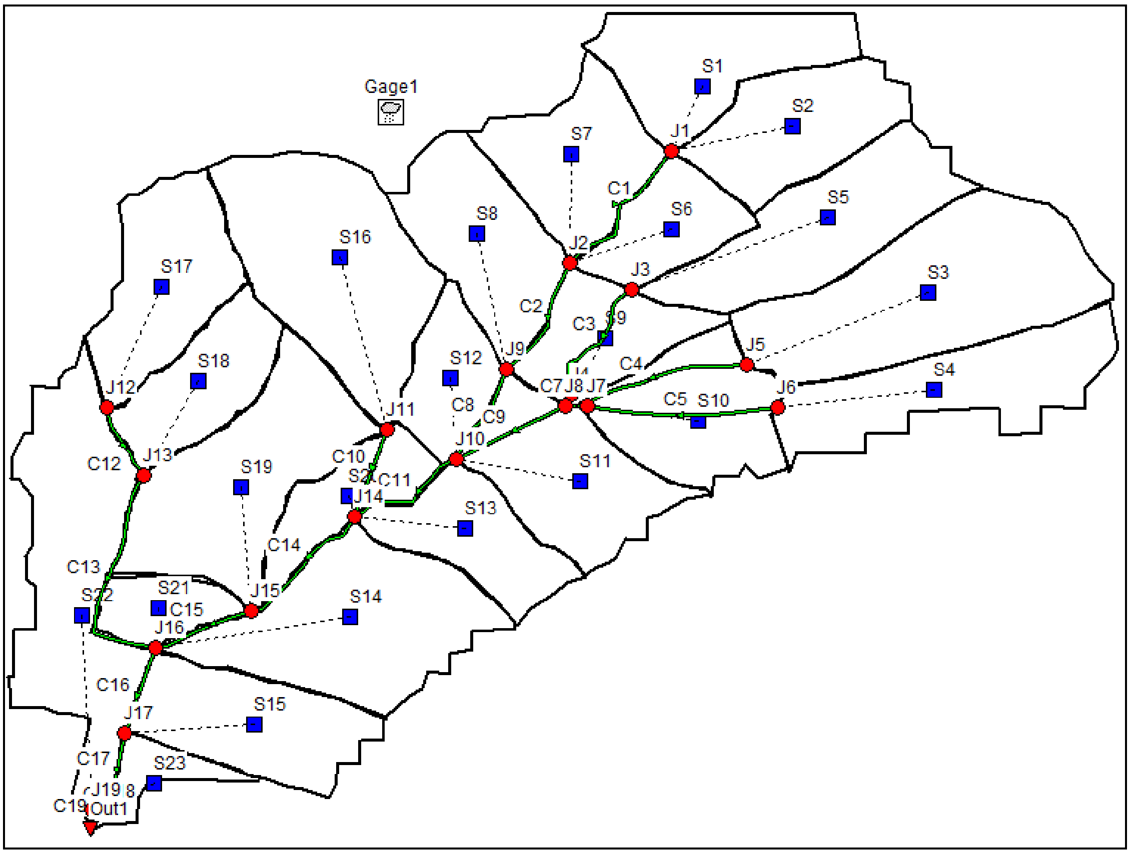


Figure 4.2: Sub-basins, Channels, and Junctions within the Study Sub Catchment

Table 4.1: Sub-basins Attributes Table

Sub Basin	Area (Ha)	Width (m)	% Imperviousness	Average% Slope
S1	27.6	262	38	1.8
S2	28.2	265	23	1.8
S3	64.7	402	39	2.1
S4	34.7	290	24	3.1
S5	37.4	305	23	2.2
S6	14	184	1	2.3
S7	26.2	255	18	2.7
S8	31	276	28	3.3
S9	17.5	205	18	1.9
S10	29.1	270	27	2.3
S11	42.2	326	14	2.2
S12	12.1	174	13	1.9
S13	19.6	221	13	2.4
S14	51.2	360	19	3.3
S15	29.1	270	29	3.8
S16	56.4	375	43	3.2
S17	29.1	270	11	3.3
S18	19.7	221	9	2.9
S19	49	350	23	2.4
S20	11.3	168	14	1.8
S21	5.2	114	15	2.2
S22	57.3	360	38	2.8
S23	3.9	100	68	3.3

4.1.2 Slope

The maximum and minimum elevation above the sea level for the study area was found to be 2176m and 2074m respectively, with a mean elevation of 2150m. The average slope was found to be 2.57% . The slope in percentage was categorized into three classes (Fig.4.3).

