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SIMULATING THE EFFECTS OF WATERSHED DEMARCATION ON THE PREDICTION OF NUTRIENTS AND HYDROLOGICAL YIELD USING SWAT MODEL

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Abstract— Watershed delineation is a crucial step in hydrological modeling, as it determines the accuracy of flow and nutrient transport predictions. This study investigated the impact of watershed delineation on the prediction of nutrients, surface runoff, and groundwater yield at the upstream section of Asa Dam River system, Ilorin, Kwara State, Nigeria. The MapWindowGIS was used to pre-process spatial data (Digital Elevation Model, Land use and Soil data) and the Soil and Water Assessment Tool (SWAT) was used to predict organic phosphorus, nitrate nutrients, surface runoff, and groundwater yield at the upstream outlet in the Asa River catchment. The catchment was delineated into 5, 9, 13, 15, 17, and 29 sub-catchments, and each routed sub-catchment was simulated using the temporal and spatial data of the study area. The predicted annual values for organic phosphorus and nitrate concentrations showed an increase from 0.734 mg/l to 6.76 mg/l and from 1.44 mg/l to 3.57 mg/l, respectively, as the watershed delineation expanded from 5 to 29 sub-basins. However, the number of sub-basin divisions had little to no effect on the average monthly predicted values for nutrients and the resulting water yield in the catchment. The simulated results indicated that the number of sub-catchment divisions significantly influenced the annual predicted values for nutrients, sediment, and streamflow yield. The monthly results for organic phosphorus and nitrate concentration for sub-catchments delineation showed no effect for surface runoff, groundwater, and water yield quantification. The outcome of this research has important implications for water resource management and policy development, especially in addressing water quality issues within the Asa Dam River watershed.

I. Introduction

Watershed delineation is a critical process in hydrological modeling, as it defines the spatial boundaries over which water flow, sediment transport, and nutrient fluxes are simulated. Accurate watershed demarcation

Accurate watershed demarcation is essential for predicting water quality and quantity, sediment yield, and nutrient loads in surface waters. The Soil and Water Assessment Tool (SWAT), a widely used hydrological model, plays a pivotal role in simulating these processes by integrating various landscape, climatic, and management factors [1]. One of the most influential inputs in SWAT is the Digital Elevation Model (DEM), which forms the basis for watershed boundary identification and hydrological flow paths [2].

The accuracy of watershed demarcation can significantly affect the predictions of hydrological yield and nutrient transport. Hydrological yield refers to the total amount of water generated from precipitation within a watershed, including surface runoff, subsurface flow, and groundwater recharge [3]. Nutrient prediction, on the other hand, involves estimating the movement of nutrients such as nitrogen and phosphorus, which are critical for understanding water quality and ecosystem health [4]. Inaccurate watershed boundaries, resulting from coarse or poorly processed DEMs, can lead to errors in predicting streamflow, sediment transport, and nutrient cycling, thereby affecting the model's reliability in decision-making [5].

However, the impacts of watershed demarcation on SWAT model predictions remain poorly understood, particularly in regions with complex terrain and diverse land use patterns. Inadequate watershed delineation can lead to inaccurate estimates of nutrient loads, hydrological yields, and sediment transport, compromising the effectiveness of water resource management strategies [6].

This study aims to investigate the effects of watershed delineation on the prediction of hydrological yield and nutrient loads using the SWAT model. By simulating watersheds with varying DEM resolutions and delineation strategies, the research will assess how changes in watershed boundaries impact the accuracy of model predictions. It is hypothesized that finer DEM resolutions will result in more precise watershed boundaries, leading to improved predictions of hydrological and nutrient dynamics [7].

Understanding the impact of watershed delineation on hydrological models like SWAT is crucial for enhancing the accuracy of predictions related to water resources and environmental sustainability. As water scarcity and pollution become increasingly critical issues globally, the findings of this research will contribute to the development of better watershed management practices, especially in regions where agricultural activities and land use changes pose significant risks to water quality [8].

II. Materials and Method

A. Description of the Case Study Area

Asa Dam is located between latitudes 8° 36′ N and 8° 24′ N and longitudes 4° 36′ E and 4° 10′ E geographical location in Kwara state, Nigeria. Figure 1 depicts the study area location in Nigeria.

