SUSTAINABLE SEDIMENT MANAGEMENT OF UPPER WATERSHED OF JEBBA DAM FOR IMPROVED POWER GENERATION

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EXECUTIVE SUMMARY

Sedimentation is a significant natural phenomenon affecting hydropower reservoirs. Apart from major watershed problems such as loss of soil fertility and productivity caused by soil erosion, increased sediment load associated with erosion processes reduces the storage capacity and shortens the useful life of hydropower reservoirs. Therefore, an investigation of the hydrological processes and sediment transport mechanism at the upstream catchments of hydropower reservoirs in Nigeria is critical to the sustainable operations of hydropower dams. The objectives of the study were to (i) simulate the hydrological and erosion processes and predict the water and sediment yield into subbasins of the selected watershed using modelling tools (ii) monitor, collect and assess suspended sediment loadings from selected tributaries into Jebba lake (iii) carry out sensitivity analysis of model parameters (iv) evaluate the performance of the selected model (v) study the impact of catchment management scenarios on sediment reduction (vi) carry out financial analysis of the catchment management scenarios.

The Soil and Water Assessment Tool (SWAT) was interfaced with Mapwindow-GIS to simulate the hydrology, predict the sediment yield and identify erosion prone areas of a watershed (12,992km²) drained by Rivers Niger, Kontagora, Awun and Eku upstream of Jebba Reservoir in Nigeria. SWAT was calibrated and validated using measured flow data from 1990 to 1995. The model was statistically evaluated using coefficient of determination, $R^2$ and Nasch-Sutcliffe Efficiency, NSE. Sediment samples collected from three locations within the watershed from May to December, 2013 were analysed and used to spatially calibrate and validate the model. Four sediment management scenarios: existing condition, reforestation, Vegetative Filter Stripping (VFS) and stone bunding were considered and used to study their effects on sediment load reduction in the watershed.

This study showed that:

i. annual sediment yield in the watershed was estimated as 255.8tons/ha/yr producing about $8.31 \times 10^9$ tons of sediment between 1985 and 2010;

ii. suspended sediment samples along River Niger/Kotangora have the highest average sediment concentration of 104.8mg/l followed by River Awun (75.4mg/l) and River Eku (26.2mg/l);

iii. evaluation of SWAT model using $R^2$ (0.57-0.68) and NSE (0.66-0.82) revealed that the model performed satisfactorily for stream flow and sediment yield prediction in the watershed;

iv. application of reforestation, VFS and stone bunds to critical zones of the watershed reduced the sediment yield up to 63.4%, 65.6% and 12% respectively; and

The study revealed that 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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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

Sedimentation has been known over the years to pose a serious threat to available storage of hydropower reservoirs around the world. Morris and Fan (1998) defined reservoir sedimentation as the process of filling of the reservoir behind a dam with sediment carried into the reservoir by streams. It can also be referred to as a process of sediments deposition into a lake formed after a dam construction. This means all reservoirs formed by dams on natural rivers are subject to some degree of sediments inflow and deposition. Due to very low velocities observed in reservoirs, they tend to be very efficient sediment traps. The flow of water from the catchment upstream of a reservoir is capable of eroding the catchment area and eventually deposit the eroded materials either upstream of the reservoir or in the still water of the reservoir.

There are many causes of reservoir sedimentation. According to Arora and Goel (1994), Garg and Jothiprakash (2008), the dominant factors among them include reservoir capacity to inflow ratio (C/I), sediment content in the water flowing in, texture and size of the sediment, the trap efficiency (Te) of the reservoir, and the method of reservoir operation. Raghunath (2006) also asserted that the nature of the material in the catchment area, the slope of the catchment area and characteristics of watershed at the upstream of reservoirs are some of the major contributing factors to reservoir sedimentation.

Reservoir sedimentation has some associated effects. Apart from major watershed problems such as loss of soil fertility and productivity caused by soil erosion processes, there is also an increased sediment load associated with erosion processes and this reduces the storage capacity and shortens the useful life of reservoirs. One of the important parameters that determine the rate of sedimentation of a reservoir is the sediment yield at the catchment located above the reservoir. Sediment yield refers to the amount of sediments exported by a basin over a period of time, which is also the amount
that will enter a reservoir located at the downstream limit of the basin (Morris and Fan, 1998). Ijam and Tarawneh (2012) concluded that adequate knowledge of sediment yield at different locations within a watershed can be useful to decision makers and stakeholders in proposing efficient sediment management measures that is appropriate for each location. This will also assist water managers in the reduction of the level of siltation of reservoirs downstream.

Consequently, reliable estimates of hydrological parameters and sediment yield in remote and mostly inaccessible areas associated with many watersheds in Nigeria is inevitable. However, this might be difficult using conventional means or method. Moreover, lack of decision support tools and scarcity of basic data for hydrological analysis of most of the catchments constitute major factors militating against research and development in this area. It is therefore desirable to opt for alternative ways to quantify these parameters for effective and sustainable management of sediment and water resources at watershed level.

One of the alternative approaches is the use of distributive erosion models for hydrologic evaluation and assessment of sediment yield in watersheds using remotely sensed data embedded in a GIS environment (Ayana, et.al. 2012; Abbaspour, et al. 2012; Jain, et al. 2010). GIS and remote sensing techniques have been reported to improve the application of hydrological modelling in many capabilities, such as in the area of data management, parameter extraction and interpolation, visualization and interface development (Fadil et. al., 2011). Hence, the use of modelling tools interfaced with GIS provides the platform to streamline GIS processes tailored towards hydrological modelling. The importance of developing hydrologic and sediment management models cannot be overemphasized as it also 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.

Apart from sustainable sediment management of watershed above the hydropower dams, there is also a growing need to manage the water resources in the watershed in an effective and sustainable way. The study of water resources at river catchment level has been widely adopted as a better way of managing and assessing the important
components of water balance in a watershed (Fadil, et al. 2011). Most importantly, knowledge of water balance and water yield in a river catchment is an indispensable prerequisite in the sustainable management of water resources at watershed and basin wide levels.

At the decision making stage, models are usually employed for the purpose of selecting an optimal course of action. Such models are often constructed to enable reasoning within an idealized logical framework about the processes (Shrestha, et al., 2010). However, due to the complexities in the representation of these natural processes and conditions, models are usually calibrated and validated with observed data prior to the application of the models to obtain a realistic description of the processes being modelled.

### 1.2 Problem Description

In many countries, the capacities of hydropower dams have been threatened by soil erosion processes and sediment related problems at the watersheds located upstream of such reservoirs. The mud and sand produced as a result of massive erosion processes are transported by the river during the flood into the dam downstream. Consequently, sediment could reach the intake easily and flow through the intake to the turbines and some other underwater equipment, causing operation difficulties for the power generation.

Based on the information gathered on the three Nigerian hydropower reservoirs (i.e. Jebba, Kainji and Shiroro), their capacities have been greatly affected by significant movement and deposition of sediments. It has also been observed that the capacities of the three hydropower reservoirs in the country have been greatly affected due to prolonged sedimentation and siltation over the years. Sizeable portion of the reservoirs have been silted up and partially sedimented and thus are in danger of filling-up with sediments. The current level of silt deposits in all the three reservoirs might have reached critical situation and have already taken their toll on the generating capacities of the hydropower stations.

In order to prolong the useful lives of hydropower reservoirs in Nigeria, an urgent rehabilitation of the dams is needed to prolong the economic and viable operating life of the hydroelectric plants. Also, proper sediment management and control strategy are
required at the watersheds located upstream of the reservoirs to reduce the erosion processes and other activities that may lead to sediment production. This can only be achieved through a thorough sedimentation studies in order to map out strategic plans and measures (structural and non-structural) on how to reduce the sedimentation problems caused by erosion processes. Therefore, a good understanding and characterisation of the hydrological processes and sedimentation mechanism in the watershed areas upstream of these reservoirs will provide the necessary information on how to manage the sediments inflow. The results obtained from the study could be used as a guide for developing sustainable management strategies for controlling sedimentation in the hydropower dams in Nigeria.

