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Storm Water Drainage Systems' Effectiveness and Adequacy in Managing Storm Water Discharge in Kisii Municipality, Kenya

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Abstract

Urbanization and increased developments have put pressure on important infrastructure like storm water drainage networks, often resulting to flash floods and blockage of drainage structures. This study assessed the effectiveness and adequacy of storm water drainage systems (channels) in Kisii municipality, in collecting and discharging storm water. The study areas for drainage networks were selected purposively based on the drainages type (concrete, earth and grass lined). Discharge was calculated based on the amount of rainfall, duration of rain, land use and slope of the study area. Land use maps and drainage network were generated in Personal Computer Storm Water Management Model (PCSWMM) using satellite maps and digital elevation models respectively. The effectiveness was established by routing runoff water in the PCSWMM. Surcharged culverts and joints indicated inefficient storm water drainage systems, resulting to ponding and flooding. Results from this study indicated that there were instabilities in conduits and surcharge in nodes. Surcharging of nodes was experienced for up to 22 hours at Daraja Mbili while ponding in Mwembe lasted for up to 22 hours. The level of surcharge and flooding on Rivers was experienced within 15 minutes of a rainfall in Nyanchwa sub catchment.

Keywords: Flash floods; Storm Water Management; Storm Water Management Model.

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1. Introduction

Storm water is defined as water that runs on land and hard surfaces such as roads, pavements, roof tops, car parks, driveways and paths, generated from a rainfall event through complex processes of hydrology [1]. It is the direct response to rainfall. Under normal circumstances it is the runoff from rainfall that flows into a ditch, stream, or storm sewer with no significant base-flow component. The United States of America has a long history of catastrophic flooding with the average annual cost of floods estimated at about $2 billion. Storm water due to urban development has significantly altered urban hydrology [2]. Cities have paved over natural green spaces to make way for streets, homes, and commercial developments. When it rains, urban storm water does not percolate into the land and recharge groundwater basins [3,4,5]. Rather, it rushes and gushes over asphalt and concrete into complex conveyance and collection systems, eventually dumping into rivers and streams all at once and altering the flow regimes of the waterways [6]. In Africa the cases of urban floods have become a menace with urban poor bearing in the highest cost due to floods [7,8]. Large-scale urbanization and population increases have led to large numbers of people, especially the poor, settling and living in floodplains in and around urban areas. In South Africa, for instance, Soweto-on-Sea near Port Elizabeth and Alexandra in Johannesburg illustrate this point [9,10]. Kenyan urban areas, including Kisii town, are continuously developing their infrastructures such as roads and pavements that result into large areas of impervious surfaces, which accumulate storm water and increase its discharge into drainage systems during rainfall events. Kisii municipality is expanding rapidly and it is expected that storm water drainage system will expand to cope with the increase population and urbanization [11]. Whereas emergency flood response can be mobilized when such events arise, appropriate management policies to address the impacts of adverse storm water events especially in Kisii town need to be established to reduce incidences of vehicles and other moveable properties being destroyed and swept downstream into the rivers. The urban storm channels need to be studied and assessed for their conformity to the current and future rain regimes in the urban setup.

2. Materials and methods

2.1. Study area

This research was conducted in Kisii Municipality, which is the major urban centre in Kisii County. It is approximately 29km^2 wide and located between latitudes 0.665933 S to 0.666982 S and longitudes 34.76283 E to 34.7767 E. Its terrain is hilly, with elevations ranging from 1596 m in areas around Daraja Mbili, which is the lowest point, to about 1841 m ASL in the areas around Nyanguru satellite, with an overall slope towards the west. Its slope ranges from approximately 2% at areas around Daraja Mbili to 9% in areas around Nyanguru. It lies in the southern end of the western Kenya highlands at an altitude of about 1660 m above sea level. The area has a bi-modal rainy pattern with long and short rainy seasons (March to May and October to November respectively). It receives an average rainfall of over 1700 mm per annum distributed almost throughout the year. Temperatures in the area range from 10°C to 30°C with relative humidity of 88%. The area is densely populated with a population of 112,000 people and a density of 2862 people/km2 [12]. There are two major rivers on the North and southern end, of the municipality running on East-west alignment. The rivers are Nyanchwa and Nyakomisaro. The tributaries to the main rivers are Jogoo, Botori, and Nyaura. Nyanchwa and Nyakomisaro rivers later join at Bonchari sub county in in Kisii County, to form river Riana, which later traverses Migori and

Homabay Counties and empty into Lake Victoria. The municipality is also endowed with numerous springs whose water is normally used for humans and animals' consumption.

