American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-11, Issue-06, pp-139-153
www.ajer.org
Research Paper Open Access

Hydrodynamic Modeling using HEC-HMS Model, River Kuja Basin, Kenya

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ABSTRACT: *River basins have experienced alterations in rainfall patterns and general hydrology occasioned by climate change effects, human population growth, land use land cover changes and urbanization. This has impacted negatively on water resources and agricultural production within the basins. Planning and management of water resources in the basins is challenging due to lack of quality data. The study was conducted to model the hydrodynamics of River Kuja basin to generate data and information that could be used to design conservation and policy measures to conserve the water resources within the basin. The study used Hydrologic Engineering Centre – Hydrologic Modeling System (HEC-HMS) model for rainfall-runoff simulation to determine the catchment and streamflow generation. The HEC-HMS model used basin shapefile, streamflow data, temperature, precipitation and soils. Precipitation was statistically compared to evapotranspiration, and basin runoff outflow. This was determine the water balance within the basin. The peak discharge was experienced on 6th February 2020 with a discharge rate of 2,481.6m³/s with a volume of 33,629.21mm. The regression analysis focusing on the relationship between rainfall and streamflow resulted in a correlation coefficient value of 0.64 and coefficient of the determinant value of 0.41. The relationship was moderate but significant. The validation process produced an NSE value of 0.32 while calibration showed an NSE value of 0.52, acceptable values. In terms of discharge volumes, the observed volume was found to be 7060.45mm while the simulated discharge at 6524.28mm. The model evaluation gave an efficiency of 0.73. The study was conducted in Kuja River basin located in southwestern parts of Kenya where there was increasing socio-economic activities with high impact on the water resources.*

Keywords: *Modeling, HEC-HMS model, rainfall-runoff modeling, calibration, simulation, Kuja River basin*

Date of Submission:01-06-2022 Date of acceptance: 14-06-2022

I. INTRODUCTION

River basins have experienced alterations in rainfall patterns and general hydrology caused by climate change effects, and land use land cover changes. Hydrological/hydrodynamic modelling is fundamental for simulation water resources for useful information in basin management. Recent studies have underscored the significance of online coupling strategies, representing feedbacks between floodplain inundation and vertical hydrology (Wen *et al*. 2013). HEC-HMS (Hydrologic Engineering Center-Hydrologic Modelling System) is preferred in river basin studies with dendritic watershed systems. It is a Semi-distributed hydrologic model developed by US Army Corps of Engineers to model the interactions of rainfall-runoff of a water resource basin. Many scientists have applied HEC-HMS model in different hydrologic and hydrodynamic studies of which the model has proven its suitability in forecasting and simulation of streamflow (Sintayehu, 2015). In modeling the relationship between rainfall and runoff in a semi-arid area in Madina, Saudi Arabia, Norhan et. al. (2016) usefully applied HEC-HMS model. During a study in the Upper Blue Nile River Basin, Sintayehu, (2015) used the model by employing exponential recession approach and Snyder unit hydrograph to simulate the surface water movements in the basin. Meiling et. al. (2016) used the HEC-HMS model in Northwestern China to model and simulate the rainfall-runoff relationship. In flash flood mitigation, Walega, (2013) reconstructed a flashflood event of short duration in Eastern regions of Algeria. The objective of this study was to investigate the Hydrodynamics of River Kuja basin to generate data and information that could be used to design conservation and policy measures to conserve the water resources within the basin.

II. MATERIALS & METHODS

The Study Area

The study was conducted in River Kuja basin in Kenya. It is an extensive basin spanning from Kiabonyoru highlands in Nyamira County downwards to Lake Victoria. It lies within coordinates 0.65^0 S 43.97^0 E (34.883110 -0.996036 Decimal Degrees) and has a total length of 147 km. The basin is averagely 2,000m above the sea level but rises to 3,000m above the sea level at its source in Nyamira.

The basin has an area of $6{,}900km^2$ (2,664 sq. mi) with a population of approximately 2,584,313 people (Census, 2009). The river has an average discharge of 58 m^3 s^{-1} (2,048 cu ft s^{-1}). The river runs across the Gucha land where it is commonly known as Gucha river. Part of it is referred to as River Mogonga, a name symbolizing the deadly effects of this river when it floods. The other part that passes through Luo communities is referred to as River Kuja.

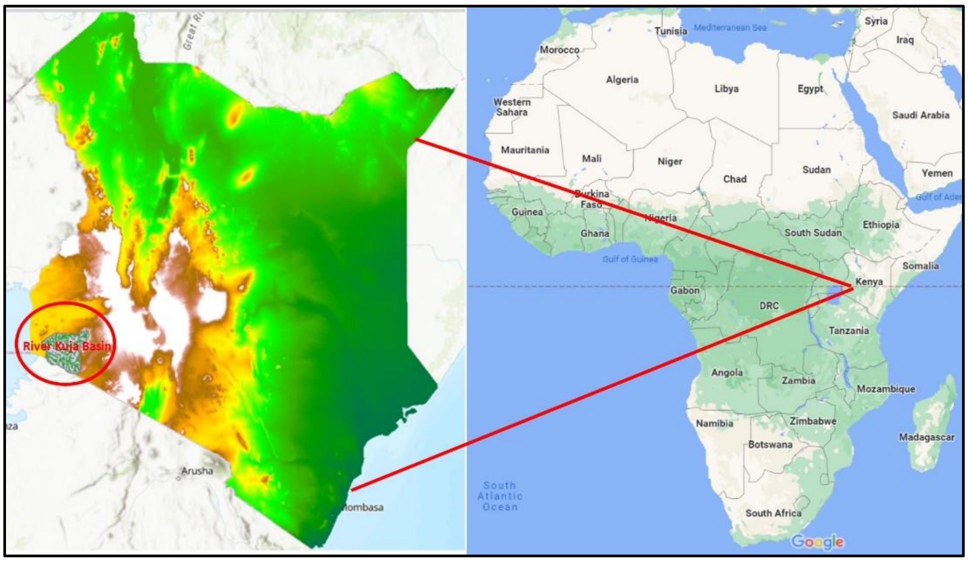


Figure 1: ***Map of River Kuja Basin (Source: Gucha-Migori basin IWRM Plan)***

Study Design

The hydrodynamic and hydrological modeling of Kuja basin was done using ArcGIS software HEC-HMS model. The data used included Digital Elevation Model (DEM), rainfall data, river Kuja discharge, temperature, soil types, land use and land cover. The DEM was downloaded from Shuttle Radar Topography Mission (SRTM) and provided elevation and slopes forming tributaries that drain into River Kuja. It was of spatial resolution of 30m by 30m. The basin was merged into five sub-basins out of the 67 sub-basins generated during ArcGIS Kuja basin shapefile processing. River discharge was obtained from Water Resources Authority for Muhuru Bay Station and it covered a period of fifty (52) years from 1969 to 2021. For the climate data, precipitation and temperature used covered the period from 1969 to 2021. Stations used included Sotik, Sony Sugar, and Muhuru Bay weather stations. Land use, land cover, and soil types were processed using remote sensing techniques. The data were processed using ArcGIS software, and extension HEC-GeoHMS was applied and exported to HEC-HMS for final results.

Methodology

Rainfall and Streamflow variability

The relationship in variability of rainfall and streamflow data was analyzed using regression analysis approach. It is a quantitative expression of how dependent and independent variables relate in nature. Streamflow was being a dependent variable was investigated by measuring its movement response to rainfall which was an independent variable. The analysis was used to determine the change in the amount of streamflow (dependent variable) with a unit change in rainfall (independent variable). The mathematical function below was used to calculate the regression model:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \qquad i = 1,2,3,\ldots,n \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(Equation 2.1)}$$

Where:

- yi = the i^{th} dependent variable response observation

- x_i = the i^{th} independent variable observation
- β_0 = intercept
- β_1 = slope
- ε_i= the random error or residual for the i^{th} observation and
- n = sample size.

