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MODELLING LONG-TERM MEAN HILLSLOPE EROSION AT A LARGE CATCHMENT SCALE

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ABSTRACT

To better understand the relative impact of land use and management practices on hillslope erosion, modelling of spatial interrill and rill erosion needs to be undertaken at a catchment scale. This paper describes a spatial modelling procedure and presents the results of the predicted mean annual soil erosion over the Masinga catchment in Kenya. The model used is the Revised Universal Soil Loss Equation (RUSLE) integrated within a Geographical Information System environment. The spatial data layers for RUSLE were generated from the digital elevation model, soil property maps, remotely sensed images and climatic data. The current land use and management practices within the catchment were evaluated to determine their effects on mean annual soil loss. The results show that the present land utilization with lack of soil conservation measures, a rather low standard of husbandry on arable land, gross overstocking and lack of management on range land is resulting in high soil erosion. With the current land use and management practices, only 9.3% of the total catchment area is experiencing soil loss within the allowable tolerable rates of 2.2–10.0 ton ha^{-1} $year^{-1}$ recommended for the Masinga area. Other feasible alternative land management practices were also modelled. The results from these simulation scenarios were used to assess the effect of implementing best management practices. The integrated approach allows for relatively easy, fast and cost-effective prediction of spatially distributed soil erosion. It thus provides a useful and efficient tool for predicting long-term soil erosion potential and assessing the erosion impacts of alternative land use/cover and conservation support practices.
Keywords: ArcView GIS, catchment management, conservation tool, hillslope, Masinga, RUSLE, soil erosion modelling.

1 INTRODUCTION

Soil erosion and sediment transport are recognized as major environmental hazards in Kenya. Soil erosion is governed by topography, climate, soil, vegetation cover, land use and management factors, through mechanisms including particle detachment by raindrop impact, hydrology, flow hydraulics and other processes. Soil erosion is a problem occurring worldwide that affects ecosystems' stability and causes irreversible degradation of vast tracts of arable and forested lands. The problem causes both on-site and off-site effects. Both on-site and off-site problems can be related to a variety of soil erosion processes. On-site effects refer mainly to a loss of agricultural and land economic productivity, and to land degradation as a whole, whereas one of the most important off-site effects is certainly the sedimentation of reservoirs and their corresponding loss in water storage capacity.

Land conversion within the developing world is occurring at an unprecedented rate. For instance, the expansion of subsistence farming practices in the form of field crop agriculture and pasture within rural areas is contributing significantly to the ecological alteration in many tropical countries [1]. Many rural and remote portions of the tropics are inherently marginal with respect to land productivity for agriculture or pasture [1]. One of the most destructive and insidious processes, steadily increasing as a result of anthropogenic activity in these areas, is soil erosion [2]. This raises many concerns regarding the potentially damaging impacts of contemporary land use in relation to the often weak or non-existent land management initiatives.

Soil erosion is not a new problem in Kenya. It has been recorded since the 19th century and during the early decades of the last century it was already regarded as a serious problem in many parts of

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the country [3]. The erosion problem has come about through increasing pressure on land in terms of people, livestock and crop production exacerbated to some extent by vagaries of climate. The land and water resources are being increasingly threatened by these rising demands. Farmers with minimal resources are moving into marginal areas (in terms of both climate and slope) with high erosion hazards and low production potential, hence worsening the problem of soil erosion.

Cultivation of steep slopes within the wet highlands as a result of the population pressure on the land, and intense grazing in the semi-arid lowlands are some of the major factors enhancing soil erosion within the Masinga catchment, the area of the present study. Future pressure to expand agricultural and grazing operations within Masinga will unquestionably accentuate the already high rate of soil erosion. This problem can only be effectively addressed through long-term strategic planning, based on a sustainable management approach at the catchment level.

As is common to many tropical countries, Kenya suffers from lack of financial resources to research, monitor and model sources and outcomes of environmental degradation. Most erosion assessment approaches in Kenya have in the past used plot-level observations to extrapolate catchment or landscape unit erosion rates [4]. In most cases, the erosion processes have been assumed to occur in a uniform manner all over the landscape and hence the results of unit observation were factored to cover the entire landscape for which data were not collected. For that reason, assumptions were made that plot-level experimental results could be used for extrapolating catchment level data [5, 6]. Although the run-off plots provide good experimental insight into the relationships between soil loss under different crops with different cover or on different soils and on different slopes, their results cannot be extrapolated to cover the whole catchment.

Until recently, there did not exist a reliable or financially viable means to model and map soil erosion within large remote areas. However, an increase in the reliability and resolution of remote sensing techniques, modification and advancement in catchment scale soil erosion modelling techniques, and advances in Geographical Information Systems (GIS) represent significantly improved tools that can be applied to both monitoring and modelling the effects of land use on soil erosion potential.

1.1 Objective

This study is undertaken to explore the application of GIS technology as a tool in catchment management planning at Masinga. The general objective is to develop readily transferable Revised Universal Soil Loss Equation (RUSLE)–GIS based procedures to be used by land resource managers to evaluate different land use and management practices in terms of soil loss potential. The primary objective is to map the spatial mean annual soil erosion over the catchment, and identify and prioritize areas with high erosion risk in order to direct the implementation of viable management options and hence formulate the best management practices (BMPs) for the catchment.

