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Cost effectiveness of sediment management strategies for mitigation of sedimentation at Jebba Hydropower reservoir, Nigeria



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Abstract In this study, a calibrated hydrologic model, Soil and Water Assessment Tool (SWAT) interfaced with Geographical Information System (GIS) tool was used to study the effect of different sediment management methods in a watershed (12,992 km²) upstream of Jebba Lake, Nigeria. Sediment management strategies considered are (i) reforestation of the watershed, (ii) application of vegetative filter strip (VFS) and (iii) construction of stone bunds. Cost analysis of implementing the selected erosion control measures within the watershed was also carried out to compare the cost effectiveness of each of the management strategies. The results showed that application of VFS, reforestation, and stone bunds to critical zones of the watershed reduced the sediment yield up to 65.6%, 63.4% and 12% respectively while the financial analysis of implementing reforestation, VFS and stone bunds revealed 84.9%, 73.3% and 70.5% reduction respectively in the costs to be incurred if sediments are allowed to accumulate in the dam. From this analysis, it can be concluded that the sediment management scenarios considered in this study are cost effective and sustainable when compared with the costs incurred in tackling the effect due to reservoir sedimentation. Overall, the study showed that hydrological models such as SWAT can be used to study strategies for water resource management. In addition, it can provide policy makers the decision support tools to evaluate the cost and benefits of adopting Best Management Practices (BMPs) particularly for sediment control in erosion prone watersheds.

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1. Introduction

Reservoir sedimentation has been a major problem confronting hydropower dams in many parts of the world. Not only that excessive sediment accumulation in the hydropower reservoirs may be responsible for loss in storage capacity of the dam, it may also lead to many negative effects both within and downstream of reservoirs which may include high turbidity, loss of flood-carrying capacity and reduction in water quality. In Nigeria, the current level of silt deposition in the three (3) hydropower reservoirs (i.e. Jebba, Kainji and Shiroro) might have reached a critical situation and has already taken toll on the generating capacities of the hydropower stations. An urgent rehabilitation of the dams is therefore, needed to enhance the economic and viable operating lives of the hydroelectric plants. Also, a proper sediment management and control strategies are required at the watersheds located upstream of the reservoirs to reduce the erosion processes and other activities that may lead to sediment production. In recent times, application of modelling tools interfaced with GIS has been frequently used in this area of research as it provides the platform to streamline GIS processes tailored towards hydrological modelling. The importance of modelling sediment management scenarios cannot be overemphasized as it provides better understanding of soil erosion processes and a guide towards identifying erosion prone areas for the purpose of proposing Best Management Practices (BMPs) to reduce sediment production in the areas of interest.

One of the most widely used models to simulate various hydrological and sediment parameters in a watershed is the Soil and Water Assessment Tool (Neitsch et al., 2011). 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 un-gauged basins (Arnold et al., 1995). The SWAT model is a catchment-scale continuous time model that operates on a daily time step with up to monthly/annual output frequency. SWAT has also been used to study various BMPs for the purpose of sediment reduction in a watershed and to curb soil erosion and sediment transport.

The application of modelling tools to study different scenarios of sediment management and land use change have been achieved by various researchers. However, the scenarios modelled and the modelling tools employed differ from one researcher to the other. One of the works in the literature is the sediment management of Upper Blue Nile basin which was modelled at a daily time step by Betrie et al. (2011). In their study, SWAT was used to assess the impact of different catchment management interventions on soil erosion and ultimately on sediment yield. It was discovered that the introduction of buffer strips, stone bund and reforestation reduced the sediment yield at the outlet of Upper Blue Nile by 44%, 41% and 11%, respectively. While the reduction of sediment yield at 15 sub-basin outlets varied from 29% to 68% by the buffer strip, 9% to 69% by stone-bund and 46% to 77% by reforestation.

Also, Ogbu and Mbajorgu (2013) applied Soil and Water Assessment Tool (SWAT) on a watershed (3765 km²) in south-eastern Nigeria, to predict streamflow and sediment discharge from the Ebonyi River Watershed. Land use change was simulated using six land-use change scenarios, representing combinations of decreasing grassland (93.76–0.09%) and

increasing agricultural land (0.09–93.76%). Results showed that expansion of agricultural land to about 19% of the watershed area increased average daily streamflow and sediment discharge to about 29% and 44%, respectively. Also, about 72% and 99% increase was obtained for streamflow and sediment discharge, respectively, when agricultural land was expanded to 94% of the watershed area.

In this work, an attempt is made to test the applicability and suitability of SWAT to study the effect of selected sediment management methods on the reduction of sediment into Jebba dam in Nigeria. Cost analysis of implementing each of the sediment management strategies was carried out.

2. Description of study area

The study area is the watershed at the upstream of Jebba Lake located in central area of Nigeria between Latitude 8.99° and 10.31° N and Longitude 4.79° and 5.01° E. It has a perimeter of about 567 km and an estimated area of 1,299,156 ha (12,992 km²). The study area forms a subbasin in the existing lower Niger River basin situated in Hydrological Zone II of Nigeria which consists of 23 principal subbasins and with an estimated area of 15.6 million ha (NWP, 2004). Fig. 1 shows the location of the study area as well as the stream network within the map of Nigeria.

The major river that traverses through the watershed is River Niger. Some of the tributaries to this River within the watershed are Rivers Awun, Moshi, Eku, Kotangora and Wuruma. The watershed has a range of elevation between 114 m and 403 m above sea level. The average monthly discharge at Jebba station situated at the outlet of the watershed is 1053 m³/s for the period of 1984–2008, with a minimum value of 378 m³/s in February, 1984 and a maximum value of 3636 m³/s in October, 1998. The soil in the study area is predominantly sandy loam soil. Vegetation within the area is guinea savannah which is mainly characterised with tall grasses and scattered trees. Main activities for sustainability in the area are farming, fishing, hunting, trading and weaving. The selection of the area to test the applicability of SWAT is based on the availability of input data at the hydrological stations established by Kainji and Jebba hydroelectric power stations and also at the Nigerian Meteorological Agency (NIMET) located at Ilorin, Kwara State.

