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SIMULATION OF SEDIMENT YIELD AT THE UPSTREAM WATERSHED OF JEBBA LAKE IN NIGERIA USING SWAT MODEL

Adeniyi Ganiyu Adeogun[1]*, Bolaji Fatai Sule[2] & Adebayo Wahab Salami[2]

[1]*National Centre for Hydropower Research and Development, University of Ilorin, PMB 1515, Ilorin, Nigeria*
[2] *Dept of Civil Engineering, Faculty of Engineering and Technology, University of Ilorin, PMB 1515, Ilorin, Nigeria*

Corresponding author: adeogun.nachred@unilorin.edu.ng*

Abstract: In this study, we focused on the applicability and suitability of Soil and Water Assessment Tool (SWAT) embedded in Geographical Information Systems (GIS) environment in the prediction of sediment yield of a watershed (12,992km^2). The watershed is drained by Rivers Niger, Kontagora, Awun and Eku and is located at the upstream of Jebba Reservoir in north central Nigeria . SWAT was run daily for 26 years (1985 to 2010) using climatic data representing three weather stations located within the watershed. The model was calibrated and validated using measured flow data from 1990 to 1995. Also due to the unavalilability of observed sediment data for the area, sediment samples were collected from three locations in the watershed from May to December, 2013 using suspended sediment sampler USDH-2A. The sediment samples were analysed and used to spatially calibrate and validate the model. The model was statistically evaluated using coefficient of determination, R^2 and Nasch-Sutcliffe Efficiency, NSE. Evaluation of the model revealed that it performed satisfactorily for stream flow and sediment yield predictions in the watershed. The model predicted the annual sediment yield in the watershed as 255.8 tons/ha/yr producing about 8.31x 10^9 tons of sediment between 1985 and 2010. Sediment concentration (mg/l) in the reach during the period of simulation showed that the highest sediment concentration was obtained in subbasins 29, 20 and 19 with values 446.3, 376.8 and 365.4 mg/l respectively. However, lowest sediment concentration occurred in subbasin 73 with a value of 108.6 mg/l. The results from the study showed that a properly calibrated SWAT embedded in GIS environment is suitable for modelling the hydrology and predicting the sediment yield in a watershed. In the light of this, SWAT can be adopted by water engineers and hydrologists in Nigeria and other sub sahara Africa countries in the region as a decision support tool to assist policy makers in achieving sustainable sediment and water management at watershed level.

Keywords: *Jebba resrvoir, sedimentation, sediment yield, SWAT, watershed.*

1.0 Introduction

Sedimentation has been regarded as a major problem threatening the capacities of hydropower reservoirs in Nigeria. Apart from the major watershed problems caused by soil erosion such as significant loss of soil fertility and productivity in the catchment area situated upstream the hydropower dams, increased sediment loads that reduces the capacities and thereby shortens the useful life of reservoirs is also one of the associated effects of soil erosion and sedimentation in the affected area. An insight into the soil erosion and sedimentation mechanism in the watershed situated upstream the hydropower reservoirs in Nigeria are necessary for sustainable sediment management. Ordinarily, adequate knowledge of sediment yield at different locations in the watersheds can be useful to decision makers and stakeholders in proposing efficient sediment management measures that is appropriate for each location for reduction in the rate of siltation and sedimentation of reservoirs downstream.

However, reliable estimates of hydrological parameters and sediment yield in remote and mostly inaccessible areas which characterized most of the catchments in Nigeria might be quite difficult using conventional means or methods. It is therefore desirable to opt for an alternative ways to quantify these parameters for effective and sustainable management of sediment and water resources at watershed level. In recent years, the latest trend is the use of mathematical models for hydrologic evaluation and assessment of sediment yield in watersheds using remotely sensed data embedded in a GIS environment (Ayana, 2012; Ijam,2012 and Asre and Awulachew,2011). The importance of this approach cannot be overemphasized as it provides better understanding of soil erosion processes and a guide towards identifying erosion prone areas which can be used to propose Best Management Practices (BMPS) for sediment yield reduction in the area.

While we have many applications of erosion models in the literature ranging from simulating and predicting runoff and sediment yield to relating the spatial variability of land characteristics to runoff generation and erosion, Soil and Water Assessment Tool (SWAT) has been reported in several studies to have shown more robustness in predicting sediment yield at different watershed scale. For example, Shrivastava *et al*.(2004) tested the applicability of SWAT on daily and monthly basis for estimating surface runoff and sediment yield from a small watershed "Chhokeranala" in eastern India using satellite data and Geographical Information System (GIS). It was reported that the performance evaluation of the model showed a good agreement between observed and simulated runoff and sediment yield during the study period. Ayana *et al.* (2012) applied SWAT model to simulate sediment yield from Fincha watershed (area 3,251 km^2) located in Western Oromiya Regional State, Ethiopia. The results of the model calibration and validation showed reliable estimates of monthly sediment yield. The researchers concluded that SWAT model is capable of predicting sediment yields and hence can be used as a tool for water resources planning and management in the study watershed.

