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Estimation of Sediment Yield in Madawaki Watershed Using GeoWEPP Model

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Abstract

Erosion is a recurrent challenge in the Madawaki watershed widely affecting farming techniques, water quality, and soil fertility. The study portrays a novel use of geographical interface of the WEPP (Water Erosion Prediction Project) model, known as GeoWEPP to estimate sediment yield in the unique agro-ecological region. Leveraging ArcGIS 10.2, detailed maps were generated to support the modeling process, signifying a high-resolution analysis of the watershed activities.The result shows an average annual sediment yield of 219 ton/ha. Among the evaluated management practice, forest perennial emerged as the most effective in reducing the sediment yield by 78.3% (47.6 tons/ha). The analysis contains a critical idea into the efficacy of GeoWEPP model in estimating and managing watershed challenges. By showing the model ability to integrate GIS mapping techniques and assess forest perennials as a sustainable management practice. It also offers an important advancement in soil and water conservation strategies. These findings proffer critical gaps in sediment yield estimation and watershed management, demonstrating the study to be a valuable contribution to the field of watershed development planning.

Key words: Sediment yield, GIS, GeoWEPP, Madawaki, Gusau

1. Introduction

Despite scientific studies and conservation efforts, soil erosion remains a significant global issue, driving land degradation and threatening ecosystems [1]. It is widely regarded as the greatest ecological danger to the survival of both animal and plant life on Earth. Erosion, caused primarily by wind or water, depletes soil by transferring sediment from one area to another. Assessments indicate that approximately 65 percent of the planet's soil has degraded due to erosion, salinity, and desertification [2].

Soil is one of Earth's most critical ecosystems, providing habitat for living organisms, supporting biodiversity, and anchoring human-made developments. Damage to soil directly endangers life by reducing its fertility, productivity, and ability to sustain vegetation. Soil erosion, primarily driven by destructive forces such as water, wind, gravity, and human interference, accelerates the depletion of organic matter and vital nutrients, undermining global food production and biodiversity [3]. Global food production is being negatively impacted by soil loss, which is currently an important ecological problem**.** This has profound environmental and economic consequences, particularly in developing nations where farming communities

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often lack resources to restore lost soil and nutrients. The ongoing imbalance, where the rate of soil loss exceeds the natural regeneration of soil, continues to reshape the environment and exacerbates the challenges of sustaining life on Earth [5].

A modified version of the Water Erosion Prediction Project (WEPP) hillslope model, the WEPP watershed model is a process-oriented, continual simulation erosion forecasting framework that may be used to calculate watershed runoff and sediment production [6]. The process of infiltration hypothesis, hydrology, soil science, plant science, hydraulics, and erosion dynamics are the foundations of the WEPP model. The creation of the climate, the cold-season process, irrigation, hydrology, soils, plant development, breakdown of residues, downstream hydraulics, erosion, and deposition are its nine components [6].

GeoWEPP had been the name of the geographic interface for the WEPP model that was initially proposed [7]. After being developed as an ArcView 3.2 extension, it is now compatible with ArcGIS. The National Soil Erosion Research Laboratory (NSERL) of the USDA-ARS and Purdue University developed the program first currently, it is updated often via the University at Buffalo's Environmental System Analysis and Modeling lab, which may be found at https://lesami.geog.buffalo.edu/projects/active/geowepp [8]. The GeoWEPP ArcGIS extension allows users to obtain and import readily available topographic, soil, and land use/land cover data layers for preparing model input and executing WEPP model scenario simulations when used in conjunction with the ArcGIS software and the independent WEPP Windows interface [8].

The study aims to estimate the sediment yield using GeoWEPP a spatial interface of the WEPP model in the Madawaki watershed of Gusau Local government, Zamfara state, Nigeria. The availability of data on sediment yield is limited in the study area and there is also limited research using the GeoWEPP model in Nigeria, therefore, the result will be validated with research conducted at different locations of the world.

2. Materials and Methods

2.1. Description of the study area

The research was carried out in the Sudan Savannah of Nigeria (Figure 1) at a height of 429 meters above sea level in Gusau (latitudes $12^0\ 11'\ 72^{"} to 12^0\ 11'\ 28^{"}$ N and longitudes $6^0\ 37'\ 17.04^{"} to 6^0\ 37'\ 17.84^{"}$ E) and a total area of 1600ha. Two seasons are different in the region's climate: the rainy season (May - October) and the dry season (November - April). Additionally, it experiences a monomodal cycle of rainfall, with a yearly average of 875 mm and a range of 750 to 1000 mm. Temperatures are 30 degrees Celsius on average every year. The short grasses that make up the landscape act as a framework for the prickly plants. River Sokoto drains and affects the Gusau area, while a few tiny river and stream systems pass through the uplands [9].

