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DISCHARGE GENERATION USING COMBINED THORNWAITE WATER BALANCE AND IHACRES MODELS: A CASE STUDY OF THE ASA RIVER BASININ NIGERIA

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Abstract: Many rainfall – runoff models exist for the estimation of streamflow discharges in ungauged basins. However, most of the parameters needed to run the models are not easily obtainable in many countries like Nigeria, hence their application is limited.The situation is even more critical when discharge data of rivers are scarce and unreliable. This study identifies two models that are amenable to the nature of data available for many rivers in Nigeria. A combination of the Thornwaite Water Balance (TWBM) and the IHACRES Models was applied to the Asa river basin in central Nigeria. Available rainfall data is of a satisfactory quality while the corresponding discharge data is fragmented and only a short portion can be considered acceptable. The acceptable data was used to calibrate the models and subsequently used to generate a better discharge data. The study has thus shown that the IHACRES model is suitable for use under the hydrological setting and data availability situation in Nigeria. This method can be applied in ungauged basin with similar data scarcity as Nigeria.
Keywords: estimation, streamflow discharges, Thornwaite Water Balance (TWBM), IHACRES Models, Nigeria, Asa river basin

1. INTRODUCTION

A good estimation of the water resources available at a selected site is of utmost importance in the planning and design of a water, irrigation, drainage or hydraulic infrastructure. In ideal situation, water resources potential at a site can be derivedfrom gauge and discharge data at the location of interest. However most rivers in Nigeria and elsewhere are ungauged. The lack of adequate and reliable data has been identified as one of the major barriers to the development of hydropower (WAEA, 2008) and water resource management in Africa (Oyebande, 2001). The lack of hydrological data as a result of progressive decline in ground based observation network largely due to lack of funds to provide and maintain gauging stations (Oman & Edwards, 2007).The ubiquitous ungauged basins incidences has made it difficult for detailed drainage basin studies and adequate water resources assessment, hence the need for better understanding of hydrological processes and their quantifications and usage. Lack of adequate data has necessitated the use of various statistical tools for flood estimation and predictions (Olukanni & Salami, 2008). Studies have also shown that most of the existing hydro metrological stations are not in proper locations. The selection of hydrometeorological station locations may have been influenced by other considerations other than their intended use and hence they have not been representative of the area they are meant to cover (Ologunorisa, 2009). The estimation of the water resources of basins has therefore been based on empirical relationships developed elsewhere and there is thus a need to identify which ones will work best for individual river basin and other locations of interest.

Rainfall – runoff models are used to generate runoff data for ungauged catchments, from rainfall data.There are many models which can be grouped or classified based on the way the runoff generation process is considered. The classification adopted by Refsgaard and Knudsen (1996) is shown in Figure 1.

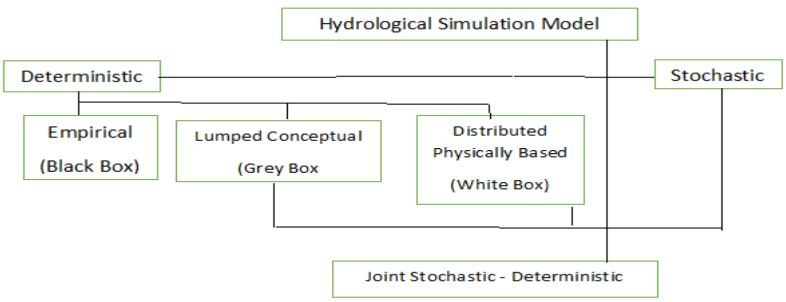

Figure1: Classification of hydrological models according to process description

Deterministic models can be classified according to whether the hydrological processes involved are empirical, conceptual or distributed. Three main classes are discernible:

a. Empirical Models (or black box)
b. Lumped Conceptual Models (or Grey Box)
c. Distributed Physically Based Models (or White Box)

Empirical black box models are developed using the measured time series instead of utilising mathematical expression describing the physical processes in the catchment. Examples include the Soil Conservation Service Model (Chow et al., 1988), the Soil Moisture Accounting and Routing Model (Goswami et al., 2002) and the Clarks Model described by Singh (1977).In lumped conceptual models, the parameters and variables represent average values over the entire catchment. Thus, the description of the hydrological processes cannot be based directly on the equations that are supposed to be valid for the individual soil columns. Some examples include the HYMOD Model (Castiglioni et al, 2010), SIMHYD Model (Chiew et al. 2008), MEDOR Model (Hreiche et al., 2004) and the Hydrological Recursive Model described by Drogue et al.,(2002). In physically based distribution models, processes are represented by one or more partial differential equations and parameters which are distributed in space. Some examples include the Grid Model described by Moore and Bell (2001), Monash Model (Weeks and Hebbert, 1980) and theKineros2 Model (Al-Qurashi et al., 2008).

