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Effects of Watershed Delineation on the Prediction of Water Quality Parameters in Gaa Akanbi Area, Ilorin

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Abstract

Watershed delineation is a required step when conducting any spatially distributed hydrological modelling. The prediction of water quality parameters in a basin entails delineation of watershed into different number of sub-basins. Thus, this research evaluated effects of watershed delineation on the prediction of water quality parameters in Gaa Akanbi area of Ilorin, Kwara state, Nigeria. The objectives are to model and predict water quality parameters in the watershed; delineate the selected watershed in various numbers of sub-basins and study the effects of watershed delineation in the prediction of water quality parameters of the basin. For proper implementation of this study, Geographical Information System (GIS) software, physically based watershed model - Soil and Water Assessment Tool (SWAT) and other data processing software were used. Since the model is physically based, the surface properties (i.e. Digital Elevation Model (DEM), stream network, digital soil map, digital land use and land cover map, climatic and hydrological data) served as input in the model. The model was daily for a period of 30 years (i.e. January 1991 to December, 2020). The results showed that the watershed was successfully delineated to 3,7,11,21,32,53 sub-basins. Also, it was noted that the predicted values of water quality parameters (Nitrate, organic phosphorus and sediment concentration) are directly proportional to increase in the number of sub-basins delineated in the watershed.

Keywords: Geographical Information System (GIS), hydrological modelling, water quality parameters, Soil and Water Assessment Tool (SWAT).

Introduction

Watershed modelling has become an important technology to explore the effects of climate change and human activities on water resources and hydrological cycles. The ability of a model is to accurately represent the spatial variability of a catchment element for the hydrological process. The accuracy required to achieve reliable simulation results relies on both the quality of the input data and also the watershed delineation in modelling. The Soil and Water Assessment Tool (SWAT) eco-hydrological model is a popular watershed model and has proven to be an effective tool for evaluating agricultural management simulations for complex landscapes and varying climate regimes worldwide (Birhanu,2009; Ndomba *et al.,* 2009; Ndomba *et al.,* 2011; Ayana *et al.,* 2012; Van Griensven *et al.,* 2012; Adeogun *et al.,* 2015).

Watersheds are always physically delineated by the area upstream from a given outlet point. This generally means that for a stream network, the contributing area is upstream of a ridgeline. Ridgelines separate watersheds from each other. In GIS, Digital Elevation Models (DEMs) are used to represent terrain. Mapwindow GIS used in this research is a free Geographical Information System (GIS) for windows and it contains its own hydrologic analysis tools including watershed delineation, flow accumulation, and flow length. In addition, it can also be used to delineate watershed properties including drainage patterns of a catchment. Mapwindow GIS use fundamental concepts of raster-based terrain

analysis tools to generate data on flow direction, flow accumulation, stream definition, and stream segmentation, as well as to delineate watershed boundaries (Puri *et al.*, 2018).
Watershed delineation is a required step when conducting any spatially distributed hydrological modelling. Automated approaches are often proposed to delineate a watershed based on a river network extracted from the digital elevation model (DEM) using the deterministic eight-neighbour (D8) method. Studies have been conducted to evaluate the effects of watershed delineation on SWAT simulated stream flow (Chen *et al.*, 2021) and other outputs (Adeogun *et al.*, 2020). Over 60% of the studies were performed for watersheds in the United States, and the majority of that subset was reported for locations in the Corn Belt regions. Other studies were conducted for watersheds in China, Ethiopia, Germany, India, South Korea, Tunisia and Turkey (Birhanu, 2009; Ndomba and Griensven, 2011; Puri *et al.*, 2018; Aynalem and Liben, 2020; Chen *et al.*, 2021). The majority of studies reported that the delineation scenarios resulted in only minor or negligible effects on SWAT-predicted streamflow. However, some studies described streamflow effects estimated with SWAT that were influenced by the various simulated delineation scenarios. Several of these studies noted that the effects on streamflow were relatively stable for more refined delineation schemes, but that the accuracy of the streamflow estimates declined for coarser Hydrological Response Unit (HRU) and/or sub-basin sub-divisions (Assefa *et al.*, 2019).

The prediction of water quality parameters in a basin entails delineation of watershed into different number of sub-basins. Based on literature, the effect of watershed delineation on the prediction of water quality parameters in a watershed has not been researched on any Nigerian watershed. Therefore, the objectives of the study are to model and predict water quality parameters in the watershed; delineate the selected watershed in various numbers of sub-basins and study the effects of watershed delineation in the prediction of water quality parameters of the basin. Outcome of the study can be a decision support tool for selection of appropriate watershed mesh for the prediction of water quality parameters in a watershed.

Materials and Methods

Study area

The study area is Gaa Akanbi area (as shown in Figure 1), which is located in Ilorin South-East local government of Kwara State in the South-western part of Nigeria. It is situated between the latitude 8° 23' N and 8° 33' N; longitude 4° 27' E and 4° 40' E. The estimated terrain elevation above the sea level is 556 meters. The rainy season of the study area starts from March and end in October while the dry season lasts from November to early March. The main occupation in the study area is trading (Elevation Map, 2022).

Model selection and description

The model selected for this study is the Soil and Water Assessment Tool (SWAT) interface with map window GIS. The selection was based on the past literature works (Neitsch *et al.*, 2005; Ndomba and Griensven, 2011; Ayana *et al.*, 2012; Adeogun *et al*; 2015; Chen *et al.*, 2021), which confirmed the efficacy of the model in the prediction of groundwater in a watershed. The model is readily available, and has good user interface, which makes the visualization of results easy (Birhanu, 2009; Ndomba and Griensven, 2011). SWAT is a process based on continuous daily step model. It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. The tool has been used by several researchers in the past and result obtained is acceptable (Adeogun *et al.*, 2015).