3. Methodology

3.1. Modelling of sediment yield with SWAT

The Soil and Water Assessment Tool (SWAT) used in this study was interfaced with Mapwindow-GIS to simulate the hydrology, predict the sediment yield and identify erosion prone areas of a watershed (12,992 km²) upstream of Jebba Reservoir in Nigeria. SWAT was calibrated and validated using measured flow data from 1990 to 1995. Sediment samples collected from three locations within the watershed from May to December, 2013 were also analysed and used to spatially calibrate and validate the model. The model was statistically evaluated using coefficient of determination, R^2 and Nash-Sutcliffe Efficiency, NSE. The model showed a good agreement between the observed and simulated values for both calibration and validation period as indicated by acceptable

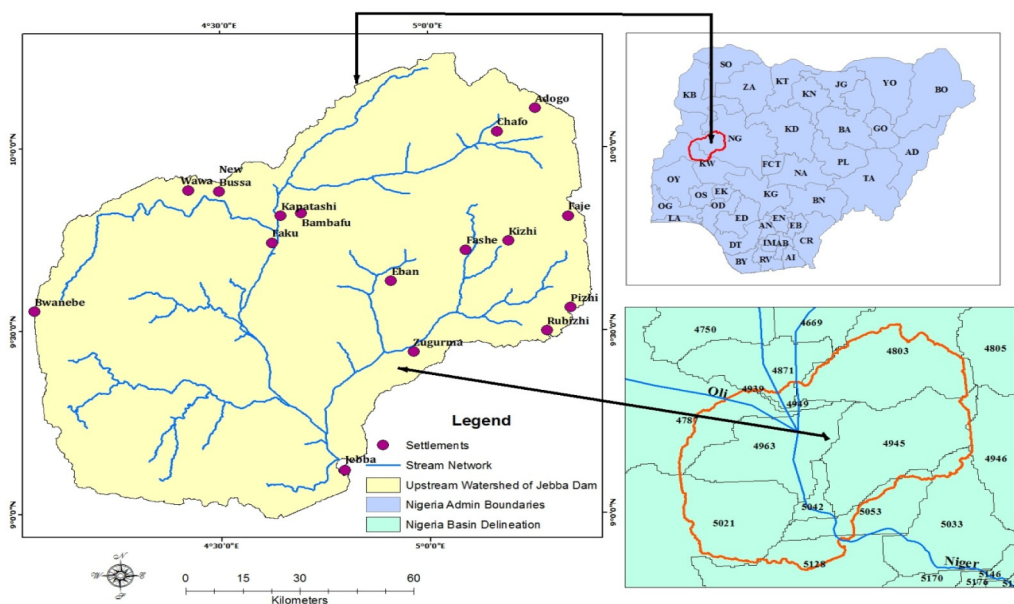


Figure 1 Map of Nigeria showing the location, major rivers, tributaries and towns within the study area.

values of $NSE = 0.82$ and $R^2 = 0.60$ for calibration period and $NSE = 0.65$ and R^2 value of 0.52 in the validation period at one of the observed locations. Details of the modelling procedure and evaluation could be found in elsewhere. (Adeogun et al., 2015).

3.2. Development of sediment management scenarios

The selection of appropriate sediment management measures used in this study was based on similar researches in the literature most especially, those involving catchments in Africa (Betrie et al., 2011; Hunink et al., 2013). Also, the watershed was visited to have an onsite assessment of the type of vegetation, land use and soil of the area. Selected BMPs considered in this work are (a) vegetative filter strips (b) reforestation and (c) stone bunds. According to Betrie et al. (2011), each of the BMPs has a different effect on flow and sediment with distinct representation of parameters. Vegetative filter strips are narrow buffer strips (about 1 m wide) that have grass or other permanent vegetation to help trap runoff, sediment and nutrient and reduce slope length, sheet and rill erosion in a contoured field. The SWAT parameter used to simulate the effect of buffer strips is (FILTERW) and this could be found in the SWAT editor interface. Reforestation as a management method was simulated by introducing land use change in the most erosion-prone area of the watershed while the application of stone bunds was studied by modifying parameters such as the curve number, slope length and the Universal Soil Loss Equation (USLE) support practice factor in the SWAT database. The BMPs were represented in SWAT by modifying certain parameters to reflect the effect which a particular practice has on the processes simulated (Bracmort et al., 2006). However, the type of BMPs and their parameter value selection is site specific and ought to reflect the physical realities and conditions in the study area.

Four (4) sediment management scenarios were used to study the selected erosion control measures in the watershed.

In Scenario A, the existing conditions of the watershed were examined before the implementation of BMPs. The calibrated values of SWAT model were used in this simulation without altering any modelling parameters.