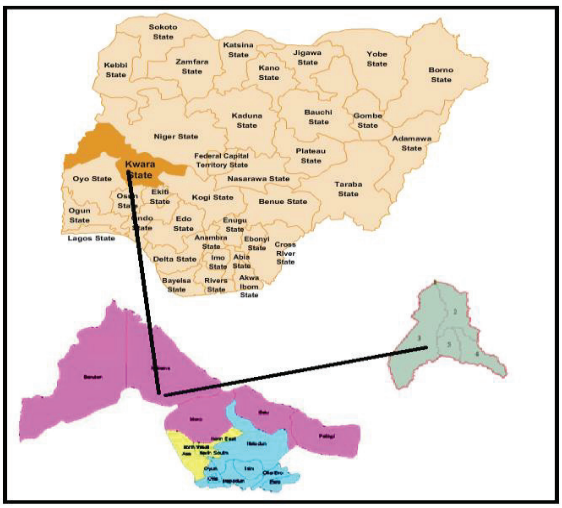


Figure 1: Map of Nigeria and Kwara State showing the location of the study area

The Asa River is approximately 56 km long and has a maximum width of about 100 m before emptying into River Niger. The river has an immense water supply and is being used for recreation activities by its inhabitants. Among the tributaries of the Asa River in Ilorin include Mitile, Atikeke, Aluko, Odota, Agba, Okun, and Osere River with a total catchment area of 1037 km^2 [9, 10]. The watershed has an annual rainfall ranging between 75 and 112 cm, with mean annual relative humidity range of between 60 to 89%. The annual mean temperature of the study area is between 27 to 30°C (Ilorin Meteorological Stations).

B. Model Selection and Description

The Soil and Water Assessment Tool (SWAT) integrated with the MapWindowGIS were chosen as the model for this study, based on previous research on its efficacy as reported in many studies [11-13]. Moreover, the model offers a user-friendly interface, in visualizing its result within the time -based setup. Though it can be run in a continuous daily step-up or monthly set-up process on the researcher aim to assess the impact of land management practices and to predict its impact on water, sediment, and agricultural chemical use over an extended period. The tool has found several uses with different soil types, land use, and management conditions. It has been used and accepted by many researchers previously [14, 15].

C. Model Data Requirements

The Soil and Water Assessment Tool (SWAT) model was configured using a combination of spatial and temporal data. Spatial data included topography from the Shuttle Radar Topography Mission-Digital Elevation Model (SRTM-DEM) with a resolution of 30 meters [16], which provided detailed information on the study area's terrain. Additionally, land use/land cover data from the National Remote Sensing Centre (NRSC) and soil data from the National Bureau of Soil Survey

(NBSS) soil maps were utilized, offering insights into soil types and properties [17]. Temporal data comprised daily weather data, including maximum and minimum temperature, humidity, wind speed, and solar radiation from a nearby meteorological station.

The model was run using the Hydrologic Response Unit (HRU) approach, which enables the simulation of hydrologic behavior in homogeneous units [18]. Each HRU was defined based on unique combinations of soil, land use, and slope characteristics. This allowed for the analysis of hydrologic behavior within each HRU, taking into account the DEM input, location-specific meteorological data, and physical characteristics. The model simulated water yield, sediment concentration, and streamflow volume for hydrological routing over a specified time scale [3].

Figure 2 provides a visual representation of the study area's topography and land cover characteristics, displaying the DEM and land-use map.

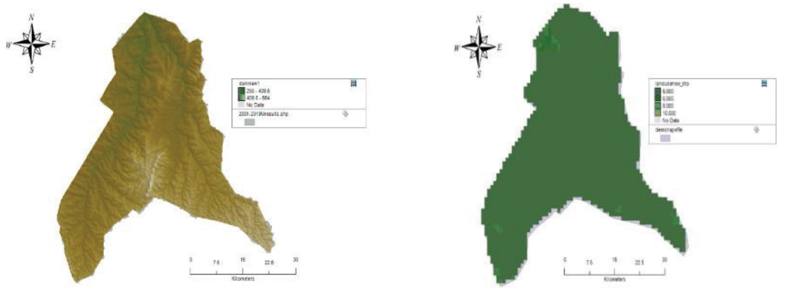


Figure 2: Digital Elevation Model (DEM) and Landmap of the study area

D. Watershed Delineation

The watershed delineation was performed using the automatic watershed delineation tool in MapWindow GIS. This tool enabled the efficient and accurate identification of watershed boundaries, which are crucial for hydrological modeling.