This study adapted SWAT model to delineate watershed with soil and land use data, and weather data definitions. One of the steps in model set-up consists of the identification of the Hydrological Response Units (HRUs) for the water balance components. For this purpose, the river network for the Sango watershed was extracted from DEM, using standard analytical techniques contained in the MWSWAT

GIS interface with a minimum upstream contributing area used as a threshold value for defining river cells. Within the SWAT conceptual framework, the representation of the hydrology of a basin is divided into two major parts: the land phase of the hydrological cycle and the routing of runoff through the river network (Neitsch *et al.*, 2005; Neitsch *et al.*, 2011).

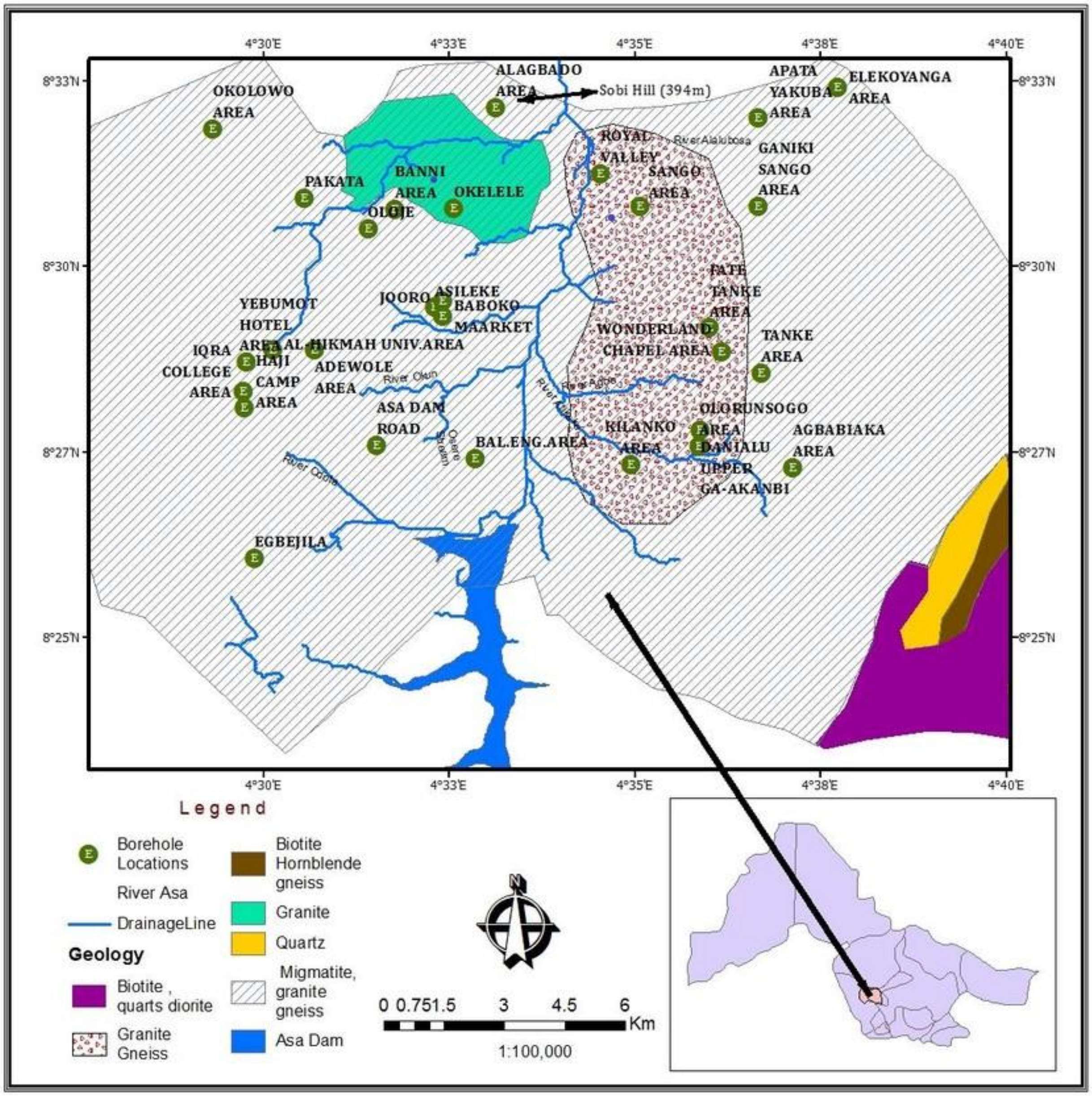

Figure 1: Location of the Study Area in Gaa Akanbi, Ilorin, Kwara State

For modelling the land phase, the river basin was divided into sub-basins, each one of which is composed of one or several Hydrological Response Units (HRUs), which are areas of relatively homogeneous land use/land cover and soil types. In this study, the watershed was delineated into 3,7,11,21,32 and 53 subbasins/HRUs using the threshold methods available in the automatic watershed delineation tool of the GIS component of the model. The characteristics of the HRUs define the hydrological response of a sub-basin. For a given time step (daily) and for a period of 30 years that the model was run, the contributions to the discharge at each sub-basin outlet point is controlled by the HRU water balance calculations (land phase). The river network then connects the different sub-basin outlets, and the routing phase determines movement of water through this network towards internal control points and finally towards the basin outlet. For modelling purposes, a watershed is partitioned into a number of sub watersheds or sub basins. The use of sub basins in a simulation is particularly beneficial when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. Referencing different areas of the watershed to one another was achieved by partitioning the watershed into sub basins.