2 STUDY AREA

The Masinga catchment area is some 6255 km^2 in extent, lying to the east of the Aberdares Mountains and south of Mount Kenya. It lies between latitudes 0°7′ and 1°15′ South and longitudes 36°33′ and 37°46′ East. The geology of the Masinga area can be broadly divided into volcanic rocks in the north and west, and a pre-Cambrian basement complex in the southeast. The landform in the catchment ranges from steep mountainous terrain with strong relief in the west to undulating plains with subdued relief in the southeast. The elevations above mean sea level in the mountainous terrain range from 2500 to 4000 m and for the undulating plains from 900 to 1200 m. The soils are generally Lithosols and Histosols (FAO classification) at the highest altitudes in the Aberdares with Humic Andosols at slightly lower elevations. Over much of the rest of the basalt foot slopes, deep fragile clays

(Eutric Nitosols) predominate. In the basement complex, the soils are mostly coarser textured and shallower and are classified as Acrisols, Luvisols and Ferralsols.

The catchment falls within five agroclimatic zones, ranging from semi-arid in the east to humid near the western side. The annual rainfall is bimodal with short rains occurring from September to November and the long rains from March to May. The mean annual rainfall varies from about 600 mm on the easterly boundary to over 2000 mm on the Aberdares Mountains. The maximum temperatures vary from 25.5 to 31.0°C generally being experienced in February or March, prior to the onset of the main rainy season (long rains). Minimum mean temperatures of 21.0–24.0°C occur in the month of July.

The catchment has an estimated population of about 2 million people (1999 census) with most people engaged in agricultural activities. Almost all the cultivation takes place in the southeast, northwest and generally in the western areas. There is scattered cultivation in the eastern half of the area with slopes greater than 15% where the soils are Vertisols and where severe erosion is taking place. The remainder of the area is used for grazing with large numbers of cattle, sheep and goats being herded on the area, which is almost completely denuded of grass and has very little cover.

3 MATERIALS AND METHODS

3.1 GIS and soil erosion modelling

In order to manage soil erosion effectively, it is necessary to estimate its magnitude and spatial distribution in a catchment. Before any meaningful soil erosion conservation can be implemented, it is necessary to first map the spatial potential mean soil erosion over the catchment based on the current land use/cover and management practices. Mapping the spatial potential soil erosion allows easier identification of hazard or erosion risk areas, which can form a basis for the government and/or the catchment stakeholders in prioritizing areas of immediate conservation and allocating resources accordingly.

While soil loss data gathered from experimental plots can be extrapolated over the entire catchment, these results may be misleading for catchments with heterogeneous land use patterns and physical characteristics. The problem may be addressed either by establishing numerous observation plots over the catchment to capture variations in soil loss across the area or by employing modelling techniques. The first option is usually a costly and time-dependent proposition particularly where financial and human resources are limited. Modelling is therefore preferred since soil loss under alternative management scenarios can be rapidly estimated at minimal cost.

In this study, the RUSLE model was applied within a GIS environment. The analytical and manipulation tools within the GIS allowed for the quantification of the parameters from available data sets. Using the vector-based GIS programme, ArcView, a complete coverage of soil erosion within the Masinga catchment was estimated under the current land use/cover and management practices. The RUSLE factors were derived from the digital elevation model (DEM), soil property maps, remotely sensed images and climatic surfaces.

3.2 The soil erosion models

Soil erosion models are used to simulate the effects of land management activities on rates of soil erosion and contribute to the development of appropriate intervention strategies. One way to reduce the negative consequences of accelerated soil erosion is to select land use and farm management practices that generate a minimum amount of soil erosion. Modelling soil erosion provides a sophisticated tool for selection of appropriate soil conservation practices. There are many soil erosion models currently in use. These include the Revised Universal Soil Loss Equation, the European Soil Erosion Model, the Water Erosion Prediction Project, the Limberg Soil Erosion Model and the Chemical Runoff and Erosion from Agricultural Management System to name but a few.

3.2.1 The RUSLE model structure

RUSLE is among the most extensively used empirical soil erosion model. It is the present state of the art in soil erosion modelling. Basically RUSLE, which lumps the interrill and rill erosion together, is a regression equation. It is an erosion prediction model designed to predict the long-term average annual soil loss from specific field slopes in specified land use and management systems. The RUSLE model was chosen for this study because its data requirements are not too complex or unattainable, it is relatively easy to understand and it is compatible with GIS [7]. When used in conjunction with raster-based GIS, the RUSLE model can isolate locations of erosion on a cell-by-cell basis, determine the role of individual variables on the rate of erosion and identify the spatial patterns of soil loss within a watershed [7].

One major improvement made using RUSLE in this study was the application of the upslope area contributing method in determining the slope length and steepness factor, which makes the model to function in a semi-distributed form. The use of time series of remote sensing imagery and daily rainfall to incorporate the effects of seasonally varying cover and rainfall intensity, and the use of new digital maps of soil and terrain properties allowed the estimation of spatial seasonal erosion for the Masinga catchment.

RUSLE is expressed using six factors, which are composite factors of many other factors. The RUSLE model is given as:

$$A = LS \times R \times K \times C \times P, \tag{1}$$

where A is the estimated average annual soil loss (tons ha^{-1} year^{-1}); LS is the combination of the slope steepness and slope length factors (unit less); R is the rainfall erosivity factor (kJ mm m^{-2} h^{-1} year^{-1}); K is the soil erodibility factor (ton ha^{-1} kJ^{-1} mm^{-1} m^2 h); C is the cover and management factor which estimates the soil loss ratio (SLR) at seasonal intervals throughout the year, accounting for effects of prior land use, canopy cover or crop, surface cover, surface roughness and soil moisture; P is the support practice factor, calculated as an SLR, which accounts for tillage techniques, strip cropping and terracing.