Scenario B involved the simulation of the impact of reforestation on erosion processes in the areas that has been affected through massive deforestation by inhabitants of the area for years. Also, the implementation area of this scenario captured the severe and extreme erosion prone areas of the watershed. In this scenario, it was opined that planting of trees at the targeted intervention area will provide good soil cover and thereby reduce overland flow at the area. The implementation area was supplanted with evergreen broad forest. The selection of this type of vegetation in SWAT database is based on the fact that it provides cover against rainfall throughout the year. It is also reported that evergreen forest could be easily adapted since it has larger area coverage as compared to other forest type (Betrie et al., 2011). Scenario C was used to assess the effect of vegetative filter Strip on erosion process of the watershed. The VFS has the effect of filtering the runoff and trapping the sediment in a given plot of land (Bracmort et al., 2006). This was simulated by changing the default calibrated value of SWAT parameter FILTERW from zero (0) to a value of 1 m in SWAT to imitate the introduction of filter strip of 1 m in the watershed. The scenario was implemented in agricultural Hydrological Response Units (HRUs) that are of the combination, of dry land, crop land and all soil classes. In Scenario D, stone bunds were placed on all HRUs, soil types and slope classes to allow comparison with other management scenarios in terms of effectiveness in sediment reduction. Appropriate parameters for representing the effect of stone bunds are the Curve Number (CN), average slope length (SLSUBSN) and the USLE support practice factor (USLE P). The value of SLSUBSN was modified by editing the HRU (.hru) input table and the value represents the spacing between successive stone bunds at field condition. USLE P and CN values were modified by editing Management (.mgt)

input table in the SWAT editor before model re-run. In this scenario, SLSUBBSN is modified to 10 m for the slope classes USLE P is adjusted from a calibrated value of 1 to 0.32. These values were adopted from [Betrie et al. \(2011\)](#) in a similar study. However, CN value was modified from a calibrated value of 79.6 to 59. This value was obtained from the SWAT user's manual version 2005 for contoured and terraced condition ([Neitsch et al., 2005](#)).

3.3. Cost Analysis of sediment management scenarios

In this study, cost analysis of selected management scenarios was divided into two categories. These are (i) the cost of implementing each of the sediment management strategies (reforestation, stone bunds and VFS) in reducing sediment loadings at the watershed and (ii) the cost implication of allowing sediments to be transported into the dam (i.e. existing condition). The analysis was based on sediment yield produced by 1 hectare of the watershed for a period of 15 years, that is, from 1984 to 1998. The range of years was selected based on the availability of certain data such as the running hours of the hydropower turbines which was used in estimating cost associated with allowing sediment into the dam. Annual sediment yield in the watershed was estimated as 255.8 t/ha/year equivalent to 3837 t/ha for 15 years under consideration ([Adeogun et al., 2015](#)). Using the estimated value of trap efficiency of Jebba Reservoir i.e. 86.5% ([Adeogun, 2015](#)), the total sediment trapped for 15 years was estimated as 3,319 t/ha. The pilot area for the study includes all the subbasins in the severe and extreme erosion zones of the watershed. This consists of thirty-three (33) subbasins in the severe zone and only one (1) subbasin in the extreme zone. This area was estimated as 6049 ha which represents about 47% of the watershed. Cost analysis was carried out using the Nigerian currency, Naira (1\$ = ₦180 at the period of this analysis).

3.3.1. Reforestation

The cost analysis involved estimating the amount to be incurred in the establishment of tree plantation in one (1) hectare of land for a period of 15 years. This include processes such as site identification and inspection, land demarcation, soil survey, land clearing, land preparation, acquisition of seedling, transportation of the seedlings, planting of cover crops, and management (supervision and security) of the project ([Oloyede, 2008](#); [Agbeja, 2004](#)). Cost per ton of sediment abated was estimated by dividing the total cost of implementing the management scenario by the total volume of sediment produced (tons) from the watershed.

3.3.2. Vegetative filter strips

This involves the cost of implementing vegetative filter strips on an hectare of land which covers major components such as land preparation, mowing, purchase of seedlings, cost of equipment, fertilizer application and periodic maintenance operation ([Leeds et al., 2014](#)). The cost of establishing VFS in one (1) hectare of the watershed for a period of 15 years was considered. The cost per ton of sediment abated was estimated by dividing the total cost of planting VFS by the total volume of sediment produced.

3.3.3. Stone bunds

Stone bunding in a watershed entails the construction of horizontal lines of stone pitched contour bunds across the sloping land surface. This sediment management strategy is practiced to intercept the runoff flowing down the slope of an embankment with either open or closed ends to conserve moisture as well as to reduce erosion. The cost of constructing stone bunds in one (1) hectare of the watershed for a period of 15 years was evaluated. The cost per ton of sediment abated was estimated by dividing the total cost of construction of stone bunds by the total volume of sediment produced.

3.3.4. Cost analysis of sediment accumulation in Jebba Reservoir

Sediments that are dislodged and transported from the watershed are usually deposited in the downstream reservoir as sediment. However, the amount that enters the reservoir to silt it up depends on the trap efficiency of the reservoir ([Morris and Fan, 1998](#)). The cost implication of allowing sediment into Jebba Hydropower dam can be grouped into three categories. These are (a) cost related to direct removal of sediment (b) cost associated with the effect of sediment on hydropower turbine and (c) cost related to loss of hydropower production due to reduced storage capacity.

3.3.4.1. Cost of direct sediment removal from Jebba dam. In this analysis, the total sediment trapped in the reservoir for a period of 15 years (1984–1998) was used. Sediment removal technique considered in this analysis is mechanical dredging which is commonly used for direct sediment removal from reservoirs in Nigeria. Sediment removal operations are charged on volume basis (e.g. cubic yard, cubic metre). The total sediment trapped in the reservoir for the period of 15 years under consideration was estimated as 2731.7 yd³ which is equivalent to 2087 m³ ([Adeogun, 2015](#)). In order to obtain the cost of dredging operation at Jebba Reservoir, volume of sediment trapped was multiplied by the average cost of sediment removal by mechanical dredging as obtained from [NIWA \(2012\)](#).