Hydrologic Model Development

During this study, HEC-GeoHMS 10.6 was used to process the data. It is a geo-processing extension of AcrGIS 10.6. The basin's geospatial information like catchment boundary, sub-basins, elevations, streamflow paths and soil type were generated and processed using Arch Hydro tools. The main data sets processed included Digital Elevation Model (DEM) which provided topographical and geological features, land use data, meteorological data (River Kuja discharge, Rainfall and Temperature) and soil types. Processing of these data generated the parameters needed as input data into the HEC-HMS model for runoff simulation.

Terrain preprocessing

The DEM was used to delineate the basin and process all the streams in the study area. The shapefile of the boundary limit formed was used to clip other data parameters such as soil map and land use land cover activities. Terrain processing was achieved by application of Arc Hydro tools using DEM and stream files. It helped in carrying out run off estimation within the watershed. Sub-surface drainage such as culverts and flood control structures were not taken into account by "bare earth' DEM. These structures were accounted for by reconditioning the DEM. The automated process achieved this by artificially lowering the DEM alignment of sub surface structures (burning in to bare earth) resulting to a HydroDEM.

Terrain preprocessing was done to help develop a hydrological correct DEM and its derivatives i.e., the flow direction and the flow accumulation grids in the vector environment. The resultant was a correct drainage pattern that met the threshold for specific model consideration. This process was considered successful when the flow patterns met the expectation of the analysis.

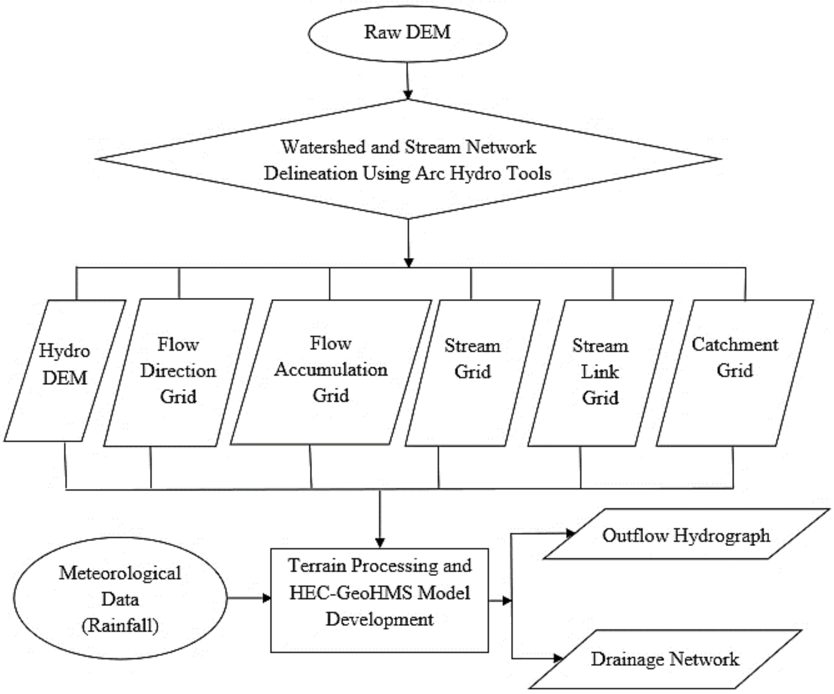


Figure 2: Schematic layout of the terrain processing in Arc Hydro

1) Preparing HEC-HMS model inputs using HEC-GeoHMS

The terrain preprocessing techniques were sequentially done by first filling the sinks thereafter determining flow direction within the basin. Filling sinks happened in areas into which the basin water, after every precipitation, flew but did not exist as a surface flow such as localized ponding. They had to be filled in terrain preprocessing stage. The fill values were represented in the figure below.

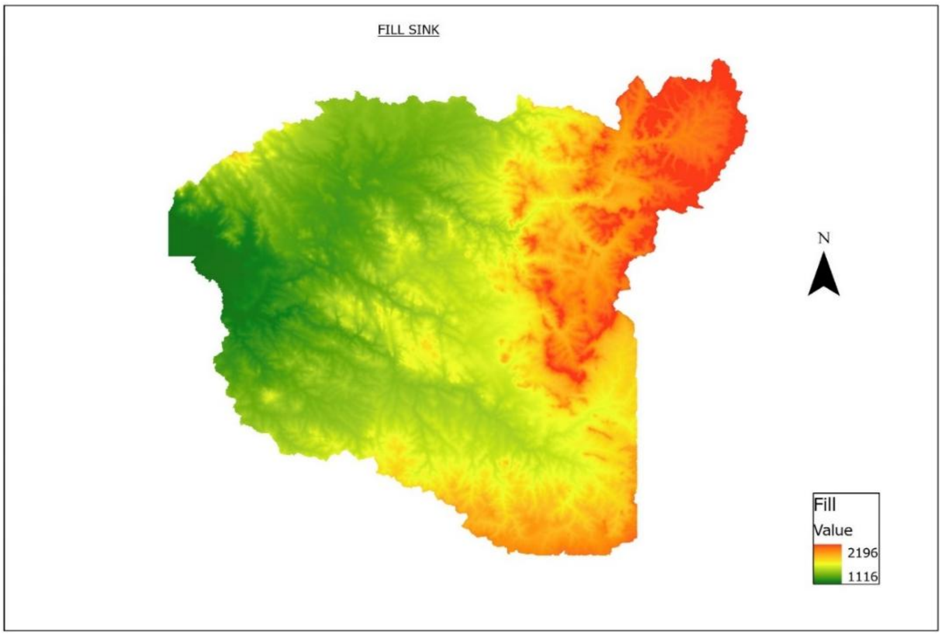


Figure 3: Illustration of Fill Sinks in the basin

Flow direction processing involved the direction of the steepest descent for each terrain cell to the next closest neighboring cell. It showed the movement of water between the terrain cells. The flow direction in Arc Hydro was based exclusively on topography i.e. on the slope defined by the terrain only. When this function was called, numerical values were assigned to each grid cell based on the steepest descent direction (i.e. N, S, E, W, NE,). The outflow point, as well as all nearby high points, were recognized and marked on the map. All of the high points were connected by a watershed boundary line. Along the steepest descent path, the boundary line traveled perpendicular to each contour line.

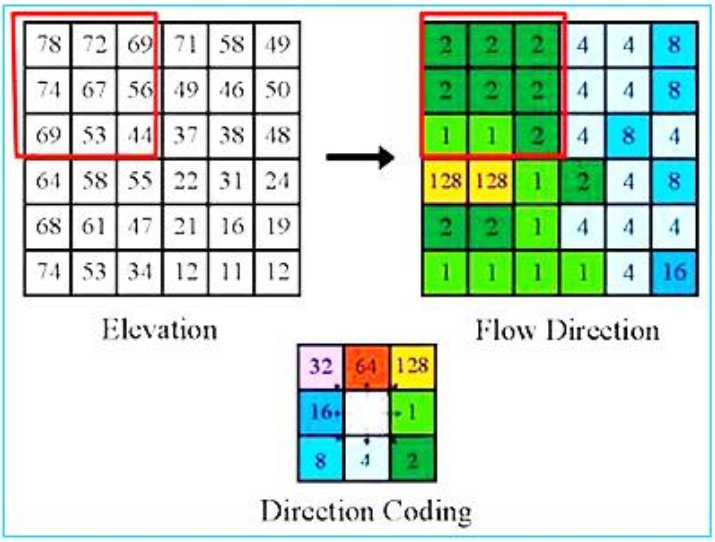


Figure 4: Flow direction illustration using D8 method

D8 method in ArcGIS software was used as shown in the Figure 4 above. It specified 8 directions for every single cell. The resultant raster had values from 1, 2, 4 up to 128 as shown in the illustration below. During the process, there was accumulation of surface water flow where the number of cells in the Hydro-DEM collected surface overflow from upstream of each cell. This created a grid with several upstream cells that drain through each Hydro DEM cell.

