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Hec-Hms Model for Runoff Simulation in Ruiru Reservoir Watershed

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ABSTRACT: *Several River Basins across the world have been simulated using hydrological models to understand hydrological processes and the availability of water resource. Some of these basins are ungauged. In this study in order to evaluate the hydrological process of Ruiru reservoir for sustainable management; HEC-HMS 4.1 hydrologic model (with Soil moisture Accounting Algorithm)is used to simulate its runoff. WMS 10.1 (Watershed Modelling Surface) was used as an interface to delineate the watershed and generate some input (basins parameters). The SMA parameters are computed in WMS using land use and soil type data. Daily rainfall and monthly evapo-transpiration for 5 years (2011-2015) were used for the meteorological inputs. The results showed a total volume of runoff 202,860,900 m^3during the five years of the simulation. The peak discharge was found to be 79.6m^3/s and the daily average of the inflow during the five years was found to be 1.28m^3/s. The model evaluation has showed the efficiency of the model to be 0.74 and 0.72 respectively for the calibration and the validation, indicating that the results of the simulation are satisfactory.*

Keywords: *HEC-HMS, Kenya, Runoff, Simulation, Ruiru Reservoir Watershed, WMS*

I. INTRODUCTION

Reservoirs play a critical role in economies….Reservoirs store water, for domestic, irrigation, industrial, hydropower, and environmental water use sectors. Due to their importance, many reservoirs have been constructed in recent times (Avakyan & Iakovleva, 1998; Gleick, 2003) and more are expected in the current century. Provision of water is a trade-off that serves to ensure a balance between water demands from various sectors and water from the reservoirs. In Kenya reservoirs are used for domestic water supply, irrigation, or hydropower. Once such is Ruiru reservoir. Ruiru reservoir is one of the sources of water supply in Nairobi and it supplies about 21,700 m^3/day (Chakava et al., 2014; Wambua, 2004). Hydrological modelling is a commonly used tool to estimate and assess the basin's hydrological response as a result of precipitation. It facilitates accurate predictions based on hydrologic response to various watershed management practices enhancing a better understanding of the implications of these practices (Choudhari, et al, 2014). HEC-HMS 4.1 hydrologic model (Developed by US Hydrologic Engineering Center) was used in this project due to its availability (open source) and its performances. It has been used worldwide by researchers like; Gebre (2015) who used HEC-HMS 3.5 to calibrate (from 1988-2000) and validate (from 2001-2005) the upper Blue Nile River Basin, and Sampath et al (2015) who described a case study of continuous rainfall-runoff modeling in part of the Deduru Oya basin in Sri Lanka. Ruiru reservoir is poorly gauged and hydrograph data are unavailable or sparse. There is then an undeniable necessity to undertake a study on hydrologic simulation to generate some runoff data for a sustainable management of the reservoir under different scenarios. The objective of this study is to apply HEC-HMS as a tool for generating runoff data for the Ruiru reservoir watershed and come up with sustainable management under different scenarios.

II. MATERIALS AND METHODS

The study Area

Location

Ruiru reservoir is located about 60 km north of the capital city in Central Kenya near Githunguri town. According to Sang et al, (2015) and Lind (1965) the reservoir covers about 100 acres and is about 18 meters deep at the dam wall. The main sources of water to reservoir are Ruiru and Kimaiti rivers. These rivers flow mainly from cultivated or grazing land within the reservoir's watershed (Lind, 1965).Ruiru reservoir is one of the strategic sources of water to the City of Nairobi. It supplies the City of Nairobi with about 21,700 m^3/day (Chakava et al., 2014; Wambua, 2004).

