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Sustainable management of erosion prone areas of upper watershed of Kainji hydropower dam, Nigeria

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ABSTRACT

Reservoir sedimentation has been a major concern to stakeholders around the world in the implementation of sustainable management of hydropower dams. Not only that it reduces the storage capacity of reservoirs, several sediment related problems such as reduction in water quality and acceleration of abrasion of underwater parts can impair the primary purpose of which the reservoir is built. Therefore, sustainable management of watersheds upstream of hydropower dam is necessary to combat the issues of sedimentation and to extend its useful life. In this study, Soil and Water Assessment Tool (SWAT) was interfaced with MapwindowGIS to model and predict sediment yield and concentration into sub-basins of the upper watershed of Kainji hydropower dam in Nigeria which has an area of 30,350 km^2. The model was run daily for 30 years and performance evaluation was carried out using Coefficient of Determination (R^2) and Nash Sutcliffe Efficiency (NSE). Model calibration and validation as well as identification of erosion prone areas were equally achieved. The results showed that average annual sediment yield and concentration were 35.29 t/ha/year and 11,903.7 mg/l respectively. Application of filter strips on critical erosion prone region showed that sediment yield and concentration could be reduced up to 37% and 34% respectively. Also, construction of stone bunds in the watershed showed a reduction of up to 75% and 84% for sediment yield and concentration respectively. The outcome of this study could allow control effort to be focused effectively on an area identified as extreme cases and could also be used by relevant authorities in prioritizing implementation of Best Management Practices (BMPs) for the area.
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1. Introduction

Sedimentation has been a subject of discussion among researchers in recent years due to its negative effect on the available water capacity of dams all over the world. As a result of low velocities of water which characterize the inflow into dams, their ability to trap sediment reduces and eventually leads to silting up of the dams. Several factors such as nature of the materials in the catchment, the slope of the catchment, capacity inflow ratio, trap efficiency (Te) of the reservoir and the method of reservoir operation have been identified as major causes of reservoir sedimentation (Arora and Goel, 1994; Garg and Jothiprakash, 2008; Raghunath, 2006).

For proper sediment management of reservoir to effectively and optimally improve the generating capacities of hydropower stations, reliable estimate of both hydrological parameters and proper identification of erosion prone areas of watershed upstream of hydropower reservoir is very critical. This approach is not only sustainable but also provides a platform for management of the dam at watershed level. Recently, the best method adopted is the application of distributive erosion models for evaluation and assessment of sediment yield in watersheds (Ayana et al., 2012; Abbaspour et al., 2007). The importance of developing hydrologic and sediment management models is very important as it provides a better knowledge of the processes of soil erosion and a means of identifying and prioritizing erosion prone areas of watershed above hydropower dams.

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In recent time, it has been observed that the capacities of the three hydropower dams in Nigeria namely, Jebba, Kainji and Shiroro plants have been greatly reduced due to reservoir sedimentation. Reduction in the capacities of the dams has negatively affects the generating capacities of the hydropower dams. Therefore, proper sediment management strategies need to be in place to arrest the siltation potential of the hydropower dams. This will also be helpful in mapping out strategic plans and measures (both structural and non structural) to reduce the effect of sedimentation caused by erosion processes thereby making enough water to drive the turbines for effective hydropower generation throughout the year.

A good knowledge and characterization of the hydrological processes in the watershed are also necessary to provide necessary information on how to manage the watershed in a sustainable way. This research therefore, focuses on the use of an hydrologic model, SWAT embedded in Geographic Information System environment to predict the sediment yield, identify and prioritise erosion prone areas in the upper watershed of Kainji hydropower dam in Nigeria for sustainable hydropower generation. Also, selected sediment management strategies were modelled to study their potentials in sediment yield reduction. Results obtained in this study can be of great assistance to relevant authorities in supporting decision on how best to manage sediment at watershed level in Nigeria and other sub-Saharan African Countries.

