PRINT ISSN 1119-8362
Electronic ISSN 2659-1499

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 28 (10B Supplementary) 3485-3492 October, 2024

Assessment of Using Rainfall-Runoff Model to Predict Stream-flow in Ungauged Awun River Watershed, Kwara State, Nigeria

[*1]ADEOGUN, AG; [1,3]ALAJAGUSI, SN; [2]ADEBAYO, KR; [1]SAMSON, IO

*[*1]Deparment of Civil Engineering, Kwara State University, Malete, P.M.B 1530, Ilorin, Nigeria.*
[2]Deparment of Food and Agricultural Engineering, Kwara State University, Malete, P.M.B 1530, Ilorin, Nigeria.
[3] YOLAS Consultants Ltd., Ilorin, Kwara State, Nigeria.

**Corresponding Author Email: adeniyi.adeogun@kwasu.edu.ng*
**ORCHID: https://orcid.org/0000-0003-2109-0327*
**Tel: +2348033781138*

Co-Author Email: skybat21@gmail.com; kehinde.adebayo@kwasu.edu.ng; yehmeeeeee@gmail.com

ABSTRACT: Predicting streamflow for an ungauged river is essential for effective water resource management, flood risk mitigation, ecological protection, and infrastructure planning, providing critical insights despite the absence of direct measurement data. Therefore, the objective of this paper is to assess the use of a rainfall-runoff model for predicting streamflow in the ungauged Awun River Watershed, Kwara State, Nigeria. Due to the absence of measured data, regional calibration techniques were employed, utilizing data from nearby gauged river with similar hydrological characteristics. The hydrologic model predicted a peak discharge of 2164 m^3/s and a total runoff volume of 19967.78 m^3 during the modeling period, providing valuable insights for flood forecasting and water resource planning. Performance evaluation metrics indicated a Nash-Sutcliffe Efficiency (NSE) of 0.54 and a Mean Error (ME) of 0.33, reflecting moderate agreement between observed and simulated runoff data. The Percent Bias (PBIAS) of 49.25% highlighted a tendency towards overestimation. Furthermore, a high R-squared (R^2) value of 0.89 demonstrated that the model successfully explained 89% of the variance in observed runoff, effectively capturing the key hydrological characteristics of the Awun River watershed. This modeling framework is valuable for land-use planning, water resource management, decision-making, and flood risk assessments in the Awun River region.

DOI: https://dx.doi.org/10.4314/jasem.v28i10.66

License: CC-BY-4.0

Open Access Policy: All articles published by **JASEM** are open-access articles and are free for anyone to download, copy, redistribute, repost, translate and read.

Copyright Policy: © 2024. Authors retain the copyright and grant **JASEM** the right of first publication. Any part of the article may be reused without permission, provided that the original article is cited.

Cite this Article as: ADEOGUN, A. G; ALAJAGUSI, S. N; ADEBAYO, K. R; [1]SAMSON, I. O. (2024). Assessment of Using Rainfall-Runoff Model to Predict Stream-flow in Ungauged Awun River Watershed, Kwara State, Nigeria. *J. Appl. Sci. Environ. Manage.* 28 (10B Supplementary) 3485-3492

Dates: Received: 16 September 2024; Revised: 07 October 2024; Accepted: 08 October 2024 Published: 31 October 2024

Keywords: Hydrological modelling; Regional calibration; Flood risk mitigation; Ungauged River; Stream flow

The accessibility of precise hydrological models is critical for effective water resource management and accurate flood prediction within river watersheds. These models are indispensable for elucidating the intricate processes involved in rainfall-runoff transformation, particularly in regions lacking comprehensive hydrological data. In watersheds where direct runoff measurements are unavailable, the Curve Number (CN) method, developed by the Soil Conservation Service (SCS-CN), serves as a robust tool for estimating direct runoff depth from rainfall depth. This method relies on an index that characterizes the watershed's runoff response. However, parameter estimation for these models presents significant challenges, especially in ungauged watersheds, where the absence of historical runoff data

