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RUNOFF RESPONSE TO CLIMATE VARIABILITY: AN ANALYSIS OF THIKA RIVER BASIN IN KENYA USING HYDROLOGICAL SIMULATION MODEL (HYSIM)

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ABSTRACT

Changes in climatic conditions have greatly affected surface runoff and stream flows both at local and global scale. This has led to adverse effects on surface run off and climatic system as a whole. Research on these hydrological changes at basin scale is of great importance to the water managers for the future planning and management of water resources. In this study, a Hydrological simulation model (HYSIM) was used to simulate runoff and quantify the effects of climate variability on runoff within the area of study. The model was calibrated and validated giving a coefficient of determination (R^2) of 0.923, an RMSE of 0.56 and a BIAS of 1.697 respectively. The future climate of the catchment is projected to be warmer and, with less confidence, wetter as simulated using the IPCC scenarios. However, stream flow could increase by between 1.2% on the lower case to 4.5% on the higher case under these projections. There is therefore need to prepare for the increased runoff as it would affect the agricultural sector, industry, urban communities, as well as the environment.

Contribution/Originality: This study documents the effects of climate variability on run off in Thika river basin and further simulates future possible occurrences using the Hydrological simulation model (HYSIM).

1. INTRODUCTION

Changes in climatic conditions have greatly affected surface run off and stream flows both at local and global scale. This variability also impacts on the functioning of water facilities in existence including flood control facilities, hydropower, irrigation and drainage facilities as well as water regulation practices [1]. The variations are a natural component of the climate which is caused by changes in the system(s) which influence the climate such as the General Circulation system. Research on hydrological changes at basin scale is of great importance to the water managers for future policies formulation, planning and management of the resource. According to Box and Jenkins [2] the traditional way of forecasting forthcoming climate conditions based on the assumption of past hydrological occurrences is no longer applicable. Adverse effects of meteorological conditions on drinking water systems aggravate the implications of other stresses, such as human population growth, changing economic activity, land-use change and urbanization [3]. While quantitative projections of changes in rain, stream flows and water levels at the river-basin scale are uncertain, it is very likely that hydrological characteristics will change in the coming years these changes call for runoff modeling which takes into account the changing conditions. The runoff should be simulated under the different climate variability scenarios. Hydrological Simulation Model (HYSIM) was used in this study by incorporating the various scenarios as suggested by the IPCC to study the impacts of the climate variability in the basin. According to Hulme, et al. [4] there are two main reasons why there is little confidence about the magnitude, and even direction, of regional rainfall changes in Africa. The first reason relates to ambiguous representation of climate variability in the tropics. This is in most GCMs via mechanisms such as ENSO, for example, which is a key determinant of African rainfall variability. The second reason is the omission in all current global climate models of any representation of dynamic land cover–atmosphere interactions. These interactions have been suggested to be vital in determining climate variability in Africa during Holocene and may also have played a role to the more recently observed desiccation of the Sahel [4]. Work is now underway however, to incorporate such links in regional climate models [5].

Unless credible models are used, the problem cannot be effectively solved. Hydrological models have been used in exploring the implication of making certain assumptions about the real-world system and predicting the behavior of the real system under a set of naturally occurring circumstances. This research used the HYSIM model to overcome the challenge of taking into account climate variability scenarios while accessing runoff within the Thika river catchment.

Climate variability and change will present challenges to water utilities, and developing mitigation now could prevent freshwater crises in upcoming years [3]. Determination of the effect of climate variability on surface runoff in Thika catchment helps the country to be in a position to determine future floods or drought and predict possible future trends to enable formulation of mitigation and preparedness measures. Exploring vulnerability means extreme events providing most important message needed for impact prediction, analysis and development of mitigation measures. The main river in this catchment is Thika River which is part of the larger Tana catchment. HYSIM model was used to simulate surface runoff from the available weather data and hence thereafter the results evaluated**.** The model used a 15 years' dataset in batches of 5 years each three stream flow gauging stations within the catchment.

Climate Variability and Change Scenarios

Based on state of the Special Report on Emissions Scenarios (SRES) [6] climate change scenarios are not the prediction or forecast of the future but rather they are potential future scenarios and each of scenario represents a way in which the future might unfold. There is little information on climate change available for East Africa at both country and local scale. In Kenya, rainfall projections are inconsistent as evidenced by a range of models and scenarios which shows increases and decreases in total precipitation [7].