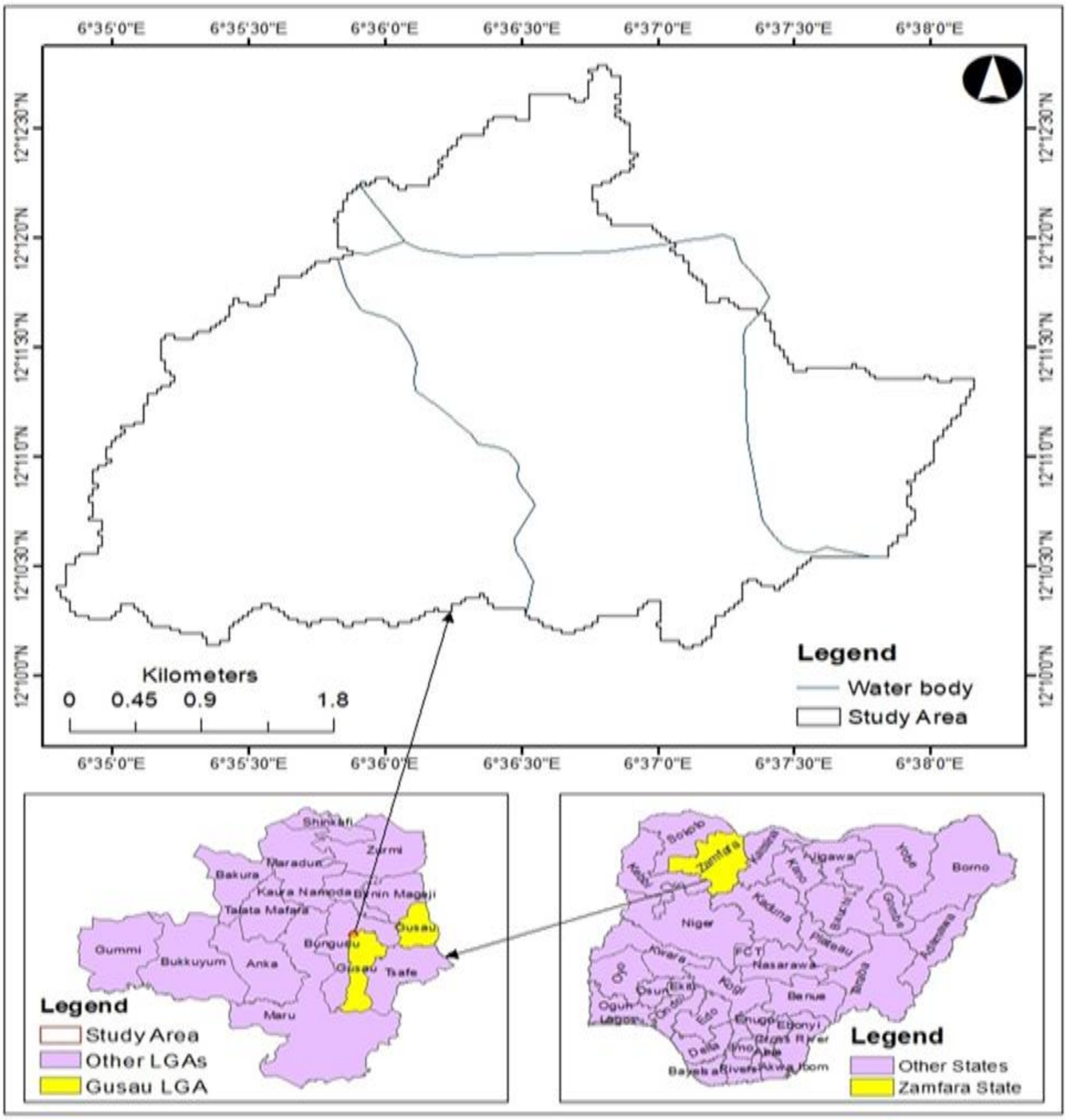

Figure 1. Study area (Madawaki Watershed)

2.2. Meteorological data

Climate data from 1992 to 2022 were obtained from the Nigerian Metrological Agency (NIMET) in Gusau, Zamfara State. Rainfall, maximum and lowest temperatures, wind direction and speed, relative humidity, and dew point are among the data. The first necessary element in the equation is rainfall erosivity. The R factor evaluates the amount and speed of runoff, which are directly related to a certain precipitation event, and is dependent on rainfall intensity in the sense of kinetic energy [10].

The rainfall data for the 30 years' time were used to obtain the rainfall erosivity in line with the formula:

$$R = \sum_{i=1}^{12} 1.735\left[1.5 \times \log_{10}\left(\frac{P_i^2}{P}\right) - 0.08188\right] \qquad (1)$$

Where R is the rainfall erosivity factor (MJ.mm.$ha^{-1}.h^{-1}.y^{-1}$) and P is the mean annual rainfall (mm) [11].

2.3. Soil data

Ten different points of soil samples were obtained from the watershed [12]. Particle size distribution analysis was carried out on the soil at the study area in the Department of Soil Science, Soil Survey Laboratory, Ahmadu Bello University Zaria, to ascertain the textural classification of the area.

2.4. Satellite data

2.4.1. Digital elevation model

The United States Geological Survey (USGS) Earth Explorer was used to obtain Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (SRTM). The slope of the image was produced as a result of processing it in the ArcGIS program. Figure 2 shows the elevation of the study area, ranging from the high, which is orange (444m) above mean sea level, to the low, which is dark blue (360m).

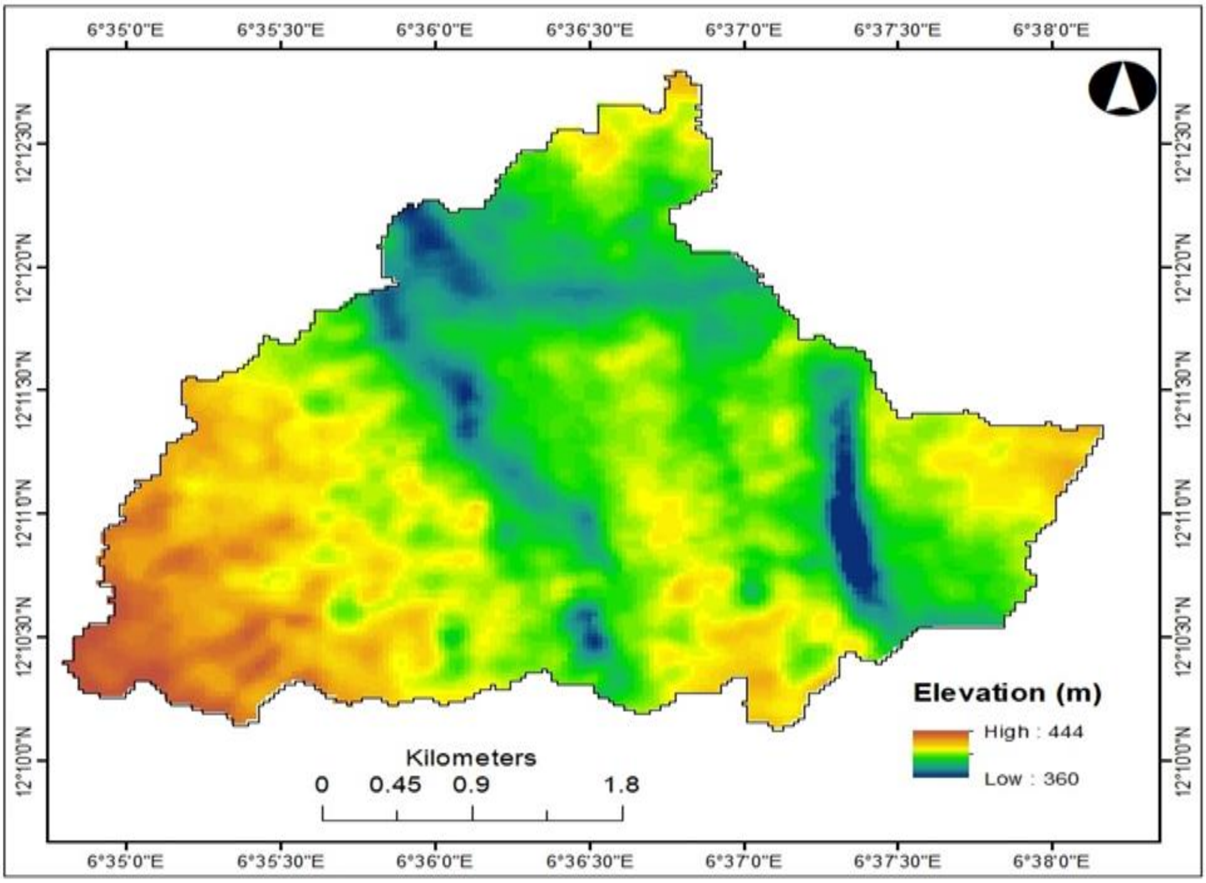

Figure 2. Elevation distribution of Madawaki Watershed

2.4.2. Remote sensing

Remote sensing data was also downloaded from the United States Geological Survey (USGS) Earth Explorer. Data from remote sensing was used to generate land use and cover. Using maximum likelihood classification and supervised classification, the LC08_L2SP190052 satellite image from 1992–2022 was categorized using ArcGIS software.