SWAT model has also been tested in Latin America watersheds. Stehr *et al*.(2008) applied readily available SWAT model to Vergara basin (4265 km^2), a sub-basin of Biobío basin (24 371 km^2) which is the third largest basin in Chile. Modelling results show that the model performs well in most parts of the study basin. The study also confirms that SWAT is a useful tool and can be used to make preliminary assessments of the potential impacts of landuse and climate changes on basin hydrology in Chilean watersheds. In a nutshell, worldwide review of SWAT applications indicated that the tool is capable of simulating hydrological processes with reasonable accuracy and can be applied to large ungauged basin. SWAT 2009 interfaced MapWindow GIS was selected to test the capability of the model in determining the effect of spatial variability of a watershed on runoff and sediment yield in Nigerian basin.

2.0 Description of Study Area

The study area is located in central area of Nigeria between Lat 10.31 Long 5.01 and Lat 8.99 Long 4.79 (see Figure 1). The watershed has a perimeter of about 567 km and an estimated area of 12,992 km^2 The range of elevation of the watershed is between 114 m and 403 m above sea level and the average monthly discharge at Jebba station situated at the outlet of the watershed is 1053 m^3/s for the period of 1984-2008. The watershed is sandwiched between two main hydropower reservoirs in Nigeria, namely Kainji and Jebba reservoir both situated in north-central zone of Nigeria. Villages within the watershed area are Zugruma, Ibbi, Patiko, Felegi (custodian of Kainji Lake National Park) and Sabonpegi. The selection of the area to test the applicability of SWAT model is based on the availability of model input data available at the three hydrological stations established by Kanji and Jebba hydroelectric power stations as well as at the Nigeria Metrological Agency (NIMET). In terms of its usefulness, the watershed plays a significant role in the national energy supply since it contributes majorly to the water flowing into Jebba lake downstream where about 764MW of hydroelectric is generated annually.

Figure 1: Map of Nigeria Showing the Location of the Watershed and its Tributaries

3.0 Methodology

In this study, SWAT 2009 model was integrated with a geographical information system, Mapwindow GIS (Leon, 2011) to simulate the runoff and predict the sediment yield of the selected watershed. SWAT is an acronym for Soil and Water Assessment Tool. It is a physically based hydrological model which uses readily available inputs. SWAT was originally developed by the United States Department of Agriculture (USDA) to predict the impact of land management practices on water, sediment and agricultural chemical yields in large ungauged basins.(Arnold *et al*.,1995) . SWAT is a catchment-scale continuous time model that operates on a daily time step with up to monthly or annual output frequency. The simulation of hydrologic cycle by SWAT is based on the water balance Eq.1:

$$SW_t = SW_o + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})_i \quad (1)$$

Where SW_t is the final soil water content (mm water), SW_o is the initial soil water content in day i (mm water), t is the time (days), R_{day} is the amount of precipitation in day i (mm water), Q_{surf} is the amount of surface runoff in day i (mm water), E_a is the amount of evapotranspiration in day i (mm water), W_{seep} is the amount of water entering the vadose zone from the soil profile in day i (mm water), and Q_{gw} is the amount of return flow in day i (mm water).

The estimation of erosion/soil loss and sediment yield in the watershed is carried out using the Universal Soil Loss Equation and Modified Universal Soil Loss Equation

(MUSLE) (Williams, 1975), respectively. The current version of SWAT model uses simplified stream power equation (Eq.2) to route sediment in the channel.

$$\mathbf{SY = 1.292EI_{USLE}K_{USLE}K_{USLE}P_{USLE}LS_{USLE}CFRG} \quad (2)$$

Where SY 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)), other factors are as defined in Eq.3. The value of EI_{USLE} for a given rainstorm is the product, total storm energy (E_{storm}) times the maximum 30 minutes intensity (I30).

$$\mathbf{SY = 11.8\left(Q_{surf}q_{peak}Area_{hru}\right)^{0.56}\ K_{USLE}C_{USLE}P_{USLE}LS_{USLE}CFRG} \quad (3)$$

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), 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. More detail description of the model can be found elsewhere (Arnold *et al*., 2011; Arnold *et al*., 2012; Arnold *et al*., 1995)

Basic inputs for running SWAT model include the Digital Elevation Model (DEM), soil and land use map of the study area as well as the point location of the weather stations. The 90 m resolution DEM (see Figure 2) used for this study was extracted from the Shuttle Radar Topography Mission (SRTM) final version developed by CGIAR (2012). Landuse map was obtained from the database of the Global Land Cover Characterization (GLCC). The GLCC database was developed by United State Geological Survey and has a spatial resolution of 1km and 24 classes of landuse representation (GLCC, 2012). Digital soil data for the study was extracted 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 landuse and soil maps were complemented with information obtained at the study area. This was used to estimate vegetation and other parameters representing the watershed. Daily precipitation, relative humidity, maximum and minimum temperature data as well as flow data for 3 meteorological stations within the watershed were obtained from authorities of Nigeria Metrological Agency (NIMET), Jebba and Kainji hydroelectric stations and used to run the SWAT model. The collected weather variables for driving the hydrological balance within the watershed are from Jan. 1985 to Dec. 2010. In the case of missing data, a weather generator embedded in the SWAT model and developed by Schuol and Abbaspour (2007) was used to fill the missing gaps.