2. Study area location and description

The study area (Fig. 1) is located between Lat 10.73°N Long 3.87°E and Lat 11.56°N Long 6.67°E and is situated upstream of Kainji Dam in Nigeria. It has an area of 30,350 km^2 and perimeter of 567 km. The watershed is attributed with many rivers and tributaries with River Niger being the largest while other tributaries are connected to it at different locations within the watershed. The elevation of the area ranged between 121 m and 671 m above sea level. Soil in the study area is predominantly sandy loam soil and the vegetation within the area is dominated by guinea savannah which is mainly characterised with tall grasses and scattered trees. Human activities in the area include farming, fishing and trading.

3. Methodology

3.1. Model selection and interfacing with geographical information system

SWAT, an acronym for Soil and Water Assessment Tool (Neitsch et al., 2005; Arnold et al., 1995) was selected for this study based on its availability and ability in prediction of different hydrological processes as reported in many studies (e.g., Omani et al., 2007; Birhanu, 2009). The model was interfaced with MapwindowGIS for the modelling of the watershed. This was due to the fact that GIS and remote sensing techniques have been reported to improve the application of hydrological modeling most especially in data management, visualization and interface development (Fadil et al., 2011). Hence, interfacing an hydrological modelling tool with a GIS application provides an ideal interface for the management of modelling data and visualisation of results.

3.2. Model data requirements, collection and processing

Model data requirements include the Digital Elevation Model (DEM), the digital soil and land use maps. All these were sourced from different online databases. The DEM (Fig. 2) is of resolution 90 m × 90 m and was obtained from Shuttle Radar Topographical Mission (SRTM) final version (CGIAR, 2012). The soil map was extracted from harmonised digital soil map of the world which was made available by Food and Agricultural Organization (FAO) of the United Nation (Nachtergade et al., 2009). The land use of the study area was extracted from Global Land Cover Characterization (GLCC) database (GLCC, 2012). The geo-processing of the DEM, land use and soil maps to a format acceptable for the running of the model was achieved using the GIS interface of the model.

Weather data required for the hydrological modelling include daily precipitation, maximum and minimum temperature, humidity, solar radiation and wind. All these were collected for a period of 30 years (January, 1984 – December, 2013) from Nigerian Metrological Agency (NIMET) Lagos, Nigeria. Observed sediment data used for calibration and validation of the model were made available by the National Centre for Hydropower Research and Development (NACHRED), Ilorin based on their previous sediment sampling along the tributaries into Kainji lake. The data were collected bi-monthly and covered a period of 8 months (May to December, 2013).

3.3. SWAT modeling procedure

The estimation of erosion/soil loss and sediment yield for each Hydrologic Response Unit (HRU) was achieved by the application of Universal Soil Loss Equation (USLE) and Modified Universal Soil Loss Equation (MUSLE) respectively already programmed in SWAT. These equations and other parameters for the prediction of sediment yield and concentration have been explained elsewhere (Arnold et al., 2012, 1995).

Modelling in SWAT entails the selection of simulation period and the method for the estimation of surface runoff out of the

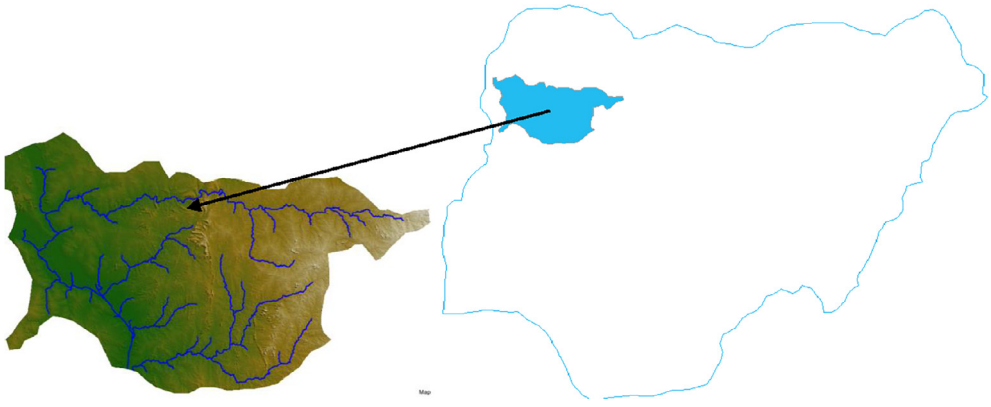


Fig. 1. Map of Nigeria showing the Location of the Watershed.