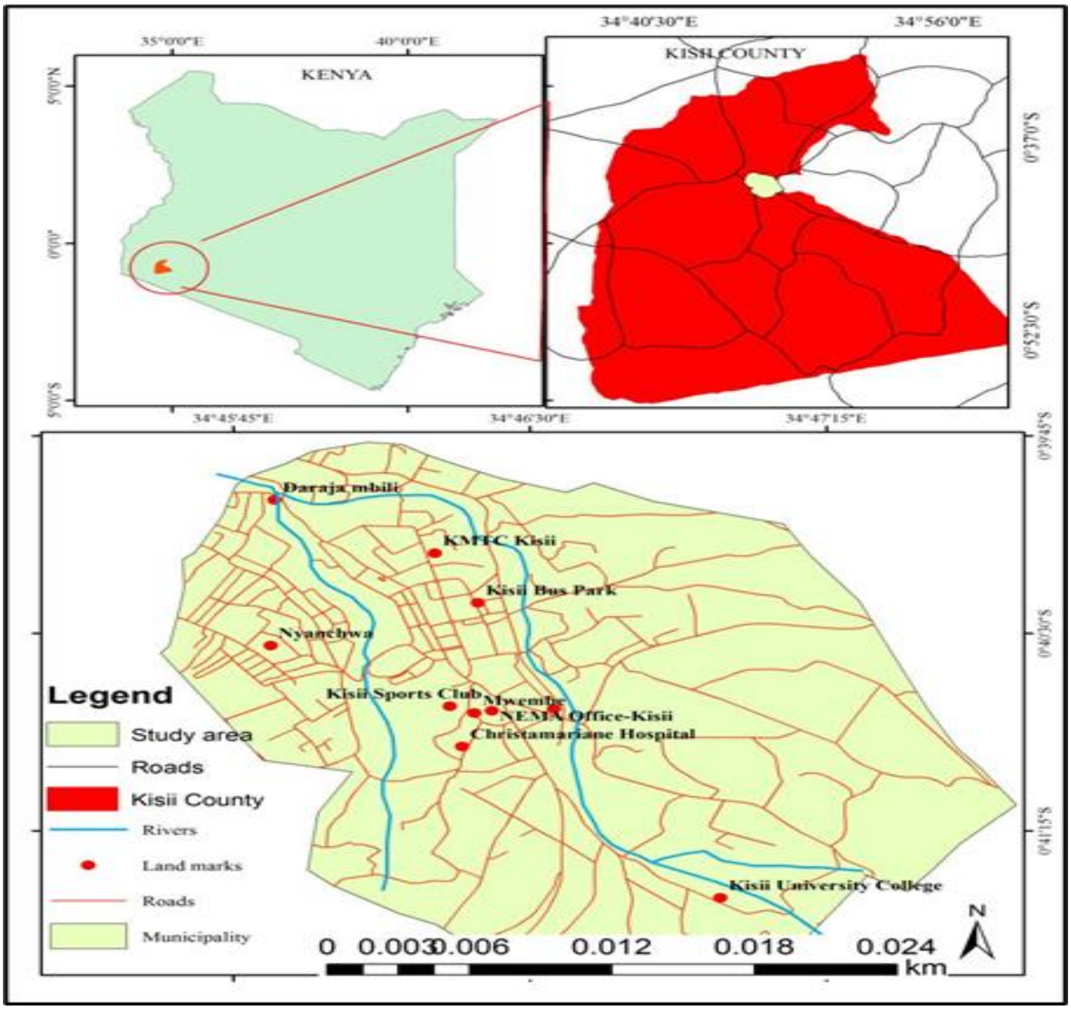

Figure 1: Study area

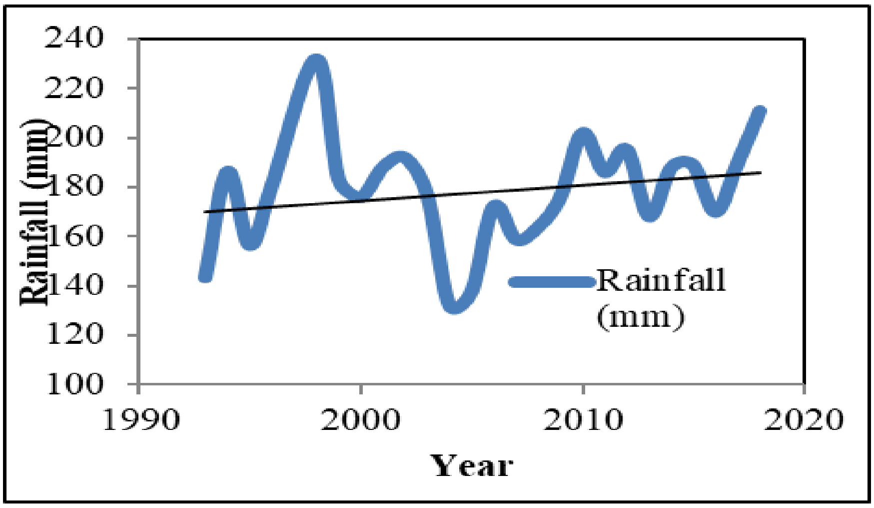

Figure 2: Rainfall pattern for Kisii Municipality

The Municipality receives an annual rainfall of 180-230mm/pa making it one of the wettest counties and towns in Kenya. Rainfall trend from 1993-2019 was plotted and it indicated a steady increase in rainfall for the past 26 years with peak rainfall in 1998-2000 probably because of EL-Niño rains. The lowest rain season was reported in the year 2005-2007.

