MODELLING THE IMPACTS OF SELECTED WATERSHED MANAGEMENT STRATEGIES ON SEDIMENT REDUCTION UPSTREAM OF SHIRORO DAM, NIGERIA

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Abstract: This research utilized a regulated hydrological model, Soil and Water Assessment Tool (SWAT) interfaced with Geographical Information System (GIS), in studying the effectiveness of the chosen watershed management strategies on sediment reduction upstream of Shiroro dam, Nigeria. Selected management approaches were modelled while calibration and validation of the model were achieved using observed streamflow data. Findings indicated a good correlation during calibration and validation period. Application of reforestation, vegetative filter strips and stone bunds in the watershed reduces sediment production by 27 %, 39 %, and 15 % respectively. Thus, the sediment management scenarios depicted within this research are considerably sustainable and effective.

Keywords: geographical information system, hydrological model, Nigeria, sediment management, Shiroro dam, watershed

1. INTRODUCTION

Watershed management as described by [1] involves the adoption of best practices aimed at sustaining land and water resources, with the overall objective of improving the quality of these resources and other attributable resources reasonably and comprehensively. The utmost challenge attributed to construction of a dam is the decrease in storage size due to reservoir siltation [1]. According to [2], as water in natural channels flows into a reservoir, its energy slope drastically reduced towards zero, resulting in the loss of transport energy and the end deposition of sediments in the reservoir occurs. The acquisition of these fluvial deposits results in the loss of reservoir capacities hence hindering the functions for which they are created for such as hydropower generation, water supply, and recreation activities. Of concern is that the accumulation of sediments impacts a reservoir's life cycle; lessens the water-retaining capacity, as well as its flows [3]. Factors such as human activities, climate change, and land-use variation alter the extent of changes in the streamflow within the catchments [4]. The sediment data, runoff, streamflow, alongside other hydrological data features are required in attaining a better understanding of land cover and land use within the hydrological processes. However, most developing countries are challenged with adequate and reliable data requirements for catchment hydrological modelling [5]. Certain hydrological data such as runoff can be obtained either through simulation models or on-site monitoring. Most of the on-site data are expensive, time-consuming and labour intensive. Thus, making the use of a "hydrological

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doi.org/10.29081/jesr.v28i4.001

simulation model" is a viable alternative in solving these problems [6] Sedimentation is defined by [7] as the "*process by which soil particles are gradually worn away and moved by the flowing water or other transporting media and accumulated as layers of solid particles in water bodies such as reservoirs and rivers*". Sedimentation has been a major challenge facing river ecosystems across the globe. The research carried out on the world's 145 major rivers with consistent long-term sediment records showed that 50 % of the rivers have statistically a significant downflow trend due to sedimentation [8]. The literature work of [9] and [10] affirmed Shiroro, Kainji, and Jebba hydropower dams in Nigeria to have been adversely impacted with large sediment influx deposits from various sources causing a reduction in the upstream dam reservoirs capacity and flood control. These have resulted in reduction of reservoir life, persistent floods, and negative impacts on hydropower generation. Not minding other adverse effects on the benefit to be derived from irrigation, water supply, wildlife development, navigation, recreation, and groundwater recharge. Hence, erosion processes and other sediments control measures are required for proper reservoir management in Nigeria particularly at the watershed upstream location of hydropower dams.

Developing quantitative prediction models for quantifying the impacts of land use and management parameter changes on runoff and sediment yield in watersheds is therefore of great significance. The significance of these models is based upon their potential for stimulating sound watershed management initiatives that may facilitate economic and environmental sustainability, whilst also forming the foundation to sound policy interventions. Amongst the most used computer simulation modelling tools for forecasting runoff and sediment yield is the Soil and Water Assessment Tool (SWAT) model [11]. SWAT has been widely applied in the selection of "Best Management Practices" (BMPs) to reduce the sediments influx, estimate future scenarios on hydrologic and water quality standards in a watershed-based on site-specific conditions like soil, topography, land use, and climatic events [12-14]. The model has also been applied to estimate future scenarios on hydrologic and water quality standards in a watershed area with increased urbanization [15-17]. On this note, this study investigated the effectiveness of selected watershed management strategies on sediment reduction upstream of Shiroro dam, Niger State, Nigeria.

