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Hydrological Modelling of Ungauged Mamu River Basin Using SWAT Model

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Abstract

Hydrological modeling of ungauged basins is necessary for decision and policymaking in water resources management. The Mamu River Basin is characterized by a wide range of environmental pressures such as erosion-caused devastation. The impact of climate change is likely to have considerable implications for water resource planning in the Basin. Despite these challenges, there is no gauged data available to evaluate the water resources of the Mamu River Basin. The objective of this study is to simulate river discharge in the ungauged Mamu River Basin using Soil and Water Assessment Tools (SWAT). A regionalization approach was employed to simulate the river flow at the Ebenebe axis of the Mamu River. Calibrated and validated model parameters from gauged Imo River were transferred to the Mamu River Basin. Shuttle Radar Topographic Misson-Digital Elevation Model (SRTM-DEM), land use, soil data, and rainfall data for the Mamu River Basin were used to improve the model. The SWAT model simulated streamflow for the basin and this was validated using discharge measurements along the Mamu River from 01/01/2021to 31/12/2022. During the validation process, the model performance indicators, NSE, $R^{2,}$ and PBIAS values were 0.77, 0.95, and 15 respectively. This study showed that the SWAT model can simulate river discharge in an ungauged river basin and will enhance our understanding of the hydrological response of the ungauged Mamu River Basin to environmental changes.

Keywords: Mamu River, Ungauged, SWAT, Calibration, Validation, Hydrological modelling.

1. Introduction

The impact of climate change is likely to have considerable implications for water resource planning, as well as adding to the risks of water infrastructures. Climate change that reduces either the overall quantity of water or the timing of when water is available for use will have important effects on agriculture, industrial and urban development (Hailemariam, 1999). Increasing variability alone would enhance the probability of both flood and drought. Attention is increasingly being paid to adaptation strategies at the regional and basin level; conversely, the current paucity of information regarding the potential risk to hydrological systems at this scale presents a substantial challenge for effective water resources planning and management. Hailemariam (1999) posited that quantitative estimates of climate change are essential for understanding and solving the potential water resource problems associated with water supply for domestic and industrial water use, power generation and agriculture as well as future water resource planning, reservoir design and management and protection of natural environment.

Thus, numerous studies (e.g. Beven and Kirkby, 1979; Ghosh and Misra, 2010; Hrachowitz et al., 2013; Iskender and Sajikumar, 2016; Singh and Saravanan, 2020; Leye et al., 2020) have successfully shown that the assessment of water resources of river basins with limited data could be addressed through hydrological modeling. This follows from the realization that several methods have been developed for hydrological prediction in ungauged basins (Kim and Kaluarachchi, 2008), of which Mamu is one. In the same vein, studies in the UK have developed various methodologies for predicting flow characteristics of ungauged catchments for example the regionalization technique (Golian, Murphy, and Meresa, 2021). The regionalization approaches transfer model parameters from monitored basins to ungauged basins based on the similarities in the watersheds' physical (area, slope, land cover, etc.) and climatic (rainfall, potential evapotranspiration) characteristics.

Mamu River basin is associated with a wide range of climatic and hydrological problems that need urgent investigation. The Basin is practically poorly/not monitored and ungauged, hence daily stream flow or discharge data, a central component of many aspects of water resource planning and management (Young and Reynard, 2004) is lacking. This is due to unavailability of required instruments or poor instrumentation and inadequate trained man power. Thus, associated water resource problems such as flooding and soil erosion have continued to reoccur with less effort in managing them. The upper parts of the basin especially around Otalu and Aghommiri sub-basins have been devastated by both flooding and soil erosion. The Agulu-Nanka soil erosion complex located in this part of the basin has constituted a major environmental problem to the inhabitants of the area and solutions to tackle it have been ongoing for the past four decades by the Federal Government. Part of the reason why the problem seems to have defied solution is the heavy reliance of intervention bodies on engineering solution to the problem. No visible attempt has been made to embark on a comprehensive basin wide management that incorporates climatic, hydrological, pedological and anthropogenic factors that constitutes this problem. Related to the issue of soil erosion in the basin is that of sedimentation. The heavily eroded part of the Awka-Orlu upland around Nanka and Oko has generated a lot of sediments that are choking the river channel downstream. The case of Odo River located between Awgbu and Amaokpala along Awka-Umunze highway is a veritable case in point where the whole valley of the river is having heavy deposits of sand that have been evacuated from the erosion site upstream. Thus, the catchment scale effects of climate change especially on basin hydrology are poorly understood in this basin. This could be attributed to the huge dearth of hydrological network to provide the much-needed hydrological information

No attempt has been made all this while to predict the potential impacts of future climate change and variability on worsening the soil erosion, sedimentation and hydrological problems of the basin. The lack of discharge data for the catchment equally makes the assessment of climate related impacts on the hydrology of Mamu River basin a difficult task (Amisigo et al., 2008; Taylor et al., 2006). Despite the need for such scientific inquiries, little effort has been made to model and predict the hydrological response of ungauged basins in the southeast of the country. Thus, this study is intended to help bridge the gap in understanding the hydrological behaviour of Mamu river basin. This study explored the applicability of SWAT model in simulating the river flow for ungauged Mamu River for water resources management.