The delineated watersheds were then used individually for hydrological modeling of the study area. By modeling each watershed separately, this approach allowed for a detailed understanding of the hydrological processes occurring within each watershed, including water yield, sediment concentration, and streamflow volume.

This watershed-by-watershed approach enabled the examination of spatial variability in hydrological responses across the study area, providing valuable insights into the complex interactions between topography, land use, and hydrological processes.

E. Model Parametrization and Run

The SWAT model can be used to predict the runoff hydrographs based on the input DEM, location meteorological data, and the physical characteristics of the catchment. In this study, the model was used to predict water quality parameters such as nitrate, organic phosphate, sediment concentration, surface run-off, and streamflow in the different sub-catchment delineation numbers. The obtained results were analyzed using Microsoft Excel software to assess the variations in the water quality parameters which could be visualized using the GIS component of the model.

F. Calibration and Validation of the Hydrological Model

The calibration technique of the model is a crucial phase in the process of watershed modelling. The calibration technique compared the measured and simulated values of monthly inflow at the Asa River gauge station, throughout both the validation and calibration periods. A total of 20 parameters were chosen for calibration using the Parasol optimisation method.[19]. The model underwent calibration using the recorded monthly inflow from the Asa River from 2001 to 2010. Additionally, the model was cross validated using a separate and independent dataset spanning the years 2001 to 2010.

The evaluation of model predictions was conducted using the coefficient of determination (R^2), and Nash-Sutcliffe

Efficiency (NSE). The coefficient of determination (R^2) was computed to assess the level of correlation between the observed and simulated discharges. Ranging from 0 to 1, an R^2 value of 1 indicates a complete correlation between the observed data and the predictions made by the model. The values of NSE range from 1 to negative infinity, with higher values indicating a more accurate forecast. According to [20] if the Normalised Standard Error (NSE) is negative or approaches zero, the model's prediction is deemed to be inappropriate.

III. Results and Discussion

A. Watershed Delineation and Sub-Basin Characteristics

The automatic watershed delineation tool was utilized to divide the study area into varying numbers of sub-basins, ranging from 5 to 29. The tool allowed adjustments to the catchment area within the boundary, enabling the exploration of different subdivision scenarios. The total combined area of the delineated sub-basins was 1,710.85 km².

Figure 3 illustrates the various divisions of the watershed's delineation, showcasing six different scenarios: (a) 5 sub-basins (b) 9 sub-basins (c) 13 sub-basins (d) 15 sub-basins (e) 29 sub-basins and (f) 17 sub-basins.

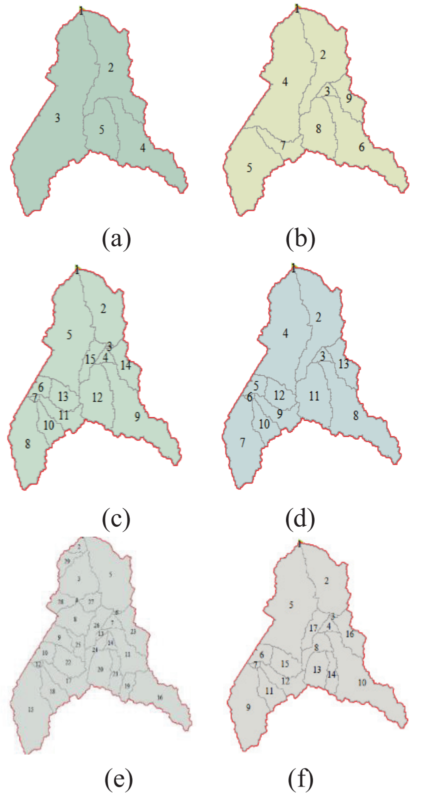


Figure 3: Delineation of watershed into subbasins

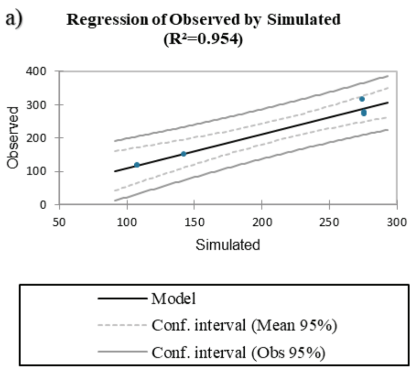
The attributes of the delineated watershed are presented in Table 1. The results indicate that the maximum and minimum area were obtained when the watershed was delineated into 17 sub-basins. Conversely, the minimum area was produced when the watershed was delineated into 9 and 29 sub-basins. The sub-basins with 13, 17, and 29 divisions had minimum stream length. In contrast, the maximum stream length was observed when the sub-basin was delineated into 5 and 9 sub-basins. Additionally, the maximum stream link was achieved with 29 sub-basins, while the minimum stream links remained consistent across all scenarios. These findings highlight the impact of sub-basin delineation on watershed characteristics, emphasizing the importance of careful consideration in hydrological modeling.