1.3 Aim and Objectives of the Study

The overall aim of the research was to investigate the application of distributive erosion model in Geographical Information Systems (GIS) environment for sustainable management of water and sediment yield of a watershed located upstream of Jebba dam in Nigeria. The specific objectives achieved in this research include:

i. simulation of the hydrological and erosion processes and prediction of water yield, water balance components and sediment yield into subbasins of the selected watershed using modelling tools.

ii. monitoring, collection and measurement of suspended sediment loadings from selected tributaries into Jebba lake.

iii. identification and prioritization of erosion prone areas of the watershed using calibrated model.

iv. studying the impact of catchment management scenarios on the reduction of soil erosion processes and sediment transport within the watershed

1.4 Description of Study Area

The study area is the watershed at the upstream of Jebba Lake located in central area of Nigeria between Latitude 10.31° and 8.99 ° N and Longitude 5.01° and 4.79° E. It has a perimeter of about 567 km and an estimated area of 1,299,156ha (12,992 km²) and forms a sub-basin in the existing lower Niger River basin situated in Hydrological Zone II of Nigeria (NWP, 2004). The major river that traverses through the watershed area is River Niger. Some of the tributaries to this river within the watershed are River Awun
with stream length of 34.6 km, catchment area 613.22 km² and average slope of 0.00341081; River Moshi with stream length 87.8 km, catchment area 1070 km² and average slope of 0.002309244; River Eku with stream length 102.9 km, catchment area 1604.2 km² and average slope of 0.000553939; River Kotangora with stream length 80.1 km, catchment area 1177.2 km² average slope of 0.00150472 and river Wuruma with stream length 45.9 km, catchment area 611.23 km² and average slope of 0.0025636.

The range of elevation of the watershed is between 114 m to 403 m above sea level and 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 3,636 m³/s in October, 1998. The watershed area is sandwiched between two main hydropower reservoirs in Nigeria, namely Kainji and Jebba reservoirs 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 soil in the study area is predominantly sandy loam soil. The vegetation within the area is guinea savannah which is mainly characterised with tall grasses and scattered trees. The main activities for sustainability in the area are farming, fishing, hunting, trading and weaving. Although, the average populace of the region is predominantly farmer, their concentration however is basically on subsistence farming i.e. farming consumptions of the immediate family. Therefore, relatively few of these people produced agricultural product on commercial basis couple with the low level of mechanise farming because most of their farming activities is still intensively on communal effort.

The selection of the area to test the applicability of SWAT model is based on the availability of model input data at the hydrological stations established by Kainji and Jebba hydroelectric power stations and also at the Nigeria Meteorological Agency (NIMET) located at Ilorin, Kwara State. The water from Jebba Lake downstream is used to produce hydroelectric power with installed capacity of about 760 MW. Figure 1.1 shows the location of the study area as well as the stream network within the map of Nigeria while Figure 1.2 shows the catchment area attributed with major rivers and tributaries.
Figure 1.1: Map of Nigeria Showing the Location and Stream Network within the Study Area

Figure 1.2: Catchment Area Attributed with Major Rivers and Tributaries
CHAPTER TWO

2.0 METHODOLOGY

2.1 Model Selection

The physically based model used in this study is the Soil and Water Assessment Tool, SWAT (Neitsch et al., 2005). The selection of SWAT for this study was based on many reasons. Among these is the fact that it is an existing, readily available tool with good documentations. Its availability and efficacy in prediction of different hydrological processes has also been reported in many studies (Omani et al., 2007; Ndomba and Griensven, 2011; Birhanu, 2009) and this make it attractive to potential users. The presence of several user groups e.g. SWAT Africa, SWAT world and Water base Google group where users from different parts of the world share their research problems and modelling experience using SWAT is a plus to the acceptability of the tool among researchers.

2.2 Theoretical Description of SWAT Model

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). The SWAT model is a catchment-scale continuous time model that operates on a daily time step with up to monthly/annual output frequency. Some of the characteristics of the model as discussed in Neitsch et.al (2009) are:

(a) It is physically based. This means rather than incorporating regression equations to describe the relationship between input and output variables, SWAT requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modelled by SWAT using these input data.
(b) It uses readily available inputs: While SWAT can be used to study more specialized processes such as bacteria transport, the minimum data required to make a run are commonly available from government agencies.
(c) Computationally efficient: Simulation of very large basins or a variety of management strategies can be performed without excessive investment of time or money.
(d) SWAT also enables users to study long-term impacts. Many of the problems currently addressed by SWAT users around the world involve the gradual build up of pollutants and the impact on downstream water bodies. To study these types of problems, results are needed from runs with output spanning several decades.

2.3 Modelling in SWAT

For modelling purposes, a watershed may be partitioned into a number of sub-watersheds or subbasins. The use of subbasins in a simulation is particularly beneficial when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. By partitioning the watershed into subbasins, the user is able to reference different areas of the watershed to one another spatially.

The major components of the model include weather, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, channel and reservoir routing. It divides a 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. The model calculations are performed on a HRU basis and flow and water quality variables are routed from HRU to subbasin and subsequently to the watershed outlet. The processes involved modelling with SWAT is as shown in Figure 2.1
The simulation of hydrologic cycle by SWAT is based on the water balance Equation 2.1

\[ SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})_i \] 2.1

where \( SW_t \) is the final soil water content (mm water), \( SW_0 \) 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 percolation and bypass flow exiting the soil profile bottom on day \( i \) (mm water), and \( Q_{gw} \) is the amount of return flow in day \( i \) (mm water).
The estimation of surface runoff can be performed by the model using two methods. These are the SCS curve number procedure USDA Soil Conservation Service and the Green & Ampt infiltration method (Neitsch et al., 2005). The SCS curve number describes surface runoff $Q_{surf}$ as:

$$Q_{surf} = \frac{(R_{day} - 0.25)^2}{(R_{day} + 0.85)}$$

Equation 2.2

In (3.2), $Q_{surf}$ is the accumulated runoff or rainfall excess (mm), $R_{day}$ is the rainfall depth for the day (mm), $S$ is the retention parameter (mm). The retention parameter is defined by Equation 3.3

$$S = 25.4 \left(\frac{100}{CN} - 10\right)$$

Equation 2.3

where CN= curve number, S=retention parameter

The total amount of water exiting the bottom of the soil profile on day $i$, ($W_{seep}$) is calculated from equation 3.4

$$W_{seep} = w_{per.ly=nl} + w_{crk.btm}$$

Equation 2.4
Where $W_{\text{seep}}$ is the total amount of water exiting the bottom of the soil profile on day $i$ (mm), $w_{\text{perc,ly=n}}$ is the amount of water percolating out of the lowest layer, $n$, in the soil profile on day $i$ (mm), and $w_{\text{crk, bt m}}$ is the amount of water flow past the lower boundary of the soil profile due to bypass flow on day $i$ (mm).

The estimation of the base or return flow is done using Equation 2.5

$$Q_{gw} = \frac{8000 \cdot K_{\text{sat}}}{L_{gw}^2} \cdot h_{\text{wtbl}}$$  \hspace{1cm} (2.5)

where $Q_{gw}$ is the groundwater flow, or base flow, into the main channel on day $i$ (mm H$_2$O), $K_{\text{sat}}$ is the hydraulic conductivity of the aquifer (mm/day), $L_{gw}$ is the distance from the ridge or subbasin divide for the groundwater system to the main channel (m), and $h_{\text{wtbl}}$ is the water table height (m).