2.2. Research design

Descriptive research design was used to obtain a picture of county plans and management of storm water drainage systems in the Municipality. A widely applied storm water model was used to assess the effects of storm water on the environment in the study area. The study focused on existing plans, county officials' statements, the public opinion on storm water drains in the municipality.

2.3. Identification of storm water drainage designs

Storm water drainage designs were identified by way of observation. They were mapped in order to establish their percent coverage, adequacy and effectiveness in managing storm water in Kisii municipality. The storm water drainage systems were assessed to establish their design and network. The various aspects of drainage network were assessed using a collection of methods as indicated in subsequent paragraphs.

Table 1: Sampled storm water drains per lining material

Lining	Area (m^2)
Concrete	93.57
Grass	99.30
Earth	109
Total	**301**

The designs were based on the Kenya's ministry of roads and infrastructure's construction and engineering manuals, while that of network were based on ground data collection using a GPS gadget. Two types of drainages were considered which were, natural drainages and artificial drainages. They were mapped using Shuttle Radar Topography Mission (SRTM) images from elevation data, to distinguish the natural from the artificial drainages. Further a GPS was used to map the artificial and enhanced natural drainages within the municipality. The GPS data collected was on: drainage design, dimensions, flow direction and adjoining drain. The images created sub-catchments based on the drainage's locality. The drainages were then classified into three categories, which were, concrete, earth and grass lined walls.

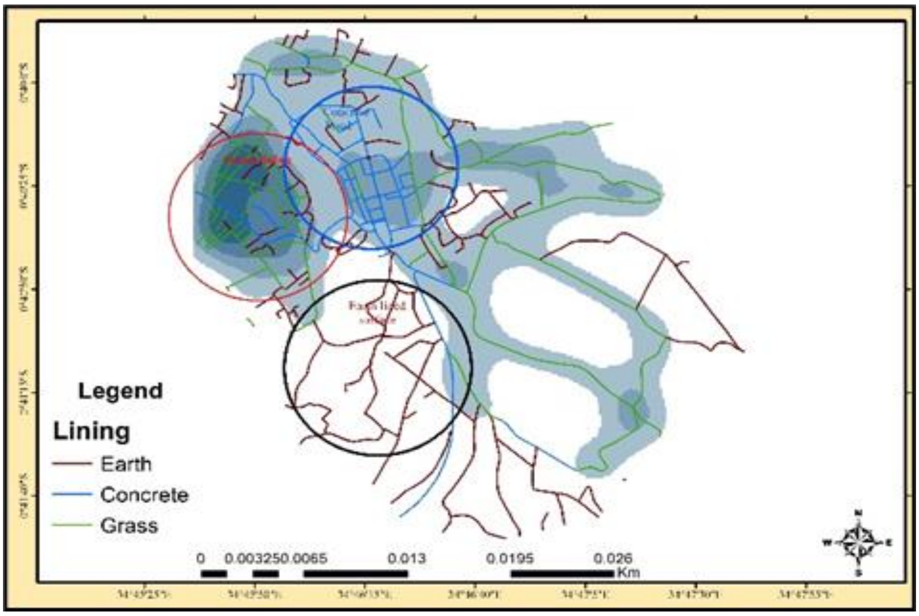

Figure 3: Lining material for storm water drainage structure

2.4. Data Analysis

Effectiveness of existing storm water drainage systems in conveying storm water during peak and off-peak rainfall seasons was assessed based on the design and network of the drains, whereas the adequacy was based on the precipitation levels and cycle, considering other factors like human waste, land use and siltation of the water ways. Data were analyzed using PCSWMM model. Spatial maps of the physical plans and the storm water drainage designs were overlaid using ArcGIS software in order to establish their relationship. A time series of water discharges for adjacent water streams in Nyanchwa and Nyakomisaro were generated to access the reliability and ability of the storm drains to hold water from adjacent side drains using PCWMM. The surface areas of the paved surfaces including roof tops were calculated using high-resolution satellite images, which were obtained from, sentinel (10m by 10m), which was obtained in February 2021. The images were classified to indicate buildup areas. Their surface area was calculated and coupled with average rainfall data in order to determine the surface runoff volume for each sub catchment.

3. Results

3.1. Existing storm water drainage systems

The respondents in the study locations indicated that they had storm drains available within their estates with 14% indicating no drainages at all. The distribution of the drainages per estates confirmed that CBD had drainages connection with 100% of the respondents agreeing, the least drained area was Mwembe 31.6% indicating they have no existing storm drains. The Mwembe area is basically covered by earth or grass drainages and it experienced ponding issues.