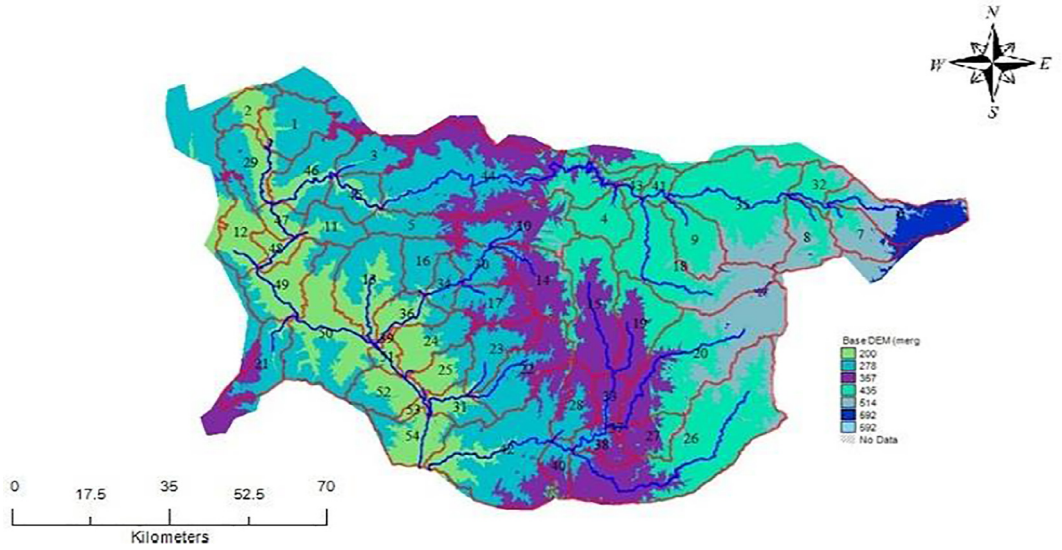


Fig. 2. Digital Elevation Model of the Study Area.

two available methods in SWAT, i.e. Curve Number or Green and Ampt method. The channel water routing may be achieved either by Variable or Muskingum method while the estimation of potential evapo-transpiration (PET) from the watershed can be modelled using Priestley, Penman–Monteith or Hargreaves methods. In this work, modelling was performed using the Runoff Curve Number method for predicting the surface runoff from precipitation. This method was adopted based on its wide applications in many countries because of its perceived stability and its dependence on a single parameter (Ponce and Hawkins, 1996). The estimation of PET was achieved using the Hargreaves method. Its adoption in this research was largely due to its simplified equations which require only two climatic parameters such as the temperature and incident radiation. Alkaeed et al. (2006) also recommended this method in cases where reliable data are lacking. The model was run for 30 hydrological years. (January 01 1984 to 31 December, 2013).

3.4. Sensitivity analysis, model performance evaluation, calibration and validation

Sensitivity Analysis (SA) of the model parameters was not carried out. However, the results of the sensitivity analysis conducted by Adeogun et al. (2014a, 2014b) was adopted in this study. The results showed that curve number (CN2), threshold water depth aquifer (GWQMN), soil evaporation compensation factor (ESCO) and soil available water capacity (SOL_AWC) are the most sensitive parameters for hydrology modeling and were used during the calibration and validation of the model.

SWAT model calibration and validation were achieved using observed sediment data along one of the tributaries into Kainji hydropower dam. The data were collected for a period of 8 months (May–December, 2013). Performance evaluation was carried out by comparing the observed and simulated sediment concentration and its ability to match monthly values of observed data. Statistical parameters such as Nash–Sutcliffe Efficiency (NSE) metric and Coefficients of Determination (R^2) as detailed in Adeogun et al. (2014a, 2014b) were also used to assess the performance of the model.

