APPLICATION OF THE GEOLOGICAL STREAMFLOW AND MUSKINGUM CUNGE MODELS IN THE YALA RIVER BASIN, KENYA

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Abstract

The nature of surface runoff and its effects in the watershed can be represented by the application of hydrologic and hydraulic models. In this study, the Geological Streamflow Model (GeoSFM) and the Muskingum Cunge (M-C) model were used to model the hydrologic processes of the Yala river network. The objective was to develop a flood early warning system to mitigate potential flood hazard risk exposed to the downstream inhabitants. Historical hydro-metric datasets of 1975-2005 were used for calibration, verification and streamflow routing based on a split record analysis. For the runoff generation, rainfall and evaporation datasets were provided by the Kenya Meteorological Department while for model calibration and verification, streamflow was obtained from Water Resources Management Authority. To determine the hydrologic connectivity, the 30 meters by 30 meters Digital Elevation Model was obtained from the International Centre for Research in Agro-forestry. The Digital Soil Map of the World developed by Food and Agricultural Organisation and the Global Land Cover data of the United States Geological Survey were used for model parameterisation. The soil moisture accounting and routing method transferred water through the subsurface, overland and river phases. The percentage of the correlation coefficient (R^2% value) was used to determine model performance. The GeoSFM modeled streamflow at the Bondo streamflow gauging station, coded 1FG02 where during the calibration and verification phases, streamflow was modeled at R^2 value of 80.6% and 87.3% respectively. The M-C model routed streamflow from 1FG02 to the Kadenge streamflow gauging station, coded 1FG03 at R^2 value of 90.8%, Muskingum K value of 2.76 hours and Muskingum X value of 0.4609. The extreme value analysis done on the modeled streamflow portrayed a unique behaviour of the system when compared to the ideal system model that should mimic the real world. It was concluded that the GeoSFM and M-C models were hence useful tools for flood mitigation by issuing flood early warning messages defined by peak streamflow and flood wave travel time.

Key words: Flood, Yala River, geological streamflow model, muskingum cunge model.

1.0 Introduction

There is a continued exposure to flood risk in the western region of Kenya (Berhane, 2005). This calls for a concerted effort to provide flood mitigation measures in form of flood warning systems. The streamflow in the Yala river causes serious flooding conditions downstream as was established by UNEP (2004). This is more so because there is no contingency protection and drainage options for any excess waters which may originate from within the Yala river (Ogallo et al., 2004). An analysis done by NBCBN-RE (2004a, b and c) showed that changes in land use and/or climate have enhanced the frequency and magnitude of flooding. Some existing land use practices enhance flooding such as the Dominion Farms Limited project located at the Yala swamp.

Rainfall run-off modeling (Todini, 1978; Wang, 1996 and Seki, 1989) is the hydrologic process of generating flood early warning systems for flood management at river catchment scale. Rainfall runoff modeling from a watershed is of vital importance as the output is required for water resources planning and management. Numerical models of watershed hydrology are designed to answer the question, ‘what happens to the rain?’ at a level of detail depending on the problem at hand and are employed in a wide spectrum of areas ranging from watershed management to engineering design (Chow *et al.,* 1988; 1994). A numerical model is a hypothesis and has to be calibrated for the catchment under study (Kiluva, 2007 and Kiluva *et al.,* 2007).

Rainfall run-off modeling involves estimation of the magnitude of streamflow at various locations in a watershed resulting from a given precipitation input. The hydrologic cycle is the basic concept onto which flood modeling is derived and it comprises of all the physical processes that affect the movement of water in its various forms. The main processes include interception, water storage in the subsurface, lakes, reservoirs, infiltration, percolation, evaporation and transpiration. Due to the complexity of the real hydrologic system, the analysis is performed using hydrologic models, which are an approximation of the reality. The input and output of the model are measurable hydrological variables and the model structure is a set of equations that relate the inputs and outputs.