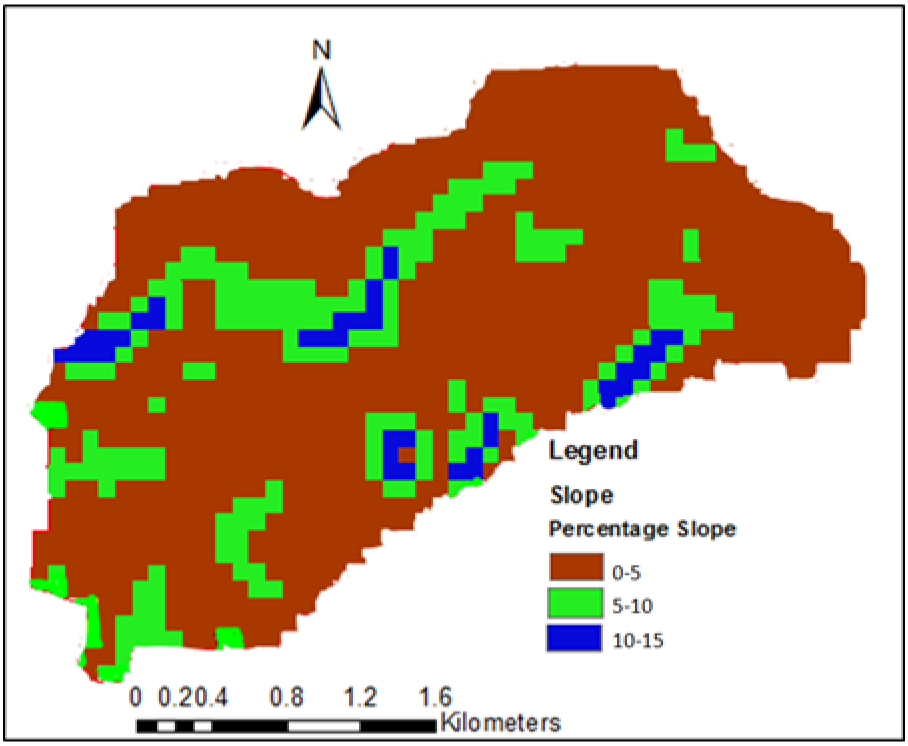


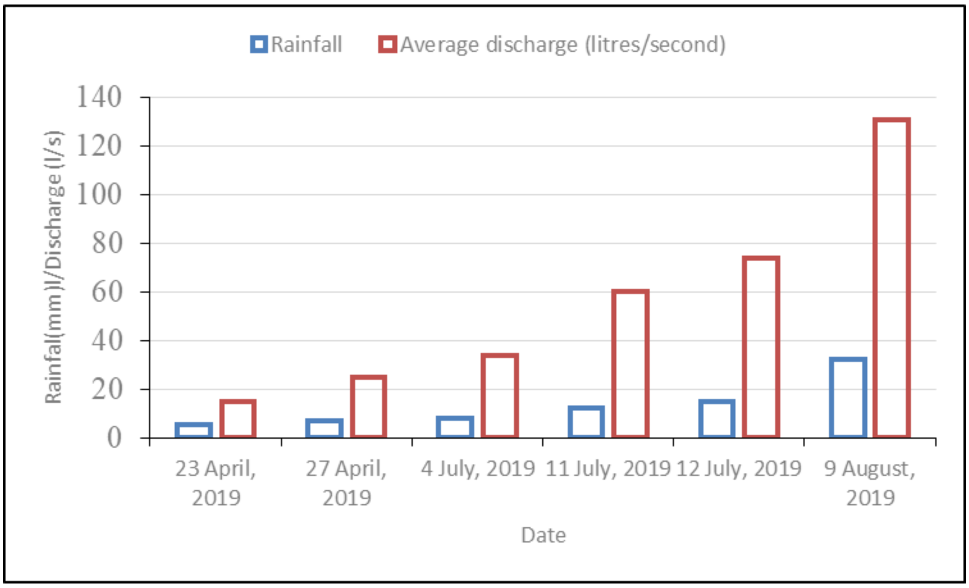
Figure 4.3: Slope Categories

4.1.3 Percent Imperviousness

The estimated impervious surface area was found to be 169.5 hectares representing 25.72% of the total sub-catchment area while 527 (74.28%) hectares constituted the pervious surfaces. Proportions of the percentage of impervious surfaces determined for each sub-basin have already been presented in Table 4.1.

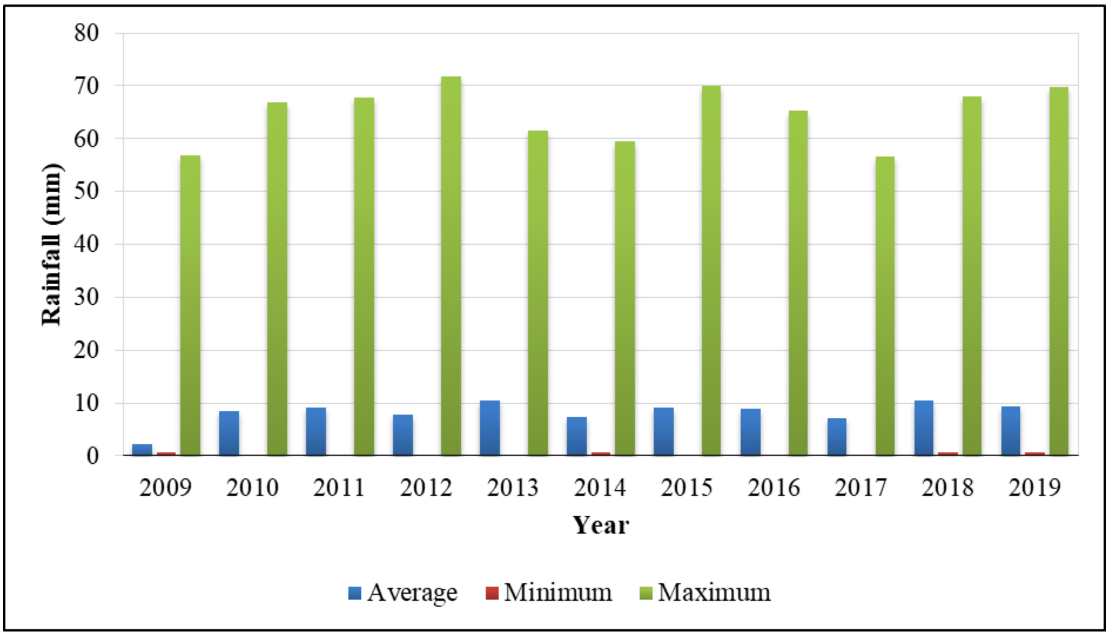
4.1.4 Rainfall and Discharge

Recorded rainfall and runoff determined during the study are presented in Graph 4.1. The highest measured rainfall was 32.40 mm while the minimum was 5.10 mm. The average measured rainfall was found to be 13.26 mm. The highest measured discharge of 0.131m^3/s was recorded caused by the maximum rainfall of 32.40 mm.



Graph 4.1: Recorded Rainfall and Discharge during the Study

The results of the analysis of historical rainfall data are presented in Graph 4.2. The results show yearly minimum / maximum and the date it was recorded, and the year-round daily average for each year covering 11 years between 2009 and 2019. The maximum daily rainfall recorded was 71.78 mm event while the average of the maximums recorded for each year was found to be 64.89 mm.



Graph 4.2: Rainfall trend: 2009 to 2019

4.1.5. Storm Water System Layout

Tables 4.2 and 4.3 present a summary of junctions and conduits parameters that were input into the model. The channels were uniform with varying lengths from one node to another.