The watershed was delineated and discretized into 77 subbasins and 107 Hydrological Response Units (HRU) (Figure 3) each with unique combination of landuse, slope and soil. Division of subbasins 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). SWAT was executed using the Runoff Curve Number method for estimating surface runoff from precipitation, the Hargreaves method for estimating potential evapo-transpiration generation, and the Variable storage method to simulate channel water routing. The simulation period was from 01 January, 1985 to 31 December, 2010.

The model was calibrated and validated from Jan.1990 to Dec.1995 using the observed monthly flow data collected from Jebba hydropower station. However, for sediment flow calibration and validation, there were no observed sediment data for the watershed. In this case, suspended sediment sampling programmes were established at three locations within the watershed along river Eku, Awun and at a confluence point of river Niger and Kotangora for the collection of sediment samples. Samples were collected using suspended sediment sampler USDH-2A for a period of 8 months (May-October, 2103) at an interval of 15 days. The samples were analyzed in a standard laboratory to obtain the sediment concentrations in each of the samples. The observed sediment data were divided into two independent datasets. Those collected from May to August 2013 were used for model calibration and observed sediment data from September to December, 2013 were used for model validation. A spatially distributed calibration and validation of the model were carried out the locations where sediment data were collected within the watershed area. Spatially distributed calibration and validation of SWAT model has been reported by Qi and Grunwald (2005) to enhance the reliability of simulations most especially in a large watershed.

A sensitivity analysis of model parameters were carried out in order to identify and rank the parameters that have significant impact on specific model output (Setegn *et al*.,2008). Model performance evaluation is necessary for the verification of the robustness of the model. In this study, performance evaluation of the model was achieved using the guidelines specified in Moriasi *et al*. (2007). This entails the use of statistical methods such as coefficient of determination (R^2) and Nasch-Sutcliffe Efficiency (NSE) (see Eq. 4 and 5 respectively). The statistical parameters provide the goodness of fit between the observed and simulated data. According to the guidelines, model simulation are judged to be satisfactory if NSE> 0.5 and the coefficient of determination, R^2 values which ranges from 0 to 1 , with a value of 0 indicating no correlation and a value of 1 representing a good fitness between the observed and simulated flow (Jain *et al*., 2010).

$$R^2 = \frac{\left[\sum_i (Q_{m,i} - \overline{Q_m})(Q_{s,j} - \overline{Q_s})\right]^2}{\sum_{m,j}(Q_{m,j} - \bar{Q}_m)^2 \sum_i (Q_{s,i} - \overline{Q_s})^2} \tag{4}$$

$$E_{NS} = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i \left(Q_{m,i} - \overline{Q_m}\right)^2} \qquad (5)$$

In Eq. 4 and 5, Q_m is the measured discharge, Q_s is the simulated discharge, $\overline{Q_m}$ is the average measured discharge and $\overline{Q_s}$ is the average simulated discharge.

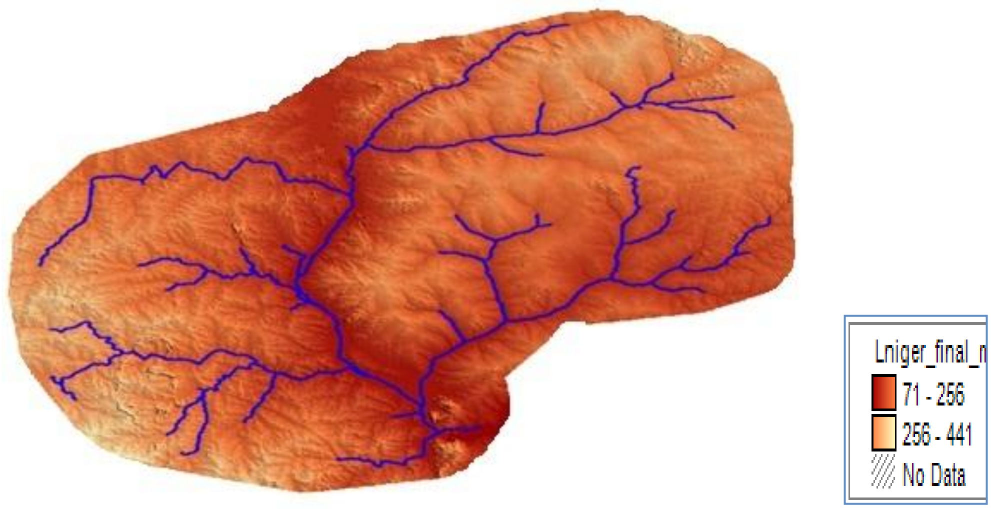


Figure 2: Digital Elevation Model (DEM) of the Study Area Attributed with Stream Networks