According to Feldman [8] a climate variability scenario is the estimation of future resource availability factoring in the estimation of the implications of climate change or variability for water stress. The scenarios describe future demographic conditions, environmental conditions, social conditions, economic conditions, technologies, and policies. The four scenarios described by the Solomon, et al. [6] are Al, A2, B1 and B2 Scenarios.

A1 Scenario

"This scenario describes a world with a very rapid economic growth and a global population that attains its peaks in mid-century. The population declines thereafter with new and more efficient technologies being rapidly introduced. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B)."

A2 Scenario

"The A2 scenario and scenario is based on describes a very heterogeneous world. The main theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines."

B1 Scenario

"This scenario shows a convergent world with the same low population growth as in the A1 scenario, but with a fast change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global to economic, social and environmental sustainability which includes improved equity, but without additional climate initiatives."

B2 Scenario

"The B2 storyline and scenario family is based on a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with an increasing population, at a rate lower than A2. The level of economic development is intermediate, and there is less rapid and more diverse technological change compared to B1 and A1 storylines. It is important to note that while the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels."

Hydrological Models

The rainfall runoff models classifications are based on the input parameters together with the physical principles applied [9]. This leads to classification of models as lumped and distributed based on the parameters which are function of both time and space. They are also classified as deterministic and stochastic models according to other criteria. The deterministic models can only give same output based on a given set of input [10]. This is contrary to stochastic models which give varying values of outputs for a given single set of inputs [9].

Moradkhani and Sorooshian [9] assert that the entire river based output is considered as a single unit. In this case, spatial variability is disregarded and outputs are generated without considering the spatial processes. In this case, a distributed model can be used in making predictions that are distributed in space. This is realized by dividing the entire catchment into small units which in most cases are square cells or triangulated irregular network. In this case, the parameters, inputs and outputs vary in a spatial manner. Based on time factor, it is possible to classify the models as static or dynamic [7]. Static model excludes time unlike the dynamic model. According to Speliotes, et al. [11] the models can be classified as event based or continuous. It is important to note that the former can only produce output in specific time intervals unlike the latter which has a continuous output. The most vital classifications are empirical model, conceptual models and physically based models [7].

Empirical Models

Empirical model also referred to as Metric model is an observation based model which only takes information from the existing data without taking consideration for the features and processes of hydrological models [7]. The models are also known as data driven models. They involve use of mathematical equations which are derived from the concurrent input and output time series and not from the physical processes of catchment [11]. These types of models are only valid when used within the boundaries. Regression and correlation are used by the statistically based methods and helps in finding the existing relationship between inputs and outputs. Some of the machine learning techniques used in hydroinformatic methods are neural network and fuzzy regression [9].

Conceptual Methods

Parametric models which are also referred to as parametric models are used in describing all hydrological processes. This consists of a number of interconnected reservoirs which are used as a representation of the physical elements in a catchment. The reservoirs are recharged by the rainfall, infiltration, and percolations and are emptied through evaporation, runoff and drainage among others [12]. Use of semi empirical equations in this method and model is not only accessed from field data but also from calibration. Large number of meteorological and hydrological data is required for calibration. Calibration includes use of curve fitting making interpretation difficult hence effects of land use cannot be predicted accurately [7]. Many of the conceptual models are developed with varying degrees of complexity. Stanford Watershed Model IV (SWM) is the first major conceptual model developed by Crawford and Linsley in 1966 with 16 to 20 parameters.

Physically Based Model

This model is a representation of a real problem mathematically. Physical based model is also known as a mechanistic model and includes principles of physical processes [10]. The model uses state variables which are measurable and are functions of time and space. Through use of finite differential equations, it is possible to represent hydrological processes of water. The model does not require use of extensive hydrological and meteorological data during calibration [12]. Despite this, there is evaluation of large number of parameters which describes the physical characteristics of the required catchment [7]. Through this method, a huge amount of data which includes soil moisture, water depth, topology and the dimensions of river network are required [10]. Physical model has the ability to overcome a lot of defects which are in the other two models since it uses parameters with physical interpretation. The model can provide a large amount of information even outside the boundary and can be used in a wide range of situations. SHE/ MIKE SHE model is an example [12].