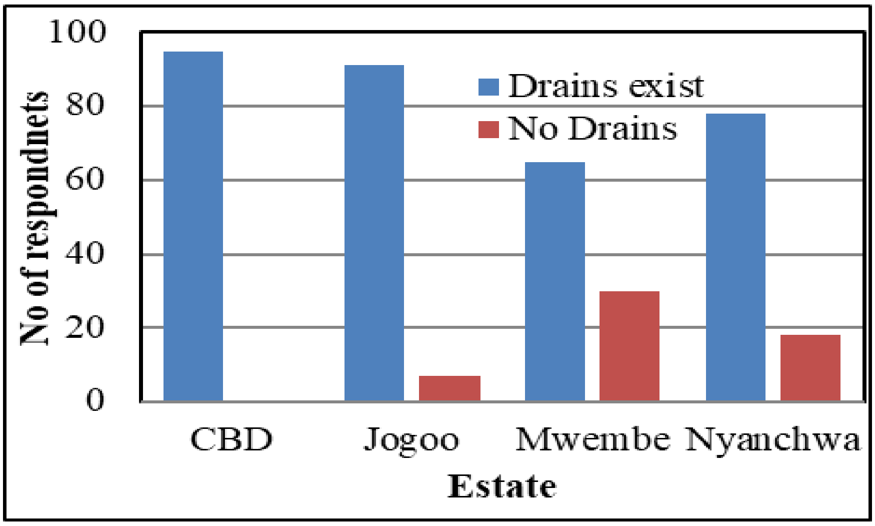

Figure 4: Interviewee responses on existing storm water drainage channels

The design of the drainage systems was categorized into three, the material or surface lining of the systems which were either Earth, concrete and grass lined. The design also took into account the shape of the drainages and it was established that Kisii town had four types; box shaped, trapezoid, semi-circular and open water drainages systems. The storm drains linings consisted of 50% being covered by earth and 23% concrete majorly at the CBD and highways. There were 3% of grass lined storm channels in Kisii Municipality with most of the storm drains located in the Estates of Nyanchwa and Mwembe.

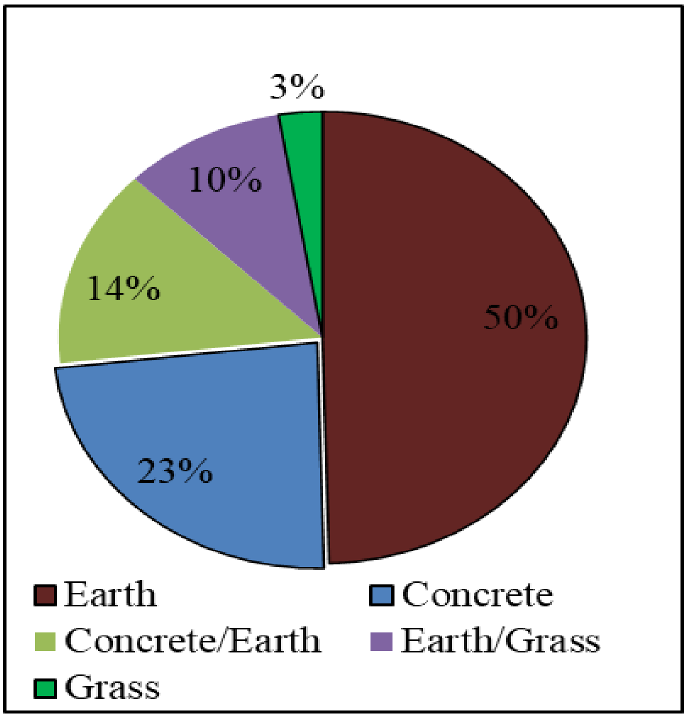

Figure 5: Storm water drainage lining

3.2. Flow rate of rivers within the Municipality

A hydrograph for Kisii Municipality was created by using rainfall data of January 2019 to June 30th 2020 for Nyanchwa and 1st January 2020 to 31st December 2020 for River Nyakomisaro. The average flow was created for each river on monthly basis.