**Corresponding Author Email: adeniyi.adeogun@kwasu.edu.ng*
**ORCHID: https://orcid.org/0000-0003-2109-0327*
**Tel: +2348033781138*

precludes traditional model calibration techniques (Hundecha *et al.*, 2008). In the context of flood prediction and runoff volume estimation, the application of an appropriate modeling technique is essential for effective flood management and mitigation strategies (Bates, 2004; Masseroni *et al.,* 2017). Advanced hydrological models must integrate various parameters and employ sophisticated computational methods to simulate the hydrological processes accurately. These models often require detailed input data, including land use, soil type, and precipitation patterns, which can be difficult to obtain in ungauged basins. Consequently, researchers and practitioners must rely on innovative approaches, such as regionalization techniques, remote sensing data, and machine learning algorithms, to enhance model parameterization and improve predictive accuracy in data-scarce environments. Short-term rainfall–runoff modeling at hourly or sub-hourly intervals is essential for protecting human lives and infrastructure, especially in small catchments with quick runoff responses to rainfall. Recently, manually calibrated and conceptual-based models have been widely used to simulate rainfall–runoff processes. However, these models require extensive climatic input data, which is challenging to obtain in high-altitude, data-scarce regions (Zhu *et al.,* 2019; Atif *et al.,* 2019). Advanced techniques, including remote sensing, data assimilation, and machine learning, are necessary to improve model accuracy and reliability in such environments.

A rainfall-runoff model is a mathematical tool that describes the relationship between rainfall and runoff within a watershed, drainage basin, or catchment. It is crucial for estimating flow from a watershed, particularly in predicting the quantity and rate of runoff from land surfaces into streams and rivers. This task is especially challenging and time-consuming in ungauged watersheds, where historical data is lacking. Such information is vital for addressing watershed development and management issues. Traditional models for predicting river discharge require extensive hydrological and meteorological data, which are costly and difficult to collect (Askar, 2014).

In watersheds where runoff has not been measured, the Curve Number (SCS-CN) method can estimate direct runoff depth from rainfall depth using an index that characterizes runoff response. However, parameter estimation is challenging in ungauged watersheds due to the absence of historical runoff data for model calibration (Hundecha *et al.,* 2008). Rainfall–runoff modeling is complex due to the influence of various climatic factors, including air temperature, precipitation, wind speed, snowpack, solar radiation, and humidity. In addition to climatic factors, watershed morphology—such as topography, shape, slope, altitude, soil type, land cover, and moisture holding capacity—further complicates the runoff process, rendering it highly nonlinear (Santos *et al.,* 2003; Feng *et al.,* 2020). During floods, streams and channels often cannot convey the generated runoff due to overland flow, and high flood levels in main streams can prevent water from escaping downstream, leading to overspill and riverbank overflow. Floods are generally caused by intense or prolonged rainfall, but can also result from embankment failures, landslides, ice jams, ocean surges (tsunami), or human activities (Carlin, 2009; Moretti and Montanari, 2008). The use of hydrological models to estimate runoff in ungauged watersheds has garnered significant attention from hydrologists and hydrology students globally. Extensive research on urban flooding has led to the development of numerous mathematical modeling tools, both free and commercial (Rangari *et al.,* 2018). Among these, the Hydrological Engineering Center-Hydrologic Modeling System (HEC-HMS) is widely utilized and highly regarded for its applicability. Numerous case studies have demonstrated the high efficiency of HEC-HMS in simulating runoff from rainfall data for various watersheds (Tassew *et al.,* 2019; Rangari *et al.,* 2018; Chang *et al.,* 2015). he Awun River in Kwara State, Nigeria, poses a unique challenge for hydrologists and water resource managers due to its ungauged status. As a crucial water source for agriculture, domestic use, and industry, its significance to the Kwara State landscape is undeniable. However, the lack of a reliable streamflow monitoring station has impeded comprehensive hydrological assessments. This knowledge gap is particularly concerning amidst increasing extreme weather events and changing precipitation patterns due to climate change. Therefore, the objective of this paper is to assess the use of a rainfall-runoff model for predicting streamflow in the ungauged Awun River Watershed, Kwara State, Nigeria

