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HYDROLOGICAL MODELLING AND IDENTIFICATION OF EROSION-PRONE ZONES IN THE UPSTREAM CATCHMENT OF EDE DAM, NIGERIA USING SWAT

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ABSTRACT

This study evaluates hydrological processes and identifies erosion-prone zones in the upstream catchment of Ede Dam, Osun State, Nigeria, using the Soil and Water Assessment Tool (SWAT). Spatial datasets, including Digital Elevation Model (DEM), land use, and soil maps, were integrated with long-term climatic data (1991–2021) obtained from the Nigerian Meteorological Agency. The watershed was delineated into 21 sub-basins and 36 Hydrologic Response Units (HRUs). Model calibration and validation showed satisfactory performance with coefficient of determination (R^2) values of 0.70 for sediment yield and surface runoff, and 0.65 for streamflow. Peak streamflow (191.26 m³/s) and sediment yield (21.46 t/ha) were recorded in 2003 and 2006, respectively, while minimum values occurred in 2008. Sub-basins 3, 5, 11, 13, 14, and 15 were identified as erosion hotspots. The study demonstrates the effectiveness of SWAT integrated with geospatial data for hydrological modelling and sustainable watershed management.

Keywords: erosion, hydrological modelling, sediment yield, surface runoff, SWAT

1.0 INTRODUCTION

Soil erosion is a major environmental challenge affecting agricultural productivity and ecosystem sustainability. It results in the loss of nutrient-rich topsoil, which is essential for crop growth (Haregeweyn *et al*., 2017; Fenta *et al*., 2021). Globally, soils are increasingly under threat due to erosion, land degradation, and unsustainable land management practices (Montanarella *et al*., 2016). The interaction between rainfall and surface runoff plays a critical role in erosion processes, particularly in areas with high rainfall intensity and poor land management practices. Alewell *et al*. (2019) asserted that soil is degraded by erosion. There is a correlation between surface runoff and erosion, when there is precipitation and the soil is fully saturated results to surface runoff which leads to erosion. The first state of soil erosion are rills, and as time goes by it becomes severe and transforms into gully. In environmental planning and natural resources, quantifying soil loss is one of the biggest problems (Arekhi *et al.,* 2010). In Nigeria, soil erosion has accelerated over time and according to Parveen *et al*. (2012), it is dependent on a number of variables, including climate, land use and cover, slope steepness, and natural calamities like forest fires. Areas with a large fraction of vegetation are less likely to experience soil erosion, as topography regulates soil transport within a watershed (Prasannakumar *et al*., 2011).

The process of creating mathematical models that describe the physical processes of the hydrological cycle using software applications is known as hydrological modelling. The use of computer simulation models to forecast soil loss for different land use and management techniques is growing in popularity (Mosbahi *et al.*, 2013). The models simulate the flow of water through the catchment, the exchange of water between the atmosphere and the earth's surface, and the transport of sediment and nutrients in rivers and streams. Researchers worldwide have employed a wide range of techniques, such as process-based models, statistical models, empirical models, and physical models, to forecast soil erosion (Dimotta, 2019). An innovative physical-based catchment model called the Soil and Water Assessment Tool (SWAT) is used to identify places that are prone to erosion, predict runoff flow, and transport sediment.

The SWAT model, which uses weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, stream routing, and pond/reservoir routing, has been used in numerous studies to examine soil erosion by water or to assess the model's accuracy (Zhang *et al.* 2008). Soufiane *et al.* (2021) assessment was based on the Revised Universal Soil Loss Equation (RUSLE) and SWAT models in the Ouergha watershed. The estimate of erosion through SWAT was consolidated by constructing an erosion map through the RUSLE method using erosion factors. The Soil and Water Assessment Tool (SWAT) is widely used for simulating these processes due to its ability to incorporate spatial variability and long-term climate data.

This study focuses on the upstream catchment of Ede Dam, a vital water supply infrastructure in Osun State. The objectives are to:

1. Simulate streamflow, surface runoff, and sediment yield using SWAT
2. Evaluate model performance through calibration and validation
3. Identify erosion-prone sub-basins within the watershed

2.0 MATERIALS AND METHODOLOGY

2.1 Study Area Description

The study area is located in southwestern Nigeria on latitude 7°45′N and longitude 4°27′E, covering approximately 195 km². The watershed drains into Ede Dam through Erinle and Otin rivers (Figure 1). The terrain elevation ranges between 375 m and 758 m above sea level. The area is characterized by tropical climate conditions with distinct wet and dry seasons. Dominant land cover includes grassland and agricultural lands, while soil types are primarily loamy and sandy. The dam supports domestic water supply, irrigation, and fishing activities, making its sustainability crucial for regional development.

