EFFECTIVENESS OF GIS BASED HYDROLOGICAL MODELLING TOOL FOR SUSTAINABLE SEDIMENT AND WATER MANAGEMENT IN ASA RIVER CATCHMENT, NIGERIA

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ABSTRACT

In this study, Soil and Water Assessment Tool (SWAT) was interfaced with Mapwindow-GIS to simulate the hydrology, predict sediment yield, water yield and water balance into sub-basins of Asa river catchment in Kwara State, Nigeria. SWAT was calibrated and validated using measured flow data from January, 2008 to December, 2014. The model was evaluated using Coefficient of Determination, R^2 and Nasch-Sutcliffe Efficiency, NSE which give acceptable results of 0.76 and 0.85 for Calibration and 0.70 and 0.74 for validation stage. Highest Annual Sediment yield of 20.71t/ha was recorded in sub-basin 13 while the lowest value of 8.9t/ha was recorded in sub-base 16. Annual sediment production rate was estimated as 437.6t/ha/yr while the total sediment yield of 4,376.t/ha was produced in the watershed during the simulation period. Predicted values of sediment concentration is highest in sub-basin 23 (153,045.9mg/l) and has a lowest value of 26,781.9 mg/l in sub-basin 1. Categorization of erosion prone areas showed that 12 sub-basins are in low erosion prone zone, two (2) sub-basins moderate zone, 14 in severe while 3 sub-basins are in extreme category. The outcome of this study confirmed that SWAT can be adopted as a decision support tool for sustainable sediment and water management in the basin and other watershed in Sub Saharan Africa Countries.

Keywords: *Asa River, GIS, Nigeria, Sediment Yield, SWAT, Water Management*

1.0. INTRODUCTION

Sustainable management of sediment and water resources in a basin has been regarded as one of the major steps in addressing myriads of sediment and water related problems occurring in a river catchment. This is even more important when considering the sustainability of downstream reservoir that may be situated within the catchment. In a situation where the dam is used for the generation of hydroelectricity, sediments can find its way into the intakes and this may accelerate the abrasion of hydraulic machinery, thereby causing a reduction in the generating capacity of the hydroelectric dam. Morris and Fan (1998) reported that there may also be a significant loss of storage facilities of a downstream reservoir as a result of improper sediment management within the watershed. Sediment yield, which has been defined as the amount of sediment reaching or passing a point of interest in a given period of time (White, 2005) is a major parameter in the management of sediment in a watershed. The estimation of sediment yield is much more needed for studies of reservoir sedimentation, river morphology, soil and water conservation planning, and also for estimation of concentration and load of chemicals adsorbed to sediment particles.

Apart from managing sediment in a watershed, there is also growing need for sustainable management of water resources which has proved effective in tackling problems associated with surface and ground water allocation and distribution in a catchment. The most important parameters in this regard are the water yield and water balance. Adequate knowledge of these parameters is important prerequisite in sustainable management of water in a watershed. Stehr *et al*. (2008) reported that the study of water resources at river catchment level has been widely adopted as a better way of managing and assessing these important natural resources.

At the decision making stage, models are usually employed for the purpose of selecting an optimal courses of action. Such models are often constructed to enable reasoning within an idealized logical framework about the processes (Shrestha *et al*., 2010). In recent times, the use of Geographical Information System (GIS) and remote sensing technique has improved the application of hydrological modelling in many capabilities most especially, in the area of visualization and interface development. Hence, the use of modelling tool interfaced with GIS has been in vogue for sustainable management of water and sediment at watershed level. Therefore, this work focused on the modeling and simulation of hydrological processes of upstream catchment of Asa River using Soil Water Assessment Tool (SWAT). Deliverables of the research

include the prediction of water yield, water balance of the catchment, the annual mean and total sediment yield into sub-basins of the watershed and priotisation of erosion prone area of the watershed.

2.0. METHODOLOGY

STUDY AREA

The study area is located between latitude $8^0$36' and $8^0$24' North and Longitudes $4^0$36' and $4^0$10' east. The watershed has a total area of 639,239.07 ha and it is within Kwara State of Nigeria. The topography is characterized with very broad and gentle slopes, having an altitude between 457m and 265m above mean sea level (a.m.s.l). The vegetation of the watershed is predominantly savannah with some trees which could be found along the river channels with the watershed (Bilewu and Salami, 2009). Major occupation of the inhabitants of the area include farming weaving and fishing. Figure 1 shows the location of the study area within the map of Nigeria

Model Selection and Description

SWAT 2009 model was selected and integrated with a geographical information system, Mapwindow GIS (Leon, 2011) to simulate the runoff and predict the sediment yield and water yield of the selected watershed. SWAT is a catchment-scale continuous time model that operates on a daily time step with up to monthly or annual output frequency. The model which was developed by the United States Department of Agriculture Agricultural Research Service is used for assessing the impact of management and climate on water supplies, sediment, and agricultural chemical yields in watersheds and large river basins (Neitsch *et al.,* 2005).