MATERIALS AND METHOD

Description of the Study Area: The Awun River, located in Kwara State, Nigeria, spans latitudes 8°28′ N to 9°00′ N and longitudes 4°30′ E to 4°45′ E, covering a total area of 954 km². The main river channel extends 80.23 km (Sule and Alabi, 2013). The Awun drainage basin is part of north-central Nigeria, with a total catchment area of approximately 2300 km². It includes the Awun sub-basin (626.66 km²), Asa sub-basin (471.94 km²), Oyun sub-basin (452.80 km²), and Moro sub-basin (751.56 km²). The study area location map is depicted in Figure 1.

Fig 1: Study Area Location Map

Digital Elevation Model (DEM): The DEM used in this study was derived from the Shuttle Radar Topography Mission (SRTM) final version, utilizing radar technology to produce a detailed representation of the Earth's surface (USGS, 2014). This high-resolution DEM was obtained from an internet-based database with a spatial resolution of 12.5 m by 12.5 m. Higher resolution enhances the clarity and detail of surface features. Figure 2 displays the sourced DEM for the study area.

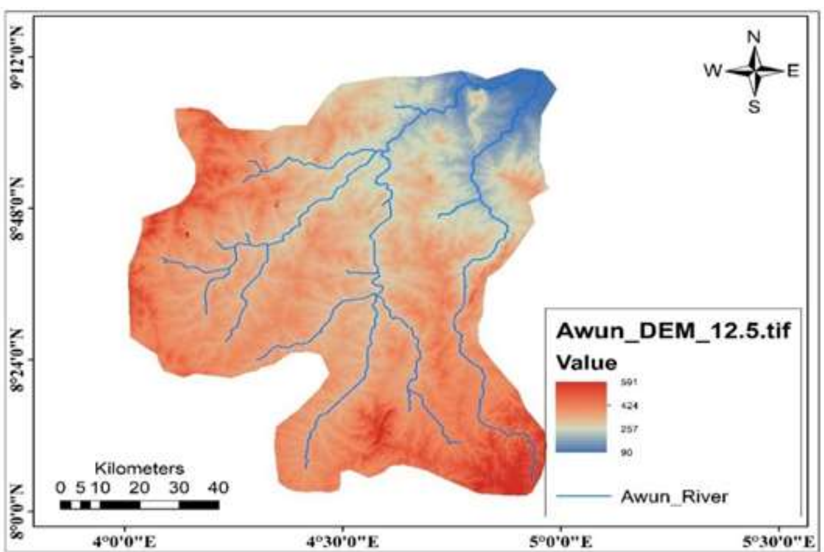

Fig 2: Digital Elevation Model for the Awun River

Land Use Land Cover (LULC): The land use map used in this study was derived from the Global Land Cover Characterization (GLCC) database (GLCC, 2023). The LULC classification for the Awun River watershed was processed using ArcMap, detailing the distribution of land cover types and their respective areas as percentages (Table 1). The predominant land cover type is scrub/shrub cover, covering approximately 48 % of the area, while flooded vegetation occupies the smallest proportion at about 0.001%. LULC classification is crucial for environmental and land management studies, providing insights into the spatial distribution and utilization of land within the study area.

Table 1: Land Use Land Cover of the Awun River and their Area (%)

Description	Area Sq.km	Area (%)
Shrub/Scrub Cover	4601.28	47.79
Tree Cover	3390.98	35.22
Water Body	57.80	0.60
Crop Cover	1161.14	12.06
Flooded Vegetation	0.40	0.00
Bare Ground	1.20	0.01
Built Up Area	415.20	4.31
Grass Cover	1.11	0.01

Soil Texture Data: The digital soil data utilized in this study were extracted from the Harmonized World Soil Database (HWSD v1.1) developed by the Food and Agriculture Organization of the United Nations. The soil texture map of the study area was processed using ArcMap, presenting the distribution of soil texture types and their respective percentages (Figure 3). The predominant soil texture is Lf26-a, covering approximately 72.42 % of the area, while the least prevalent is Lf61-3a at about 0.09%. Overall, the soil texture classification indicates that the study area is predominantly composed of Sandy Clay Loam.