Rainfall – Runoff Models

USDA HL-74 Watershed Model

This is a continuous model intended specifically for small Agricultural watershed [13]. The SWBM is continuous model which is suitable for an ASAL Watersheds but its use is constrained by availability of stream flow data, measured for at least five years [14]. However, this model could not be applicable in the assessment of climate variability effects on Thika catchment because the catchment does not fall in ASAL area.

HEC-1Model

The hydrologic modelling system (HEC-1) model is a continuous simulation model developed by US corps of Engineers for planning design and operation of water project in the Columbia River Basin [15]. HEC-1 is a single event lumped parameter model frequently used to develop hydrographs for project design rather than climate studies [16].

VIC Model

Also, referred to as Variable Infiltration Capacity model, it is a semi distributed grid based hydrology model which uses both energy and water balance equations. The main inputs are precipitation; minimum and maximum daily temperature and wind speed and allows many land cover types within each model grid [17]. The processes like infiltration, runoff and base flow are based on various empirical relations. Surface runoff is generated by infiltration excess runoff (Hortonian flow) and saturation excess runoff (Dunne flow) [9]. VIC simulates saturation excess runoff by considering soil heterogeneity and precipitation [18]. It consists of three layers where the top layer allows quick soil evaporation, middle layer represent dynamic response of soil to rainfall events and lower layer is used to characterize behavior of soil moisture [19].

Stanford Watershed Model

Stanford watershed model developed by Stanford faculty members Ray Linsley, Joseph B. Franzini, and John K. Vennard in 19th century is a continuous, distributed model is intended for application into watershed of all sizes.

Primary data input includes the hourly and daily precipitation and daily maximum and minimum temperatures. According to Devia, et al. [20] the greatest drawback with the model is in its incapacity to take in various climate scenarios when simulating.

HYSIM Model

HYSIM was authored by Manley [21] as a commercial package. The model origin can be traced back to the 1970s. Despite this, the commercial PC version of HYSIM was coded in Visual Basic for DOS by Microsoft and released in 1992. At the point of model development, the author had the essential prerequisite that the parameters of the model ought to be physically significant [22]. This information on HYSIM is prevalently based on the data distributed in the user and technical guides [23]. It was created by the Water Resource Associates (WRA). WRA are a group of experts in water assets, water quality, hydrology, groundwater hydrology and flooding. Their customers include probably the most critical water administration bodies in Europe such as the European Union, United Kingdom Environmental Agency, National Power, French government, British Waterways and SNIFFER [24].

HYSIM can be connected to single or various sub-catchments, each of which ought to be homogeneous regarding the soil structure. The model requires an input of five particular data types; of which none are compulsory. These are:

i. Catchment average precipitation time series;
ii. Catchment normal potential evapotranspiration;
iii. Catchment normal potential melt rate for snow;
iv. Net emanating/surface water abstraction rate;
v. Total groundwater abstraction rate.

The time venture for this information can be monthly, daily or sub-daily despite the fact that there is an option of using data with varying time steps. The model has been coded in a way that the water driven and hydrological parts can likewise be kept running on various time steps [25]. Parameters modifications are split into three segments inside HYSIM, these are information, basic and advanced. According to Osbahr and Viner [26] standard calibration technique, which is based on the HYSIM User Manual [25] the information specific and advanced hydraulic parameters stay at their default values. The essential hydrological parameters that are changed are outlined at their default values in Table 2.2.

Table-1.2. Model Parameters

Parameters	Description	Default
Interception storage (mm)	Moisture storage before infiltration	2.00
Impermeable Proportion	Portion of the catchment where water cannot penetrate	0.02
Time to peak (hrs.)	time interval from the start of the resulting hydro graph	2.00
Rooting Depth (mm)	the depth of soil from which plant roots take up water, or the depth of soil to which roots reach	1000.00
Pore size distribution index	measure of the void (i.e. "empty") spaces in a material	0.15
Permeability (horizon boundary) (mm/hr.)	the state or quality of a material or membrane that causes it to allow liquids or gases to pass through it	10.00
Permeability (base lower) (mm/hr.)	the state or quality of a material or membrane that causes it to allow liquids or gases to pass through it	10.00
Interflow (upper) (mm/hr.)	Movement of water between layers	10.00
Interflow (lower) (mm/hr.)	Movement of water between layers	10.00
Precipitation factor	Weighting factor for precipitation	1.00
PET factor	sum of evaporation and plant transpiration from the Earth's land	1.00
Catchment Area (sq. km)	Catchment Area	1.00