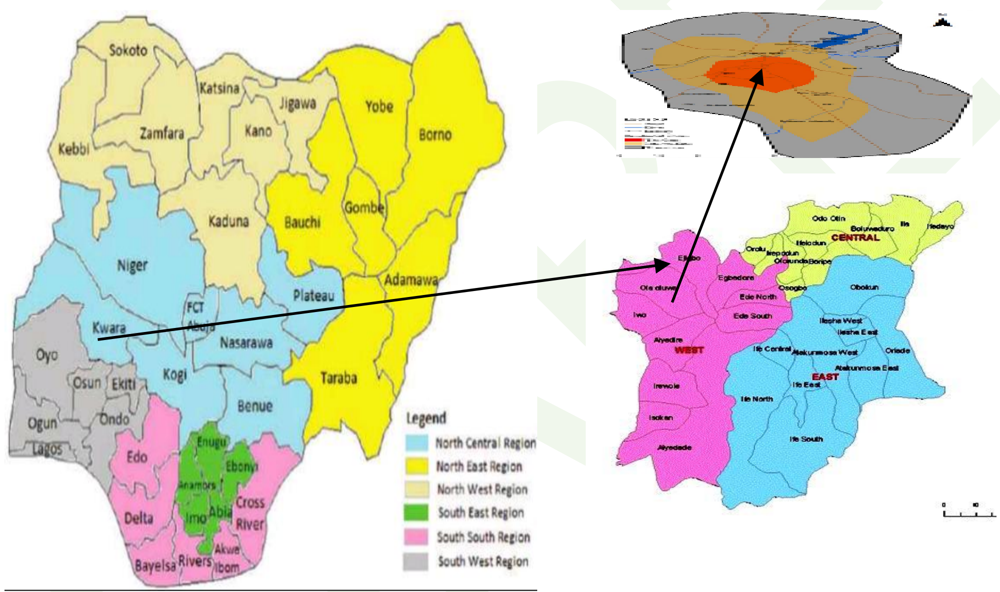

Figure 1. Location of study area (Ede Dam) within the map of Nigeria

2.2 SWAT Model Development

SWAT is a physically based, continuous-time hydrological model developed by the United States Department of Agriculture–Agricultural Research Service (USDA–ARS). It operates by dividing a watershed into sub-basins and Hydrologic Response Units (HRUs), representing unique combinations of land use, soil, and slope (Arnold *et al*., 2012; Di Lucio *et al*., 2004). The model has been widely validated across different climatic and hydrological conditions, demonstrating its robustness in watershed-scale simulations (Di Lucio *et al*., 2004). The model is based on the water balance equation as shown in equation 1:

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

Where:

SW_t : final soil water content (mm)

SW_o : initial soil water content (mm)

t : time (days)

R_{day} : precipitation (mm)

Q_{surf}: surface runoff (mm)

ET_i : evapo-transpiration (mm)

W_{seep} : soil interflow (mm)

Q_{gw} : return flow (mm).

2.3 Data Collection

Two types of data are required for modelling hydrological tools. They are spatial data and temporal data or weather data.

2.3.1 Spatial data

The spatial data comprises of these three major components as shown in Figures 2,3 and 4;

i. Digital Elevation Model (SRTM, 90 m resolution) obtained from the CGIAR-CSI database (CGIAR-CSI, 2012).
ii. Land use map (Global Land Cover Characterization database)
iii. Soil map (Harmonized World Soil Database, HWSD v1.1) which provides globally standardized soil property data for hydrological modelling (Nachtergaele *et al*., 2020).

The integration of globally recognized datasets such as SRTM DEM and the Harmonized World Soil Database ensures consistency and reliability in watershed characterization (CGIAR-CSI, 2012; Nachtergaele *et al*., 2020).