Model data requirements

SWAT modelling data requirement are spatial data and temporal data. The spatial data include the digital elevation model (DEM), soil and land use maps; whereas the temporal data which is known as weather data include maximum and minimum temperature, humidity, wind, solar radiation.

Digital elevation model (DEM): The DEM is one of the main inputs of the SWAT model. Topography was defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution. A 90 m grid DEM was downloaded from STRM (Shuttle Radar Satellite Mission). The DEM was used to delineate the boundary of the watershed and analyse the drainage patterns of the land surface terrain. Terrain parameters such as slope gradient and slope length, and stream network characteristics such as channel slope, length and width were derived from DEM. Figure 2shows the DEM of the study area.

Soil map: The soil textural and physicochemical properties required by the SWAT model include soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for each soil type. Soil data was extracted from harmonized digital soil map of the world (HWSD) produced by food and agricultural organization of united nation (Nachtergaele *et al.*, 2009). Table 1 show the soil map and its information of the study area.

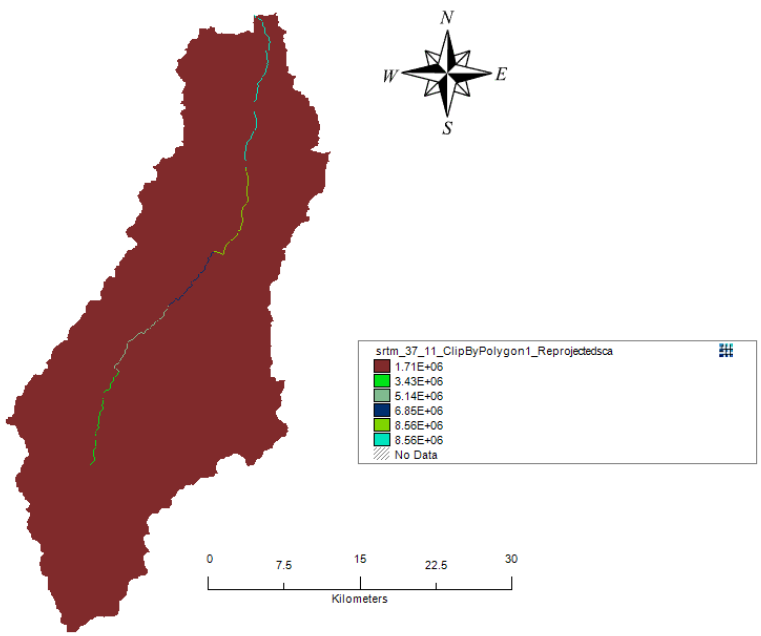

Figure 2: Digital Elevation Model (DEM) of the Study Area

Table 1: Information on Soil Map of the Study Area

Swat Code	Description	Area (ha)	% Watershed
Lf12-a-1430	Sandy Clayey Loam	10901.81	11.82
Lf26-a-1443	Sandy Clayey Loam	77803.68	84.33
Lf49-1475	Sandy Clayey Loam	3556.36	3.85

Source: Digital Soil Map of the World (Nachtergaele *et.al*.,2009)

Land-use map: The land use of an area is one of the most important factors that affect groundwater flow, surface erosion and evapo-transpiration in a watershed during simulation from the Global Land Cover Characterization (GLCC) database and used to estimate vegetation and other parameters representing the watershed area (GLCC, 2012, Adeogun *et al.*, 2015). The GLCC database was developed by United States Geological Survey and has a spatial resolution of 1 km and 24 classes of land use representation (GLCC, 2012). Figure 3 and Table 2 show the land use map and its information of the study area.

Weather Data: The 30 years climatic data necessary to be used for simulation in the SWAT model is obtained from Nigeria Meteorological Agency (NIMET) station based in Ilorin. The data collected includes daily precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed for 30 years which covers a period from January, 1991 to December, 2020.The collected weather variables were used to drive the hydrological balance within the watershed. To account for any missing data, a weather generator installed in the SWAT model was used to estimate the missing information (Arnold *et al.*, 2011).

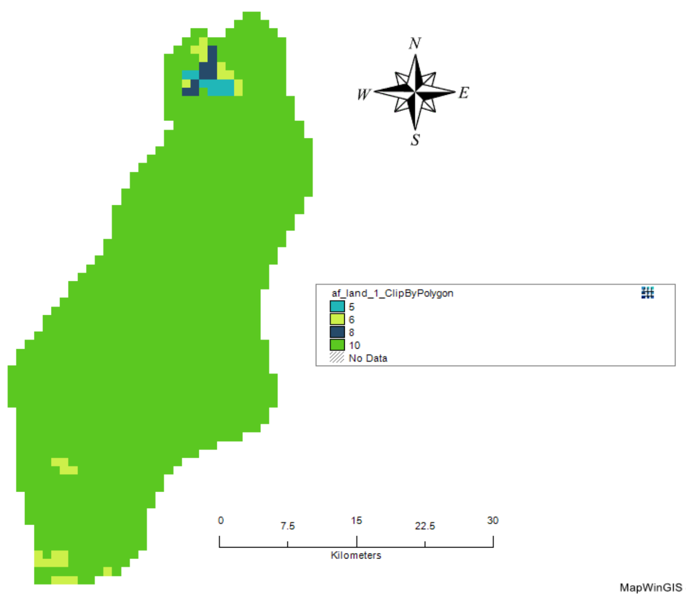

Figure 3: Land-use Map of the Study Area

Table 2: Information on Land Use of the Study Area

SWAT Code	Description	Area(Ha)	% Watershed
CRWO	Crop and Wood	1312.70	1.42
SAVA	Savannah	89480.73	96.99
SHRB	Shrub	731.70	0.79
CRGR	Cropland/Grassland Mosaic	736.72	0.80