Table 4.2: Junctions and Conduits Data

Nodes			Links		
Junction	**Invert Elevation (m)**	**Maximum Depth (m)**	**Conduit**	**Length (m)**	**Roughness Coefficient**
J1	2160	1.5	C1	653	0.05
J2	2144	1.5	C2	541	0.05
J3	2144	1.5	C3	517	0.05
J4	2132	1.5	C4	713	0.05
J5	2148	1.5	C5	824	0.05
J6	2150	1.5	C6	89	0.05
J7	2133	1.5	C7	60	0.05
J8	2131	1.5	C8	447	0.05
J9	2131	1.5	C9	512	0.05
J10	2122	1.5	C10	394	0.05
J11	2127	1.5	C11	511	0.05
J12	2131	1.5	C12	326	0.05
J13	2118	1.5	C13	967	0.02
J14	2115	1.5	C14	607	0.05
J15	2103	1.5	C15	427	0.05
J16	2090	1.5	C16	381	0.05
J17	2081	1.5	C17	340	0.02
J18	2076	1.5	C18	47	0.02
J19	2075	1.5	C19	80	0.02
Out1	2074	1.5			

Table 4.3: Channel Dimensions

Property	**Measurement**
Maximum Depth	1.5m
Bottom Width	1.2m
Top Width	1.5m
Side Slopes	8.33%

4.2 Calibration and Validation of SWMM Model for Eldoret

4.2.1 Sensitivity Analysis

The sensitive input parameters were found to be Manning's roughness coefficient for the impervious area (N-Imperv), Manning's roughness coefficient for the pervious area (N-Perv), Depth of depression storage on the impervious area (Destore-Imperv) and Depth of depression storage on the pervious area (Destore-Perv).

4.2.2 Calibration and Validation

Three events were used in the calibration of the model while the other three were used in validation. Observed and simulated values during calibration and validation are presented in Table 4.4.

Table 4.4: Observed and Simulated Values for Calibration and Validation

	Calibration	
Date	Observer Avg. Runoff	Simulated Avg. Runoff
27/4/2019	0.025	0.024
23/4/2019	0.015	0.015
4/7/2019	0.034	0.033
	Validation	
12/7/2019	0.074	0.076
9/8/2019	0.131	0.132
11/7/2019	0.060	0.057

The adjusted values for calibration otherwise known as modeling parameters are presented in Table 4.5. The results of model performance evaluation for both calibration and validation are presented in Table 4.6.

Table 4.5: Modeling Parameters

Parameter	Description	Initial Value	Calibrated Value
N-Imperv	Manning's roughness coefficient for impervious area	0.01	0.015
N-Perv	Manning's roughness coefficient for impervious area	0.1	0.45
Dstore-Imperv	Depth of depression storage on impervious area	0.05	2.5
Dstore-Perv	Depth of depression storage on pervious area	0.05	8

Table 4.6: Measures of fitness with evaluated values for Calibration and Validation

Measure of Fitness	Calibrated	Validated
Coefficient of Determination (R^2)	0.99	0.99
Nash–Sutcliffe Efficiency(NSE)	0.972325	0.995051
Integral Square Error **(**ISE)	3.021713	1.411946
Root Mean Square Error (RMSE)	0.001291	0.00216

Figures 4.4 and 4.5 show the comparison of observed and simulated flow using the coefficient of determination (R^2) for calibration and validation respectively.

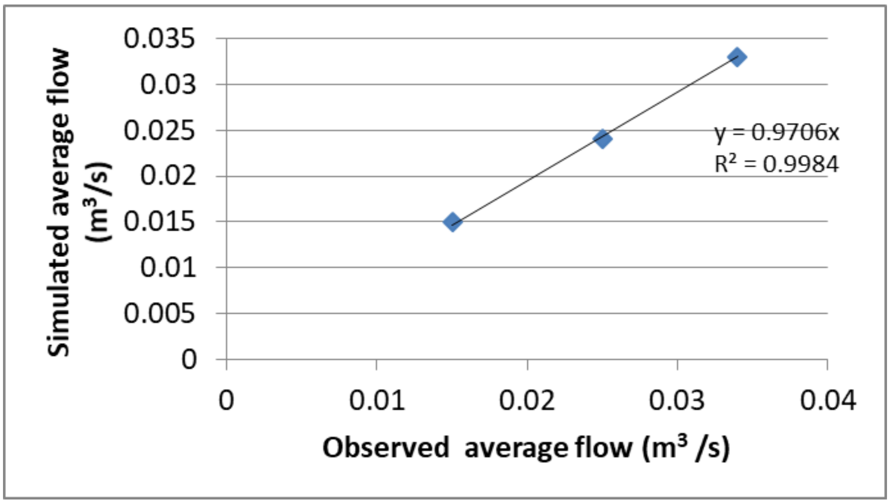


Figure 4.4: Simulated versus Observed Average Flow during Calibration

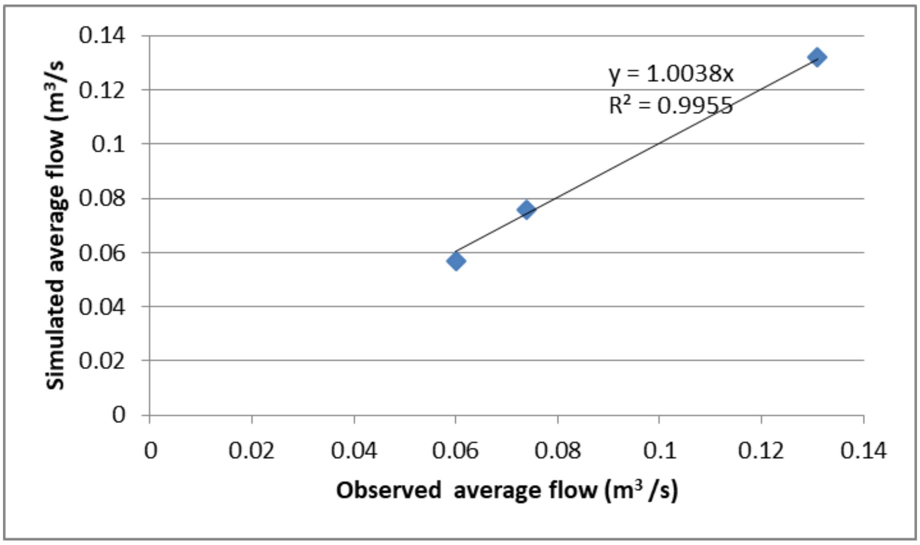
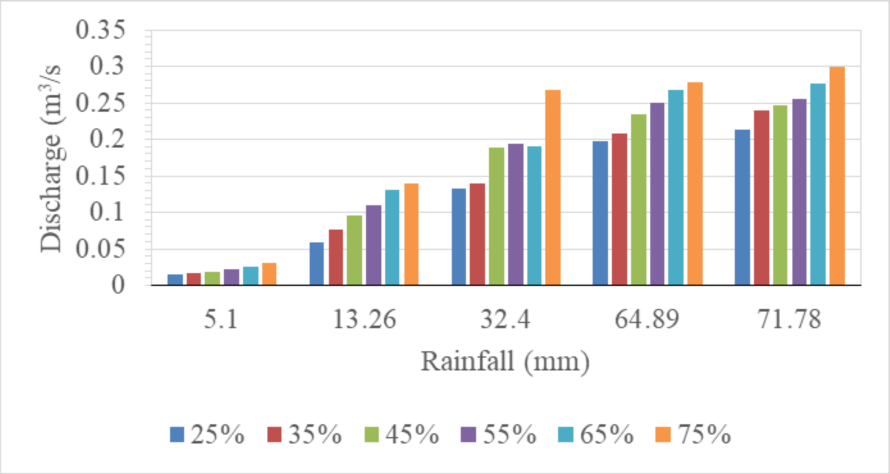