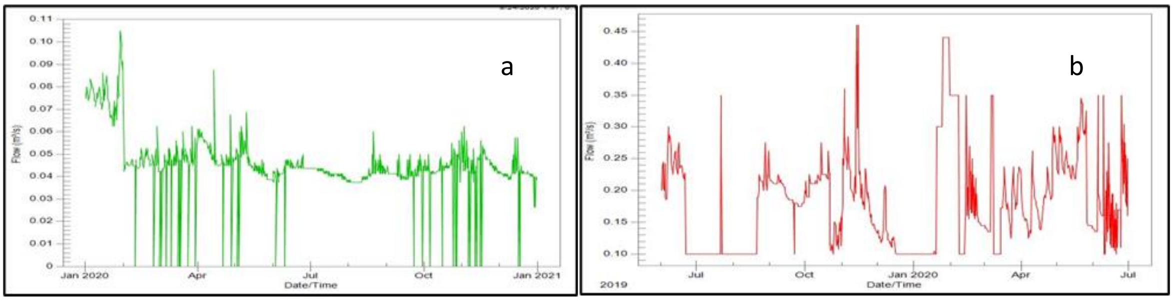

Figure 6: Hydrographs of Nyanchwa (a) and Nyakomisaro (b) rivers

The overflow rate at Nyanchwa River was at 0.89m^3/s and that was the instance when floods were recorded. The highest recorded level was at 1.63 m^3 at the onset of the set rain in 2020. There were 266 points of exceedances with a total of 961 hrs. in a cumulative duration of 402 days. The flow rate of Nyanchwa flooded out 695,400 m^3 of water 1,917,000 m^3 of water pass through the channel; the water loss that overflows represents 32.6% of the total river discharge. The river has sharp surcharge levels and water speeds attain optimum speed on a short period of time because of the narrow river channel along the stream.

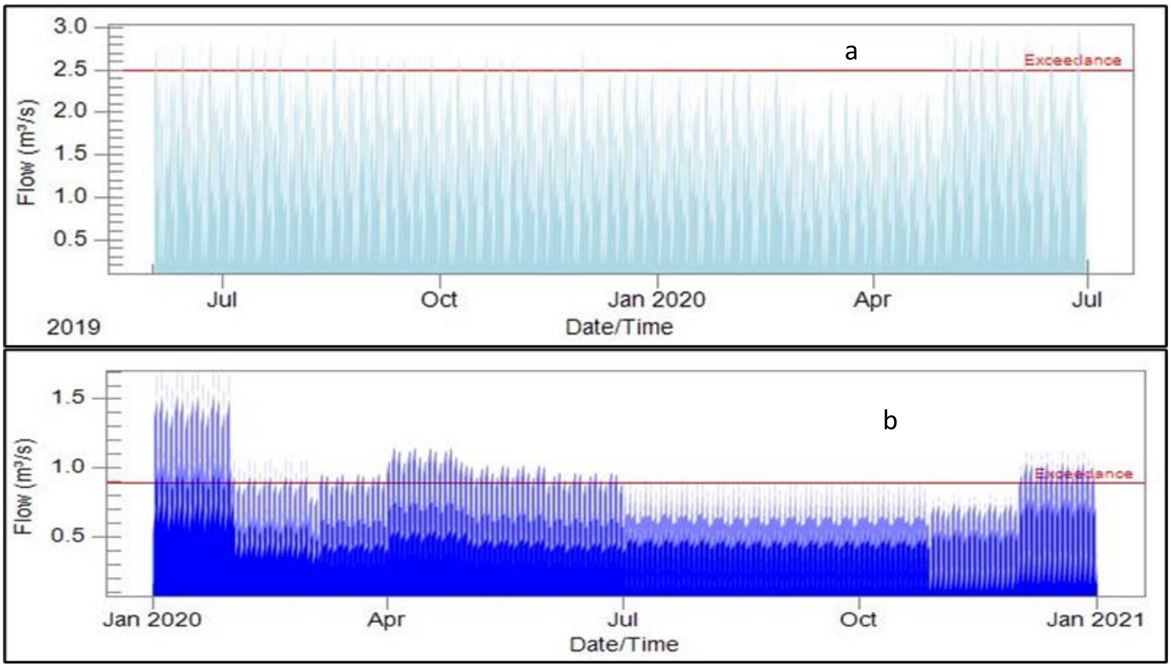

Figure 7: Exceedance levels of Nyanchwa (a) and Nyakomisaro (b) rivers

River Nyakomisaro flows along the Northern block of Kisii CBD and it has a wider river channel with a higher water holding Capacity. The river flows at considerably higher speeds than Nyanchwa at peak discharge speed of 2.91 m^3/s. The river discharged 47,520,000 m^3 of water in duration of 433 days with flood threshold levels at

2.52 m^3/s the river had 414 instances of flooding and 121,400m^3 of water overflowed, that is 0.25% of water loss.

3.3. Storm water drains effectiveness

The study used PCSWMM and (Environmental protection Agency (EPA) Soil Water Management Model (SWMM). The Total precipitated are in hectare were 3518.47 and a depth of 1133 mm of rainfall experienced. The infiltration and surface loss were 21.79 mm and 3375. 73 mm. The Final storage as a result of infiltration and surface recharge was 128.4 h/m. The municipality catchment areas were split into 50 sub catchments considering topography, water channels and manholes. There were 56 Links/water ways (storm drains and rivers) and 63 nodes/junctions. The residence of Kisii municipality responded on the effectiveness of the current storm drains and it was observed that 22.3% noted that the drains were in a good shape and functionality with 54.5% noting a fair drainage on medium precipitation and bad during high storm periods.