SWAT is semi-physically based, and allows simulation of a high level of spatial detail by dividing the watershed into a large number of sub-watersheds. The major components of SWAT include hydrology, weather, erosion, plant growth, nutrients, pesticides, land management, and stream routing as reported in Abbaspour et al. (2007). One of the main goals of SWAT model is to predict the impact of land management practices on water quantity and quality over long periods of time for large complex watersheds that have varying soils, land use and management practices (Neitsch *et al*., 2005).

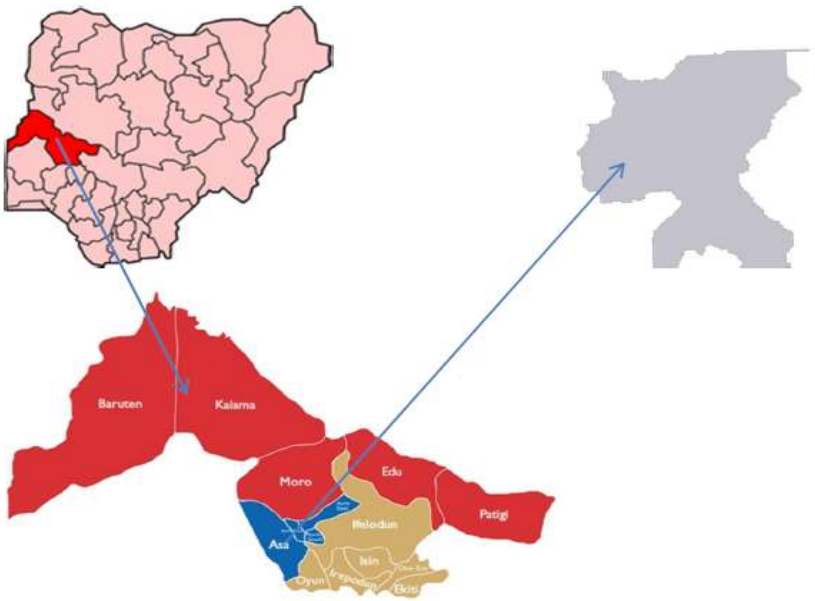


Figure 1: ***Map of Nigeria showing the location of the watershed***

Modeling Sediment and Water Yield in SWAT

Modeling sediment in SWAT entails estimation of erosion/soil loss and sediment yield for each Hydrologic Response Unit (HRU). This is achieved with the usage of Universal Soil Loss Equation and Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), respectively.

$$\mathbf{S_{ed}} = \mathbf{1.292EI_{USLE}K_{USLE}C_{USLE}P_{USLE}LS_{USLE}CFRG} \quad \mathbf{1}$$

In equation 1, S_{ed} is the sediment yield on a given day (metric tons), EI_{USLE} is the rainfall erosion index (0.017 m-metric ton cm/(m^2 hr)), K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm)), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor, and CFRG is the coarse fragment factor. The value of EI_{USLE} for a given rainstorm is the product of total storm energy (E_{storm}) and the maximum 30 minutes intensity (I_{30}). Hence,

$$\mathbf{S_{ed}} = \mathbf{11.8}\left(\mathbf{Q_{surf}q_{peak}Area_{hru}}\right)^{\mathbf{0.56}}$$

$$\mathbf{K_{USLE}C_{USLE}P_{USLE}LS_{USLE}CFRG} \quad \mathbf{2}$$

Where Q_{surf} is the surface runoff volume (mm), q_{peak} is the peak runoff rate (m^3/s), $Area_{hru}$ is the area of the HRU (ha), and other parameters are defined in equation 1. More detail description of the model can be found elsewhere (Arnold *et al.,* 2011; Arnold *et al.,* 2012; Arnold *et al.,* 1995).

Model Input Data Collection and Processing

The basic spatial input datasets used by the model include the Digital Elevation Model (DEM), land use/cover data, soil data and weather data each of this is described in Table 1.

Table 1: Model Input Data for Asa River Watershed

S/N	Data type	Description	Resolution	Source
1	Topography	Digital Elevation Model	90mx90m	Shuttle Radar Topographical Mission
2	Land Use Map	Land Use Classification	1km	Global Land Cover Classification, Satellite Raster
3	Soil Map	Soil Types and Texture	10km	Digital Soil Map of the World
4	Weather	Daily precipitation, Min. and Max. Temp, Rel. Humidity Wind, Solar Radiation	Daily	Nigerian Meteorological Agency, Ilorin

Digital Elevation Model and Land Use Map

Digital Elevation Model 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. The DEM (Figure 2) used for this study was extracted from the Shuttle Radar Topography Mission (SRTM) final version developed by CGIAR (2012). Terrain parameters such as slope gradient and slope length, and stream network characteristics such as channel slope, length and width were derived from the DEM. The land use map of the study area was obtained from the database of the Global Land Cover Characterization (GLCC). GLCC database was developed by United State Geological Survey and has a spatial resolution of 1km and 24 classes of land use representation. Description of the Land use SWAT code is presented in Table 2.