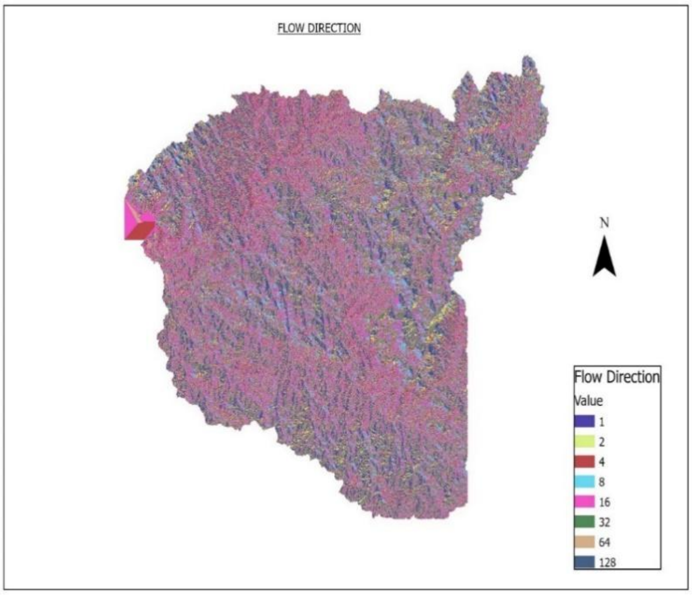


Figure 5: Flow Direction map of the basin

All cells having a flow accumulation greater than the user-defined threshold were classified as being part of the stream network. It recognized "stream" cells, which were defined as cells that drain more area than a user-specified threshold, which was 1% of the maximum flow accumulation. The threshold and drainage lines that resulted were utilized to optimize performance for subsequent operations. The stream grid was segmented in this step. A stream segment is a stretch of a stream that runs between two junctions. Between the confluences, it uniquely numbered stream segments (LINK). To ensure the entire DEM gets processed, it was ensured that the "SINK Link Grid" and "SINK Watershed Grid" entries in the form were "null."

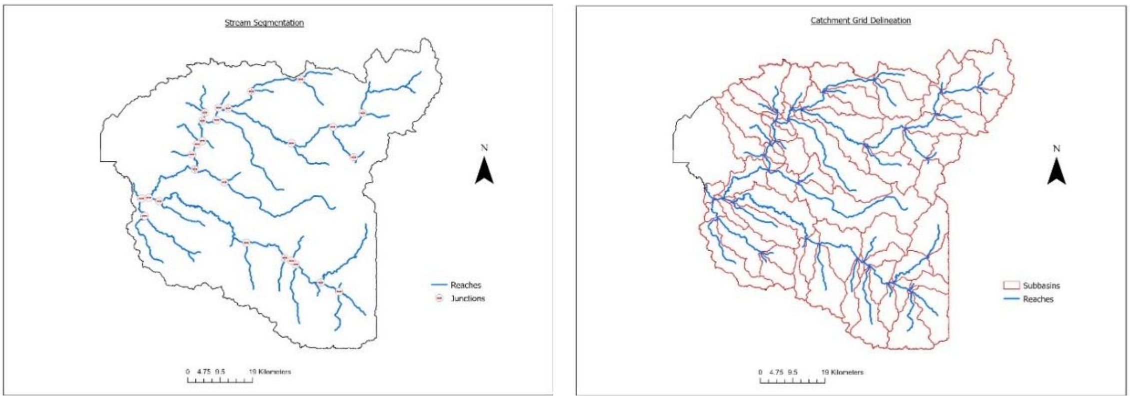


Figure 6: Stream Segmentation and Grid Delineation of the basin

HEC-HMS modeling

The raster outputs and vector outputs from terrain preprocessing i.e. raster outputs (raw DEM, Fill sink, flow direction, Flow accumulation, stream network, stream link, catchment grid, slope grid) and vector outputs (catchment, drainage lines, adjoin catchment) were input data in the HEC-HMS project set up. The HEC-HMS project set up menu included tools for determining watershed outlets and delineating the HEC-HMS project's watershed. Multiple layers HMS models were created using the same spatial data. The "Break Point" and "Project Area" feature classes from terrain preprocessing outputs were used to manage these models. The entire project area included the run-off contributing area as well as the non-contributing region.

The splitting of the basin into sub-basins and merging the extremely small sub-basins into five major ones was followed by processing the river profile. The river profile was mapped and exhibited a time of concentration of 5.35 hours. Hydrological characteristics of the River Kuja basin that calculated during the processing included river slope, length, basin slope, longest flow path, basin centroid, centroid elevation and river profile. The river Kuja profile is shown in the figures below.

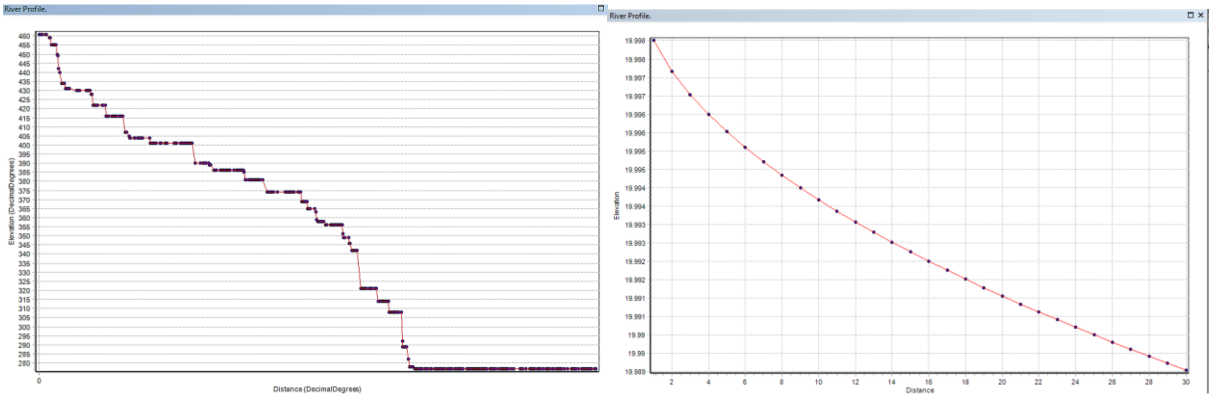


Figure 6: River Kuja profile in HEC-HMS model

Creating a New HMS project

A new HMS project is created before the hydrologic model is run to identify the Project Area and Break Point. The pour points depict the drainage line's outlets, whereas the project area depicts the complete project area, which includes both run-off contributing and non-contributing areas. We have two feature classes as a result of this step: project point and project area, which are utilized to define a new project for the entire area of interest

Basin Modeling

Basin modeling is done solely to generate the various sub basins and these enables the extraction of various basin parameters e.g. basin slope and river parameters e.g. river length. These parameters will later be used in run off prediction in HMS. Before extracting these basin characteristics, basins with shared pour points are merged. This method avoids multi-routing during the routing process. The river profile is also examined to determine its functionality; it allows the display of the profile of the selected river reach and may be used to split the river or watershed at a steep slope change.

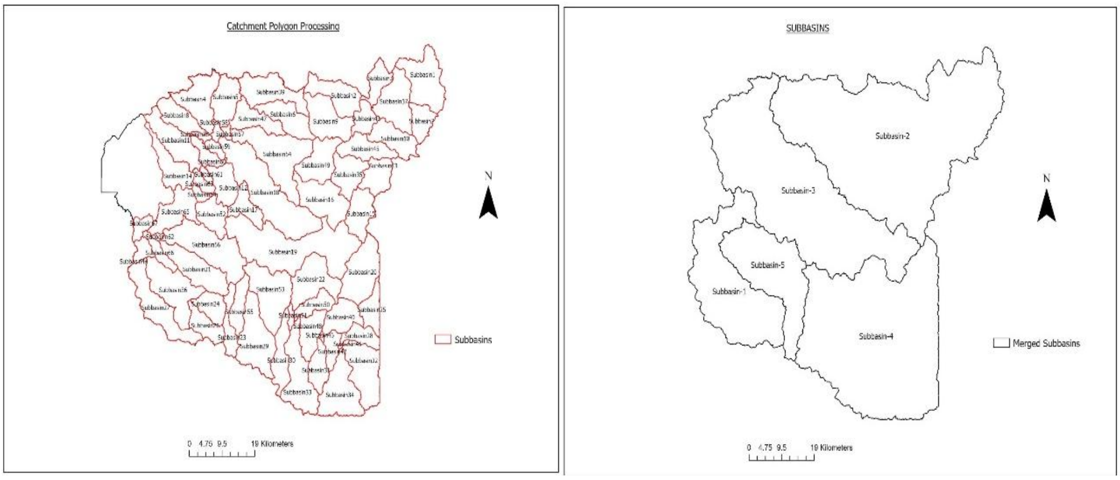


Figure 7: Catchment polygon processing (Sub-basins) and their merging into five smaller sub-basins

HMS Parameters

These are the parameters that will be used in the HMS process. These parameters are acquired in sequential as follows:

1. **Routing-**Muskingum method

This is predefined arithmetical method for determine the channel route. In this method the X and K parameters must be evaluated. Theoretically, K parameter is time of passing of a wave in reach length and X parameter is constant co-efficient that its value varies between 0-0.5. these constants were varied based on each reach characteristics. The *Muskingum* routing method uses a conservation of mass approach to route an inflow hydrograph. The model will be calibrated through trial and error after initial parameter estimates are made using GIS and observed data.