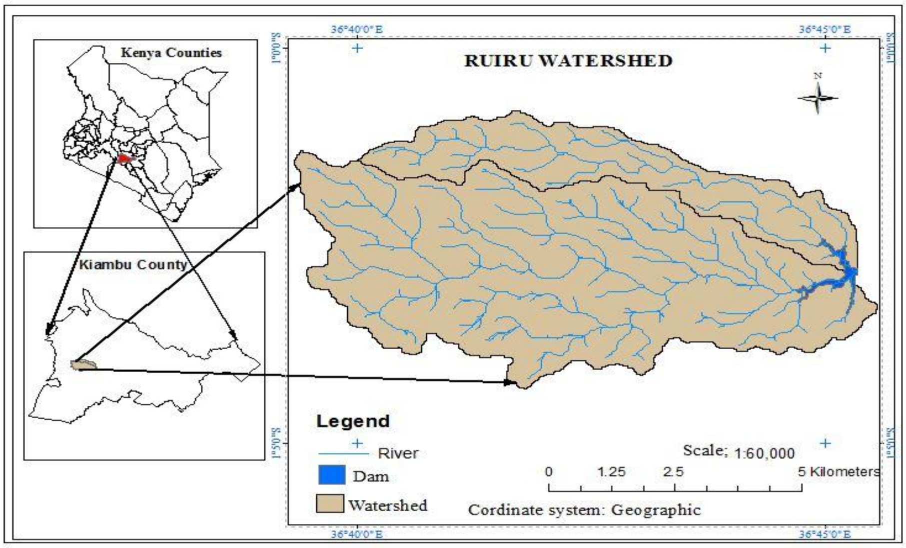

Figure 1*: Location of the Study Area*

Climatic Condition

According to Athi Water (2016); the region is characterises by equatorial climatic conditions and rainfalls is highly influenced by altitude and proximity to the Aberdare forest. Rainfall in the area comes in two seasons, long rains come between March to May and short rains come between October and December. The annual mean rainfall varies from 1070mm to 1750mm. Climatic condition is impacting on the watershed hydrograph during the whole year.

The mean temperature in the study area is approximately 26^0C with temperature ranging from 17.1^0C in the upper high lands to 34^0C in the lower midlands. July and August are the months during which temperatures are lowest, whereas January to March is the hottest. The temperature are impacting on the Evapotranspiration so on the volume of the reservoir.

Land use

The area is dominantly under mixed farming, which is influenced by agro-ecological zones, Soil fertility and climate as well as cultural practices. Land use in the study area is dominated by crop growing where majority of the land is planted with tea, coffee, vegetables, bananas and agro-forestry. Other land use activities in the area include: Intensive dairy farming, housing, land occupied by infrastructure, forestry as well as Water masses. The land use is influencing the drainage of the watershed.

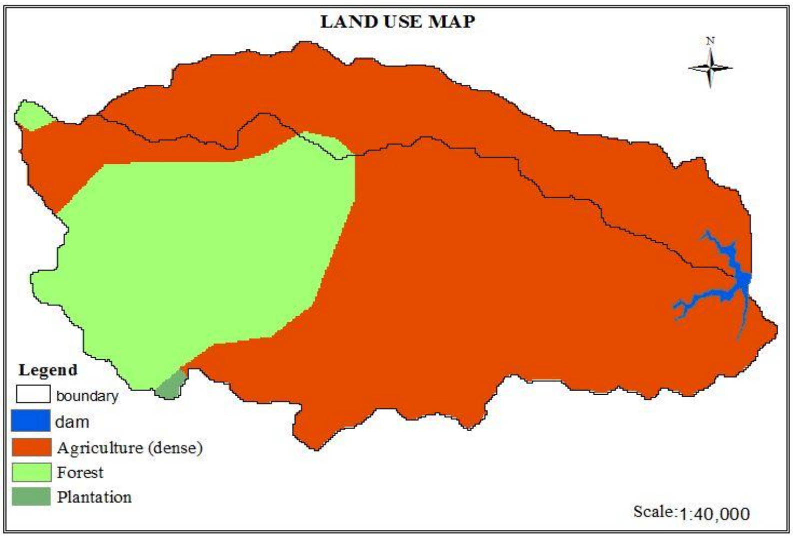

Figure 2: Ruiru Reservoir Watershed Land Use

Geology and soil

According to Athi Water (2016); the geology of the study area is part of the eastern border zone of the Rift Valley filled with Kaino zonic volcanic and sediments directly underlain by the upper Athi series, which consists mainly of sandy sediments and Tufts. These upper Athi series generally provide good aquifers with high precipitations ensuring sufficient recharge of ground water. Soil types are depended on underlying rock formations, surface drainage conditions and rainfall patterns. The effect of sedimentation on the reservoir is related to the geology and the type of soil of the study area.