The estimation of erosion/soil loss and sediment yield for each Hydrologic Response Unit (HRU) 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 3.8 derived by Bagnold (1977) to route sediment in the channel.

$$S_{\text{ed}} = 1.292 \cdot E_{\text{USLE}} K_{\text{USLE}} C_{\text{USLE}} P_{\text{USLE}} L_{\text{USLE}} C_{\text{FRG}}$$  \hspace{1cm} (2.6)

Where $S_{\text{ed}}$ is the sediment yield on a given day (metric tons), $E_{\text{USLE}}$ is the rainfall erosion index (0.017 m-metric ton cm/(m$^2$ hr)), other factors are as defined in Equation 3.7. The value of $E_{\text{USLE}}$ for a given rainstorm is the product of total storm energy ($E_{\text{storm}}$) times the maximum 30 minutes intensity ($I_{30}$), hence,

$$S_{\text{ed}} = 11.8 \left(Q_{\text{surf}} q_{\text{peak}} A_{\text{hr u}}\right)^{0.56} K_{\text{USLE}} C_{\text{USLE}} P_{\text{USLE}} L_{\text{USLE}} C_{\text{FRG}}$$  \hspace{1cm} (2.7)

Where $Q_{\text{surf}}$ is the surface runoff volume (mm), $q_{\text{peak}}$ is the peak runoff rate (m$^3$/s), $A_{\text{hr u}}$ is the area of the HRU (ha), $K_{\text{USLE}}$ is the USLE soil erodibility factor (0.013 metric ton $m^2$ hr/(m$^3$-metric ton cm)), $C_{\text{USLE}}$ is the USLE cover and management factor, $P_{\text{USLE}}$ is the USLE support practice factor, $L_{\text{USLE}}$ is the USLE topographic factor, and $C_{\text{FRG}}$ 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)

### 2.4 Model Inputs

One of the major issues encountered in the application of hydrologic models in developing countries is the scarcity or unavailability of required data for model input. In order to overcome these challenges, an hybrid data was used in the creation of database in this study. This involves combining local and in-situ data gathered from local agencies or administrations and global data got from multiple organizations or global database. In some cases, data collection was also carried out at the selected locations within the watershed area and the information obtained used to update the online global database. The summary of the main set of input data are as shown in Table 2.1

**Table 2.1: Model Input data for the upper watershed of Jebba Dam**

<table>
<thead>
<tr>
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<th>Description</th>
<th>Resolution</th>
<th>Source</th>
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<td>Topography</td>
<td>Digital Elevation Model</td>
<td>90mx90m</td>
<td>Shuttle Radar Topographical Mission</td>
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<td>2</td>
<td>Land Use Map</td>
<td>Land Use Classification</td>
<td>1km</td>
<td>Global Land Cover Classification, Satellite Raster</td>
</tr>
<tr>
<td>3</td>
<td>Soil Map</td>
<td>Soil Types and Texture</td>
<td>10km</td>
<td>Digital Soil Map of the World</td>
</tr>
<tr>
<td>4</td>
<td>Weather</td>
<td>Daily precipitation, Min and Max Temp, Relative humidity Wind, Solar Radiation</td>
<td>Daily</td>
<td>NIMET, Jebba HP Station</td>
</tr>
</tbody>
</table>
2.4.1 Digital Elevation Model (DEM)

The 90m resolution topography data used for this study was extracted from the Shuttle Radar Topography Mission (SRTM) final version (CGIAR, 2012). The CGIAR-CSI GeoPortal is able to provide SRTM 90m Digital Elevation Data for almost every part of the world. The SRTM digital elevation data provided has been processed to fill data voids, and to facilitate its ease of use by a wide group of potential users. This data is provided in an effort to promote the use of geospatial science and applications for sustainable development and resource conservation in the developing world (CGIAR, 2012). Also, the elevation at selected locations within the watershed area were taken using Total Station equipment and GPS and the obtained data was used to update the database of the DEM (see Plate 1). The modified DEM used for the SWAT modelling is as shown in Figure 2.3. The DEM provides the basis for watershed delineation into sub-basins. Also, topographic parameters such as terrain slope, channel slope and reach length are derived from the DEM.

Plate 1: Obtaining Elevation Data of Selected Points within the Watershed using Total Station and GPS
2.4.2 Land Use and Land Cover (LULC)

Land use map needed to run SWAT was extracted from the Global Land Cover Characterization (GLCC) database and used to estimate vegetation and other parameters representing the watershed area. The GLCC database was developed by United States Geological Survey and has a spatial resolution of 1km and 24 classes of land use representation (GLCC, 2012). A reconnaissance survey was also conducted on the watershed to obtain information on the land use and land cover of the area. The data obtained were used in conjunction with the GLCC database to arrive at the land use map of the study area. Figure 2.4 shows the land use and land cover types and Table 2.2 shows their approximate percentage area coverage for the upstream watershed of Jebba reservoir.
Table 2.2: Information on Land use of the Study Area

<table>
<thead>
<tr>
<th>S/N</th>
<th>SWAT Code</th>
<th>Description</th>
<th>Area(Ha)</th>
<th>% of Watershed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>URMD</td>
<td>Urban and Built-Up Land</td>
<td>129.92</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>CRDY</td>
<td>Dry land Cropland and Pasture</td>
<td>332.8</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>CRGR</td>
<td>Cropland/Grassland Mosaic</td>
<td>4885.48</td>
<td>0.38</td>
</tr>
<tr>
<td>4</td>
<td>CRWO</td>
<td>Cropland/Woodland Mosaic</td>
<td>2109.11</td>
<td>0.16</td>
</tr>
<tr>
<td>5</td>
<td>GRAS</td>
<td>Grassland</td>
<td>915.2</td>
<td>0.07</td>
</tr>
<tr>
<td>6</td>
<td>SHRB</td>
<td>Shrub land</td>
<td>1863.67</td>
<td>0.14</td>
</tr>
<tr>
<td>7</td>
<td>SAVA</td>
<td>Savannah</td>
<td>1257234.26</td>
<td>96.77</td>
</tr>
<tr>
<td>8</td>
<td>FOEB</td>
<td>Evergreen Broadleaf Forest</td>
<td>166.4</td>
<td>0.01</td>
</tr>
<tr>
<td>9</td>
<td>WATB</td>
<td>Water bodies</td>
<td>20164.26</td>
<td>1.55</td>
</tr>
<tr>
<td>10</td>
<td>BSVG</td>
<td>Barren or Sparsely Vegetated</td>
<td>11432.57</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>1299233.67</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Figure 2.4: Land use Map of the Watershed
2.4.3 Soil Data

Digital soil data for the study was extracted from harmonised digital soil map of the world (HWSD v1.1) produced by Food and Agriculture Organization of the United Nations (Nachtergaele et al., 2009). The digitized soil map was completed in January 2003 and the database provides data for 16,000 different soil mapping units containing two layers (0 - 30 cm and 30 - 100 cm depth). Seven soil units are then extracted from the database and completed by additional information gathered by taken soil samples from different locations within the watershed area. Sixteen soil samples were collected from two different layers (0 - 30 cm and 30 - 100 cm depth) and the samples were analysed in the soil laboratory. Based on the analysis, it was discovered that the soil in the study area were predominantly sandy loam soil. Plate 2 shows the collection of soil sample and other geographical information of the watershed area while Tables 2.3 and 2.4 give the soil data composition and percentage composition of different classes of soil respectively.

