



ORIGINAL RESEARCH ARTICLE

MODELING OF RAINFALL-RUNOFF OF THE YOBE RIVER BASIN USING HEC-HMS

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ABSTRACT

The Yobe river basin which drains into the Lake has experienced low flows which has been attributed to high evapotranspiration and infiltration rates and the growth of weeds such as *Typha Australis* in river channels. This research involved modeling rainfall-runoff of the Yobe River Basin in North-Eastern Nigeria using the HEC-HMS 4.8 application package for the purpose of forecasting and determination of low-flow events. Collection of Streamflow data was affected due to insurgency where water resources planning and management within the basin was impacted. Observed Climatic data (Precipitation and Evapotranspiration) were obtained from two gauging stations (Gashua and Gudumbali) for sixteen (16) years (1990-2005). Both climatic and streamflow data were subjected to Normality and Homogeneity tests and used for modeling, with the Climatic data as the Input data, while the Streamflow data were used for calibration and validation. In addition, Streamflow data for three gauging stations (Gashua, Geidam and Damasak) were also obtained from periods between 1990 to 2005 (16) years. The streamflow data were calibrated and validated with NSE (>0.63 to 0.68) in calibration for daily time steps. It was observed that the validation yielded NSE (>0.62 to 0.78). Therefore, HEC-HMS model can be used to project runoff from available climatic data in the Yobe River Basin. Furthermore, soil management of the Catchment area, channel improvement and river augmentation are some of the key strategies of buttressing the effects of high evapotranspiration and infiltration rates, as well as sustaining flow in the river up to the Lake Chad.

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1.0 Introduction

The major threat to freshwater systems in some developing countries is spontaneous infrastructural development, agricultural activities, deforestation, land cover change and irrigation (Khafaji and Challabi, 2020; Chukwu, 2015). For instance, in Nigeria, an increase in the delivery of constant water supply, despite its vast surface and groundwater potentials has not met the rapid population growth and urbanization (Merem et. al., 2017; Devi et. al., 2015). Surface water in streams around the Yobe River appears seasonal usually from August to October while for the rest of the year are dry and the only source of water is groundwater (Adamu et. al., 2020). The Yobe River is one of the main tributaries of Lake Chad from Nigeria, initially contributing up to 10% of the total water inflow into the lake (IUCN, 2013). Over the years, however, this contribution has drastically reduced to about 1 to 2 percent of the total inflow into the Lake due to the recession of the river (IUCN, 2013). This recession has been attributed to the invasion of reeds and weeds such as *Typha Australis* in the river reaches, blocking streams and causing some of the river water to meander along undefined channels. The Komadugu Gana (Misau River), which is the Yobe River's main tributary, now barely reaches the Yobe River (IUCN, 2013). Also, research has shown that 18% of its annual inflows are lost as a result of infiltrations towards phreatic water tables and the underlying sedimentary formation (Salman and Momha, 2009).

Advancement in technology has also brought about innovations in the field of watershed management, mostly due to its complex nature. These innovations involve simplification of the real-life domain of watersheds in

the form of hydrological modelling (Panahi *et al.*, 2021). These models were developed over the years from simple Linear correlations to peculiar technical interfaces such as the HEC packages, SWAT, WEPP, SWMM, HSPF-Fortran, MODFLOW etc. (Bouizrou *et al.*, 2021; Akter *et al.*, 2020). These models vary depending on their intended purposes and input requirements. Thus, the quest for increased precision in output data has led to the evolution of these models. It is noteworthy that there has been remarkable acceptance these models in watershed management, river modeling, policy management, and forecasting (Marahatta *et al.*, 2021). HEC-HMS is a state-of-the-art Windows-based model for precipitation-runoff simulation. HEC-HMS provides a variety of options for simulating precipitation-runoff and routing processes and is comprised of a graphical user interface, integrated hydrologic analysis components, data storage and management capabilities, graphics, and reporting facilities (Tedla *et al.*, 2021). The software was used in this study to facilitate streamflow forecasting for the purpose of planning and management within the Yobe River Basin.

2. Methodology

2.1 The Study Area

Yobe river drains into Lake Chad in North-East Nigeria. It is situated at the southern fringe of the Sahara Desert, east of the Sahel region between 12°20' and 14°20' latitude North; 13°20' and 15°20' longitude East. The river lies within the geographical locations of 12°44'49.42"N and 11°02'56.17"E in Gashua to 13°41'43.49"N and 13°22'14.49"E in Malum-Fatori (Salman and Momha, 2009). Annual rainfall amount is strongly contrasted throughout the basin ranging from 1,500mm annually in the south of the basin to less than 100mm in the north. Due to high temperatures, the potential evapo-transpiration exceeds 2,000mm annually at the centre of the basin. The river originates from Gashua (Yobe State), immediately downstream of the Nguru wetlands and flows through Geidam (Yobe State), Damasak (Borno State) and then Malum-Fatori (Borno State) before emptying into Lake Chad. The river flows at a distance of about 340km before flowing into the Lake. The main tributary of the Yobe River is the Komadugu Gana (or Misau River), which seasonally meets the Yobe river at Damasak. The Komadugu Gana river originates from Nangere LGA of Yobe state and flows through Fune, Tarmuwa and Geidam but barely reaches Damasak during the wet season. The origin of the Yobe river at Gashua is underlain by a sedimentary formation that reaches Lake Chad (IUCN, 2013).