The complexity of any watershed compels one to use simplification and abstraction while conducting the study. Depending on which problem is being dealt with, sub-areas of the watershed are determined with regard to the contents and spatial relations that are considered as relevant in each case. If a modeler is only interested in particular objects in the system, for instance the Yala river basin, this selection leads to the first simplification. If the selected attributes of these objects are regarded to be significant, for instance the hydrology, this implies further abstractions (Young, 2001). This way the modeler gets from reality to a model which sufficiently describes the objects of interest in a way specific to the problem (such as flooding).

The GeoSFM has a universal applicability and success in modeling floods in Africa and the world at large. The GeoSFM which is a semi-distributed model incorporates the physical features of the catchment by ingesting geospatial and soils datasets of the study area (Kiluva *et al.,* 2010). Most catchments are ungauged and thus a methodology to compute the flood wave propagation down a river reach or through a reservoir is required. An example of a simple and most popular hydrologic flood routing technique used in natural channels is the physically based M-C flood routing method (Gorbrecht and Brunner, 1991a; 1991b and Todini, 2007).

Great works in the area of rainfall runoff modeling have been done under the auspices of the Capacity Building and Networking of the Nile countries: Flow Regime from International Experimental and Network Data (FRIEND) by Bashar *et al.,* (2006), Mutua and Kadwan, (2006) and Mutua *et al.,* (2006). The findings from the studies of the Nile countries confirm that flooding is a potential hazard in the larger Nile basin and hence the same is true in the Lake Victoria basin that includes the Yala river basin. Flood mitigation measures are hence a requirement to reduce the flood risk in the downstream inhabitants of the Yala river basin. The M-C streamflow routing technique has been applied by Macchione (2009); Craig and Boroughs (2004); Jasem and Ismail (2006); Tewolde and Smithers, (2006); Shrestha and Franz (2007) and Rolando *et al.* (1994) but none of these applications have attempted to verify the M-C model. This wide spectrum of the utilization of the M-C technique indicates its universal acceptability as a flood routing tool. This study did not estimate flood levels but instead, streamflow rate was generated in addition to the flood wave travel time.

1.1 Objectives of the Study

The general objective was to develop a flood early warning system to mitigate potential flood hazard risk from the Yala river basin. To achieve the general objective, the following were the specific objectives:

(i) To perform the sensitivity analysis, calibration and verification of the GeoSFM system.
(ii) To simulate streamflow at Yala at Bondo streamflow gauging station (1FG02) using the GeoSFM system.
(iii) To route the simulated streamflow from the Yala at Bondo streamflow gauging station (1FG02) to Yala at Kadenge streamflow gauging station (1FG03) using the M-C streamflow routing technique.

2.0 Research Design and Methods

2.1 Data for the Study

Several data sets (Table 1 and Figures 1-3) were used to model streamflow using the GeoSFM and M-C models.

Table 1: Data types, period, category and sources

Data Type	*Period*	*Category*	*Data Sources*
Rainfall data	1975-2005	Secondary data	Kenya Meteorological Department, Nairobi
Evaporation data	1975-2005	Secondary data	Kenya Meteorological Department, Nairobi
Streamflow data	1975-2005	Secondary data	Water Resources Management Authority
Soils data	1997	Secondary data	Digital Soil Map of the World developed by Food and Agricultural Organization
Land cover data	2006	Secondary data	United States Geological Survey
Digital elevation model (DEM)	2009	Secondary data	International Centre for Research in Agro-forestry
River channel hydrologic characteristics	2009	Primary data	Measured using the River Discharge Measurement System (Qliner) at 1FG02 and 1FG03 sub-reaches

Rainfall, evaporation and streamflow gauging stations from the Yala river basin were as shown in Figure 1.