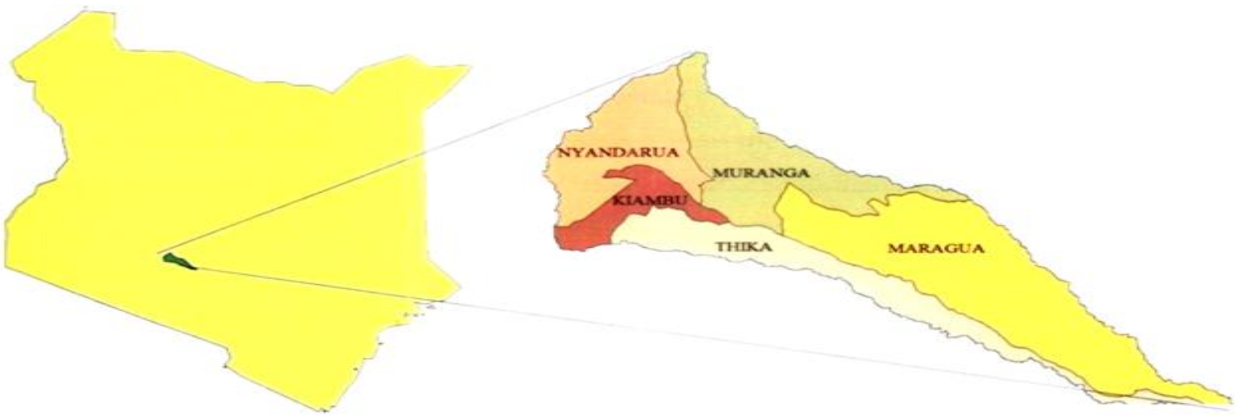
Source: Manley [25]

Through model calibration, it becomes possible to have proper water management. The greatest problem faced in calibration is inconsistency. A model can only reproduce one event but cannot reproduce another. Calibration in this case is aimed at "Single parameter" optimisation whereas confirming that PET factor has been selected and that "maximum iterations" selected as 10. For a successful calibration, it is important to obtain an accurate mean flow through adjusting the PET factor. Hydrological simulation involved two important exercises that must be carried out successfully. These are calibration and validation of the model [10]. According to Beven [27] calibration exercise is used in determining the best parameters in modeling studies and which is vital in the being that parameters can only be found through the calibration exercise.

2. METHODOLOGY

Study area

Thika river catchment lies between latitude 36^{0}35' and 37^0 35'E and longitude 0'35' and 1' 10'S and encompasses Murang'a, Thika, Machakos and Nyandarua sub counties in Kenya as shown in Template 2.1.



Template-2.1. River Thika Catchment

The catchment has an area of 867 km^2 and is approximately 40 km North West of the city of Nairobi [3] and it is part of the Tana catchment. Rivers Thika and Chania originate from the slopes of Nyandarua ridges and flow south eastwards for approximately 100 km before joining in Thika town to form the main Thika River. The river then flows for approximately 100km before joining River Tana. Within the larger catchment is Thika dam, located at a distance of about 80km north of Nairobi city. The dam catchment area features a fragile ecosystem, owing to deforestation of Aberdare ranges, and a weak soil structure that is prone to landslides [28]. The land slopes generally in the eastern direction. Altitudes vary from 1525m a.m.s.l. at the catchment outlet and rises to 3,906m a.m.s.l at the headwaters of the Thika River. The average elevation is 1,700m a.m.s.l [3]. Thika River which rises from the eastern Aberdare ranges drains the catchment. The river maintains a steep gradient in the upper reaches, but the gradient flattens out as it approaches the lower reaches of the catchment. The river flows south east wards to Thika town where it joins River Chania and forms the main Thika River about 100kms downstream [28]. Thika River flows into River Tana on which the hydroelectric power dams are located. Two types of channels are defined within the catchment i.e. the main channel and tributary channels. In the Aberdare forested areas, runoff is minimized by the vegetation canopy unlike in the coffee zone where runoff is comparatively high [3]. The soils in the catchment vary with the parent material and also altitude. Deep into the forest the soils are well drained, very deep dark, silty clay loam, with humic top soil of mollic Andosols combined with well drained, dark reddish brown to very dark grayish brown, friable and slightly smeary clay, with a humic top soil of Ando curvicp haeozems [3]. In the middle zone where small scale farming is mostly practiced the soils are extremely deep dark reddish brown to dark brown, friable and slightly smeary clay, with acidic humid topsoil generally of nit soils and sols type [22].