Figure 3: Delineation of study area into 77 subbasins and 107 Hydrological Response Units (HRU)

4.0 Results and Discussion

4.1 *Parameter Sensitivity Analysis and Stream Flow Calibration*

The hydrologic simulation using SWAT model involves several parameters that have to be adjusted during the calibration and validation process which often become cumbersome and time consuming. In this study, we evaluated the relative sensitivity analysi 27 flow model parameters using auto calibration procedure. Model calibration and validation for stream flow were achieved using aggregated observed monthly flow data at the gauge station located at Jebba Hydroelectric power station. Monthly inflow data from Jan., 2004 to Dec.2007 were used for the calibration period while observed inflow data between Jan. 2008 till Dec.2011 were used for the validation period. The results of the sensitivity analysis and stream flow calibration of the model have been presented elsewhere (Adeogun *et al*., 2014).

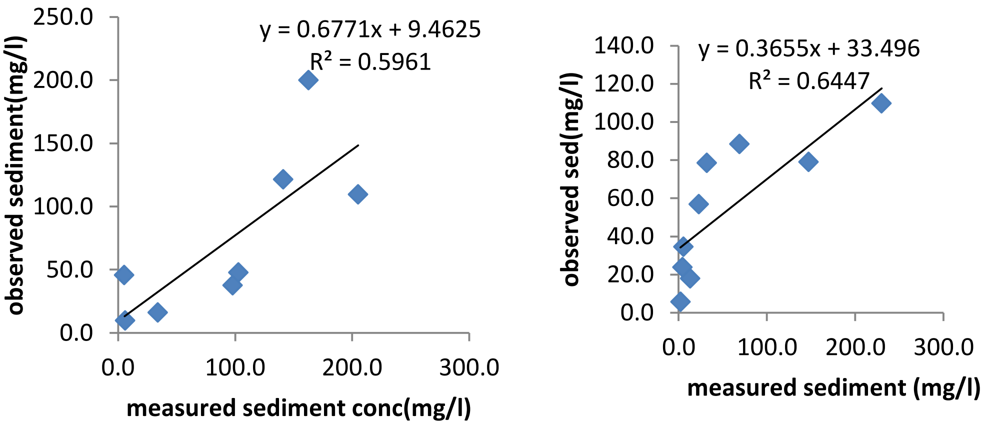
4.2 *Sediment load Calibration and Validation*

Summary of the performance evaluation of the model using statistical parameters, NSE and coefficient of determination, R^2 is as shown in Table 1. The calibration and validation plots for the three locations are as shown in Figure 5- 7. The comparison of the observed sediment concentration and the simulated values are as presented in Figure 8-10. As indicated in Table 1, the model showed a good agreement between the observed and simulated values for both calibration and validation period for River Awun as indicated by acceptable values of the NSE = 0.82, R^2 = 0.60 for calibration period and NSE = 0.65, and R^2 value of 0.52 in the validation period. River Eku also performed well during the calibration, with R^2 and NSE values, 0.68 and 0.66 and validation period 0.68 and 0.55 respectively. These values are above the standard limit as specified by Morris *et al.*,(2007). Further analysis of the results showed that the values of R^2 and NSE (0.57 and 0.8 respectively) for the calibration period of river Niger/Kotangora sampling point fell within the acceptable values while the model performance during the validation period could be regarded as unsatisfactory with R^2, 0.23 and NSE, 0.48. The unsatisfactory performance of the model at this location could be attributed to excess sediments load reaching the sampling point which was noted during the sampling periods. The excess sediment load could be as a result of the activities of local miners at the upstream of the river which could not be adequately captured by the SWAT model. Figure 4 shows the activities of the local miners at the river bank along River Kontagora within the watershed.

Table 1: Summary of the Performance Evaluation of the Model

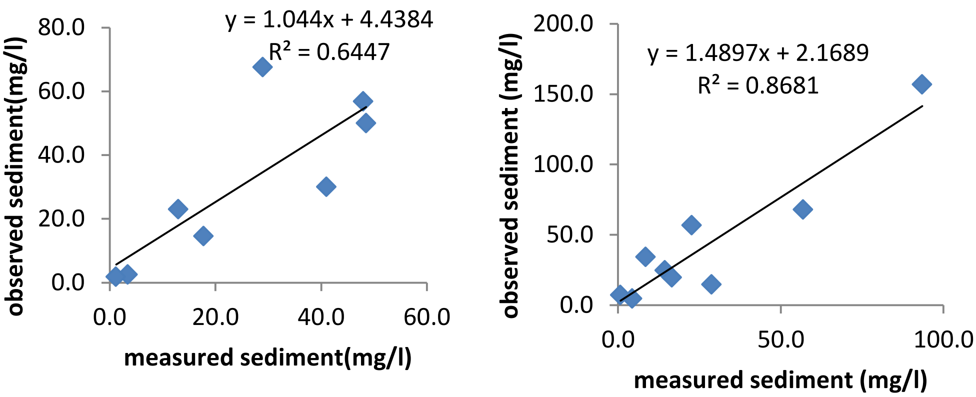
S/N	Sampling Points	Calibration		Validation	
		R^2	NSE	R^2	NSE
1	River Awun	0.60	0.82	0.65	0.72
2	River Eku	0.68	0.66	0.68	0.55
3	Confluence of R.Niger/Kotangora	0.57	0.8	0.23	0.48

Figure 0: Activities of Local Miners at the River Bank of River Kotangora. Note the Heaps of Soil Excavated during the Mining Activities at the Left Hand Side.