Plate 2: Collection of Soil Samples and other Geographical Information on the study area
Table 2.3: Soil Data Information of the Study Area

<table>
<thead>
<tr>
<th>S/N</th>
<th>EAWAG Code</th>
<th>Area</th>
<th>%age</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nd8-1a-1572</td>
<td>476478.33</td>
<td>36.68</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>2</td>
<td>I-60</td>
<td>1599.1</td>
<td>0.12</td>
<td>Loam</td>
</tr>
<tr>
<td>3</td>
<td>Lf26-a-1443</td>
<td>673507.48</td>
<td>51.84</td>
<td>Sandy Clayey Loam</td>
</tr>
<tr>
<td>4</td>
<td>I-Nd-1276</td>
<td>147571.14</td>
<td>11.36</td>
<td>Loam</td>
</tr>
</tbody>
</table>

Table 2.4: Percentage Composition of Different Classes of Soil within the Study Area

<table>
<thead>
<tr>
<th>EAWAG Code</th>
<th>Clay(%)</th>
<th>Silt(%)</th>
<th>Sand(%)</th>
<th>Rock(%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd8-1a-1572</td>
<td>39</td>
<td>28</td>
<td>33</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>I-60</td>
<td>24</td>
<td>14</td>
<td>62</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Lf26-a-1443</td>
<td>23</td>
<td>37</td>
<td>40</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>I-Nd-1276</td>
<td>27</td>
<td>19</td>
<td>54</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

2.4.4 Meteorological Data

Meteorological data necessary to run the SWAT model were obtained from Nigeria Meteorological Agency (NIMET) Station based in Ilorin. Additional data were collected from Jebba and Kanji Hydro Electric meteorological stations. A total of three weather stations representing the study area were used. The data collected for each of the stations includes daily precipitations, maximum and minimum temperature, solar radiation, relative humidity and wind speed. The collected weather variables for driving the hydrological balance within the watershed are from the period 1985-2010. In the case of missing data, a weather generator embedded in the SWAT and developed by Schuol and Abbaspour (2007) was used to fill the gaps. The geographical information of the weather stations used for the study is shown in Table 2.5 and their locations are displayed in Figure 2.5.
Table 2.5: Geographical Information of the Weather Stations Used for the Study Area

<table>
<thead>
<tr>
<th>ID</th>
<th>Station ID</th>
<th>Source</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>924410</td>
<td>NIMET</td>
<td>9.21</td>
<td>4.38</td>
<td>227</td>
</tr>
<tr>
<td>2</td>
<td>954700</td>
<td>Jebba</td>
<td>9.52</td>
<td>4.69</td>
<td>140</td>
</tr>
<tr>
<td>3</td>
<td>984700</td>
<td>Jebba</td>
<td>9.84</td>
<td>4.69</td>
<td>108</td>
</tr>
</tbody>
</table>

Figure 2.5: Geographical Locations of Weather Stations used for the Study

\[19\]
2.4.5 Weather Generator

When measured data is not available or when there are missing records in the meteorological data in the created database, SWAT uses data simulated by a weather generator program which uses parameters supplied in weather generator files. The weather generator input file contains the statistical data needed to generate representative daily climate data for the subbasins. Ideally, a minimum of 20 years of record is needed to calculate the parameters in the weather generator file (Arnold et al., 2011). MWSWAT supports the use of one weather generator file, which is then used for all subbasins, or a weather generator table, which can contain the parameters for a number of weather stations, each represented by one line in the table. Details of the parameters in the weather generator file and how they are estimated can be found in Schuol and Abbaspour (2007). For this study, climatic data from 1985 – 2005 were used for the creation of weather generator file.

2.5 Data Collection and Analysis

2.5.1 Stream Flow Data

Stream flow data necessary for calibration and validation of SWAT model was provided by the hydrology department of Jebba Hydropower Plc. These data were presented as average monthly inflow (m³/s) into Jebba Lake and covered period from January, 1990 to December, 1995 (16 years).

2.5.2 Sediment Concentration Data

Observed sediment concentration data are necessary for model calibration and validation exercise. At present, there is no observed sediment concentration data for the modelled watershed. Therefore, sediment sampling programme was established along some of the tributaries within the watershed area in order to monitor, assess and collect sediment samples. Samples collected were later analysed in a laboratory to obtain sediment concentrations in the samples.
2.5.2.1 Sampling Site

The first stage of sediment sampling in a river or canal is the selection of a suitable sampling site. According to Singhal et al. (1981), the site should satisfy certain criteria such as: (a) It should be in a straight reach of length at least 4 times the width of the channel, but not less than 150 m (b) The chosen reach should be stable, i.e. neither silting nor scouring (c) A normal section should be located in the middle of the selected reach. (d) It should not be adjacent to hydraulic structures (e) It should be accessible, and preferably located near a village or town.

Before the commencement of sampling, a reconnaissance survey of the proposed locations was carried out in conjunction with hydrologists at Jebba Hydropower Plc. After careful consideration and deliberation by the reconnaissance team, the sampling sites within the catchment area that nearly met sampling criteria specified by Singhal et. al., (1981) were identified and as stated in Table 2.6. It should be noted that sampling at the confluence point of River Niger and Kotangora involved the use of speed boat to convey the equipment and technical team to the sampling point. However, at the other two locations, the sampler was deployed into the river through the use of rope from the top of the bridge deck into the river. Plate 3 shows the pictorial view of sampling at different locations within the study area.

<table>
<thead>
<tr>
<th>River</th>
<th>Description of site</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Awun</td>
<td>on a bridge deck along Jebba-Adeniran village</td>
<td>Lat 9.2°N, Long 4.55°E</td>
</tr>
<tr>
<td>Eku</td>
<td>on a bridge deck along Mokwa-New-Bussa road</td>
<td>Lat 9.9°N, Long 4.66°E</td>
</tr>
<tr>
<td>Niger/Kotangora</td>
<td>at confluence point of river Kotangora and Niger</td>
<td>Lat 9.28°N, Long 4.75°E</td>
</tr>
</tbody>
</table>
Plate 3: Sampling locations within the study area: (a) on the bridge deck along Mokwa-Kainji road for Awun river, (b) at the confluence point of river Niger and Kotangora (c) on a bridge deck along Jebba-Adeniran road
2.5.2.2 Description of Sampling Equipment

The suspended sediment sampler used in this study is the USDH-2A sampler. It is a version of depth integrating sampler that traverses the complete depth of the stream and back at a uniform rate. It collects samples which have concentration equal to the average concentration in the vertical (USDH-2A, 2013). The sampler is 20 inches long, weighs about 15kg, and uses a bag as the sampler container which can accommodate about 1-litre of water. The relatively small size and weight of the sampler allows it to be raised and lowered by hand line or rope. However, if multiple samples are to be collected the use of a bridge board and reel, or crane and reel, is recommended (USDH-2A, 2013).

The streamlined body of the sampler is fitted with four vanes, which orient and stabilise the sampler in flowing water. Three different sizes of nozzles may be used when sampling. The diameter of the nozzles are 0.36, 0.48 and 0.64 cm, (5/16, 3/16 and 1/4inch). The nose and tail are made up of plastic materials. The plastic nose supports the nozzle and nozzle holder and key in into the sampler’s body with hand pressure. The nose is furnished with a monofilament line attached at the bottom while the opposite end of the line is attached to the sampler body to prevent accidental loss of the nose, nozzle, and nozzle holder. The US DH-2A was designed and fabricated to meet the protocols for water-quality sampling as outlined in the USGS National Field Manual for the Collection of Water-Quality Data (see Plate 4).
2.5.2.3 Sediment Sampler Assemblage and Sampling Procedure

The US-DH-2A sampler was designed to collect representative flow-weighted samples in streams with velocity from 2 to 6ft/sec. The sampler has to be lowered and raised through the water column at a predetermined transit rate. The maximum transit rate for any depth integrating sampler is 0.4 times the mean stream velocity (US-DH-2A, 2013). Information on the mean stream velocities of selected rivers within the catchment was obtained from the Hydrology department of Jebba Hydro Plc prior to sampling and used to estimate the transit rate of the sampler.