Table 2: Storm water drainage functionality rating by respondents during rainy season

Rating	Frequency	Percent
Good	87	22.3
Fair	213	54.5
Bad	91	23.2
Total	391	100.0

3.4. Sub catchments Runoff

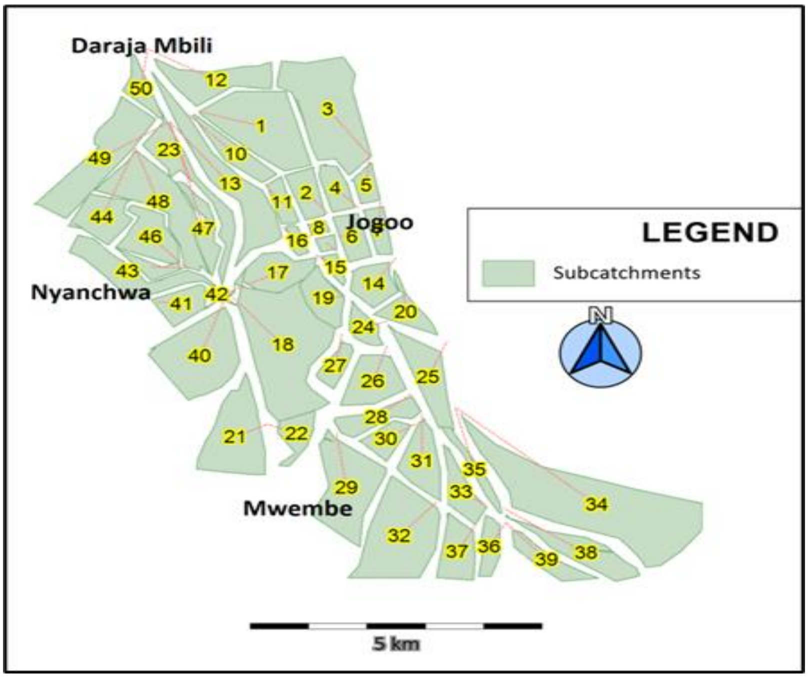

Figure 8: Sub catchments in Kisii Municipality

There was a total of 50 sub catchments in the study area. The sub catchments had varied porosity indices based on subsoil cover material. The Surface runoff rates were higher than infiltration rates because of slope that encourages runoff rather than infiltration. The Runoff rates per catchment were computed in CMS and it ranged from 10cms->40cms. This was based on the porosity index. The distribution of the sub catchments per study location were based on existing man-made drainage channels and CBD had the highest sub catchments at 18, Nyanchwa 15, Mwembe 12 and Jogoo 5.

The total precipitation per catchment were similar since they used the same rain gauges and the rainfall was 1132mm.The catchments were considered for total infiltration, impervious runoff (mm), pervious runoff and, Total runoff and peak runoff.

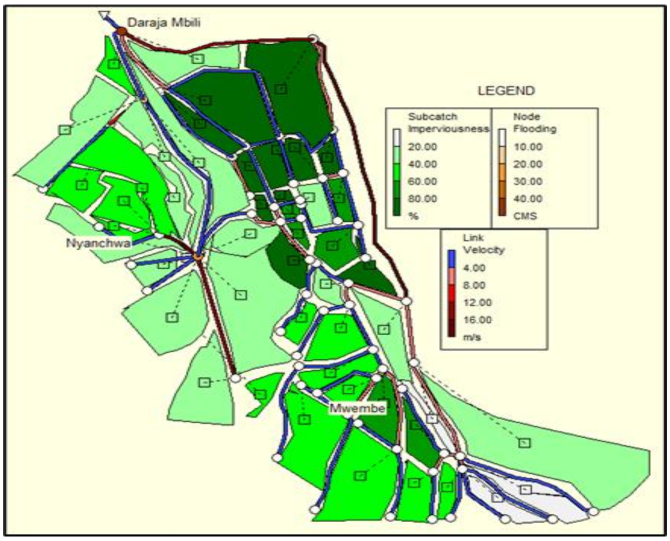

Figure 9: Catchment imperviousness in Kisii Municipality

3.5. Storm junctions

There was a total of 63 nodes/junctions within the study area linking major water channels. The junctions were grouped into natural and man-made and they majorly comprised of culverts rivers or confluences. The factors assessed for the joints were; total inflows, hours surcharges, maximum flood rate and total flood volume. The flooding on Junctions and culverts was determined to ascertain the effectiveness of the nodes in handling maximum precipitation. There were 34 junctions which experienced flooding in the study area. Flooding refers to all water that overflows a node, whether it ponds or not. The study recorded flooding in junctions which could overflow for up to 23 hours. The nodes in green and deep green indicate flooded points in the system ways, there were more floods on River Nyanchwa than in the CBD and R. Nyakomisaro. The flood water at Daraja Mbili on a 24-hour period is estimated at 7453×10^6 litres. Flooded nodes in Daraja and upstream along River Nyanchwa are attributed to the narrow nodes receiving water from upstream channels.