2. MATERIALS AND METHODS

2.1. Overview of study area

The study area, upstream of Shiroro dam is situated at former Shiroro village, North-Central Nigeria. It can be found between Latitude 9.35° N, Longitude 6.45° E and Latitude 11.28° N Longitude 8.55° E with an appraised land area of 32,125 km^2. The watershed has a mean elevation of 683 m above sea level. The Shiroro dam derives its water sources from the Kaduna watershed (32,125 km^2), which consists of four sub-watersheds. These four sub-watersheds are named after some commonly known rivers - Dinya, Gutalu, Sarkinpawa and Kaduna. The Dinya (365 km^2) consists of a basin; Gutala (2,672 km^2) and Sarkinpawa (3,413 km^2) on the other consists of seven basins; whilst the largest of them, the Kaduna sub-watershed (25,675 km^2) contains 69 basins. The hydropower dam was commissioned on the 21st of June 1990, by the former Nigeria Head of State, General Ibrahim Badamosi Babangida and the hydroelectric power plant which consist of four (4) turbines can conveniently generate up to 600 MW of electricity under optimal performance and this generation is enough to power about 400,000 household in Nigeria [18]. Figure 1 shows the location of the study area in Nigeria.

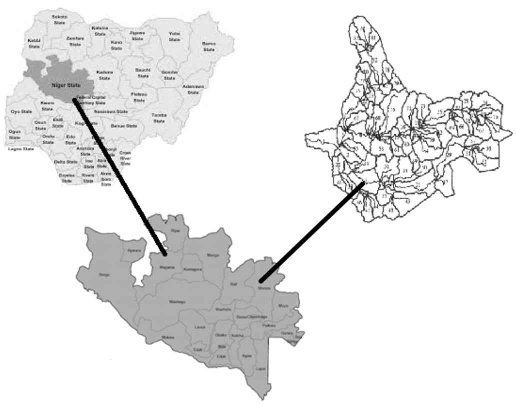

Fig. 1. Map of Nigeria and Niger State showing the location of the study area.

2.2. Model selection and data requirements

The semi-physical model (SWAT) was selected for this study based on its availability and efficacy as reported in many literatures [19-22]. The major components of the model include weather, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, channel and reservoir routing. Transport of sediment, nutrients and pesticides from land areas to water surface is a consequence of weathering that acts on landforms and each of these scenarios were captured in development of SWAT source code. The model operates by dividing the catchment into sub-catchments. Each sub-catchment is connected through a stream channel and further divided into a Hydrologic Response Unit (HRU). The HRU is a unique combination of a soil and vegetation types within the sub-catchment. Detail theoretical documentation of the model can be found in [23].

Model data requirements include the spatial and temporal data. The spatial data are obtained from global databases and local in-situ data gathered from local agencies to form the hybrid data source used to run the model. Observed Streamflow data collected from the hydrology department of Shiroro Hydropower Station was utilized during the calibration and validation processes of the model. The temporal data used for the modelling are daily in nature and cover a period of 30 years (January 1988 to December 2017). Summary of the input data and their sources is presented in Table 1.

Table 1. Model input data for the upper watershed of Shiroro dam.

S/N	Data type	Description	Resolution	Source
1	Topography	Digital Elevation Model	30 m x30 m	Shuttle-Radar Topographical Mission
2	Land Use Map	Land Use Classification	1 km	Global Land Cover Classification, Satellite Raster
3	Soil Map	Soil Types and Texture	10 km	Food and Agricultural Organization (FAO)
4	Weather	Solar radiation, wind speed, Relative humidity, Minimum and Maximum Temperatures, Daily precipitation, Flow data	Daily	Nigerian Meteorological Agency (NIMET), Shiroro Hydropower Station

2.3. Watershed delineation

The Digital Elevation Model of the study area was delineated by launching an "Automatic Watershed Delineation" (AWD) dialogue box from the SWAT model interface by browsing to the file location after selection of appropriate unit (meters) among the various units (sq. km and hectare) or by the number of cells for threshold size. The threshold size of 50 km^2 was outlet was created and the model was run to delineate the watershed into sub-basins. A total of 83 sub-basins were created in the watershed and were subdivided into 101 Hydrologic Response Units (HRU). The watershed delineated is as shown in Figure 2.