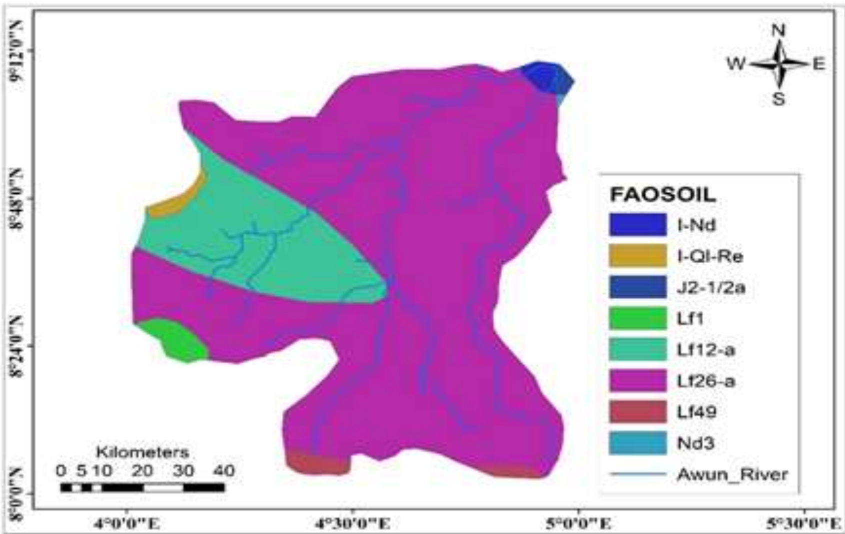

Fig 3: Soil Texture Map for the Awun River watershed

Temporal Data: Daily climate data, encompassing mean temperature (°C), average daily precipitation (mm/day), maximum and minimum temperature (°C), wind speed, and relative humidity, were obtained from the Nigerian Meteorological Agency (NiMET). This dataset spans a 30-year period and was utilized for simulating hydrological processes in the study area. These parameters are essential inputs for accurate modeling of rainfall-runoff dynamics and other hydrological analyses within the Awun River watershed.

Watershed Analysis of the Catchment: This study employed the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) within the ArcGIS environment, developed by the US Army Corps of Engineers. HEC-HMS is specifically designed for simulating complex rainfall-runoff dynamics in hydrological basins. The system includes four main modules: basin modeling, meteorological modeling, control specifications, and various data input sources (time-series, paired data, gridded data). In simulating infiltration losses, HEC-HMS utilizes several methods such as deficit and constant, exponential, Green and Ampt, initial and constant, SCS curve number, Smith-Parlange, and Soil Moisture Accounting (SMA) techniques. These methods are crucial for accurately modeling how precipitation infiltrates the soil, a key component in understanding runoff processes within the Awun River watershed. To achieve the objective of watershed analysis, three primary processes were undertaken: terrain pre-processing, watershed delineation, and terrain processing, along with basin model development. These steps are essential for preparing and modeling the hydrological characteristics of the Awun River watershed.

HEC-HMS facilitates the transformation of excess precipitation into surface runoff through various methods, including Clark unit hydrograph, kinematic wave, ModClark, SCS unit hydrograph, Snyder unit hydrograph, user-specified graph, and user-specified unit hydrograph. These methods are critical for accurately simulating how precipitation contributes to overall runoff dynamics. Furthermore, HEC-HMS employs routing models such as kinematic wave routing, lag routing, modified puls routing, Muskingum routing, Muskingum-Cunge routing, and Straddle Stagger routing to simulate the movement of water through the basin's channels and conveyance systems. These routing techniques provide insights into the flow dynamics within the Awun River watershed, essential for comprehensive hydrological analysis.