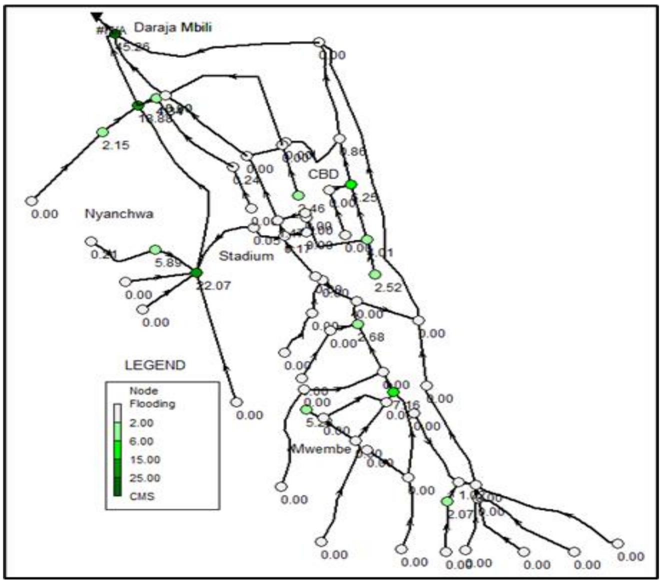

Figure 10: Flooding at junctions

3.6. Channel/Link flows

A total of 56 (links/channels/storm ways) were established on Kisii municipality. The channels were natural (Rivers, streams) and artificial (urban storm channels). The channels were either lined with grass, concrete or earth and took shape of Open rectangle, trapezoidal, semicircular and half cut. The Channels are water ways designed to ferry water down slope by effect of gravity to reduce ponding/flooding. In checking on storm channels flow stability and effectiveness to handle storm water on maximum precipitation, the study conducted a flow instability indexes of the conduits/drains. There were five channels with significant instability at CBD and they had an instability index of 2 and 1. The flow instability was majorly caused by adjacent junctions discharging to a smaller width channel causing overflow and instability.

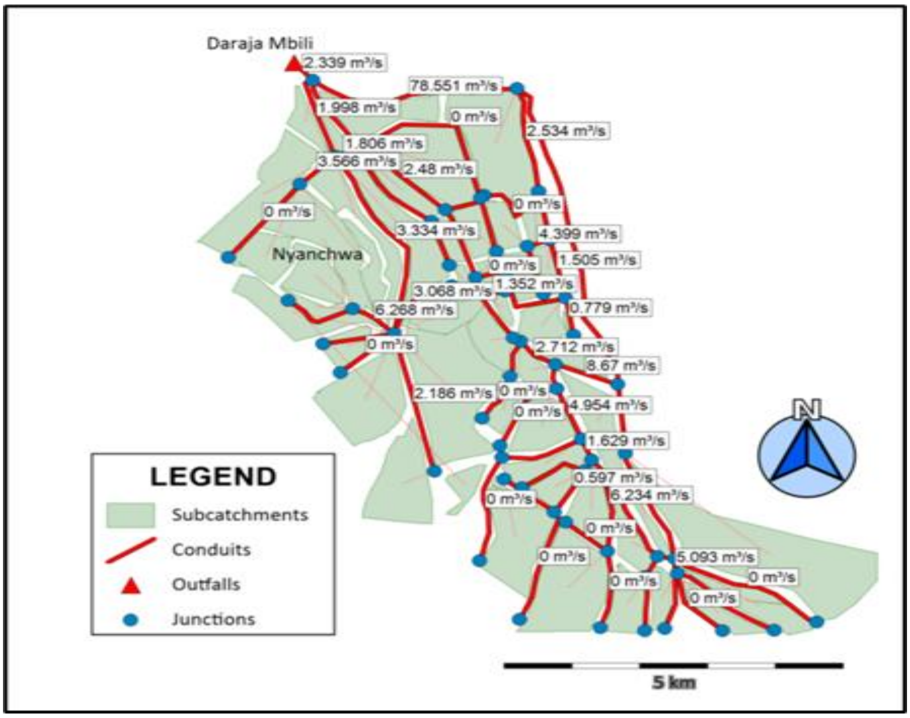

Figure 11: Links maximum flow

4. Discussion

4.1. Storm water drainage systems

Increased rainfall in Kisii town and increased surface runoff. The effectiveness of the channels was assessed and it was found that most of the channels were either clogged with dirt (market, food waste), soils, debris from farms and small rocks/pebbles. The effectiveness of the drainages was based on its width, amount of rainfall it can hold at peak hours and the debris lodged on its inflow and outflow points. These points were majorly junctions linking minor to major drains.