The Yobe river basin has exhibited a significant level of sensitivity to weather variability and demographic characteristics amongst others (Gana *et al.*, 2018). Lake Chad has shrunk by about 90% over the past 60 years with a total area of about 26,000 km² in 1963 to about 1,500 km² in 2021. The effect of the demographic characteristics is related to the increase in the population in the region between 13 million in 1963 to over 40 million people in 2021 (Thematic Report, 2022).

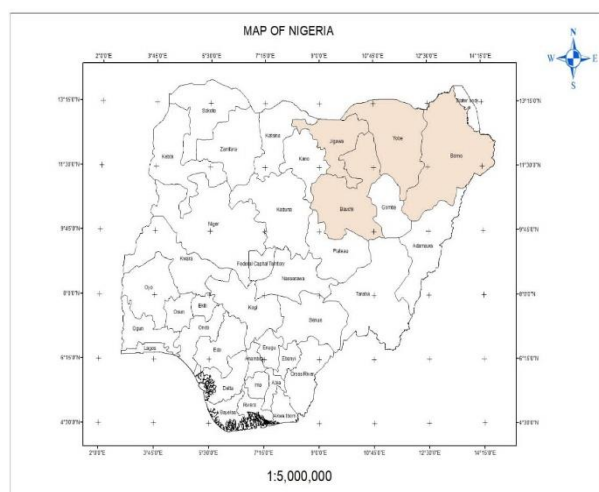


Figure 1. Map of Nigeria showing states covering the study area

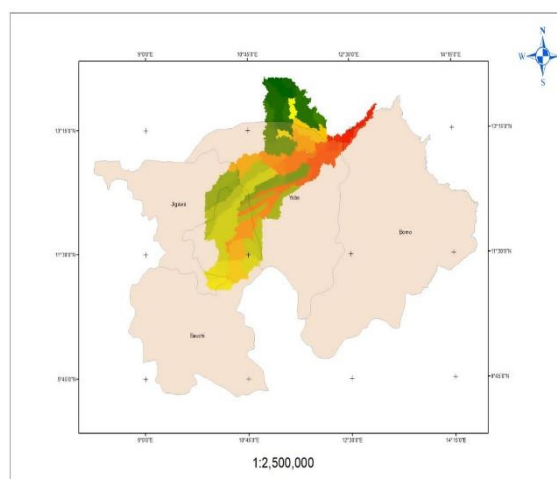


Figure 2. Map of the study area

2.2 Data Collection

2.2.1 GIS data source

Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) 90m by 90m was obtained from the United States Geographic Service (USGS) Earth Explorer website. GIS Raster and Vector shape files were used. The Land Use Land Cover (LULC) map was obtained from the Sentinel-2 10m LULC database by Corresponding author's email address: abdulhamidalkali.aa@unimaid.edu.ng

Environmental Systems Research Institute (ESRI), 2022. The LULC data used were two raster data files that were merged and clipped by the Basin Map in ArcGIS 10.7.1. The Soil map used for this study was obtained from the United Nations Food and Agriculture Organization (FAO).

2.2.2 Climate data

In this study, climatic data such as precipitation and evapotranspiration were used while daily data for the Yobe River was obtained in respect of Gashua and Gudumbali stations from 1990 to 2005. Each dataset was subjected to Homogeneity tests before use for simulating rainfall-runoff. For authenticity and accuracy, data used in the study was obtained from the Nigerian Meteorological Agency (NIMET).

2.2.3 Flow data

Daily discharge data was used for calibration and validation of the hydrological model for HEC-HMS. The data of the flow was obtained from the Hadejia-Jama'are-Komadugu-Yobe Trust Fund (HJKY-TF), Damaturu, Yobe State from the period between 1990 to 2005. The data available were for the Gashua, Geidam and Damasak stations. The data sets were also subjected to normality and homogeneity tests.

2.3 Yobe River Watershed Modeling with HEC-HMS

The Yobe river watershed was delineated using the GIS toolbar of HEC-HMS. Various models were used to simulate the watershed. The Deficit and Constant Loss Model was used to represent the Loss due to evapotranspiration and infiltration. The Direct Runoff model used was the Soil Conservation Service-Unit Hydrograph (UH) to transform rainfall into runoff. The Recession baseflow method was used for modeling baseflow and the Muskingum method was used for routing.