Hydrological Modeling with HEC-HMS: HEC-HMS utilizes a comprehensive suite of tools and methodologies to model hydrological processes effectively. The meteorological model supports diverse precipitation data inputs, including frequency storm, gauge weights, gridded precipitation, inverse distance, HMR52, SCS storm, specified hyetograph, and standard project storm. These methods enable integration of various meteorological data sources into the modeling framework. The basin model within HEC-HMS includes essential hydrologic elements such as sub-basins, reaches, junctions, sinks, sources, and diversions. Geographic Information Systems (GIS) such as ArcGIS are utilized to import Digital Elevation Model (DEM) data for basin delineation. Terrain processing techniques in GIS assist in creating sub-basins and defining basin structure. Land-use and Curve Number (CN) maps are generated to assign CN values to each sub-basin, with weighted CN values calculated using averaging methods and incorporated into sub-basin models. The control specification model governs simulation parameters such as start/stop times, dates, and time step durations across different simulation intervals. Datasets comprising basin characteristics, precipitation data, and control specifications are imported to facilitate hydrologic simulations. HEC-HMS employs Soil Conservation Service Curve Number (SCS-CN) techniques to analyze land-use and land-cover changes and evaluate runoff losses within the basin. Precipitation transformation utilizes the SCS-Unit hydrograph method, while flood routing employs methods like Muskingum routing to compute flood hydrographs and peak discharge values during extreme rainfall events. These computations rely on maximum rainfall event data, providing critical insights into basin hydrological behavior under extreme conditions.

Performance Evaluation, Model Calibration, and Validation: Calibration and validation of the hydrological model involved comparing simulated flow results against observed flow data. This study advocates for regional calibration using observed flow data, which entails estimating model parameters based on regional information. This approach assumes that catchments with similar characteristics exhibit analogous hydrological behaviors, allowing for the extrapolation of model parameters. Regionalization of hydrological model parameters based on catchment characteristics is a viable method to enhance model accuracy in catchments with limited discharge records (Bárdossy, 2007).

RESULTS AND DISCUSSION

Development of Hydrological Model for the Study Area: Addressing the challenge of limited runoff data in the Awun River watershed, this study employed rainfall-runoff modeling using the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS). The ungauged Awun watershed was delineated by extracting its shape file from the Africa basin map and processing it in ArcGIS. This process integrated a Digital Elevation Model (DEM) with a resolution of 12.5 m x 12.5 m, alongside Africa Soil and Land Use maps. The geo-processed Awun watershed was then imported into the HEC-HMS environment, where meteorological models were developed using rainfall data and control specifications defining the simulation period and time steps. The SCS-Curve Number method was employed to estimate runoff volume, while Unit Hydrograph and Muskingum methods were utilized for runoff and flood frequency estimation, respectively. Figure 4 illustrates the graphical interface of the developed HEC-HMS model tailored for the Awun River watershed, demonstrating the integration of GIS-based spatial data and advanced hydrological modeling techniques for comprehensive analysis and management of water resources in the study area.

Peak discharge and volume of flow of Awun river: The global summary of simulated flows for all modeled hydrological elements of the Awun River includes the drainage area (km^2), peak discharge (m^3/s), time of peak, and runoff volume. Using the SCS-curve number method, the volumetric flow of the Awun watershed was predicted to be 402.22 m^3/s in September, as illustrated in Figure 5.

Model Calibration and Validation (Regional calibration): The model was calibrated using observed daily flow data of the Asa River through regional calibration methodology. The hydrographs of observed and simulated annual data are presented in Figure 6. To evaluate the model's reliability, statistical performance metrics were calculated: NSE = 0.54, MES = 0.33, PBIAS = 49.25%, and R^2 = 0.89. An NSE of 0.54 indicates that the model reasonably fits the observed data, outperforming a simplistic mean-based prediction and capturing a substantial portion of observed variability, though with room for improvement.