2.4. SWAT model setup and run

The SWAT model is a catchment-scale continuous time model that operates on a daily time step with up to monthly/annually output frequency. The major components of the model include weather, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, channel, and reservoir routing. The simulation of hydrologic cycle by SWAT is based on the water balance equation (1):

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

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

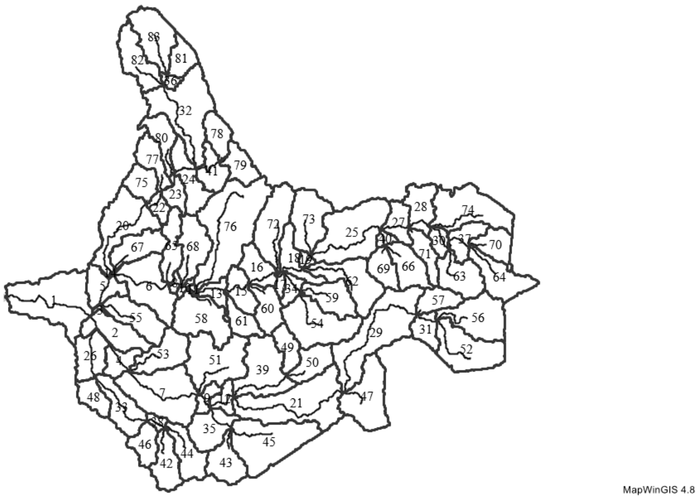

Fig. 2. Shiroro watershed delineated into 83 sub-basins.

Soil erosion rates on cultivated land was modelled in SWAT by using the Universal Soil Loss Equation developed by Wischmeier and Smith in 1978 as reported in [24]. This method is based on statistical analyses of data from 47 locations in 24 states in the Central and Eastern United States. The Universal Soil Loss Equation can be written as in equation (2):

$$A = R * K * L * S * C * P \tag{2}$$

In equation 2, A is the computed soil loss in tons/acre/year, R - rainfall factor, K - the soil-erodibility factor, L - slope-length factor, S - slope-steepness factor, C - cropping-management factor, P - erosion-control practice factor. The Modified USLE, or MUSLE, is given by equation 3 [25]:

$$S = 95[(QP_P)]^{(0.56*K*L*S*C*P)} \tag{3}$$

where S is sediment yield for a single event in tons, Q - total event runoff volume (ft^3), Pp - event peak discharge (ft^3/s), and K, S, C, and P are as defined earlier as USLE parameters.

The model simulation was carried out after data file completion and model data were inputted. The configuration of the model comprised simulation periods setting (start and finish), alongside the choosing of weather-sources within the SWAT database. The SWAT setup has options for simulating surface runoff using the Curve Number or Green and Ampt method. Potential evapotranspiration can be simulated using Priestley-Taylor, Penman-Monteith, or Hargreaves method. In the current research, the runoff curve number method was used in estimating surface runoff from precipitation. The simulation period for this research was between the 1^{st} of January 1988 and 31^{st} December 2017 (30 years). The parameters simulated by SWAT include surface runoff, sediment yield, sediment concentration, and outflow from each of the sub-basins of the watershed.

Performance of the model was assessed by comparing the model ability to match monthly values of observed flow (mean monthly discharge) and simulated flow. In addition to comparing mean values for the calibration and validation periods, model performance was evaluated using statistical parameters such as the Nash-Sutcliffe Efficiency metric (NSE) and Coefficients of Determination (R^2). Figure 3 presented the flowchart of the procedure adopted for the research.

2.5. Visualization of the results

The final stage of the modelling procedure is the visualization of the result. The results shapefiles were extracted from the database of the model. The outputs were visualized statically with the use of Microsoft Excel. For this study, the modelled parameters that were visualized include surface runoff (SURQ), sediment yield (SYLD) sediment concentration (SEDCON), and outflow (FLOW_OUT).