2. Materials and Method

2.1 Study area

The Mamu River basin is located in the southeastern part of Nigeria and cuts across Anambra and Enugu States. It is located with latitude 6^0N and $6^0 50^1$N and longitude 6^0 50^1 E and 7^0 30^1E (Figure 1). The Mamu Basin is found within the Anambra River Basin. The Basin experiences a tropical wet and dry climate with an average of 8months of rainy season and 4months of dry season. The annual rainfall varies between 1900mm and 2500mm.The Mamu River empties into the Anambra River. It is underlain by sedimentary formations of Nanka sands, Ameki and Asaba formation.

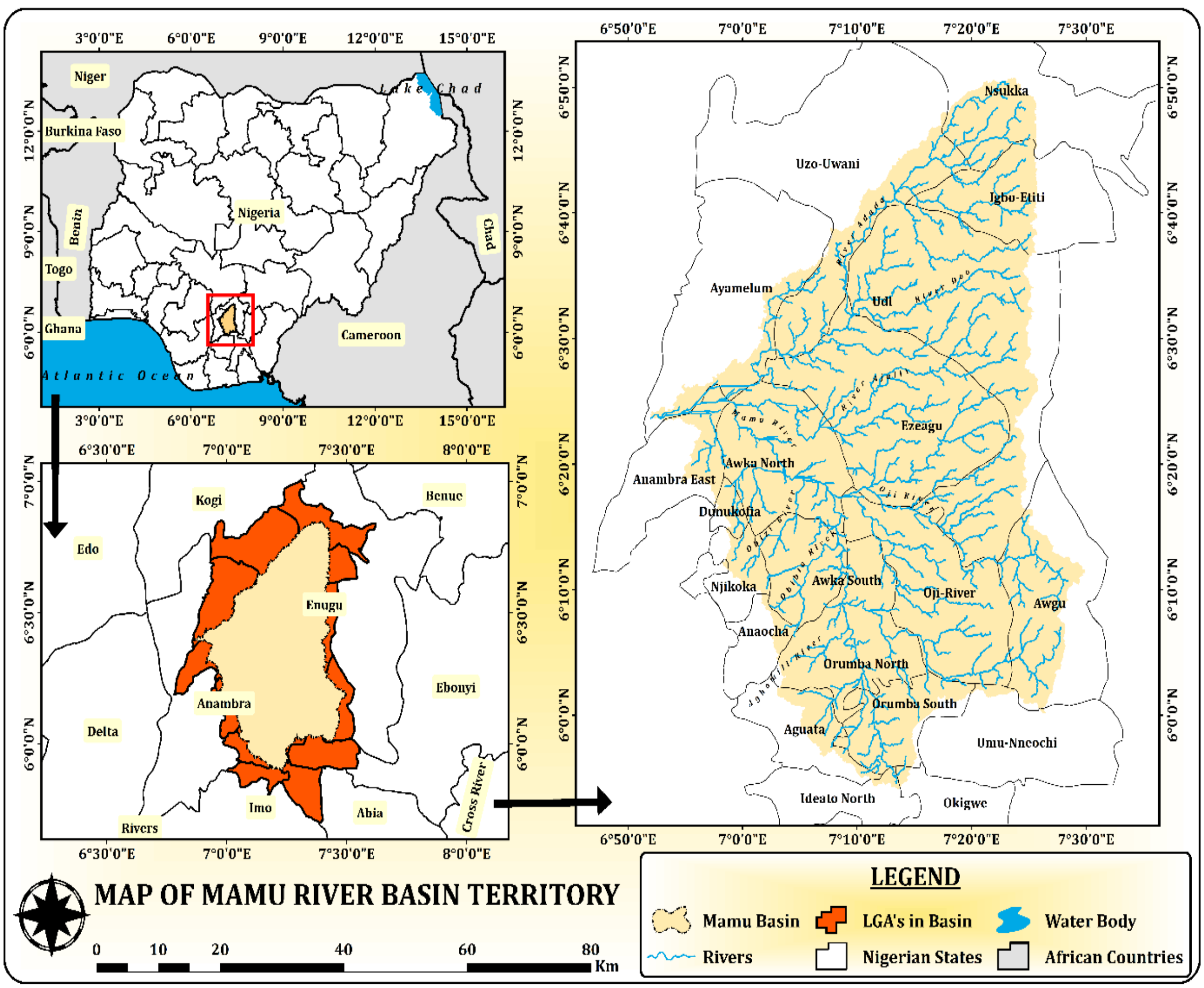

Fig 1: Mamu River Basin

2.2 Methodology

2.2.1 Data input

Climate and soil data

Data utilized in the study were obtained from both primary and secondary sources. Table 1 summarizes the type of data, source, and spatial resolution. The basic climatic data need include minimum and maximum air temperature, daily rainfall, relative humidity, solar radiation, and windspeed were downloaded from https://globalweather.tamu.edu. The soil data for the study area was obtained from FAO harmonized world soil database v.12. The soil data contained 5 soil classes (see Figure 4).