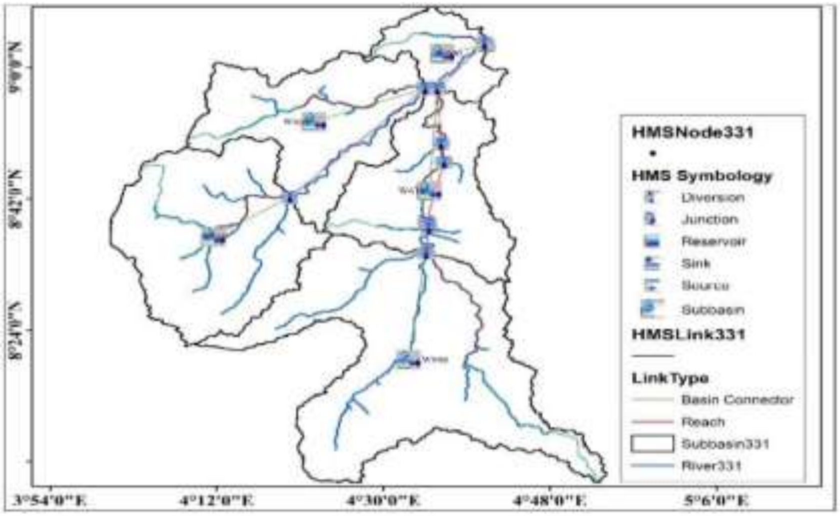

Fig 4: Development of a hydrological Model for the Awun River Watershed

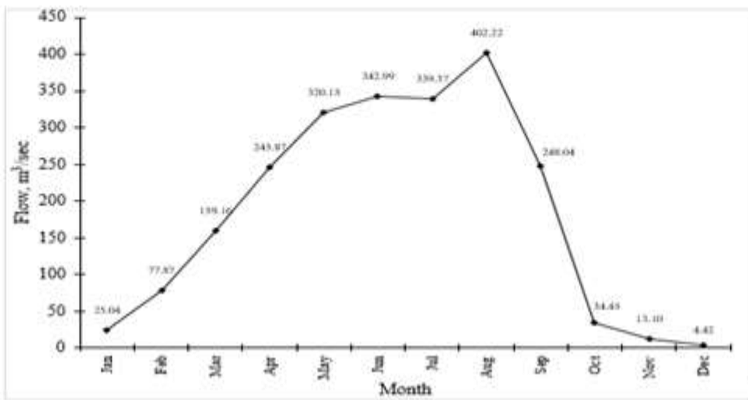

Fig 5: Volumetric flow of the Awun watershed using SCS-curve number.

Flood Accruable in Awun River watershed: The combined hydrograph is crucial in hydrological analysis, depicting simulated flows across various return periods, typically from 2 to 200 years (Figure 7). It represents hydrological variability within the study area, offering insights into a full spectrum of conditions. The highest peak discharge of 502.9 m³/s during the 200-year event is significant for flood risk assessment, essential for designing resilient infrastructure like bridges, levees, and flood control systems. This data also informs floodplain boundaries and building codes. Conversely, the lowest discharge of 0.0 m³/s during the 2-year return period signifies minimal flow, indicating potential drought conditions. Understanding low-flow conditions is vital for effective water resource management, aiding in planning drought mitigation strategies and sustainable water use. The combined hydrograph provides a comprehensive view of the temporal distribution of flows, essential for understanding the timing and duration of peak events. This information is critical for flood prediction, emergency response planning, and environmental impact assessments. Temporal data helps anticipate rapid versus gradual flow increases, enhancing preparedness and response efforts. Additionally, the hydrograph integrates historical flow data with simulated data to calibrate and validate hydrological models, ensuring accuracy. This combined approach supports informed decision-making in flood risk assessment, infrastructure design, and ecological impact analysis, aiding the protection of ecosystems, wildlife habitats, and water quality within the study area.