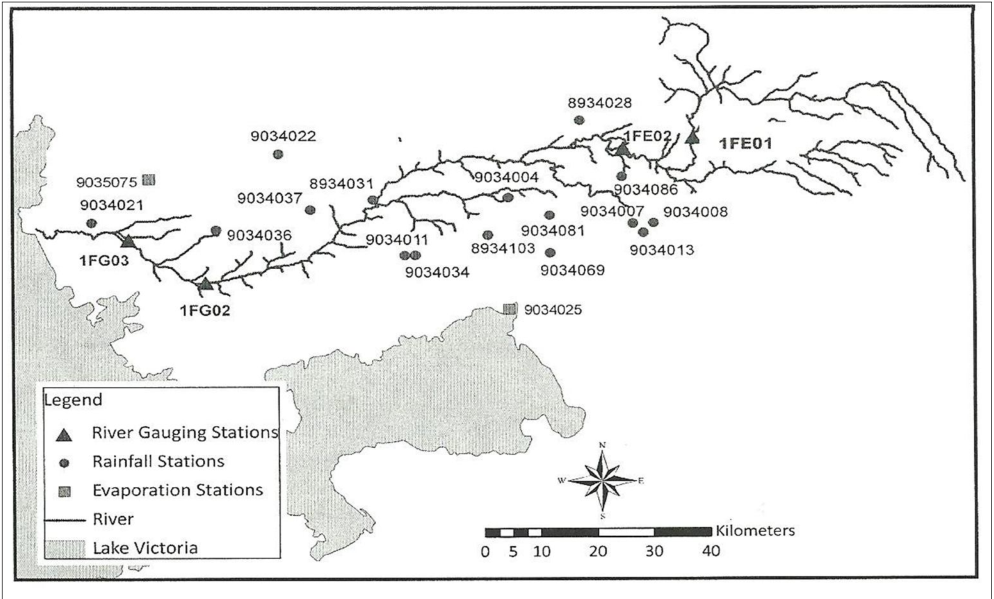
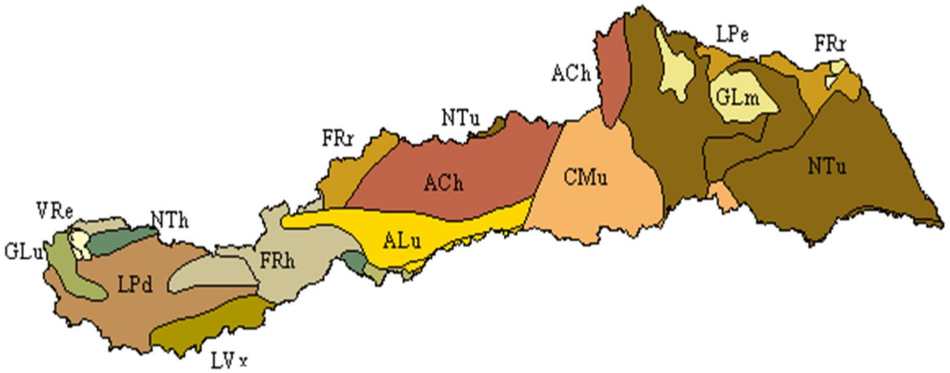


Figure 1: Rain gauges, streamflow gauges and evaporation stations used for modeling the Yala River basin



ACh - Haplic Acrisols
ALu - Humic Alisols
CMu - Humic Cambisols
FRh - Haplic Ferralsols
FRr - Rhodic Ferralsols
GLm - Mollic Gleysols
GLu - Umbric Gleysols
LPd - Dystric Leptosols
LPe - Eutric Leptosols
LVx - Chromic Luvisols
NTh - Haplic Nitosols
NTu - Humic Nitosols
VRe - Eutric Vertisols

Figure 2: Category of soils in the Yala river basin (FAO, 1997)