Before deployment of sampler into the river, it has to be properly assembled through insertion of hanger bar in the slot at the top of the sampler and secured with a bar pin. Then the hanger bar is connected to a cable or hand line. For this study, a nozzle size 3/16inch (0.48 mm) nozzle which has a maximum sampler depth of 20ft was selected. Selection of the nozzle size was based on the mean stream velocity depth table available in the manual supplied with the equipment. Prior to nozzle and nozzle holder assemblage, both were properly checked for damage and also to ensure that the nozzle entrance is round without burrs and deformation. Sample bag was properly flattened to remove as much air as possible from the bag. The bag is then secured to the adaptor by cinching it with a hook and loop strap (see Plate 5).
Plate 5: Securing Sample Bag with Hook and Loop Strap and Removal of air from the Sample Bag

At each sampling, the USDH-2A sampler was lowered into the water surface. The sampler’s lower tail fin will hang below the bottom of the sampler while the nozzle will be pointed upward at an angle of around 20-30 degrees. This allows the tail fin to enter the stream first and orient the sampler and the nozzle into the flow. During the sampling exercise, the sampler was lowered from the surface to the bottom of the stream and returned to the surface at almost the same constant rate. This was to ensure that the sampler did not hit the bottom of the stream to avoid disturbance of the bed which might introduce sediment into the nozzle thereby distorting the concentration of the sample. Sediment sampling was done twice in a month starting from May to December, 2013. In all, 51 samples were collected (18 samples per each of the rivers Eku, Awun and Niger/Kotangora) over the period. At the end of each sampling, the samples were poured in a clean container and properly labelled before transporting them to the laboratories for analysis. Plate 6 shows the pictorial view of suspended sediment samples collections at the three locations.

Plate 6: Suspended Sediment Samples Collection at (a) River Eku (b) the confluence point of River Niger/Kontagora

2.5.2.4 Sediment Transportation and Data Analysis Samples

All sediment samples collected for this study were transported and analysed at two different laboratories. The determination of suspended sediment concentration and total suspended
solids in the samples were done at the Chemistry Department of the University of Ilorin. The turbidity measurement of the samples was carried out using the turbidity meter supplied with water quality laboratories equipment at the National Centre for Hydropower Research and Development (NACHRED), University of Ilorin (see Plate 7 and 8). The concentration of suspended sediment in the water samples was determined in the laboratory using the method described in Bartram and Ballance (1996) and APHA (1992). The sand concentration was negligible and not required separately, so a known volume (say 100ml) of raw water was filtered through a pre-weighed 0.45 µm pore diameter filter paper. The filtering apparatus were then connected by inserting the shaped filter paper into the funnel appropriately and filtered to a conical flask. Water samples were filtered through the filtering apparatus and the resulting residue in the filter papers were dried at room temperature.

Total Suspended Solid (TSS) was then calculated in mg/l using:

\[
\text{TSS} = \frac{(A-B)}{\text{vol of sample (ml)}} \times 1000
\]

where A is the weight of the dried filter paper containing residues measured by a chemical balance (mg) and B is the weight of dry filter paper (mg) before experiment.

Plate 7: Sediment Sampling Analysis at the Chemistry Department of the University of Ilorin, Ilorin
2.6 Model Configuration and Setup

The configuration and setting up of MWSWAT model starts with the projection of all required spatial datasets to the same projection called UTM Zone 31N Northern Hemisphere, which is the universal transverse Mercator projection parameters for the selected watershed area in Nigeria using ArcGIS 9.1. Other steps involved in the configuration and setting up are as follows:

2.6.1 Automatic Watershed Delineation

To start the delineation process, the Automatic Watershed Delineation (AWD) dialogue box has to be launched from the model interface and the base DEM should be selected by browsing to the file location. The elevation units is set to meters and this should be applicable to the base DEM (Figure 2.6).
Figure 2.6: Interface of Mapwindow GIS Automatic Watershed Delineation Plug-in

Focusing mask which encapsulates the watershed was drawn and saved as a shape file. The threshold size of the subbasin was set for the model and this can be set by area, in various units (sq km, hectare) or by number of cells. For this study, a threshold value of 100 km$^2$ is used. In order to complete the settings for watershed delineation, an outlet point, which should be in the form of a shapefile need to be created and selected. For the selected watershed, a total of 77 sub-basins were delineated after running the AWD (Figure 2.7).
2.6.2 Creation of Hydrological Response Units (HRUs)

The creation of HRUs that are used by SWAT followed immediately after the watershed delineation. This is the division of subbasins into smaller pieces each of which has a particular soil and landuse or slope range combination. In order to achieve this, the already prepared landuse and soil maps were selected and the relevant database tables read by the model. Recommended thresholds of 10% for land cover and 5% for the soil area were used and a slope band of 0, 10, 20 and 90% were used for the modelling exercise (Leon, 2011). A multiple HRUs option was also selected and this process further subdivided the subbasins into 107 HRUs each with unique combination of landuse, slope and soil (Figure 2.8). Subdividing the sub watershed into areas having unique land use, soil and slope combinations made it possible to study the differences in evapo-transpiration and other hydro-logic conditions for different land covers, soils and slopes (Setegn et al., 2008).

Figure 2.7: Delineation of Study Area into Subbasins
2.6.3 SWAT Setup and Run

This step involves the settings of the simulation period (start and finish date) for the modelling exercise and the selection of the weather sources from the SWAT data base. Also, at this stage, an option to choose the methods for the estimation of surface runoff (Curve Number or Green and Ampt method), channel water routing (variable or Muskingum method), potential evapo-transpiration (Priestley, Penman-Monteith or Hargreaves) are available. For this case study, SWAT was executed using the Runoff Curve Number method for estimating surface runoff from precipitation. The SCS curve number method is a rainfall-runoff model that was designed for computing excess rainfall (direct runoff). This method assumes an initial abstraction before ponding that is related to curve number. This method was adopted in this study because of its widely applications in many countries due to its perceived simplicity, predictability, stability and its reliance on only one parameter (Ponce...
and Hawkins, 1996). King et al. (1999) have also shown that curve number method has a better prediction in SWAT applications when compared with the Green-Ampt method. The Hargreaves method was adopted for estimating potential evapo-transpiration generation because of its simplified equation which requires only two climatic parameters, that is, the temperature and incident radiation. This method has also been recommended for use in cases where reliable data are lacking (Alkaeed, et al. 2006). The variable-storage routing method which causes the outflow volume to be a function of the storage coefficient and the volume stored was selected to simulate channel water routing. The simulation period is from 01 January 1985 to Dec 31 2010. All the necessary files needed to run SWAT were written at this level and the appropriate selection of weather sources done before running the SWAT executables.

2.6.4 Visualization of Results

The SWAT outputs can be visualized in two different forms. One of this is to use a stand-alone SWATPLOT application which is a tool designed to select SWAT output values from the files (output.rch, output.sub, output.hru, output.rsv and output.wtr.). The normal way to plot such values is to import the SWAT output file into Excel, use an Excel filter to select the reach, subbasin, hru and reservoir and then use Excel graphing facilities to draw graphs or histograms format (George, 2008). Alternatively, shape file could also be created on the Mapwindow interface. The idea is to display the results of one of the SWAT outputs on the interface using appropriate legends for the displayed outputs. However, the intended result layer to be shown on the interface has to be ‘switched on’ while at the same time dragged to the top of other layers on the MapWindow interface. The outputs can be visualized either statically or dynamically (animation) mode.