3.3.4.2. Cost associated with damages to hydropower turbines. Damages to hydropower turbine are caused by many factors such as cavitation erosion, water quality, erosion caused by sediment laden water and also if there is any manufacturer defects on the turbine before installation. All these factors work together in reducing the efficiency and the useful life of hydro turbine over time. Data used for analysis include the cost of Kaplan (Fixed Blade) Turbine, salvage value and useful life of Kaplan turbine. The present salvage value of the turbine was estimated using the straight line depreciation method. Analysis of energy generation at Jebba Hydropower plc for 15 years (1984–1998) period revealed that the average number of turbines in use during the period was three (3). The total cost associated with damages to hydropower turbines was calculated by deducting the present salvage value of turbines from the initial cost. The cost was then distributed among the factors responsible for damages to turbine using the ratio method of Weighted Matrix Delivery Decision Approach ([NRC, 2009](#)).

3.3.4.3. Cost related to loss in hydropower production. The installed capacity at Jebba Hydropower reservoir is 578.4 mW (6 turbines each with capacity 96.4 MW). The difference between installed and generated capacity (MW) at

the Jebba Hydropower dam was calculated between 1984 and 1998 (15 years duration). This loss was distributed among major factors responsible for the loss in hydropower production using the Weighted Matrix Delivery Decision Approach. The identified factors are mechanical, electrical, civil, maintenance, hydrological, reservoir sedimentation and others. Then, energy loss due to reservoir sedimentation was converted to equivalent cost using the current energy rate in Nigeria as obtained from IBEDC (2014).

4. Results and discussion

4.1. Sediment management scenarios

4.1.1. Scenario A (existing condition)

Erosion prone areas of the watershed were identified in this scenario using average annual sediment yield from each of the subbasins. The erosion classes are categorised into four levels partly adopting the classification as used in [Betrie et al. \(2011\)](#) and information retrieved during reconnaissance survey of the watershed. These are 0–20 t/ha/year as low, 21–30 t/ha/year as moderate, 31–60 t/ha/year as severe and above 60 t/ha/year as extreme. [Fig. 2](#) shows the delineation of various soil erosion zones in the catchment. Simulation results showed that 5 subbasins are in the category of low erosion prone areas, 38 subbasins in moderate zone, 33 subbasins in severe erosion area while only one subbasin (subbasin 75) is in the extreme erosion category. It was also noticed that the combination of the severe and extreme erosion areas, which has about 51% of the total average annual sediment yield of the catchment area are predominantly in the basins along River Niger which is the largest river flowing through the catchment area. The results showed the variation of erosion within the catchment which can be employed in prioritising BMPs implementation strategy.

4.1.2. Scenario B (reforestation)

The impact of reforestation in the area showed a reduction in the total sediment yield of the area by 1093.92 t/ha. This is about 46.4% of the total sediment yield of the area. The reforestation scenario has also changed the configuration of the erosion zones from what was obtainable in the existing condition scenario. Thirty Seven (37) subbasins are now in the low (0–20 t/ha) category while 38 subbasins are now in the moderate zone (21–30 t/ha) and 2 subbasins in the severe (31–60 t/ha) zone. There was no subbasin in other category (extreme). Further investigation on the impact of reforestation in reducing the sediment yield in the area was conducted by implementing reforestation at the 25 subbasins in the moderate zones. This increased the total implementation area to about 12,602 ha representing 96.9% of the watershed. It was noticed that the sediment yield of the area reduced by additional 400 t/ha. This increased the percentage sediment reduction of the area to 63.7% while the erosion zone of the area is made up of only the low (0–20) category. [Fig. 3](#) depicts the erosion classifications after the introduction of reforestation at the extreme and severe erosion zone of the watershed area.

4.1.3. Scenario C (vegetative filter strip)

The introduction of filter strip of width 1 m in the implementation area brought a significant reduction in sediment yield of the area. Total sediment yield was reduced by 1202.33 t/ha at both the subbasins and the basin level in the watershed. This represents about 49% total sediment load reduction. Also, it was discovered that 37 subbasins are now in the low (0–20 t/ha) zone and the remaining 40 subbasins in the moderate (21–30 t/ha) zone. The impact of the vegetative filter strip in reducing the sediment yield at the watershed was further investigated with the inclusion of moderate zone of the erosion classification. The total implementation area increased to 12,602 ha representing 96.9% of the watershed. Modelling

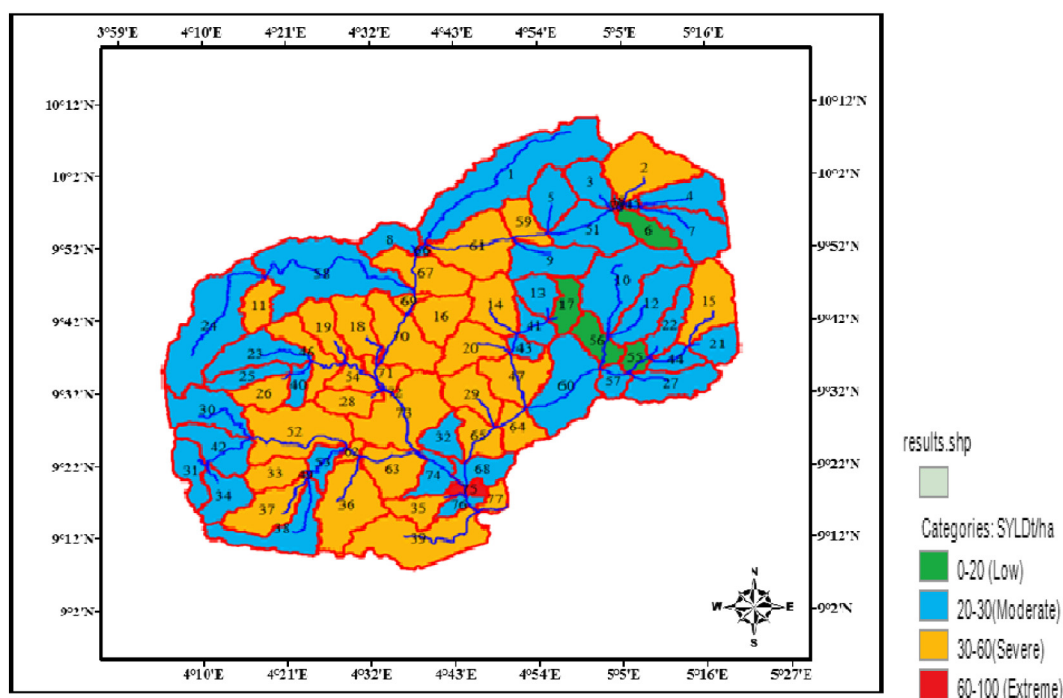


Figure 2 Relative erosion prone areas of the existing watershed scenario.