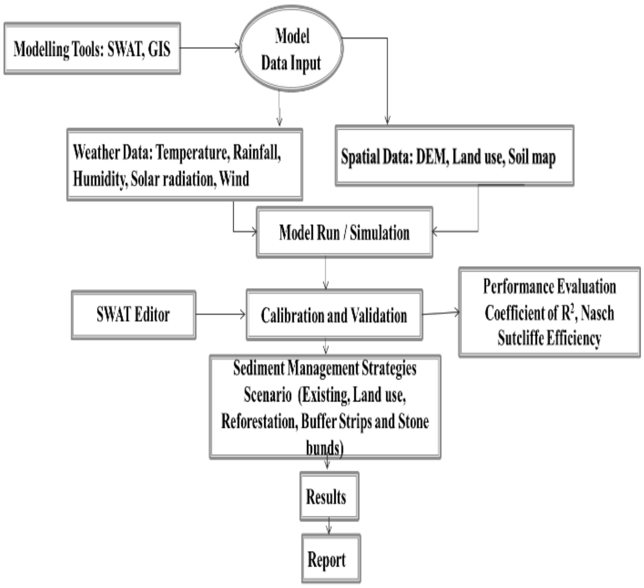

Fig. 3. Flow chart of the methodology adopted in the research.

2.6.1. Scenario A (Existing or Do nothing)

Scenario A was developed to simulate the watershed existing conditions prior the application of BMPs. The calibrated values in the SWAT model were utilized for this simulation without any prior alteration in the model parameters. The results obtained provided a guide in selecting the implementation areas for other scenarios. Also, it provides the basis for comparison with other scenarios on the impact made through the introduction of sediment management interventions.

2.6.2. Scenario B (Reforestation)

Scenario B was developed to simulate the effect of reforestation on sheet erosion within the regions that may have been affected by massive deforestation by the residence of this region. The application of this scenario was captured from the result of "scenario A" which include all sub-basins that fell into extreme erosion prone area. The tree planting strategy within targeted regions provides arable soil cover and thereby reduces overland flow in the area. It was discovered that the implementation of evergreen broad forest planting assists in trapping erosion and sediment particles. This was also supported by [26] that evergreen forest could also be adapted as a control measure for sediment production since it provides a larger cover when compared to other forest types.

2.6.3. Scenario C (Vegetative Filter Strips)

This was simulated through the alternation of the default calibrated value of SWAT parameter FILTERW from zero (0) to a value of 1m in SWAT. This scenario was conducted in agricultural Hydrologic Response Units, which combined different dry land, cropland, and all soil classes. The effects of this Buffer Strip on the erosion process filtered the runoff and trapped sediment along, within the provided plot of land as supported by [28].

2.6.4. Scenario D (Stone Bunds)

The stone bunds laying is a well-known technique to check runoff and erosion control, especially in most Sub-Saharan West Africa [27]. The technique provides logical backup for the collection and transportation of stones along a natural contour of the land. The stone bunds strategies were placed on all HRUs, soil types, and slope classes. This was performed to enable a comparison with other management scenarios. Using appropriate stone bunds strategy where the Curve Number (CN), average slope length (SLSUBBSN), and the USLE support practice factor (USLE P). The values of SLSSUBSN were modified by editing HRU through an input table with adequate spacing in-between successive stone bunds laying at field conditions. USLE P and CN values are usually modified by editing the input table in the SWAT editor before re-running the model. In this scenario, the values of the modified parameters of SLSUBBSN were equal to 10 m for the modified scenario with the calibrated value of 79.6 to 59. This modification was based on the recommendation from SWAT user's manual version for changes to the terraced condition and contoured mapping [29].