3.3 Data source and model factor generation

Four primary data themes were required to develop the RUSLE factors. These were the DEM, which is a three-dimensional raster representation of the topography, the climatic data (precipitation), the soil type coverage and the land use coverage, and conservation practices. The DEM was required to derive the slope length (L) and the slope steepness (S) factors. The climatic data were required to derive the rainfall erosivity (R) factor. The soil type coverage was required to derive the soil erodibility (K) factor, and the land use coverage was used to derive the crop management (C) and conservation practice (P) factors.

The data for this study was acquired from various sources. Among the sources of data was the reconnaissance survey that was carried out in the study area. The survey was carried out between July and September 2003. In addition to the survey and the field data collection, more data were collected from relevant ministries, departments, research centres and agencies in Kenya. Other data was acquired from relevant existing databases.

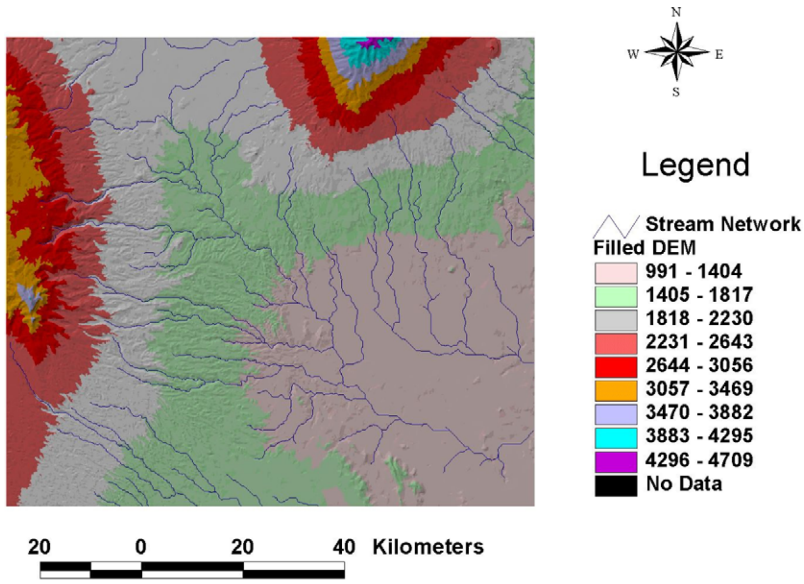

Figure 1: The ‘corrected’ (depressionless) DEM for the Masinga catchment. The elevations are in metres above mean sea level. The stream network is for a threshold value of 500.

3.3.1 The digital elevation model

A DEM of scale of 1:250 000 and grid resolution of 90 m covering the study area was purchased from the United States Geological Surveys. The DEM was projected using the Universal Transverse Mercator 37 North (UTM-37N) reference system. Most DEMs often contain pits or local depressions. These pits can reflect real-life conditions but are often the result of poor input data or interpolation errors. Since the contributing area is based on routing the cumulative area downslope, these pits can act as sinks if not removed and therefore hinder flow routing. In this study, a depressionless DEM (Fig. 1) was created using the ‘Fill the Sink’ command from the ArcView ‘Hydro’ extension menu that allows the removal of the sinks or pits from the DEM.

To calculate a drainage network, a grid must exist that is coded for the direction in which each cell in a surface drains. The flow direction for this study was based on the eight-direction pour point algorithm (8D). The 8D algorithm identifies the grid cells, out of the eight surrounding cells towards which water will flow if driven by gravity. For every 3×3 cell neighbourhood, the grid processor stops at the centre cell and determines which neighbouring cell is lowest.

In order to generate a drainage network for the study area, it was necessary to determine the ultimate flow path of every cell on the landscape grid. This was done by determining the flow accumulation data layer, which defines the amount of upstream area draining into each cell. A threshold value, which defines the number of grid cells that must flow through an area to be called a stream, must be established. A threshold value of 500 was selected for this study. Flow accumulation was used to generate a drainage network, based on the direction of flow of each cell. In order to determine the *LS*-factor for the Masinga catchment, the DEM was delineated to have only the area represented by the catchment. ArcView supports a number of extensions that can be used to delineate the catchment. The ArcView spatial analyst and the ‘Hydro’ extension were used to delineate the Masinga catchment (Fig. 2).

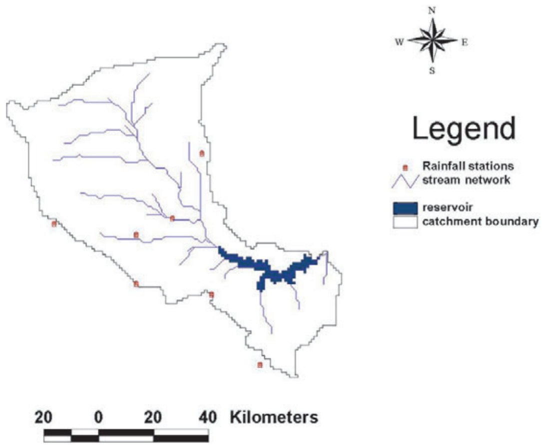

Figure 2: The delineated catchment from the DEM that has been corrected for sinks.