2.5. Best management practices (BMPs)

When used in physically based model applications, BMP can enhance watershed planning and effectively reduce sediment yield, and its effects [13]. Many cropping and tillage options are accessible in the WEPP database to be considered to lessen the effects of sediment yield. Therefore, the conventional tillage was taken as the baseline. At the same time, the forest perennial, corn, soybean no-till, corn, soybean-fall mulch till, and corn fall mulch till were used as the four scenarios in testing the best management practice in the watershed [14].

2.6. Model input parameters

2.6.1. Model calibration

The DEM, land use/cover, and soil map were uploaded into the Geospatial interface of the WEPP model (GeoWEPP) add-in in the ArcGIS 10.2 environment, while the climate, soil, and land cover files from WEPP were inputted for simulation. The climate data of 2001 and 2011 were used to calibrate the model using a trial-and-error method.

2.6.2. Climate data

The WEPP model's climate (.cli) file was imported from the Breakpoint Climate Data Generator (BPCDG) aggregated climate data.

2.6.3. Slope

The TOPAZ interface generated the slope from the DEM and the channel network delineation.

2.6.4. Soil data

The converted ASCII soil file generated from GIS was used in the simulation.

2.6.5. Management file

Corn, soybean, spring chisel plow WEPP inbuilt file was adapted, and the same farming practice was used in the study area.

2.7. Channel network delineation

To define the drainage pattern and watershed with sub-watershed, the wizard was determined, and the channel parameters and the watershed outlet cell. The wizard integrates Topography Parameterization (TOPAZ), a program for topographic analysis. To determine the channel network, TOPAZ needs a minimum source channel length (MSCL) and a critical source area (CSA). The wizard provides a tool to set the outflow for the watershed of interest once the network outline satisfies the outline seen in the area [7].

Channel parameters and watershed outlet were set and the drainage pattern was delineated by Topography Parameterization (TOPAZ). The critical source area (CSA) of (20ha) and the minimum source channel length (MSCL) of (300m) was set for the channel network delineation [7]**.** The allowable soil loss tolerance limit will be 1.5ton/ha [15].

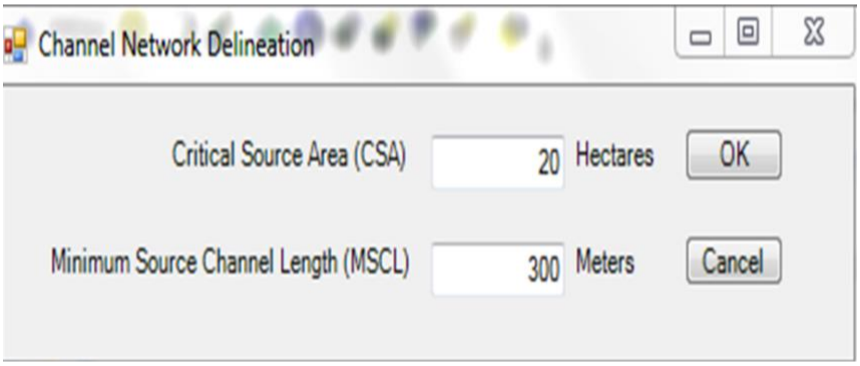

Figure 3. Channel Network Delineation setup from TOPAZ of Madawaki Watershed

2.8. WEPP equations

The WEPP model calculates the soil erosion and deposition processes using the steady-state sediment continuity equation [16]. Erosion prediction in the WEPP model starts with detailing soil parameterization. Some mathematical equations are used for computing soil detachment and subsequent sediment deposition processes. Soil detachment by prevailing driving forces can be obtained using this equation, expressed as:

$$\frac{dG}{dx} = D_f + D_i \tag{2}$$

Where x = distance downslope (m), G = sediment load (kg/s/m^2), D_i = interrill erosion rate (kg/s/m^2), and D_f = rill erosion rate (kg/s/m^2).

Hence, the soil sediment capacity by concentrated flow process is expressed as:

$$T_c = K_{tr} q_w S \tag{3}$$

Where K_{tr} = constant rill erodibility parameter, q_w = flow discharge per unit width (m^2/s), S = slope (%).

In a situation where the soil sediment load exceeds its transportation capacity, a net deposit occurs and it is calculated using the equation:

$$D_f = \left[\frac{V_f}{q}\right] [T_c - G] \tag{4}$$

Where V_f = the sediment's effective fall velocity (m/s), and q = the flow discharge per unit width (m/s^2).

As a process, the climate generator (CLIGEN) component of WEPP generates the rainfall intensity, while the hydrologic component of the WEPP computes the runoff peak and duration. The effective runoff duration is obtained using the equation:

$$t_r = \frac{V_r}{P_r} \tag{5}$$

Where t_r = length of the effective runoff (s), V_t = total volume for rainfall event (m), and P_r = peak runoff per unit area (m/s) [17].

The motion of suspended sediment in rill, interill, and channel flow zones is found by applying a steady-state erosion model to solve the sediment continuity equation. The values for detachment, transport, and deposition are obtained from the steady-state solution of the sediment continuity equation [18].