2.3.1 HEC-HMS model calibration and validation

The dataset was divided into Eleven (11) years for Calibration and Six (6) years for Validation, giving a percentage distribution of 70%-30%, respectively. The data was calibrated for daily time-series. The daily data were aggregated for the Mean with the use of Hydrognomon 4.1 software package. Nash-Sutcliffe Efficiency (NSE), was used as model performance evaluators and were applied by Pokhrel and Karki (2021); Rajput et. al. (2021) and Ibrahim et. al., (2022) given in equation (1);

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^n (Q_i^{obs} - \bar{Q}^{obs})^2}$$

Where Q_i^{obs} = observed streamflow; Q_i^{sim} = simulated streamflow; \bar{Q}^{obs} = mean of observed flow and n is the number of observations

3. Results and Discussion

3.1 Results of GIS Data

The DEM of the Yobe river basin is shown in Figure 3 with the blue section indicating higher elevation of up to 642m to the lower section of about 283m above mean sea level.

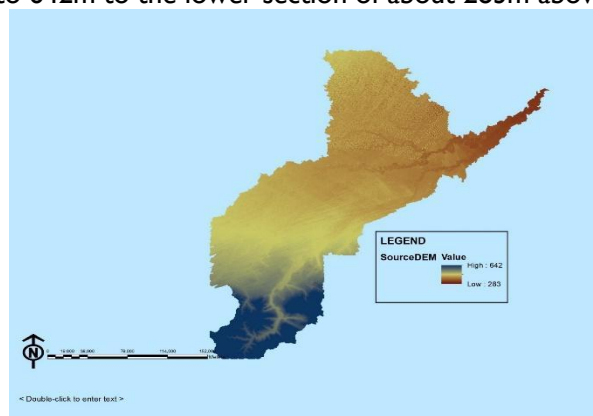


Figure 3: Digital Elevation Model for Yobe River Basin

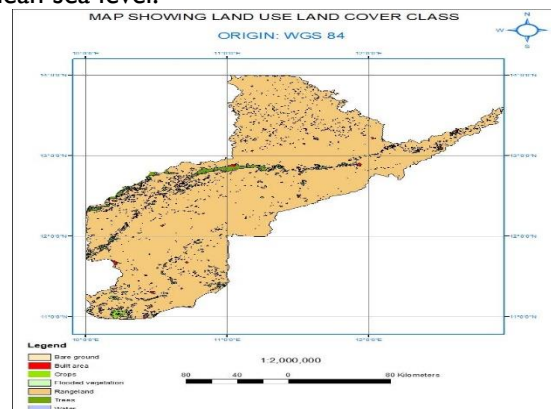


Figure 4: Land Use Land Cover (LULC) Map of the Yobe River Basin

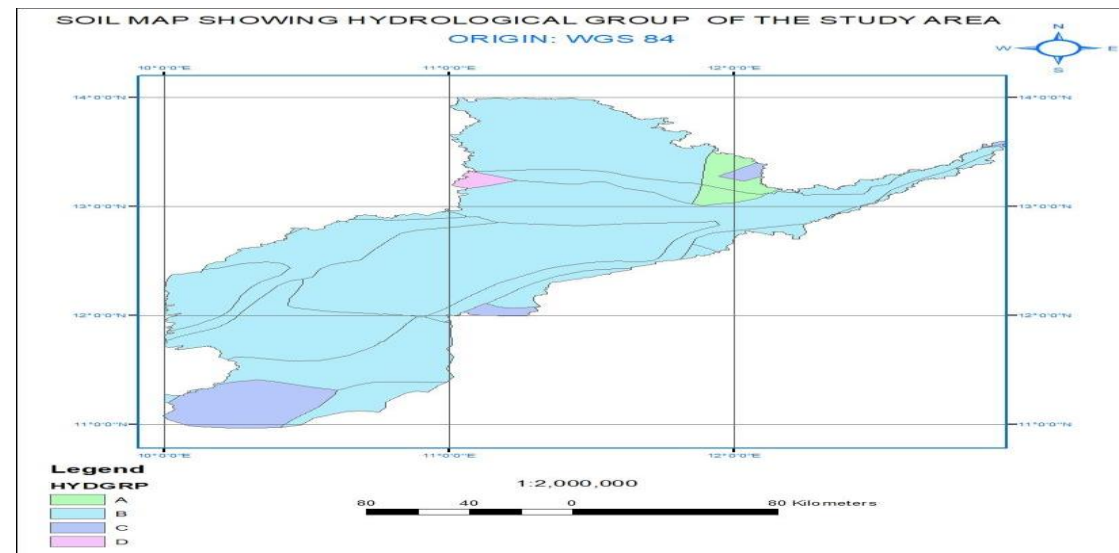


Figure 5: Soil Map of the Yobe River Basin

Figure 4 shows the LULC map. The results revealed that about 73.5% of the Yobe Basin lies within the “Rangeland” category. Rangelands serve as an important area for livestock production and can also provide habitat for wildlife. The Yobe River Basin falls within the semi-arid to arid climatic zone of the Sahel region. However, the arid climate limits the growth of trees and supports the dominance of grasses and shrubs. In addition, bare soil occupies approximately 6.12% of the basin with limited vegetation cover and exposed soil. Similarly, these areas may be devoid of plants due to several activities such as erosion and human activities including but not limited to deforestation, intensive farming and construction. In addition, water and trees share 4.1% and the remaining 10.18% is shared between built area, flooded vegetation and crops. The classification of hydrological soil groups (HSGs) A, B, C, and D categorizes soils based on their infiltration characteristics according to Rajput (2021). These classifications help in estimating runoff and designing storm-water management systems. Basically, the infiltration rates of these soils decrease from A to D. As seen in Figure 5, the predominant soil type falls under Group B and covering an estimated 79% of the catchment area. Arguably, the soil type includes loamy soils with moderate permeability. However, group B Soils followed in dominance by Group C, which covers 10% of the Yobe River Basin. It