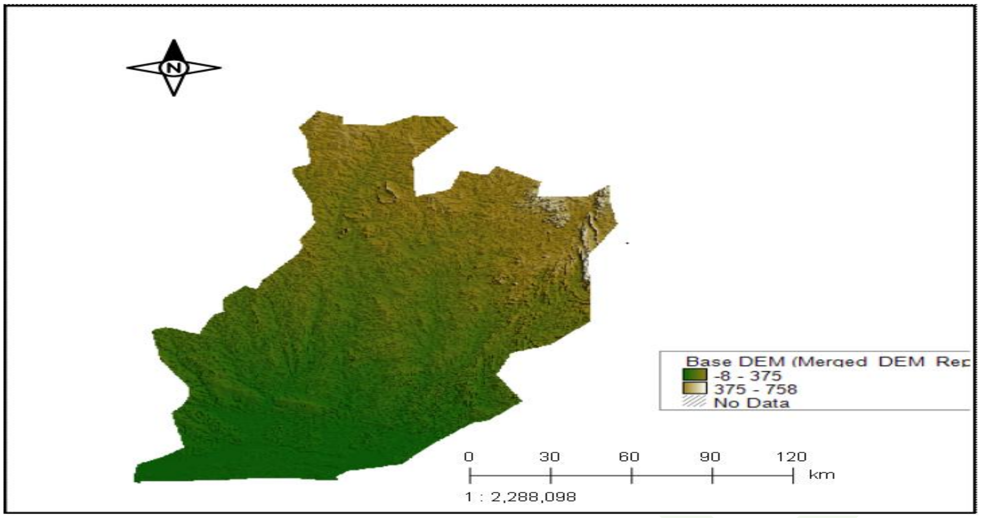

Figure 2. Digital Elevation Model (DEM) of the study area

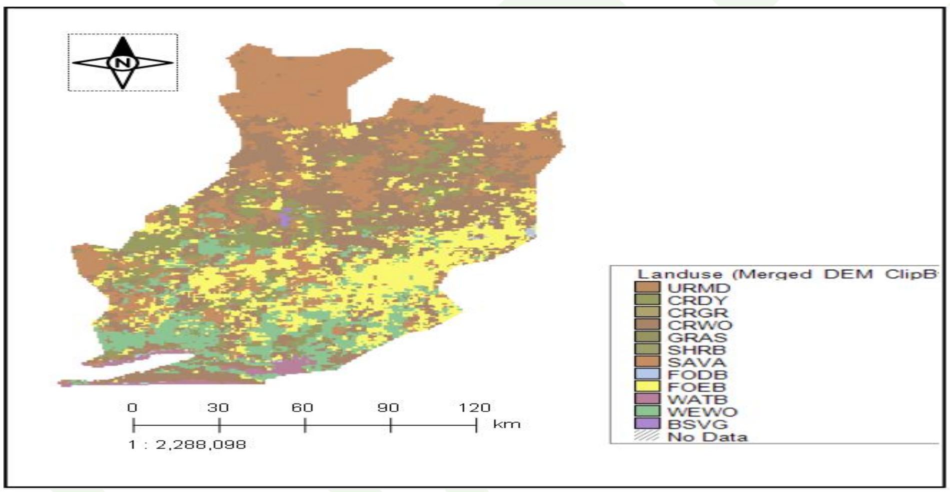

Figure 3. The generated land use map of the study area.

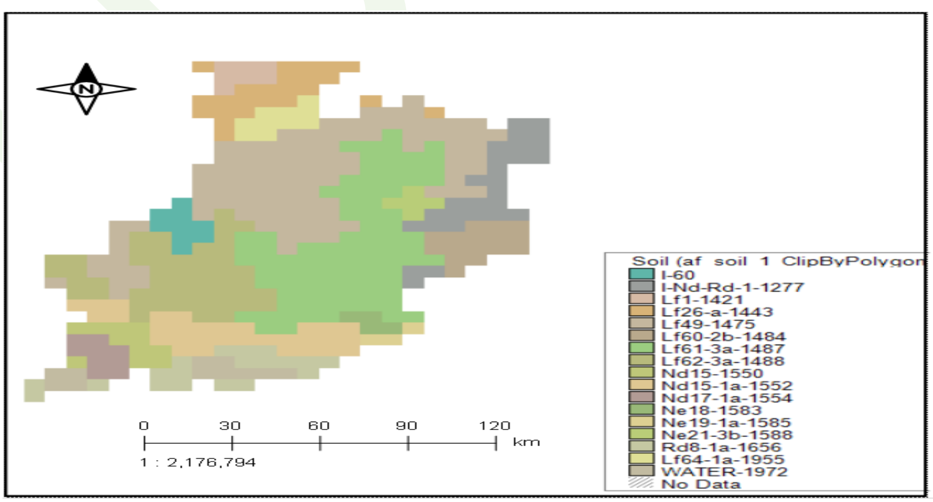

Figure 3. Developed soil map of the study area.

2.3.2 Temporal data

Daily climatic data (1991–2021) were obtained from the Nigerian Meteorological Agency, with missing data filled using the SWAT weather generator according to Arnold *et al.* (2011). These include Rainfall, Temperature, Relative humidity, Wind speed, Solar radiation.

2.4 Hydrologic Response Units (HRUs) Delineation

The watershed was delineated using DEM within the SWAT interface. A threshold area of 30 km² was applied, resulting in 21 sub-basins as shown in Figure 5 and 36 HRUs, each has a distinct mix of soil, slope, and land use.