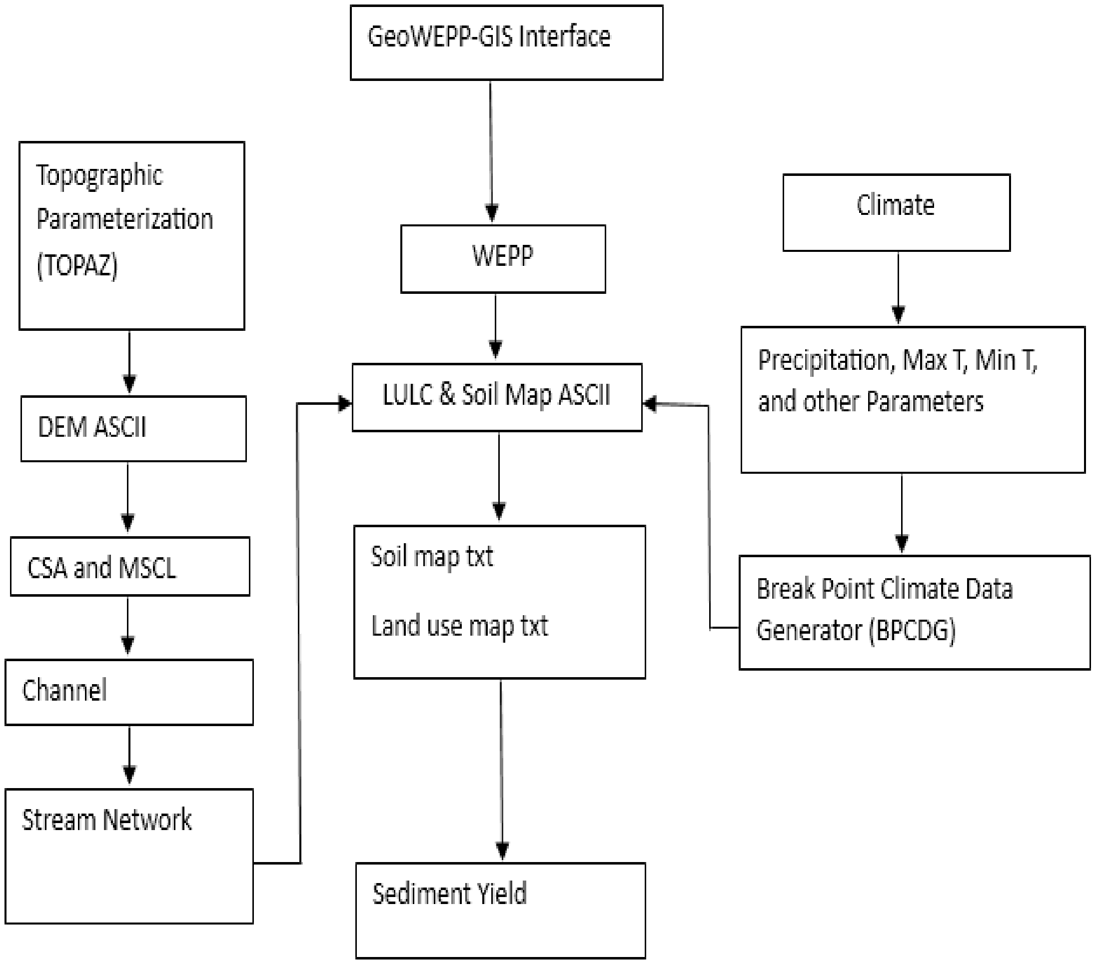

Figure 4. Flow chart for simulation

3. Results and Discussion

Figures 5 and 6 below, show the rainfall map and the rainfall erosivity factor map. The map in Figure 5 shows areas in the watershed where rain was high and low while in Figure 6, the map shows areas where the erosivity factor is high and low.

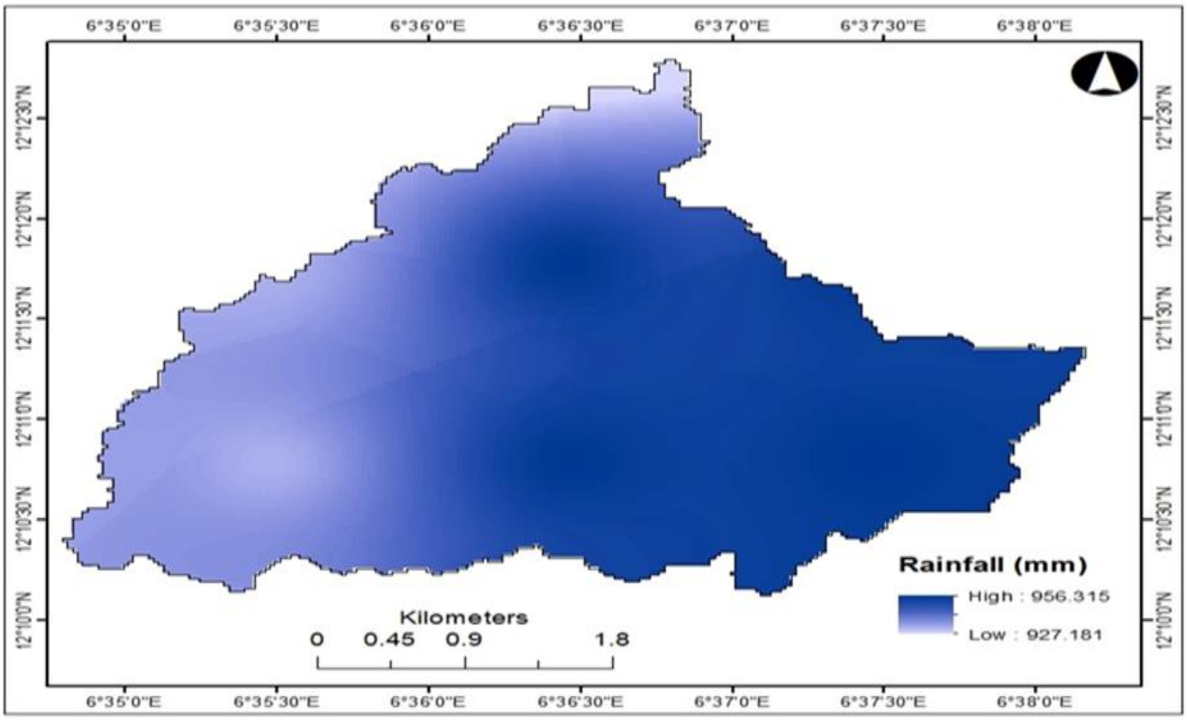

Figure 5. Rainfall map of Madawaki Watershed

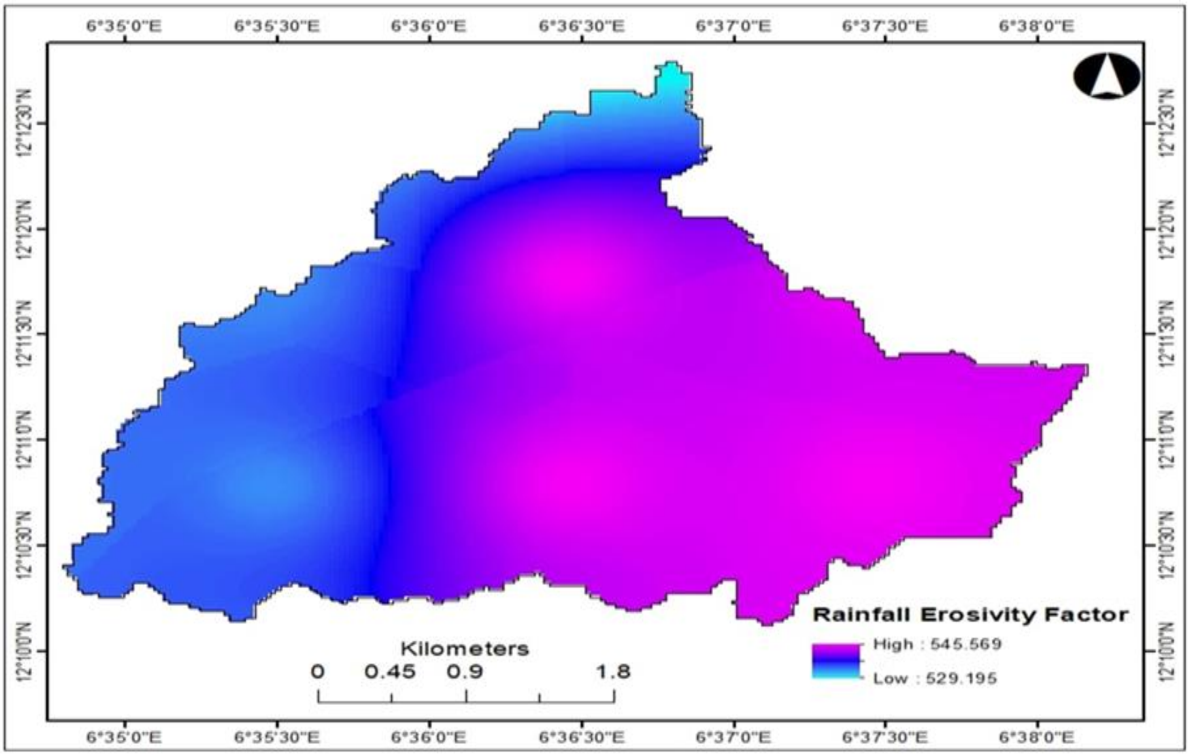

Figure 6. Rainfall erosivity map of Madawaki Watershed

Thirty years' worth of rainfall records are used to calculate the R factor, which indicates the erosive potential of rainfall. Volume, intensity, length, and pattern of rainfall all have a significant impact on how erosive a downpour is. The result shows that the mean annual rainfall ranges from 927.2mm north to 956.3mm southeastern part of the area and mean annual R factor values range from 529.2MJmm/ha/yr north to 545.6 MJ mm/ha/yr in the southeastern part of the study area.