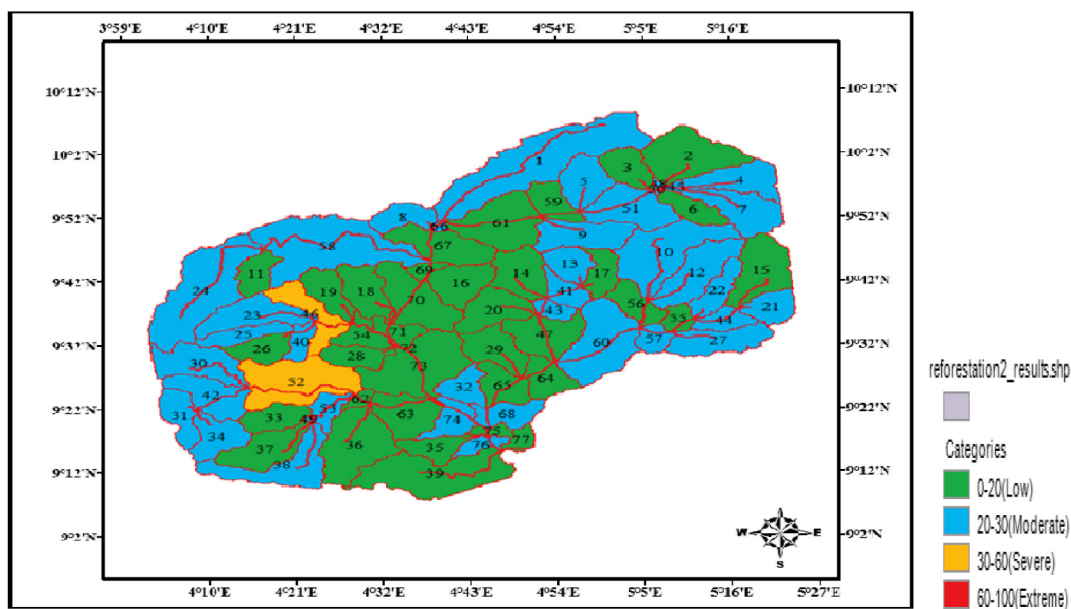


Figure 3 Erosion prone area after introduction of reforestation at selected locations in the study area.

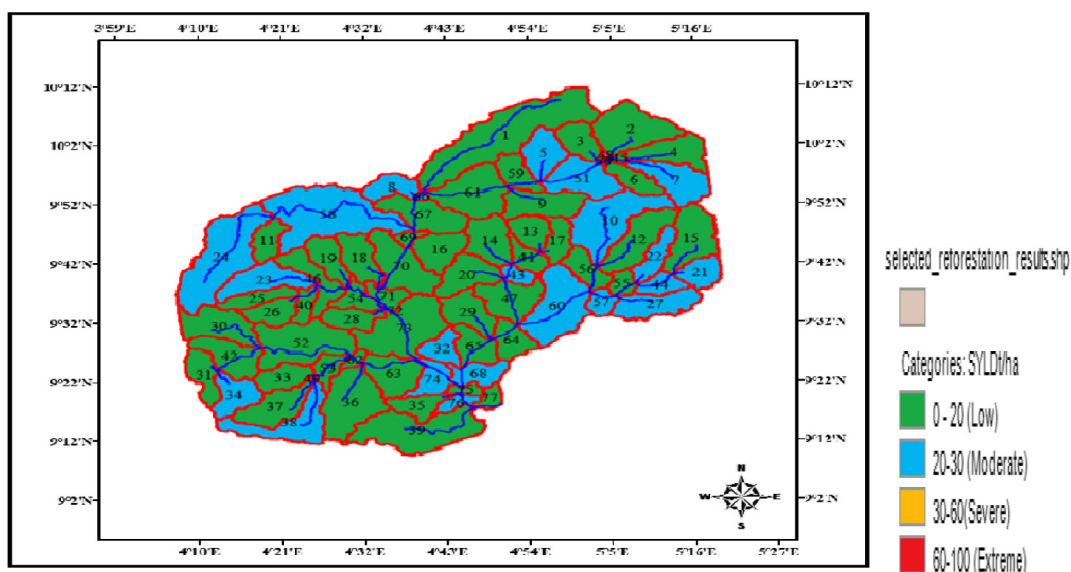


Figure 4 Erosion Prone Area after Introduction of Filter Strips at Selected Locations in the Study Area.

results showed a further reduction of sediment yield by additional 488.14 t/ha. This increased the percentage sediment reduction in the area to 69.6%. The implementation of this scenario also brought about reduction in the erosion classification to only the low (0–20 t/ha) category. Fig. 4 depicts the erosion classification after the introduction of vegetative filter strip at the watershed area.