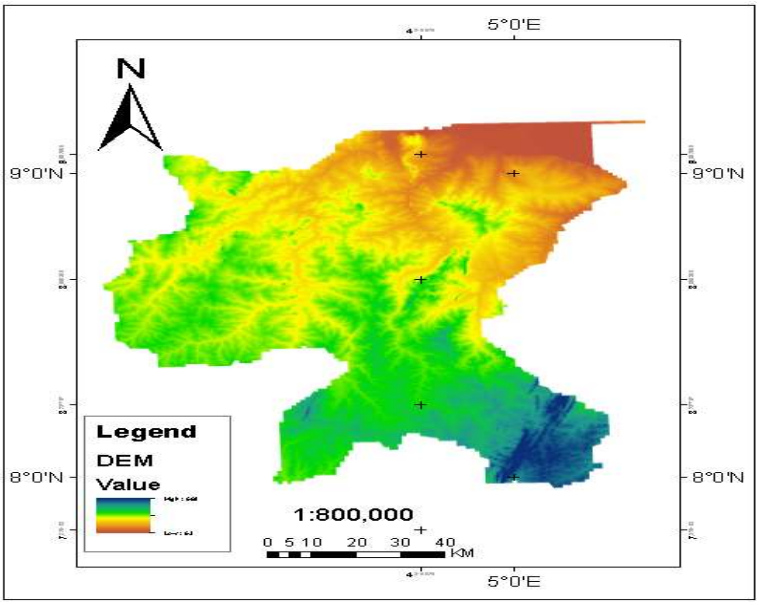


Figure 2: Digital Elevation Model (DEM) of the Study Area

Table 2: ***Information on Land use of the Study Area***

S/N	SWAT Code	Description	Area (Ha)	% of Watershed
1	CRDY	Dryland/ Cropland and Pasture	56.39	0.01
2	CRGR	Cropland/Grassland Mosaic	749.11	0.12
3	CRWO	Cropland/Woodland Mosaic	10288.11	1.61
4	SHRB	Shrubland	749.11	0.12
5	SAVA	Savannah	603710.03	94.44
6	WATB	Waterbodies	3182.47	0.50
7	BSVG	Barren or Sparsely Vegetated	589.19	0.90
	Total		639239.07	100.00

Soil Data and Climatic Data

The soil textural and physicochemical properties required by SWAT model include soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for each soil type (Ayana *et al.,* 2012). Digital soil data for the study was obtained from harmonized digital soil map of the world (HWSD v1.1) produced by Food and Agriculture Organization (FAO) of the United Nations ((Nachtergaele *et al*., 2009). The soil map of the area is shown in Figure 2 while information on the soil map is presented in Table 2. Climatic data required to run SWAT include daily precipitation, minimum and maximum temperatures, wind speed, relative humidity and solar radiation. These data were obtained from Nigeria Meteorological Service Agency (NIMET) located in Ilorin, Nigeria. The time series data collected covered a period of 10 years i.e. (August 1st, 2004 to July 31st, 2014).

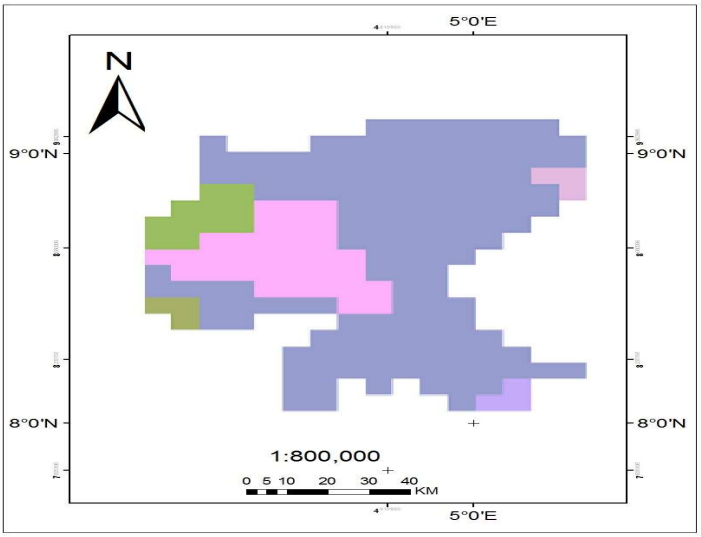


Figure 3: ***Soil Map of the Study Area***

Table 3: ***Information on soil map of the study area***

S/N	SWAT Code	Description	Area(Ha)	% of Watershed
1	I-Ql-Re-1281	Loam	32824.66	5.13
2	Lf1-1421	Sandy Loam	5526.61	0.86
3	Lf12-a-1430	Clayey Loam	159378.61	24.93
4	Lf26-a-1443	Sandy Clayey Loam	415467.82	64.99
5	Lf49-1475	Sandy Clayey Loam	6126.74	0.96
6	Nd3-1565	Sandy Loam	19914.63	3.13
	Total		639239.07	100.00