Model Input Data

A 30m x 30m digital elevation model (DEM) obtained from USGS was used to set up the SWAT model. Subbasin partitioning and stream networks were computed automatically through the QSWAT interface with the manual configuration of the outlet feature classes to include the subbasin 1 channel of the Mamu River catchment as a calibration feature at the top of the Mamu River watershed (see Figure 1).

Information on land use was obtained from fieldwork carried out by the research team. This information played a critical role in training the Landsat images obtained for the Mamu River Basin. The band compositions adopted were bands 2, 3, 4, and 5. A false colour composite operation was performed using the IDRISI software. The False Colour Composite was further classified using the Maximum Likelihood Classification Technique. A supervised classification was performed by creating a training sample and based on the spectral signature of the curve, six land use types and cover classes were identified and the land use data were adapted for use in the SWAT model.

Table 1: Data types and sources

Data Type	Description	Sources	Resolution
Digital Elevation Model	SRTM DEM	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1	30m x 30m
Land use	Landsat 8 Operational Land Imager	https://earthexplorer.usgs.gov/	30m x 30m
Soil map	FAO harmonized world soil database v.1.2	https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/	1:1, 000, 000
Meteorological data		https://globalweather.tamu.edu	

SWAT Model Configuration

The Soil and Water Assessment Tool (SWAT2012) was used to estimate streamflow for the ungauged Mamu Basin through the QSWAT interface. SWAT is a watershed-modelling tool capable of simulating the effects of various land management and climatic scenarios on the hydrologic response of watersheds (Arnold et al., 1998). The SWAT model divided the Mamu watershed into subbasins for better representation of spatial heterogeneity. The subbasins are further divided into hydrologic response units (HRUs) based on soil types, land use, and slope. For every single HRU, the soil water content, surface runoff, crop growth including management practice, and sediment yield is compiled and then aggregated to the subbasin level by a weighted average. The model requires several parameters (specified at the watershed, sub-basin, and HRU levels) to simulate hydrologic processes. These include weather, soils, groundwater, channel, plant water use, plant growth, soil chemistry, as well as sub-basin and HRU characterization data. For this study, the Mamu River basin was dissected into 38 subbasins (Figure 1). The hydrological response units were delineated and the basin is shown to have a total of 10,337 hydrological response units (HRUs). The HRUs are modeling entities that have the same soil, topography, and LULC characteristics but are still different from each other. Runoff was predicted separately for each HRU and routed at the subbasin level to obtain total runoff figures (Neitsch et al, 2011; Roth et al., 2016).

Parameterization of SWAT model for Mamu River Basin

The regionalization technique was employed in model parameter transfer from a gauged basin to the ungauged Mamu Basin. A wide range of regionalization efforts have been developed. He *et al.* (2011) classified these into two: direct regionalization of flow and flow metrics, and regionalization of model parameters, both of which are based on either regression methods, or some kind of distance measures between gauged and ungauged sites This study adopted spatial proximity regionalization approach (Hrachowtiz et al., 2013) in the transferring of model parameters from monitored Imo River Basin to ungauged Mamu basins based on basins' physical and climatic characteristics. The transferred model parameters from the Imo River Basin to the Mamu River Basin have been calibrated and validated based on a study by Ezenwaji, Nzoiwu, Okoye, Nnabude and Umeogu (2024). After all the necessary files needed to run the SWAT were inputted, the simulation ran successfully.

Model evaluation

The QSWAT model was run on a monthly time step for a period of 2years (2021 – 2022). The performance of the SWAT model was examined using the Nash-Sutcliffe efficiency (NSE) and the percent bias (PBIAS). The theoretical range of NSE is from -∞ to 1, with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as the most efficient parameters for model predictive ability, whereas values less than 0.0 indicate that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. PBIAS is a measure of over-and-underestimation (Politi, Cutler and Rowan, 2012) or the average tendency of the simulated data to be larger or smaller than the observed counterparts (Ma, Wu, Liu, and Abuduwaili, 2014). The optimal value of PBIAS is 0.0 with low values indicating accurate model simulation.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs} - Q_{mean\ obs})^2}$$

$$PBIAS = \frac{\sum(Q_{obs} - Q_{sim})}{\sum Q_{obs}} \times 100$$

where Q_{obs}, Q_{sim} and $Q_{mean\ obs}$ are the observed, the simulated, and mean of the observed data.

The model performance ratings as defined by Moriasi et al (2007) are shown in Table 2 and these ratings were applied in this study for runoff prediction.

Table 2: Performance Rating for Recommended Statistics

Performance rating	**NSE**	**PBIAS**
Very good	0.75<NSE≤1.00	PBIAS<±10
Good	0.65<NSE≤0.75	±10≤PBIAS<±15
Satisfactory	0.50<NSE≤0.65	±15≤PBIAS<±25
Unsatisfactory	NSE≤0.50	PBIAS≥±25

3. Results and Discussion

The SWAT model dissected the basin into 38 subbasins (Figure 2). The hydrological response units were delineated and the basin is shown to have a total of 10,337 hydrological response units (HRUs). The HRUs are modelling entities that have the same soil, topography, and LULC characteristics but are still different from each other. The basin has a total land area of 382,632.25

hectares. A total of 29.48% of the basin land area constitutes the floodplain of the basin while the upslope part of the basin is 70.52% of the land area.