Figure 4.5: Simulated versus Observed Average Flow during Validation

4.3 Scenarios of Rainfall and Impervious Proportions on Runoff Generation

To evaluate the influence of impervious surfaces on runoff generation, five scenarios were formulated. The formulation of the five scenarios was guided by the available five rainfall events which could be used for simulation; three measured during study and two historical rainfall events. The results are presented in Graph 4.3.



Graph 4.3: Scenarios of Rainfall and Impervious Surfaces Proportions on Runoff Generation

The measured rainfall events were 5.10 mm (minimum measured daily rainfall during the study), 13.26 mm (average of measured daily rainfall during the study) and 32.40mm (maximum measured daily rainfall during the study), while 64.89 mm (Historical average daily maximum rainfall recorded between 2009 and 2019) and 71.78 mm (historical daily highest rainfall recorded between 2009 and 2019) events were historical.

During simulation, three rainfall events caused flooding in the system for the actual estimated imperviousness percentage of 25.72% in the study sub-catchment. The maximum daily measured rainfall of 32.40 mm caused 21.1% of conduits to flood while the average daily historical rainfall of 64.89 mm and the maximum daily historical rainfall of 71.78 mm caused 57.9% and 78.9% flooding of the conduits respectively. The results are presented in Table 4.7.

Table 4.7: Flooded Conduits on Actual Estimated Study Area Imperviousness

Rainfall Amount (mm)	Generated Runoff Volume (m^3)	Flooded Conduits	% Flooded Conduits
32.40	46949	C11,C14,C15,C16	4/19 (21.1%)
64.89	70204	C2,C3,C9,C10,C11,C14,C15,C16,C17,C18,C19	11/19 (57.9%)
71.78	76183	C2,C3,C4,C5,C6,C8,C9,C10,C11,C14,C15,C16,C17,C18,C19	15/19 (78.9%)

4.4 Influence of Low Impact Developments on Stormwater Runoff

Two low impact developments (infiltration trench and bio-retention ponds) were considered for modeling and simulation in this study to determine their influence on runoff generation. Three scenarios were formulated; application of infiltration trenches to treat 100% of the impervious area, application of bio retention ponds to treat 100% of the impervious area, and a combination of both treatments each treating 50% of the impervious area. Simulations were run and compared with no low impact development scenario.

The results indicated a reduction of average runoff flow by 25% when infiltration trenches were used to an extent of 100% treatment of impervious area and a reduction in total runoff volume by 19.6%. Bio retention cells used to an extent of 100% treatment of impervious area resulted in a slight reduction of average flow by 1.6% while total runoff volume was reduced by 4.4%. The combination treatment reduced total runoff volume and average flow by 10.7% and 5.9% respectively. The results are presented in Table 4.8.

Table 4.8: Average flow and total runoff for the three scenarios of LIDs treatment

Parameter	**Without LIDs**	**100% BRC**	**Combination of 50% IT and 50% BRC**	**100% IT**
Average Flow (m^3/sec)	0.256	0.252	0.241	0.192
Total Volume (m^3)	93,711	89,579	83,640	75,345

CHAPTER FIVE

DISCUSSION

5.1 Sub catchment characteristics

The DEM analyses indicated that the outfall of the study sub-catchment drains an estimated area of 696.5 ha. The sub-catchment was sub-divided into 23 sub-basins averaging 30.3 ha with the largest sub-basin being S3 with an area of 64.7 ha and the smallest being S23 covering an area of 3.9 ha.

Similar studies on large urban catchment using the SWMM model have been done before. The same methodology for estimating the study area size was applied. For instance a study in Rwanda on Evaluating drainage systems performance and infiltration enhancement techniques as flood mitigation measures in Nyabugogo Catchment covered an area of 1628 km^2 (Paterne, 2019). The effect of bio-retention cells on runoff generation was evaluated it the study. Another study earlier covering an area of 10.24 km^2 was carried out in Estonia involving modeling stormwater runoff, quality, and pollutant loads (Mahajan *et al.*, 2017). The size of the catchment in the study lies within the same range with the area of the catchment in this study which is 6.965 km^2

The average estimated imperviousness for the study area was 25.72%.The sub-catchment with the highest imperviousness was S23 with a value of 68% while the least impervious sub-catchment was S6 with a value of 1% imperviousness. The average slope for the study area was found to be 2.57%.

Measured rainfall of 32.4 mm resulted in a measured average flow of 0.131 m^3/s caused an overflow of the drain. This discharge was used as a reference during scenario analysis. Results of rainfall analysis for historical rainfall in the study area between 2009 and 2019 indicated that the year with the highest daily average amount of rainfall mm was 2018 with an average of 10.44mm while 2009 had the lowest daily recorded mean rainfall of 2.19 mm. The year 2016 recorded the lowest minimum precipitation of 0.05 mm on 03/19/2016 while the year 2012 recorded the highest maximum precipitation of 71.78mm on 5/28/2012 which was used in scenario simulation for LID.

5.2 Calibration and Validation of SWMM5 Model for Eldoret Catchment

5.2.1 Sensitivity Analysis

Sensitivity analysis was first performed to identify parameters for model calibration and validation. This is because SWMM is sensitive to different parameters in different catchments (Beling *et al.,* 2011). For Eldoret catchment, the sensitive input parameters were found to be Manning's roughness coefficient for the impervious area (N-Imperv), Manning's roughness coefficient for the pervious area (N-Perv), Depth of depression storage on the impervious area (Destore-Imperv) and Depth of depression storage on the pervious area (Destore-Perv).