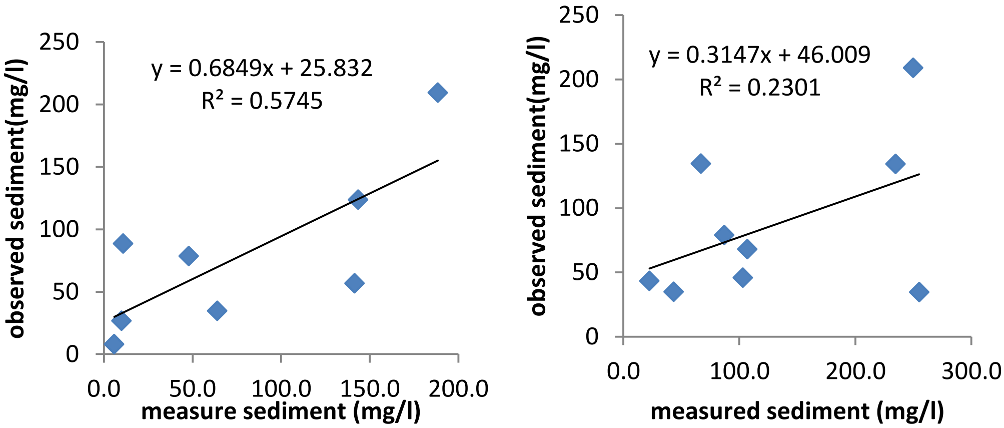
(a) (b)

Figure 5: Calibration (a) and Validation (b) plots for River Awun



(a) (b)

Figure 6: Calibration (a) and Validation (b) plots for River Eku



(a) (b)

Figure 7: Calibration (a) and Validation (b) plots for River Niger/Kotangora

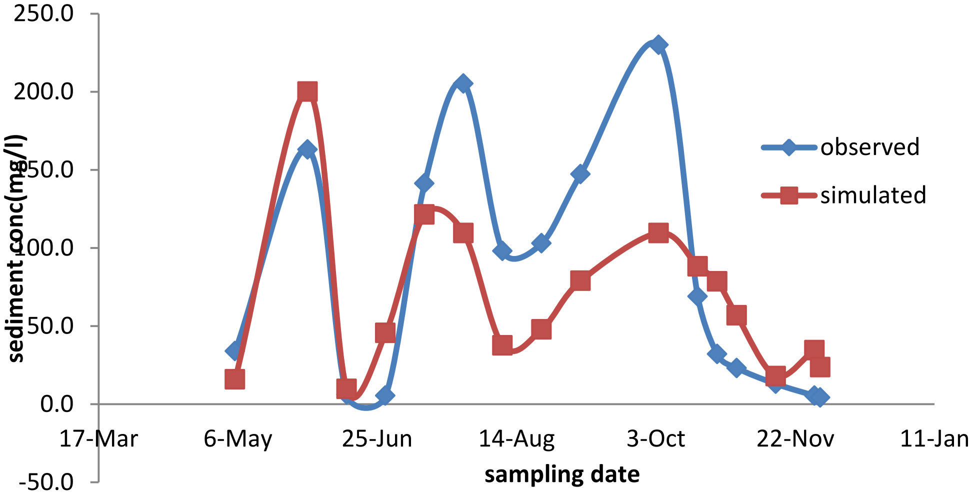


Figure 8: Comparison between Observed and Simulated Sediment along River Awun for both Calibration and Validation Period