3.5. Sustainable sediment management procedure

Sediment production in a basin usually varies from one location to another and most of the sediment entering a reservoir downstream is delivered from only a small percentage of the upstream catchment in a fraction of time (Morris and Fan, 1998). Hence, effort should be deployed to identify and characterize both the spatial and timewise nature of sediment in a watershed as this is an important step towards an effective management of sediment in a watershed. This procedure helps in reducing sediment production in the watershed or its deposition in the downstream reservoir.

Minimizing the amount of sediment into reservoirs can be achieved in varieties of ways. One of these is by reducing siltation potential of reservoirs, or by direct removal of sediments that have been impounded by the reservoirs over the years. It could also be achieved through reduction in the sediment yield of watershed above the reservoirs by implementing various sediment management strategies that can impart sediment production at watershed levels. Each of the methods presents various techniques for implementation. Sediment management methods such as reforestation, erection of stone bunds, terracing and implementation of vegetative filter strips have been modeled and the results confirmed that they have capacity of reducing sediment production in the watershed. (Betrie et al., 2011; Adeogun et al., 2016). The procedure used in this work include firstly, the identification of the erosion prone area of the watershed and classification of the areas into four zones, namely, low, moderate, extreme and severe. Then, the effect of two sediment management methods which are implementable in the savannah dominated watershed of the study areas such as construction of stone bunds and planting of vegetative filter strips were studied. The effect of these selected management methods are only considered for the severe and extreme cases and were implemented in the SWAT database as described in Betrie et al. (2011).

Application of filter strip was simulated by modifying the width of filter strip (FILTERW) as embedded in SWAT model parameters with extension (.mgt). The default value of zero in the .mgt file was edited to 1 m as used in previous research (Betrie et al., 2011) to simulate the effect of 1 m filter width on the sediment production in the identified erosion prone areas (severe and extreme cases). Reforestation which has the effect of reducing overland flow in the watershed was modeled by replacing about 25% of the area occupied by savannah into evergreen forest which is considered to have widest coverage compared to other type of forest in the zone.

The implementation of stone bunds as a management intervention entails construction of terraces parallel to each other from broken stone along the contour and it functions as an impediment that reduces the velocity of runoff generated from the watershed.

Another function of the stone bunds is its ability to improve percolation of rainwater into the soil and spread more evenly over the land. The reductions in the overland flow assist in the building-up a layer of fine soil thereby increases the nutrient in the soil (Gupta and Gupta, 2008). SWAT parameters for representing the effect of stone bunds are the average slope length (SLSUBBSN, the Curve Number (CN),) and the USLE support practice factor (USLE P). CN value was modified from calibrated value of 75 to 59 and this was obtained from the SWAT user's manual version 2005 for contoured and terraced condition (Neitsch et al., 2005). The default value of SLSUBBSN was modified to 10 m while a value of 32 was used for USLE P.

4. Results and discussion

4.1. Model calibration and validation

Calibration and validation of model results are presented in Fig. 3a and b. The results showed that there was a good correlation between the observed and simulated sediment concentrations at both calibration and validation stage. This was indicated by the values of NSE and coefficient of R^2 as 0.76 and 0.73 respectively during calibration period and NSE and coefficient of R^2 of 0.70 and 0.88 respectively for the validation period.

4.2. Spatial distribution of sediment yield in the sub-basins of the watershed

Spatial distribution of total sediment yield predicted in each of the 54 sub-basins is as shown in Fig. 4a while an annual mean sediment yield result is shown in Fig. 4b. For total sediment yield into sub-basins of the watershed, highest value of 1147 t/ha was predicted in sub-basin 10 while the lowest value of 146 t/ha was obtained in sub-basin 39. Further analysis of the results showed that 31,757 t/ha was predicted as the total sediment yield in the basin. Annual Mean sediment yield results showed that a minimum value of 4.9 t/ha was predicted in sub-basin 39 and maximum value of 38.2 t/ha predicted for sub-basin 10. The average annual sediment yield was estimated as 35.29 t/ha/year. When the predicted results were compared with literature, annual average value of 35.29 t/ha obtained for the watershed was a bit higher than the value of 24.3 t/ha/year obtained by Gebiaw,et al. (2017). However, the result seemed too low when compared with what was obtained in a study conducted in a watershed upstream of Jebba dam in Nigeria where yearly sediment production was predicted as 255.8 t/ha/year (Adeogun et al., 2015).