Source: Global Land Cover Characterization (2012)

Model set up and run

For proper implementation of this study, Geographical Information System (GIS) software, physically based watershed model SWAT and other data processing software were used. Since the model is physically based, the surface properties such as DEM, stream network, digital soil map, digital land use and land cover map, climatic and hydrological data served as input into the model. All other settings necessary for the running of the model were done at this stage. The model was run daily for a period of 30 years (Jan. 1991- Dec. 2020)

Watershed Delineation: Watershed delineation generates the sub-basins as shown in Figure 4, which is the first level of the subdivision of watershed area. The DEM was used to produce the stream network. Since the DEM generated from the GIS is in geographical coordinate system, so it is re-projected using projected coordinate system. The final watershed delineation is done using the automatic watershed delineation tool which forms part of the GIS component of the MWSWAT model. The watershed delineation was carried out using the threshold method which can be varied by the number of cells or the area of sub-basin and this is used to generate the flow direction and accumulation. A custom outlet and inlet definition was created to complete the delineation processes. Each of the sub-basins delineated within a watershed boundary contains at least one Hydrological Response Unit (HRU) a tributary channel and the main channel. The outflow of the sub-basin enters the next sub-basin. Thus, there is a particular spatial relationship among the sub-basins.

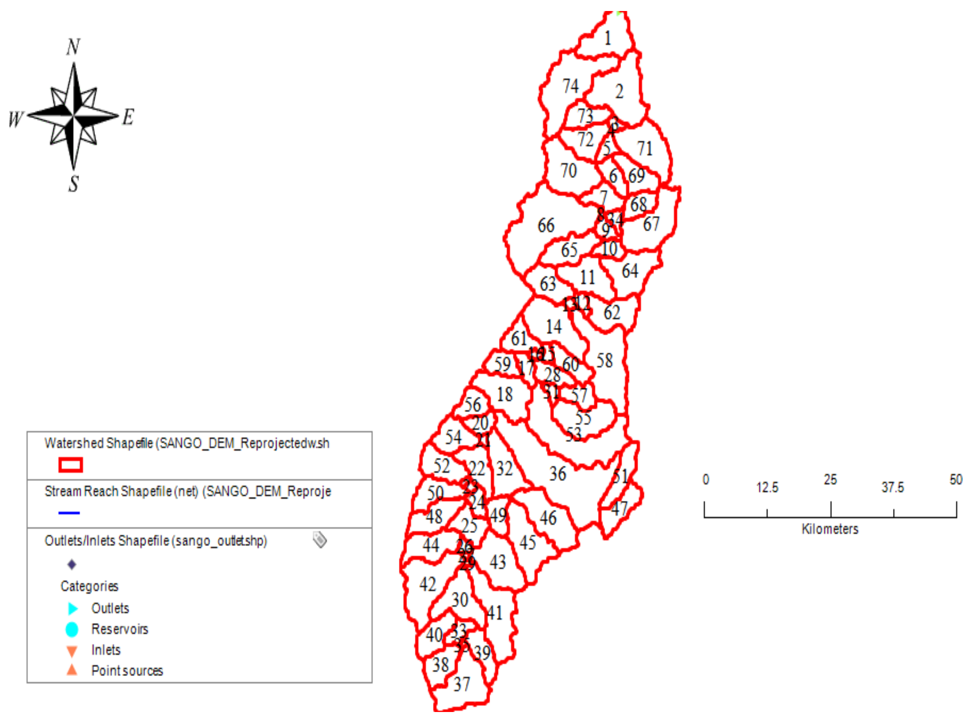

Figure 4: Watershed Delineation into Sub-basins.

Creation of Hydrological Response Units (HRU): With the introduction of HRU, it is possible to represent similar hydrologic behaviour in each unit, which can be modelled easily. An attempt has been made in this study to delineate HRUs in a basin which has high spatial heterogeneity. Using basin characteristics, such as physiographic, land use, soil, elevation, and slope in a geographical information system, HRUs are delineated. The hydrologic behaviour of these HRU is also discussed based on basin characteristics, which can be used in a physically based or conceptual hydrologic model to simulate groundwater and water yield.

Prediction of water quality parameters

The water quality parameters that can be predicted by the SWAT model include the Nitrate, Organic phosphate, and sediment concentration. Prediction of water quality parameters of the sub-basins in the watershed was caried our using the temporal and spatial data for the study area. The results obtained were processed using Microsoft Excel software while the spatial and temporal variations of water quality parameters of the watershed were plotted using the GIS component of the model.

Model Calibration and Validation

The hydrological model developed for the study area have been calibrated and validated using observed streamflow of Asa River from 2008 to 2014. The model was calibrated with the observed monthly inflow from 2008 to 2010, and cross-validated with another set of independent data set from 2011-2014 Results showed a good correlation between the observed flow and the simulated flow, indicated by NSE and R^2 of 0.76 and 0.85, respectively for calibration period; NSE and R^2 of 0.70 and 0.74, respectively for the validation period (Figures 5 and 6 respectively). More details of the results of the calibration and validation have been reported in Adeogun et al. (2020).