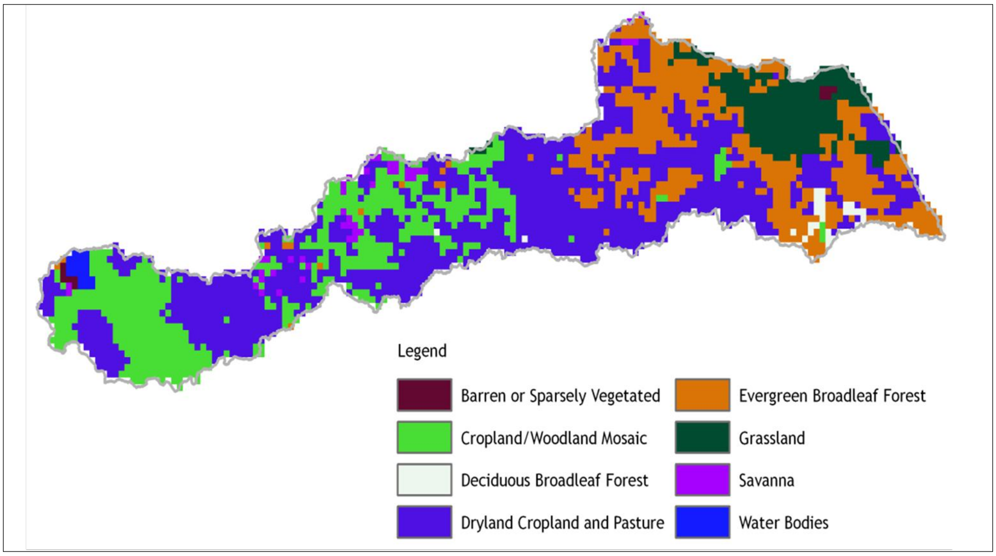


Figure 3: Land cover for Yala River basin (Source: USGS continent data sets)

2.1.1 Split Record Analysis

Split record analysis (Table 2) was done on the daily series datasets of rainfall, evaporation and streamflow for the purposes of model calibration, verification and flow routing. This split record analysis represented the diverse weather and climatic conditions and hence fully characterized the features and the dynamic nature of the catchment.

Table 2: An illustration of split record analysis on the hydro-meteorological datasets

Modeling phase	*Record considered*	*Duration (years)*
GeoSFM calibration	1980-1985	6
GeoSFM verification	2000-2005	6
M-C streamflow routing	1975-2005	31

2.2 Parameter Sensitivity Analysis

In order to guide the calibration process, parameter sensitivity analysis was done to identify which parameters had much impact in the model's generated streamflow. Rainfall from the sampled 20 raingauges and evaporation from the two evaporation gauges in the Yala river system were used to perform the parameter sensitivity analysis. Initially, interpolation of station data to grid was done to equally spread and distribute the rainfall and evaporation over the entire river basin. The major model parameters are the river Manning's coefficient (n), the Runoff Curve Number (RCN), Active Soil Depth (ASD) and the Water Holding

Capacity (WHC) of the soil (McCuen, 1998; Guleid et al., 2007 and Asante et al., 2007).

2.3 Model Calibration

The calibration of the GeoSFM computer code was automatically done using the Multi-Objective Shuffled Complex Evolution Metropolis (MOSCEM) Algorithm (Vrugt et al., 2003). The hydrologic datasets for the Yala river system were divided into two sets to create a set used for model calibration (period 1980-1985) and another set used for validation (period 2000-2005). This period was considered suitable for it had the least number of missing values in daily observed streamflow data. An agreement between the observed and simulated streamflow was made in terms of coefficient of determination (R^2 value) and a visual examination was done on the input data, recorded and simulated streamflow to determine any discrepancies from the regression charts.

2.4 Model Validation

To validate the GeoSFM, the already calibrated model should be able to make sufficient accurate predictions. Daily rainfall and evaporation data for the period of 2000-2005 were used. This period was specifically chosen for the validation exercise because high streamflow values or floods were known to have occurred in Yala river system during this time, 2003 in particular, hence a good test period for the GeoSFM computer code performance. The resulting streamflow was compared to the observed values, and the goodness of fit evaluated.

2.5 Streamflow Routing

The main purpose of calibrating the GeoSFM computer code was to use it in forecasting streamflow for the Yala river basin at 1FG02 situated at Yala at Bondo bridge in readiness for applying the M-C streamflow routing technique. This was done so that in the case of an impending flood, the people living in the floodplains areas could be warned in advance of the impending flood hazard.

2.6 Simplifications/Assumptions Adopted in the Study

When modeling the hydrology of the Yala river channel using the M-C model, the following assumptions were made:

(i) When routing streamflow from station 1FG02 to 1FG03, it was assumed that the hydrologic and channel characteristics did not change but only varied at 1FG03 station

(ii) That there was no lateral inflow of water from the surrounding area into the river channel.