2. **Loss-**SCS Curve Number method

This method estimates the accumulated precipitation excess as a function of cumulative precipitation, soil cover, land use and moisture. In this modelling, the curve number (CN) is a key variable which is obtained from the look-up table of TR-55. The TR-55 table contains predefined values that are developed by the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA). The SCS-CN model is unable to give more specific runoff information due to TR-55's limitations in describing complex urban areas and identifying land use/cover types. Moreover, because Kuja Basin area consists several soil types and land uses, a composite CN was calculated. The composite CN was calculated by merging hydrological soil group data and land cover data.

3. **Transform-**SCS unit hydrograph method

This method estimates direct run off. The basin lag time is parameter of SCS unit hydrograph Model which is 0.6 times the time concentration as suggested by Panigrahi (2014).

4. Baseflow-Exponential method

It is used to represent watershed base flow and estimates initial base flow, recession constant and the threshold values

Calibration and validation of the model

The success of a hydrologic watershed model is determined by how effectively it is calibrated, which is determined by the hydrological model's technical capacity as well as the quality of the input. The HEC- HMS watershed model is calibrated for the event-based simulation. This aligns simulated run-off volumes, run-off peaks, and hydrograph timing with observed data. Using the HEC-HMS watershed (already calibrated and validated) the run off volumes for each sub basin were estimated and quantified in cubic meters

Simulation of rainfall-run off process using HEC-HMS

HEC-HMS is a physically based and conceptually semi-distributed model designed to model a wide range of geographic areas, including run off volume calculation, direct run off calculation, and base flow modeling. The following data were used in order for the simulation process to be conclusive enough.

III. RESULTS AND DISCUSSION

A. HEC-HMS model Output

The HEC-HMS model was run with the input parameters data estimated using the HEC-GeoHMS extension. Tools for assigning and calculating different river and watershed parameters were provided in the hydrologic menu. The tools assisted in determining key parameters such as channel routing coefficients, time of concentration and Soil Conservation Service (SCS) curve number (CN). Muskingum routing method was adopted in calculating the channel routing since it takes into account the amount of water stored by the river and also relates it to both the inflow and the outflow values. The resulting Muskingum equation was represented by the equations 3.1 and 3.2 below;

$$S = K(xI + (1 - x)O) \quad \text{.........................(Equation. 3.1)}$$

$$O_2 = C_1I_2 + C_2I_1 + C_3I_1 \quad \text{......................... (Equation. 3.2)}$$

Where;

- S = for storage,
- I = for inflow,
- O = for outflow,
- t = travel time, and
- K and x = Muskingum parameters (constants).

In the calculations x was assumed to have a value of 0.2 and K to be same value as the CN lag time.

$$C1 = 0.5\Delta t - Kx \ K - Kx + 0.5\Delta t \quad \text{.........................(Equation. 3.3)}$$

$$C2 = 0.5\Delta t + Kx \ K - Kx + 0.5\Delta t \quad \text{.........................(Equation. 3.4)}$$

$$C3 = K - KX - 0.5\Delta t \ K - Kx + 0.5\Delta t \quad \text{.........................(Equation. 3.5)}$$

$$C1 + C2 + C3 = 1 \quad \text{.........................(Equation. 3.6)}$$

Where; C1, C2 and C3 are routing parameters obtained from the equations above. They all sum up to one as shown in equation 3.6.

The Soil Conservation Service (SCS) Curve Number (CN) method was used to measure land use as the indicator while determining surface runoff. CN values range from 0-100 whereas the value tends towards 100, there is a decreasing trend in infiltration capacity of the soil and vice versa. Factors taken into consideration while determining SCS CN included land cover types, antecedent runoff conditions, hydrological soil types and imperviousness of the soil. The runoff factor was expressed by the equation below (SCS, 1986);

$Q = (P-Ia)2/(P-Ia)+S$ …………………….(Equation. 3.7)

Where;

- Q = runoff measured in mm,
- P = rainfall measured in mm,
- S = potential maximum retention of the soil after runoff begins measured in mm,
- I_a= initial abstraction measured in mm.

The I_a referred to all losses of water during precipitation before runoff begun. It varies depending on so many factors and in case of River Kuja watershed, it was approximated using the equation below;

$I_a = 0.2S$ ……………… (Equation 3.8)

While eliminating Ia, an independent parameter, from the equations, S and P were allowed to produce an amount of surface runoff. This was achieved by substituting equation 3.8 into equation 3.7 and obtaining equation 3.9.

$Q = (P-0.2S)2/(P+0.8S)$ ………………(Equation 3.9)

In this equation 3.9, S was determined in relation to land use factors and soil conditions of Kuja basin through the CN and their relationship was given by equation 3.10 below;

$S = 1000CN - 10$ ….…………..(Equation 3.10)

As expressed by Wurbs and James (2001), the Soil Conservation Service unit hydrograph was used based on its simplicity of its two basic parameters, that is, lag time tL and watershed area A. The CN lag method function in HEC-GeoHMS was used to compute sub basins weighted time of concentration. The resultant lag time was in hours and represented time from the center mass of excess hydrograph to the peak of the hydrograph.

$Qp = 484A\ Tp$ …………….(Equation 3.11)

$Tp = D\ 2 + tL$ …………….(Equation 3.12)

Where;

- Qp= peak unit hydrograph measured in m^3/hr,
- A = catchment area measured in m^2,
- Tp = flow to peak; a function of lag time, tL (hrs) and rainfall duration, D
- D = rainfall duration measured in hrs
- tL = lag time measured in hrs.