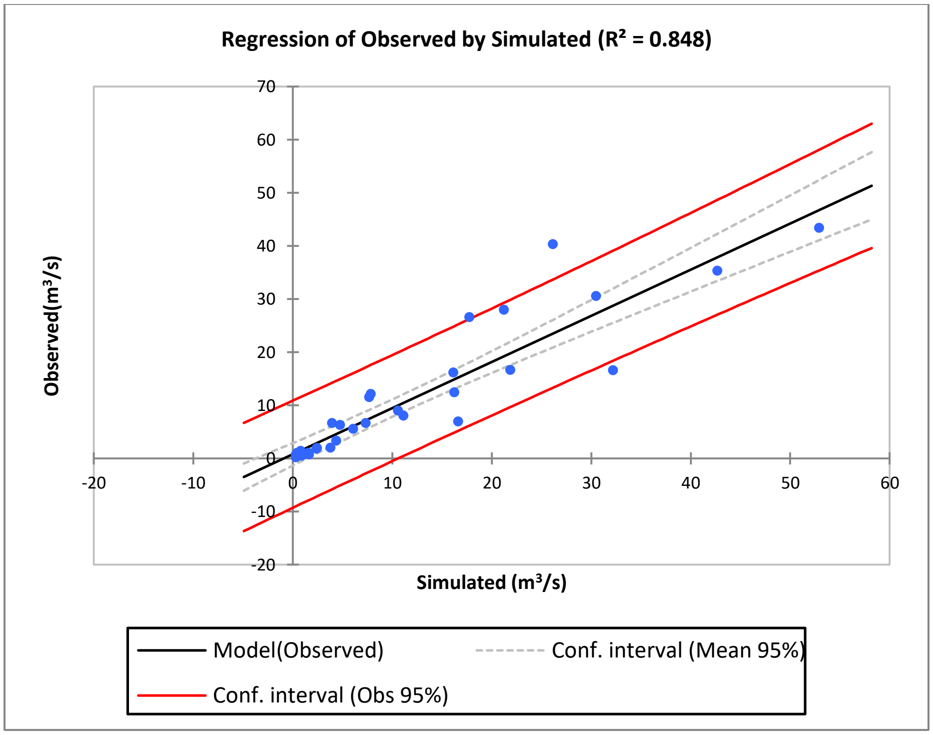

Figure 5: Regression of Observed with Simulated during Calibration Period (Adeogun *et al.,* 2020)

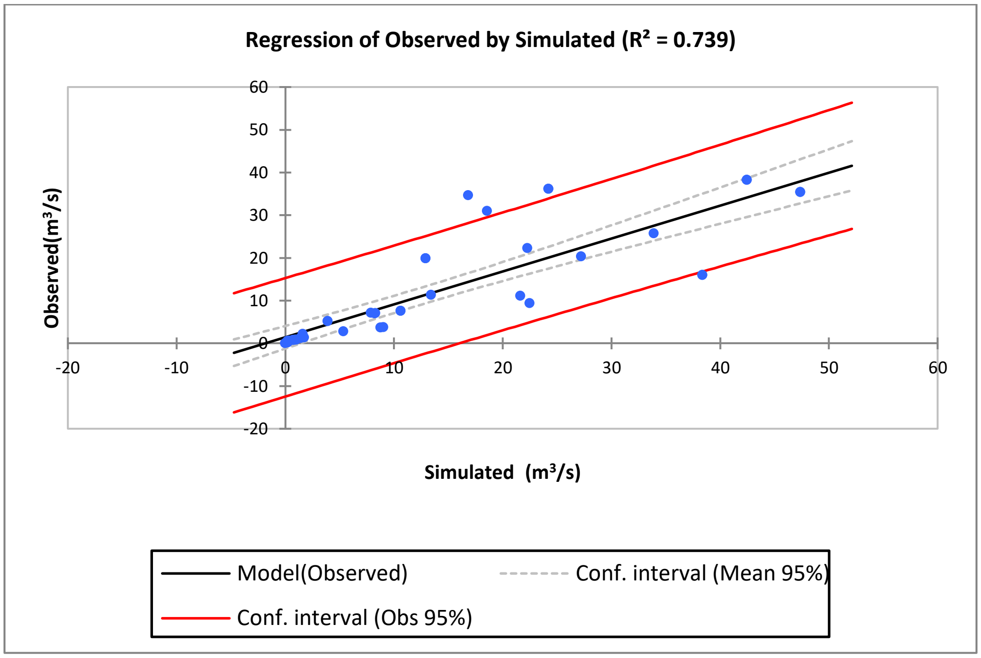

Figure 6: Regression of Observed with Simulated during Validation Period (Adeogun *et al.*, 2020)

Results and Discussion

Delineation of watershed into sub-basins

The result shows that the watershed is delineated into different sub-basins. As previously explained, the number of subbasins to be delineated can be varied by either increasing the decreasing the area of watershed within the boundary as specified in the automatic watershed delineation. Based on the division, the minimum number of delineations was 3 while the highest number of divisions was 53. Other subdivisions are 32, 21, 11 and 7. Figures 7 to 9 depict the various divisions of the watershed's delineation.