4.1.4. Scenario D (stone bunds)

The simulation of stone bund scenario revealed the least reduction of sediment yield in the watershed when compared with other management scenarios. Modelling results showed a total sediment reduction of about 258.18 t/ha with this option. This represents 11.33% reduction in the total sediment yield. The

configuration of erosion prone areas is as depicted in Fig. 5. After the implementation of the BMP, it was noticed that 5 subbasins are in the low (0–20) zone, 26 subbasins are in the moderate (21–30) zone, 31 subbasins are now in the severe (31–60 t/ha) zone and one (1) subbasin is in the extreme zone.

4.2. Cost analysis of sediment management scenarios

4.2.1. Scenario A (existing situation)

4.2.1.1. Cost related to direct sediment removal. The estimates showed that sediment removal by mechanical dredging is N2,713,100. This estimate was used in conjunction with other related costs such as cost associated with damages to hydro-power turbines and lost in hydropower production, in arriving

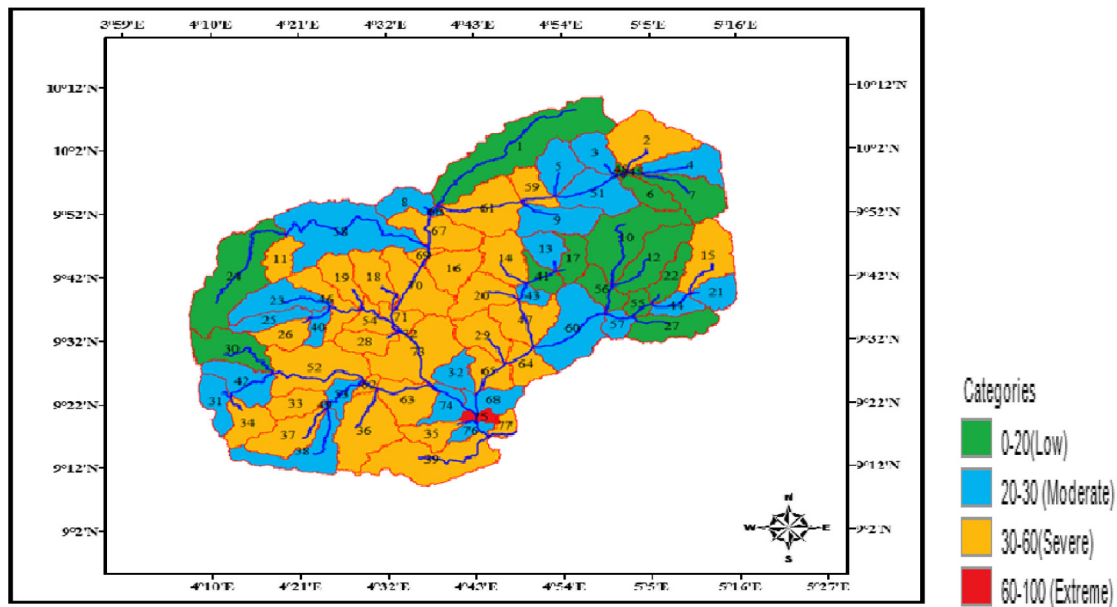


Figure 5 Erosion prone area after introduction of stone bunds at selected locations in the study area.

at the total estimates associated with allowing sediment into the dam (existing situation). As previously stated, mechanical dredging cost was used in this analysis due to local usage of the method in Nigeria facilitated by the availability of equipment and personnel to carry out the operation.

4.2.1.2. Cost associated with damages to hydropower turbines. Straight Line Depreciation method was used to estimate the present salvage value of Kaplan turbine installed at Jebba Hydro plc which is equivalent to N 42,882,300. Analysis of energy generation at Jebba Hydropower plc for 15 years period revealed that the average number of turbines in use during the period were three (3). This means that the cost implication due to damages on the three turbines was N128,646,900. This cost was distributed among the factors responsible for damages to turbine using ratio method of Weighted Matrix Delivery Decision Approach. Table 1 shows the distribution of cost associated with damages to the turbines among the identified factors. From the table, the total cost due to contribution of sediment laden water was estimated as N 8,747,989.20 (i.e. 6.8% of N128, 646,900)

4.2.1.3. Cost related to loss in hydropower production. Table 2 shows the difference between the installed and generated capacity during the stipulated period with a total of 57,195 MW. The distribution of the loss to identified factors responsible to loss in hydropower production is as shown in Table 3. The table shows that the loss which may be attributed

to reservoir sedimentation is estimated as 3,177.48 MW. This value is for the effect of sediment produced in the entire watershed (1,299,156 ha). This translates to a value of 2.45 kW when converted to sediment produced by one hectare of land considered in this analysis. Total energy produced was estimated by multiplying the power loss (2.45 kW) by the average running hours of the turbines for the period (77,332 h) as obtained from Jebba Hydropower plc to arrive at the total energy attributable to hydropower production as 189,463 kW-hr. At the prevailing rate of 1 kW hr equivalent to ₦12.90 (IBEDC, 2014), the total energy cost associated with loss in hydropower production was estimated as N2,444,074.70 .

4.2.2. Scenario B (reforestation)

The total cost of implementing reforestation at the pilot area was estimated as N2,425,825. Breakdown of this cost revealed that land preparation will gulp N50,000 representing about 2% of the total cost. Planting (preparation and exercise) cost N96,500 (4%), Maintenance operation such as weeding, fire tracing and clearing of rides cost N410,000 (16.9%). Other Maintenance practices such as monitoring and supervision, transportation of maintenance crew cost N1,750,000 representing 72.3% of the total cost. To take care of the unforeseen expenditure, incidental cost was estimated as N 115,325 (5% of the total cost). In summary, N631.20 per ton of sediment abated was estimated for reforestation of the watershed. This is about 85% reduction in the cost when compared with the cost incurred if the dam is silted up with sediment.

Table 1 Weighted matrix for factors influencing damages to turbine.

