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Full Length Research Paper

Soil erosion prediction using MMF model on highly dissected hilly terrain of Ekiti environs in southwestern Nigeria

Ande O. T.[1]*, Alaga Y.[2] and Oluwatosin G. A.[1]

[1]Institute of Agricultural Research and Training Obafemi Awolowo University, P. M. B. 5029, Apata, Ibadan, Oyo State, Nigeria.
[2]National Remote Sensing Centre, Bukuru, Jos, Nigeria.

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Assessment of soil erosion risk is important to formulate effective soil conservation plans for sustainable development. Information from remote sensing techniques can help decision makers prepare resource map accurately in less time and cost. GIS assists in linking those maps with other information related to geographic location and helps modeling, analyzing and solving complex problems. The objective of this study was to assess the potential of Morgan, Morgan and Finney (MMF) Model (Morgan et al., 1984) in predicting soil erosion in an agrarian Ekiti environment with highly dissected hilly and rolling terrain in southwestern Nigeria. Soil loss prediction by MMF approach involve factor maps from kinetic energy of rainfall, topsoil rooting depth, percentage rainfall contributing to permanent interception and stream flow, crop cover management factor, ratio of actual to potential evapotranspiration, soil moisture storage capacity. These were used to generate output maps like volume of overland flow, rate of soil detachment by raindrop impact and transport capacity of overland flow. Annual soil loss estimation was calculated by comparing two maps of soil detachment rate and transport capacity and taking the minimum value from them. Results showed that MMF model could predict erosion risks effectively in the highly dissected hilly and rolling landscape of Ekiti environ. Erosion was low in the area in spite of the landscape. The highest soil loss was 1.275 kgm^{-2} yr^{-1} from rock hill with slope greater than 15%. The lowest was 0.942 kgm^{-2} yr^{-1} at low lands covered with riparian forest. The average estimated annual soil loss of the study area was 1.112 kgm^{-2}, which is less than tolerable standard of 1 kg 1233 m^{-2} yr^{-1}. The MMF model shows that the current land-use/cover in Ekiti environs is sustainable because erosion risk is below the critical level.

Key words: Soil erosion, MMF model, land use, hilly landscape, Nigeria.

INTRODUCTION

Soil degradation by accelerated water and wind-induced erosion is a serious problem and will remain so during the 21st century, especially in developing countries of tropics and subtropics. Erosion is a natural geomorphic process occurring continually over the earth's surface. However, the acceleration of this process through anthropogenic perturbations can have severe impacts on soil and environmental quality. Accelerated soil erosion has adverse economic and environmental impacts (Lal, 1998). Economic implications of soil loss include reduction in farm income as a result of fertility decline and consequent adverse impact on crop/ animal production. Saha (2004) described soil erosion as a three stage process: (1) soil detachment, (2) transport, and (3) deposition of eroded particles. Different energy source agents determine different types of erosion. There are four principal sources of energy: physical, such as wind and water, gravity, chemical reactions and anthropogenic, such as tillage. Soil erosion begins with detachment, which is caused by break down of aggregates by raindrop impact, sheering or drag force of water and wind. Detached particles are transported by flowing water (over-land flow and inter-

*Corresponding author. E-mail: funmiande@yahoo.com.

flow) and wind, and deposited when the velocity of water or wind decreases by the effect of slope or ground cover.

Three processes viz. dispersion, compaction and crusting, accelerate the natural rate of soil erosion. These processes decrease structural stability, reduce soil strength, exacerbate erodibility and accenttuate susceptibility to transport by overland flow, interflow, wind or gravity. These processes are accentuated by soil disturbance (by tillage, vehicular traffic), lack of ground cover (bare fallow, residue removal or burning) and harsh climate (high rainfall intensity and wind velocity). The soil erosion process is modified by biophysical environment comprising soil, climate, terrain and ground cover and interactions between them. Soil erodibility – susceptibility of soil to agent of erosion - is determined by inherent soil properties, such as texture, structure, soil organic matter content, clay minerals, exchangeable cations and water retention and transmission properties. Climatic erosivity includes drop size distribution and intensity of rain, amount and frequency of rainfall, runoff amount and velocity, and wind velocity. Important terrain charac-teristics for studying soil erosion are slope length and steepness. Ground cover exerts a strong moderating impact on dissipating the energy supplied by agents of soil erosion.