2.7 Catchment Management Intervention Scenarios

Catchment management intervention involves an introduction of best management practices (BMPs) to curb soil erosion and sediment transport. The BMPs were represented in the SWAT model by modifying SWAT 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.
The selection of BMPs and their parameters were based on similar researches in the literature most especially, those involving catchments in Africa (Betrie et al., 2011; Huninks et al, 2013). It was also noted that the upstream watershed of Jebba dam has been plagued with massive deforestation by local people living in the area. The felled trees are used for commercial production of charcoal as cooking fuel which has contributed immensely to erosion in the area (see Plate 9).

Plate 9: One of the Charcoal Depots that can be found within the Study Area

Selected BMPs considered in this work are (a) vegetative filter strips and (b) reforestation and (c) Stone Bunds. According to Betrie et al., (2011), each of the BMPs has a different effect on flow and sediment, therefore, each has distinct representation of parameters. Vegetative filter strips are narrow buffer strips about 1m 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 as shown in Figure 2.9.
Reforestation of the watershed was also 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 USLE_support practice factor in the SWAT database. Four (4) sediment management scenarios were developed to study their effect as erosion control measures in the watershed area. The descriptions of the scenarios are as summarised in Table 3.2.

Scenario A was developed to simulate the watershed existing conditions before the implementation of BMPs. The calibrated values of the SWAT model were used in this simulation without altering any modelling parameters. The results obtained may provide a guide in selecting the implementation areas for other scenarios. Also, it will provide basis for comparison with other scenarios on the impact made through the introduction of sediment management interventions.
Scenario B was developed to simulate the impact of reforestation on sheet erosion in the areas that has been affected by massive deforestation by the inhabitants of the area for years. Also, the implementation area of this scenario will capture severe and extreme erosion prone areas from the result of scenario A. It was opined that the planting of trees at the targeted intervention area will provide good soil cover and thereby reduce overland flow at the area. The implementation area will be 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 formed to assess the effect of Buffer Strip on erosion process of the watershed. The Buffer Strip 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 1m in SWAT. The scenario was implemented in agricultural 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 (SLSUBBSN) and the USLE support practice factor (USLE P). The value of SLSUBBSN 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 re-running of the model. In this scenario, the modified parameters values of SLSUBBSN is equal to 10 m for the slope classes, USLE P is adjusted from calibrated of 1 to 0.32. These values were as used by Betrie, et al (2011) in a similar study. However, CN value was modified from calibrated value of 79.6 to 59 and this was obtained from the SWAT user’s manual version 2005 for contoured and terraced condition (Neitsch et al., 2005). Table 2.7 shows the summary of the sediment management scenarios and the corresponding SWAT parameter modified.
Table 2.7: Description of Sediment Management Scenarios used in the Study

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Description</th>
<th>SWAT parameter modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Existing Condition</td>
<td>Assigned by SWAT</td>
</tr>
<tr>
<td>B</td>
<td>Reforestation</td>
<td>Initial Land Cover (.mgt)</td>
</tr>
<tr>
<td>C</td>
<td>Filter Strips</td>
<td>Filter width FILTERW(.hru)</td>
</tr>
<tr>
<td>D</td>
<td>Stone Bunds</td>
<td>Curve Number(.hru), Slope Length, USLE Support Factor (.mgt)</td>
</tr>
</tbody>
</table>
CHAPTER THREE

3.0 RESULTS AND DISCUSSION

3.1.1 Stream Flow Calibration and Validation

Performance evaluation of the model was done by comparing the observed and simulated monthly inflow at Jebba gauge station for both the calibration and validation periods. In total, 14 parameters were selected to be calibrated through the Parasol optimization method. The model was calibrated with the observed monthly inflow of Jebba Lake from 1990 to 1992, and cross-validated with another set of independent data set from 1993 -1995.

The results of the calibration are presented in Figure 3.1 and 3.2 for calibration, while Figures 3.3 and 3.4 are for the validation period. As it can be seen from the Figures, there is a good correlation between the observed flow and the simulated flow, indicated by NSE and $R^2$ of 0.76 and 0.72, respectively, for calibration period, and NSE and $R^2$ of 0.70 and 0.78, respectively, for the validation period. In addition, the correlation coefficient of 0.85 for calibration data and correlation coefficient of 0.88 for the validation data indicate that the experimental data are reliable. Furthermore, the data for the calibration and the validation exercises are within the confidence interval of 95% (see Figures 4.3 and 4.5)

**Figure 3:1:** Simulated Versus Observed Monthly Flow during the Calibration Period (1990-1992)
Figure 3: Comparison of Simulated and Observed flows during the Calibration Period (1990-1992)

Figure 3: Simulated and Observed Monthly Flow during the Validation Period (1993-1996)
3.1.2 Sediment load Calibration and Validation

In order to carry out the calibration and validation of the model using the suspended sediment concentration along the tributaries, the model was simulated from May 2013 to December 2013 using the weather flow data corresponding to the period for simulation in SWAT. The observed sediment data obtained through suspended sediment sampling along the three tributaries into Jebba lake were divided into two independent datasets. Those collected from May to August 2013 were used for model calibration and observed sediment data from September - December, 2013 were used for model validation.

Summary of the performance evaluation on the model results using statistical parameters, NSE and Coefficient of determination $R^2$ is as shown in Table 3.1. A spatially distributed calibration and validation of sediment data was established at the three different locations where sediment data were collected for the watershed. Spatially distributed calibration and validation of SWAT model has been reported to enhance the reliability of simulation most especially in large watershed (Qi and Grunwald, 2005). The fit between the model sediment

Figure 3:4: Comparison of Simulated and Observed flows during the Validation Period (1993-1996)
predictions and the observed concentrations at both the calibration and validation stage for the locations are as presented in Figures 3.5-3.7. The comparison of the observed sediment concentration and the simulated values were as presented in Figure 3.8-3.10.

### Table 3.1: Summary of the Performance Evaluation of Sedimentation Modelling of Measured Data at River Sites

<table>
<thead>
<tr>
<th>Sampling Point</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R²</td>
<td>NSE</td>
</tr>
<tr>
<td>River Awun</td>
<td>0.60</td>
<td>0.82</td>
</tr>
<tr>
<td>River Eku</td>
<td>0.68</td>
<td>0.66</td>
</tr>
<tr>
<td>Confluence of R.Niger/Kotangora</td>
<td>0.57</td>
<td>0.8</td>
</tr>
</tbody>
</table>

As indicated in Table 3.1, 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, R² = 0.60 for calibration period and NSE = 0.72, and R² value of 0.65 in the validation period. River Eku also performed well during the calibration and validation period with the NSE and R² values above the standard limit as specified by Moriasi, et al. (2007). Further analysis of the results showed that the values of R² and NSE (0.57 and 0.8) for the calibration period of River Niger/Kotangora are within the acceptable values while the model performance during the validation period could be regarded as unsatisfactory with (R²=0.23, NSE=0.48). This could not be unconnected with excess sediments load reaching the sampling point as a result of the activities of local miners which could not be adequately captured by the model.
Figure 3.5: Showing (a) Calibration and (b) Validation plots for River Awun
Figure 3.6: Showing (a) Calibration and (b) Validation plots for River Eku

(a) 

(b) 

y = 1.044x + 4.438  
R² = 0.644

y = 1.489x + 2.168  
R² = 0.868
Figure 3.7: Showing (a) Calibration and (b) Validation plots for River Niger/Kotangora

(a) $y = 0.684x + 25.83$
$R^2 = 0.574$

(b) $y = 0.314x + 46.00$
$R^2 = 0.230$
Figure 3.8: Comparison between Observed and Simulated Sediment along River Awun for both Calibration and Validation Period

Figure 3.9: Comparison between Observed and Simulated Sediment along River Eku for both Calibration and Validation Period
Figure 3.10: Comparison between observed and simulated sediment along River Niger/Kotangora for both calibration and validation period

3.2 Assessment of Sediment Yield and Sediment Concentration

3.2.1 Total Sediment Yield

The predicted total sediment yield for each of the 77 subbasins is as shown in Figure 3.11 and displayed as bar chart in Figure 3.12. 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 2,217, 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. Annual sediment production in the watershed was estimated as 255.8 t/ha/yr which translate to about $8.31 \times 10^9$ tons of sediment between 1984 and 2010.
Figure 3.11: Predicted Annual Sediment Yield for each of the Subbasins in the Watershed

Figure 3.12 Simulated Annual Sediment Yield in each of the 77 Subbasins in the Study Area
3.2.2 Sediment Concentration

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 3.13. 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 having a value of 108.6mg/l. The contribution of the release from Kainji dam upstream of the modelled watershed was estimated as 207.9 mg/l. Other details on the sediment concentration in each of the reach within subbasins could be found in Appendix H.