Soil and Surface Cover Loss

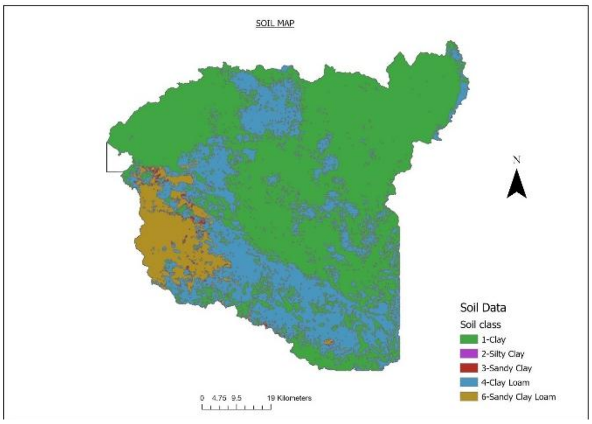


Figure 8: Soil Map of River Kuja basin

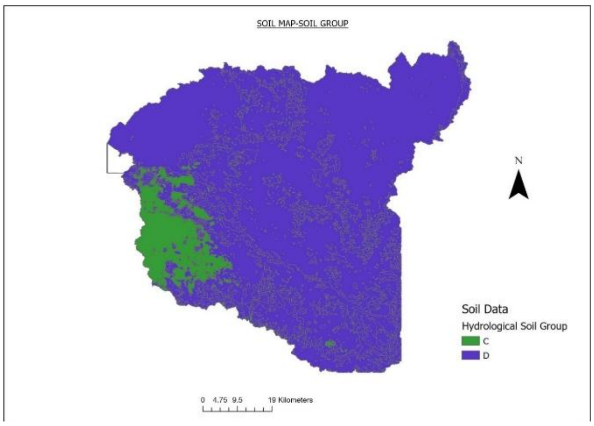


Figure 9: Categorization of soil cover into Hydrological soil Groups

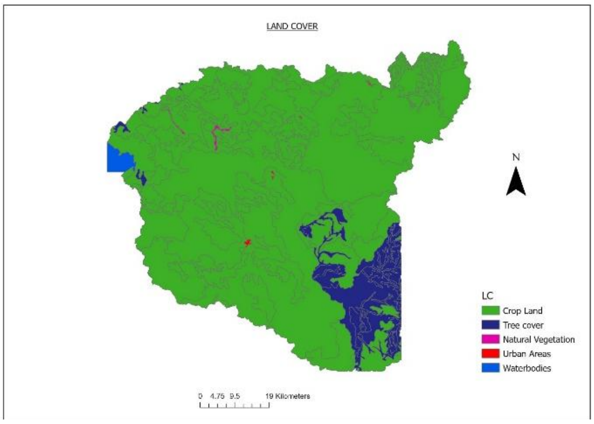


Figure 10: Land Cover and soil group map

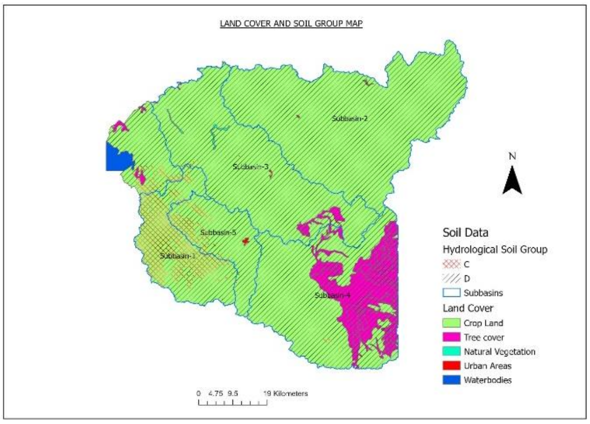


Figure 11: Extraction of composite curve numbers in respect to each sub-basin.

B. Variation in Rainfall and Streamflow Results

The relationship between average daily rainfall and average daily river discharge at the River Kuja outlet was investigated by applying regression analysis method and the outcome was presented in Figure 12. The regression analysis results showed a significant relationship between daily river flow and daily rainfall. The value of coefficient of determination represented by R^2 was found to be 0.42 hence significantly showing that rainfall streamflow related by 42% variation. This value indicates a moderately average relationship. However, the p-value was at 0.008 which is a significant relationship and the regression equation was represented as below;

$$y = 1.2749x + 6.1419 \quad \text{........ (Equation 3.13)}$$

The river discharge trend shows an increasing trend from 1990 to 2020. The increase is relatively minimal but has overally affected the river flow volume at the basin's outlet causing floods during peak storms. This increasing surface water flow could be attributed to factors such as land use changes where forests and land cover are converted to bare lands, and climate change.

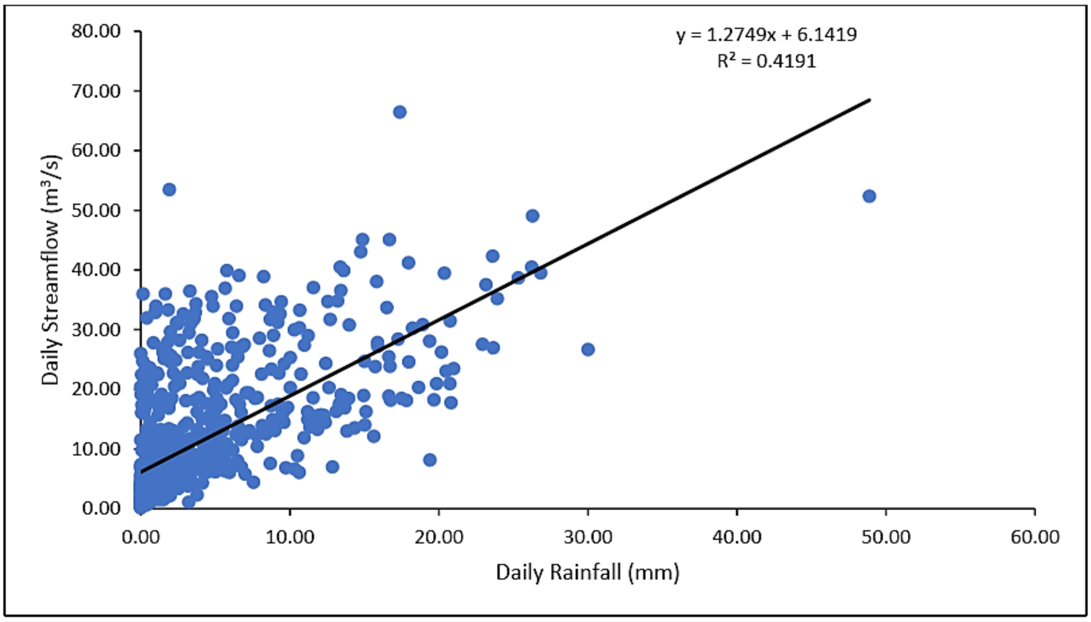
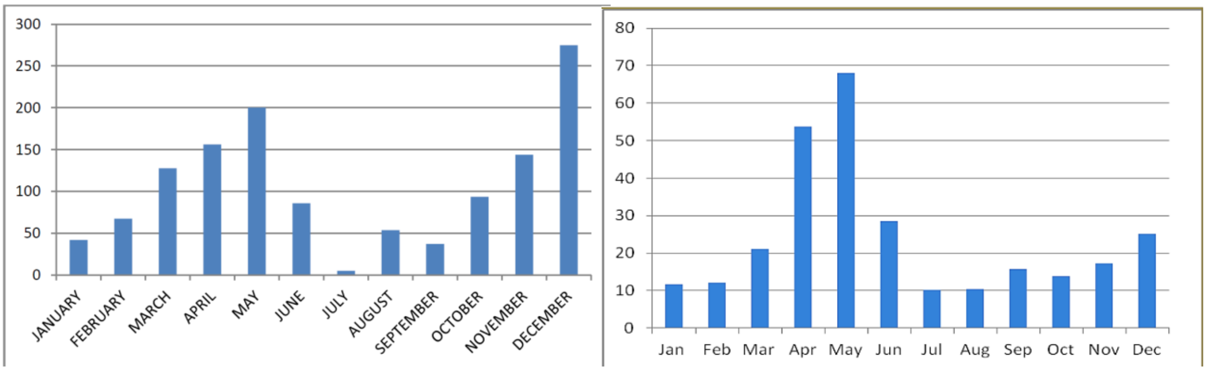


Figure 12: Regression Analysis Plot between the Daily Stream flows and Average Daily Rainfall Data



A B

Figure 13: River Kuja basin (A) Average annual rainfall (B) Annual Discharge at the Muhuru Bay Station

Observed rainfall data and simulated rainfall data used in the modeling process produced a significant relationship. The regression analysis conducted among the three meteorological stations showed a good correlation value which indicated that all the station's data were relevant for the simulation processes. Comparison between observed and simulated data for Muhuru, Sony Sugar and Sotik stations produced correlation values r as 0.80, 0.71 and 0.74 respectively. These results from the three stations were presented in the figure below. The correlation values above were obtained from calculating the square root of R^2 value. The R^2 value was determined by regression analysis process and each of the stations gave regression formulas relevant for generating future data.