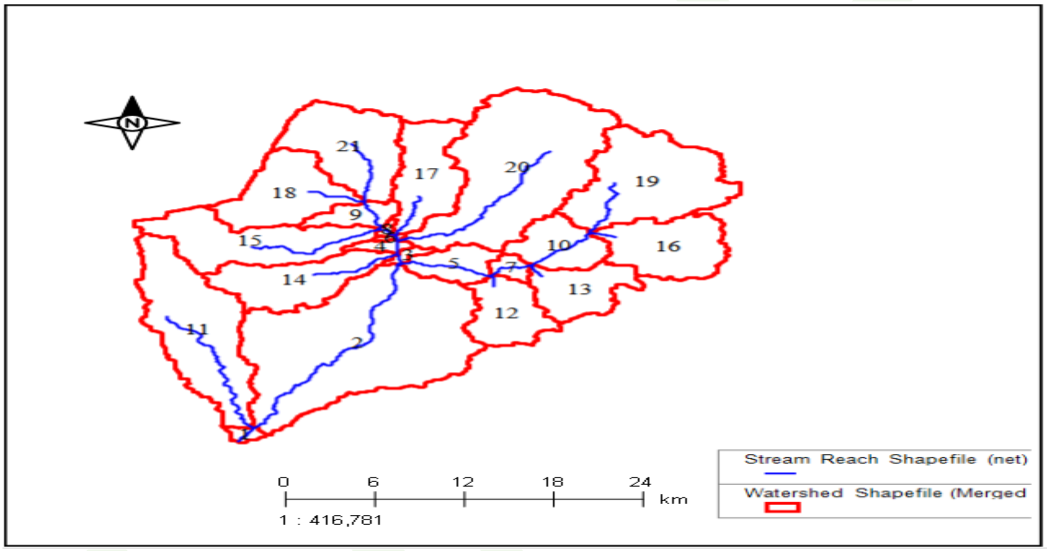

Figure 5. Delineation of watershed into Sub-basins

2.5 Model Setup

The major key modelling methods selected include:

i. Curve number method for runoff estimation
ii. Hargreaves method for evapotranspiration
iii. Variable storage method for channel routing

The simulation period spanned 1991–2021, with initial years used for model warm-up.

2.6 Calibration and Validation

Calibration involved adjusting model parameters to match observed data, while validation tested model reliability using independent datasets (Arnold *et al*., 2012). Model performance was evaluated using the coefficient of determination (R^2).

3.0 RESULTS AND DISCUSSION

3.1 Streamflow Simulation

The SWAT model adequately reproduced the temporal variation in streamflow within the study watershed. The peak flow of 191.26 m³/s recorded in 2003 corresponds to periods of high rainfall intensity, while the minimum flow of 30.31 m³/s observed in 2008 reflects reduced precipitation and possibly increased infiltration losses. The simulated streamflow pattern shows a strong dependence on rainfall variability, which is consistent with findings from previous studies in tropical catchments. Adeogun *et al.* (2014) reported similar hydrological responses in the upstream watershed of the Jebba Reservoir, where peak flows were strongly linked to rainfall intensity and distribution. This confirms that precipitation remains the dominant driver of streamflow generation in ungauged basins within the region. Flow variability corresponded strongly with rainfall distribution as shown in Figure 6.