has been observed that soils in this category normally have low infiltration rates and high runoff potential and including clayey soils with low permeability. Furthermore, another predominant soil type falls under Group A, representing 6.5% of the Yobe River Basin. Interestingly, soils in this group are believed to have high infiltration rates and minimal runoff potential. Also, it was observed that Group D soil represents the least predominant soil in the Yobe River Basin characterized by very low infiltration rates and very high runoff potential. It occupies an area corresponding to approximately 3.5% such as highly compacted soils, rocky soils, or soils with an impermeable layer.

3.2 Homogeneity tests on Climatic and Flow Data

Parametric and non-parametric tests were conducted on the climatic and flow data. The climatic data provided p-values above 0.05, implying that there is no sufficient evidence to reject the null Hypothesis stating that “there is no change point within the dataset” (Mbah and Paothong, 2015; Pandzic et. al., 2019). However, the flow data showed a contrary result, viz the SHNT provided in Table I.

Table I: Homogeneity test on discharge data from three different locations

S/N	Test	Gashua		Geidam		Damasak	
		P-Value	Remarks	P-Value	Remarks	P-Value	Remarks
I.	SNHT	0.04	Not Homogeneous	<2.2 × 10 ⁻¹⁶	Not Homogeneous	<2.2 × 10 ⁻¹⁶	Not Homogeneous

It was seen that for Gashua, the p-value obtained from the SNHT is p = 0.04. This value is less significance level which suggests a statistically significant change or shift in the discharge data and therefore not homogenous. In Geidam station, a value less than 2.2 × 10⁻¹⁶ also suggests a non-homogeneous distribution in the dataset. The p-value obtained for Damasak similar to that of Geidam station provided a p-value less than 2.2 × 10⁻¹⁶ which is less than the 5% significance level, and as such is statistically significant implying a non-homogeneous distribution in the dataset..

3.3 Data Homogenization

The Null Hypothesis states that there is no change point and that the dataset follows a homogeneous distribution. Conversely, the Alternative Hypothesis states that there is a change point and the dataset does not follow a homogeneous distribution (Pandzic *et. al.*, 2019). The results of data homogenization are provided in Figures 6 to 8. Figure 6 shows the data before homogenization (BH) and after homogenization (AH). The Climatol package uses the Standard Normal Homogeneity Test (SNHT). The initial p-value estimated by using the SNHT was 0.04. The result obtained after homogenization was 0.09. This value implies that there is no sufficient reason to reject the null hypothesis that there is no change point and that the series is homogeneous.