2. STUDY AREA

The conversion of rainfall to runoff depends very much on the relief, geology, soil and climate of the area under study. The Asa river basin in central Nigeria lies between latitude 8.40°N – 8.60°N and longitudes 4.16°E – 4.60°E. It has an area of 962km^2 at the Asa dam in Ilorin. The average daily temperature is between 26°C and 32°C and the annual mean rainfall will usually be between 1300 – 1400mm. there are two marked seasons in the area; the rainy season is from April to October while the dry season lasts from November to March. Most part of the basin is located within the transition zone between the southern rain forest and the northern savannah grassland. The soil is mostly of the basement complex stock. Figure 2 shows the study area within themap of Nigeria.

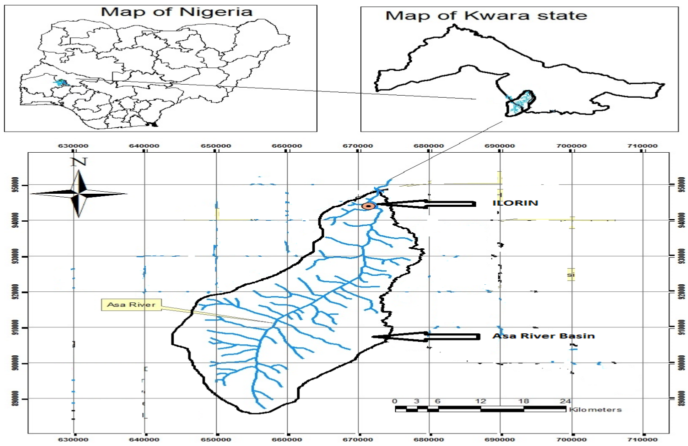

Figure 2: Map of Study Area

3. METHOD OF STUDY

Various Rainfall - Runoff Models (RRM) were studied to identify those or a combination thereof that can sufficiently reproduce discharge from available rainfall data. Two models were found suitable. The basis for the choice of these two was that they require less parameters to run or that the required parameters to run them are available for the study area. They have also been proven to be useful in other instances similar to the hydrological environment in Nigeria. The two models, already fully described in literature are:

a. The United States Geological Survey (USGS) Thornwaite Water Balance Model (TWBM): This model has seven input parameters. These are runoff factor, direct runoff factor, soil moisture storage capacity, latitude of location, rain and snow temperature thresholds and maximum snow melt rate of the snow storage (McCabe &Markstrom, 2007). A computer program with some graphical interface disables all snow related terms and parameters based on the latitude of the basin location. The simulated values were compared with the measured values from the basins and the error checked. To establish the parameter set that gives the least error and to optimize the model parameters, a *matlab* code was used to compare the simulated runoff with the measured values and compute the error. The code also carried out a Monte - Carlo simulation to establish a set of posterior probable parameters which gave the least error. In running the code, it was established that 100,000 simulations was sufficient to establish a reasonable set of parameters.
b. The **I**dentification of **H**ydrographs **A**nd**C**omponents from **R**ainfall, **E**vapotranspiration and **S**treamflow data (IHACRES) Model: The IHACRES version 1.03, was released in 2005. Well described by Littlewood*et al* (1997), it was developed jointly by the Centre for Ecology and Hydrology, Wallingford and the Integrated Catchment Assessment and Management Centre (ICAM) of the Australian National University in Canberra. First, the model was calibrated using corresponding available data for rainfall, temperature and discharge. This gave a parameter set for each catchment. Missing discharge values were generated with a*matlab* code which has as input the obtained parameter sets with the available rainfall and corresponding temperature data.