4.3. Predicted sediment concentration in the river reaches

The model was used to predict the sediment concentration (mg/l) of each of the tributaries in the watershed. Simulation results as predicted are as shown in Fig. 5a. The results showed that sediment concentrations are highest in river reaches within sub-basins 21, 27 and 10 with values of 23,589.9, 13,184.7 and 12,582.4 mg/l respectively. The lowest sediment concentration was predicted in sub-basin 46 with a value of 1,338.9 mg/l while average value of 11,903.7 mg/l was predicted for the watershed throughout the period of simulation. Based on the spatial distribution of sediment concentration in the basin, it was discovered that sediments are highly concentrated at the sub-basins in the lower part of the watershed when compared with those situated in the upper region. This may be due to the effect of eroded materials which are likely to contribute to the concentration of the runoff towards the downward region of the watershed.

4.4. Identification and prioritization of erosion prone area of the watershed

In this study, soil erosion prone areas of the watershed were identified for the existing condition using the annual sediment yield of each of the sub-basins. The erosion classes are categorized into four levels. Sub-basins with sediment yield between 0and 15 t/ha/year are classified as low erosion prone area. Those having values between 15 and 20 t/ha/year are categorized as moderate erosion zone and erosion classes of 20–30 t/ha/year as severe and 30–40 t/ha/year as extreme zone. Classification of erosion zones was based on the potential soil erosion risk and severity of sub-basins of the watershed. It was also done specifically for the purpose of sediment management of the basin and was in line with procedure as reported in Kamuju (2016) and Betrie et al. (2011). Simulation results showed that 11 sub-basins are in low erosion prone category, 23 sub-basins in moderate zone, 12 sub-basins in

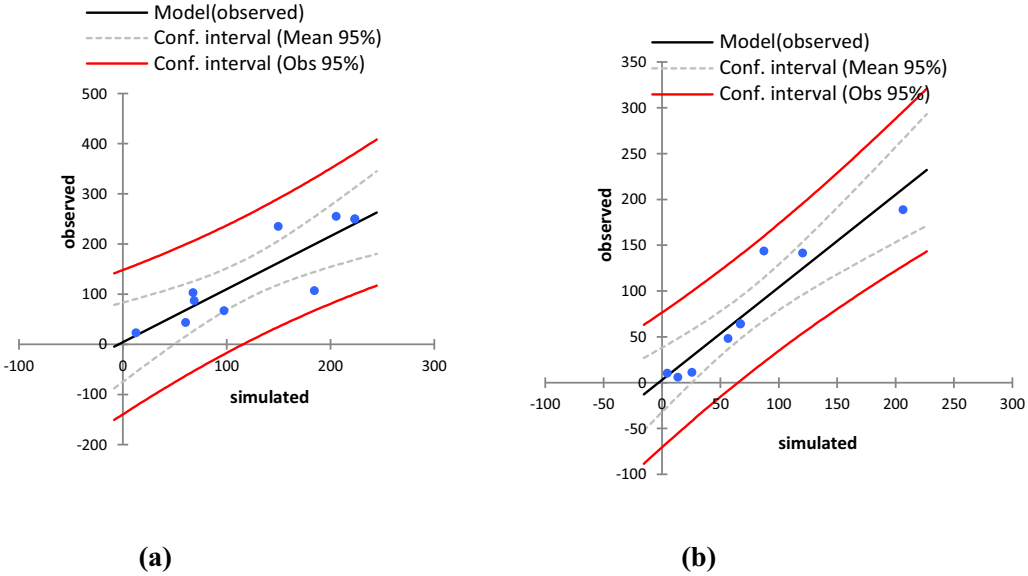


Fig. 3. A plot of simulated against the observed sediment concentrations during (a) calibration period (b) validation period.