3. RESULTS AND DISCUSSION

3.1. Model calibration, validation, and performance evaluation

Performance evaluation of the model was carried out through a comparison of the observed and simulated monthly inflow at the Shiroro gauge station, amongst the validation and calibration periods. The SWAT model was evaluated using four statistical parameters which include percent bias (PBIAS), Observations standard deviation ratio (RSR), Nash–Sutcliffe efficiency (NSE) as well as the coefficient of determination (R^2). The calibration period was from January 2003 to December 2005 and the validation period starts from January 2006 to December 2009. The results showed a good correlation between the predicted and observed flows for both the calibration and validation period as shown in Figures 4 and 5 while Table 2 showed the model performance evaluation.

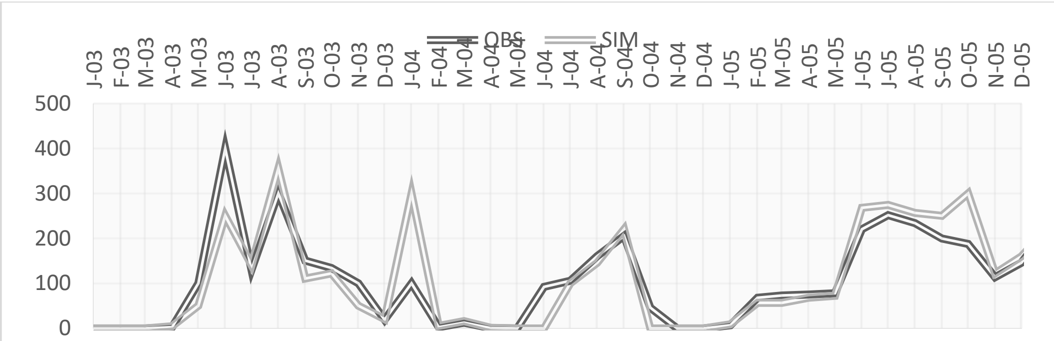

Fig. 4. Monthly observation versus simulated streamflow for the calibration period.

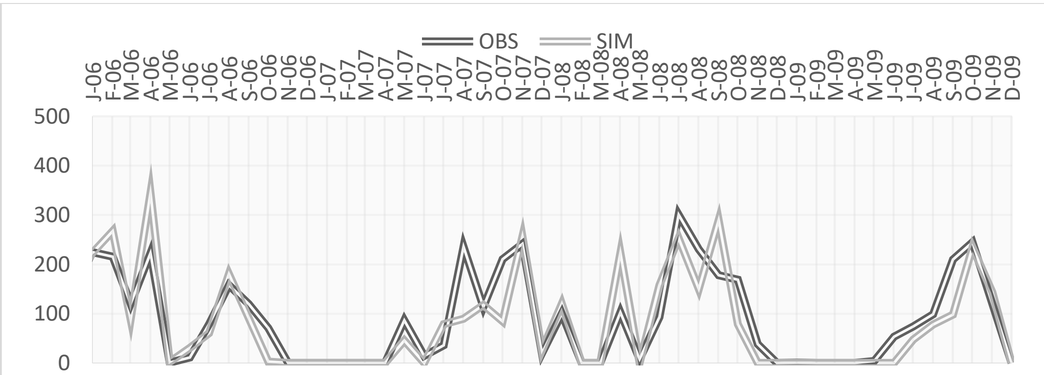

Fig. 5. Monthly observation versus simulated streamflow for the validation period.

Table 2. SWAT Model calibration and validation performance

Stage of model	Evaluated Statistics			
	R^2	NSE	RSR	PBIAS (100 %)
Calibration (2003 - 2005)	0.81	0.66	0.58	25.9
Validation (2006 – 2009)	0.87	0.65	0.59	28.2

The calculated Nash Sutcliffe coefficient (NSE), coefficient of determination (R^2), RMSE-observations standard deviation ratio (RSR), and positive bias (PBIAS) were 0.70, 0.76, 0.68, and 1.9 % respectively for the calibration period and the values for the validation period were 0.66, 0.72, 0.64 and 8.1 % respectively. The NSE values are within the recommended limit of 0.36 to 0.75 while the coefficient of determination, $R^2 > 0.5$ as specified by [30]. These values are also in accordance with [31] which stated that model simulation can be the judged as satisfactory if NSE > 0.5, R^2 >0.5, and RMSE < 0.7 respectively.