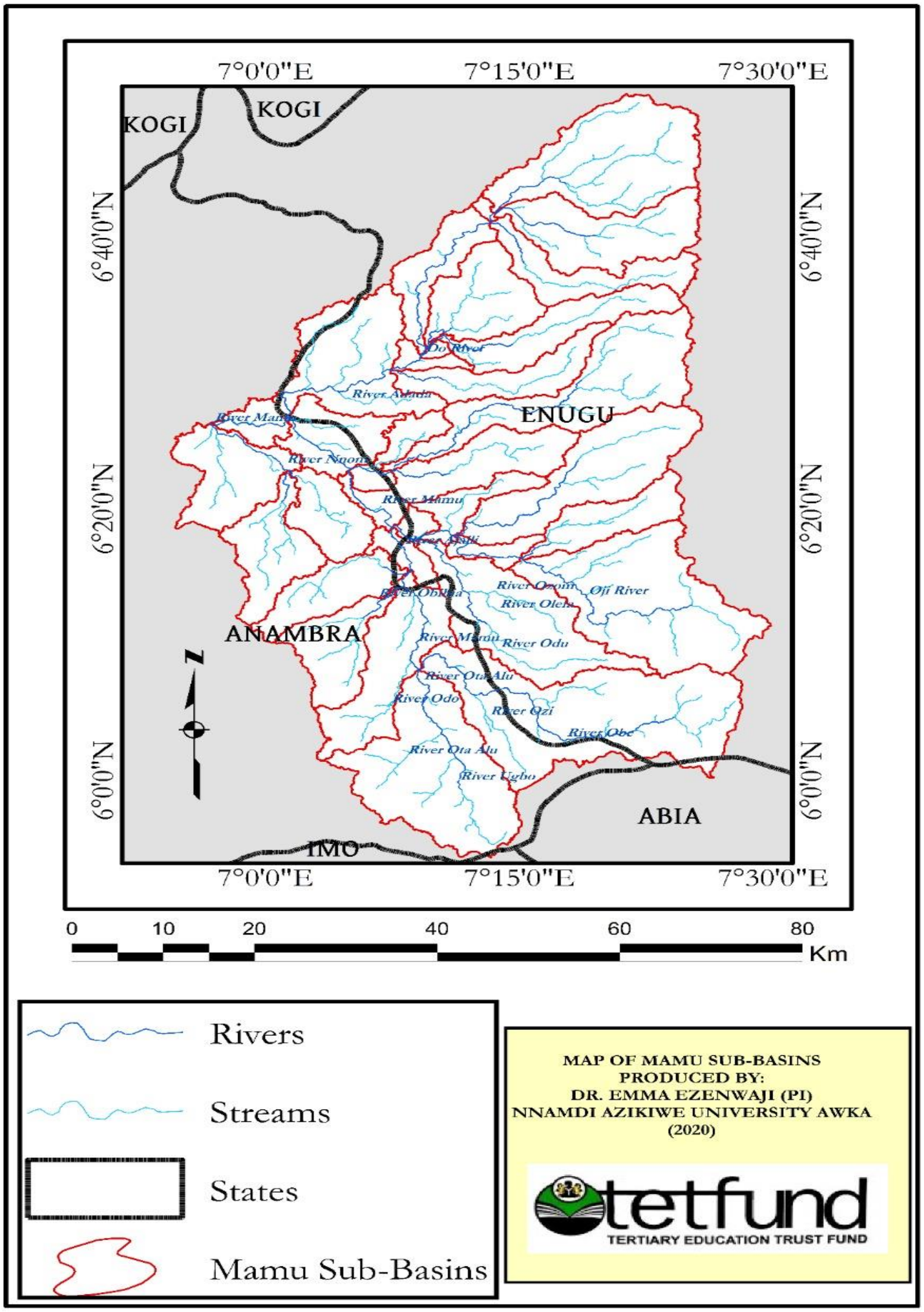

Fig 2: Sub-basins of Mamu River Basin

The land use classes found in the Mamu basin consist of seven land use types classified as Forested areas, Marshy/Swampy areas, Farmlands, Bare grounds, Grasslands, waterbody, and built-up. In the SWAT database, the land use types are classified as FRST, SHRB, and GRAS. The land use map is shown in Figure 3. As shown in Table 1, the built-up environment and drainage channels constitute