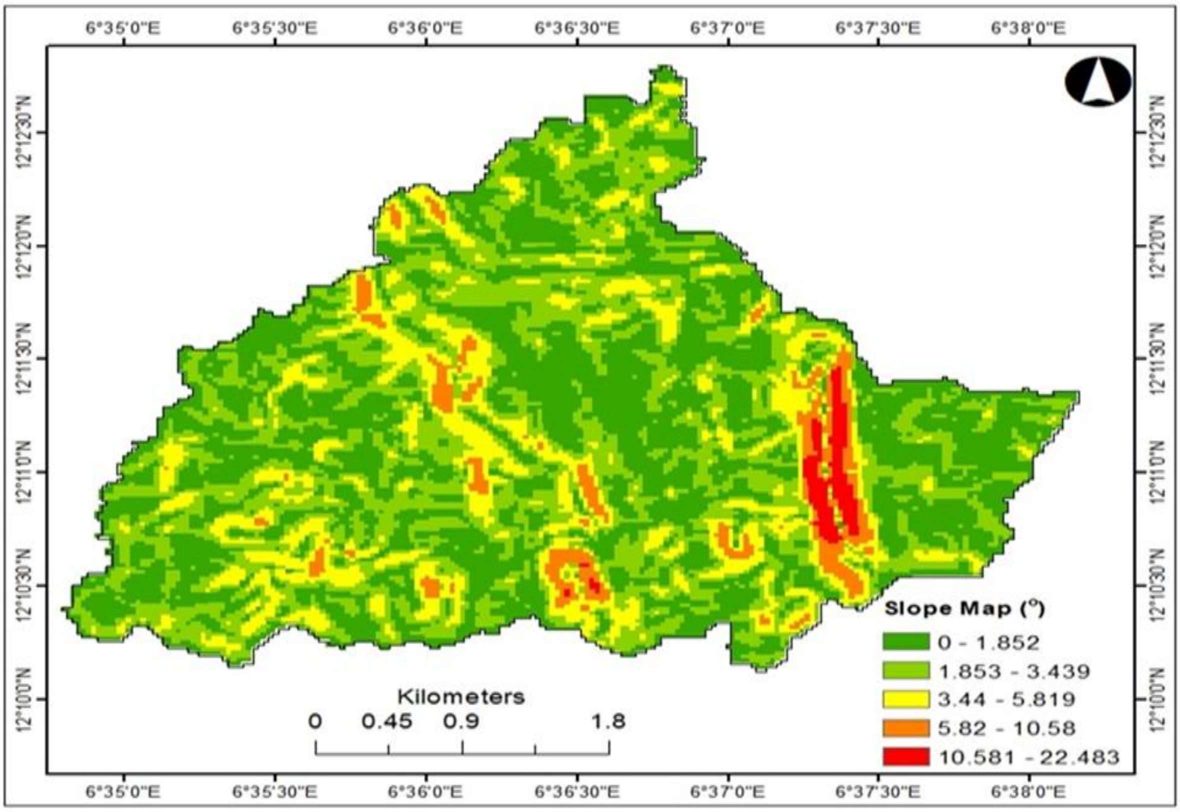

Figure 7. Slope map of Madawaki Watershed

As a result, the study area constitutes different classifications ranging from normal zone to productive zone to sensitive zone and their various slope percentages. The slope of 5^0 and above shows sensitive areas in the study area. Figure 8 shows different classifications of land cover in the study area, which include: bare land, build-up, vegetation, and water bodies. İt also shows the land use/cover map of the Madawaki watershed with ground points superimposed to the map generated from ArcGIS 10.2 which validated the classification. Ten (10) points were obtained from each class to check for the agreement between the map and the points.

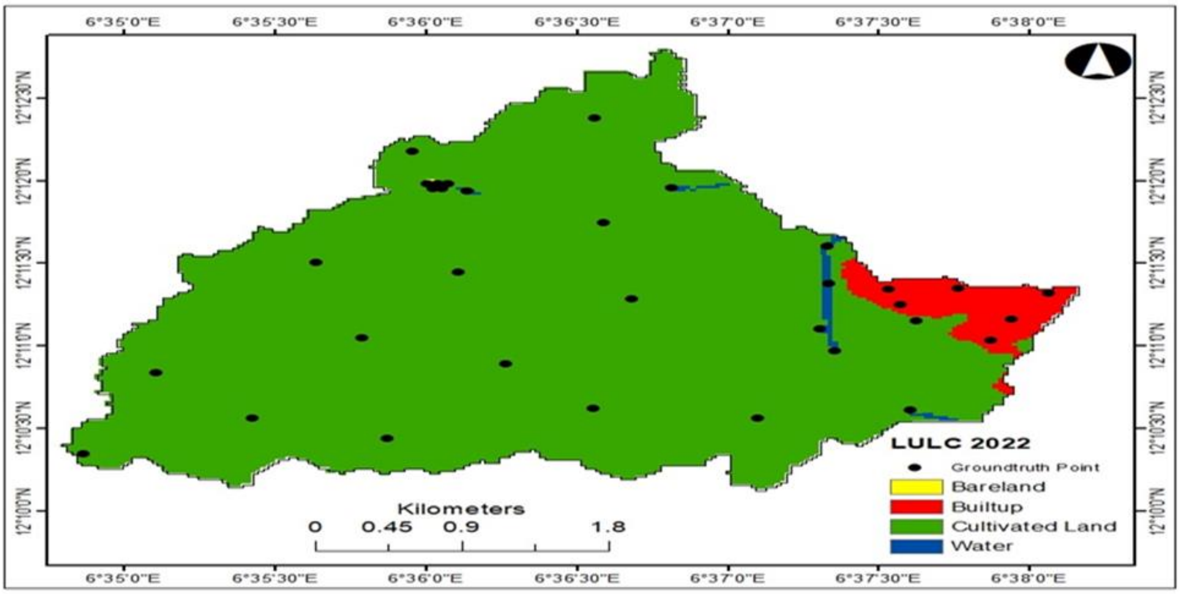

Figure 8. Land use/cover map of Madawaki Watershed with ground truth point

Table 1 shows the classes of land use in the Madawaki watershed, the area they cover and the percentage of the area covered. A confusion matrix analysis was performed using a Microsoft Excel sheet to evaluate the precision of the ground truth points superimposed on the geographical representation of land use and cover in Table 2 above to show agreement between the ground truth points and the map. The kappa value obtained was 0.72, which shows a substantial agreement with the map. Figure 9 shows the soil map of the study area obtained from ArcGIS 10.2. It clearly shows different textures from sandy clay loam, loam, and silty loam to sandy loam.