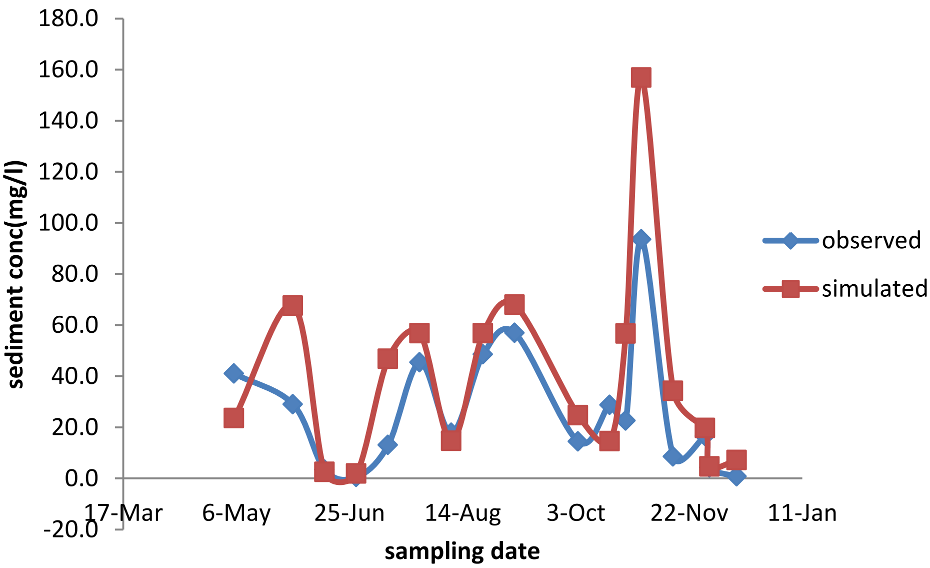


Figure 9: Comparison between Observed and Simulated Sediment along River Eku for both Calibration and Validation Period

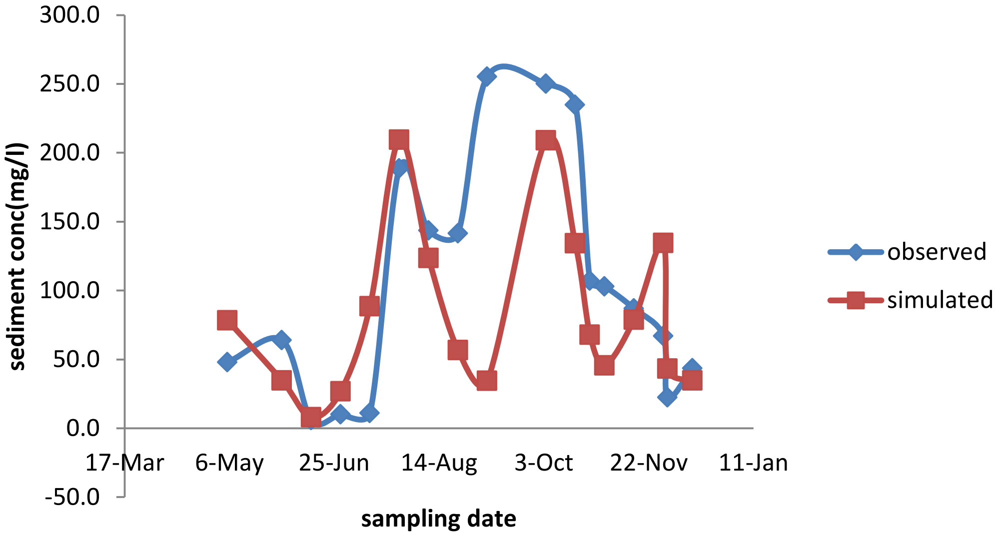


Figure 10: Comparison between Observed and Simulated Sediment along River Niger/Kotangora for both Calibration and Validation Period

4.3 *Spatial Distribution of Sediment Yield and Concentration*

Total sediment yield for each of the 77 subbasins is as shown in Figure 11 and displayed as bar chart in Figure 12. The results indicated that sediment yield is predominantly high at the middle of the catchment area along the major river (Niger) that passes through the middle of the watershed. The highest sediment yield were recorded in subbasins 75, 33 and 16 with values of 2217, 1301.5 and 1259.13 t/ha respectively. Lowest sediment yield were obtained in subbasins 72, 17, and 56 with values of 301.98, 379.9 and 428.8 t/ha respectively. A total sediment yield of 54,382 t/ha was produced in all the subbasins during the simulation period. Average annual sediment production in the watershed was estimated as 255.8 t/ha/yr which translate to about 8.31x 10^9 tons of sediment between 1985 and 2010. Sediment concentration (mg/l) in each of the reach in subbasins through the period of simulation as predicted by the model is as shown in Figure 13. Highest predicted values of sediment concentration are noticed in subbasins 29, 20,and 19 with values 446.3, 376.8 and 365.4 mg/l respectively. However, lowest sediment concentration occurred in subbasin 73 with a value of 108.6 mg/l .

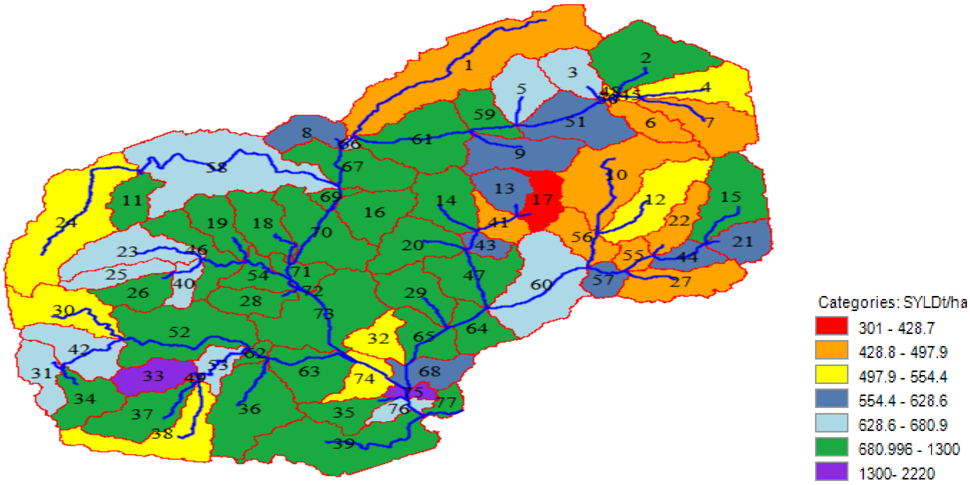


Figure 11: Predicted Annual Sediment Yield for each of the Subbasins in the Watershed