Data Source

DEM, world imagery imported from WMS 10.1 were combined with a SRTM of 30 m downloaded from USGS to delineate the watershed using WMS.10.1. Geological data, land use and soil information from International livestock Research Institute (ILRI) were used to understand the nature of the watershed. Rainfall data collected from Kenya Meteorological Department (KMD) and Evapo-transpiration data collected from Coffee Research Institute (CRI) were used like input data in model. Streamflow used for calibration and validation were collected from Water Resource Management (WARMA).

Watershed Delineation

WMS 10.1 was used for watershed delineation. The watershed and sub basins delineation was carried out based on an automatic delineation procedure using a Digital Elevation Model (DEM) and digitized stream networks.

HEC-HMS

The Hydraulic Engineering Center - Hydrologic Modelling System (HEC-HMS) is a software developed by the US Army Corps of Engineers-Hydrologic Engineering Center. HEC-HMS is intended to simulate the entire hydrologic processes of dendritic watershed systems. The software consists of many traditional hydrologic analysing procedures such as hydrologic routing, unit hydrographs, and event infiltration. The model also incorporates procedures necessary for continuous simulation including soil moisture accounting, snowmelt, and evapo-transpiration. Advanced capabilities are also provided for gridded runoff simulation using the linear quasi-distributed runoff transform (ModClark). Supplementary analysis tools are provided for forecasting streamflow, model optimization, depth-area reduction, water quality, sediment transport and erosion, and assessing model uncertainty. The software features a fully integrated work environment that includes data entry utilities, a database, results reporting tools, and computation engine. A graphical user interface provides the user seamless movement between the different parts of the software (USACE, 2015). HEC-HMS Model setup consists of four main model components: basin model, meteorological model, control specifications, and input data (time series, paired data, and gridded data).The Basin model for instance, contains the hydrologic element and their connectivity that represent the movement of water through the drainage system USACE (2015).

Soil Moisture Accounting Method (SMA)

For a Continuous simulation it is the Soil Moisture Accounting (SMA) model that is adequate. Unlike previous models, SMA is a model that can consider long periods with an alternation of rain and dry weather. SMA simulates the movement of water through the various components of a watershed. From the data of precipitation and evapotranspiration, it calculates surface runoff, seepage, evaporation and deep percolation. The watershed is represented by a series of storage layers: Storage interception by plant, which represents the layer of the water held by vegetation (grasses ,trees ...) and so does not reaches the ground, evaporation is the only way to clear it; Storage by surface intercept is the layer which is filled when the maximum infiltration is reached, when full, it overflows to create surface runoff; Storage subsurface which is representing the water retained in the soil at shallow depth and may be submitted to evapotranspiration and the last is Storage of groundwater where the water is obtained by percolation (the rate is to be determined) and considered lost to the system. The rate of infiltration, percolation and evapotranspiration are calculated every minute from the respective maximum potential rate and system status to the previous time. This simulates the flow between the different layers in each time. The parameters needed for needed for SMA model (surface depression storage, canopy maximum interception infiltration rate storage, soil storage, soil zone percolation rate) and tension zone storage) are estimated using land cover land use and soil information data downloaded from International livestock Research institute Web site. The Soil's physical properties, such as porosity and field capacity were estimated of soil parameters from the soil type downloaded from International livestock Research Institute (ILRI. Groundwater 1 and 2 (hereafter referred as GW1 and GW2) storage depths and storage coefficients estimated by stream flow recession analysis of past stream flow observations. The soil percolation rate based on the hydraulic conductivity of soil profile. The groundwater 1 and 2 percolation rates were determined through model calibration.