After the selection of the models, further analysis was carried out as follows:

a. Available rainfall data for some stations around the study area was obtained from the Nigerian Meteorological Agency NIMET as shown in Table 1.

b. Available discharge data for some basins were also collected from the Kwara State Water Board, owners of the Asa Dam.

c. The rainfall data was checked for quality and consistency using the Budyko diagram and the Double Mass Curve (DMC). The Budyko Curve represents an indication of the annual water balance which represents the ratio of evaporation to precipitation. This measures the way rainfall is partitioned into evaporation and runoff (Creed & Spargo, 2014). A DMC is a plot on a graph paper of the cumulative figures of one variable against the cumulative figures of another variable or against the cumulative computed values of the same variable for a concurrent period of time (Searcy & Hardison, 1960).

Table 1: Summary of Obtained Rainfall Gauging Stations

S/No	LOCATION	LONGITUDE (ºE)	LATITUDE (ºN)	ELEVATION (m.a.s.l)	PERIOD OF DATA	NO of YEARS
1.	Minna	6.50	9.62	254	1960 - 2010	51
2.	Ilorin	4.58	8.50	305	1960 - 2010	51
3.	Ibadan	3.97	7.37	200	1960 - 2010	51
4.	Osogbo	4.62	7.80	317	1960 - 2010	51
5.	Akure	5.08	7.25	335	1980 - 2010	31
6.	Ondo	4.83	7.08	277	1960 - 2010	51
7.	Jebba	4.83	9.13	077	1984 - 2010	27
8.	Kainji	4.60	9.87	139	1980 - 2011	32
9.	Shiroro	6.84	9.96	382	1990 - 2010	21
10.	Lokoja	6.75	7.82	67	1960 - 2010	51

d. Various other sources of rainfall data were consulted for comparison and quality control.This include the Tropical Rainfall Measuring Mission, which is a joint mission between the National Aeronautics and Space Administration (NASA) of the United States and Japan Aerospace Exploration Agency (JAXA) designed to monitor and study tropical rainfall, the Climate Research Unit of the University of East Anglia in the United Kingdom and MODIS (The MODerate resolution Imaging Spectro-radiometer) which is a key instrument aboard the Terra and Aqua Earth Science Satellite Missions of the NASA.

e. Rainfall values for the basin were obtained by Kriging interpolation. Many interpolation methods were considered and an appropriate method was chosen by cross validation. The Kriging gave the least error.

Using the obtained rainfall values, discharge data was generated with the application of a combination of TWB and ICHARESRainfall – Runoff models.

4. RESULTS AND DISCUSSION

4.1. Budyko Diagram

The Budyko relation was plotted for the Asa river basin. The precipitation and runoffdata obtained was used in conjunction with temperature data to calculate runoff ratios and aridity indexes for the catchment. The runoff ratio (ratio of runoff to rainfall) and aridity index (ratio of potential evapotranspiration to rainfall) obtained were 0.25 and 0.94 respectively. The runoff ratio is less than unity inferring that actual evapotranspiration is also less than the potential evapotranspiration as shown in the shaded areas on Figure 3. This is an indication that the site data is reasonable and can be used for further analysis. The shaded area indicates inconsistent or unreasonable data.

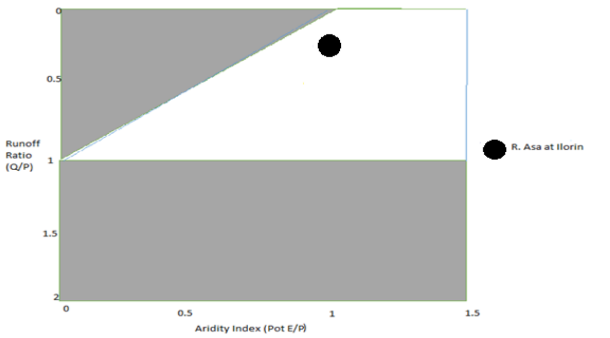

Figure 3: Budyko Diagram of the Basin showing the Runoff Ratio and the Aridity Index

While the data is reasonable, its consistency was checked with the Double Mass Curve (DMC). In the construction of the DMC, stations used had no missing data. The rainfall records for the nearest rain gauge station to the basin (Ilorin) were used for the construction of the DMC in figure 4.