Table 1. Classes of land use/cover with the areas and percentages

Name	Area (ha)	Percentage (%)
Water	10.44	0.65
Built-up	66.15	4.10
Bare land	1.17	0.07
Farmland	1537.56	95.15
Total	1615.32	100

Table 2. Confusion matrix of the land use/cover

Class name	Water	Built-up	Bare land	Cultivated Land	Total	User Acc.	Kappa
Water	4	0	0	1	5	0.80	
Built-up	0	5	0	1	6	0.83	
Bare land	0	0	4	1	5	0.80	
Cultivated Land	1	1	1	14	17	0.82	
Total	5	6	5	17	33	0.00	
Producer Acc.	0.80	0.83	0.8	0.82	0	0.82	
Kappa							0.72

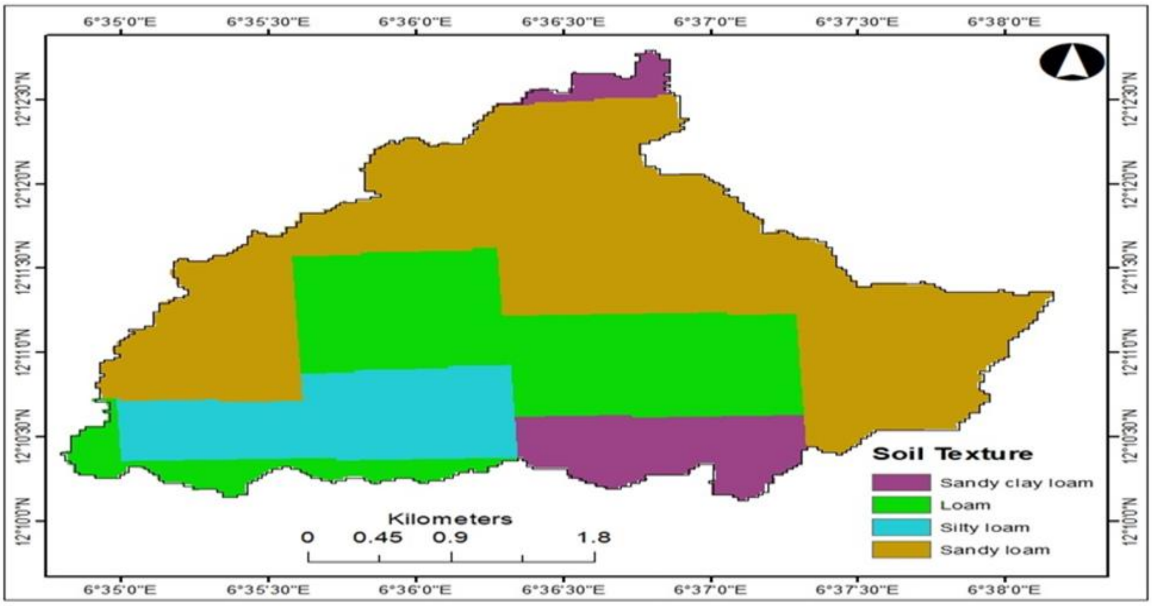

Figure 9. Soil map of Madawaki Watershed

Validation of soil map by conducting physical test as seen above in Table 3, shows textural classes of soil obtained. Sandy loam predominantly covers the watershed. The watershed was divided into four (4) different sub-watersheds for easy delineation then the sediment yield was simulated. The WEPP model yielded the average annual outcome for each sub-watershed.

Table 3. Particle size distribution analysis results: The research area's results were used as the validation of the soil map

S/N	BLK	(DT*0.36)	40SECS R	2 HRS R	% CLAY	% SILT	% SAND	TEXTURAL CLASS
1	0	2	21	2	8	38	54	Sandy Loam
2	0	2	15	8	20	14	66	Sandy Loam
3	0	2	12	2	8	20	72	Sandy Loam
4	0	2	8	1	6	14	80	Loamy Sand
5	0	2	18	5	14	26	60	Sandy Loam
6	0	2	32	6	16	52	32	Silt Loam
7	0	2	12	4	12	16	72	Sandy Loam
8	0	2	28	8	20	40	40	Loamy Sand
9	0	2	18	2	8	32	60	Loam
10	0	2	17	2	8	30	62	Sandy Loam

3.1. Sediment yield

The average annual sediment yield of the erosion site is $219 tons/ha$. These findings (219tons/ha) are comparable with the findings of [18].

Table 4. Sediment yield obtained from GeoWEPP model

Sub-watershed	Average Annual Sediment Yield(ton/ha)	Sediment Delivery Ratio
SW1	150	0.32
SW2	20	0.48
SW3	36.1	0.88
SW4	12.8	0.21

3.2. Spatial distribution

This section demonstrates the spatial distribution of the sediment yield in Madawaki watershed. It portrays the channel network delineation followed by the spatial distribution maps (Figure 10). Figure 11 displays the spatial distribution of sediment yield at the watershed. The sediment yield ranges from light greenish, which signifies a low amount of sediment deposition to pinkish which signifies the highest level of sediment deposition. The map shows critical areas that require urgent attention for effective soil and water conservation management.