Destore-Imperv and N-Imperv had negative coefficients, an indication that their decrease leads to an increase in output values. The sensitive parameters helped in the determination of values for model calibration and validation.

Several studies identified the same parameters among others as sensitive to calibration and validation. A study conducted on modeling the quality and quantity of runoff in a highly urbanized catchment using a stormwater management model, (C.Li *et al*, 2016) found that the depth of depression storage on impervious areas had the most influence on the hydrology and hydraulic component together with conduit roughness. They also found out that Destore-Imperv was the most sensitive parameter in the determination of the total flow. Mahajan *et al.* (2017) did a study in Estonia using SWMM and they identified several sensitive parameters among them impervious depression storage which regulated the initial peak flow.

5.2.2 Calibration

The calibrated values for the SWMM model in Eldoret catchment are presented in Table 4.6. The model performance during calibration was evaluated using four measures of fitness namely; Coefficient of Determination (R^2), Nash–Sutcliffe Efficiency (NSE), Integral Square Error (ISE) and Root Mean Square Error (RMSE). The attained values were R^2 of 0.99, NSE of 0.97, ISE of 3.02, and RMSE of 0.00.

For hydrologic studies on daily measurements, model performance is judged very good for values of R^2 equal/greater than 0.8 (Moriasi *et al.*, 2015). NSE of 0.5 to 1.0 and ISE 0 to 3 is judged excellent and the model could be applied for planning, preliminary design, and even final design (Shamsi & Koran, 2017). The ideal value for RMSE is 0 but a value range of 0 to 1 is also acceptable (Kornecki *et al.*, 1999).

The calibrated SWMM model for Eldoret catchment is acceptable for runoff simulation studies since the indicators show that there is a good fit between simulated and observed runoff for the three events used in calibration.

5.2.3 Validation

Model validation was done using the ideal parameters that were resulting or derived in the calibration process presented in Table 4.6. Validation was done to confirm the model’s ability to simulate events after calibration. The model efficiency to simulate for validation was also evaluated using the four measures of fitness applied in calibration which include Coefficient of Determination (R^2), Nash–Sutcliffe

Efficiency (NSE), Integral Square Error (ISE) and Root Mean Square Error (RMSE). The attained values for validation were R^2 of 0.99, NSE of 0.99, ISE of 1.41, and RMSE of 0.00.

As earlier described on the judgment of the measures of fitness applied for the calibration process, the measures of fitness during validation resulted in values that indicate the model is acceptable and can be used to carry out simulations in Eldoret sub-catchment. Kourtis *et al.,* (2017) in a study on Calibration and validation of SWMM model in two urban catchments in Athens validated the model and attained values of R^2 0.9666, RMSE 0.2166 and d 0.9855 concluding that the model was fit to carry out simulations in the two urban sub catchments. Similar results were attained by (Barco et al., 2008; Del and Padulano, 2016).

5.3 Scenarios of Rainfall and Impervious Proportions on Runoff Generation

Five scenarios of rainfall events against six scenarios of percentage imperviousness were analyzed in the present study. Results of the average flow and total runoff generated are presented in section 4.3 of this thesis research. The results indicate that increasing imperviousness over the sub-catchment has an increasing effect on the amount of average flow and total runoff generated. Analysis of a 3 – hr event of 71.78mm that resulted in system flooding during simulation, reveals that there was a 28% increase in average runoff when percentage imperviousness was varied from 25% to 75% and 26% increase in total runoff generated.

Scenario 1 (Maximum measured rainfall and incremental increase of imperviousness) resulted in average flows greater than 0.131 m^3/s meaning that overflow of the drain occurred. The average flow doubled when the level of imperviousness was increased from 25% to 75%. Scenario 2 (Average observed rainfall) showed that overflow occurred when percent imperviousness was more than 55%. There was no overflow of drain for Scenario 3 (minimum measured rainfall). Both Scenario 4 (Maximum historical rainfall) and Scenario 5 (average historical rainfall) resulted in the overflow of the drain. All this can be interpreted to mean that the drain is inadequate to carry the floods in the future when the percent imperviousness increases.

Generally, all the events analyzed indicated an increase in average runoff and total runoff ranged when the percentage imperviousness was varied from 25% to 75% in stages of 10% increments. This study indicates that impervious surfaces in urban areas are a determining factor in runoff generation and affects both flow and total runoff positively.

A study on assessing the effectiveness of imperviousness on stormwater runoff in micro-urban catchments modeled effects of imperviousness on runoff generation (Yao *et al.*, 2016a). The study results by model simulation used EPA SWMM to model the effects of imperviousness on runoff. The rainfall with a 3-year return period was used to establish the scenarios for modeling rainfall-runoff. The results showed that the impervious areas contributed a lot to total and peak runoff depth. Other studies including (Yao *et al*, 2016b; Dietz and Clausen, 2008) also concluded that impervious areas associated with urbanization results in increased runoff generation in urban areas.

5.4 Influence of Low Impact Developments on Stormwater Runoff

Two low impact developments (infiltration trench and bio-retention ponds) were considered for modeling and simulation in this study to determine their influence on runoff generation. Three scenarios were formulated; application of infiltration trenches to treat 100% of the impervious area, application of bio retention ponds to treat 100% of the impervious area, and a combination of both treatments each treating 50% of the impervious area. Simulations were run and compared with no low impact development scenario.

The results indicated a reduction of average runoff flow by 25% when infiltration trenches were used to an extent of 100% treatment of impervious area and a reduction in total runoff volume by 19.6%. Bio retention cells used to an extent of 100% treatment of impervious area resulted in a slight reduction of average flow by 1.6% while total runoff volume was reduced by 4.4%. The combination treatment reduced total runoff volume and average flow by 10.7% and 5.9% respectively.

In a related study done in Rwanda (Paterne, 2019), the effect of bio-retention ponds on mitigating floods in Nyabugogo catchment was assessed by simulating scenarios and the results showed good performance on reducing water depth; 9.5 % less compared to no application of LID. Munyaneza *et al.*, (2013) in a study on design of Hydraulic structures design for flood control found out that infiltration trenches had a roll in runoff depth reduction.