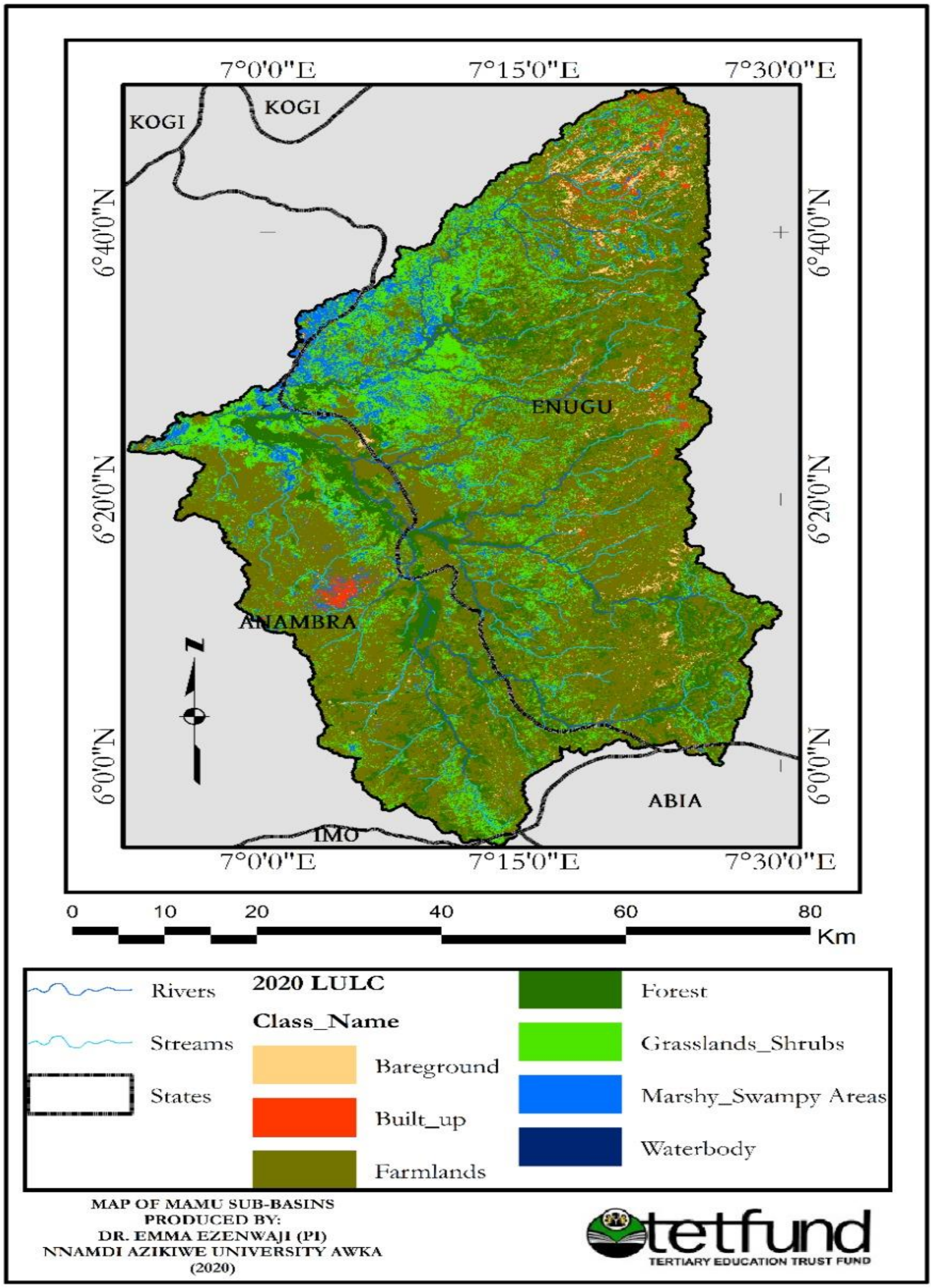

Fig 3: Land use/Land cover of Mamu River Basin

less than 1% each of the total land area. Bare soils or grasslands occupy only 0.6% of the total land area of the basin. For the vegetation class, forested vegetation type dominated the landscape of the basin up to about 56.54% of the total land area. The forest land use maintained a 17.88% share of the total land area while farmlands (AGRL) occupy 10.79% of the total land area of the basin. Forested lands dominate the southern part of the basin towards the basin outlet. The soil characteristics of the basin is shown in Figure 4.