The GIS technology allows calculation of the slope length and steepness, and the LS-factor for the rill and interrill erosion through the estimation of the upslope contributing area per unit contour width by computing the flow direction and flow accumulation. Generally, the upslope contributing area per unit contour width is taken as the sum of the grid cells from which water flows into the cell of interest [8–10]. Desmet and Govers [9] suggested an automatic approach for generation of the L-factor based on the original concepts of Foster and Wischmeier [11]. The unit contributing area for the slope length value was substituted as the slope length within the equation provided by Foster and Wischmeier [11] with each of the grid cells within the DEM considered as a slope segment having uniform slope. Substituting the values for cell outlet and cell inlet into the Foster and Wischmeier [11] equation gives the slope length L component as:

$$L_{i,j} = \frac{A_{i,j\text{-out}}^{m+1} - A_{i,j\text{-in}}^{m+1}}{(A_{i,j\text{-out}} - A_{i,j\text{-in}})(22.13)^m}, \qquad (2)$$

where $L_{i,j}$ is the slope length factor for the cell with coordinates $(i,\ j)$, $A_{i,j\text{-out}}$ is the contributing area at the outlet of the grid cell with coordinates $(i,\ j)$ (m^2), $A_{i,j\text{-in}}$ is the contributing area at the inlet of the grid cell with coordinates $(i,\ j)$ ($m^2\ m^{-1}$) and m is the slope length exponent of the RUSLE S-factor.

The concept of replacement of slope length with upslope drainage area per unit of contour length was applied in this study. With this substitution each of the grid cells within the DEM is considered as a slope segment having uniform slope. To incorporate the impact of flow convergence, the hillslope length factor was replaced by upslope contributing area A. The modified equation for the computation of the LS-factor in GIS in finite difference form for erosion in a grid cell representing a hillslope segment was derived by Mitasova *et al*. [10]. A simpler, continuous form of the equation for the computation of the LS-factor at a point $r = (x,\ y)$ on a hillslope is given as:

$$LS(r) = (m+1)[A(r)/a_0]^m[\sin b(r)/b_0]^n, \qquad (3)$$

where A is the upslope contributing area per unit contour width (m), b is the slope (deg), m and n are parameters, and $a_0 = 22.1$ m is the length and $b_0 = 0.09 = 9\% = 5.16$ deg is the slope of the standard USLE plot.

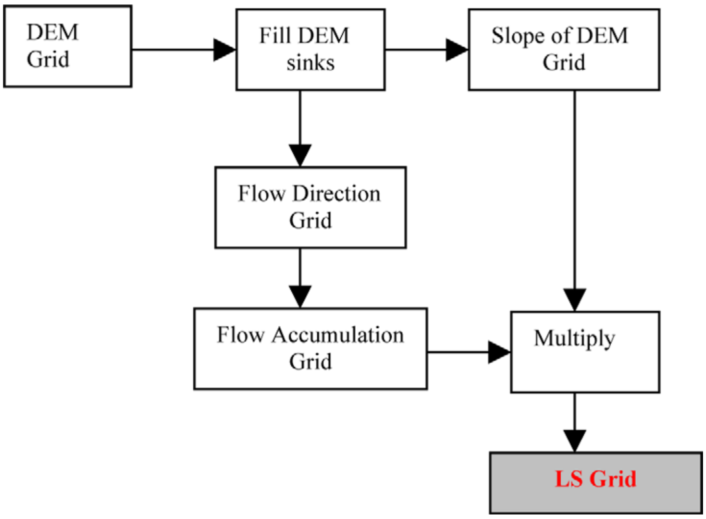

Figure 3: Flowchart for estimating the *LS*-factor from a DEM.

In reality, a zone of deposition or concentrated flow would generally occur when a slope length becomes long. The limiting slope length for interrill and rill erosion is about 120–150 m. Since RUSLE is only suitable for estimating erosion due to interrill and rill processes, there was a need to determine an upper bound on the slope length by limiting the flow accumulation. This was done by limiting the maximum flow accumulation to a given number of cells. To determine the number of cells, an upper bound slope length of 300 m was assumed and the DEM resolution of 90 m × 90 m was used. A slope length of 300 m was assumed, although greater than the allowed length, because the available DEM for this study was of a coarse resolution.

The slope steepness *S*-factor was computed from the DEM using the ArcView's spatial analyst extension. The map algebra in the ArcView was applied to combine the upslope contributing area component ($L_{i,j}$) with the slope factor using a modified equation given as:

$$LS = (F_{\text{accum}} \times CS/22.13)^{0.6} \times (\sin \text{slope}/0.0896)^{1.3} \times 1.6, \tag{4}$$

where F_{accum} is the flow accumulation expressed as the number of grid cells; *CS* is the cell size [resolution of the DEM (90 m)]; sin slope is the slope grid that had to be converted into radians; 0.6 and 1.3 are slope exponents adapted from the values estimated by Mitasova *et al*. [10]. The steps for determining the *LS*-factor from a DEM are summarized in the flowchart shown in Fig. 3.

3.3.2 Rainfall–runoff factor *R*

The rainfall–runoff erosivity factor (*R*) of RUSLE according to Renard *et al*. [12, 13] is generally recognized as one of the best parameters for the prediction of erosion potential of raindrop impact and therefore the potential transport capabilities of runoff generated by erosive storms. At a large-scale level, climatic erosivity data can be used as an indicator of potential risks as described by Morgan [14]. The accurate computation of each storm rainfall erosivity EI_{30} calls for high-resolution rainfall measurements on a small time step. Generally this kind of record is not available for the Masinga catchment, particularly over the large periods recommended for estimating the *R*-values (about 20 years of rainfall records).