Tasks	Turbine shaft vibration	Cavitations	Water quality	Frictional force	Sediment laden water	Manufacturer's defect	Others
Ranking	1	2	3	4	5	6	7
Weighting	70	50	40	30	15	10	5
Normalising (%)	31.8	22.7	18.2	13.6	6.8	4.5	2.3

Table 2 Difference between installed and generated capacity (MW) at Jebba Hydropower plc) from 1984 to 1998.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1984	472.3	463	444.7	446.8	415.2	382.2	313.7	344.9	337.5	455.7	420.8	420.6	4917.3
1985	394.4	432.4	433.7	444.5	446.7	473.8	477.5	387	156.6	162.4	344.4	238	4391.1
1986	259.5	380	353.1	353.7	320.1	329	330.5	351.6	386	334.4	331.5	370.3	4099.7
1987	330.1	372.5	355.6	381.9	379.9	304.1	376.7	376.8	303.8	341.5	367.8	371.6	4262.2
1988	376.8	405.5	366	416.1	385.6	383.3	382.3	362	317.9	311.9	383.3	359.3	4450.1
1989	358.6	412.2	357.2	387.9	382.3	389.9	386.3	374.8	317.9	311.9	342.1	336.3	4357.4
1990	299.7	376.2	322.7	375.5	376.8	376.8	372.1	374.1	324.4	330.2	350	341	4219.6
1991	385.5	311.2	432.6	394.7	372.5	474.8	118.4	77.7	216.7	156	336.6	316.4	3593.1
1992	277.2	348.7	345.2	336.4	337.3	317.1	369.9	439.9	376	239.8	270	298.2	3955.7
1993	323.5	303.1	258.3	313.4	394.1	446.3	467.1	466.7	317.9	354.1	376.2	381.9	4402.6
1994	351.9	362.4	314.5	332.2	334.9	371	379.2	202.4	81.6	124.3	152	189.1	3195.5
1995	127	170.1	133	276.7	224.5	141.1	259.3	191.8	191.8	130.7	193.7	306.5	2346.4
1996	260	288.3	284.3	353.9	350.6	398.1	345	329.5	232.2	211.5	249.7	293.7	3596.9
1997	220.8	245.5	257	257.5	347.1	335.6	348.5	438.9	256.5	286.5	344.9	339	3677.6
1998	223.3	193.5	194.9	198.1	239.5	185.7	104.9	64.4	74.4	67.3	67.9	115.4	1729.3

Table 3 Weighted matrix for factors related to loss in hydropower production.

Task	Mechanical	Hydrological	Electrical	Civil	Maintenance	Sedimentation	Others
Ranking	1	2	3	4	5	6	7
Weighting	60	35	30	15	20	10	10
Normalising (%)	33	19	17	8	11	6	6
Estimated power loss (MW)	19,065	11,121	9532	4766	6355	3177	3177

The cost of implementing VFS is made up of land preparation which cost N50,000 (2.1%), planting operations such as supplying and transportation of seedlings, planting and fertilizer application amounted to N345,750 (14.2% of the total cost). Maintenance operation gulped about N1,330,000 (54.9%) while other expenditure such as pre-emergence herbicide application, transportation for maintenance crew, purchase of equipment and soil test cost about N1,810,000 (74.7%). Incidental cost for the implementation VFS at the pilot area was N115,325 representing 5% of the total cost. The grand total for the application of VFS is about N3,709,419. This is equivalent to N1,117.63 per ton of sediment abated which is about 73.3% difference in cost when compared with cost incurred in the existing condition scenario (i.e. allowing sedimentation of the reservoir to take place).

Construction of stone bunds in the pilot area consists of land preparation which costs N50,000 (1%), procurement and transportation of stone bunds which amounted to about N300,000 (7%). The construction of stone bunds is about N2,910,500 (72%) while other expenditure such as maintenance and incidental cost for the implementation of stone bunds at the pilot area is about N600,000 (15%) and N195,500 (5%) of the total cost respectively. The grand total for the construction of stone bund is N 4,105,500. This translates to N1,237 per ton of sediment abated. This is equivalent to about 70.5% difference in cost when compared with the existing condition scenario (when sedimentation is allowed in the reservoir).

4.2.3. Summary of cost analysis of BMPs

Summarily, cost analysis of different management scenarios showed that reforestation and application of VFS have discernible impacts on sediment load reduction at the

watershed. The results revealed that the implementation of the sediment management methods i.e. reforestation, VFS and stone bunds at the watershed upstream of Jebba Reservoir in Nigeria will cost N 631.20 (\$3.51), N1,117.63 (\$6.21) and N1,237 (\$6.87) per ton of sediment abated respectively. On the other hand, the total cost associated with sediment accumulation into Jebba dam was estimated as N13,905,163.90 (\$77,250.91). This is made up of the cost of removal of sediment by the use dredging operation N2,713,100 (\$15,072.78) and other costs such as damages to turbine which was valued at N8,747,989.20 (\$48,599.94) and hydropower production lost estimated as N2,444,074.70 (\$13,578.19). This is equivalent to about N4,189.60 (\$23.28) per ton of sediment impounded by the reservoir.

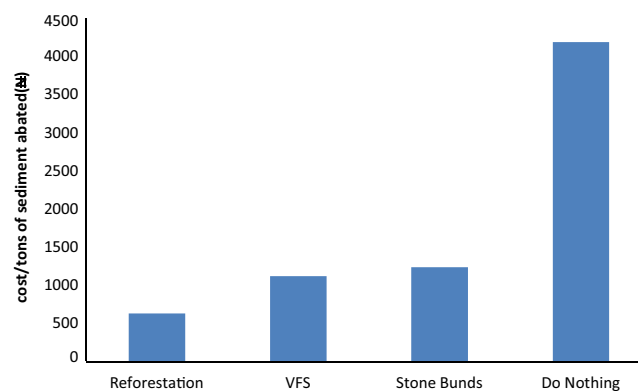


Figure 6 Cost comparison of sediment management methods and in combating sediment accumulation in Jebba Hydropower dam.