Year	Z Station Cumulative (mm)	9-Station Cumulative (mm)
1966	1249.3	1386.044
1967	2155.3	2516.878
1968	3891.8	4150.811
1969	5314.2	5507.222
1970	6252.5	6698.256
1971	7359.3	7958.967
1972	8556.6	9209.056
1973	10017.4	10487.01
1974	11273.9	11775.3
1975	12364.4	13032.77

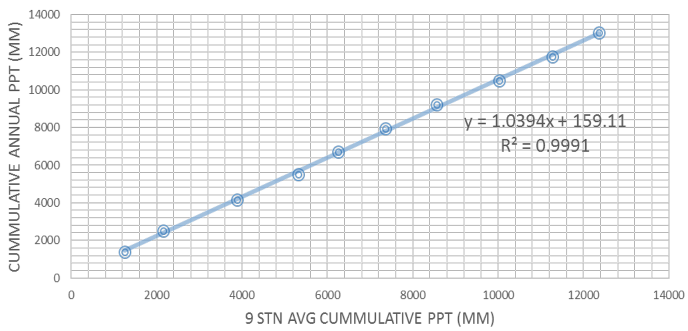

Figure 4: Double Mass Curve for Ilorin Based on 9 Gauging Stations

The DMC for the station showed some satisfactory consistency. R^2 value was 0.999. There was no obvious break in slope which will be an indication of inconsistency. There was thus no need for rainfall data adjustments. It is reasonable to conclude that there was no change in gauge locations, type, environment and climate as to significantly affect the quality and consistency of available rainfall data.

The rainfall data has been subjected to various analysis. In spite of this, historical rainfall data was sourced from the Climate Research Unit of the University of East Anglia (CRU-UEA) in the UK. Established in 1972, the CRU-UEA has gathered a lot of historical rainfall data from all over the world which in some cases dates back to the year 1900. Rainfall data obtained from CRU-UEA was plotted (Figure 5) and compared with the ones obtained locally and a high correlation coefficient of 0.8 was obtained. This is a further confirmation that the rainfall data obtained locally is a fair representation of the storm events.

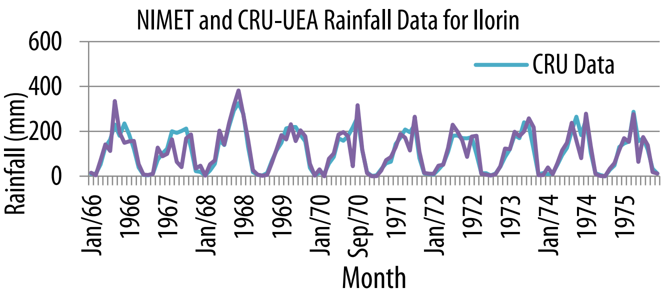

Figure 5: Comparison of rainfall datafor Ilorin from local and international sources

4.2.Determination of Basin Rainfall

Available discharge data for the Asa River at the control point (Ilorin) was obtained. However there was a need to determine as accurately as possible the corresponding representative precipitation that generated the discharges. To do this, the catchment area was marked out and the location of the centroid established. Using the Universal Kriging method of interpolation with the processed data earlier described, the rainfall that generated the discharges was determined. The obtained data was used to plot Figure 6. In normal circumstances, there should be some degree of agreement between the rainfall and the runoff. The rainfall – runoff correlation for the basin based on measured rainfall and runoff was 0.15. A major factor that is responsible for this poor correlation is the seasonal weather in Nigeria. In the study area, there will usually be some six months of rainfall and a six months period of no rain. In the period of no rain (usually from November to April), all water losses will be from ground storage. The water table goes down and many plants will wilt. At the onset of rain, the depleted groundwater is recharged until the soil storage capacity is achieved before the commencement of significant runoff. Thus, at the onset of the raining season, runoff does not correspond to rainfall. In times of low intensity and low duration of rainfall, it is also possible that there will be no runoff from a storm event. Where there is a high intensity, low duration rainfall, the soil infiltration rate and the reach of the main channel play an important role in the runoff volume generated from the basin.

From Figure 6, it is seen that some flow data do not follow the pattern of the storm events. While making allowance for delays, it is obvious that some flow data are either too low or too high to be reasonable. There are some instances where the flow is almost equal or more than the precipitation or where the flow is too low for the precipitation. Data like these will surely affect the overall correlation of the rainfall - runoff relationship.