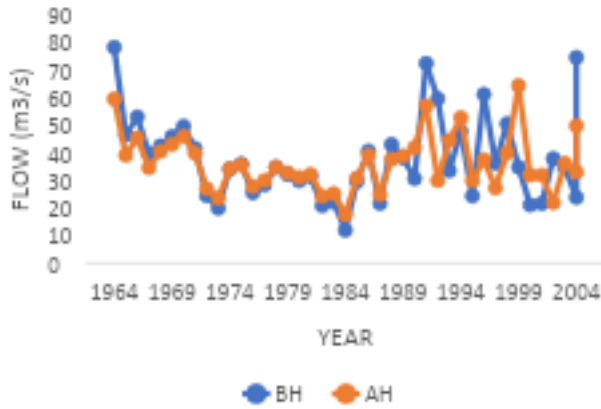


Figure 6: Discharge of Gashua before and after Homogenization

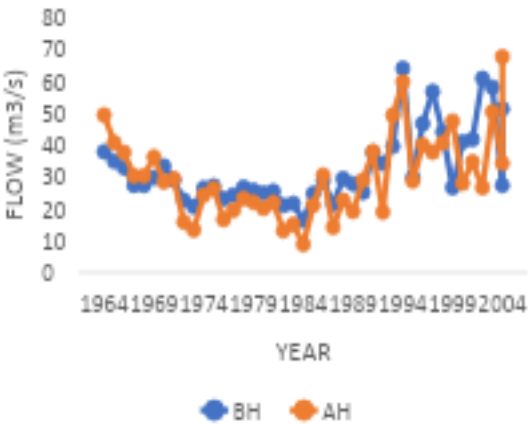


Figure 7: Discharge of Geidam before and after homogenization

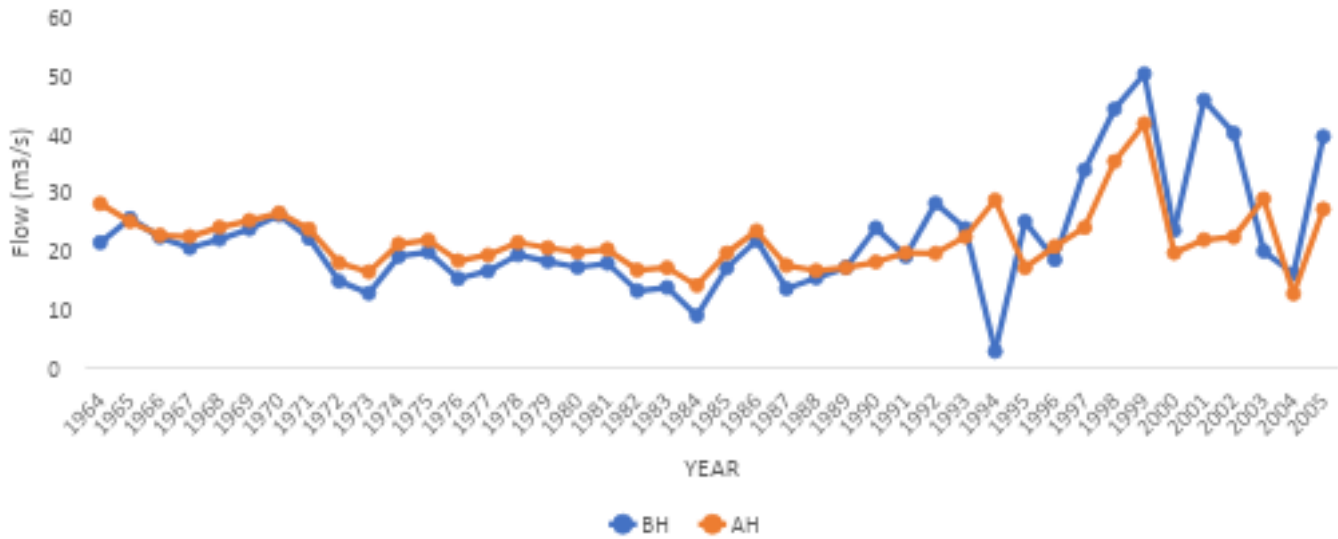


Figure 8: Discharge of Damasak before and after Homogenization

Figure 7 provides the original and homogenized data for the Geidam station. The initial p-value estimated by using the SNHT was less than 2.2×10^{-16} which later improved to 0.062. Figure 8 shows the original and homogenized data for the Damasak station. The initial p-value estimated by using the SNHT was less than 2.2×10^{-16} . A p-value of 0.24 was obtained after homogenization. Values for both Geidam and Damasak yielding p-values above 0.05 after homogenization by Climatol further indicate that the difference in the dataset is no longer statistically significant. The summary is provided in Table 2.

Table 2: Results of tests after Homogenization

S/N	Test	Gashua		Geidam		Damasak	
		P-Value	Remarks	P-Value	Remarks	P-Value	Remarks
I.	SNHT	0.09	Homogeneous	0.062	Homogeneous	0.24	Homogeneous

3.4 Performance of HEC-HMS Simulation

The results of the watershed delineation, catchments curve number extraction, lag time and time of concentration, routing, base flow values, calibration and validation results were provided.