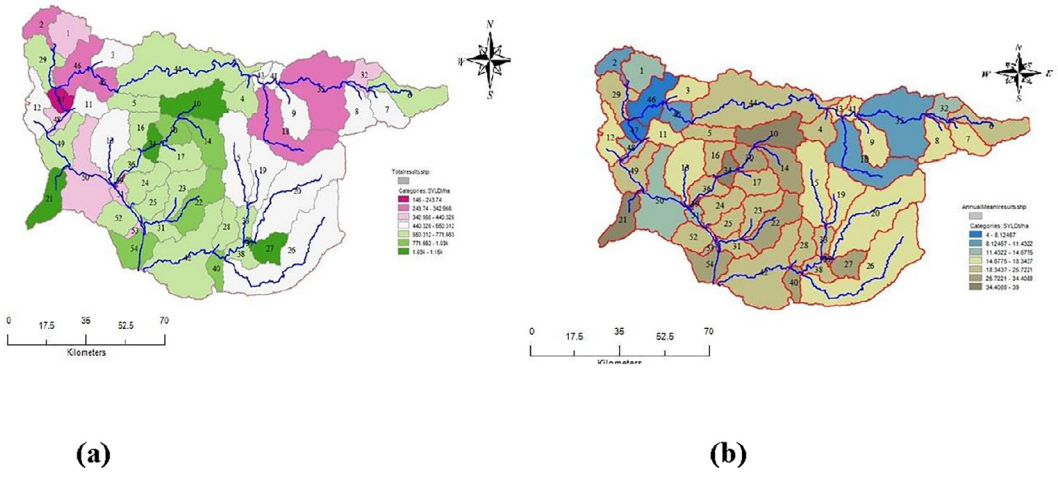


Fig. 4. Spatial variation of (a) total sediment yield (b) annual mean sediment yield in the watershed.

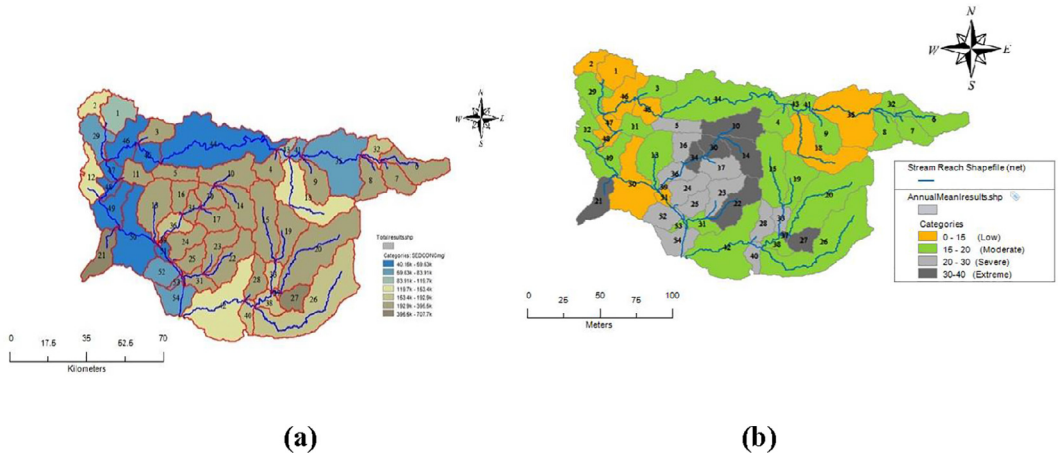


Fig. 5. (a) Total Sediment Concentration (b) Relative Erosion Prone Areas of the Watershed.

severe erosion category while 8 sub-basins are in the extreme erosion category. Fig. 5b shows the relative erosion prone areas of the watershed using calibrated SWAT Model results. It could be inferred from the results that a combine total land area of 7779.3 km^2 representing about 25% of the watershed are in the severe and extreme erosion zone category. This area produced 51.7% of the total sediment yield of the watershed. This result is very close to the one obtained in a similar watershed upstream of Jebba dam in Nigeria where the combination of the severe and extreme erosion areas has about 51% of the total average annual sediment yield of the catchment area (Adeogun et al., 2016). This categorization of erosion prone area could allow control effort to be focused effectively in area identified as extreme and severe cases. The results are also an indication of the level of variation of erosion within the catchment which can be employed in prioritizing Best Management Practices (BMPs) implementation strategy.