3.2. Assessment of sediment yield and sediment concentration

The spatial and temporal variation of predicted sediment yield for each of the sub-basins is presented in Figures 6 and 7 respectively. Thus, this demonstrates that, the average sediment yield predicted in the watershed ranges from 5.4 t/ha to 51 t/ha. The predicted values are in similar trend as in previous studies [32-33]. Low sediment yield in the watershed can be attributed to the topography of the area which is mainly characterized with low and gently slope flatland. The spatial and temporal variation of predicted sediment concentration for each of the sub-basins is shown in Figures 8 and 9 respectively. The highest sediment concentration was forecasted amongst sub-basins 24 and 77 with values of 15.89 and 15.28 kg/ha respectively. Whereas the lowest sediment concentration was predicted in sub-basins 3 and 14 having values of 0.78 and 1.30 kg/ha respectively. The contribution of the release from Shiroro dam upstream of the modelled watershed was estimated at 887.07 kg/ha.

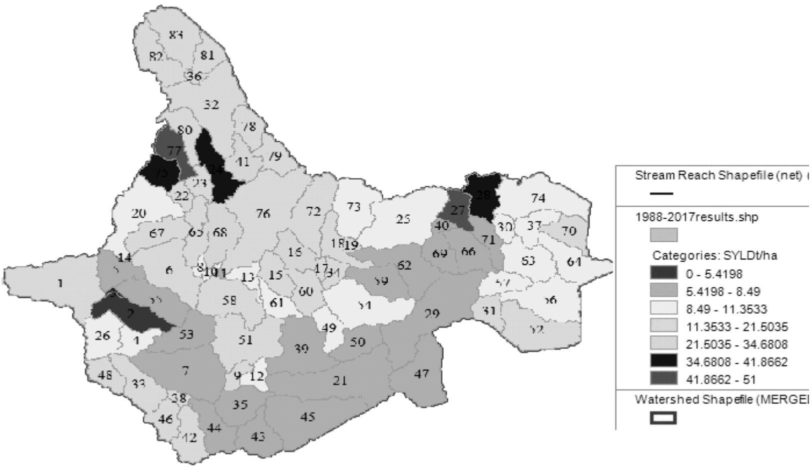

Fig. 6. Spatial variation of predicted sediment yield for each of the sub-basins.

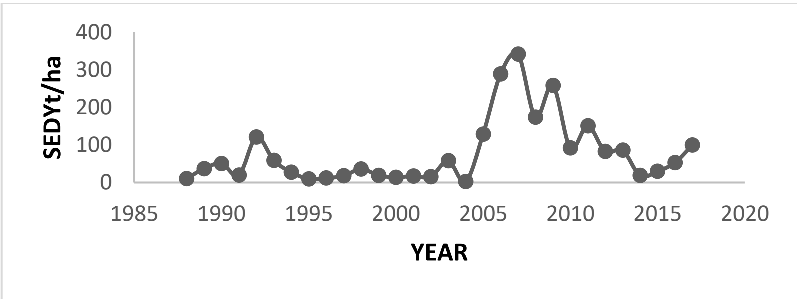

Fig. 7. Temporal variation of predicted sediment yield.

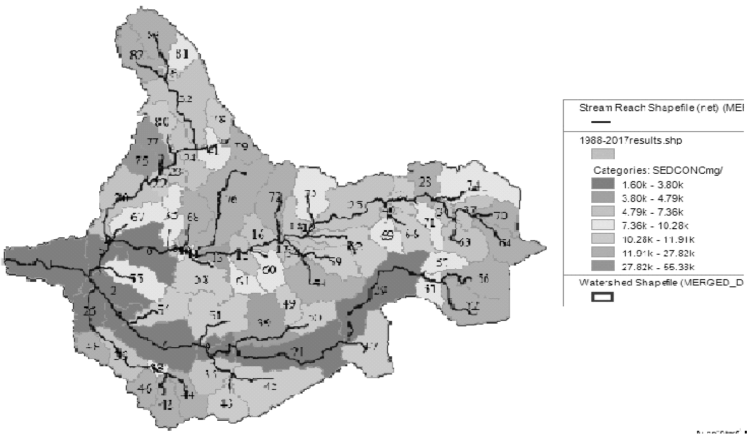

Fig. 8. Spatial variation of predicted sediment concentration for each of the sub-basins.