2.7 Overview of the GeoSFM Hydrologic Modeling System and the M-C Model

2.7.1 The GeoSFM Hydrologic Modeling System

The GeoSFM is a semi-distributed hydrologic model developed by the United States Geological Survey's Earth Resources Observation System (EROS) Data Centre. The GeoSFM simulates the dynamics of runoff processes by using remotely sensed and widely available global datasets. The GeoSFM model assimilates spatially distributed data to simulate streamflow on a daily basis. The model is a physically-based catchment scale hydrologic computer code. It consists of a Geographical User Interface (GUI) and a rainfall-runoff simulation component. The GeoSFM GUI component runs within the GIS for model input, data preparation and visualization of the model outputs. Topographic, land cover and soil information are the basic inputs to derive and parameterize the hydrologic modeling units.

The GeoSFM uses a linear reservoir concept to route overland flow. The integral equation of continuity for an unsteady, constant density overland flow is used to route the overland flow and is expressed as Eq. 1.

$$\frac{\delta s}{\delta t} = I(t) - Q(t) \quad \ldots\ldots (1)$$

where, (*S*) is the volume of fluid stored in control volume,

($\frac{\delta s}{\delta t}$) is the change in storage,

{*I (t)*} is the inflow,

{*Q (t)*} is the outflow.

The GeoSFM utilises the modification of Eq. 1 to determine the overland flow, as in Eq. 2.

$$S_j = S_0 + \sum_{i=1}^{j} (I_i - O_i) \quad \ldots\ldots (2)$$

Where, (S_0) is the initial storage at time (*0*),

(S_j) is the storage after time (*j*).

(I_i) is the inflow after time (*i*).

(O_i) is the outflow after time (*i*).

2.7.2 The M-C Model

The Muskingum Cunge (M-C) model is applied in the streamflow routing module of the GeoSFM. Mathematically, the M-C model is expressed using the conventional original Muskingum Eqs. 3 and 4.

$$\frac{\Delta S}{\Delta t} = I - Q \quad \ldots\ldots (3)$$

$$S = K[XI + (1 - X)Q] \quad \ldots\ldots (4)$$

The Muskingum K and X coefficients are estimated using Eqs. 5 and 6.

$$K = \frac{\Delta x}{\bar{c}} \qquad (5)$$

$$X = \frac{1}{2} - \left(\frac{\bar{Q}}{2\bar{c}\bar{B}S_e \Delta x} \right) \qquad (6)$$

where, ($\bar{Q}$) is the streamflow (m^3/s),

(*K*) is the Muskingum *K* coefficient (seconds),
(*X*) is the Muskingum *X* coefficient (dimensionless),
($\bar{c}$) is the average flood wave celerity corresponding to the streamflow ($\bar{Q}$) in meters per second,
($\bar{B}$) is the average channel width associated with the streamflow ($\bar{Q}$) in meters,
(S_e) is the dimensionless friction or the channel bed slope,
(Δx) is the length of the channel (meters),
(*S*) is the storage in the channel at time (*t*) in meters per second,
(*I*) is the inflow (m^3/s).

The GeoSFM was calibrated, verified and subsequently applied on the Yala river basin based on a split record analysis (Table 2) to model streamflow at 1FG02 station which was then routed by the M-C model to 1FG03 station to generate flood early warning system for the river basin downstream inhabitants.

3.0 Results and Discussions

Daily series of the rainfall, evaporation together with the soils, land use and topographical information modeled streamflow. Daily series of observed streamflow data compared with the model's generated streamflow to assess the correlation between the two for model performance testing. All hydro-meteorologic variables spanned within the period 1975 to 2005 that defined and incorporated climate change aspects. A digital elevation model of the study area guided and routed the generated streamflow to the downstream region guided by the terrain of the catchment. The hydro-meteorological datasets used in this study included streamflow data records of the streamflow gauging stations 1FE01, 1FE02, 1FG02 and 1FG03, rainfall data records for 20 rain gauging stations and the evaporation data records for Kisumu and Kadenge evaporation stations. The results from sensitivity analysis, calibration, verification and routing are presented in the sub-sections that follow.