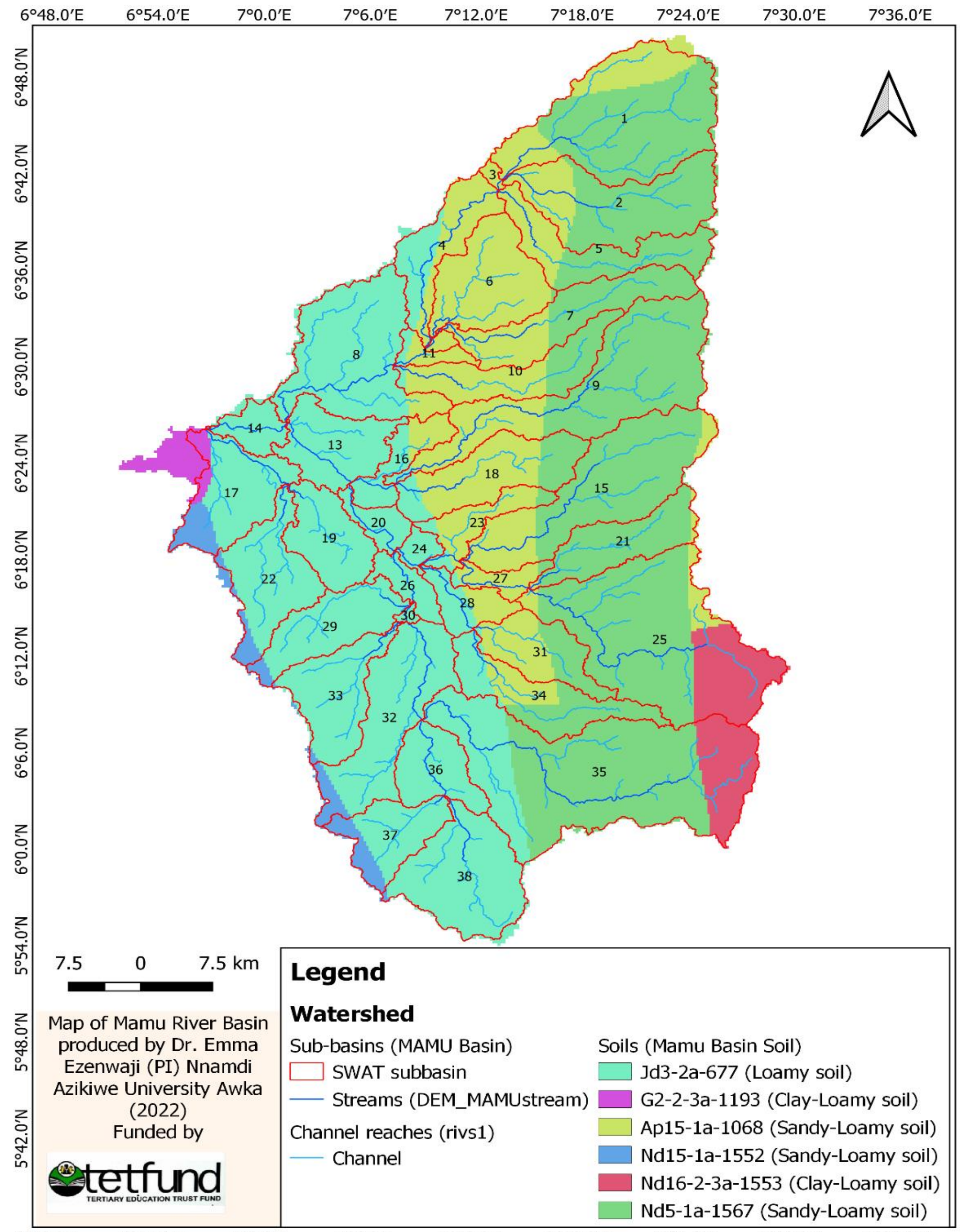

Fig 4: Soil map of Mamu Basin

Parameterization of SWAT model for Mamu River Basin

Model parameters which have previously been calibrated and validated in Ezenwaji, et al. (2024) were transferred to Mamu River Basin. In their study, the SWAT model was manually calibrated on a monthly basis in SWAT-Cup using SUFI-2, with 200 iterations. They achieved this by iteratively modifying the sensitive parameters to yield values close to the observed monthly flow values from the Imo River basin. The final calibrated results for the parameters which were used to simulate streamflow in the present study for Mamu River Basin are shown in table 1. The performance of these parameters when calibrated for simulating river flows by Ezenwaji et al (2024) revealed an NSE value of 0.66 and PBIAS of 13.4 while the validation of the river flow for Imo River Basin yielded an NSE coefficient of 0.98 and a PBIAS value of 4.35. The outcome of the validation results is shown to be good based on the performance rating and were better than the calibration.

Table 1: Streamflow parameter ranges for calibration (Source: Ezenwaji et al., 2024)

S/N	Parameter	Definition	Fitted parameter range
1	CN2	Curve number	35 – 95
2	revap_co	Groundwater “revap” coefficient	0.02 – 0.2
3	revap_mn	Threshold depth of water in shallow aquifer for “revap” to occur	0 – 500
4	alpha	Baseflow alpha factor	0 – 1
5	esco	Soil evaporation compensation factor	0.01 – 1
6	canmx	Maximum canopy storage	7.5 – 92.5
7	awc	Available water capacity of soil layer	0.85 – 1
8	usle_p	USLE equation support practice	-1.5 – -0.5
9	slope	Average slope	-0.5 – 15
10	uslec_lte	Min value of USLE C factor applicable to land cover/plant	0.001 – 0.29
11	uslek_lte	USLE soil erodibility factor	-0.34 – 0.2
12	uslels_lte	USLE topographic factor	0.1 – 0.9
13	cherod	Channel erodibility factor	-0.5 – 0.6
14	ovn	Manning’s “n” value for overland flow	0.01 – 15
15	chn	Manning’s “n” value for the tributary channels	-0.01 – 0.29

Simulation of Ungauged Mamu Catchment

The SWAT model parameters validated on the Imo River basin were transferred to Mamu basin to explore their applicability and success in simulating the runoff in Mamu River Basin for the period 2021 to 2022. This was done through validation process. To achieve this, the calibrated parameter ranges fitted in Imo River Basin were used to simulate the model in Mamu River Basin, which is approximately two times larger. The plot of the simulation is shown in figure 5.