Field studies for prediction and assessment of soil erosion are expensive, time-consuming and need to be collected over many years. Though providing detailed understanding of the erosion processes, field studies have limitations because of complexity of interactions and the difficulty of generalizing from the results. Soil erosion models can simulate erosion processes in the watershed and may be able to take into account many of the complex interactions that affect rates of erosion. Morgan et al. (1984) developed a model to predict annual soil loss which endeavors to retain the simplicity of USLE and encompasses some of the recent advances in understanding of erosion process into a water phase and sediment phase. The water phase considers the energy of the rainfall and the overland flow per raster cell, where as the sediment phase comprises two predicttive equations, one for rate of splash detachment and one for the transport capacity of overland flow. The model uses six operating equations for which 15 input parameters are required. The model compares predictions of detachment by rain splash and the transport capacity of the runoff and assesses the lower of the two values as the annual rate of soil loss, thereby denoting whether detachment or transport is the limiting factor. The potential utility of remotely sensed data in the form of aerial photographs and satellite sensors data has been well recognized in mapping and assessing landscape attributes controlling soil erosion, such as physiography, soils, land use/land cover, relief, soil erosion pattern (Pande et al., 1992). Remote Sensing (RS) can facilitate studying the factors enhancing the process, such as soil type, slope gradient, drainage, geology and land cover. Multi-temporal satellite images provide valuable information related to seasonal land use dynamics. Satellite data can be used for studying erosional features, such as gullies, rainfall interception by vegetation and vegetation cover factor. DEM (Digital Elevation Model) is one of the vital inputs required for soil erosion modeling and can be created by analysis of stereoscopic optical and microwave (SAR) remote sensing data. Geographic Information System (GIS) has emerged as a powerful tool for handling spatial and non-spatial geo-referenced data for preparation and visualization of input and output, and for interaction with models. There is considerable potential for the use of GIS technology as an aid to the soil erosion inventory with reference to soil erosion modeling and erosion risk assessment. Erosional soil loss is most frequently assessed by USLE. Spanner et al. (1982) first demonstrated the potential of GIS for erosional soil loss assessment using USLE. Several studies showed the potential utility of RS and GIS techniques for quantitatively assessing soil erosion rates (Saha et al., 1991; Saha and Pande, 1993; Mongkosawat et al., 1994). Satellite data analyzed soil and land cover maps and DEM derived and ancillary soil and agro-climatic rainfall data are the basic inputs used in most erosion models for computation of soil loss. MMF model was used for quantification of soil loss by water erosion in GIS environment using various satellite remote sensing derived inputs (ASD, 2002). The availability of GIS tools and more powerful computing facilities makes it possible to overcome difficulties and limitations and to develop distributed continuous time models, based on available regional information. Recent development of deterministic models provides some spatially distributed tools, such as AGNPS (Young et al., 1989); ANSWERS (Beasley et al., 1980), and SWAT (Arnold et al., 1993). The primary layers required for soil erosion modeling are terrain slope gradient and slope length which can be generated by GIS aided processing of DEM. Flanagan et al. (2000) generated the necessary topographic inputs for soil erosion and model simulations by linking WEPP model and GIS and utilizing DEM.

The study area

Ekiti State environs lies between 7°15` and 8° 02` N and between 4°45` and 5°50`E and elevation ranges between 200 and 730 m a.s.l. The area is generally upland underlain with metamorphic rock of basement complex. Land surface is generally undulating with a characteristic landscape that consists of old plains broken by steep-sided rock outcrops. The area is dotted with rugged hills. The climate of the area is tropical with two distinct seasons; the raining season (April – October) and the dry season (November – March). Temperature ranges between 21-28°C and humidity is high. The south-westerly wind and the north-east trade wind blow in the rainy and dry seasons (harmattan) respectively. Tropical forest exists in the south, while guinea savannah occupies the northern area. The current demand to increase production in the area and the consequent effects of more human pressure on available land calls for better understanding of erosion on available