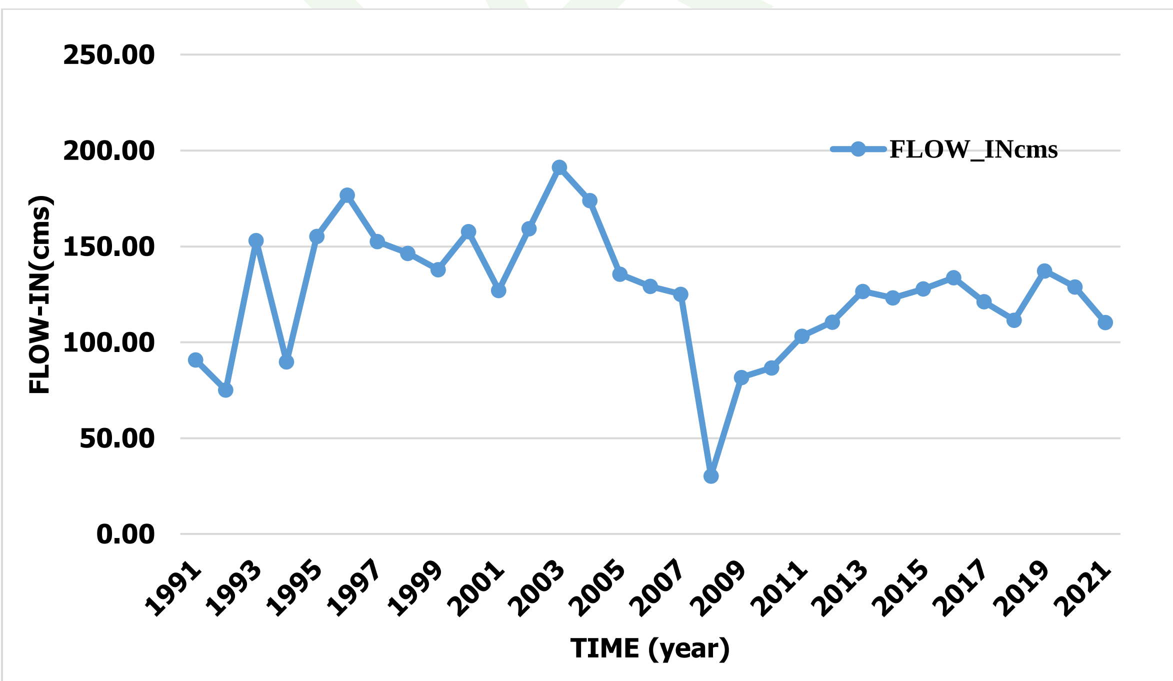

Figure 6. Simulated annual flow at the upstream of the dam.

3.2 Sediment Yield

Sediment yield exhibited significant inter-annual variability, with a maximum value of 21.46 t/ha in 2006 and a minimum of 2.49 t/ha in 2008, resulting in an average annual erosion rate of 8.37 t/ha/year. The elevated sediment yield in 2006 can be attributed to increased surface runoff and rainfall intensity, which enhance soil particle detachment and transport. This observation aligns with the work of Haregeweyn *et al.* (2017) and Fenta *et al.* (2021), who reported that sediment yield in tropical watersheds is highly sensitive to rainfall erosivity and land surface conditions. Furthermore, the results are consistent with SWAT-based studies that demonstrate a direct relationship between runoff volume and sediment transport capacity. Unlike earlier statements, the relationship between rainfall and sediment yield is not merely linear but influenced by additional factors such as land use, slope gradient, and soil characteristics. This explains the spatial variability observed across sub-basins in the study area.

A strong positive relationship was observed between rainfall, runoff, and sediment yield, indicating that increased precipitation enhances erosion processes as shown in Figure 7.