Calibration and Validation

The model calibration and validation is done using streamflow observed data for 2003 and 2004 respectively for calibration and validation. Due to lack of streamflow data, only basin 1 is calibrated and validated. The streamflow gage called 3BC07 located at longitude: at -1.0372 and latitude: 36.7425 was used. Parameters transfer was made on the whole watershed. Parameters transfer consist to change the parameters of the watershed considering the percentage of change of the parameters value in basin 1 after calibration and validation. The sensitivity analysis of the model was performed to determine the important parameters which had to be precisely assessed to make precise prediction of basin yield. Thus, at first the model was implemented with the model input values making the base data file, estimated by methods presented above and base output was collected. This was then followed by comparing each input parameter within suggested range keeping the others constant and running the model. The output values were analyzed to determine their variations with respect to the base output set and this acts as a measure of the sensitivity. It was then calibrated for the identified sensitive parameters to improve the agreement between the observed and simulated data. However, the automated calibration procedure in HEC-HMS uses an iterative method to minimize an objective function, such as sum of the squared residuals, sum of the absolute residuals, peak-weighted root mean square error etc. (HEC 2000). Thus, both manual and automated calibration methods were used for this study.

Model Evaluation

To evaluate the model for this study the criteria adopted are the Percentage Error in simulated volume (PEV) , Percentage error in simulated peak (PEP), and Net difference of observed and simulated time to peak (NDTP), as given below:

$$PEP = \frac{Vol_o - Vol_c}{Vol_o} \text{x} 100 \tag{1}$$

$$PEP = \frac{Q_{po} - Q_{pc}}{Q_{po}} \text{x} 100 \tag{2}$$

$$NDTP = \frac{T_{po} - T_{pc}}{T_{po}} \text{x} 100 \tag{3}$$

Vol_o is the observed runoff volume (m^3); Vol_c is the computed runoff volume (m^3); Q_{po} is the observed peak discharge (m^3 /s); Q_{pc} is the computed peak discharge (m^3 /s); T_{po} is the time to peak of observed discharge (h); and T_{pc} is the time to peak of computed discharge (h).

The PEV value is the measure of deviation between the simulated and the observed volume of stream flow. NDTP and PEP values measure the average absolute time lag and the percent deviation between the simulated and observed peak flows, respectively. The prediction of overall performance of the model was assessed using Nash - Sutcliffe model efficiency (EFF) criterion (Nash and Sutcliffe, 1970), recommended by ASCE Task Committee (1993) where Q_{oi} is i^{th} ordinate of the observed discharge (m3 /s); Q_o is the mean of the ordinates of observed discharge (m3 /s); Q_{ci} is i^{th} ordinate of the computed discharge (m3 /s).

$$EFF = \frac{\sum_{i=1}^{n} (Q_{oi} - \overline{Q_o})^2 - \sum_{i=1}^{n} (Q_{oi} - Q_{ci})^2}{\sum_{i=1}^{n} (Q_{oi} - \overline{Q_o})^2} \tag{4}$$

The EFF values can vary from 0 to 1, with 1 indicating a perfect fit of the data. Conventionally, simulation results are considered to be good for values of EFF greater than or equal to 0.75, while for values of EFF between 0.75 and 0.36 the simulation results are considered to be satisfactory (Motovilov et al., 1999).

III. RESULTS AND DISCUSSION

Basin Model

After the watershed delineation total area was found to be 50.27 Km2 and it was devised in two sub basins. The following table give the different information about the characteristic of the two sub basins.