Model Configuration and Run

Model setup involved five steps. These are data preparation, sub-basin discretization, HRU definition, parameter sensitivity analysis and calibration and uncertainty analysis. The DEM was used to delineate the watershed and to analyze the drainage patterns of the land surface terrain. Stream network of the study was obtained through the processing of the DEM using the GIS component of the model. Sub-dividing watershed into areas having unique land use, soil and slope combinations makes it possible to study the differences in evapo-transpiration and other hydrologic conditions for different land covers, soils and slopes (Setegn *et al*., 2008). The creation of HRUs that are used by SWAT followed immediately after the watershed delineation. This is the division of sub-basins into smaller pieces each of which has a particular soil and landuse or slope range combination. The model was simulated from 01 August 2004 to 31 July 2014.

3.0 RESULTS AND DISCUSSION

Model Calibration and Validation

Performance evaluation of the model was achieved by comparing the observed and the simulated monthly inflows at Asa River gauge station for both the calibration and verification periods. In total, 14 parameters were selected to be calibrated through the Parasol optimization method. The model was calibrated with the observed monthly inflow into Asa River from 2008 to 2010, and was verified with another set of independent data set from 2011-2014. Plot of observed data against simulated results are presented in Figure 4. Results showed that there is 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, and NSE and R^2 of 0.70 and 0.74 respectively for the

validation period. In addition, the good correlation for calibration data and validation data indicated that the experimental data are reliable.

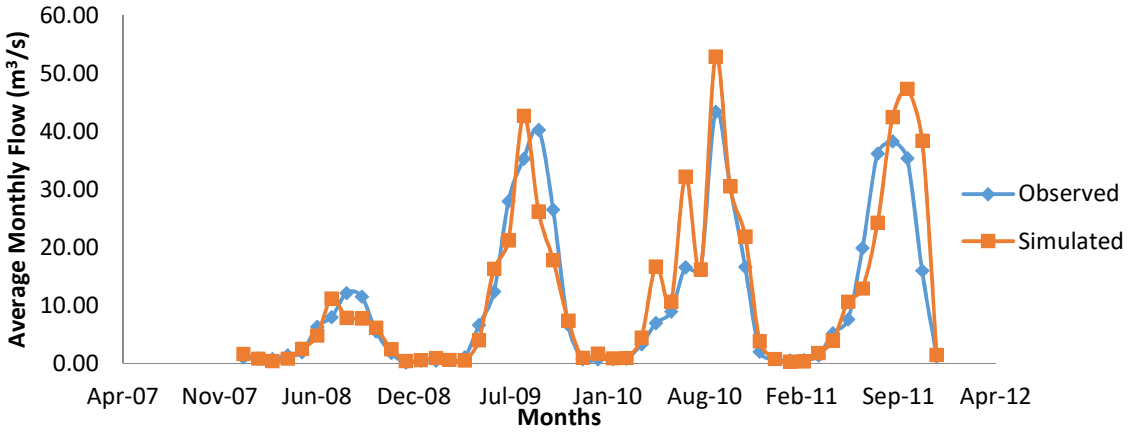


Figure 4: ***Observed against Simulated Monthly flow for both Calibration and Verification Period***

3.1 Assessment of Sediment Yield and Sediment Concentration

Total Sediment Yield

The predicted total sediment yield for each of the 31 sub-basins is shown in Figure 5 and displayed as bar chart in Fig 6. The results indicated that sediment yield is predominantly high in the western extreme of the catchment area. The highest total sediment yield were recorded in sub-basins 23 and 25 with values of 174.5, to 230.9t/ha, respectively. Lowest total sediment yield were obtained in sub-basins 1, 3, and 12 with values of 134.8, 130.2 and 106.1t/ha, respectively. Total sediment yield of 4376.4t/ha was produced in all the sub-basins during the simulation period.