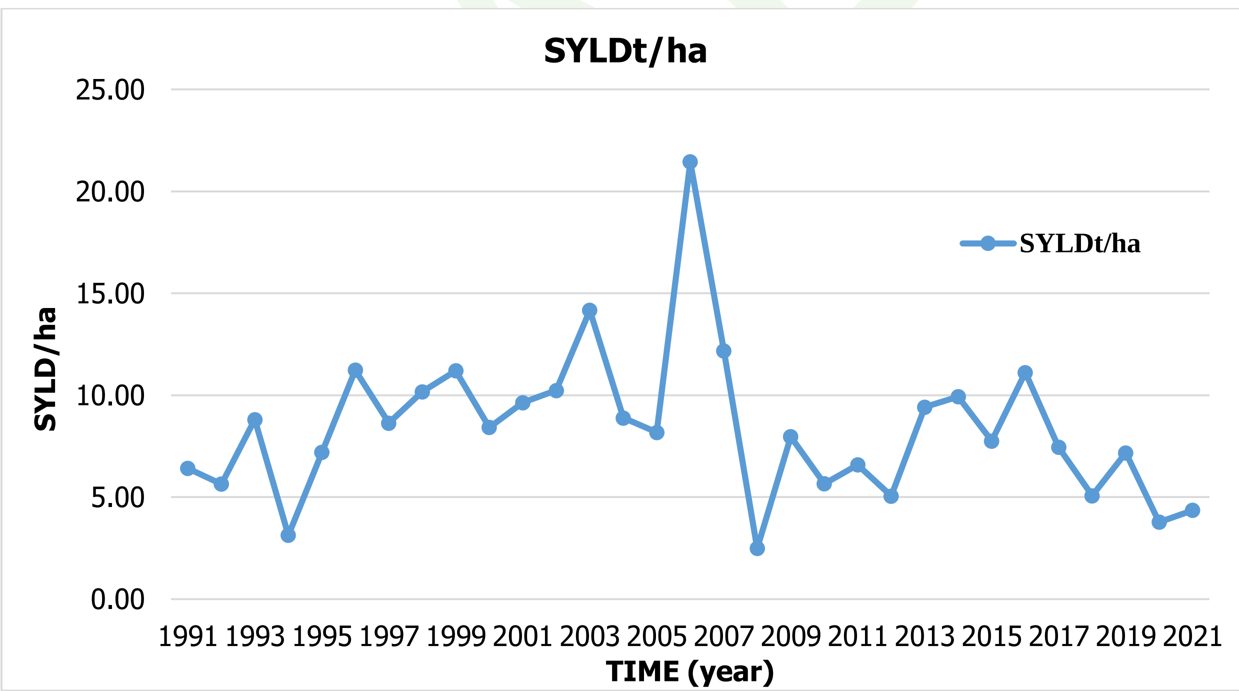

Figure 7. Simulated annual sediment yield at the upstream of Ede dam

3.3 Surface Runoff

Surface runoff varied considerably over the simulation period, with a maximum value of 666.67 mm in 2006 and a minimum of 56.55 mm in 2008. The trend closely follows rainfall distribution, indicating that runoff generation is primarily rainfall-driven in the watershed.

However, runoff response is also influenced by land use and soil properties. Areas dominated by agricultural activities and sparse vegetation tend to generate higher runoff due to reduced infiltration capacity. This finding supports the conclusions of Prasannakumar *et al.* (2011), who emphasized the role of land cover in regulating runoff and erosion processes. Runoff trends closely followed rainfall intensity, confirming the dependence of runoff generation on precipitation as shown in Figure 8.

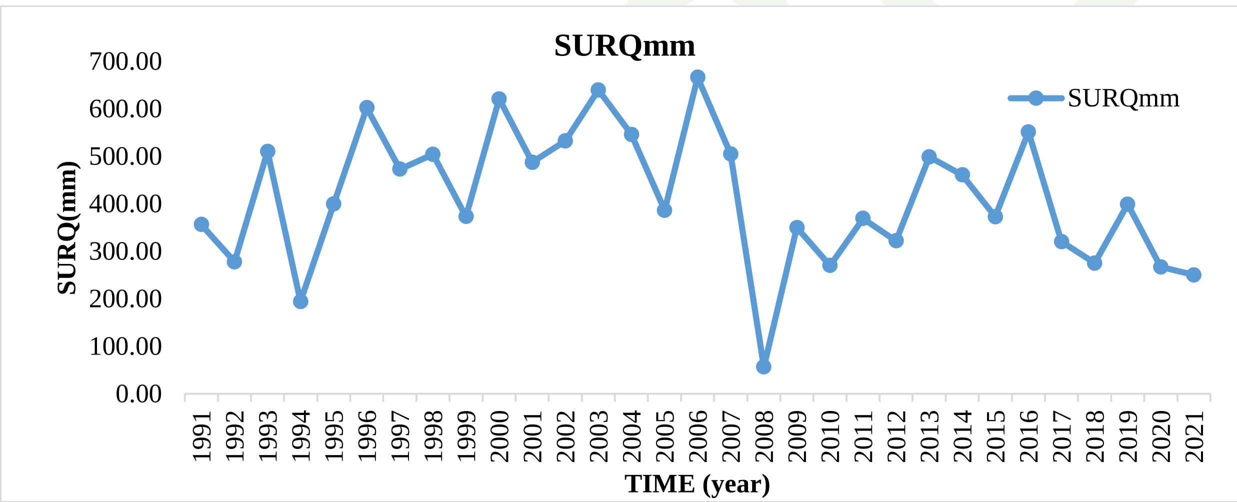

Figure 8. Simulated annual surface runoff at the upstream of Ede dam.

3.4 Model Performance

The model performance evaluation yielded coefficient of determination (R^2) values of 0.70 for sediment yield and surface runoff, and 0.65 for streamflow. These values indicate satisfactory model performance for hydrological simulations in data-scarce regions. Comparable studies using SWAT in similar environments have reported R^2 values within this range, suggesting that the model reliably captures the dominant hydrological processes. Adeogun *et al.* (2014) obtained similar performance metrics in a Nigerian watershed. These values indicate satisfactory model performance, consistent with similar studies as shown in Figures 9 and 10.