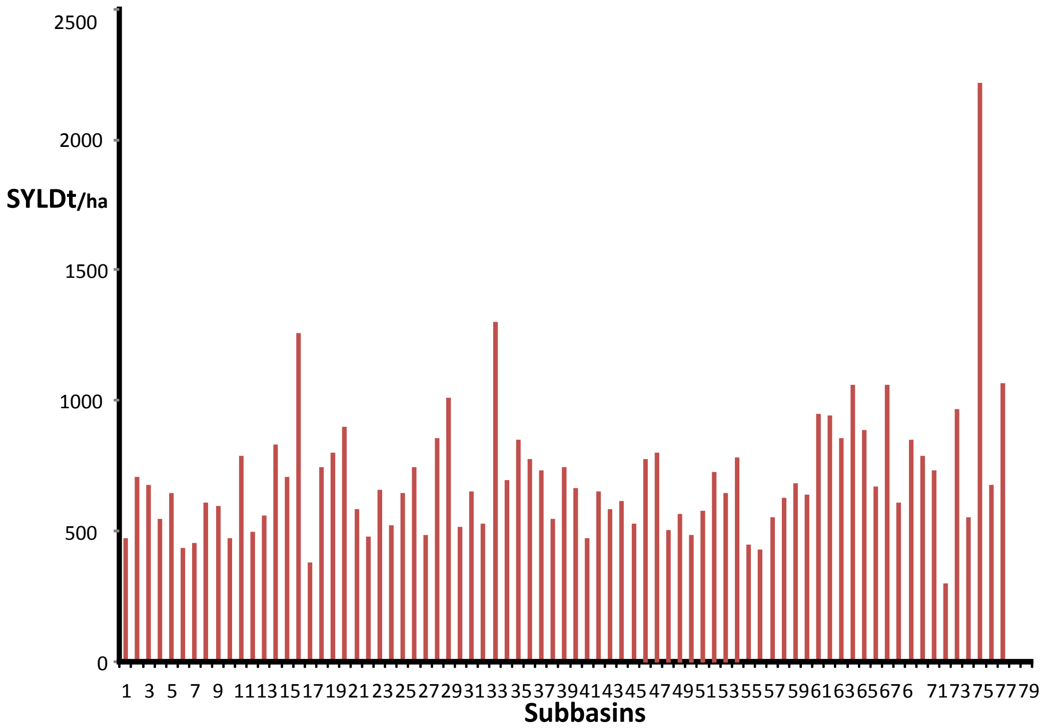


Figure 12: Predicted Annual Sediment Yield in each of the Subbasins in the Watershed

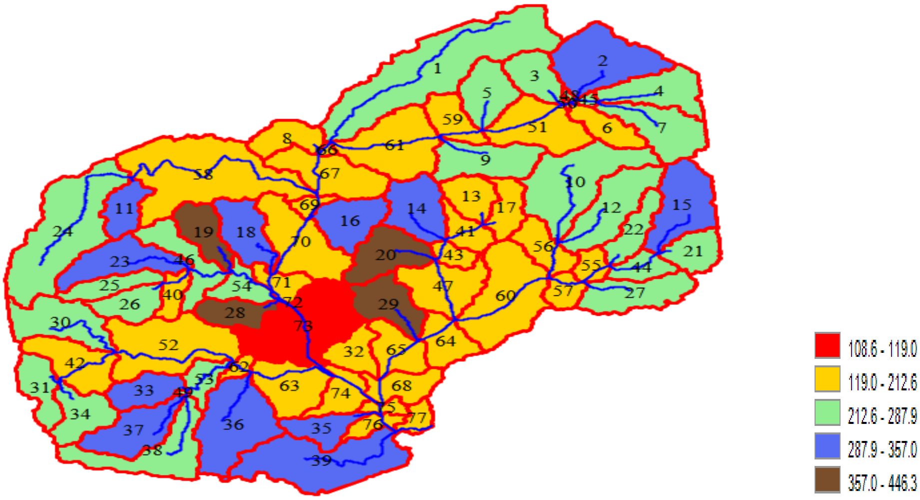


Figure 13: Predicted Sediment Concentrations in each of the Subbasins in the Watershed