It can be deduced from this study that low impacts developments, in this case, infiltration trenches and bio-retention ponds have an effect of reducing flow and total volume in the study area. The two low impact developments can therefore be used for flood control in the study area. It can further be noted that infiltration trenches are more superior to the bio retention ponds in reducing flow and runoff in the study area.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

6.1.1 Catchment Characterization

It was found that the study area sub-catchment drains an area of 696.5 ha. The average estimated imperviousness for the study area was found to be 25.72%, while the average slope for the study area was found to be 2.57%. The highest daily rainfall in the study area recorded for a period of 11 years from 2009 to 2019 was found to be 72.78mm.

6.1.2 Calibration and validation of the SWMM model for the Study Area

SWMM model was successfully calibrated and validated for the Eldoret sub-catchment. The four measures of fitness gave satisfactory values for model application in the study area; R^2 had a value of 0.99 & 0.99, NSE 0.97 & 0.99, ISE 3.02 & 1.41 and RMSE value of 0.00 & 0.00 for calibration and validation, respectively.

6.1.3 Scenarios of rainfall and imperviousness proportions on runoff generation.

As per the estimated actual imperviousness percentage (25.72%) over the study area, three out of the five scenarios resulted in the flooding of the drain. Scenario 2 and 3 did not flood the drain. This shows that the drain is inadequate to handle future runoff as the percent imperviousness increases.

6.1.4 Influence of infiltration trenches and bio-retention cells

Infiltration trenches are the most effective low impact developments in reducing flooding in the study area. The infiltration trenches reduced runoff flow by 25% and total volume by 19.6% as compared to bio-retention ponds which reduced runoff flow and volume by 1.6% and 4.4% respectively.

6.2 Recommendations

1. Infiltration trenches installation is recommended (APPENDIX: I) to reduce and control flooding in the study area.
2. The study's scope was limited to the calibration of the model for runoff quantity simulation. Calibration of the SWMM model for water quality simulation in the study area is needed and is recommended for future research.
3. The data for model calibration and validation for runoff was limited due to lack of gauging in the catchment and resource constraints in collection of more data during the study. A recommendation is made to collect more data for the calibration and validation of the model for runoff simulation in Eldoret.

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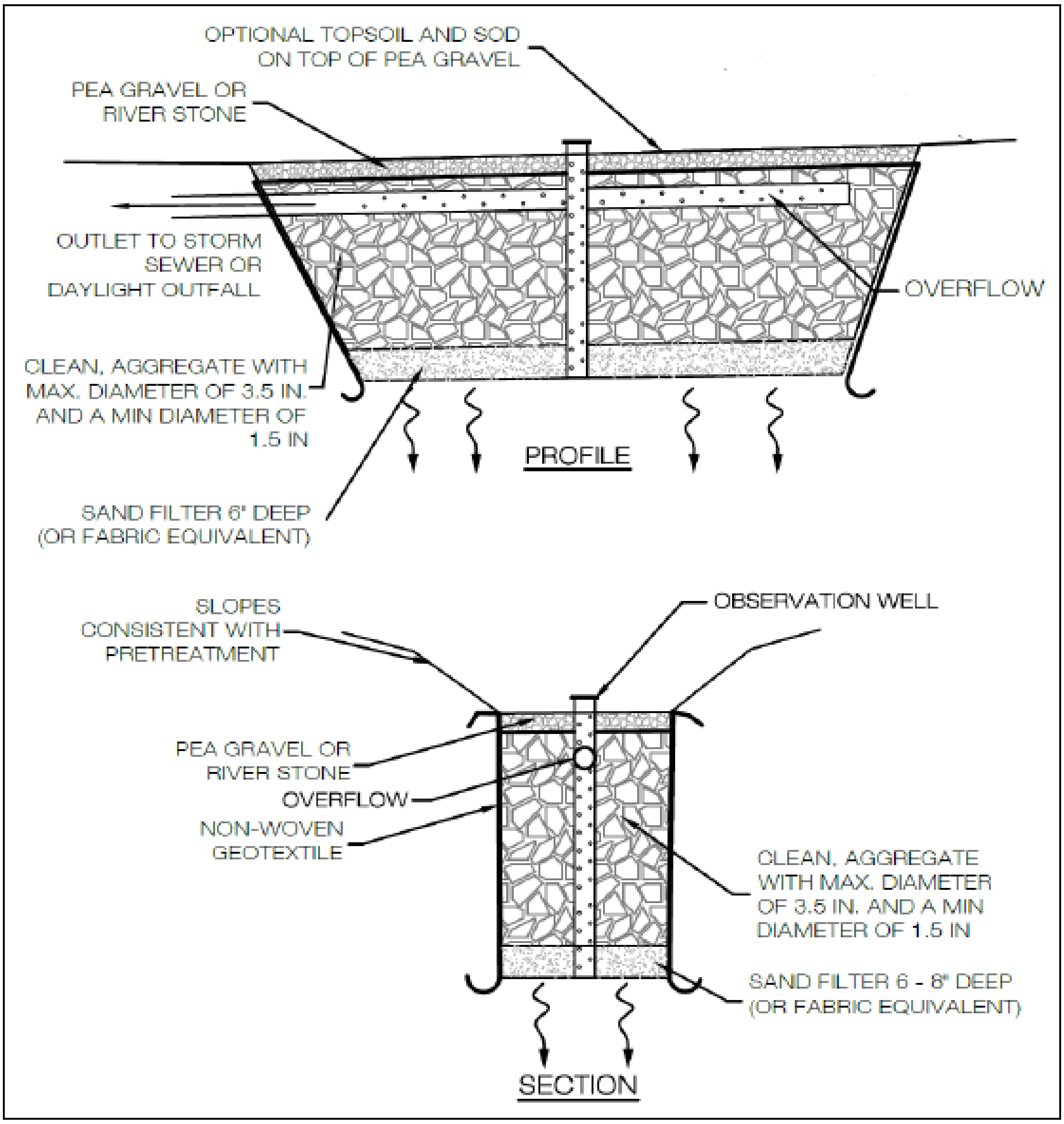
APPENDIX I