Runoff Simulation

This involved simulation of changes in surface runoff considering the climate variability scenarios as suggested by IPCC. The base period was between the years 1981 and 1995 while the period 2017 -2022 was chosen as an ideal comparative period and data obtained from the Second Generation Global Climate Model (GCM) for the period [29]. The input data required for this study included PET data, rainfall data, stream flow data and topological maps. This data was available from various sources which included IPCC weather data website, water resources management authority as well as Kenya Meteorological Department (KMD). The data was partitioned in two sets where 75% of it was used for testing and calibration and the rest 25% used for validation. Rainfall data was obtained from rainfall recording stations in and around the catchment. The data was in the form of daily mean rainfall for a period starting the year 1981 to 1996 for the calibration process and the period between 1960 to 1964 for the validation of the model. This was obtained from KMD stations in the catchment and then abstracted in its raw form from daily record sheets at the stations to excel sheets. Potential evapotranspiration data was also required. However due to inability to obtain adequate and reliable PET data records, Osbahr and Viner [26] used Thornwaitte's equation to generate the data required. For this purpose, monthly mean temperatures as well as hours of sunshine were obtained from Water resources management authority that was used to generate the data. The PET data was divided into two sets the calibration set representing 75 percent of the data while the rest was used on validation. Long term climatic data for Karuga, Kimakia, Thika stations was also obtained from the IPCC website. This data comprised of the long term means of the main climate change drivers i.e. rainfall and temperature. This data set for the period 1976 to 2006 was used for trend analysis. Discharge data (daily mean discharges) was required from the study area. This was obtained from gauging stations around the catchment. These were 4CB04 - Thika, 4CB05- Ndakaini and 4CB07 – Kimakia stations. This data was cleaned by an inbuilt function of the model that checked the missing data, infilled and also checked for its consistency respectively.

Model Calibration and Validation

The HYSIM model was calibrated with daily stream flow data from years with the least number of missing values in both observed daily rainfall and stream flow. Calibration was done by manually adjusting the model calibration parameters. The direction and the rate of change of the parameters were guided by the results of the parameter sensitivity analysis as described by the user manual for the model. Visual and numerical methods were used to assess the goodness of fit between the simulated and the observed stream flow. In visual method, the simulated and the observed stream flow was plotted on the same graph against time and compared visually. In numerical method observed and simulated stream flow was compared using the coefficient of determination (R^2) [10]. Rainfall, stream flow, and PET data from suitable period were used to validate the model. The simulated stream flow was compared to the observed. According to Kandel, et al. [10] the model performance is evaluated using both visual and statistical methods as in the calibration exercise. Assess and validate HYSIM model's ability to simulate surface runoff through use of rainfall, stream flow, and PET data from year 1981 to 1995 for 4CB04, 4CB05 and 4CB07 stations.