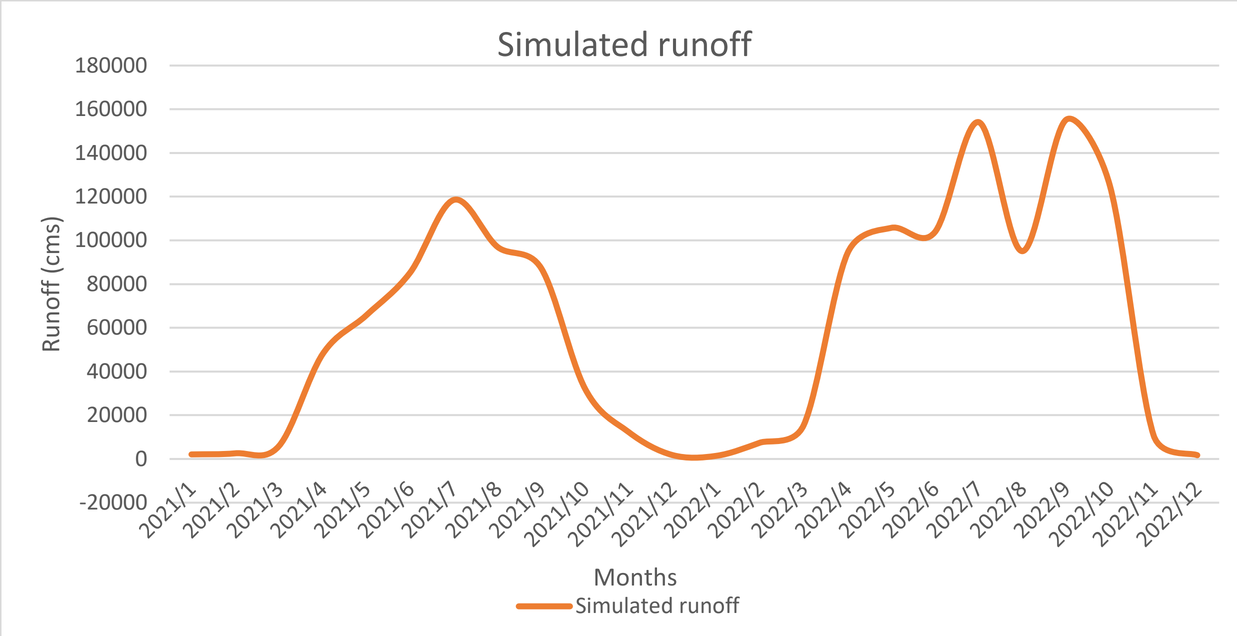

Fig 5: Hydrography of monthly simulated runoff for Mamu River Basin

We went further to validate the runoff simulated for Mamu River Basin by establishing a hydraulic station where we measured runoff between 2021 and 2022. The purpose was to further evaluate the performance of the validated SWAT model in simulating runoff for Mamu River Basin. The validation of runoff for the Mamu River Basin was to find out if the model parameter transfer from Imo River Basin is successful (Figure 6). The river flow validation produced decent results given the outcome of the performance ratings. Given an NSE value of 0.77, this indicates that the model is satisfactory. Based on this outcome, the validation of the model for Mamu River Basin by transferring calibrated and validated model parameters yielded good results. The correlation graph between the observed and simulated data for Mamu is shown in Figure 7. The R^2 value of 0.95 was observed for the validated Mamu River basin. More so, the calculated PBIAS statistics yielded a value of 15, indicating that the validation falls within good based on Moriasi et al (2007).