3.1 Parameter Sensitivity Analysis

The most sensitive parameters (Table 3) obtained after parameter sensitivity analysis were soil water holding capacity with a standard deviation (SD) value of

0.489mm, total soil depth with a sd value of 0.443cm, excess rainfall with a SD value of 0.421 mm, river channel roughness coefficient (Manning n) with a sd value of 0.314 and scs runoff curve number with a sd value of 0.223.

Table 3: Parameter sensitivity analysis results of the GeoSFM system

S. No.	***Sensitivity parameters category***	***Maximum value***	***Mean value***	***Standard deviation (SD) value***
1	SoilWhc [soil water holding capacity (mm)]	1.790	0.550	0.489
2	Depth [total soil depth (cm)]	1.822	0.402	0.443
3	Texture [soil texture]	0.255	0.031	0.043
4	Ks [saturated hydraulic conductivity (cm/hr)]	0.775	0.061	0.144
5	Interflow [interflow storage residence time (days)]	0.014	0.009	0.003
6	HSlope [average sub-basin slope]	0.050	0.006	0.011
7	Baseflow [baseflow reservoir residence time (days)]	0.026	0.009	0.009
8	CurveNum [SCS runoff curve number]	0.654	0.157	0.223
9	MaxCover [permanently impervious cover fraction]	0.895	0.171	0.250
10	BasinLoss [fraction of soil water infiltrating to ground water]	0.000	0.002	0.000
11	PanCoeff [pan coefficient for correcting PET readings]	0.849	0.275	0.262
12	TopSoil [fraction of soil layer that is hydrologically active]	0.504	0.078	0.099
13	RainCalc [excess rainfall (mm)]	1.229	0.278	0.421
14	RivRough [river channel roughness coefficient (Manning n)]	0.384	0.100	0.314
15	RivSlope [average slope of the river]	0.013	0.000	0.001
16	RivWidth [average channel width]	0.010	0.000	0.001
17	RivLoss [fraction of the flow lost within the river channel]	0.035	0.002	0.003
18	RivFPLoss [fraction of the river flow lost in floodplain]	0.267	0.019	0.037
19	Diffusion [flow attenuation coefficient (m^3/sec)]	0.000	0.000	0.000
20	Celerity [flood wave celerity (m/sec)]	0.022	0.000	0.001

3.2 Calibration phase of the GeoSFM

The GeoSFM performed better during the verification phase than during the calibration phase. At the verification phase, the R^2 value obtained was 87.3% while a the calibration phase, it yielded a R^2 value of 80.6%. Figure 4 shows the mean rainfall (mm), observed and simulated streamflow (m^3/sec) for the period 1980 to 1985 during the model calibration phase in the Yala River basin.

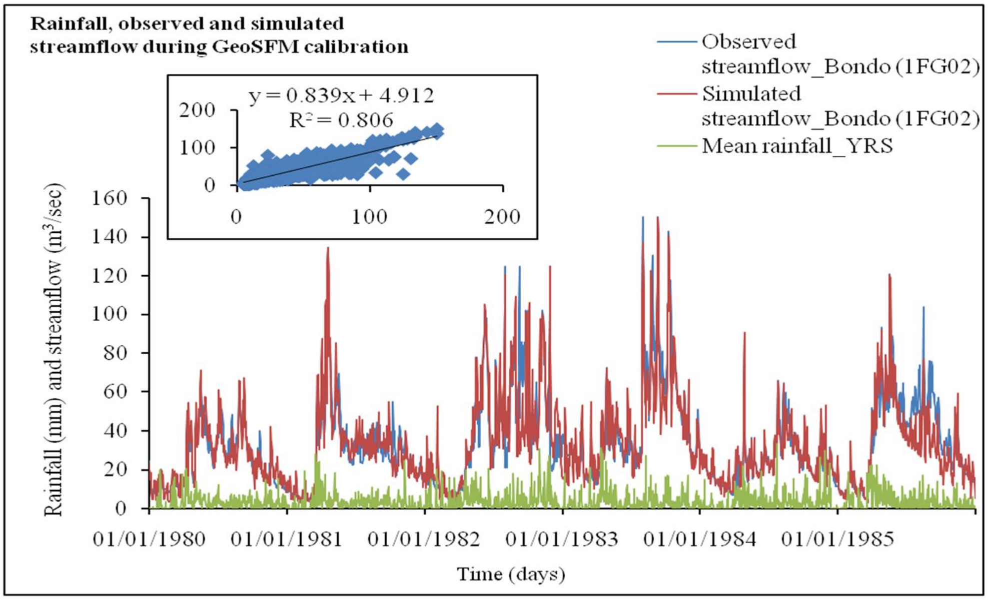


Figure 4: A hydrograph showing rainfall, observed and modeled streamflow for station 1FG02 in the Yala River basin during the calibration phase