To effectively simulate flow, the Nash–Sutcliffe efficiency (NSE) [26] percent bias (PBIAS) [26] and the mean absolute error (MAE) [26]were used to evaluate parameters behavior. The NSE evaluates the line of best fit between the observed flow against the simulated flow [26]. An NSE value closer to 1 reflects a very good accuracy for the hysim model. PBIAS is expressed as a percentage between the simulated flow being more or less than the observed flow. + (-) PBIAS values reflects that the simulated flow exceeds (was below) the observed flow. The hydraulic parameters tested under this analysis were as outlined by Manley [12]. This was done using the default hydraulic parameters initially and later adjusted to determine their sensitivity to the hydrological simulation. The parameters tested were Chanel top width, channel base width, channel depth, channel roughness, reach gradient, flood plain width, flood plain roughness, catchment area and reach length as suggested by Manley [12]. Culler, et al. [23] suggested the following procedure where an incremental addition to the parameters should be done followed by substitution by other values other than the default for a period not less than 6 months of the observed data. This was applied for the data for the period starting January 1960 to December 1963. Parameter sensitivity was calculated as the percentage difference between the simulated data and the observed data immediately after running the model as shown on equation 2.1.

$$\text{Sensitivity} = ((\text{Observed value} - \text{Simulated value})\% \qquad \text{Equation 2.1}$$

3. RESULTS AND DISCUSSION

Records of stream flow at for the period from 1960 to 2003 were readily available in digital form for the WRMA office. For the purposes of this study, three stream gauges were examined. The temporal coverage of the data at these gauges varied, and were operational at the same time. A summary of the stream gauges is as presented in Table 3.1.

Table-3.1. Thika river characteristics

Station	Annual Max Flow (m^3/sec)	Annual Min Flow (m^3/sec)	Annual Mean Flow (m^3/sec)	Monthly Min Flow (m^3/sec)	Monthly Max Flow (m^3/sec)	Monthly Mean Flow (m^3/sec)	First Date Available	Last Date Available
4CB04	21.9	1.1	4.2	1.1	6.2	4.1	01/01/1960	31/12/2003
4CB05	27.3	6.2	7.3	6.8	27.2	7.2	01/01/1960	03/08/1998
4CB07	19.5	2.8	10.2	2.8	20.3	10.8	01/01/1960	15/10/2000

Source: Kenya Meteorological Department [3]

From the results presented in Table 3.1, gauge 4CB04 had a maximum annual flow of 21.9m^3 and minimum annual flow of 1.03m^3 which gave an average annual flow of 4.27m^3. Gauge 4CB05 showed a maximum annual flow of 27.3m^3 and a minimum annual flow of 6.27m^3 giving an average annual flow of 7.36m^3. Lastly, Gauge 4CB07 gave a maximum annual flow of 19.5m^3 and a minimum annual flow of 2.86m^3 which gave an average annual flow of 10.26m^3. This dataset was then to be used as an input to rainfall runoff modelling software. Rainfall data was one of the inputs for the hydrological model. The rainfall data used for Thika catchment in this study was obtained from different sources and had varying quality and coverage over times. These sources were KMD and the IPCC website [6]. Data availability is shown on Table 3.2.

Table-3.2. Rainfall Stations

Station	Annual Max (mm)	Annual Min (mm)	Annual Mean (mm)	Monthly Min (mm)	Monthly Max (mm)	Monthly Mean (mm)	Data Set Period
9036220	3996	0	772	0	1656	423	1976 - 2006
9036233	4023	0	759	0	1423	526	1976 - 2006
9137048	3026	10	765	10	1296	624	1976 - 2006

Source: Kenya Meteorological Department [3]

The yearly rainfall data was available in almost every station. The stations which had some missing data were Karuga farm – station ID 9036220 in 1987 and Kimakia - station ID 9036233 in 1983. The mean annual rainfall from the three stations was 772mm in Karuga farm, 759mm in Kimakia and 765 in Thika. The rainfall analysis started by carrying out thorough quality control of the data from KMD. Quality control in this case was used in correcting errors in the data and filling gaps where appropriate. The years chosen for use had less gaps in the flow records. The model infilled the gaps using an inbuilt model function with a default value of -999.9.

Sensitivity Analysis Results

This was performed on the hydraulic model parameters namely channel top width, channel base width, channel depth, channel roughness, reach gradient, flood plain width, flood plain roughness, catchment area and reach length. Murphy 2006 found Chanel top width, channel base width, channel depth, channel roughness, reach gradient, flood plain width, flood plain roughness and reach length insensitive in catchments below an area below 1000 sq.km. This was confirmed by this study where only the catchment area was found to be sensitive. An increment in the catchment area showed an increment (decrement) in the simulated flows while the parameters tested (decrement) showed no or minimal effects on the simulated flow for the period between January 1960 and December 1963.