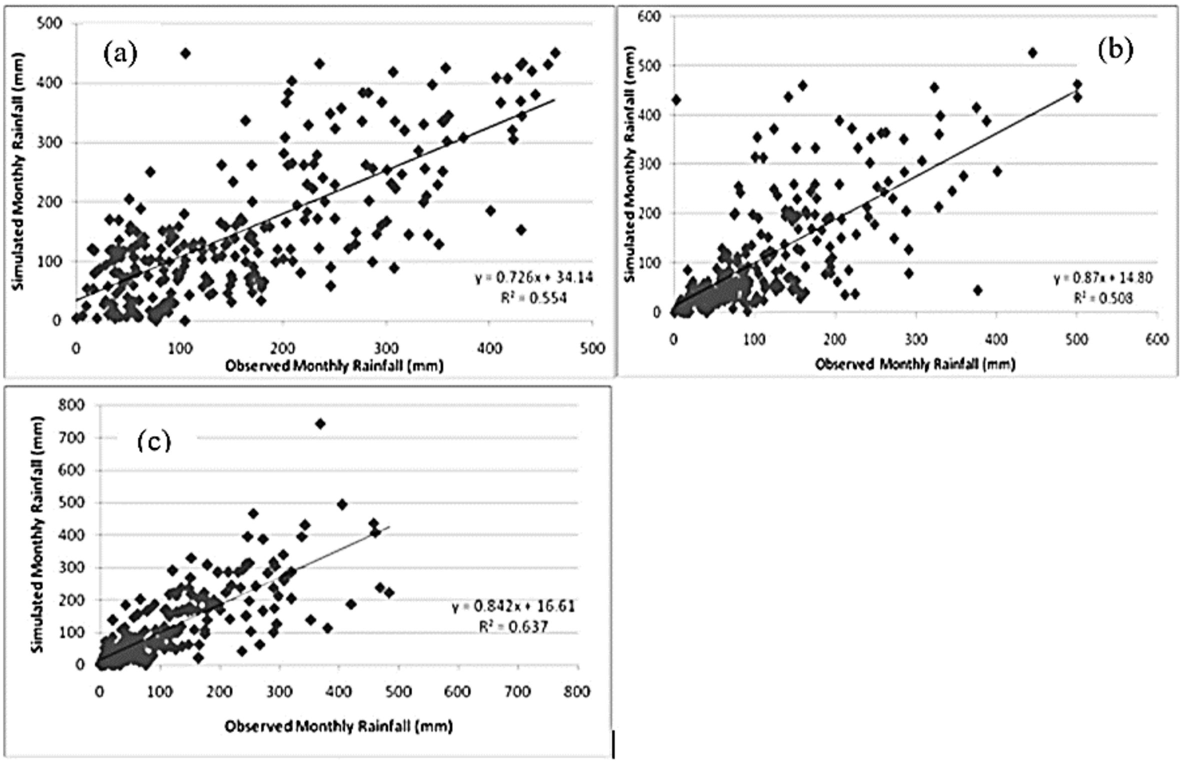


Figure 14: Graph of Regression Analyses of Observed and Simulated Monthly Rainfall Data for a) Sotik, b) Sony Sugar and c) Muhuru Bay Stations

C. Streamflow Simulation Using HEC-HMS

Model simulation results

The initial values of the basin that were computed in the HEC-GeoHMS were as shown in Table 1. Simulations were done using the same values but the output hydrograph was not reasonable with its simulated and observed streamflow values not close to each other. The disparities possibly emerged from merging the sub basins and using the average parameters in the simulation process. The initial and optimized values are presented in the table showing a big gap in their relationship.

Table 1: Initial Parameters from HEC-GeoHMS Used in the HEC-HMS Model

Parameter Name	Initial Value	Optimized Value
Land Use Curve Number	67.10	35.00
Lag Time SCS	318.60 minutes	662.04
Muskingum X-value	0.20	0.17
Muskingum K-value	5.31 hours	26.77
Basin Reach	2.00	1.00
SCS CN - Curve Number Scale Factor	1.00	0.01

A ten years period between 2000 to 2009 was chosen to run the model on a daily time step. The values obtained from calibration and validation processes were used in the simulation processes. Comparison hydrograph results of simulated and observed parameters were presented as in Figure 15 below.

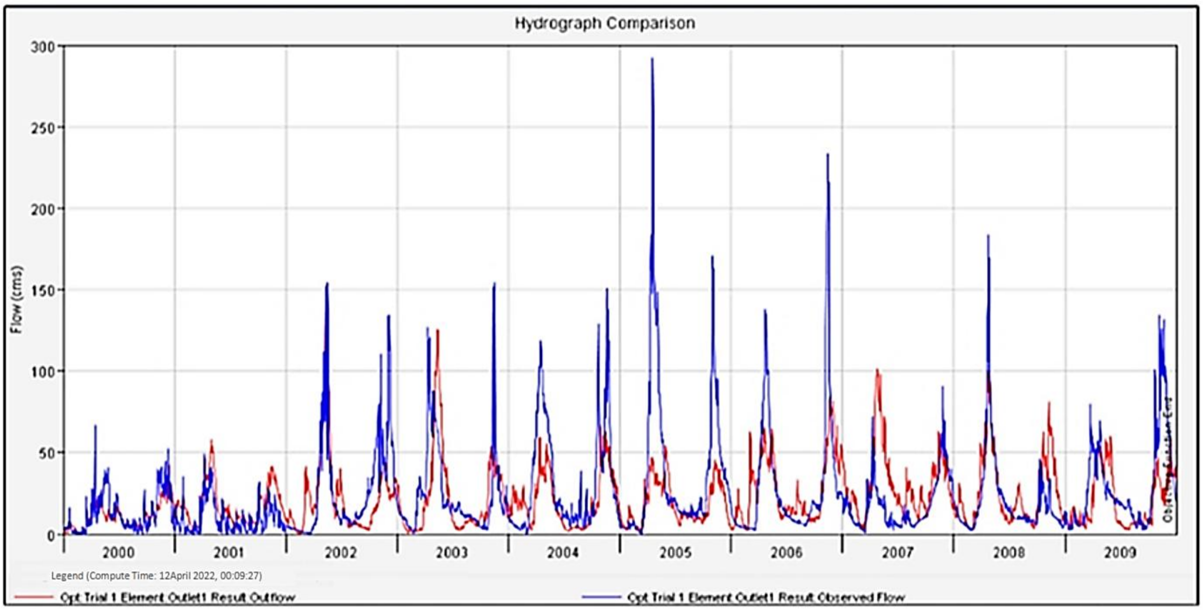
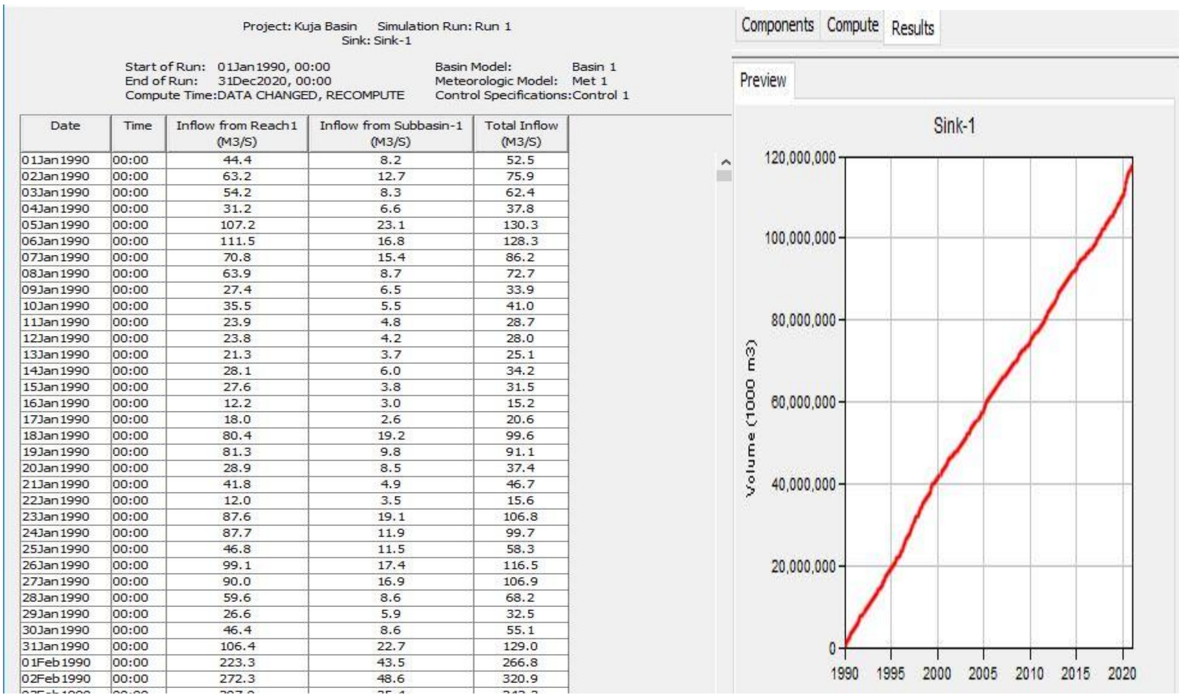


Figure 15: Hydrograph Comparison Simulation of the basin from 2000 to 2009

In the analysis of the hydrographs produced over the, the values observed exceeded the values simulated by the model by 8.2%. In terms of discharge volumes, observed volume was found to be 7060.45mm while the simulated discharge at 6524.28mm. The small difference was reasonable and hence acceptable within the permissible limits of 10% for an accepted simulation comparison value. It was observed that the model underestimated the low flows and peak flows as represented in the figures above. The modeling tools as provided in the HEC-GeoHMS model were very relevant in analyzing the hydrology of the basin. Integration of the tools with ArcGIS software enabled hydrologic processing and easy manipulation of various basin parameters. Therefore, the model was helpful in hydrodynamic simulations hence can be applied in any other river basin and sub-basins in the entire region.