3.4.1 Outcome of watershed delineation using HEC-HMS

The DEM was delineated using the GIS toolbar in HEC-HMS to provide 49 Sub-Basins. Dividing the Yobe River Basin into smaller sub-basins allows for a more detailed analysis of the basin's hydrological characteristics (Geosense, 2018). Smaller sub-basins may respond more quickly to rainfall, leading to flash flooding, while larger sub-basins may have a more delayed response but can contribute significant runoff volume to the main river system (Pandi et. al., 2023). Parameters such as land cover, soil type and topography can vary within the basin, and modeling each sub-basin separately allows for a more accurate representation of these variations (Khelifa and Mosbahi, 2021). The area of the sub-basins varies considerably, ranging from 13 km² to 3,758 km². The maximum flow length of each sub-basin ranges from 8.2km to 269km. The average watershed slope ranges from 1.7% to 3.6%. The Maximum Potential Retention (MPR) ranges from 0.64 to 2.99, depending upon the Curve Number. The MPR values represent the retention capacity of different parts of the Yobe River Basin. Higher MPR values indicate a greater capacity to retain rainfall within the basin, while lower values suggest a higher likelihood of generating runoff (Pokhrel and Kharki, 2021). Time of concentration (T_c) is influenced by various factors, including watershed size, slope, land cover, soil type and channel characteristics (Tassew et. al., 2019). The shortest basin has a T_c of 4.02 hours and the longest Basin has a T_c of 71.72 hours. Lag time is the time delay between the peak of the rainfall input and the peak of the resulting hydrograph at the watershed outlet. Lag time is influenced by similar factors as T_c , with the shortest and longest times of 2.41 and 43 hours, respectively.

3.4.2 Routing and base flow recession values

The Muskingum K often denoted as the wave travel time in hours ranging from 0.1 to 150 hr while the x referred to as the weighting factor from 0 to 0.5, determines the proportion of the inflow at the current time step and the inflow at the previous time step used in computing the outflow at the current time step (Khelifa and Mosbahi, 2021). The typical values are **K=0.5** and **x=0.25**. For K=0.5, it means that the river reach has moderate storage capacity, which will lead to a moderate degree of attenuation in the flow response. The Base-flow Recession Constant chosen for this study is 0.8, while the Ratio to Peak of 0.2 according to USACE (2024).

3.4.3 HEC-HMS model calibration

Calibration involves adjusting model parameters to improve the match between model predictions and observed data. The Calibration results for the daily time series are presented in Figures 9 to 11.

i. Gashua Station

The Transform and Routing are the most sensitive parameters in the calibration process of the daily series as a result of trial-and-error adjustments. The Deficit and Constant Loss method represented the observed flow well, and the values had been kept constant. The Transform parameter was multiplied by 11. The Muskingum was increased from 0.5 hrs to 145 hrs. The computed peak discharge was found to be 207 m³/s on the 5th of September, 1999, while the observed peak was 199m³/s on the 1st of October, 1999. A volume of 11,927 MCM was computed while an observed volume of 14,539 MCM was recorded. This shows that the model slightly overestimates the peak discharge while it underestimates the volume. The NSE was found to be 0.68 which falls under the "Acceptable" range according to Moriasi et. al., (2015).

ii. Geidam Station

The calibration result for the Geidam station is provided in Figure 10. The same parameter value for Transform and Routing was used for Geidam Station. The Peak discharge was simulated as 193 m³/s on the 9th of September, 1999 while the observed value recorded was 220m³/s on the 18th of September, 1994, indicating an underestimation. The simulated volume was found to be 11,816 MCM against a recorded observed value of 13,203 MCM, also indicating an underestimation. The performance evaluation of the model yielded NSE value of 0.63 which can be interpreted as "Acceptable". Hussain et. al. (2021) modeled flow simulation in tributary catchments of Kaohsiung Area of Taiwan using HEC-HMS and the model performance was satisfactory with NSE ranging from 0.51 to 0.86 for both calibration and validation.