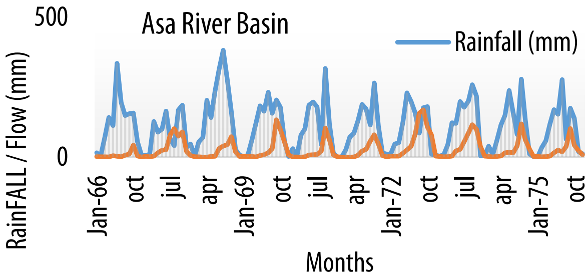

Figure 6: Rainfall and Flow plots for Asa River at Ilorin

Errors in the discharge data is to be expected. Discharge measurements will normally be done with Current Meters or Acoustic Doppler Current Profiles. In Nigeria, most of the old discharge measurements were done with the aid of Stage Heights Gauges and Rating curves. The Stage Height Gauge will usually be attached to bridge piers or in a stilling well. Most of the times, these stream gauge structures are damaged by flood or they can settle over time. Unless these structures are routinely surveyed relative to some permanent elevation benchmarks, there is bound to be a lot of uncertainties and errors in the field data. Having established that the precipitation data is satisfactory but some of the discharge data is suspect, a careful observation of Figure 6 gives a fair idea of some good years and some not so good years. There are no historical records of hydrologically significant extractions or events during the period of measurement and thus is safe to assume that some of the errors observed are genuine; hence it is necessary to reduce as much as possible the propagation of all errors. Young (2002) demonstrated that longer records of discharge reduce sampling error and that while shorter periods make more gauging stations accessible for use, they are influenced more by very wet and very dry years within the measurement record. This is the case with the Asa River.

4.3.Discharge Data Generation

Two Rainfall-Runoff Models were earlier identified as feasible for the generation of a more reliable discharge data. These are the Thornwaite Water Balance Model (TWBM) and the IHACRES. The input requirements of both models differ. For the WBM, generation of runoff requires seven input parameters. The IHACRES requires just the rainfall, temperature and runoff data. The models were first calibrated with known data and then more runoff data was generated using the calibrated parameters and measured values of rainfall and temperature.Both models were made to complement each other. While the IHACRES requires less input parameters for calibration, it is necessary that such input be of good quality otherwise the propagation of errors will lead to a bad simulation.

In using the water balance model (WBM) which has seven input parameters, some assumptions were made. For instance, since there is no snowfall at any time in the study area, terms that are snow related were ignored and this had no effect on the model output. The United States Geological Survey (USGS) Program based on the WBM was used. This Program has some default settings which were used to make the initial calculations and runoff generation. In order to estimate these values for sites in the study area, the runoff generation algorithm was subjected to a *monte carlo* simulation process. The objective was to obtain input parameters that give runoff values closest to the measured ones. Several simulations were carried out. The best results were obtained with 100,000 simulations. The obtained optimal parameter values for the Asa River basin are shown in Table 2.

Table 2: WBM Optimal parameter values for Asa River Basin

SN	Parameter	Default Value	Optimized Value
1.	Runoff Factor	0.5	0.367
2.	Direct Runoff Factor	0.05	0.106
3.	Soil Moisture Storage Capacity	150mm	382mm

The optimized parameters were used with the obtained measured rainfall data to generate some runoff data. The generated runoff was compared with measured runoff values as shown in Figures 7. This helped to identify some good and bad years of measured and recorded runoff data at the gauge site. The identified good years were subsequently used to calibrate the IHACRES model.Figure 7 shows that the good years for the Asa River basin were 1969, 1970, 1971, 1973 and 1974.