Date	Time	Inflow from Reach1 (M3/S)	Inflow from Subbasin-1 (M3/S)	Total Inflow (M3/S)
01Jan1990	00:00	44.4	8.2	52.5
02Jan1990	00:00	63.2	12.7	75.9
03Jan1990	00:00	54.2	8.3	62.4
04Jan1990	00:00	31.2	6.6	37.8
05Jan1990	00:00	107.2	23.1	130.3
06Jan1990	00:00	111.5	16.8	128.3
07Jan1990	00:00	70.8	15.4	86.2
08Jan1990	00:00	63.9	8.7	72.7
09Jan1990	00:00	27.4	6.5	33.9
10Jan1990	00:00	35.5	5.5	41.0
11Jan1990	00:00	23.9	4.8	28.7
12Jan1990	00:00	23.8	4.2	28.0
13Jan1990	00:00	21.3	3.7	25.1
14Jan1990	00:00	28.1	6.0	34.2
15Jan1990	00:00	27.6	3.8	31.5
16Jan1990	00:00	12.2	3.0	15.2
17Jan1990	00:00	18.0	2.6	20.6
18Jan1990	00:00	80.4	19.2	99.6
19Jan1990	00:00	81.3	9.8	91.1
20Jan1990	00:00	28.9	8.5	37.4
21Jan1990	00:00	41.8	4.9	46.7
22Jan1990	00:00	12.0	3.5	15.6
23Jan1990	00:00	87.6	19.1	106.8
24Jan1990	00:00	87.7	11.9	99.7
25Jan1990	00:00	46.8	11.5	58.3
26Jan1990	00:00	99.1	17.4	116.5
27Jan1990	00:00	90.0	16.9	106.9
28Jan1990	00:00	59.6	8.6	68.2
29Jan1990	00:00	26.6	5.9	32.5
30Jan1990	00:00	46.4	8.6	55.1
31Jan1990	00:00	106.4	22.7	129.0
01Feb1990	00:00	223.3	43.5	266.8
02Feb1990	00:00	272.3	48.6	320.9

Figure 16: Model Simulation parameters

D. Model calibration results

The initial parameters were used in calibrating the model as shown in Table 1. The parameters yielded river flow results that were not acceptable as well as very low NSE value of -41. During the several calibration trials conducted, the best results showed an NSE value of 0.52, an acceptable value considering that it ranges between the standard ranges of 0 to 1. The result gave confidence since in Pakistan, Yassin et al. (2015) modelled hill torrents using the same model and obtained a calibration value of 0.54 which was considered acceptable. The errors realized during the calibration process could be due to filling in the missing values in the observed data. It was also as a result of merging the small sub-basins into five major sub-basins and only using their averages. In conclusion, the calibration results were accepted because the values fell within the NSE scientific ranges. Figures 18 and 19 below show the calibration results.

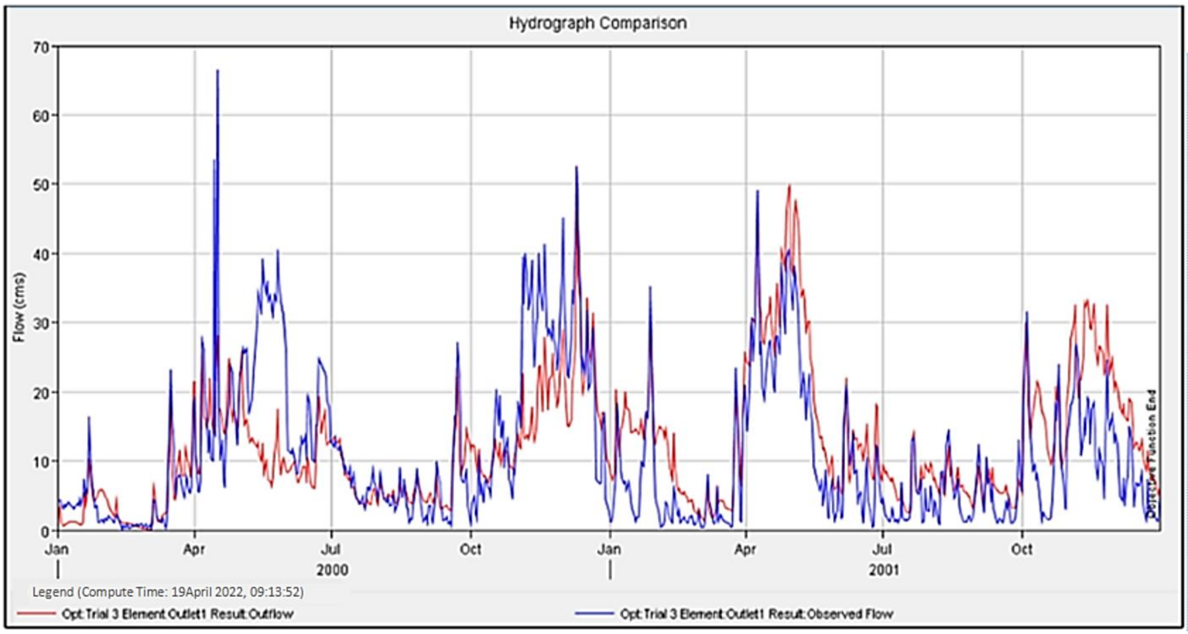


Figure 17: Model Calibration Hydrograph for the Period between 2000 to 2001

Volume Units: (•) MM ( ) 1000 M3

Measure	Simulated	Observed	Difference	Percent Difference
Volume (MM)	718.33	654.07	64.26	9.82
Peak Flow (M3/S)	52.6	66.5	-13.9	-20.9
Time of Peak	10Dec2000, 00:00	16Apr2000, 00:00		
Time of Center of Mass	16Feb2001, 23:29	19Dec2000, 07:01		

Figure 18: Summary of the Objective Function Results for the Model Calibration

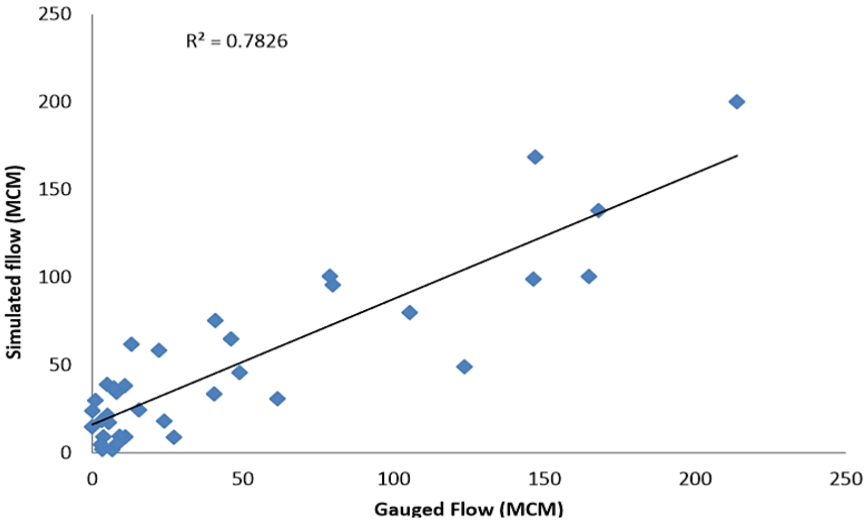


Figure 19: Simulated river Kuja flow

Model validation results

The validation of the model was done using data for the period January 1, 2002 to December 31, 2003. This was an outer period from the model calibration period. Optimized parameters in Table xxx were the baseline in carrying out simulations to achieve valid outcomes. The validation process produced NSE value of 0.32. The value was acceptable since it was within the NSE ranges of 0 to 1. According to Yassin (2015) in Pakistan, his calibration results were higher than the validation results. The variation in the validation results was attributed to the fact that rainfall data used during this research was not representing the entire basin but rather from only three gauging stations. Subsequently, merging of sub-basins also contributed to the low NSE value. The figures below show the results of validation process, Figure 21 and Figure 22.