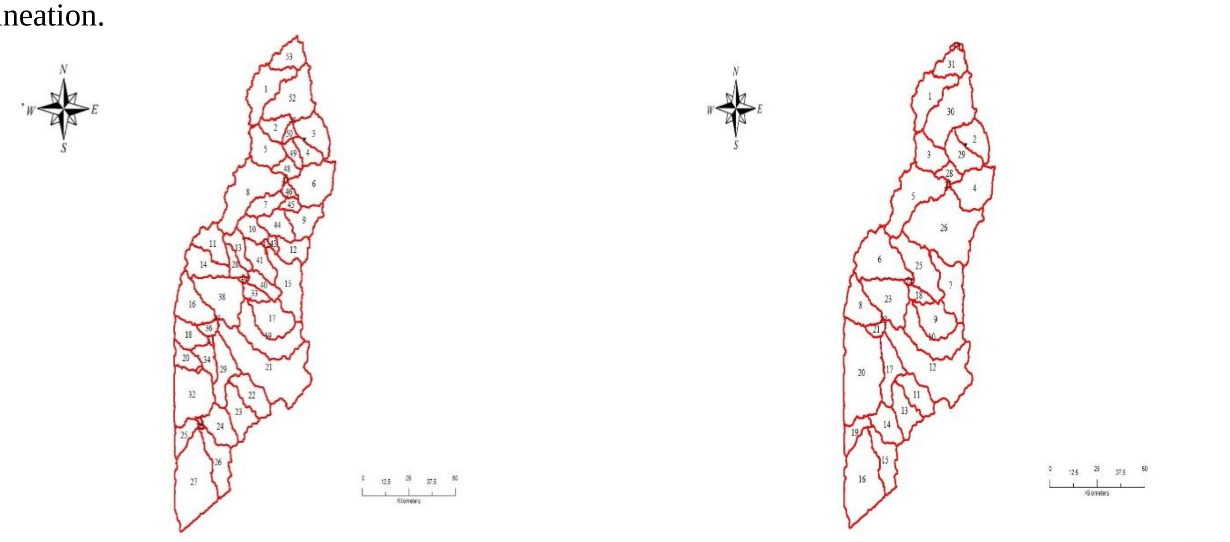

Figure 7: Watershed divided into (i) 53 Sub-basins and (ii) 32 Sub-basins

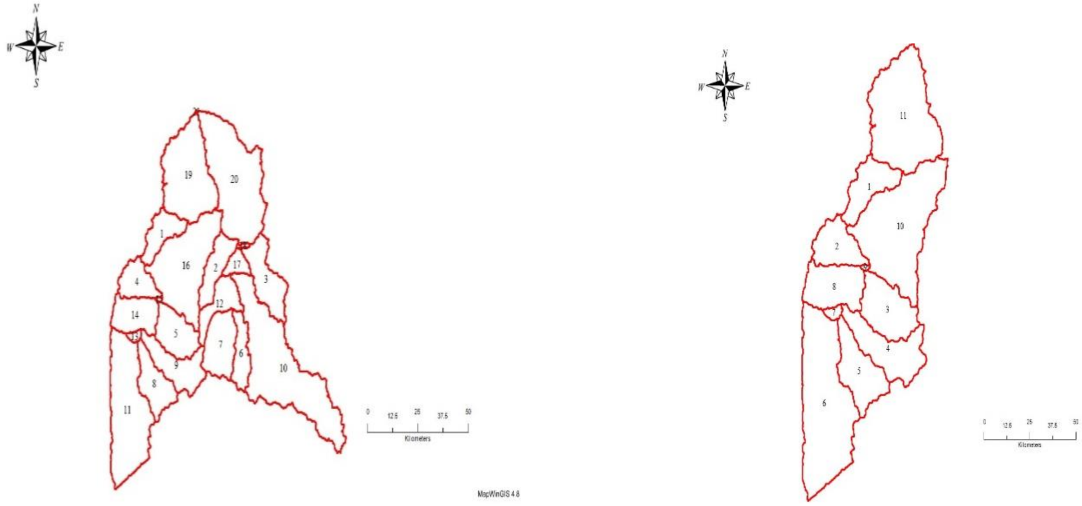

Figure 8: Watershed divided into (i) 21 Sub-basins and (ii) 11 Sub-basins

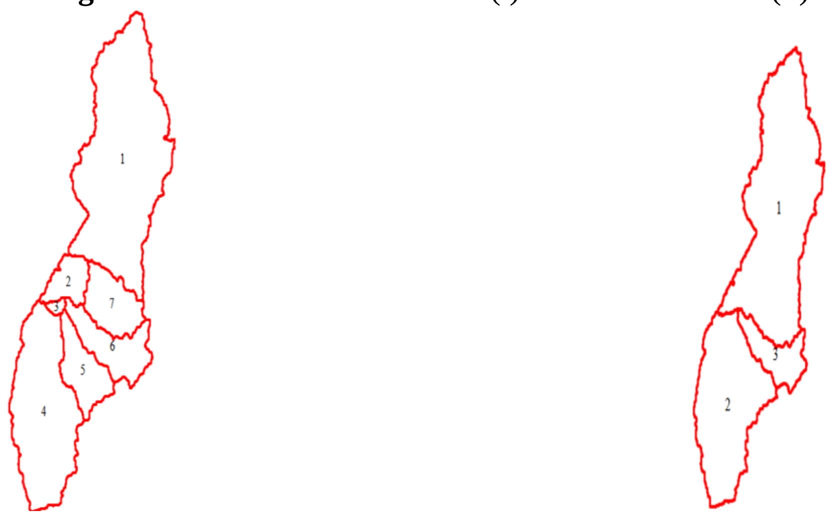

Figure 9: Watershed divided into (i) 7 Sub-basins and (ii) 3 subbasins

Effects of watershed delineation on water quality parameters

The results of the model prediction on water quality parameters (Nitrate, Organic phosphate, and sediment concentration) using different numbers of delineated subbasins were compared. Generally, the results showed an increase in the value of water quality parameters as the number of sub-basins increases. For Sediment Concentration, SEDCON (see Figure 10). It was noted that a lower value of around 100,000 mg/L was predicted when the number of sub-basins was three (3). However, a higher value of around 1.1million mg/L was predicted when the number of sub-basins increases to 53. This result seems outrageous and may not adequately represent the actual situation of sediment concentration in the watershed. This variation may be due to the sensitivity of overland slope and slope length, channel slope, and drainage density. Changes in these parameters may cause changes in sediment degradation and deposition, and, finally, to the amount of sediment yield and sediment concertation predicted in the river reach. Therefore, according Jha et al. (2004), an appropriate sub-watershed scale should be identified that can efficiently and adequately simulate the behaviour of a water shed. A similar trend was also noticed in the predicted values of Nitrate where a higher value of more than 35,000kg/ha was predicted for a delineated sub-basin of 53 (Figure 11). The effects of watershed delineation on the prediction of organic phosphorus sub-basin shows an increase in the value predicted as the number of sub-basins increase. This result holds for all the delineated sub-basins. It was noted that sub-basin 53 has the highest parameters discovered, while sub-basin 3 has the lowest parameters discovered.