3.3 Verification/validation phase of the GeoSFM

The calibrated GeoSFM was applied on the mean rainfall of the period 2000-2005 to verify the ability of the model to reproduce well fitted and accurate hydrographs. In general, at the verification phase, the GeoSFM proved to very well simulate the streamflow at the 1FG02 station with a R^2 value of 87.3%. The hydrograph for the period 2000-2005 was selected for presentation as in Figure 5 which shows the mean rainfall (mm), observed and simulated streamflow (m^3/sec) obtained during the model verification phase in the Yala river basin.

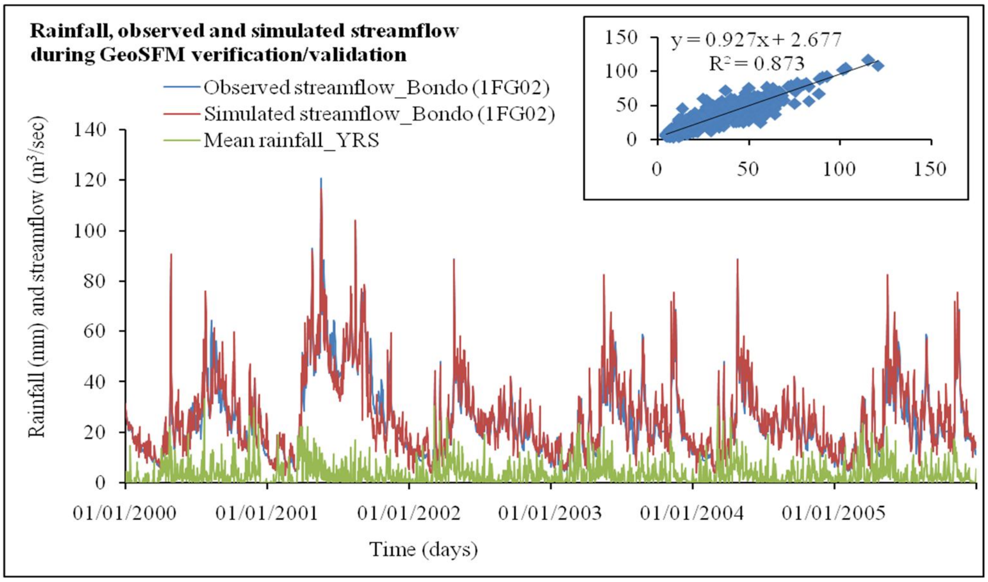


Figure 5: A hydrograph showing rainfall, observed and modeled streamflow for station 1FG02 in the Yala river basin during the verification phase

3.4 Streamflow Routing Phase using the Muskingum Cunge Model

Figure 6 shows the correlation between the observed and the routed streamflow at 1FG03 streamflow gauging station as was routed by the M-C model.