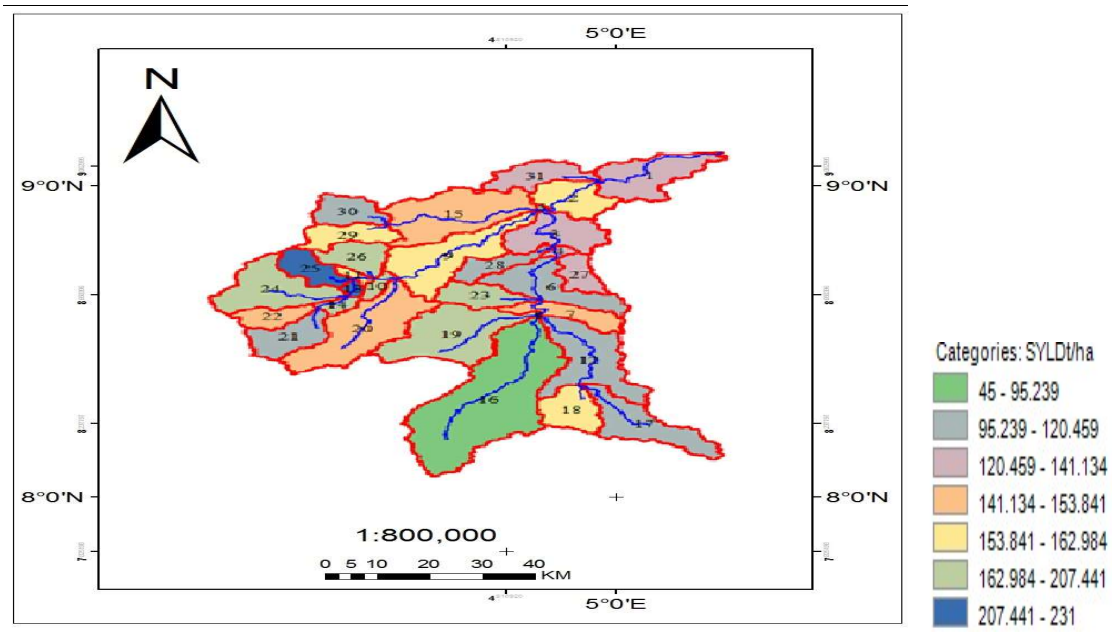


Figure 5: ***Simulated total sediment yield for each of the sub-basins of the watershed***

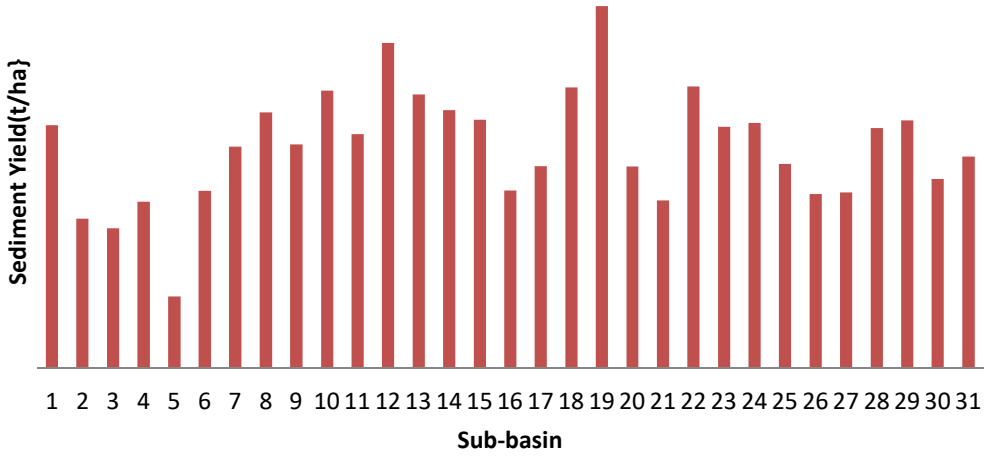


Figure 6: ***Simulated total sediment yield in each of the 31 sub-basins in the study area***

Annual Sediment Yield

The predicted annual sediment yield for each of the 31 sub-basins is shown in Fig. 7 and displayed as bar chart in Fig. 8 .The highest annual sediment yield values were recorded in sub-basins 25 and 13 with values of 23.1 and 20.7 t/ha respectively. Lowest sediment yield were obtained in sub-basins 16 and 17 with values of 8.9 and 9.5 t/ha, respectively. Average Annual sediment production rate in the watershed was estimated as 437.6 t/ha/yr. The rate of production of sediment in the watershed is almost twice the rate when compared with similar modelled watershed of upstream of Jebba dam as reported in Adeogun *et al*. (2015).