The effects of watershed delineation on the prediction of organic phosphorus shows an increase in the value predicted as the number of sub-basins increases (see Figure 12). This result holds for all the delineated sub-basins up till 23 subbasins. It was noted that a sharp decrease in the predicted value of organic phosphorus was noted, and the result seems to be stabilised at a delineated sub-basin of 32 and this trend continues up to when the number of sub-basins was 53. A proportional increase in the value of predicted water quality may be due to the fact that a finer Hydrological Response Unit (HRU) definition tends to generate more runoff because it captures a refined level of watershed variability, and this may culminate into more predicted values of water quality parameters. Aynalem and Liben (2020) also expressed that the physical watershed characteristics such as climate, slope, watershed shape and area, rainfall, soil type and land use/cover have effects on hydrological processes. The result from this work is in tandem with a previous study conducted by Chang (2008) on the effects of watershed delineation on runoff and pollutant transport predictions. In his work, the study area was divided into 43, 25, 15 and 9 sub-basins respectively and concluded that the uncertainties or errors induced by too much simplification of watershed delineation could be carried over and amplified to the pollutant transport process and the modelling results of pollutant exports. The work of Chen et al. (2021) on the effects of watershed delineation and climate datasets density on runoff predictions for the upper Mississippi river basin using SWAT also revealed that the average channel slope and drainage density increased significantly from 8-digit to 12-digit sub-basins which resulted in higher lateral flow and groundwater flow estimates, especially for the lateral flow.