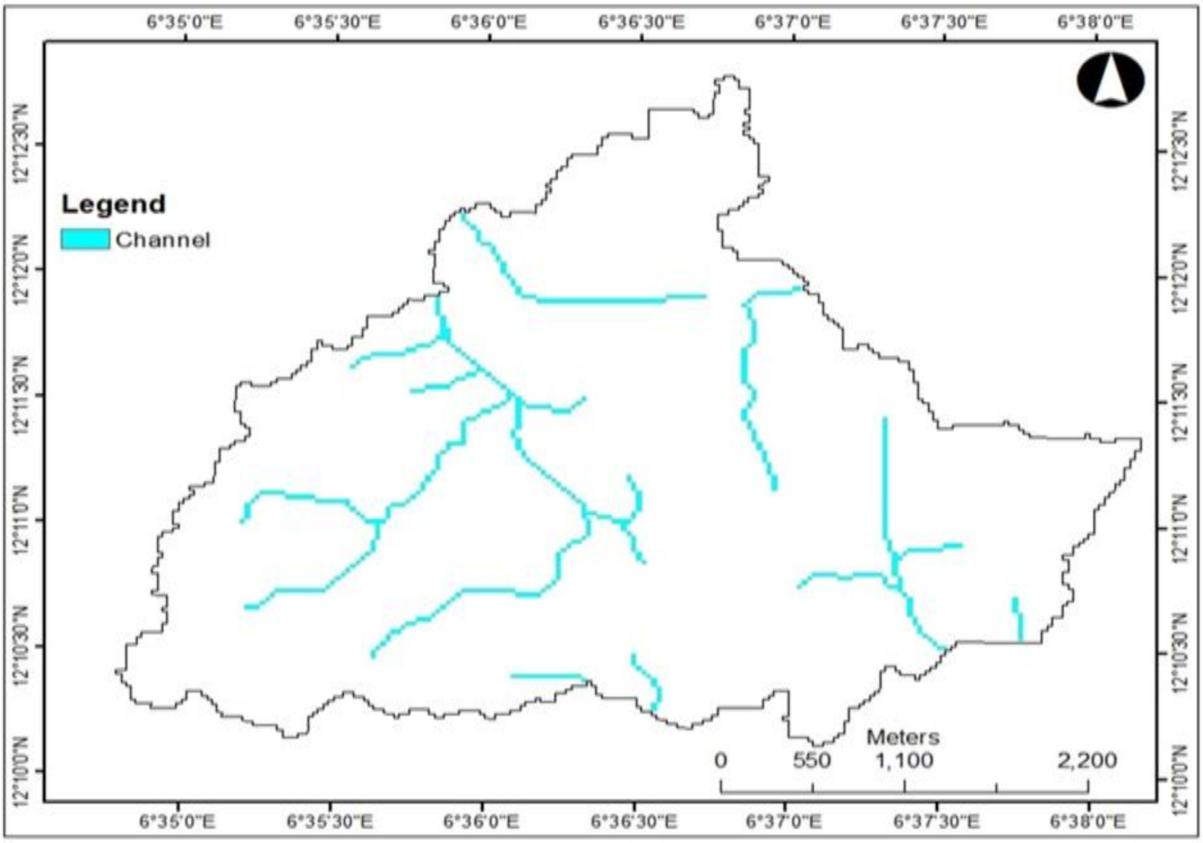

Figure 10. Channel network delineation in the Madawaki Watershed

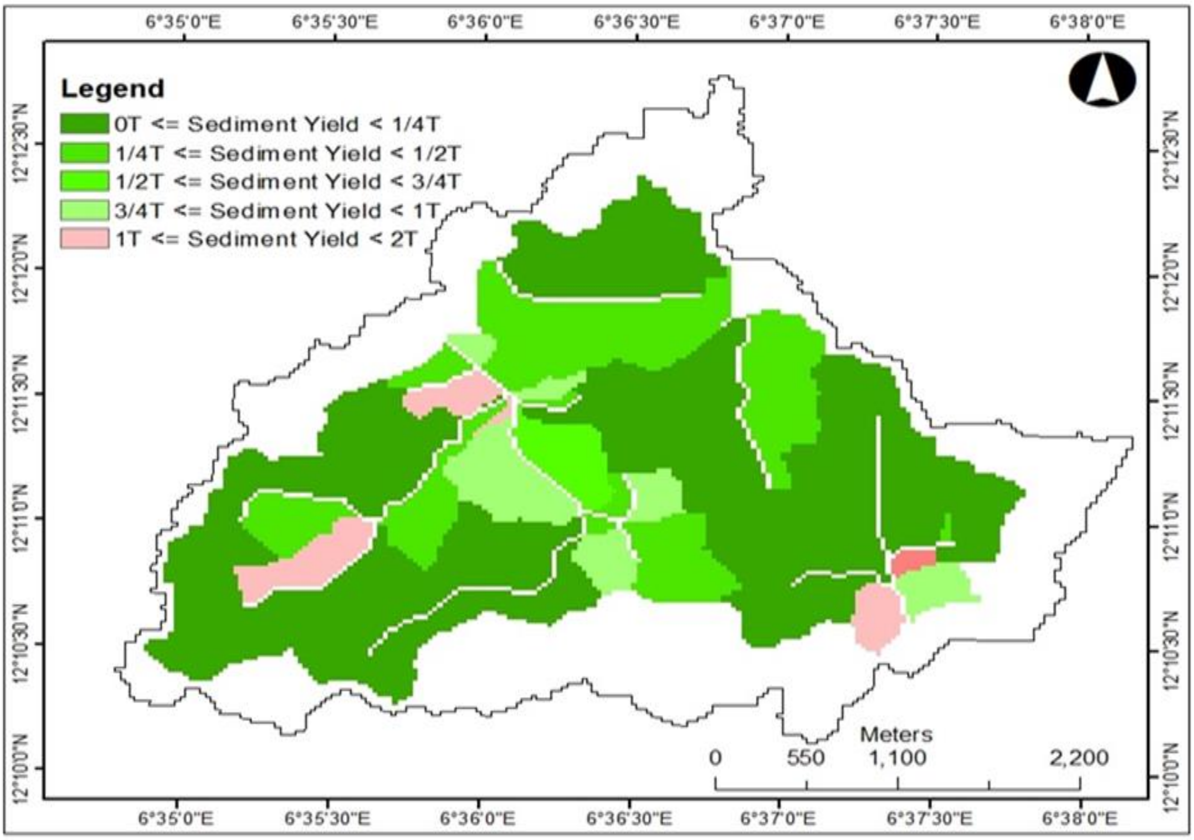

Figure 11. Spatial distribution of sediment yield in the Madawaki Watershed

3.3. Best management practices (BMPs)

Recognizing the critical areas, there is a need to provide solutions for water and soil conservation management. To do that, baseline (conventional tillage) and four different scenarios were analyzed to effectively reduce sediment yield. The scenarios are forest perennial (S1), corn, soybean no-till (S2), corn, soybean fall mulch till (S3), and corn fall mulch till (S4).

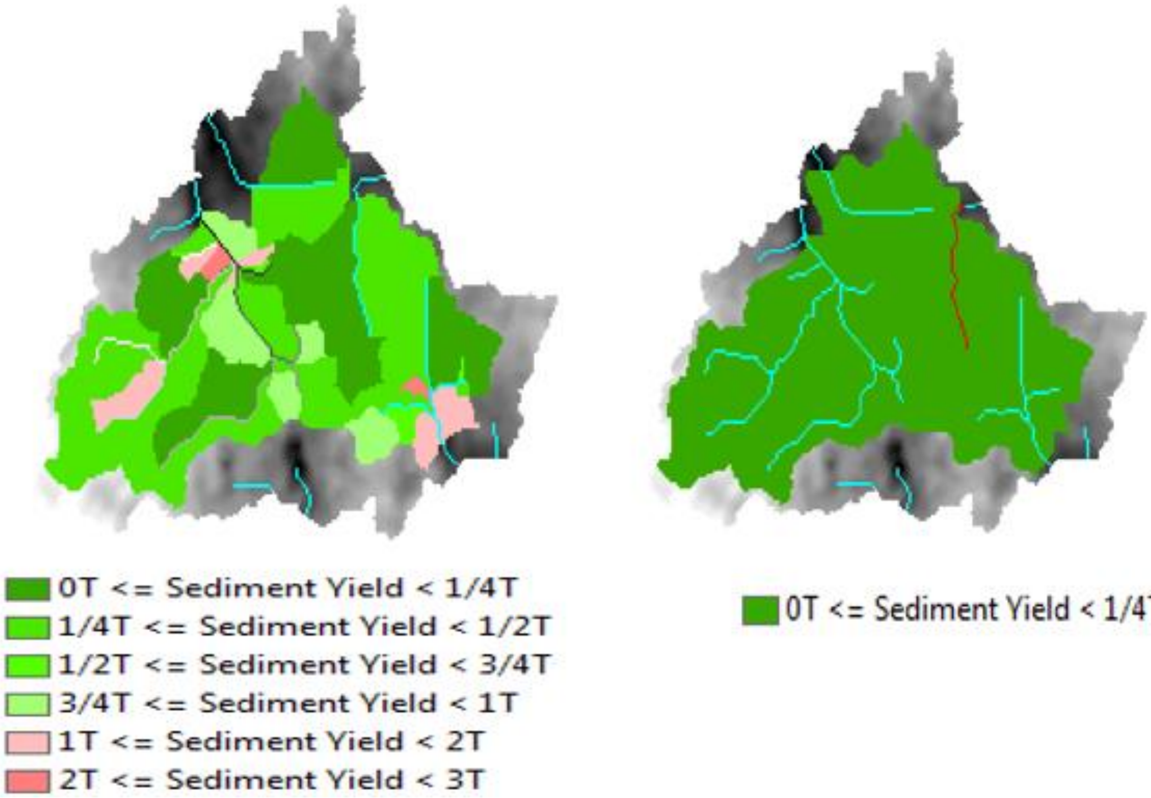

Figure 12. Conventional tillage (baseline) and forest perennial (Scinario1)