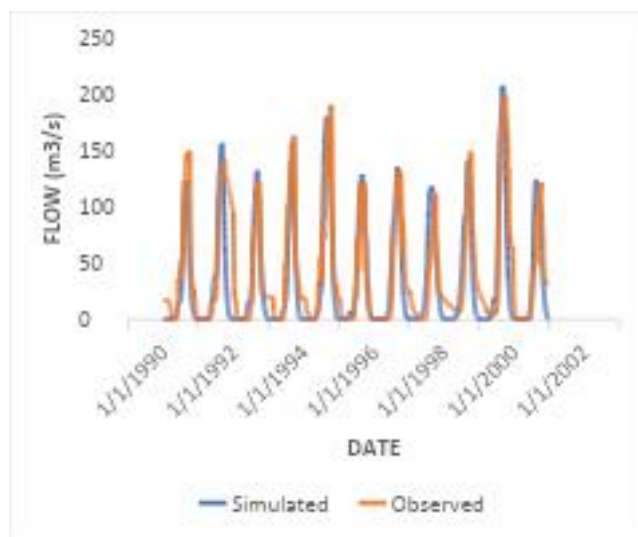


Figure 9: Calibration of Daily Time Series for Gashua Station

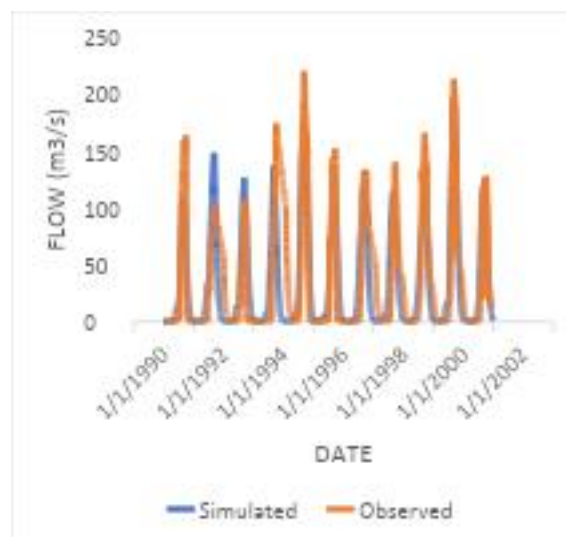


Figure 10: Calibration of Daily Time Series for Geidam Station

iii. Damasak Station

The Calibration result for Damasak Station is provided in Figure 11. The daily calibration for Damasak station yielded the same values of 145hr and a multiplication factor of 11 for the routing and transform, respectively. The Peak discharge of 111 m³/s on the 18th of September, 1999 was simulated, while a Peak discharge of 120 m³/s on the 14th of August, 1999 was observed. A simulated volume of 7,062 MCM against an observed value of 8,478 MCM was obtained, indicating an underestimation in both Peak discharge and volume.

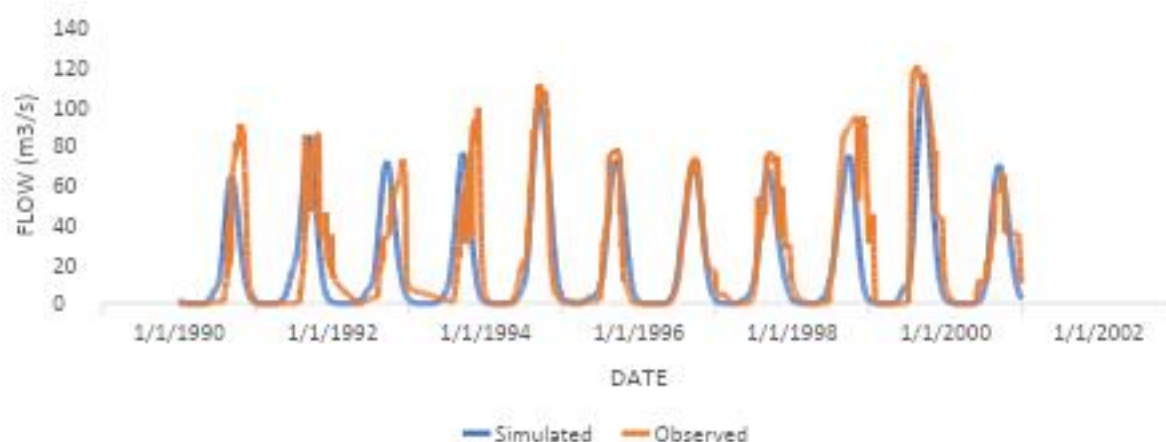


Figure 11: Calibration of Daily Time Series for Damasak Station

The performance evaluation of the model yielded 0.63 for NSE indicating an “Acceptable” relationship. Rauf and Ghumman (2018) assessed the impact of rainfall-runoff simulations of the Upper Indus River Basin of Pakistan using HEC-HMS. The catchment area is about 970,000 km² and the calibration produced satisfactory results with the calibration giving NSE values of 0.84. The HEC-HMS may have performed better for the catchment in Upper Indus River Basin due to the smaller catchment area. Summary is provided in Table 3.

Table 3: Summary of Calibration Results of Daily Time Series for HEC-HMS

S/N	Station	Value	Remarks
1	Gashua	0.68	Acceptable
2	Geidam	0.63	Acceptable
3	Damasak	0.63	Acceptable

3.4.4 HEC-HMS Model Validation

The model validation was done for years between 2001 to 2005 and is presented in this section.

The validation of the model is presented for each station from Figures 12 to 14.

i. Gashua Station:

The result for validation of the model for the Gashua station is presented in Figure 12. All the parameters for calibration were maintained and simulated volume of 5,529 MCM was obtained while observed volume of 5,506 MCM was recorded. The Performance evaluation of the model according to Moriasi *et. al.* (2015) for validation was found to be 0.78 for NSE indicating a Very good relationship.