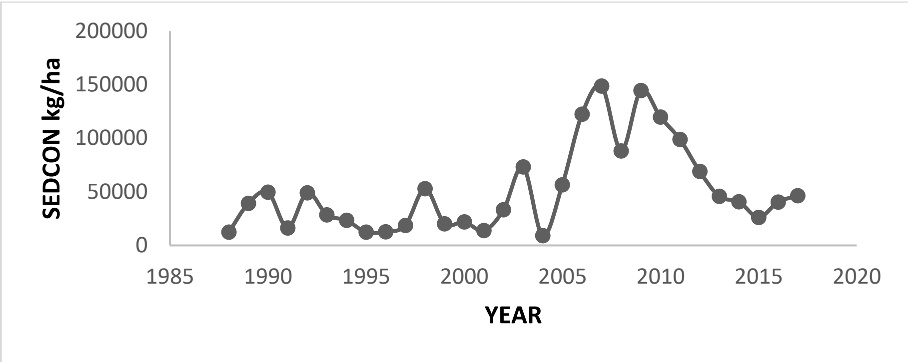

Fig. 9. Temporal variation of predicted sediment concentration.

3.3. Prediction of the impacts of watershed management strategies on reduction of sediment yield and sediment concentration

The results of the simulation indicated that sediment yield and sediment concentration were reduced in all the management scenarios simulated. The highest percentage reduction of sediment yield was experienced during the simulation of vegetative filter strips while the lowest percentage reduction occurred while simulating the effect of stone bunds in the watershed. The highest changes in sediment concentration were predicted in the simulation of filter strips scenario while the lowest changes occurred in the simulation of stone bunds. There was a 27 % reduction in sediment yield and a 34 % reduction in sediment concentration in the simulation of the reforestation scenario. The simulation of the vegetative filter strip scenario was predicted to have a reduction of 39 % in sediment yield and a reduction of 46 % in sediment concentration. In the simulation of the stone bund scenario, there was a reduction of 15 % in sediment yield and a reduction of 30 % in sediment concentration.

The results of the modelling were compared with what was obtainable in the literature. It was discovered that a 39 % reduction in sediment yield using vegetative filter strip is in tandem with the results obtained [25] which reported 44 % sediment yield reduction. Also [9] obtained a 49 % sediment reduction in the modelling of VFS in a similar catchment upstream of kanji dam in Nigeria. However, the results of the modelling of stone bund in sediment reduction at the watershed was quite low when compared with the value obtained in the literature. While [34] obtained up to 68 % sediment yield reduction, a higher percentage of between 72 % and 100 % was obtained by [35] in the application of stone bund for sediment yield reduction. The low sediment reduction value obtained in the watershed may be due to the type of terraces that characterizes the watershed. Tables 3 and 4 show the percentage change in annual sediment yield and sediment concentration in each of the simulated scenarios in Shiroro watershed while Figures 10 and 11 presented bar graphs of results of the management scenarios simulated.

Table 3. The percent changes in annual sediment yield of the watershed.

Sediment Yield (t/ha)	Original land use (Do nothing scenario	Scenario 1 reforestation		Scenario 2 (VFS)		Scenario 3 (stone bunds)	
		Value	%	Value	%	Value	%
Total	33479.99	24462.95	27	27	39	28422.35	15
Annual	1116.00	948.08	27	774.06	39	1039.96	15

Table 4. The percent changes in annual sediment concentration of the watershed.