DESIGN OF INFILTRATION TRENCHES

Introduction

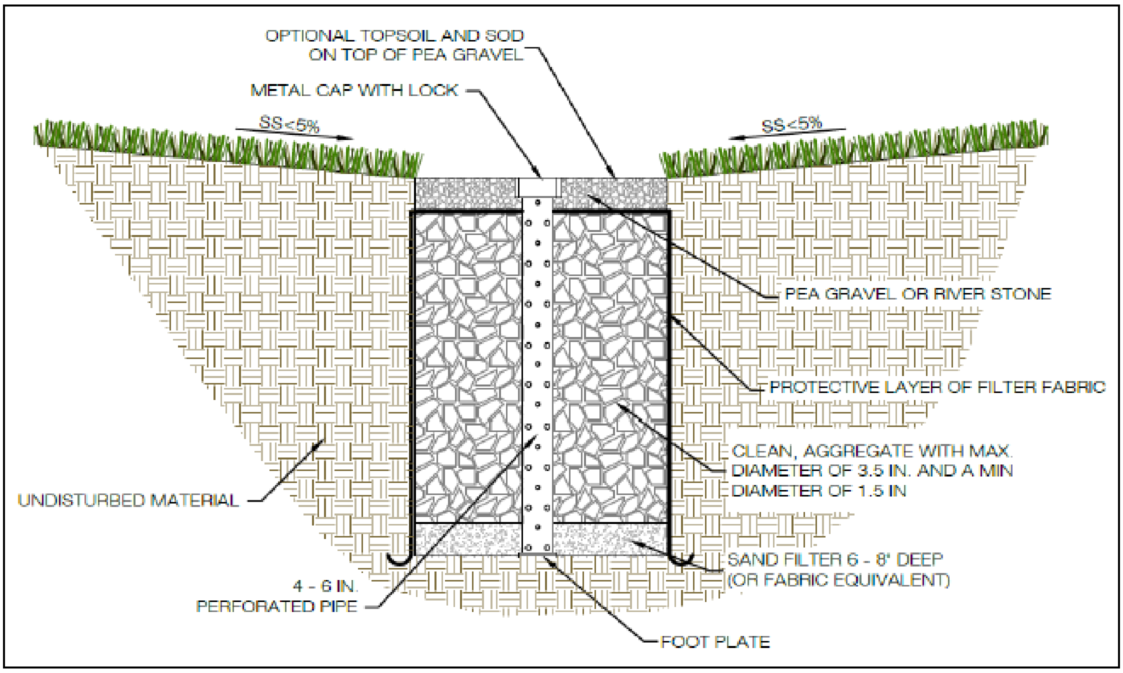
An infiltration trench is an excavation on the earth surface lined with a geotextile filter fabric and filled with coarse stone aggregate. These trenches serve as underground infiltration reservoirs. Storm water runoff directed to these trenches infiltrates into the surrounding soils from the bottom and sides of the trench (MOAWMS, 2008). Infiltration trenches are one of the most common stormwater facilities for infiltration, and are also known as soakaways (Nilsson & Stigsson, 2012). Infiltration trenches can be used both to; control stormwater runoff and reduce the stormwater pollutant load to recipients (Silva, *et al.*, 2010). They can be applied to capture runoff from a wide range of impervious areas including parking lot runoff, roof top runoff, roadway runoff, airport runoff, residential runoff etc., but are not appropriate to receive runoff from industrial facilities where runoff is likely to contain industrial pollutants (MOAWMS, 2008).

In order for infiltration trenches to be effective, they must be located in areas where the local soil is appropriate for infiltration and they must be designed accordingly (MOAWMS, 2008). A general design of an infiltration trench constitutes of a linear excavation filled with a coarse stone aggregate, such as single or macadam (Stahre, 2006). The grain size of the macadam should be between 22.4 to 90 mm (Swedish Road Administration, 2009). The excavation can also be lined with a geotextile and covered with for instance topsoil, grass or pavement (Butler & Davies, 2004). In this case, stormwater is stored in the void space between the aggregates and can infiltrate into the surrounding ground or be released into the stormwater sewer system (US EPA, 2006). There are different forms and sizes that are common for infiltration trenches (Lampe, *et al.*, 2004), because of geographically varying ground conditions. The most efficient sites are ones in which the contributing area dimensions are nearly square and the infiltration trench can be constructed along one side of the square. Appendix I 1 shows typical infiltration trench profile and sections.

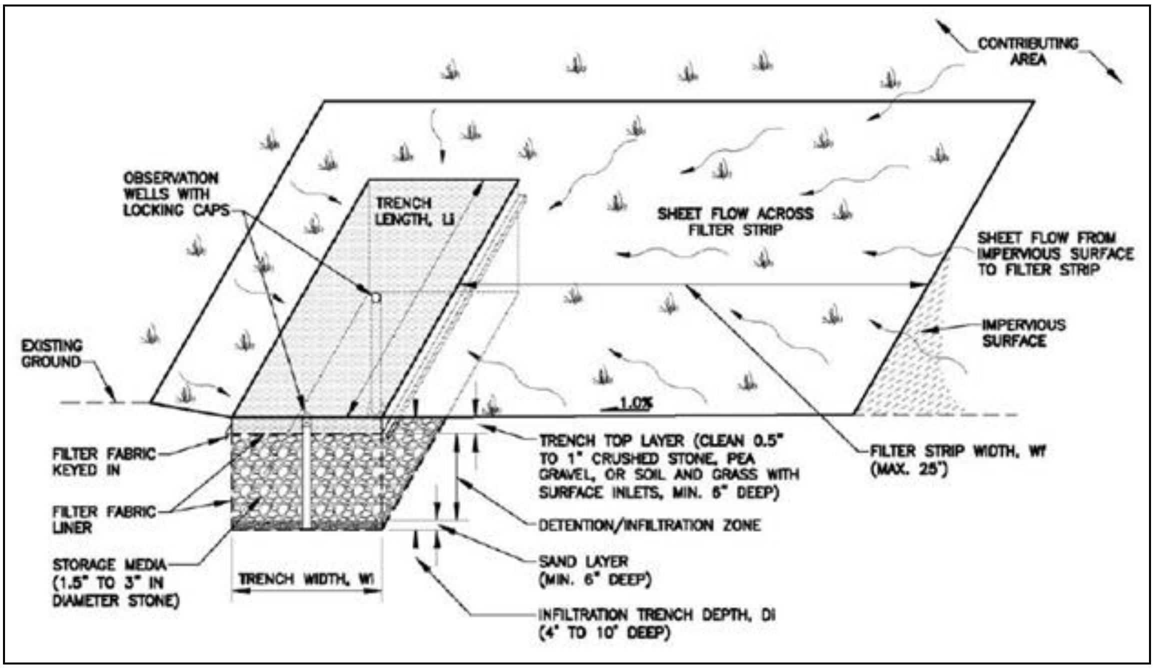


Appendix I 1: Typical Infiltration Trench profile and section (Source: VA DEQ, 2011).