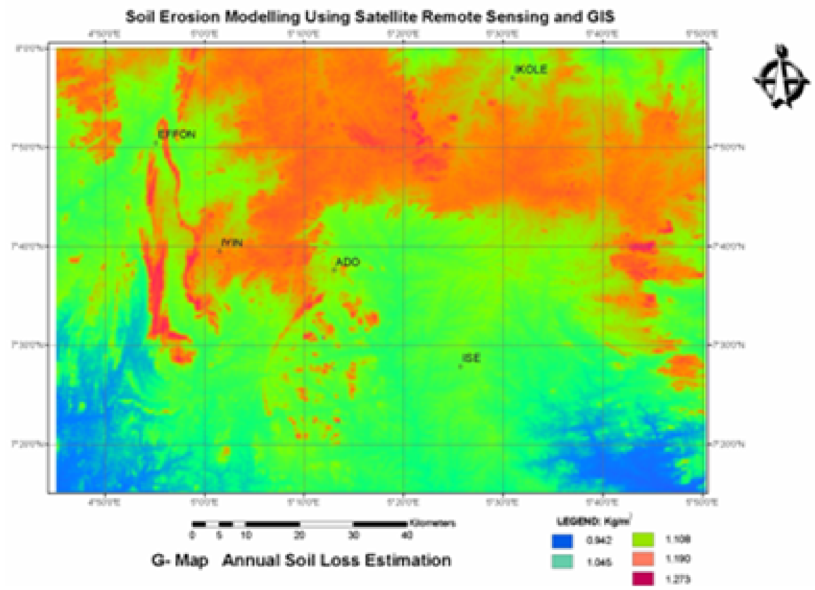

Figure 1. Annual soil loss estimation (G-map).

process in the area because of its highly dissected hilly terrain and high precipitation to avoid soil degradation.

Data used

Base and contour maps were prepared from toposheets of Survey Department. The map of land uses was prepared from images of the Landsat ETM satellite (May, 2002). Soil and rainfall data were taken from the state meteorological stations and from soils survey of central Nigeria (Smyth and Montgomery, 1962) and confirmed by ground truthing.

METHODOLOGY

The toposheets where scanned and given respective geographic latitude and longitude projection to the corners. To get a single toposheet from four, they where mosaicked together. Output map is again projected into universal transverse mercator. Contour map and spot height point map where prepared by digitising contour (50 m) lines and spot heights from the toposheets. Interpolation of these maps was done for getting final output map of DEM (Figure 1). Supervised classification and visual interpretation of the satellite image was done for land use mapping.

Morgan et al. (1984) developed the model to predict annual soil loss from field sized areas on hill slope. This model considers soil erosion to result from detachment of soil particles by raindrop impact and the transport of those particles by overland flow. The process of detachment by runoff is ignored. The model is a process-based model and it runs in two phases comprising water and sediment phases.

Water phase

Water phase mainly comprises of prediction of detachment by rain splash. It thus requires data related to rainfall such as the intensity of rainfall (I, mm h^{-1}), number of rainy days (R_n) and average annual rainfall (R, mm). Kinetic energy of rainfall (E, J m^{-2}), volume of overland flow (Q, mm) are calculated as follows:

$$E = R(11.9 + 8.7 \log I) \quad (1)$$

$$R_C = 1000 \cdot MS \cdot BD \cdot RD \cdot (E_t / E_0)^{0.5} \quad (2)$$

$$Ro = R/Rn \quad (3)$$

$$Q = R \exp(-Rc/R0) \quad (4)$$

where MS (%, w/w) is the soil moisture content at field capacity, BD (Mg m^{-3}) is the bulk density of the topsoil layer, RD (m) is the topsoil rooting depth, and E_t/E_0 is the ratio of actual and potential evapotranspiration.

Sediment phase

Sediment phase comprises of two predictive equations, one for the rate of splash detachment and the second for the transport capacity of overland flow. The model allows incorporating the effects of soil conservation practices as they affect changes in evapotranspiration, and rainfall interception that will ultimately play a significant role in either increasing the volume of runoff, the rate of detachment and the transport capacity or vice versa.