Table 1: Watershed delineation attributes

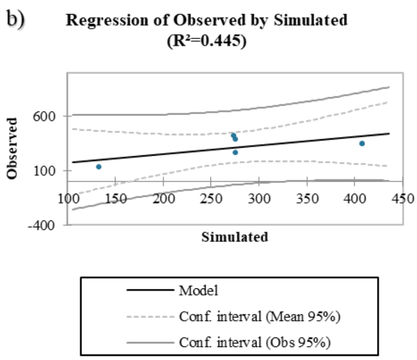
Number of subbasin	Max. subbasin area (ha)	Min. subbasin area (ha)	Min. Stream Length (m)	Max. Stream Length (m)
5	468958.63	883970307	959	63650
9	108865.4	305484689	959	47734
13	468958.65	23560096	0	40232
15	468958.65	23560096	954	40232
17	398011906	108865.4	0	40232
29	108865.4	235660096	0	31778

B. Calibration and Validation of the Hydrological Model

The findings revealed a strong positive correlation between the observed flow and the simulated flow, as evidenced by the Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (R^2) values of 0.93 and 0.95, respectively, during the calibration. Similarly, during the validation, the NSE and R^2 values were 0.28 and 0.45, respectively. Furthermore, the connection observed between the calibration data and validation data suggests that the experimental results can be considered unreliable since it is approaching zero. Furthermore, a significant proportion of the data about the calibration and validation period lies inside the 95 % confidence interval. The standardised residuals for both the calibration and validation periods are depicted in Figure 4 (a) and (b), respectively.



(a)



(b)

Figure 4: Regression of Observed and Simulated Flow at (a) Calibrated (b) Validated period

C. Influence of the Watershed Delineation on Hydrological Processes

The subbasins were delineated based on their areas measured in square kilometres (km^2) and the accompanying nitrate values expressed in mg/l. The subbasin numbers span from 5 to 29, exhibiting a uniform area size of roughly 1,710.85 km^2. The observed nitrate concentrations range from 1.44mg/l (subbasin No. 5) to 3.57mg/l mg/l (subbasin No. 29). This observation aligns with [15] research findings, which indicate a positive correlation between the subbasin's number and the projected nitrate content. These results emphasize the significance of defining watershed boundaries for Nitrate concentration prediction. It demonstrates that a more detailed subdivision of subbasins offers a clearer insight into Nitrate dispersion and pollution levels. [21] expressed that utilizing the insights obtained from this watershed delineation can be applied to enhance pollution control approaches, refine land use planning, and advance water resource management

D. Effects of Watershed Delineation on the Predicted Organic Phosphorous Concentration

This result revealed how variations in the numbers of subbasin delineation impact the predicted organic phosphorous concentration within the study area. Initially, organic phosphorous concentration values were studied for different subbasins delineated based on their respective areas. It was noted that varying subbasins (e.g., Subbasin 5, 9, 13, 15, 17, and 29) exhibited notable differences in organic phosphorous concentration, which were directly related to their delineated areas as in Table 2. For instance, subbasin 17, with an area of 1,710.86 km^2, demonstrated a significantly higher organic phosphorous concentration (5.7 mg/l) compared to the other subbasins delineated with similar areas. On the other hand, subbasin 5, 9, 13, 15, and 29, all with an area of 1,710.85 km^2, displayed varying Organic Phosphorous concentrations (increasing from 0.731mg/l to 6.76 mg/l). As discovered in a similar study of the water quality assessment by [15] where the phosphate concentration increases with the increase in the numbers of watershed delineation. This variability underscores the influence of subbasin delineation on organic phosphorous concentration predictions, emphasizing the need to consider the watershed's subbasin numbers when predicting the nutrient concentrations in the river. These findings align with prior studies on watershed delineation's impact on hydrological processes by [22], emphasizing its crucial role in predicting organic phosphorous concentration within river systems. The insights gained from this study can significantly contribute to enhancing water resource management, particularly in addressing challenges related to nutrient control and ecosystem health in river basins.