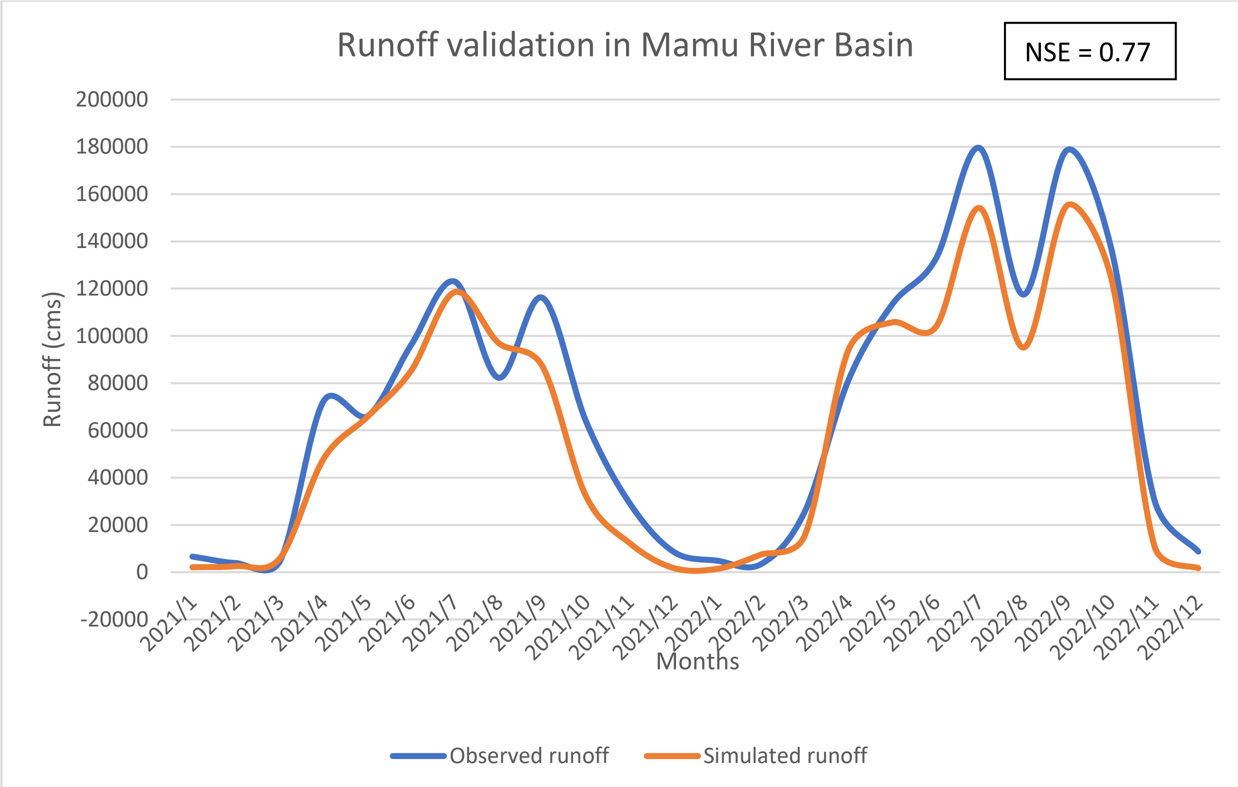

Fig 6: Model performance during validation

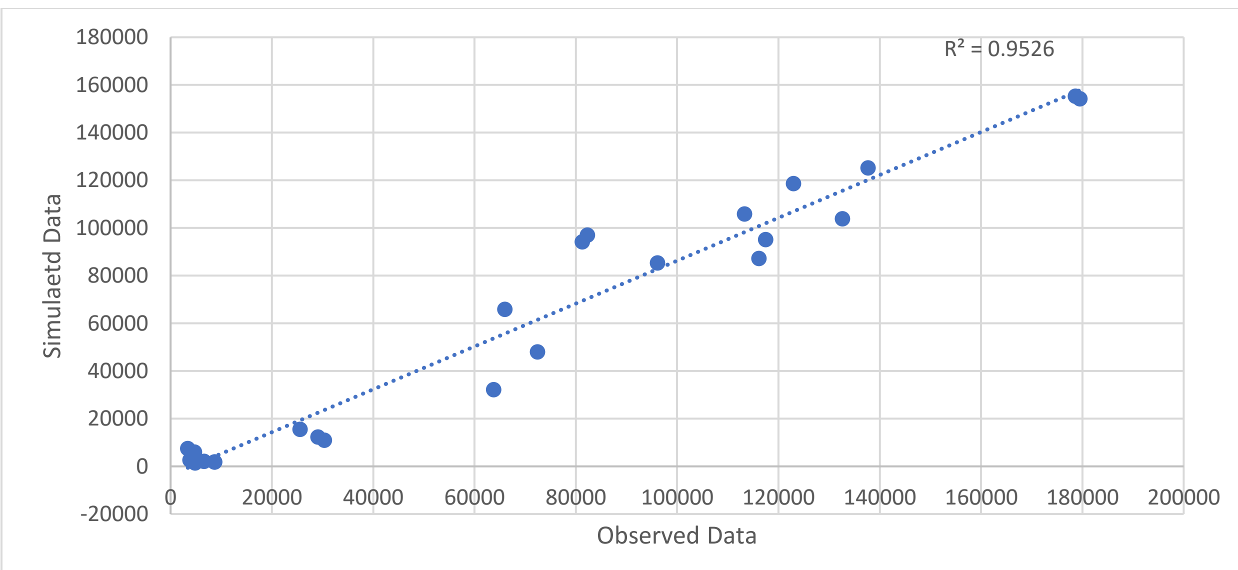

Fig 7: Correlation performance of validation

4. Conclusion

For the first time, the streamflow of the Mamu River was simulated by a hydrological model. In this research, the SWAT model was applied in the Mamu River Basin to simulate the stream flow. The simulation attempt was achieved following the transfer of calibrated and validated model parameters from the Imo River Basin. The performance of the 15 parameters that constitute the build model was assessed by Ezenwaji et al (2024) during calibration and validation yielding a satisfactory outcome. The model parameters were deployed in simulating streamflow in Mamu River for two years (2021-2022). To further validate the outcome and the success of SWAT modeling of flow response in the basin, we obtained flow measurements from Mamu River from January 2021 to December 2022. The statistical indicators (NSE, $R^{2,}$ and PBIAS) assessed the performance of the model in Mamu during validation. For the monthly time step, NSE, R^2, and PBIAS values were 0.77, 0.95, and 15 respectively. This indicates there is a practically good agreement between observed and simulated streamflow data and less uncertainty. The result of this study in the Mamu River Basin is vital for understanding the hydrologic response of the basin and portends great opportunity and possibilities in future research in the river basin, which is a significant source of water supply for many communities. This research opens up other areas of investigation in the Mamu River Basin such as the use of SWAT in simulating sediment flow in the basin and water quality assessment of the basin using the SWAT model. The result of this study and the possible outcomes of these future investigations will help water resources management and policymakers in efficient watershed management. Future investigations in the Basin will include higher resolution soil data, DEM, and remotely sensed images to improve simulation and the incorporation of climate scenarios to estimate the future response of the Basin to climate change.

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