5.0 Conclusion

In this study, a physically based semi-distributed hydrological model (SWAT) interfaced with MapWindow GIS software was applied to predict the sediment yield and sediment concentration of a watershed located upstream of Jebba reservoir, north central Nigeria. The preparation of thematic maps and database necessary for the successful running of the model was done using the GIS components. The model was run daily for a period of 26 years (1985 to 2010). The SWAT model was used to simulate the hydrology and predict the sediment yield and sediment concentration in the watershed. The annual sediment yield in the watershed was estimated as 255.8 tons/ha/yr producing about 8.31x 10^9 tons of sediment between 1985 and 2010. Evaluation of SWAT model using coefficient of determination, R^2 and NSE revealed that the model performed satisfactorily for stream flow and sediment yield prediction in the watershed. The result obtained from the study is an indication that if properly calibrated, SWAT embedded in GIS environment is suitable for modelling the hydrology and predict the sediment load and concentration in a Nigerian watershed. SWAT can also be a promising candidate for water engineers and hydrologists in Nigeria to support policies and decision making by relevant authorities for sustainable sediment and water management at watershed level.

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References

Adeogun, A.G., Sule, B.F., and Salami, A.W. (2014) *Validation of SWAT Model for Prediction of Water Yield and Water Balance: Case Study of Upstream Catchment of Jebba Dam in Nigeria*: International Journal of Mathematical, Computational, Physical and Quantum Engineering, 8(2):264-270

Arnold,J.G., Kiniry,J.R., Srinivasan R,Williams,J.R.,Haney,E.B., and Neitsch, S.L. (2011). *Soil and Water Assessment Tool Input Output File Documentation*. Soil and Water Research Laboratory, Agricultural Research Service, Grassland, 808 East Blackland Road, Temple, Texas, USA

Arnold,J.G., Moriasi, D.N.,Gassman, P.W., Abbaspour,K.C., White, M.J., Srinivasan,R.,Santhi. C., Harmel, R.D., van Griensven, A., Van Liew, M.W., Kannan. N, and Jha, M.K. (2012) *SWAT: Model Use, Caliberation and Validation*. Transactions of the American Society of Agricultural and Biological Engineers 55(4): 1491-1508

Arnold, J.G., Williams, J.R. and Maidment, D.R. (1995) *Continuous-time water and sediment-routing model for large basins*. . Journal of Hydraulic Engineering, 121(2): 171-183.

Asres, M.T and Awulachew, S,B (2011) *SWAT Based Runoff and Sediment Yield Modelling: a Case Study of the Gumera Watershed in the Blue Nile Basin*. Ecohydrology & Hydrobiology 10: 191-199, DOI http://dx.doi.org/10.2478/v10104-011-0020-9

Ayana, A.B., Edossa, D.C., and Kositsakulchai, E. (2012) *Simulation of Sediment Yield using SWAT Model in Fincha Watershed, Ethiopia*. Kasetsart Journal of Natural Science 46: 283 - 297

CGIAR (2012) *SRTM 90m Digital Elevation Data* available at: http://srtm.csi.cgiar.org. Assessed on 8th May 2013

Ijam,A.Z. and Tarawneh, E.R. (2012) *Assessment of Sediment Yield for Wala dam Catchment Area in Jordan*. European Water : 38: 43-58

Jain, S.K., Tyag, J, and Singh, V. (2010) *Simulation of Runoff and Sediment Yield for a Himalayan Watershed Using SWAT Model.* Water Resources and Protection 2: 267-281

Leon,L.F.(2011) *MapWindow Interface for SWAT (MWSWAT) Users Manual*, available at www.waterbase.org , accessed on 28th November,2013

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L (2007). *Model evaluation guidelines for systematic quantification of accuracy in watershed simulations*, Transactions American Society of Agricutural and Biological Engineers, 50, 885–900

Nachtergaele,F., Velthuizen, H.V., and Verelst, L. (2009) Harmonized World Soil Database (HWSD). Food and Agriculture Organization of the United Nations, Rome

Neitsch, S.L., Arnold, J.G.,Kiniry, J.R..Williams,J.R.(2005) *Soil and Water Assessment Tool Theoretical Documentation Version.* Grassland,Soil and Water Research

Laboratory,Agricultural Research Service 808 East Blackland Road,Temple,Texas 76502;Blackland Research Centre,Texas Agricultural Experiment Station 720,East Blackland, Texas USA

Qi, C.and Grunwald, S. (2005) *GIS− Based Hydrologic Modeling in the Sandusky Watershed Using SWAT*. Transactions of the American Society of Agricutural and Biological Engineers Vol. 48(1): 169−180

Schuol,J.and Abbaspour, K.C. (2007) *Using Monthly Weather Statistics to Generate Daily Data in a SWAT Model Application to West Africa*. . Ecological Modeling 201: 301-311

Setegn,S.G., Srinivasan, R. and Dargahi,B. (2008) Hydrological *Modelling in the Lake Tana Basin, Ethiopia Using SWAT Model.* The Open Hydrology Journal 2: 49-62

Shrivastava,P.K., Tripathi, M.P. and Das, S,N, (2004) *Hydrological Modelling of a Small Watershed Using Satellite Data and GIS Technique*. Journal of the Indian Society of Remote Sensing 32 (2): 145-157