In areas where long-term pluviograph data are not available, the *R*-factor may be estimated using annual rainfall data or the Modified Fournier Index [15–19]. Alternatively, 2-year, 6-h rainfall intensity probability values may be used to estimate the *R*-factor [20–23]. These approaches, however, do not allow determination of the seasonal distribution of rainfall erosivity, which is important in calculating the average annual cover and management factors. Seasonal distribution of rainfall erosivity is important for assessing erosion hazards, and to adequately represent the erosive potential of rainfall for each temporal distinctive period, it is recommended that the RUSLE cover management factor be calculated on a 15-day or monthly basis [24].

To overcome the problem with limited pluviograph data and the inability to estimate the seasonal distribution of rainfall erosivity, a model using daily rainfall data was used in this study. The daily erosivity model by Yu and Rosewell [25, 26] and Yu [27] is adapted with model parameter modification for the study area. The rainfall erosivity model in which the storm EI_{30} for the month j is related to the daily rainfall amount, R_d, in the form:

$$\mathrm{EI}_{30}(j) = \alpha[1 + \eta\cos(2\pi fj - \omega)]\sum_{d=1}^{N} R_d^{\beta} \quad \text{when } R_d \geq R_0, \tag{5}$$

where R_0 (set to 12.7 mm) is the threshold rainfall amount to generate runoff and N is the number of days with rainfall amount $\geq R_0$ α, β, η and ω are model parameters. The first part of eqn (5) is a sinusoidal function with a wavelength of 12 months and a fundamental frequency $f = 1/12$. This part of the equation is used to describe the seasonal variation of rainfall erosivity for a given amount of daily rainfall.

The idea of using threshold values for both intensity and depth has been built into the latest methods of calculating the EI_{30} by leaving out rainfall of less than 12.7 mm, which is separated from other rainfall periods by more than 6 h. The storm events that have total rainfall depth ≥12.7 mm are considered to be potentially harmful in terms of erosion and sediment transport. Therefore, only those events are included in calculation. In this study, a threshold value of 12.7 mm was set as the erosive rainfall to be consistent with that used in the USLE by Wischmeier and Smith [22].

The model parameters α, β and η derived by Yu [27] for tropical regions (New South Wales, Australia)were adapted and modified in this study. For the case of $R_0 \geq 12.7$ mm, the following sets of equations were used:

$$\alpha = 0.395[1 + 0.098\exp(3.26 \times \psi/M_\mathrm{R})], \tag{6}$$

$$\beta = 1.49, \tag{7}$$

$$\psi = 0.29, \tag{8}$$

where M_R is the mean annual rainfall (mm) and ψ is the mean long rains (March–May for the Masinga area). In this study, the parameter ω in eqn (5) was set at $2\pi/3$, implying that for a given amount of daily rainfall the corresponding rainfall erosivity is highest in April, for most parts of the Masinga catchment.

Seven rainfall stations in Masinga with continuous daily rainfall records for at least 20 years were identified and georeferenced. The daily rainfall records from 1 January 1981 to 31 December 2000 were used. The ratio ψ/M_R for the selected stations was calculated using the daily rainfall data. An Excel spreadsheet was used to determine the number of days with daily rainfall amounts ≥12.7 mm and their sum for each month for every station for the 20 years' records. Equation (5) was then used to estimate the monthly EI_{30} for each station. The monthly EI_{30}values were summed up and averaged over 20 years to yield the mean annual erosivity, the *R*-factor for each station.

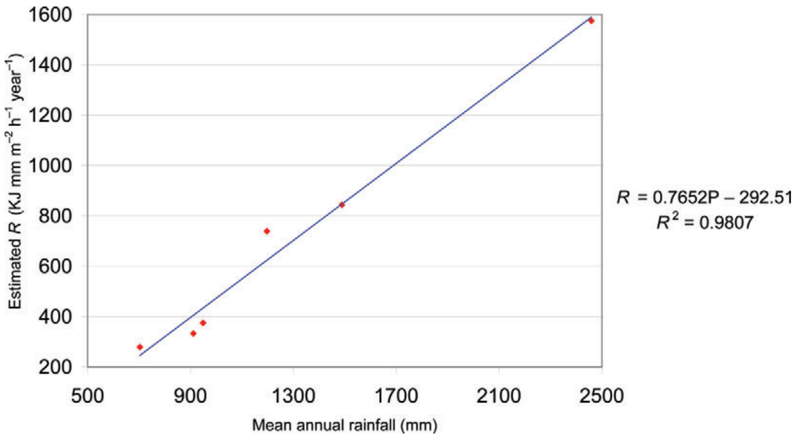

Figure 4: Relationship between mean annual rainfall and mean annual erosivity (*R*-factor).

In order to estimate the *R*-values for stations with only mean annual records, a regression equation based on the *R*-values obtained with eqn (5) and the corresponding mean rainfall records for the seven stations with daily records was developed for this study. Figure 4 shows the relationship between mean annual rainfall based on daily records and their associated mean annual *R*-values. The developed equation [eqn (9)] shows a regression coefficient of $r^2 = 0.9807$ which shows that there is a high positive correlation between the mean annual rainfall and the mean annual erosivity based on the daily rainfall record model. Equation (9) was used to estimate *R*-values for other stations with only annual mean rainfall records. The established regression equation based on the daily rainfall record model is given as:

$$R = 0.7652 \times P - 292.51, \tag{9}$$

where R is the estimated mean annual erosivity (kJ mm m^{-2} h^{-1} $year^{-1}$) and P is the mean annual rainfall (mm).