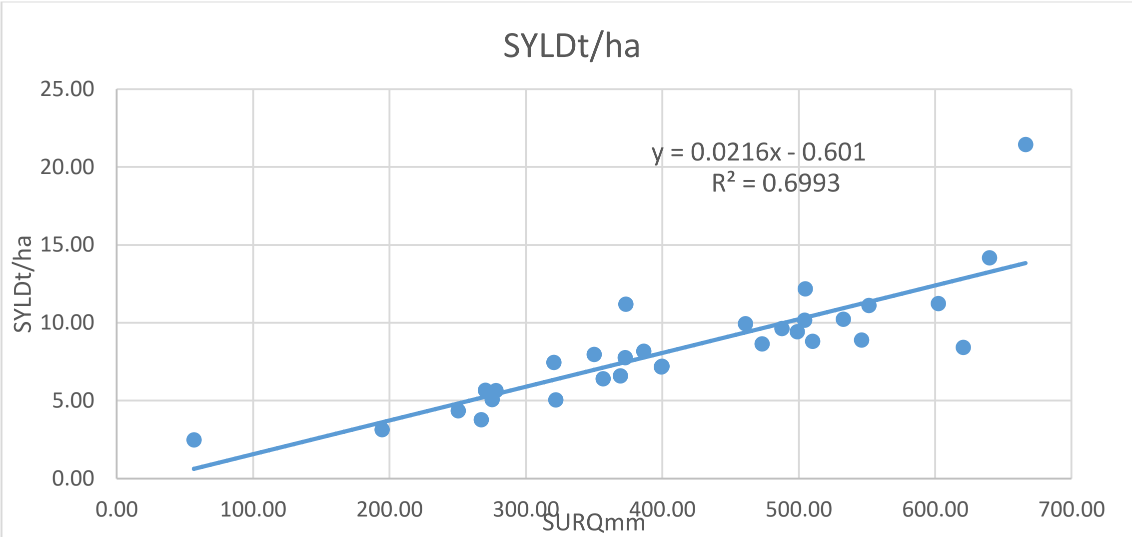

Figure 9. Relationship between sediment yield (SYLD) and surface runoff (SURQ)

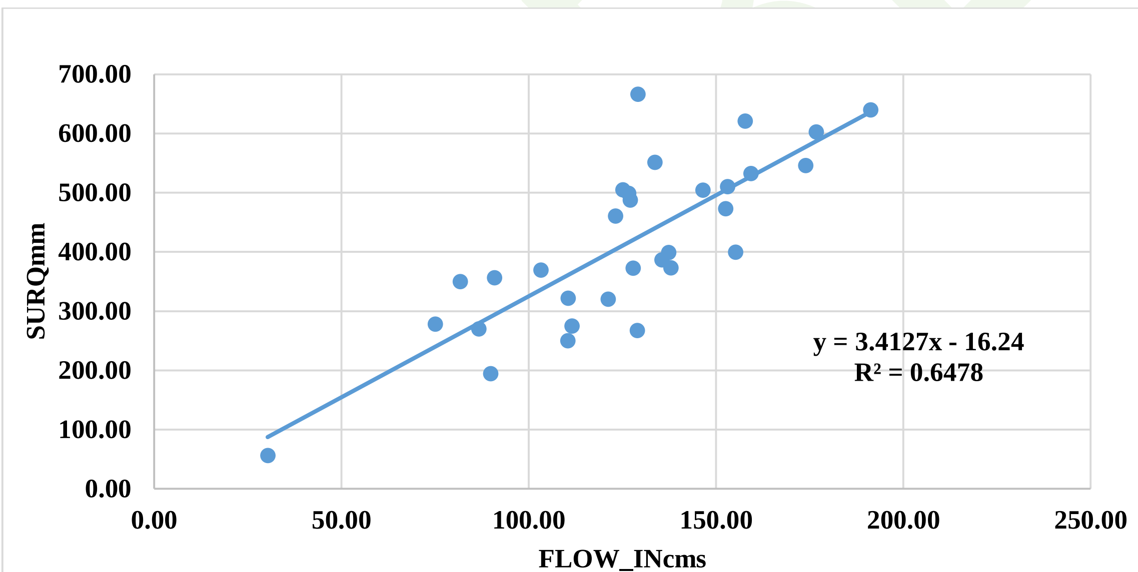

Figure 10. Interaction between surface runoff and simulated flow

3.5 Identification of Erosion-Prone Areas in the Basin

The spatial analysis identified sub-basins 3, 5, 11, 13, 14, and 15 as highly erosion-prone zones, while sub-basins 3, 4, and 7 exhibited high flow variability as shown in Figure 11. These areas are characterized by a combination of steep slopes, high runoff generation, and less protective vegetation cover. The spatial distribution of erosion risk highlights the influence of topography and land use on sediment dynamics. Similar spatial patterns have been reported in watershed studies using SWAT and GIS-based approaches, where erosion hotspots are typically associated with high slope gradients and anthropogenic land disturbances. These critical sub-basins require targeted soil conservation management measures such as afforestation and vegetation restoration, contour farming and construction of check dams and terraces. Implementing these interventions would significantly reduce sediment yield and improve the sustainability of the Ede Dam watershed.