Figure 3.13 : Sediment Concentrations in each of the subbasins in the watershed area

3.3 Temporal Variations of Suspended Sediment along Selected Rivers and Tributaries within the Watershed

The temporal variations of suspended sediment concentration of the selected three tributaries into Jebba Lake are as displayed in Figure 3.14 -3.16 and summarised in Table 4.2. The
results showed that the sediment concentration for River Awun ranged from the lowest value of 2.2mg/l in the month of December and has the highest concentration of 230mg/l in October. In the case of River Eku, the lowest sediment concentration value of 0.7mg/l was recorded in the month of December while highest value of 93.5mg/l took place in the month of November, 2013. Sediment concentration values at the confluence of River Niger and Kontagora ranged from the lowest value of 22.5mg/l in the month of December to highest value of 255mg/l in September, 2013.

In a similar study conducted by Kiragu, et al. (2011) where the levels and constituents of the suspended sediment loading in the upper basin of Mara River (Kenya) and how they relate to the environmental flow requirements of the basin were determined, it was discovered that the sediment concentration for Nyang’ores river in the basin ranged from 35.5 mg/l to 268.5 mg/l, while the sediment loading for the Amala River ranged from 26.4 mg/l to 258 mg/l. Also, Lai and Samsuddin (1985) observed and measured suspended and dissolved sediment concentrations from two disturbed watersheds situated in Selangor, Malaysia over a period of six months. The result showed that suspended sediment concentrations ranged from 2 to 1305 mg/l for watershed A, a relatively more disturbed watershed and 1 to 292 mg/l for watershed B, a less disturbed catchment.

![Figure 3.14: Variation of Suspended Sediment Concentrations at River Awun Sampling Location](image-url)
Figure 3.15: Variation of Suspended Sediment Concentrations at River Eku Location

Figure 3.16: Variation of Suspended Sediment Concentrations at River Niger /Kotangora Location

Generally, it was noticed that the average sediment concentration at the confluence of rivers Niger/Kotangora (104.8mg/l) are higher than that of River Eku (26.2mg/l) and Awun (75.4mg/l). The higher values obtained at this location may be attributed to activities of some local inhabitants of the area along river Kontogora. The people in the area engage in mining for precious stones through digging of holes at the embankment of river Kotangora, resulting
into substantive quantities of dugged soil placed at the river bank. This could be eroded and taken into suspension in the event of increased flow of water during and immediately after intensive rainfall in the area. (Plate 10 shows local miners along River Kontagora). There was also evidence of soil and gully erosion in the farms around the Rivers Niger and Kontagora. The activities of herdsmen rearing cows along the bank of the river may also contribute to higher sediment concentration obtained in River Niger/Kontagora.

Table 3.2: Summary of the Temporal Variation of Suspended Sediment Sampling along the Tributaries

<table>
<thead>
<tr>
<th>Sampling Locations</th>
<th>Lowest Value(mg/l) (Month)</th>
<th>Highest Value (mg/l) (Month)</th>
<th>Average value(mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Along River Awun</td>
<td>2.2 (December)</td>
<td>230 (October)</td>
<td>75.4</td>
</tr>
<tr>
<td>Along River Eku</td>
<td>0.7 (December)</td>
<td>93.5 (November)</td>
<td>26.2</td>
</tr>
<tr>
<td>Confluence of R.Niger and Kotangora</td>
<td>22.5 (December)</td>
<td>255 (September)</td>
<td>104.8</td>
</tr>
</tbody>
</table>

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Plate 10: 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

### 3.4 Sediment Concentration and Turbidity Relationship

Turbidity is a measure of water clarity. It shows how the material suspended in water decreases the passage of light through the water (EPA, 2013). The relationships between the sediment concentration and turbidity at the three sampling sites were established using the results of sediment sample analysis (Figures 3.17 -3.18). The regression analysis equations for the three sampling locations are as written as follows:

(a) River Awun

Turbidity= 0.5968 *sediment concentration+ 0.2036, \( R^2 =0.7571 \)

(b) River Eku

Turbidity= 0.6407*sediment concentration+ 2.0551, \( R^2 =0.9638 \)

(c) River Niger/Kotangora

Turbidity= 0.6407*sediment concentration+ 7.606, \( R^2 =0.8114 \)

River Awun has a range of turbidity values between 4.2NTU in December and 147 NTU in October, 2013. River Eku turbidity values ranged from 2.2 NTU in October to 63.5 NTU in November 2103. Samples taken at the confluence of River Niger and Kontagora has a range of 3.2 NTU in December to 187.5 NTU in September, 2013. Further analysis of the results showed that river Kotangora was the most turbid with average turbidity value of 77.7NTU
followed by River Awun with average turbidity value of 50.39NTU. River Eku was the least turbid of all the three locations with average turbidity value of 15.8NTU. The turbidity equations derived for the tributaries could be used to estimate the suspended sediment concentrations of the rivers once the turbidity of the river is known. This result is in line with the work of Kiragu, et al.(2011) where a range of 64.4 NTU to 266.6 NTU was obtained for Amara river and 59.5- 236.14 NTU for Nyang’ores river. Both rivers are tributaries to Mara River, which is an international river shared by Kenya and Tanzania.

![Figure 3.17: Relationship between Suspended Sediment and Turbidity at River Awun](image1)

![Figure 3.18: Relationship between Suspended Sediment and Turbidity at River Eku](image2)
Figure 3.19: Relationship between Suspended Sediment and Turbidity at River Niger/Kotangora

3.5 Watershed Sediment Management Scenarios

3.5.1 Scenario A (Existing or Do Nothing)

Soil erosion prone areas of the watershed were identified for the existing condition using the average annual sediment yield from each of the subbasin. The erosion classes are categorised into four levels. These are 0-20 t/ha/year as low, 20-30 t/ha/year as moderate, 30-60 t/ha/year as severe and above 60 t/ha/year as extreme. Figure 3.20 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 level of variation of erosion within the catchment which can be employed in prioritising BMPs implementation strategy.
To study the effect of the three BMPs (i.e. Reforestation, Filter strips and Stone Bunds) for the case study area, erosion prone area of the existing vegetation was used as a guide in selecting the implementation area for the two scenarios. All the subbasins in the severe and extreme zones were initially used as implementation area. This consists of 33 subbasins in the severe and only one subbasin in the extreme zone. The total implementation area was 6,049 ha which was about 47% of the total watershed area.