Infiltration trenches can be designed to receive runoff from sites with length to width ratios as low as 3:1 with moderate increases in the percentage of the relative area required for the trench. During the site evaluation process, it can be assumed that the area required for the infiltration trench and filter strip(s) is 35% of the total contributing area (MOAWMS, 2008). Appendix I 2 and I 3 show observation well section and infiltration trench installation plan respectively.



Appendix I 2: Observation well section (Source: VA DEQ, 2011)



Appendix I 3: Conceptual Infiltration Trench layout (Source: MOAWMS, 2008)

Factors considered in siting and design of Infiltration Trenches

1. Soil textures; the soil should have a minimum infiltration rate of 12.5 mm/ hour. Higher infiltration rates are desirable (Maryland Department of Natural Resources, 1984). These soils include loam, sandy loam, loamy sand, and sand.
2. Maximum allowable drain time; it is required that the infiltration must fully drain the design runoff volume within 72 hours (NJDEP, 2004).
3. Surface ponding time; can be specified as the maximum ponding depth divided by the infiltration rate (Guo, 2001).
4. Bottom slope; the infiltration basin bottom must be as level as possible to uniformly distribute runoff for infiltration although a slope of up to 1% can be allowed (VA DEQ, 2011).

5. Design permeability rate; the rate can be maintained over time by adding a 150 mm sand on the bottom of an infiltration basin (NJDEP 2004).
6. Distance above the water table; the minimum distance is 0.6 m measured from the bottom of the sand layer ((NJDEP 2004).

Sizing Infiltration Trenches

The design of infiltration trenches is based on the balance of inflow, outflow and detention water volumes; this balance assumes the differential form as expressed in equation I 1 (Campisano *et al.*, 2011).

$$\frac{dW_t}{dt} = Q_{in} - Q_{out} \qquad \text{(I 1)}$$

Where; W_t is the trench detention volume, Q_{in} (m^3/s) is the trench inflow rate; Q_{out} (m^3/s) is the trench outflow rate given by $Q_{out} = Q_{inf} + Q_{overflow}$, where Q_{inf} (m^3/s) is the infiltration flow rate and $Q_{overflow}$ (m^3/s) is the overflow from the trench.

The inflow rate Q_{in} (m^3/s) depends on the rain event and on the watershed characteristics upstream from the trench. The infiltration flow rate Q_{inf} (m^3/s) depends on the infiltration processes in the surrounding soil and can be evaluated by the following relationship (Equation I 2):

$$Q_{inf} = kA_{inf} \quad \text{(I 2)}$$

Where A_{inf} (m^2) and k (m/s) are the infiltration area and infiltration capacity, respectively. In particular, A_{inf} is the area of the trench structure where infiltration is assumed to occur. The area can be computed by equation I 3 (Stafford *et al.*, 2015):

$$A_{inf} = (L \times W) + 2d(L + W) \quad \text{(I 3)}$$

Where L is the basin length in meters, W is the basin width in meters, and d is the depth of the basin in meters.

The depth of the infiltration trench in millimeters can be computed by equation I 4 (NJDEP, 2004) as follows:

$$d = f \times T_P \quad \text{(I 4)}$$

Where; f is the final infiltration rate of the basin area in millimeters per hour, while T_p is the maximum allowable ponding time in hours; normally 72 hours.

APPENDIX II

Appendix II 1: Recorded Rainfall and Discharge during the Study

Year	Date	Rainfall recorded (mm)	Average Discharge at Catchment Exit(m^3 /s)
2019	23 April, 2019	5.1	0.015
2019	27 April, 2019	7.00	0.025
2019	4^{th} July 2019	8.00	0.034
2019	11^{th} July, 2019	12.10	0.060
2019	12^{th} July, 2019	15.10	0.074
2019	9^{th} August, 2019	32.40	0.131

Appendix II 2: Rainfall trend: 2009 to 2019

Year	Year Round Average (mm)	Minimum (mm)	Maximum (mm)
2009	2.19	0.68 (9/19/2009)	56.78 (4/23/2009
2010	8.45	0.21 (10/29/2010)	66.78 (4/16/2010)
2011	9.23	0.08 (1/09/2011)	67.71 (5/28/2011)
2012	7.81	0.06 (1/10/2012)	71.78 (5/28/2012)
2013	10.4	0.01 (02/29/2013)	61.41 (04/02/2013)
2014	7.45	0.68 (01/1/2014)	59.61 (3/30/2014)
2015	9.23	0.07 (01/02/2015)	70.01 (6/20/2015)
2016	8.91	0.05 (03/19/2016)	65.28 (4/01/2016)

2017	7.16	0.08 (03/19/2017)	56.78 (5/13/2017)
2018	10.44	0.68 (04/19/2018)	67.91 (4/07/2018)
2019	9.34	0.68 (04/19/2019)	69.78 (06/17/2019)

Appendix II 3: Scenarios of Rainfall and Impervious Surfaces Proportions on Runoff Generation

Scenario	Rainfall (mm)	Parameter	Imperviousness Percentage						Remarks
			25%	**35%**	**45%**	**55%**	**65%**	**75%**	
Scenario 1	32.40	Average Flow (m^3/s)	0.132	0.139	0.188	0.194	0.191	0.267	Maximum measured rainfall
		Total runoff volume (m^3)	46949	54239	61158	67815	74341	103872	
Scenario 2	13.26	Average Flow (m^3/s)	0.059	0.077	0.095	0.110	0.130	0.140	Average measured rainfall
		Total runoff volume (m^3)	20789	27901	33476	38760	44049	49291	
Scenario 3	5.10	Average Flow (m^3/s)	0.015	0.017	0.018	0.022	0.026	0.030	Minimum measured rainfall
		Total runoff volume (m^3)	5168	7080	8990	10890	12802	14703	

Scenario 4	71.78	Average Flow (m^3/s)	0.214	0.240	0.247	0.256	0.276	0.299	Maximum historical rainfall
		Total runoff volume (m^3)	76183	82530	88360	93711	98854	103872	
Scenario 5	64.89	Average Flow (m^3/s)	0.197	0.208	0.234	0.251	0.267	0.279	Average historical rainfall
		Total runoff volume (m^3)	70204	77117	83581	89626	95469	101085	

APPENDIX III: Similarity Index/Anti-Plagiarism Report

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