To enable the mapping of the *R*-factor in a spatial domain, it is required first to prepare the precipitation surface for the catchment. The stations' data were georeferenced using their latitudes and longitudes. The data was converted into a 'dbaseIV' and then exported to the ArcView platform. A point theme was created using the ArcView GIS software. The point theme was converted to a shapefile and added as a new view using the ArcView procedure. A surface rainfall map for the catchment was then created by interpolating the rainfall point grid (Fig. 5) using the inverse distance weighting interpolation method, a procedure supported by ArcView. Using the analysis tool and the map calculator in ArcView, eqn (9) was then applied to the interpolated surface rainfall grid and a resulting spatial *R*-factor map was generated.

3.3.3 Soil erodibility factor *K*

The Exploratory Soil Map of Kenya of scale 1:1 000 000 obtained from Kenya Soil Survey was first digitized. To enable mapping of different soil types and their associated parameters in a spatial domain, the soil map of the Masinga catchment was clipped from the digitized soil map of Kenya. A map of this scale was used because there were no soil maps of finer resolution covering the entire catchment, while technical and fiscal constraints could not permit a full-scale soil survey of the area.

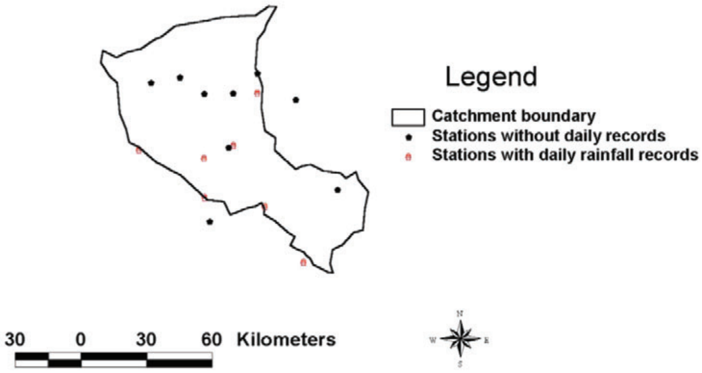

Figure 5: Distribution of rainfall stations within the Masinga catchment.

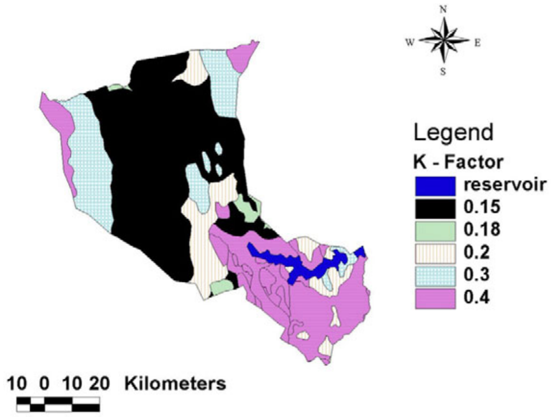

Figure 6: The spatial K-factor map for the Masinga catchment.

The map obtained thus contained the major soil-mapping units based on a FAO–UNESCO [28] classification.

Assignment of erodibility values to the FAO–UNESCO soil classification scheme for the catchment was conducted using a table of soil types and associated characteristics. In this study, the K-factor values were derived from the existing literature from previous studies carried out in Kenya by Sombroek *et al*. [29]. By assuming that the resolution of the K-values matched that of the soil-mapping units, the mean K-factors for each soil type were assigned. A soil erodibility map of the catchment, expressed in class ranges (Fig. 6) was generated.

3.3.4 Cover management factor C

In RUSLE, the C-factors represent weighted average SLRs that are determined from a series of subfactors that include prior land use, canopy cover, surface cover and surface roughness [12]. However, it was not possible to determine the magnitude of these subfactors in this study because the land use/cover data available for the Masinga catchment only defined broad land use categories. Therefore, in this study the land use map for the catchment was clipped from the land use map of Kenya that was prepared using remote sensing techniques and previous field surveys. The major land use/cover types were identified and classified, and their associated C-factor values were assigned for

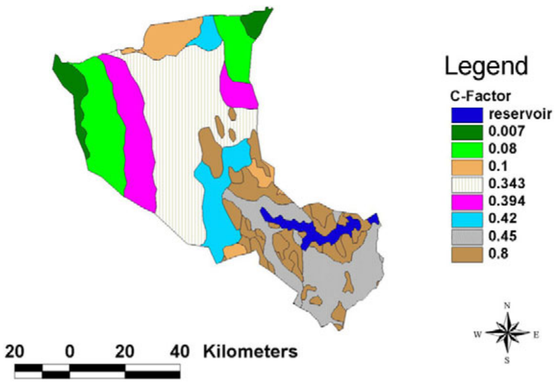

Figure 7: The spatial C-factor map for the Masinga catchment based on broad land use/cover type.

each land use/cover category based on estimated values for similar crops and land cover for Kenya by Angima *et al*. [30]. A spatial C-factor map for the study area (Fig. 7) was then generated.