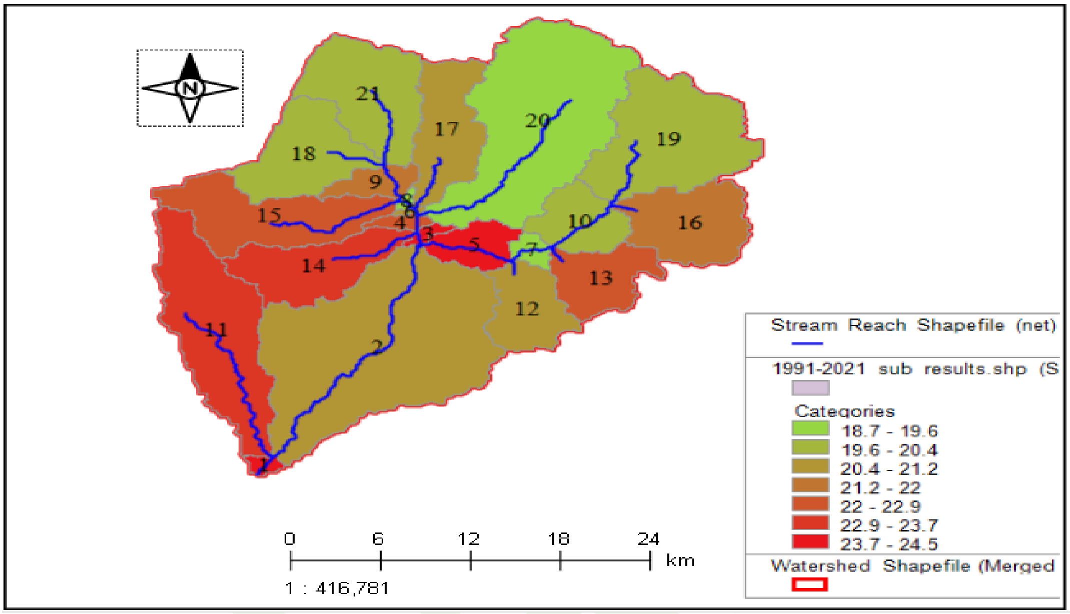

Figure 11. Variability in spatial pattern of annual soil loss showing the erosion prone area in the watershed

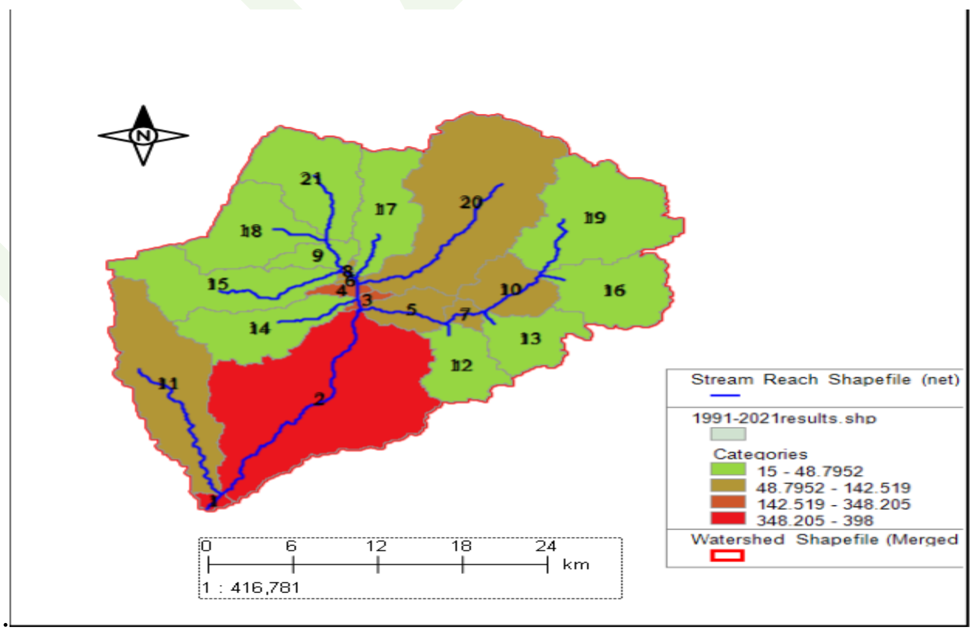

Figure 12. Variability in spatial pattern of flow within the watershed.

4. Conclusion

The SWAT model successfully simulated hydrological processes in the Ede Dam watershed and identified key relationships between rainfall, runoff, and sediment yield. Erosion-prone sub-basins were effectively delineated, highlighting critical areas for intervention. The integration of hydrological modelling and geospatial analysis provides a robust framework for sustainable watershed management in the region.

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