The model has been proved to be sensitive to changes in annual rainfall and soil type. Thus good information in context of rainfall and soil is required for successful prediction (Morgan et al., 1984). Rate of soil detachment by rain drop impact, (F) and Transport capacity of overland flow (G) are calculated as follows:

$$F = K (E_e^{-Aa}) b \times 10^{-3}, \text{ Kg/m} \quad (5)$$

$$G = C * Q^d * \sin S * 10^{-3}, \text{ Kg/m} \quad (6)$$

Where, K(g/J),is soil detachability index ,E(J/m) is Kinetic energy of rainfall A is the Percentage rainfall contributing to permanent interception and stem flow, C is the Crop cover management factor, sin S is the steepness of the ground slope expressed as the slope angle and a (0.05), b (1.0) and d (2.0) are the values of exponents

Crop cover management values were assigned to the particular crop type in the land use map.

RESULTS AND DISCUSSION

The study showed that the area was majorly covered with vegetation with patches of arable farm land, tree crops like cocoa and cola nut. The areas with slopes >700 m were covered with rock outcrops. Below the rock hills are forest vegetation between pockets of rock and soil cover. The inter-fluvial slopes were covered with old plantation which most have been taken over by forest. The lower slopes and valley bottom fringes were dominated by thickets and riparian forest. The land form therefore include from rock outcrops, rock hills, hill slopes, inter-fluvial slopes, and lower bottom fringes. Different land uses occupied the terrain categories. Each terrain category was characterized by unique land cover which made correlation of DEM, and land cover with soil loss estimation possible. Valley bottom was usually covered with tree canopy from lower slopes and valley bottom fringes because of the narrow (<5 m) nature of the valley. The erosion factor maps produced from water phase and sediment phase equations include volume of overland flow, Q, rate of soil detachment by raindrop impact, F and transport capacity of overland flow, G. The map of the annual soil loss was calculated by comparing the two maps of soil detachment and transport capacity and taking the minimum value from them (Figure 1). Soil erosion intensity was crossed with the digital elevation model and land cover to get the amount of soil loss from differrent slope facets and land uses. Average annual soil loss was estimated at 1.11 kg m^{-2} in spite of the hilly to rolling terrain of the area. This could be attributed to high vegetal cover more than 70%. The highest annual soil loss was 1.27 kg m^{-2} yr^{-1} from the rock hills with slope greater than 15%. The lowest was 0.94 kg m^{-2} yr^{-1} from the valley bottom fringes which were under riparian fo-rest with patches of arable farms. The inter-fluvial slopes were dominantly used for arable cultivation (such as maize, yam, cassava sole or intercrops) contributed 1.045 to 1.108 $kgm^{-2}yr^{-1}$ to soil loss. These values were lower than those estimated in hill-slope facets because the cropping system involved bush fallow where erosion risk only occurs when crops have not formed enough canopy for soil protection. However, the plant stover was usually left on soil surface which could also reduce rate of transport of soil particles. Soil losses increase as slope values or elevation increase but forest provides excellent protection on the soil against erosion (Figure 1). Vegetation maintains high rates of evapo-transpiration, rainfall intercept-tion and runoff infiltration. The average annual soil loss was less than the 1.33 $kgm^{-2}yr^{-1}$ or 3 tons $acre^{-1}yr^{-1}$ which is the tolerable standard.

More rainfall on the rock hill areas resulted to more soil loss as reflected also in increasing rate of soil detachment. More annual rainfall was due to the effects of orographic rainfall. Soils on hill slope area are well covered with vegetation and thus reducing erosion hazard to less than critical value. The early and the latter rains in the tropics are very erosive. Hence, rapid establishment of crops is important. If land use (shifting cultivation) and good vegetal cover on hills are maintained, erosion risk and soil degradation should not be a serious problem for sustained use in spite of the hilly terrain.

Conclusion

Land degradation by erosion is one of the major problems of agriculture in Nigeria. Soil erosion prediction is very essential for land use monitoring because high intensity of rainfall characterizing rainforest zones of Nigeria in which Ekiti is located. The study revealed that the effects of rainfall on a dissected hilly terrain depend on the land cover/uses and steepness of the terrain. The order of soil loss was lower slope with riparian forest < inter-fluvial slope with arable crops < rock hill with bush regrowth. The overall impact of high intensity rainfall characterizing Ekiti resulted to soil loss below critical level. The MMF model was found to be useful in predicting soil loss in Ekiti environs. The current land use and land cover are sustainable for long term production. Therefore these should be maintained to avoid land degradation by soil erosion.

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