3.3.5 Conservation practice factor P

The conservation or support practice factor P in RUSLE is the ratio of soil loss with a specific support practice to the corresponding loss with up and down slope tillage, which is assigned a value of 1. The support practices principally affect erosion by modifying the flow pattern, grade or direction of surface runoff. For cultivated land, the support practice generally includes contouring, strip cropping, terracing, subsurface drainage, minimum tillage, etc. The P-factor is calculated by multiplying the subfactors such as contouring, terracing and strip cropping. To create a spatial map for the P-factors in this study, the digitized map of the soil units and land use/cover polygons was used. A spatial percentage slope map was created and each of the polygon units was assigned a P-value based on its percentage slope and the current conservation practice. The P-values for contour cultivation and strip cropping and their corresponding percentage slopes from Wenner's results [31] were used. The forestland was assigned a P-factor of 1, and urban areas, water bodies and roads were assigned a value of 0.

3.4 Integrating the RUSLE–GIS

The RUSLE data themes and their associated attribute tables were integrated in Arcview 3.2 to predict the average annual soil loss for the catchment. The primary advantage of using the GIS to model soil loss is the ability to analyse spatial variability in erosion potential over the catchment based on influencing factors such as slope, soil type, land use/cover and rainfall.

The data themes in the form of shapefiles were converted into grid files for analysis. The use of raster data facilitated modelling because data themes could be manipulated mathematically. The analytical and manipulation tools within the GIS allowed for the quantification of the parameters from available data sets. The overall steps of integrating the RUSLE–GIS are summarized in the schematic diagram given in Fig. 8.

3.4.1 Prediction of the potential mean annual soil loss

In order to formulate the BMPs for the Masinga catchment, four simulation scenarios were carried out. The land use and management practices were the factors that were altered in each scenario.

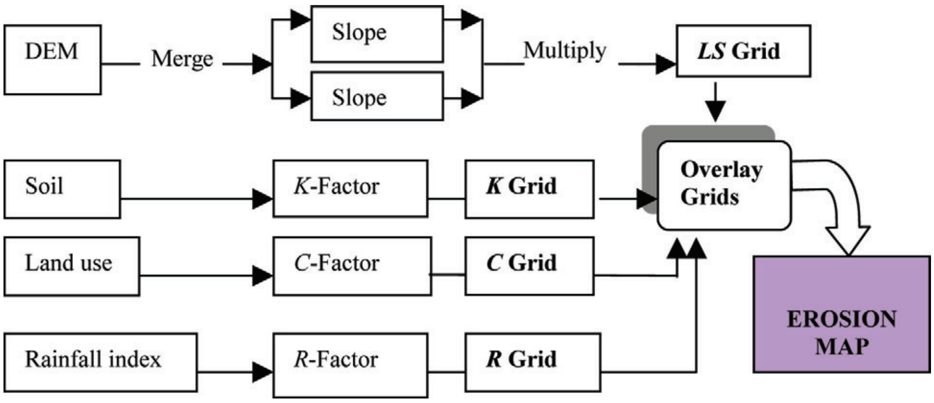

Figure 8: Schematic diagram for the RUSLE–GIS model.

Combinations of single viable conservation practices were simulated and the results of each simulation were compared with the others. The simulation scenarios were based on varying the *C*-factor and the *P*-factor depending on the land use and management practices.

In formulating alternative management options at the Masinga catchment, it is required to have a thorough knowledge of the interacting factors within the catchment. The choice to model an alternative land use and/or conservation practice was based on the following factors:

1. agroclimatic zone for each subcatchment,
2. general percentage slope for each subcatchment,
3. soil properties for each subcatchment,
4. cultural aspects of the people and the catchment stakeholders, and
5. viability of the perceived management option(s).

3.4.2 Benchmark simulation scenario (S1)—current management practices

The first simulation scenario was to map the spatial soil erosion based on the current land use/cover and management practices. Using the vector-based GIS program, ArcView, a complete coverage of soil erosion within the Masinga catchment was estimated under the current land use/cover and management practices. This formed the benchmark simulation scenario whose database was used to formulate other scenarios. In this scenario, the *C*-factor and the *P*-factor values were estimated from the current land use/cover and management practices, respectively. Most of these factors were derived from existing databases, government reports (Ministry of Agriculture) and results of field survey carried out in the study area. Most of the factor values were based on annual averages.

3.4.3 Simulation scenario 2 (S2)—changing conservation practices (P_1)

The second scenario involved assigning different *P*-values depending on the selected conservation practice for each area within the catchment. For areas with steep slopes greater than 15%, the combined contour cultivation and strip cropping was applied. This did not include the forestland, which is not under cultivation. For the undulating plains and the lower areas, especially where water conservation is also a priority particularly in the southeast of the catchment, *P*-values for combined contour cultivation and level terracing were used.

The selection of a conservation practice for a given subcatchment was based on the factors listed under Section 3.4.1. Isolated studies for some runoff plots within the catchment have shown that the use of hedges, Napier grass, creeping grass and trees can compliment other conservation structures such as terraces and cut-off drains. In addition to conserving the soil, the agroforestry practice provides other benefits such as fodder for the livestock, timber and fuel wood for energy. To model this scenario, P-values were assigned to each management practice for each particular subcatchment. The database for the P-values was updated with the new values assigned. The other factors (R, LS, K and C) were maintained as in the benchmark scenario.