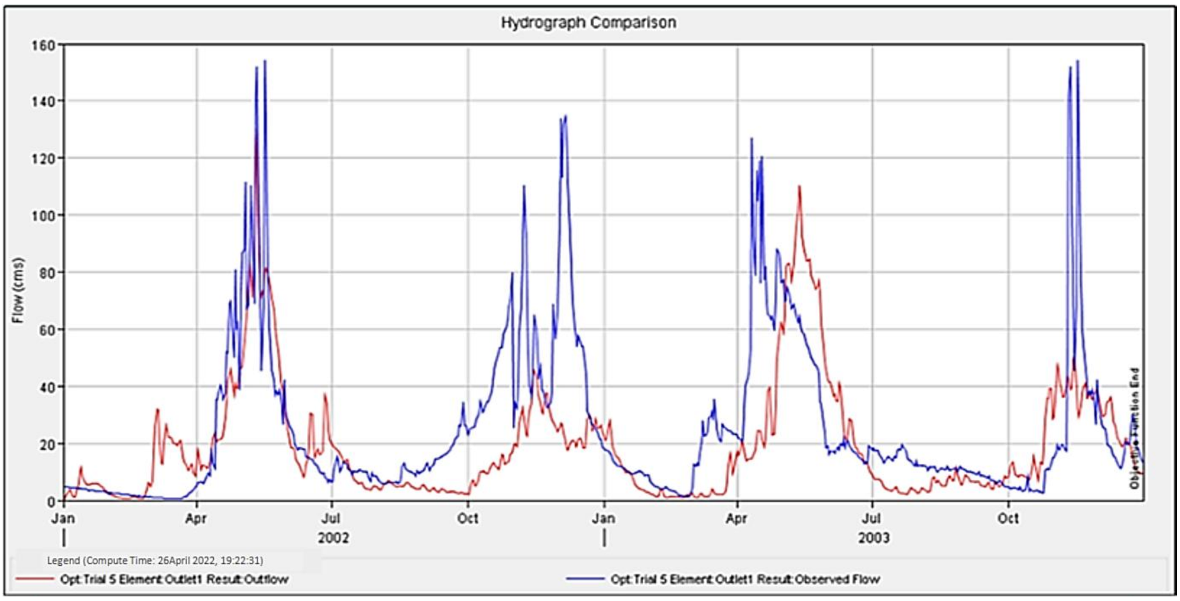


Figure 20: Model Validation Hydrograph for the Period between 2002 to 2003

Volume Units: MM / 1000 M3

Measure	Simulated	Observed	Difference	Percent Difference
Volume (MM)	1127.91	1501.63	-373.72	-24.89
Peak Flow (M3/S)	84.5	154.3	-69.8	-45.3
Time of Peak	13May2003, 00:00	17Nov2003, 00:00		
Time of Center of Mass	20Jan2004, 09:30	03Feb2004, 22:01		

Figure 21: Objective Function Summary Results for the Model Validation

E. Hydrodynamics of the Basin

The peak discharge was experienced on 6th February 2020 with a discharge rate of 2,481.6m^3/s with a volume of 33,629.21mm. The rainfall patterns turned to be unpredictable since 2010 with high peak discharges hence causing floods along the river channel. Most of the peak discharges were obtained off the usual rainy seasons. The heavy rains upstream from the Kisii highlands cause massive runoff downstream which erodes the soils leading to heavy sedimentation within the river channel. Sedimentation causes the shallowness of River Kuja downstream hence water overflows the natural channel forming floods in the buffer region.

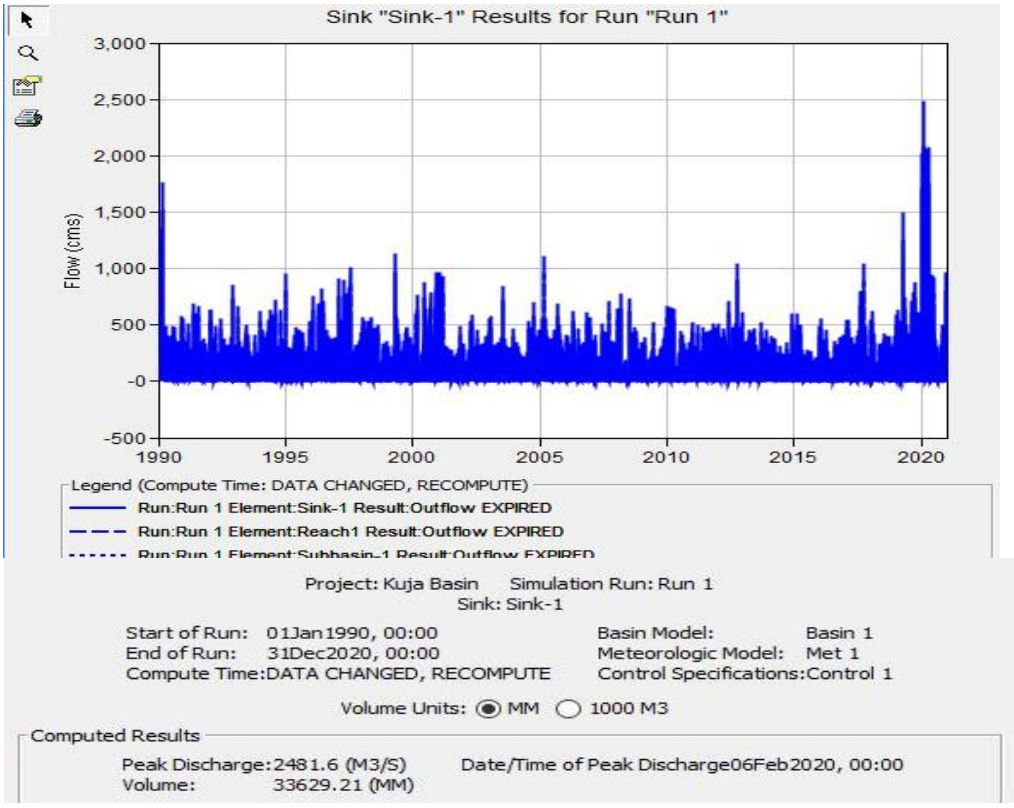


Figure 22: River Kuja flow for the period 1990 to 2020.

Alterations in climatic and weather patterns, anthropogenic activities, population growth and infrastructural development are some of the key factors contributing to increasing floods in the basin. Several properties, lives, crops and livestock are damaged due to flash floods generated from up hills.

IV. CONCLUSIONS AND RECOMMENDATIONS

Conclusion

Hydrodynamic modeling of River Kuja basin using HEC-HMS model produced significant results. The regression analysis focusing on the relationship between rainfall and streamflow resulted in correlation coefficient value of 0.64 and coefficient of determinant value of 0.41. The relationship was moderate but significant. Towards the year 2020, there was increase in discharge with unpredictable rainfall patterns. Different land use practices have significantly altered the hydrology of the basin. With the precipitation variations expressed in the modeling parameters, probability of floods are expected to be higher in future due to the increasing rainfall intensity and increasing surface runoff. Overall River Kuja annual runoff discharge increased gradually. It was concluded that heavy unpredictable precipitation resulted into high river flow events hence the flash floods along the River Kuja buffer regions.

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