Table (1): watershed's sub basins physical parameters

Basins	**Area (Km^2)**	**Basin slope (m/m)**	**Basin Length(Km)**	**Mean Basin elevation**	**Max stream length (km)**	**Concentration time (hrs)**	**Coeff of storage**
Basin1	11.77	0.103	11.77	2154.5m	12.52	3.2 hrs	35
Basin2	38.5	0.1122	11.46	2180.23m	13.85km	3.5 hrs	80

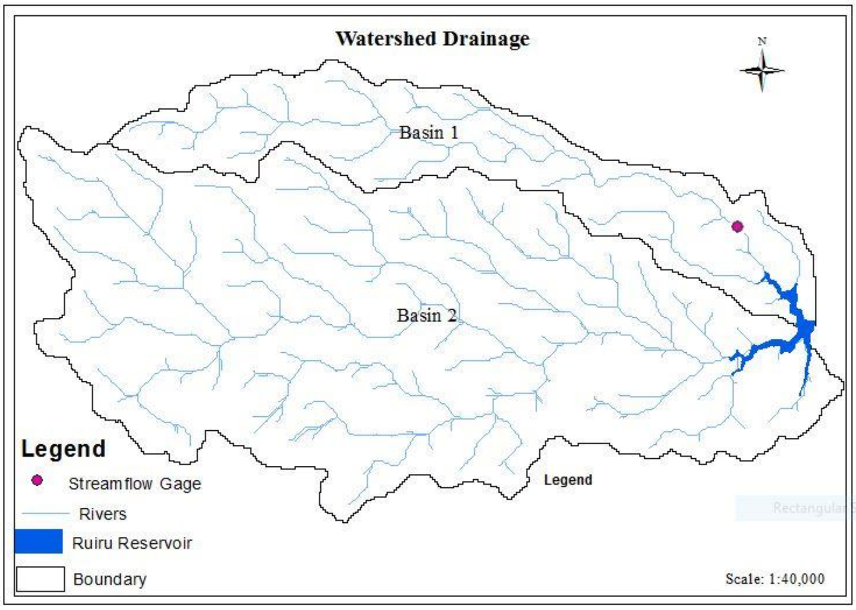

Figure 3: Ruiru Watershed Drainage

Calibration and Validation

SMA model parameters

The SMA model parameters were computed and estimated in WMS. Some of these parameters were changed after the calibration to match with the observed data. These parameters are discussed below in Sensitive analysis section. The following table give the SMA model parameters.

Table (2): SMA model parameters for Ruiru reservoir watershed simulation

Parameters	Default	Adjusted
Canopy storage	1 mm	1 mm
Surface storage	53 mm	55 mm
Soil Storage capacity	0.5 mm	2 mm
Soil tension storage capacity	1.5 mm	0.5 mm
Soil maximum Infiltration Rate	0.6 mm/hr	0.6 mm/hr
Soil Maximum percolation Rate	0.6 mm/hr	0.6 mm/hr
Groundwater 1 Storage Capacity	55 mm	55 mm
Groundwater 1 Max percolation Rate	0.8 mm/hr	0.8 mm/hr
Groundwater 1 Storage Coefficient	4500	6000
Groundwater 2 storage Capacity	50 mm	50 mm
Groundwater 2 Max Percolation Rate	0.8 mm/hr	0.8 mm/hr
Groundwater 2 Storage Coefficient	1500	2000

Model evaluation Results

It was found three parameters are the most sensitive; the most sensitive parameter is soil storage following by the groundwater Storage coefficient and the soil tension storage capacity. Observed flow data from basin 1 for year of 2003 were used for the calibration. We noticed that the percentage error in simulates volume (PEV) was found to be 44.95 %, the percentage error simulates peak flow (PEP) was found to 27.2%, the net difference of observed and simulated time to pick (NDTP) was found to be 1 and the model Efficiency was 0.74. To validate the model; observed flow data from basin 1 gage station were used. We noticed that the percentage error in simulate volume (PEV) was 10.22%, the percentage error simulates pick flow (PEP) was found to be 9.5%, the Net difference of observed and simulated time to peak (NDTP) was found to be 4 and the model Efficiency (EFF) was 0. 72. Table 3 is giving more details on the Calibration and validation.