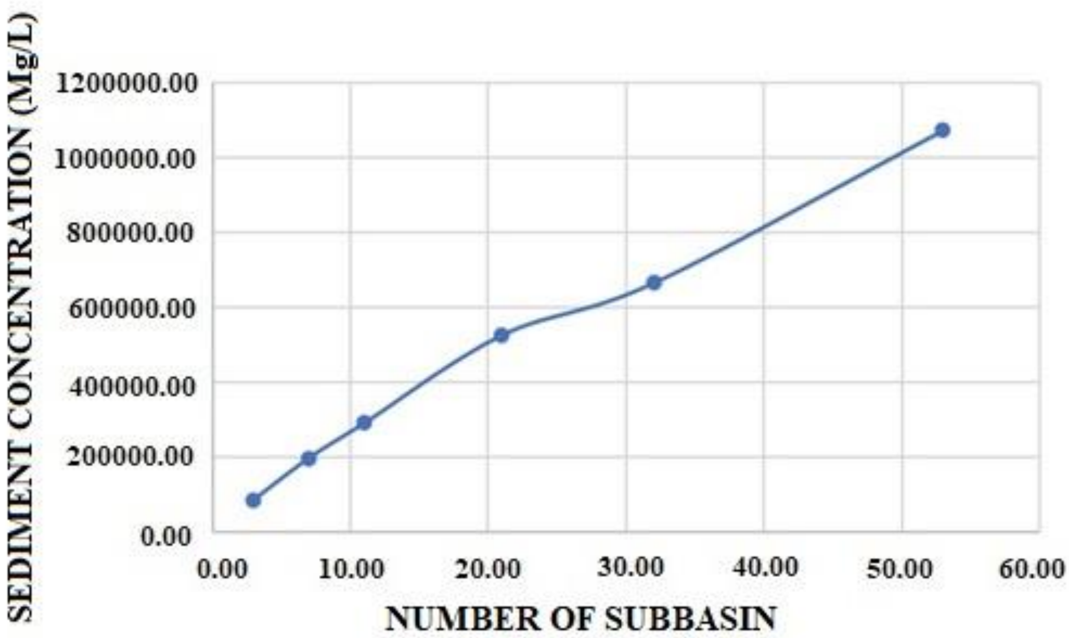

Figure 10: Variation of sediment concentration with number of sub-basins

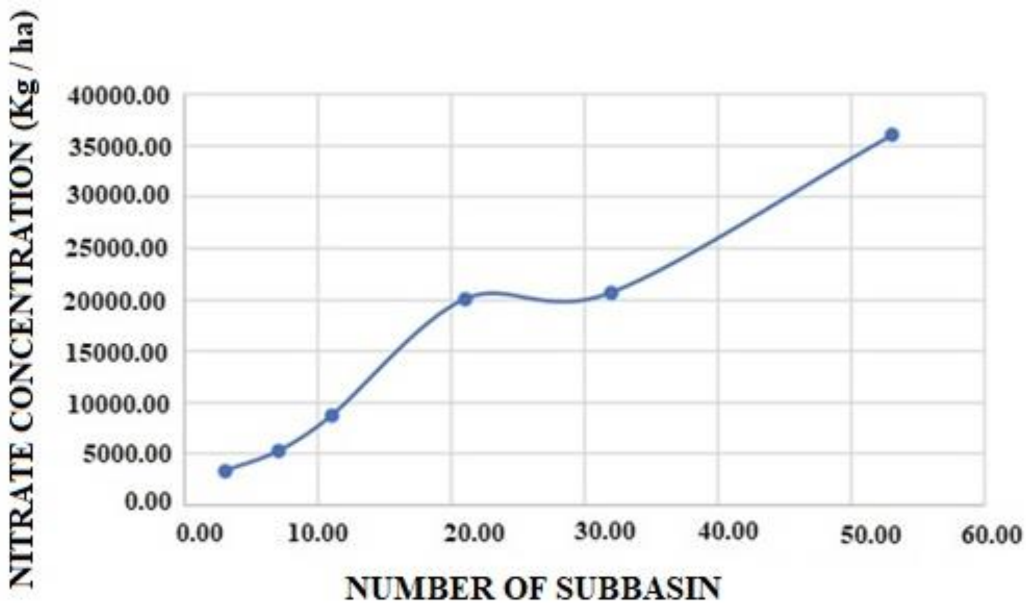

Figure 11: Variation of nitrate concentration with number of sub-basin

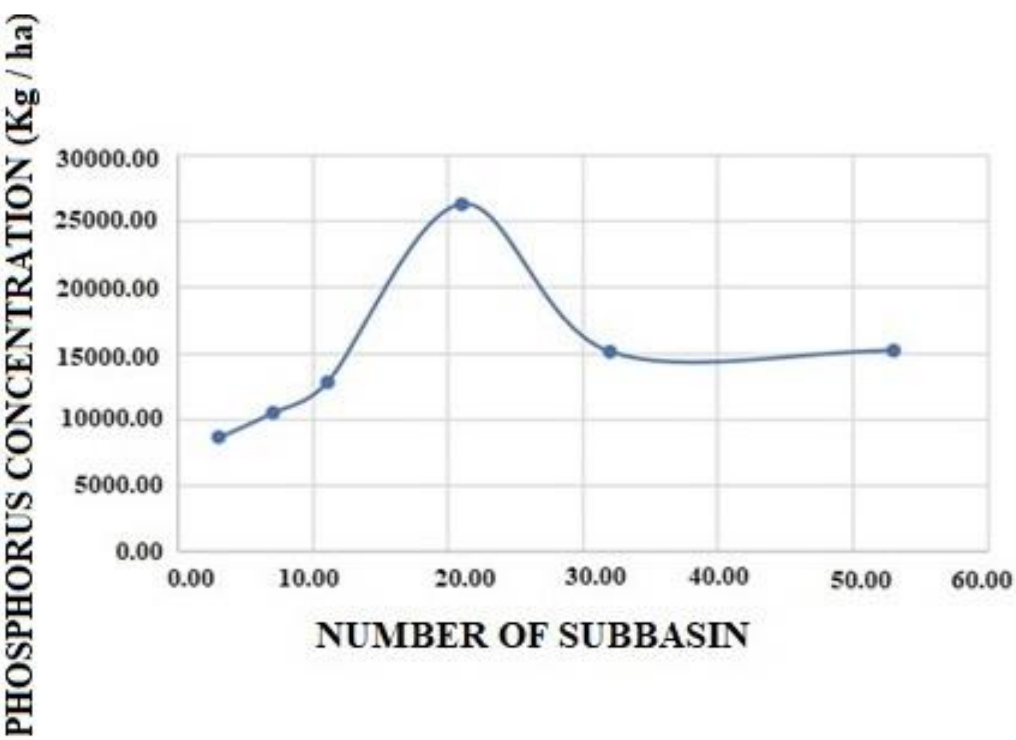

Figure 12: Variation of phosphorus concentration with number of sub-basin

Conclusion

The study focused on effect of watershed delineation on the prediction of water quality parameters at Gaa Akanbi area of Ilorin, Kwara State with the use of SWAT, a physically based semi-distributed hydrological model interfaced with mapwindow GIS software. The preparation of thematic maps and database necessary for the successful running of the model was done using the GIS components.

The outcome of the research indicated that there was a noticeable change in the nitrate, phosphorus, and sediment concentrations as the number of subbasins delineation increases in the watershed. However, the predicted values of these water quality parameters seem to stabilize at higher levels of subdivision, resulting in using smaller threshold drainage areas of the total watershed. Based on these findings, it is recommended that the threshold value for deciding on the required number of watershed drainage density for the prediction of water quality parameters should be evaluated by trial-and-error procedure. Also, the fact that different thresholds may have resulted from different indicators emphasize the need for SWAT users to assess which indicators have highest priority in their analyses before finalizing on the results of the modelling.

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