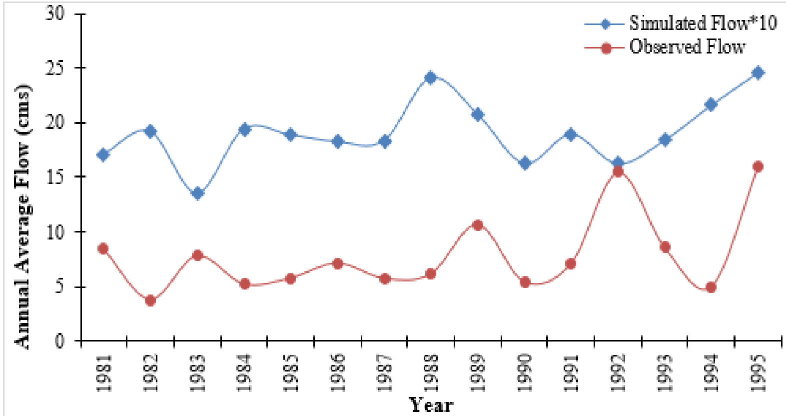

Fig 6: Model Calibration & Validation (Regional calibration) for the Watershed

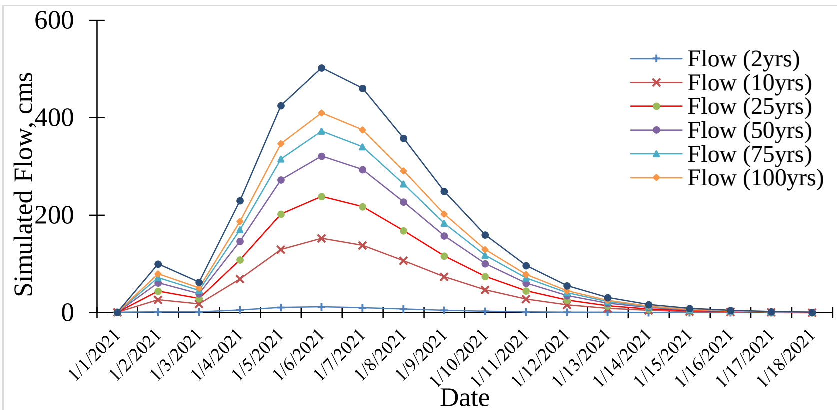

Fig 7: Combined Hydrograph of the simulated flows for different return periods

Conclusion: This research developed a rainfall-runoff model for the ungauged Awun River watershed in Kwara State, Nigeria, using the HEC-HMS tool and regional calibration with data from nearby gauged rivers. The model estimated a peak discharge of 2164 m^3/s and a total runoff volume of 19967.78 m^3, aiding flood forecasting and water resource planning. Performance evaluation indicated moderate agreement between observed and simulated runoff (NSE of 0.54, ME of 0.33, PBIAS of 49.25%) and a high R-squared (0.89), capturing key hydrological characteristics. This framework is valuable for land-use planning, water resource management, decision-making, and flood risk assessments in the Awun River region.

Declaration of Conflict of Interest: The authors declare no conflict of interest

Data Availability Statement: Data are available upon request from the corresponding author

REFERENCES

Arnold, JG; Moriasi, DN; Gassman, PW; Abbaspour, KC; White, MJ; Srinivasan, R; Santhi, C; Harmel, RD; van Griensven, A; Van Liew, MW; Kannan, N; Jha, MK (2012). SWAT (Soil and Water Assessment Tool) Transactions of the ASABE. 55(4): 1491-1508. doi: 10.13031/2013.42256.

Askar, MK (2014). Rainfall-runoff model using the SCS-CN method and geographic information systems: a case study of Gomal River watershed WIT Transactions on Ecology and The Environment, Vol 178. doi: 10.2495/13WS0141, pg 159-170.

Atif, I; Iqbal, J; Su, L.-j (2019). Modeling Hydrological Response to Climate Change in a Data-Scarce Glacierized High Mountain Astore Basin Using a Fully Distributed TOPKAPI Model. Climate, 7, 127. https://doi.org/10.3390/cli7110127.