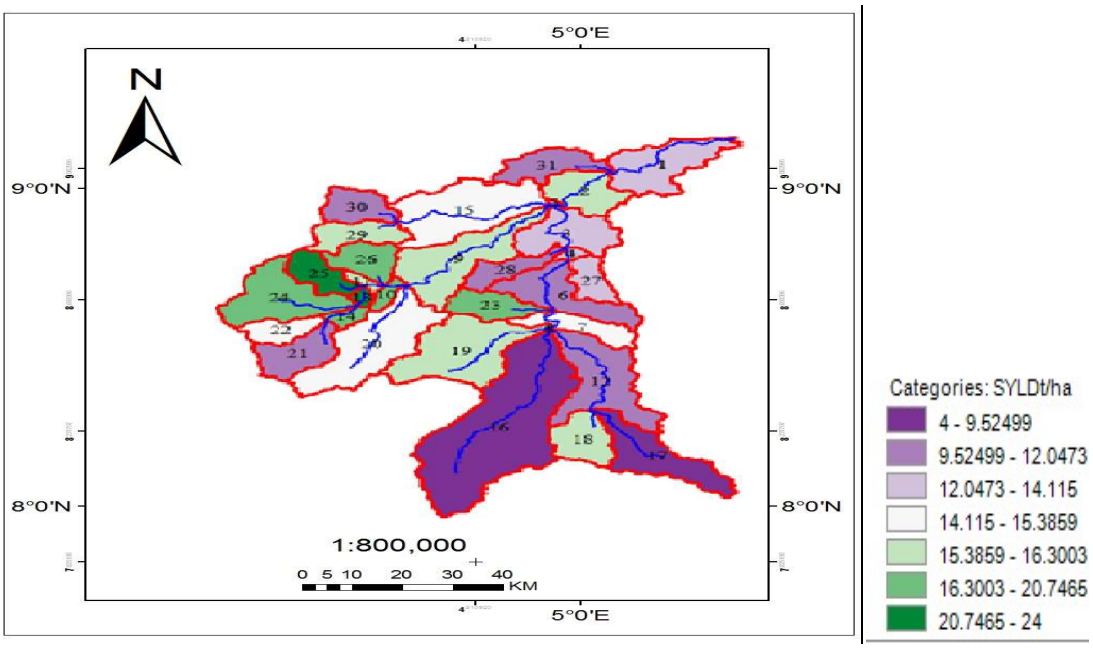


Figure 7: ***Predicted annual sediment yield for each of the sub-basins of the watershed***

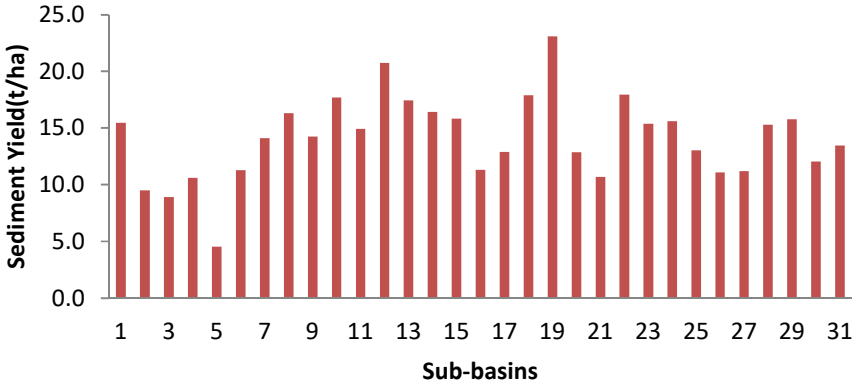


Figure 8: ***Simulated annual sediment yield in each of the 31 sub-basins in the study area***

Total and Annual Mean Sediment Concentration

Highest predicted values of sediment concentration are noticed in sub-basins 23 and 25 with values 153,045.9 and 110,825.3 mg/l respectively. However, lowest sediment concentration occurred in sub-basins 1, 12 and 3 having values of 26,781.9, 28,810.6 and 29,246.1 mg/l, respectively. For predicted annual mean sediment concentration for each of the sub-basins, highest predicted values of sediment concentration were noticed in sub-basins 23 and 25 with values 15,306.3 and 11,083.8 mg/l respectively. However, lowest sediment concentration occurred in sub-basins 1, 3, and 12 with value of 2,678.5, 2,881.4 and 2,924.9 mg/l respectively. Total sediment concentration (mg/l) in each of the reach of the sub-basins is shown in Fig. 9.

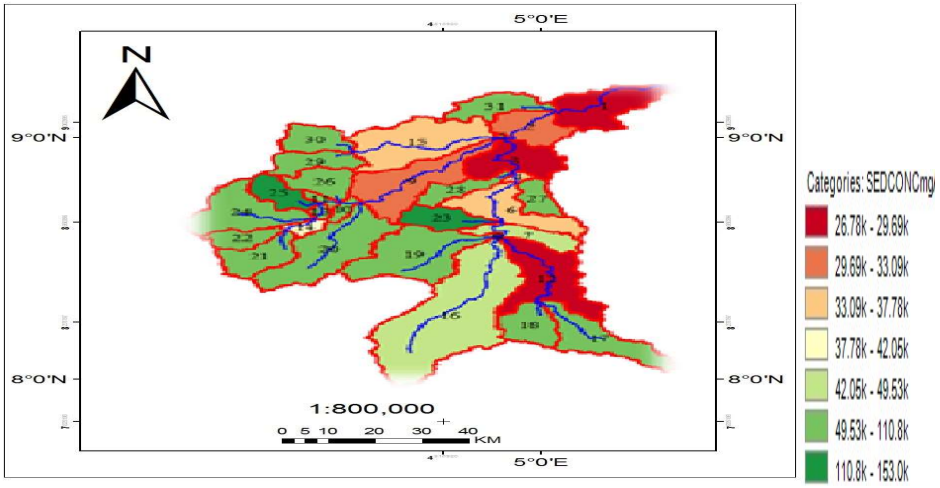


Figure 9: ***Predicted total sediment concentration for each of the sub-basins of the watershed***