HYSIM Model Calibration and Validation

The objective of model calibration was to minimize the error between observed and simulated water levels. This was done through the adjustment of the model parameters. Initial parameters before and after calibrations are presented in Table 3.3.

Table-3.3. HYSIM Parameterization variables

Parameters	Default	Calibrated value
Interception storage (mm)	2.00	20.00
Impermeable Proportion	0.02	0.02
Time to peak (hrs.)	2.00	2.00
Rooting Depth (mm)	1000.00	2000.00
Pore size distribution index	0.15	0.16
Permeability (horizon boundary) (mm/hr.)	10.00	11.03
Permeability (base lower) (mm/hr.)	10.00	10.98
Interflow (upper) (mm/hr.)	10.00	9.42
Interflow (lower) (mm/hr.)	10.00	9.56
Precipitation factor	1.00	1.04
PET factor	1.00	5.34
Catchment Area (sq. km)	1.00	897

Source: Speliotes, et al. [11]

The results for the calibration and validation stages of the HYSIM model are detailed in Table 3.3.

Table-3.3. Calibration and validation results

Catchment Name	Measured Average Calibration	Simulated Average Calibration	Calibration (1981 - 1995)	Measured Average Validation	Simulated Average Validation	Validation (1960 - 1964)
			R^2			R^2
Thika Catchment	5.8	6.3	0.95	4.3	5.6	0.92

Source: Speliotes, et al. [11]

The results of the calibration and validation stage were very encouraging and showed that the HYSIM model was performing extremely well over the full period of record. The performance criteria is as summarized in Table 3.4.

Table-3.4. Performance criteria for calibration and validation

Statistic	Calibration		Validation	
	Value	Performance	Value	Performance
BIAS	1.697	Good	-3.72	satisfactory
RMSE	0.56	Satisfactory	0.61	Not satisfactory
NSE	0.95	Very good	0.92	Very good

Source: Speliotes, et al. [11]

Surface Runoff – Comparative Period

The surface runoff for the comparative period of 2017-2021 was simulated and is presented below graphically in Figure 4.3 and tabulated in Table 3.5.

Table-3.5. Surface Runoff - Comparative (Year 2017 - 2022)

Year	Comparative Period (mm)	Scenario 1 (mm)	Change between Sc.1 and the Comparative period	Scenario 2 (mm)	Change between Sc.1 and the Comparative period
2017	7135	7185	50	7310	175
2018	27448	28026	578	29753	2305
2019	32041	32257	216	32902	861
2020	25995	26242	247	26932	937
2021	23823	24074	251	24830	1007
2022	22062	22241	179	22719	657
Total			1524		5943

Source: Speliotes, et al. [11]

The two scenarios described in the methodology were carried out and the comparative period runoff simulated. Further analysis of the runoff simulated indicated that in both scenarios (both high and low) there was an increase. In the low scenario an increase of 1524 mm over the comparative period was observed. This was an increase of 1.2% in surface runoff over the comparative period. In the high scenario, an increase of 5943 mm over the comparative period was observed. This was an increase of 4.5% in surface runoff over the comparative period. Since the climate variability changes and trends in the catchment are potentially a result of global climate change, the future climate, including rainfall and temperature, is of utmost interest to water resource management and planning, agriculture, and water users in the region. The scenarios used in this study were results of climate change studies by IPCC in the region. This change in the main climate change drivers (temperature and precipitation) were developed using the Second-Generation Global Climate Model. In both cases the GCM's prediction was that both temperature and precipitation would increase. This confirms results I obtained from the trend analysis that indicated increase over the past three decades. Thus, an increase in precipitation in the catchment coupled by an increase in temperatures can still result in a projected increase of stream flow. This will produce a serious challenge for water resources management in the NCP region and enhance the vulnerability of water resources.

4. CONCLUSION

The HYSIM model proved to be a near perfect model for simulating runoff within the catchment. Upon calibration, the model gave a coefficient of determination of 0.923 which was confirmed upon validation with a value of 0.916. Furthermore, the scenario analysis on the comparative period showed that surface runoff will increase with between 1524 mm and 5943 in the coming 5 years. Intensive water resource management is therefore required to ensure minimal loss as well as conservation of this precious resource.

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