Bárdossy, A (2007). Calibration of hydrological model parameters for ungauged catchments. *Hydro. Earth Syst. Sci.,* 11:703–710. https://doi.org/10.5194/hess-11-703-2007.

Bates, PD (2004). Remote sensing and flood inundation modeling. Hydrol. Processes. 18, pg 2593–2597. doi: 10.1002/hyp.5649.

Carlin, N (2009). Spatial analysis using Geographic Information Systems (GIS) to evaluate areas susceptible to repeat flash flooding in La Crosse County, Wisconsin.; 11:12 p. Papers in Resource Analysis. Saint Mary's University of Minnesota Central Services Press. Winona, MN. Retrieved on 2012-01-05 from http://www.gis.smumn.edu.

Chang, TJ; Wang, CH; Chen, AS (2015). A Novel Approach to Model Dynamics Flow Interactions between Storm Sewer System and Overland Surface for Different Land Covers in Urban Areas. *J. Hydro,* 52(4): 662-679. doi: 10.1016/j.jhydrol.2015.07.019.

FAO/UNESCO Soil Map of the World; c2023 [cited 25 October 2023]. Available from: https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/.

Feng, ZK; Niu, WJ; Tang, ZY; Jiang, ZQ; Xu, Y; Liu, Y; Zhang, HR (2020). Monthly runoff time series prediction by variational mode decomposition and support vector machine based on quantum-behaved particle swarm optimization. *J. Hydro*. doi: 10.1016/j.jhydrol.2020.124627.

GLCC. Global Land Cover Characterization; c2023 [cited 13th October 2023]. Available from https://www.usgs.gov/centers/eros/science/usgs-eros-archive-land-cover-products-global-land-cover-characterization-glcc.

Hundecha, Y; Ouarda, TBMJ; Bárdossy, A (2008). Regional estimation of parameters of a rainfall-runoff model at ungauged watersheds using the spatial structures of the parameters within a canonical physiographic-climatic space. Water Resour Res, 44: W01427. doi: 10.1029/2006WR005439.

Masseroni, D; Cislaghi, A; Camici, S; Massari, C; Brocca, L (2017). A reliable rainfall–runoff model for flood forecasting: review and application to a semi-urbanized watershed at high flood risk in Italy. *Hydro. Resea*, 48(3): 726–740. https://doi.org/10.2166/nh.2016.037.

Moretti, G; Montanari, A (2008). Inferring the flood frequency distribution for an ungauged basin using a spatially distributed rainfall-runoff model. *Hydro. Earth Syst Sci*, 12, 1141-1152. doi: 10.5194/hess-12-1141-2008

Nachtergaele, F; Velthuizen, H.V; Verelst, L (2009). Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Luxemburg, Austria. https://www.fao.org/3/aq361e/aq361e.pdf.

Rangari, VA; Sridhar, V; Umamahesh, NV; Patel, AK (2018). Rainfall Runoff Modeling of Urban Area Using HEC-HMS: A case study of Hyderabad city, Trends and Recent Advances in Civil Engineering (TRACE 2018) held between 23-24,August, 2018 At: Amity University Uttar Pradesh, India.

Santos, CAG; Srinivasan, VS; Suzuki, K; Watanabe, M (2003). Application of an optimization technique to a physically based erosion model. *Hydro. Proc*, 17(5):989–1003. doi: 10.1002/hyp.1176.

Sule, BF; Alabi, SA (2013). Application of synthetic unit hydrograph methods to construct storm hydrographs. *Intern. J. Wat Resour. Environ Engin*, 5(11): 639-647. doi:10.5897/IJWREE2013.0391

USGS United State Geological Survey. Earth Explorer; c2023 [cited 27 October 2023]. Available from: https://earthexplorer.usgs.gov/.

Zhu, S; Heddam, S; Wu, S; Dai, J; Jia, B (2019). Extreme learning machine-based prediction of daily water temperature for rivers. *Environ Earth Sci.* doi: 10.1007/s12665-019-8202-7.