Table (3): The performance of the model for the Calibration and validation Years

Measure	Simulated	observed	Difference	Percentage difference	Model Efficiency
` **CALIBRATION (2013)**					
Volume(1000m^3)	26510.8	18289.2	-8221.6	-44.95	0.74
Peak Flow (m^3/S)	12.6	9.9	2.7	27.2	
Time of Peak	07May2003	06May2003	1	-	
VALIDATION (2015)					

Volume (1000 m^3)	16862.0	15298.8	1563.1	-10.22	0.72
Peak Flow (m^3/S)	5.1	4.7	0.4	9.5	
Time of Peak	10Oct2004	14Oct2004	4	-	

Notice that for the calibration EFF= 0.74 means the model was satisfactory and for Validation EFF= 0.72 means simulation result is considered to be satisfactory. The all model can be considered to satisfactory.
The below hydrographs are expressed the results discussed above.

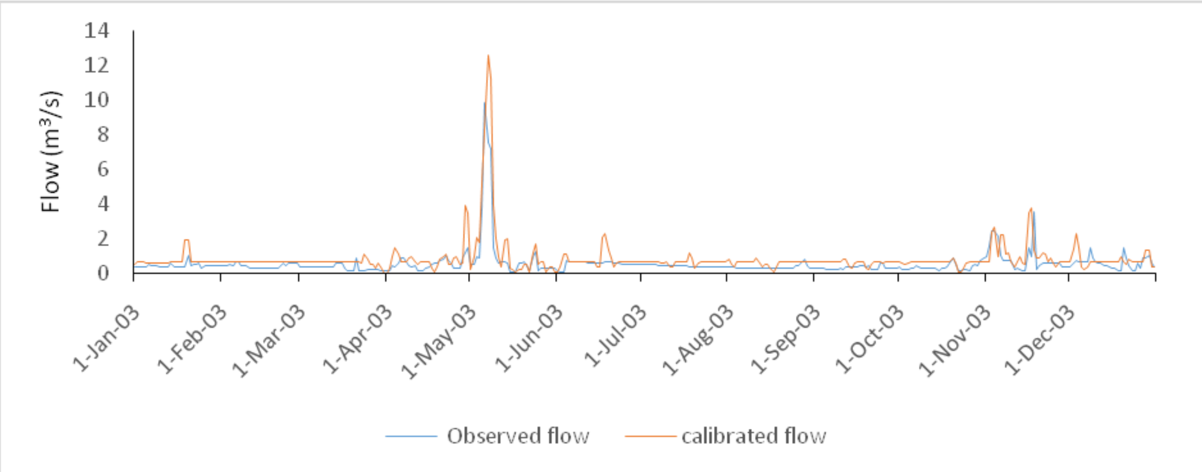

Figure 4: Observed and calibrated hydrograph for 2003

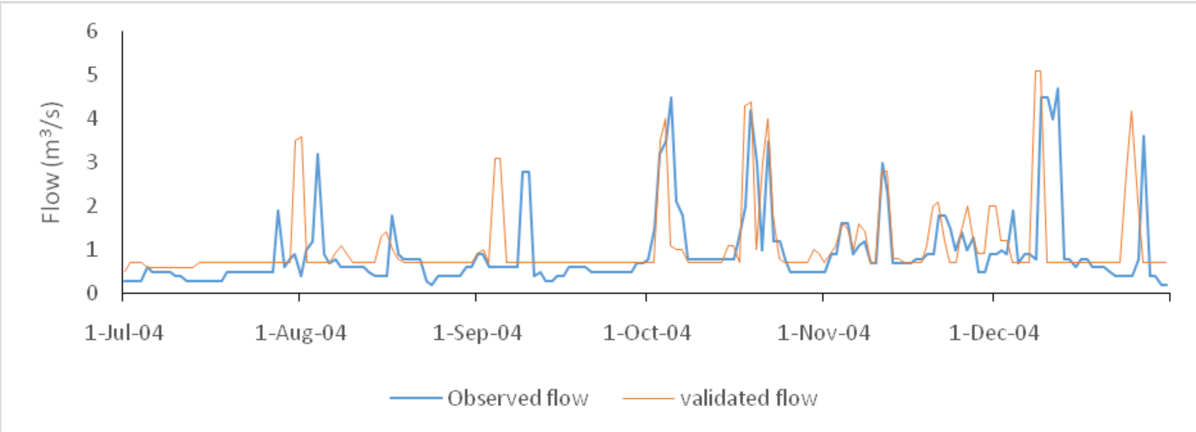

Figure 5: Observed and validated hydrograph for 2004(July - December)

The Watershed Runoff Simulation

After the calibration and validation we can now be confident with the runoff generated by the model. The total runoff observed during the five years (2011-2015) in the watershed was found to be 202,860,900 m^3 (154,264,400 m^3 for basin 1 and 154,264,400 m^3 for basin 2). The peak discharge is 79.6 m^3/s. This peak was registered on 11Nov2015. This peak is due to phenomenon called El-nino; which happened between the months of October and December of 2015. The daily average the flow for the 5 years was found to be 1.28m^3/s .The table below and the graph expresses the discussion above.