Table 2: Organic Phosphorous variations with different subbasins

Number of subbasins	Area (km^2)	ORGP_IN (mg)
5	1,710.85	0.731
9	1,710.85	0.740
13	1,710.85	0.773
15	1,710.85	0.793
17	1,710.86	5.775
29	1,710.85	6.764

E. Effects of Watershed Delineation on the Predicted Surface Runoff, Groundwater, and Water Yield

Surface runoff, groundwater, and water yield predictions are important aspects of hydrological modeling. The result in Table 3 reveals variations in these metrics across different subbasins (subbasin 5, 9, 13, 15, 17, and 29), all having an area of approximately 1,710.85 to 1,710.86 km². When comparing the Groundwater (GW_Qmm) values, subbasin 29 has the highest GW_Qmm of 7145.33 mm, indicating a potentially significant groundwater contribution compared to the other subbasins. On the other hand, subbasin 9 has the lowest GW_Qmm of 184.62 mm. In terms of Water Yield (WYLD mm), subbasin 29 was predicted to have the highest value of 15532.74 mm, indicating a substantial water yield in that specific subbasin. Subbasin 9 has the lowest WYLDmm value of 397.046 mm. In the study by [23], the sensitive parameters of the SWAT model on the Brantas watershed also found that climate change, especially rainfall, had a strong effect on water yield.

Regarding Surface run-off (SURQmm), subbasin 29 also exhibits the highest value of 8310.548 mm, suggesting significant surface runoff in the subbasin. Subbasin 9 has the lowest SURQmm value of 210.5388 mm. These sub-basins which fall under high runoff, was characterized by intensive cultivated land which leads to high runoff susceptibility of the watershed. The model performance showed a significant correlation between these simulated runoff values, and very similar to the result of [24], which also used the SWAT model to estimate surface runoff in the Tapi sub-catchment area in India. The results though conform with the existing literature, [25] evaluated different surface runoff estimation techniques in SWAT and found that the use of daily evapotranspiration improved hydrologic predictions such as surface run-off, water yield and groundwater.

Table 3: Variation of Hydrologic Parameters with different numbers of subbasins

Number of Subbasins	GW_Q (mm)	WYLD (mm)	SURQ (mm)
5	1058.49	2174.689	1105.128
9	184.62	397.046	210.5388
13	3184.53	6883.133	3664.786
15	3668.03	7942.29	4236.599
17	4154.13	9001.515	4803.756
29	7145.33	15532.74	8310.548

It can be inferred from Table 3 that as the size of the subbasin changes, there is a general increase in the prediction of Surface run-off. This connection between Subbasin and Surface run-off displays a positive trend, implying that greater Subbasin sizes are linked to higher values of Surface run-off. This correlation is bolstered by the high value of coefficient of R^2 (0.9151), denoting a robust association between subbasin and sediment concentration. The R-squared value signifies that approximately 91.51% of the fluctuations in surface run-off can be accounted for by alterations in subbasin magnitudes. Consequently, the subbasin factor significantly influences the variations observed in Surface run-off.

In summary, the data highlights considerable variability in these water-related metrics (Groundwater, Water Yield, and Surface runoff) across the different subbasins. [26] emphasized that these variations are significant for understanding watershed dynamics and can aid in effective water resource management and planning, echoing the implications discussed.

IV. Conclusion

This study investigated the impact of varying catchment delineation into Hydrologic Response Units (HRUs) on predicted nutrient, surface runoff, and groundwater yield using the Soil and Water Assessment Tool (SWAT). The watershed was delineated into 5-29 sub-basins, and the results showed significant variations in:

- Organic phosphorus levels across sub-basins
- Streamflow, sediment concentration, and sediment yield
- Surface runoff, groundwater, and water yield predictions

Calibration and validation results showed good positive correlations between observed and simulated flows (Nash-Sutcliffe Efficiency: 0.76-0.70, R^2: 0.85-0.74). The study highlighted the importance of accurate watershed delineation in predicting water quality parameters and emphasized that the number of sub-basins significantly impacts projected values. The findings have implications for water resource management and policy development, particularly in addressing water quality concerns within the Asa Dam River watershed. For further research, it is recommended that Machine learning algorithms could be explored for optimizing watershed delineation and improving SWAT model performance. AI-driven techniques may enhance prediction accuracy and reduce computational uncertainties associated with traditional delineation methods.

V. Acknowledgement

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