4.5. Managing sediment production in the watershed

4.5.1. Application of filter strip

For existing condition in severe erosion prone area, total average sediment yield in 12 sub-basins making up the area was estimated as 278.7 t/ha with the highest sediment production of 28.2 t/ha in sub-basin 54. The total annual average sediment concentration (mg/l) in the erosion prone area was simulated as 94,107.3 mg/l. With the introduction of 1 m width of filter strip across the sub-basins, total sediment yield was obtained as 176.4 t/ha. This value is about 36.7% reduction in the yield. Sediment concentration also reduced to 63,941.5 mg/l which translate into a reduction of 32.1% when compared with the existing condition in the sub-basin. Results from existing condition of the extreme erosion prone area revealed that 269 t/ha of sediment was produced from 8 affected sub-basins, with the highest contribution from sub-basin 10 (38.2 t/ha). Sediment concentration of this area was simulated to be 94,161.8 mg/l. Introduction of filter strips reduced the sediment yield and concentration to 170.3 t/ha and 61,866.71 mg/l respectively. These results showed that a reduction percentage of 37% was achieved in sediment production while 34.3% was obtained for sediment concentration in the reaches in the watershed. The results obtained compared well with what is obtainable in the literature. For example, Betrie et al. (2011) reported 44% sediment yield reduction through the application of filter strips in a watershed while a lower percentage (20%) was reported by Verstraeten et al. (2006). Also, Adeogun et al. (2016) reported 49% sediment reduction in a similar watershed modeled in Nigeria and this was very close to the result obtained in this study.

4.5.2. Construction of stone bunds

Simulation of the effect of introducing stone bunds at the most critical erosion prone areas of the watershed was equally studied.

A reduction of sediment yield to an annual mean value of 29.2 t/ha and sediment concentration to 23,680.77 mg/l were obtained in sub-basin located within extreme prone area. The results showed that a reduction of up to 89.2% can be obtained in the sediment yield while sediment concentration in the reach can be reduced up to a value of 84.1%. For sub-basins in severe erosion prone areas, total average annual sediment yield was reduced to 45 t/ha while the sediment concentration value for the same area was estimated as 23,680.8 mg/l. This showed that a reduction of about 84% was obtained in the introduction of stone bunds while the sediment concentration reduced by about 75% when compared with the existing scenario. This outcome is in tandem with what have been previously reported in the literature. For example, Gebremichael et al. (2005) obtained a sediment yield reduction of 68% while Herweg and Ludi (1999) reported values between 72% and 100%. The outcome of the research showed that application of stone bund for sediment management in a basin can be a better alternative as it showed a greater sediment yield reduction compared with filter strip application.

5. Conclusions

Based on the outcome of this study, the following can be concluded:

1. Model performance is satisfactory with values of coefficient of determination, R^2 and NSE lying within acceptable range with minimum values of 0.70 and 0.74 at both calibration and validation stage respectively.
2. Total sediment yield in the watershed was estimated at 31,757 t/ha while average annual sediment yield was estimated at 35.29 t/ha/year. Average annual sediment concentration in the river reaches within the basin was predicted as 11903.7 mg/l.
3. Identification of erosion prone area of the watershed showed that 11 sub-basins are in low erosion prone category, 23 sub-basins in moderate zone, 12 sub-basins in severe erosion category while 8 sub-basins are in the extreme erosion category.
4. The result of sediment management methods implemented in the watershed viz, filter strips and stone bunds showed that both methods are capable of reducing the sediment production in the watershed if effectively implemented. Application of filter strip on the erosion prone region showed that sediment yield and concentration could be reduced up to 37% and 34% respectively. On the other hand, implementation of stone bund can reduce sediment yield and concentrations in the watershed up to about 89% and 84% respectively.

It is to be noted that cost analysis of the sediment management methods discussed in this study is an important factor that would supplement the current results. Cost analysis will provide very good measure as to which technique to choose in the management of sediment production of the watershed. However, this part will be dealt with in future study. Overall, the outcome of this study could be of use by the Kainji dam management and relevant authorities in Nigeria and other countries in the sub-Sahara region in Africa interested in the sustainable water and sediment management at watershed scale.

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