Further analysis of the results showed that reforestation management option will cost 85% reduction (i.e. 15% of do nothing scenario) while the application of VFS and stone bunds revealed 73.3% cost reduction (about 26% of do nothing) and 70.5% (about 29% of do nothing scenario) respectively. From this analysis, it can be concluded that the sediment management scenarios considered in this study are cost effective and sustainable when compared with the costs incurred in tackling the effect due to reservoir sedimentation (Fig. 6).

5. Conclusion

From the results obtained in this study, the following conclusions can be drawn:

- i. Application of sediment management strategies such as VFS, reforestation, and stone bunds to critical erosion zones of the watershed reduced the sediment yield up to 65.6%, 63.4%, and 12% respectively.
- ii. Cost analysis of implementing each of the management options (i.e. reforestation, VFS and stone bunds revealed 84.9%, 73.3% and 70.5% reduction respectively in the costs to be incurred if sediments are allowed to accumulate in the dam.
- iii. SWAT embedded in GIS environment is suitable for modelling the hydrology and sediment load and for identification of critical erosion prone areas in a watershed. The results are useful for sustainable water and sediment management at watershed scale in Nigeria.

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References

- Adeogun, A.G., 2015. Sediment Management Modelling of Upstream Watershed of Jebba Reservoir in Nigeria (Ph.D. thesis). Faculty of Engineering and Technology, University of Ilorin, Ilorin, Nigeria. Unpublished.
- Adeogun, A.G., Sule, B.F., Salami, A.W., 2015. Simulation of sediment yield at the upstream watershed of Jebba lake in Nigeria using SWAT model. *Malays. J. Civil Eng.* 27 (1), 25–40.
- Agbeja, B.O., 2004. Valuation of investment on teak plantation establishment on a 15-year-rotation for intending small holders in Nigeria. In: *A Paper Presented at International Workshop on Small-Holder Timber Production held at World Agroforestry Centre* (ICRAF), United Nations Avenue, Gigiri, Nairobi, Kenya, 29 Nov.–1 Dec. 2004.
- Arnold, J.G., Williams, J.R., Maidment, D.R., 1995. Continuous-time water and sediment-routing model for large basins. *J. Hydraul. Eng.* 121 (2), 171–183.
- Betrie, G.D., Mohammed, Y.A., van Griensven, A., Srinivasan, R., 2011. Sediment management modelling in the blue Nile basin using SWAT. *Hydrol. Earth Syst. Sci.* 15, 807–818.
- Bracmort, K.S., Arabi, M., Frankenberger, J.R., Engel, B.A., Arnold, J.G., 2006. Modelling long term water quality impact of structural BMPs. *Trans. ASABE* 49 (2), 367–374.
- Hunink, J.E., Niadas, I.A., Antonaropoulos, P., Droogers, P., de Vente, J., 2013. Targeting of intervention areas to reduce reservoir sedimentation in the Tana catchment (Kenya) using SWAT. *Hydrol. Sci. J.* 58 (3), 600–614.
- IBEDC, 2014. Ibadan Electricity Distribution Company Electricity bill for May, 2014 Challenge Business Unit, Ilorin, Kwara State, Nigeria.
- Leeds, R., Brown, L.C., Sulc, M.R., Van Lieshout, L., 2014. Vegetative filter strips: application, installation and maintenance, Ohio State University Extension, Food, Agricultural and Biological Engineering, 590 Woody Hayes Dr., Columbus, Ohio 43210, available online at <<http://ohioline.osu.edu/aex-fact/0467.html>> (accessed on 2/6/2014).
- Morris, G., Fan, J., 1998. *Reservoirs Sedimentation Handbook: Design and Management of Dams, Reservoirs and Watershed for Sustainable Use*. McGrawHill Book Company, New York.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R. and Williams, J.R., 2005. Soil and water assessment tool theoretical documentation version 2005. 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.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and water assessment tool theoretical documentation version 2009. Grassland, Soil and Water Research Laboratory – Agricultural Research Service Blackland Research Center – Texas AgriLife Research.
- NIWA., 2012. Mechanical Dredging of river Niger contracted by Nigerian inland waterway, Bill of Engineering Measurement and Evaluation (BEME) Report of Nigerian Inland Waterway, Lokoja, Nigeria.
- NRC, 2009. A guidebook for the evaluation of project delivery methods. In: *TCRP Report 131, National Research Council. The National Academies Press, Washington, DC, USA.*
- NWP., 2004. National Water Policy, Federal Ministry of Water Resources, Federal Republic of Nigeria. Available at <<http://awdrop.org/uploads/3/1/7/8/3178681/national-water-policy.pdf>> (accessed on 26th May 2013).
- Ogbu K.N., Mbajiorgu, C.C., 2013. Evaluation of impact of land-use change in the Ebonyi River Watershed, South-Eastern Nigeria, Using SWAT Journal of Agricultural Engineering and Technology (JAET), vol. 21(2). <[http://www.niae.net/journals/Vol21\(No.2\)Dec2013.pdf](http://www.niae.net/journals/Vol21(No.2)Dec2013.pdf)>.
- Oloyede, I.O., 2008. Afforestation and reforestation: The UNILORIN experiment, Presentation at the High Level Technical Workshop on Afforestation and Climate Change in Africa Organised by the Centre for Human Security of the Olusegun Obasanjo Presidential Library (OOPL) and Nigeria Tree Planters, December 15–17.