![Figure 3.20: Relative Erosion Prone Areas of the Existing Watershed Scenario using Calibrated SWAT Model Results.](image)

### 3.5.2 Scenario B (Reforestation)

The impact of reforestation in the area showed that the total sediment yield of the area was reduced 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 zone from what was obtainable in the existing condition scenario. 37 subbasins are now in the low (0-20 t/ha) category while 38 subbasins are now in the moderate zone (20-30 t/ha) and 2 subbasins in the severe (30-60 t/ha) zone. There was no sub-basin 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 area. 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%. At this level, the erosion zone of the area is made up of only the low (0-20) category. Figure 3.21 depicts the erosion classifications after the introduction of reforestation at the extreme and severe erosion zone of the watershed area. The simulation of reforestation scenario by Betrie et al. (2011) showed the least reduction of sediment loads ($104 \times 10^6$ yr$^{-1}$) from current conditions with 46% to 77% reduction in sediment yield under reforestation scenario.

![Figure 3.21: Erosion Prone Area after Introduction of Reforestation at Selected Locations in the Study Area](image)

### 3.5.3 Scenario C (Vegetative Filter Strip)

In the case of scenario C, the introduction of filter strip of width 1m in the implementation area brought a higher reduction in sediment yield of the area. 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 (20-30 t/ha) zone. 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. The impact of the vegetative filter strip in reducing the sediment yield at the watershed was further
investigated by implementing the management option the watershed with the inclusion of moderate zone of the erosion classification. The total implementation area is about 12,602 ha representing 96.9% of the watershed. Modelling results showed that the sediment yield of the area reduced by additional 488.14 t/ha. This increased the percentage sediment reduction in the area to 69.6%. The erosion classification has only the low (0-20 t/ha) category. Figure 3.22 depicts the erosion classification after the introduction of vegetative filter strip at the watershed area. Betrie, et al. (2011) in a related study revealed that the filter strips scenario reduced the sediment yield by 29% to 68% which is greater than sediment reductions under stone bunds scenario for equal implementation area.

Figure 3.22: Erosion Prone Area after Introduction of Filter Strips at Selected Locations in the Study Area

3.5.4 Scenario D (Stone Bunds)

The simulation of stone bund scenario showed the least reduction of sediment yield from the existing conditions at the watershed upstream of Jebba hydropower reservoir. Modelling results showed that total sediment reduction of about 258.18 t/ha was achieved using the scenario. This represents approximately 11.33% reduction in the total sediment yield reduction. The configuration of the erosion prone areas is as depicted in Figure 3.23. 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 subbasin is in the extreme zone. A similar study by Betrie et al. (2011), the sediment reductions ranged from 9% to 69% under stone bunds scenario.

Figure 3.23: Erosion Prone Area after Introduction of Stone Bunds at Selected Locations in the Study Area
CHAPTER FOUR

4.0 CONCLUSION AND RECOMMENDATIONS

4.1 Introduction

In this study, a physically based distributed hydrological model, SWAT2009 was interfaced with MapWindow GIS software. The model was applied to simulate the hydrology, predict the sediment yield and identify erosion prone areas of a watershed situated at the upstream of Jebba reservoir in Nigeria. The preparation of thematic maps and database necessary for the successful running of the model was carried out using the GIS components.

The model was run at a daily time step for a period of 26 years (1985 to 2010) using data collected from local agencies and global database. A sensitivity analysis of model parameters (flow and sediment) was carried out to identify most sensitive parameters on model results. Flow prediction by SWAT was calibrated and validated against measured flow data from 1990 to 1995 while the performance evaluation of the model was achieved using coefficient of determination (R²) and Nasch-Sutcliffe Efficiency (NSE).

Sediment samples were also collected from three locations within the watershed between May to December, 2013 using suspended sediment sampler USDH-2A. The results from the laboratory analysis of the samples were processed and used to spatially calibrate and validate the model. Four sediment management scenarios: existing condition (do nothing), reforestation, vegetative filter strip (VFS) and construction of stone bunds were developed to study the effect of applying BMPs for sediment reduction into the watershed. Also, cost analysis of implementing the selected erosion control measures within the watershed was carried out and these were compared with the cost implication of not implementing any of the sediment management measures at the watershed. This study has shown that modelling approach could be helpful for decision makers to evaluate the cost and benefits of particular BMP measures.
4.2 Conclusions

Based on the outcome of this study, certain conclusion could be drawn at each state of the research and these are as presented. The calibration and validation stage of the model shows has shown that curve number (CN) is the most sensitive parameter that affected both stream and sediment flows within the catchment. The performance evaluation of the model using statistical method (coefficient of $R^2$ and NSE) revealed a satisfactory performance for stream flow as both $R^2$ and NSE were greater than 0.7. However, performance evaluation of sediment flow at three different locations (Awun, Eku and Kontogora) in the watershed showed that the model performed well at both calibration and validation stage for the River Awun and Eku, but the validation period of River Kontogora/Niger did not produce acceptable results.

Temporal variation of suspended sediment along three tributaries into Jebba Lake was also studied. The results showed that River Niger/ Kotangora has an average sediment concentration of (104.8mg/l) during the sediment sampling period followed by River Awun (75.4mg/l) and River Eku (26.2mg/l). The higher sediment concentration along River Niger/Kontogora may be attributed to activities of local miners along the two rivers.

The relationship between sediment concentration and turbidity was also established and regression equations for the three sampling locations showed a high correlation between sediment concentration and turbidity. The developed sediment rating equations can be used as sediment monitoring tools for the three sampling locations.

The results of the estimation of the useful life of Jebba hydropower reservoir revealed that the dead storage of the reservoir ($1 \times 10^9 \text{ m}^3$) will be completely filled with sediment after 33 years in operation of the dam, that is, from 1984 to 2017. Also, the result indicated that the useful life of Jebba reservoir is estimated as 168 years (1984-2152) when about 80% of the total capacity of the reservoir would have been lost due to sediment deposition in the reservoir.

The SWAT model was also used to study the effect of Best Management Practices (BMPs) on sediment reduction at the upstream watershed of Jebba Lake. Four scenarios were developed with scenario A depicting the existing condition (do nothing), scenario B is reforestation,
scenario C is use of vegetative filter strips and scenario D is the construction of stone bunds in some of the areas plagued by soil erosion. For existing scenario, the total sediment yield was 2,358.83 t/ha in all the 77 subbasins for the simulation period. The erosion areas were also classified into four zones: (0-20 t/ha) as low zone and has 5 subbasins, (20-30t/ha) as moderate zone with 38 subbasins dominating the area, (30-60t/ha) as severe zone dominated 33 subbasins and (60-100t/ha) as extreme zone has only one subbasins.

Scenario B, the introduction of reforestation into highly prone erosion area of the watershed reduced the sediment yield by 46.4%. However, when the management method was extended to include the moderate zone of the erosion prone areas, the sediment load reduction increased and has a percentage reduction of 63.4% was obtained. For Scenario C, which was the effect of applying filter strip, the existing sediment yield at both the subbasins and basin level by 48.9%. This was increased to 65.6% when the management option was extended to cover the moderate zone of the erosion prone areas of the watershed. Scenario D, the application of stone bunds reduced the sediment production in the watershed by about 12%. These results indicate that the application of BMPs could be effective in reducing sediment transport for sustainable water resources management of the basin. However, the implementation of catchment management measures to reduce sediment yield in the area entails the use of resources and the willingness of the decision makers.

Generally, the performance obtained with application of SWAT to Jebba Reservoir watershed suggests that the modelling tool could be a promising candidate to model the hydrology and predict the sediment yield for sustainable water and sediment management at basin and sub-basin levels in Nigeria. Overall, the study showed that hydrological modelling can be used to generate strategies for water resources management. In addition, it can provide policy makers the decision support tools to evaluate the cost and benefits of adopting BMPs particularly for sediment control in erosion prone watershed.
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