Figure 12: Debris filled and blocked channels (CBD, Mwembe)

4.2. Storm drains effectiveness

Sub catchment total infiltration rates of >10mm were recorded by 5 sub catchments. The sub catchments with highest infiltration rates were in the southeastern part of the study area and they were composed of forests and wetlands. The infiltration rates in the southern parts of the study area indicated that there was less surface runoff and less discharge to adjoining junctions. This has been evident by studies conducted in Dire Dawa City Ethiopia where the amount of generated surface runoff is affected by forest land cover, bare land cover, and settlement cover [13]. The highest infiltration rate was recorded at catchment 38 (Mwembe/Kereri) the infiltration rate was 11.61mm. The CBD recorded areas with the lowest infiltration rates with sub catchment 4 recording a 0.25mm of infiltration and 1104.66mm of impervious runoff. The total runoff of sub catchment 34 was 3279 L/day which had the highest flow rate of 58cms in all the catchments. Catchment located at the Eastern is on a slope of 7% and a 26% of impervious surface, the high flow rate is attributed to its size and absence of cover crops. Storm nodes/Junctions and culverts are major source of surcharging. Simulation for 24 Hours period was conducted on nodes and the maximum rate of 115.073CMS of water was recorded on Daraja Mbili (Catchment 67) which was the highest because it is a collection point from River Nyakomisaro and Nyanchwa and (Nyanchwa 52) at 114CMS, the flooding on a 24hr 280mm of rain would be sustained for 22 hours before the water recedes to its base level. The junctions/nodes in Kisii municipality for channeling storm waters are not performing optimally because of size, design and water volumes upstream. The channels need to be cleaned and regularly maintained. The channels at Stadium linking Nyanchwa and Nyanchwa experience a higher surge than any upstream culvert because of siltation from nearby farms. In the CBD the nodes have a low speed at <5CMS indicating a clog free node and efficient in transmitting storm waters from one channel to another. The water channels were simulated for effectiveness and ability to hold water at peak durations. The links were tested on volume, velocity and capacity to transmit water from one node to the next node. The water flow in speed varied by links the maximum flow speed was recorded at 78.55CMS at conduit 99 (Daraja Moja). River Nyakomisaro had the highest speed of water along its conduits with all links having speeds of >10m/s. The water velocities at these conduits are attributed to stream channel orientation, water volume and gradient. Storm drainage systems in Kisii municipality from the field findings indicate a constrained waterway system with 54% of nodes experiencing flooding and 5 waterways having high flow instability index. It is also noted that Southern part of the study area experiences higher flooding with higher number of nodes getting flooded. There is maximum flooding at Daraja Mbili, which is caused by constrained nodes and restrained storm channels. The effectiveness of the storm channels in the CBD is at 60% for nodes and 50% for conduits.

5. Conclusion

Storm water management in urban area is a dynamic management activity that changes with physical and weather conditions. In urban areas with good planned drainage systems, flooding and destruction of property is limited and urban life becomes habitable. Storm drains causes major challenge on urban centres due to their ineffectiveness and connection. Poorly planned storm drains have been linked to flooding and high compromise on domestic water quality. The nature of culverts/joints and storm ways/links were tested for effectiveness and adequacy in managing storm water discharge of Kisii municipality. The amount of rainfall received in Kisii had a peak of 280mm in the month of April 2020 and this was used to create a time series and model simulation events to determine the holding capacities of links, conduits rivers, springs drainage systems and joints. A survey around the town indicated a high debris causing clogging of culverts/joints/conduits. The effectiveness was established by routing runoff waters using Kinwave method. Surcharging of culverts and joints indicated inefficient drains resulting to ponding and eminent flooding in the adjacent land uses. Surcharging of nodes was experienced for up to 22hrs at Daraja Mbili and ponding in Mwembe was up to 22hrs. River Nyanchwa experienced a high flooding surge on peak rain hours owing to its narrow channels and confluence of streams and storm drains from the CBD. Flow instability index was conducted to assess on stability of storm links. The instability index indicates a surcharge of links based on offset of outlet joint caused by inconsistency in rim levels. There were five links which had flow instability and it caused a surcharge 15 minutes after downpours. Unstable links reroute waters by spilling to nearby facilities increasing runoff and pollutants. The flow of water at Daraja Mbili on peak rainy season was 78.5CMS indicating a high flow rate.

6. Recommendations

The study makes the following recommendations;

- Functionality of storm water drainage network systems in Kisii municipality was recommended to be enhanced. The Kisii municipality management team could embrace the use of PCSWMM in indicating flooded and possible clogging areas based on precipitation, and therefore make informed decisions during designing of storm water management systems.
- Links to be synchronized with adjoining nodes to reduce surcharges and spillage of water to adjacent properties.
- Channels for conveying storm water were recommended to be realigned on nodes where surcharge occurred, in line with the PCSWMM model design.

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