Sediment Conc. (g/ha)	Original land use (Do nothing scenario	Scenario 1 reforestation		Scenario 2 (VFS)		Scenario 3 (stone bunds)	
		Value	% Reduction	Value	% Reduction	Value	% Reduction
Total	887.07	587.40	34	476.83	46	621.92	30
Annual	29.57	19.48	34	12.31	46	22.70	30

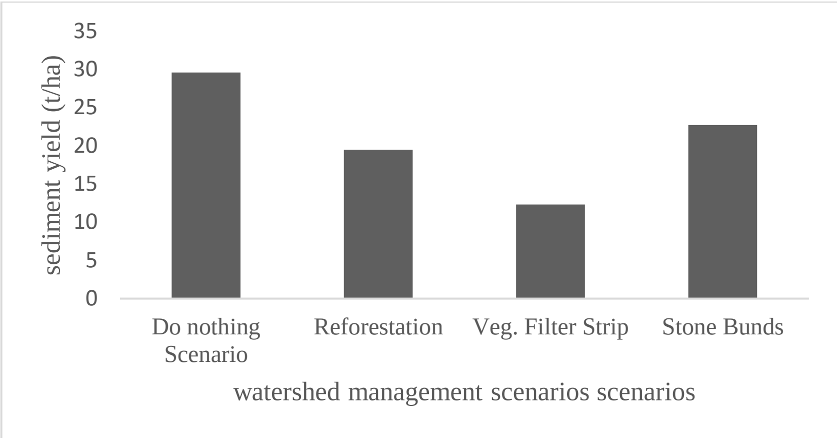

Fig. 10. Effects of management strategies on reduction of sediment yield.

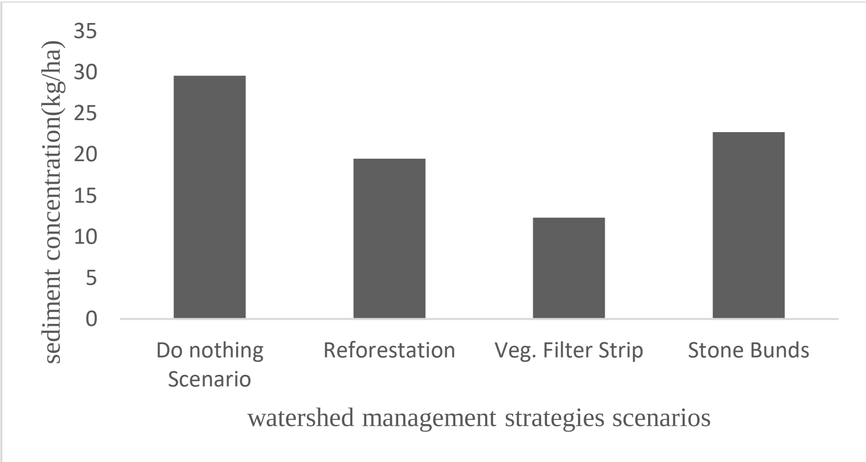

Fig. 11. Effects of management strategies on reduction of sediment concentration.

4. CONCLUSION

In this study, SWAT was applied to predict the effectiveness of watershed management strategies on sediment reduction upstream of Shiroro dam, Nigeria. The model was run daily for a period of 30 years (1988 to 2017) and it was used to simulate the hydrology and predict the sediment yield and sediment concentration in the watershed. In line with the findings of this study, the following inferences can be made:

- Model calibration and validation were successfully carried out with the values of NSE obtained as 0.66 and 0.65 during the calibration and validation period while the coefficient of determination R^2 values are 0.81 and 0.87 respectively.
- Erosion-prone areas were identified and classified as low, moderate, and severe erosion-prone areas.
- Simulation of existing management scenarios predicted the sediment yield of 33379.99 t/ha and sediment concentration of 887.07 kg/ha in the study area.
- Simulation of reforestation shows a reduction of 27 % in sediment yield and a 34 % reduction in sediment concentration while vegetative filter strips scenario reveals a reduction of 39 % in sediment yield and 46 % reduction in sediment concentration.
- The application of stone bunds scenario shows a reduction of 15 % in sediment yield and 30 % changes in sediment concentration.

Hence, as deduced from this research, it can be concluded that the watershed management strategies modelled are effective and sustainable and any of them can be recommended to relevant agencies for sustainable management of sediments within the "upper watershed" of Shiroro dam in Nigeria. However, the recommendation should be based on the cost effectiveness of each of the management scenarios.

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