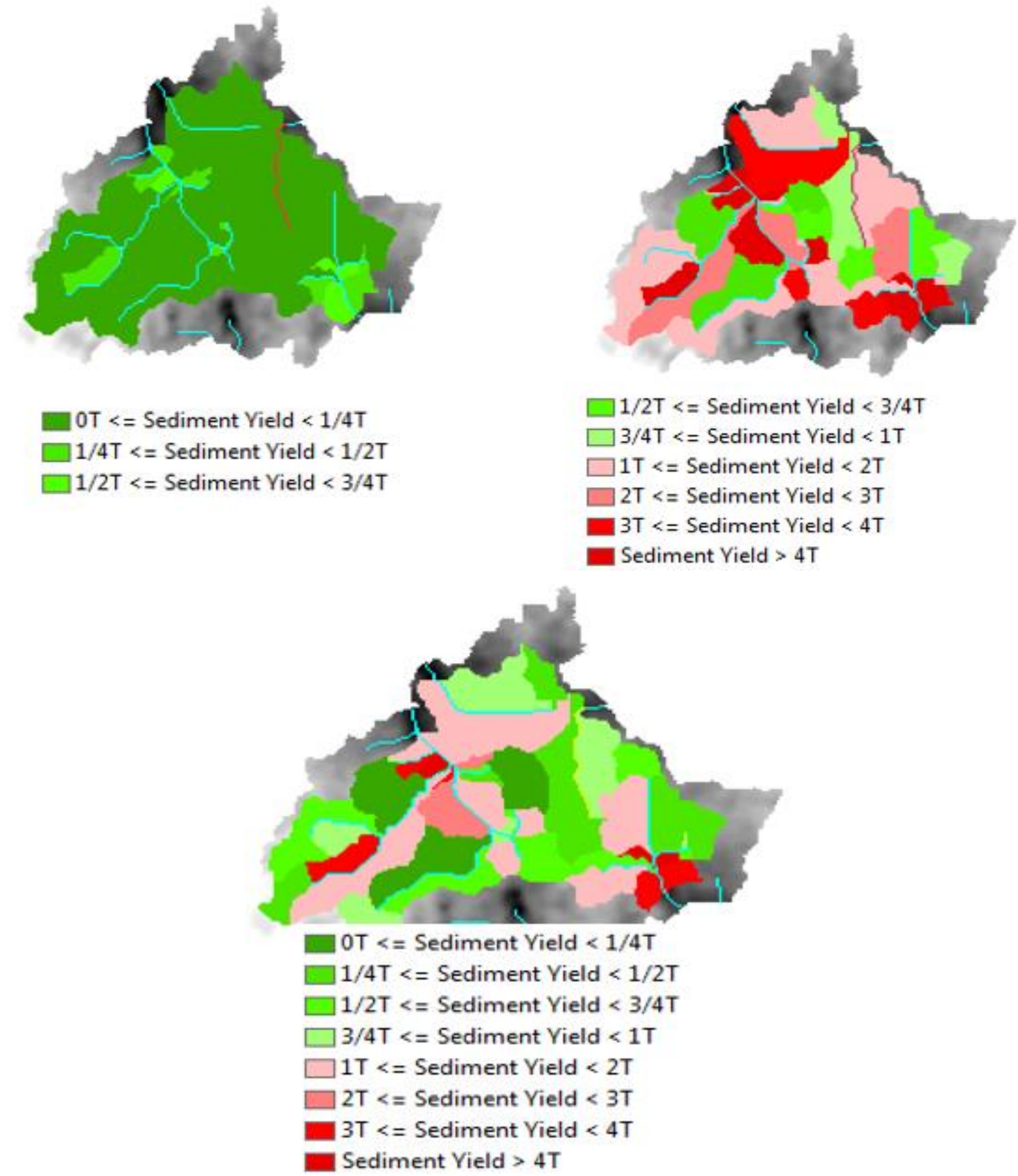

Figure 13. Corn, soybean no-till (S2), corn, soybean fall mulch till (S3), and corn fall mulch till (S4)

Upon the application of the management practices, there is a reduction in sediment yield which ranges from 36.3% to 78.3%. Analyzing the baseline and the other four scenarios, the scenario forest perennial (S1) appears to be the most effective management practice in reducing with a percentage reduction of 78.3% (47.6 tons/ha) of sediment yield (Table 5). This result is comparable with the findings of [18].

Table 5. Sediment yield management scenarios in the Madawaki Watershed

Scenario	Sediment Yield(ton/ha)
Conconventional tillage (Baseline)	272.9
Forest Perennial (S1)	47.6
Corn, Soybean no-till (S2)	139.4
Corn, Soybean-fall mulch till (S3)	1601.8
Corn fall mulch till (S4)	617

4. Conclusion

In this study, WEPP model efficacy was tested to predict sediment yield and runoff at Madawaki watershed. Based on the research, the following conclusions were drawn:

- The study's findings have demonstrated that the Madawaki watershed was affected by a sediment yield of (219ton/ha) 30% less than a study by [19].
- The scenario forest perennial has shown to be the best management practice in the Madawaki watershed with a percentage reduction of sediment yield of 78.3%. The scenario corn and soybean no-till is the least with a percentage reduction of 36.3%. Scenario corn, soybean-fall mulch till, and, corn fall mulch till have shown an increase in the sediment yield with 86% and 64.5%.
- The Madawaki watershed can benefit greatly from these discoveries in terms of land management, conservation, and sustainable development, to reduce sediment yield, and so also preserve the health of ecosystems.

Then, it is recommended that:

- Researchers should use the GeoWEPP model to estimate sediment yield and to provide necessary measures to curtail the increase.
- It is anticipated that GeoWEPP users will increase in Nigeria as GIS techniques and computer-based methods are widely used across the globe for erosion prediction.
- The effectiveness of the model needs to be evaluated across larger areas. More research and focused actions are needed.

Conflict of Interest

No potential conflicts of interest were reported by the author.

Author Contribution

I. A. led the conceptualization, data collection, analysis, and initial drafting of the manuscript. J. O. contributed to the literature review and research design, and assisted in revising the manuscript. M.A. supervised the overall research process, provided insights, and supported the final editing.

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