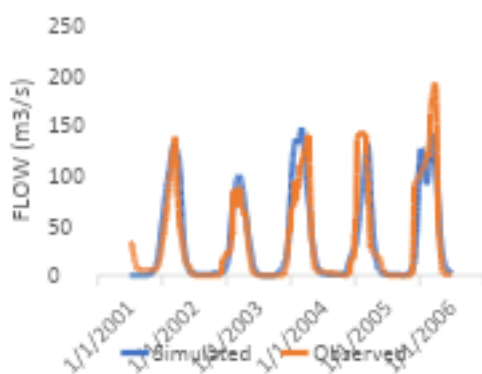


Figure 12: Validation of Daily Time Series for Gashua Station

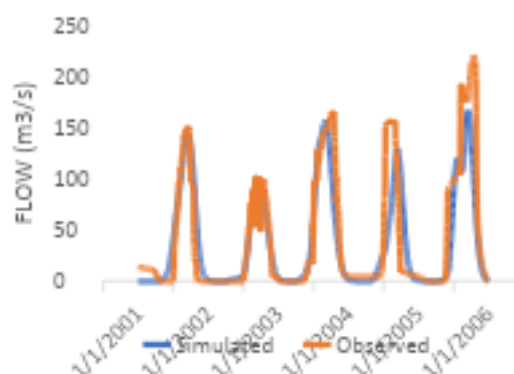


Figure 13: Validation of Daily Time Series for Geidam Station

ii. Geidam Station

The daily validation result for Geidam station is presented in Figure 13. The simulated volume is 5,842 MCM while the observed volume is 6,776 MCM. The NSE value for the model was 0.75, implying a “Very Good” relationship between the simulated and observed flows. This is in accordance with works conducted by Hussein *et. al.* (2021).

iii. Damasak Station

The result for the daily validation for the Damasak station is provided in Figure 14. A simulated volume of 3,271 MCM was obtained while the observed volume was recorded as 3,634 MCM..

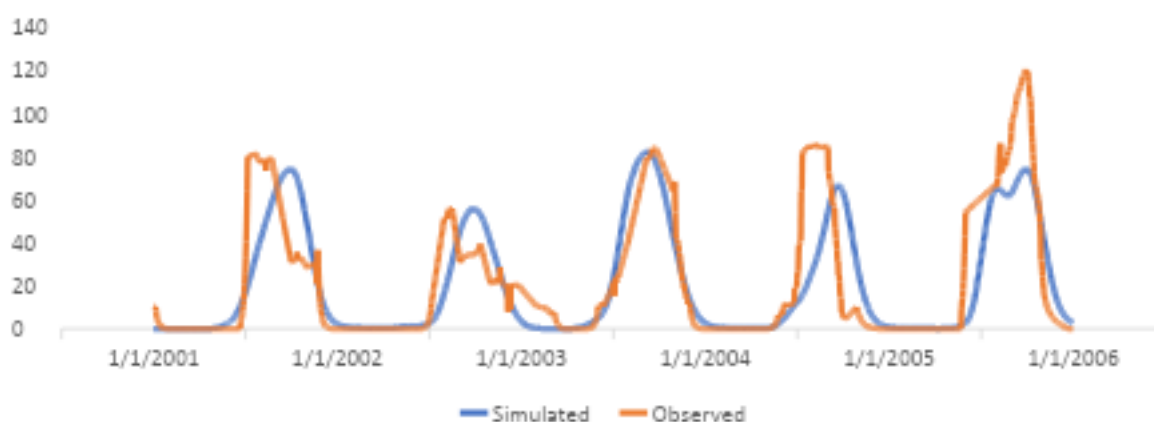


Figure 14: Validation of Daily Time Series for Damasak Station

NSE of 0.62 was obtained as the model Performance evaluation value, indicating a good relationship. Rauf and Ghuman (2018) obtained NSE of 0.70 for validation which could also be attributed to the smaller catchment area of the Upper Indus River Basin in Pakistan. Summary of the results for Validation are provided in Table 4.

Table 4: Values for validation for Daily Time Series for HEC-HMS

S/N	Station	Value	Remarks
1	Gashua	0.78	Very Good
2	Geidam	0.75	Very Good
3	Damasak	0.62	Good

5. Conclusion

The research involved modeling rainfall-runoff of the Yobe River Basin in North-Eastern Nigeria using HEC-HMS application package. Observed Climatic data (Precipitation and Evapotranspiration) were obtained from two gauging stations (Gashua and Gudumbali) for sixteen (16) year period between (1990-2005). Streamflow data for three gauging stations (Gashua, Geidam and Damasak) were also obtained for the same period. The research revealed the physiographic characteristics of the Yobe River Basin with HEC-HMS identifying 49 Sub-basins with maximum lag time of 43 hours. Also, rainfall was simulated to yield runoff using HEC-HMS. The HEC-HMS produced results with a range of NSE (>0.63 to 0.68) in calibration for daily time steps. The validation results also produced NSE (>0.62 to 0.78). These results generally implied a Very Good relationship between the simulated and observed runoff and can hence be used for forecasting streamflow for the Yobe River basin. Therefore, there is need for intervention in terms of forestation in the Yobe River basin to preserve rainwater for a longer period of time and to reduce the effect of evapotranspiration. The HEC-HMS model can be used to project runoff from available climatic data in the Yobe River Basin and basins of similar catchment characteristics for the purpose of water resources policy making, planning and management.

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