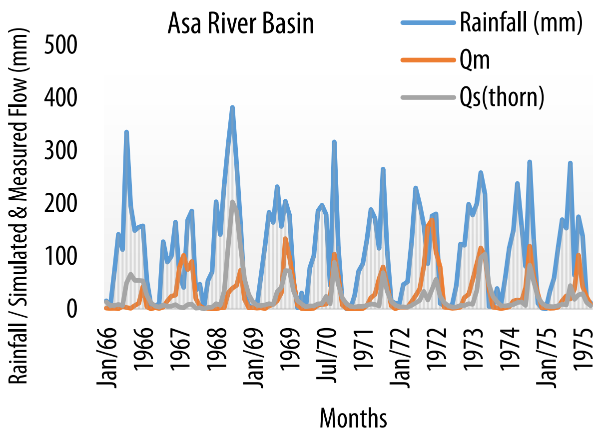

Figure 7: Rainfall and Measured / Optimized WBM Simulated Flows for Asa Basin

In normal circumstances, the parameters in Table 2 should have been readily available for use in the WBM without resorting to optimization. However in a data sparse environment like Nigeria, this is not so. It is also to be noted that there are many different sets of parameter values within this model structure that may be consistent with data availability for calibration which led to the concept of "*equifinality*". This made the use of the IHACRES model for further simulation more acceptable than the WBM. Attempts were made to verify the *equifinality* concept on the WBM by running 100,000 *monte carlo* simulations on the same data several times and on each occasion, different combination of parameter sets obtained were found to satisfy the model requirement. The values in Table 2 were judged to be reasonable as they returned the least error.

Furthermore, it has been observed that the WBM simulates baseflow recession over summer months poorly at some locations. This was confirmed when the default parameter values were used for simulation. However, Boyle et al (2011) has suggested the addition of a baseflow component to represent the contribution of groundwater to runoff to improve the model performance. Again, since there is no reliable information on groundwater contribution to baseflow in the Asa River basin, the authors avoided the need to make any new assumptions which could further increase the errors.

Table 3: IHACRES Calibration Parameters for the Basin

		Asa
	R^2 = Correlation coefficient between measured and simulated flow	0.86
S/N	Parameters	
1.	T_w = Drying rate at reference temperature	6.0
2.	F = Temperature dependence on drying rate	5.0
3.	T_R = Reference temperature	24.0
4.	L = Moisture threshold for producing flow	1.0
5.	C = Mass balance term	0.000822
6.	P = Power on soil moisture	1.5
7.	T_S = Time constant	0.780
8.	V_S = Volume proportion	1.0

After calibrating the IHACRES model, it was subsequently used to generate a better runoff data from measured rainfall values. The PC-IHACRES version 1.03 was used in this work. Table 3 gives the calibration parameters for the basin. IHACRES plots and models the input data, establishes trends, calculates delays which often are related to concentration time of the basin and provides some parameters to be used to simulate more flow values.

Based on the parameters in Table 3, a *Matlab* code was used to simulate discharge data from measured rainfall and temperature data. Figure 8 shows measured rainfall, measured flow and the simulated flows. The instrumental variable best suited for the Asa River is the exponential store and instantaneous store in parallel. This means the river has the tendency for some baseflow at the control point (Ilorin).

Figure 8 also shows how the simulated flow data compares with the measured rainfall and flow. In the earlier analysis, there were some months where measured flow did not correspond to storm events even at the peak of the raining season. This has been largely corrected by the simulation.

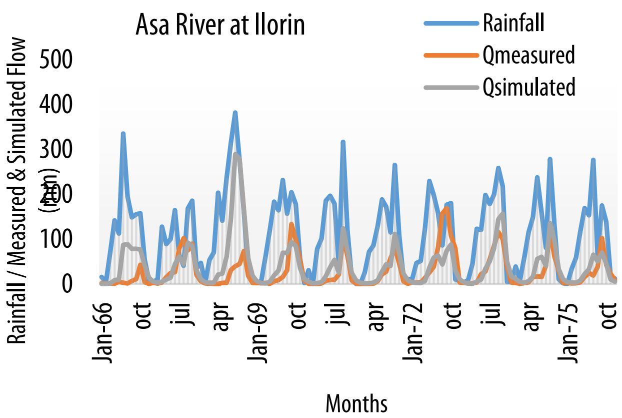

Figure 8: Graph of Rainfall, Measured and IHACRES Simulated Flows for Asa River

5. CONCLUSION

The need for discharge data in Nigeria will continue to increase with increase in water resources infrastructure works, but there is no indication for now that the financial outlay required for improved data gathering will be available. It is thus reasonable to assume that most part of Nigeria will remain ungauged for a long time. This study has confirmed that the rainfall data collected and collated by local agencies, especially NIMET is of good quality and can be used for water resources planning. It fairly represents the storm events over central Nigeria and probably Nigeria as a whole. Discharge data is scarce and the quality of the available ones, especially in years past is not very reliable. There is thus a frequent need for a reliable rainfall – runoff model suitable for the nature of hydrological data in Nigeria. While both the TWBM and the IHACRES provide some good results of runoff simulation from rainfall data in the study area, the IHACRES is recommended for use because it requires less number of parameters when compared to the TWBM.

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