Table (4): Summary of Runoff Simulation

Hydrologic Elements	Drainage Area(Km^2)	Peak discharge (m^3/s)	Date of pick	Volume(1000m^3)
Basin 1	11.77	18.6	11Nov2015	48,596,500
Basin 2	38.50	61.0	11Nov2015	154,264,400
Watershed	50.28	79.6	11Nov2015	202,860,900

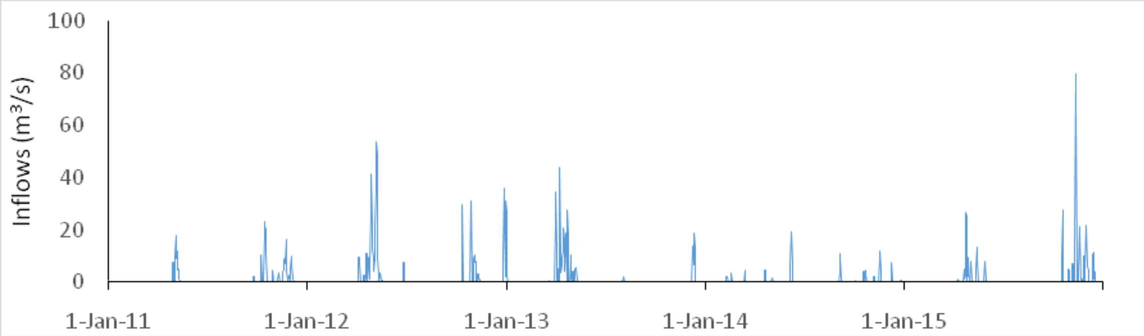

Figure 6: Ruiru Reservoir Simulated Inflow Hydrograph

IV. CONCLUSION AND RECOMMENDATIONS

This study has help to understand a part of the hydrological behaviour of Ruiru reservoir watershed. Runoff data for 5 years (2011-2015) were generated using HEC-HMS 4.1 model. The sensitive analysis has showed that the most sensitive parameters are soil storage following by the groundwater Storage coefficient and the soil tension storage capacity. The Efficiency of the model 0.74 and 0.72 respectively for the calibration and the validation indicating that the results of the simulation are good. So that this Model can be used for further studies or to predict some missing data. Lack of the discharge gage station just at the outlet didn't make easy this study. The only discharge gage found was the one for basin 1; but also had some missing data. For more accurate results of simulation of Ruiru reservoir watershed runoff, we recommend to set up a discharge gage station at the outlet. For further studies these runoff may be used to evaluate the water balance in the reservoir.

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