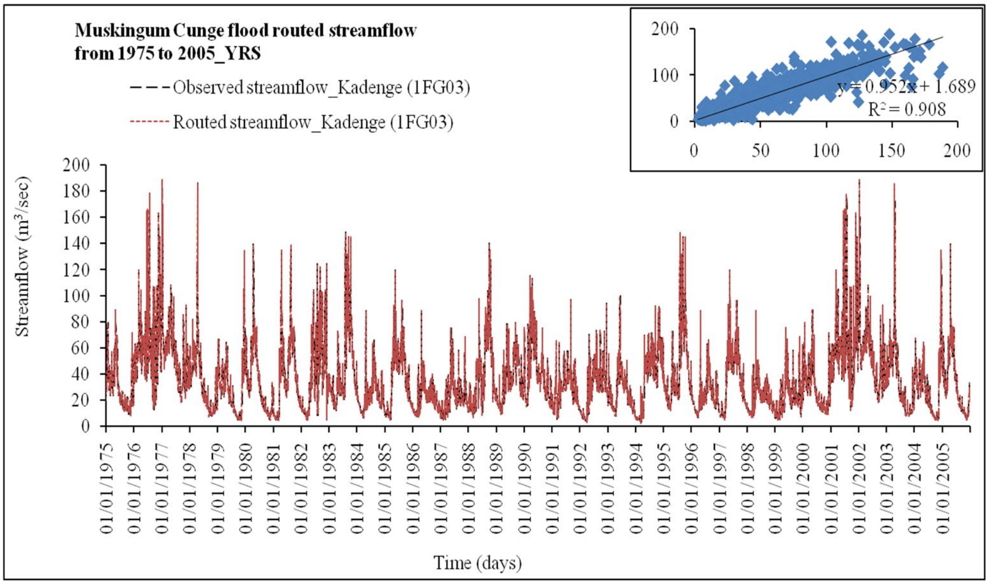


Figure 6: A hydrograph of the observed and routed streamflow showing the R^2 value at station 1FG03 for the period 1975-2005 in Yala river basin

From Figure 6, the highest flood peak values were identified in the years 1978, 1989, 1997, 2002 and 2003. As indicated by historical flood records, these years recorded flood incidents downstream of the Yala river basin. In general, streamflow was routed using the M-C streamflow routing method from the station 1FG02 to the station 1FG03 for the period 1975-2005 at a R^2 value of 90.8%. The lack of fit with the rising and falling limbs of the measured outflow hydrograph that made the R^2 value not to yield 100% was probably due to out-of-bank floodplain inundation. The M-Cunge K and X parameter values obtained on routing the flood from 1FG02 station to 1FG03 station were as shown in Table 4.

Table 4: Muskingum Cunge K and X parameter values obtained during the streamflow routing phase

Streamflow Routing Phase (1975-2005)	
Muskingum Cunge parameters and channel length	River sub-reach
	1FG02 to 1FG03 gauging station
Channel length Δx (Kilometers)	14.00
Computational time Δt (seconds)	7200
Muskingum K (seconds)	9953
Muskingum K (hours)	2.76
Muskingum X (ratio)	0.4609

Based on the derived M-C parameter values in Table 4, it meant that a drop of water that was released from 1FG02 station at time zero seconds took 9953 seconds, which was equivalent to 2.76 hours, to propagate along the river channel to 1FG03 station. The inhabitants of the downstream region of the 1FG03 station in the Yala river basin hence needed to be warned 2.76 hours in advance of an impending flood disaster originating from the Yala river basin when streamflow monitoring was based at 1FG03 station.

3.5 Application of the Results

The downstream zone of the Yala river basin is not protected from riverine flooding. Flood mitigation can be achieved by either utilizing structural measures (include dykes and dams among others) or non-structural measures (include early warning and awareness creation among others). The generated 2.76 hours of early warning forms a non-structural flood mitigation strategy when it is communicated to the inhabitants downstream of the Yala river basin. In the event of an impending flood, the inhabitants of the downstream zone are able to evacuate the area to safer areas within a period of 2.76 hours. This evacuation will save both their lives and livelihoods from the flood inundation. This lead-time is also important to decision makers who administer flood mitigation measures in the floodplain.

4.0 Conclusions

This study concludes that:

(i) The sensitivity analysis, calibration, verification and flow routing applications using the GeoSFM and M-C models on the hydro-meteorologic and geospatial datasets were able to model streamflow in the river channel sub-reaches with high R^2 values. Decision makers could then administer flood mitigation measures in the Yala river floodplain on an informed foundation.

(ii) The modeled streamflow was able to generate the flood wave travel time. This provided a non-structural solution to the flood problem in the Yala river floodplain.

(iii) The GeoSFM and M-C models were applied to predict and route floods using variables in the Yala river and it was postulated that the methods could be used to model floods in other ungauged rivers in Kenya and in other countries experiencing riverine flooding.

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