Watershed Sediment Management Strategies

Soil erosion prone areas of the watershed were identified for the existing condition using the total sediment yield from each of the sub-basin. Based on the results obtained for the watershed and similar classifications in related researches (Betrie *et al.,* 2011; Adeogun *et.al.* 2016), the erosion classes are categorized into four levels. These are 45-135 t/ha/year as low, 135-143 t/ha/year as moderate, 143-180 t/ha/year as severe and above 180 t/ha/year as extreme. Figure 10 shows the delineation of various soil erosion zones in the catchment. Simulation results showed that 12

sub-basins are in the category of low erosion prone areas, 2 sub-basins in moderate zone, 14 sub-basins in severe erosion area while 3 sub-basins are in the extreme erosion category.

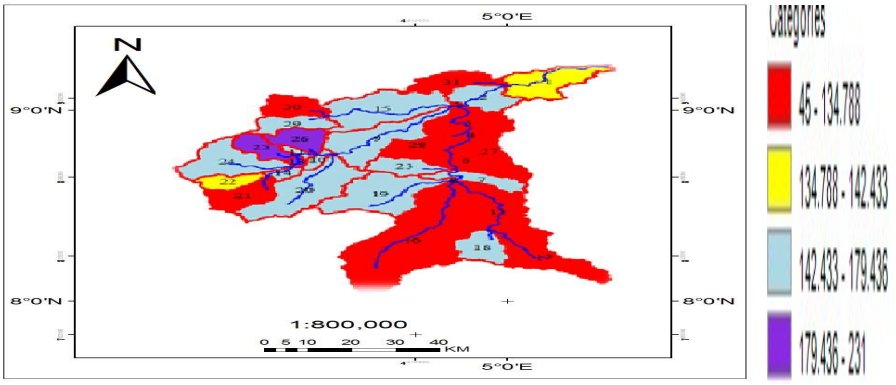


Figure 10: ***Delineation of various soil erosion zones in the catchment***

3.2 Prediction of Water Yield of the Basin

Average Annual Water Yield

The contributions of each sub-basins the watershed area to water yield during the period of simulation period were examined using the calibrated SWAT model. It was noted that sub-basin 31 with catchment area of 639239.07 km^2 has the highest contribution to water yield of the area during the simulation period. Figure 11 shows the distribution of Average Annual Water Yield of each of the subbasin in the watershed.

Estimation of Water Balance Components

SWAT was used to quantify each of the hydrological processes occurring in the study area. Analysis of the results showed that evapo-transpiration has the highest percentage of the total water balance with values ranging from 58% (2004) to 57% in the year (2005). High evapo-transpiration rate predicted for the watershed could be attributed to the type of vegetation cover (mostly savannah) and high temperature associated with the area. Lateral flow has the lowest percentage with values between 0.18% (2013) to 0.39% (2008). Other water balance components predicted are potential evapotranspiration, soil water, surface runoff, lateral flow and ground water. Some of the results of water balance components for selected years are presented in Figure 12.

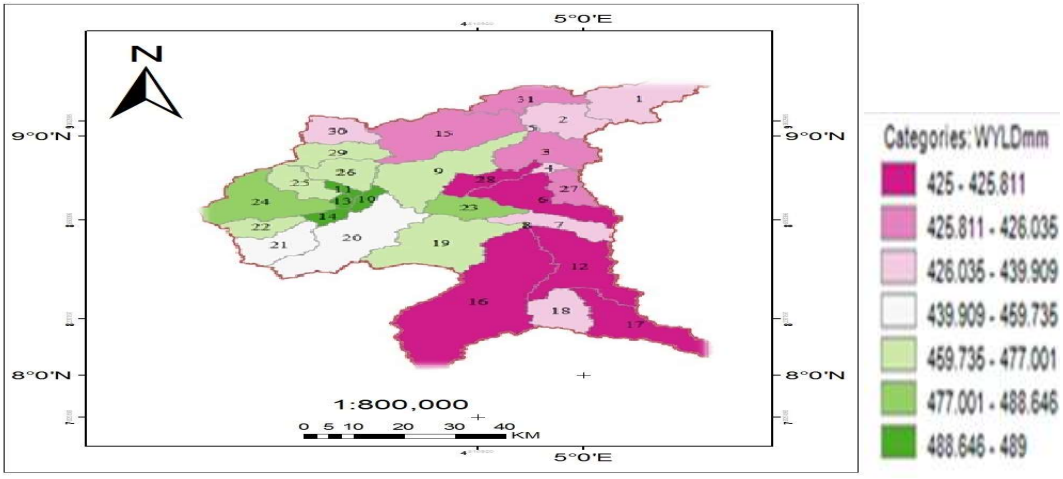


Figure 11: ***Average Annual Water Yield of Each of the Subbasins in the Watershed***

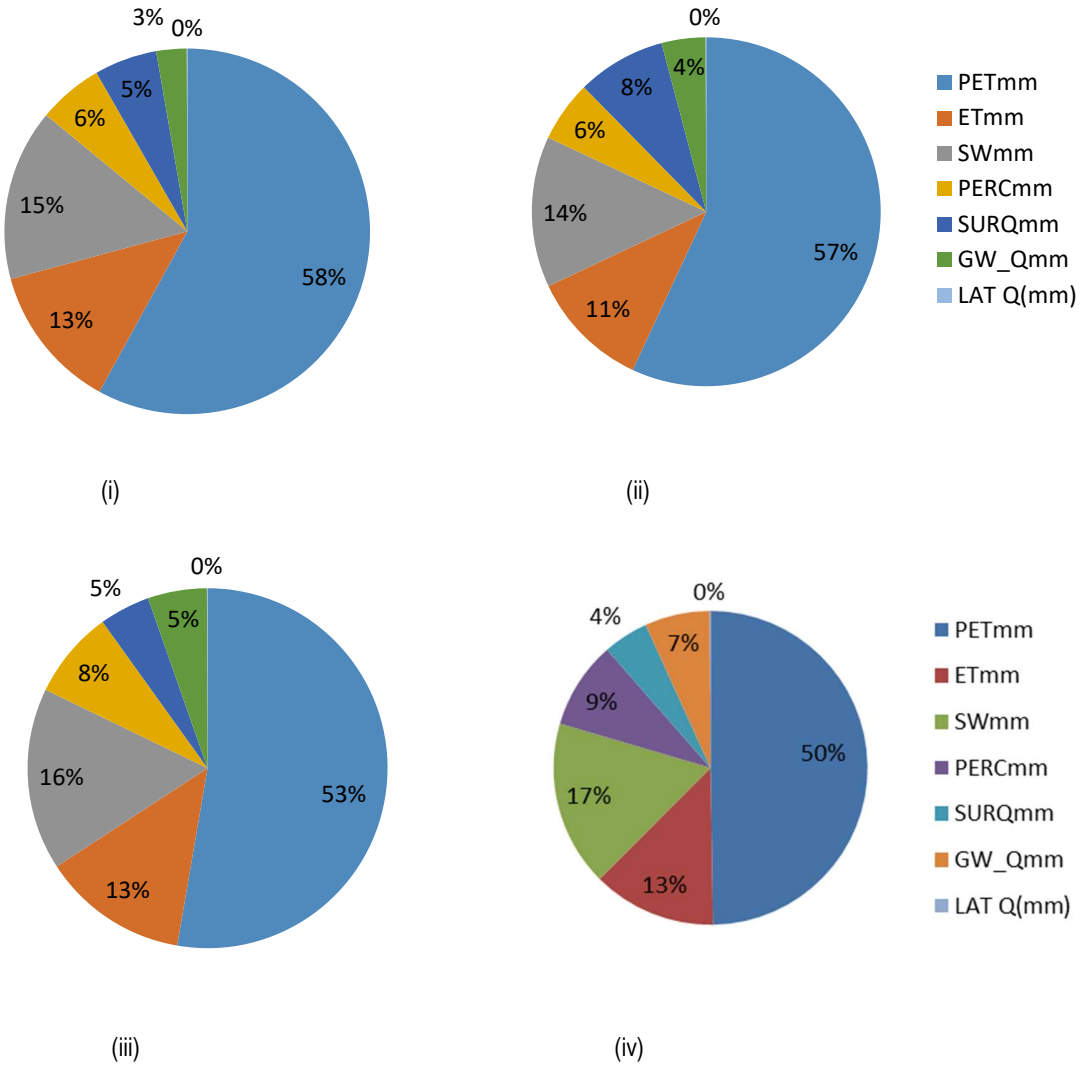


Figure 12: ***Water Balance Components for selected years in the Basin (i) 2004 (ii) 2005 (iii) 2006 and (iv) 2011***

4.0 CONCLUSION

This study described the ability of GIS based SWAT model to predict the sediment and water yield of Asa river watershed, Kwara State of Nigeria. GIS component of the model was used to prepare all the necessary thematic maps viz DEM, land use and soil maps for running of the model. The model was run daily between January 2004 and December, 2014. Performance evaluation of the model was achieved using Nash Sutcliffe Efficiency (NSE) and Coefficient of Determination, R^2 which gave acceptable values for both calibration and validation stage. The results obtained in this research further proved that SWAT model can successfully be adopted by water managers and other stakeholders in water sectors in Nigeria and other sub-Saharan African countries to support decisions in the management of water and sediments at watershed scale level.

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