3.4.4 Simulation scenario 3 (S3)—changing the land use/cover (C_1)

Different land use/cover types were selected for each subcatchment. The selection of an alternative land use was based on the factors listed in Section 3.4.1. Intercropping, crop rotation and pasture cultivation were selected as alternative land use activities in the humid and semi-humid regions. Agroforestry, land husbandry, controlled grazing through ranching and planting indigenous trees were considered as the appropriate land use practices for the arid and semi-arid regions where, currently, severe soil erosion is taking place. Leaving residue after harvest over the land surface especially in the arid zones was also considered as an alternative land cover. In the arid zones of the catchment, the use of vegetative and legume cover crops especially at the onset of the rainy season when the soil is bare and more prone to severe erosion was modelled. For each of the selected land use practices, appropriate C-values were assigned and the benchmark database updated. The model was again run with the new C-values and the benchmark factors (R, LS, K and P) were maintained.

3.4.5 Simulation scenario 4 (S4)—combining P_1 and C_1 data sets

Some studies within the catchment show that the application of cover crop alone could not control soil erosion effectively. A few studies that have been carried out within the Masinga catchment using runoff plots show that by combining the land use and management practices there are a number of advantages that can be realized, which include: erosion control, improved soil fertility (which translates to improved crop yield), source of fodder for livestock, building material and firewood.

A scenario was therefore formulated to combine both the land use and management practices. In areas where the slope is greater than 50%, a combination of cut-off drains, graded terraces, vegetative cover (e.g. creeping grass), cover cops such as legumes, intercropping and contour cultivation were used to determine the P_1- and C_1-factors. In the low lands and undulating areas, level terraces, vegetative cover crops and crop residue were modelled for both soil and water conservation. For each combination, the P_1- and C_1-factors were determined by assigning appropriate values. The P_1 and C_1 grid layers were then overlaid together with the benchmark R, LS and K grids.

4 RESULTS AND DISCUSSION

4.1 Results of the benchmark scenario

The grid themes (R, LS, K, C and P) were multiplied together using ArcView's map calculator to generate the spatial soil erosion map as shown in Fig. 9. The quantitative output of the predicted soil erosion rates for the Masinga catchment resulting from the current land use/cover and management practices were computed and grouped into six ordinal classes. The results for the benchmark scenario (S1) are summarized in Table 1.

The critical areas that require urgent soil and water conservation management are easily identified from the spatial erosion map (Fig. 8). Based on the Kenyan standard for classification and gradation of soil erosion, an annual estimated soil loss tolerance (T) for the Masinga catchment of 2.2–10 ton ha^{-1} year^{-1} was suggested [30]. The results from Table 1 show that only 9.3% of the total

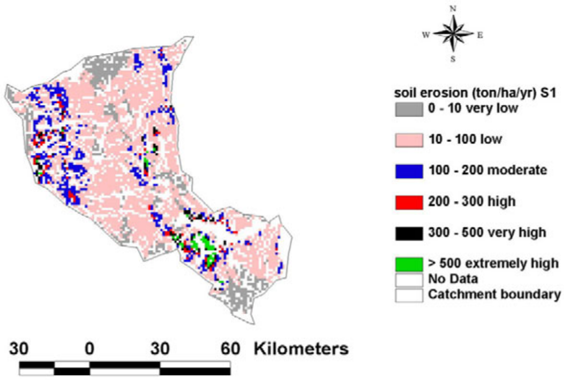

Figure 9: Spatial erosion classification for the benchmark scenario (S1).

Table 1: Results of soil erosion for the benchmark scenario (S1).

Soil class	Soil loss range (ton ha^{-1} year^{-1})	Description of soil loss class	Area (km^2)	Catchment area (%)	Mean	Standard
1	0–10	Very low	582	9.3	5.11	2.60
2	10–100	Low	2628	42.0	40.49	23.22
3	100–200	Moderate	522	8.3	137.78	27.56
4	200–300	High	116	1.9	240.03	28.14
5	300–500	Very high	101	1.6	379.66	53.60
6	>500	Extremely high	57	0.9	779.13	285.58

catchment area is experiencing soil erosion within the tolerable rates. About 54.7% of the total catchment area is experiencing soil erosion ranging from 10 to over 500 ton ha^{-1} year^{-1}. Although the soil classification of 10–100 ton ha^{-1} year^{-1} is described as low, this is still beyond the tolerable rates.

The areas experiencing soil erosion rates varying between 100 and over 500 ton ha^{-1} year^{-1} are in the northwest, western, southeastern and a bit of the eastern zones of the catchment. These are the subcatchments that have critical potential soil erosion. The southeastern zone of the catchment is experiencing increased erosion rates as a result of lack of proper animal husbandry and soil and water conservation management.

Based on the soil loss classification, a greater percentage (42.0%) of the total catchment area is experiencing soil loss in the range of 10–100 ton ha^{-1} year^{-1} under the current land use and management practices. There is pressure for more people to encroach on the remaining forest cover and therefore proper land use/cover and management practices need to be put into place. From the spatial soil erosion map, scenario 1 (Fig. 9), it can be inferred that the present land utilization with lack of soil conservation measures, a rather low standard of husbandry on arable land, gross overstocking and lack of management on range lands is resulting in high soil erosion.

4.2 Comparison between the benchmark scenario (S1) and other simulation scenarios

The spatial soil erosion for all the scenarios are shown in Fig. 10, and the areas under different erosion range are summarized in Table 2. From Table 2, it can be shown that the area under tolerable soil

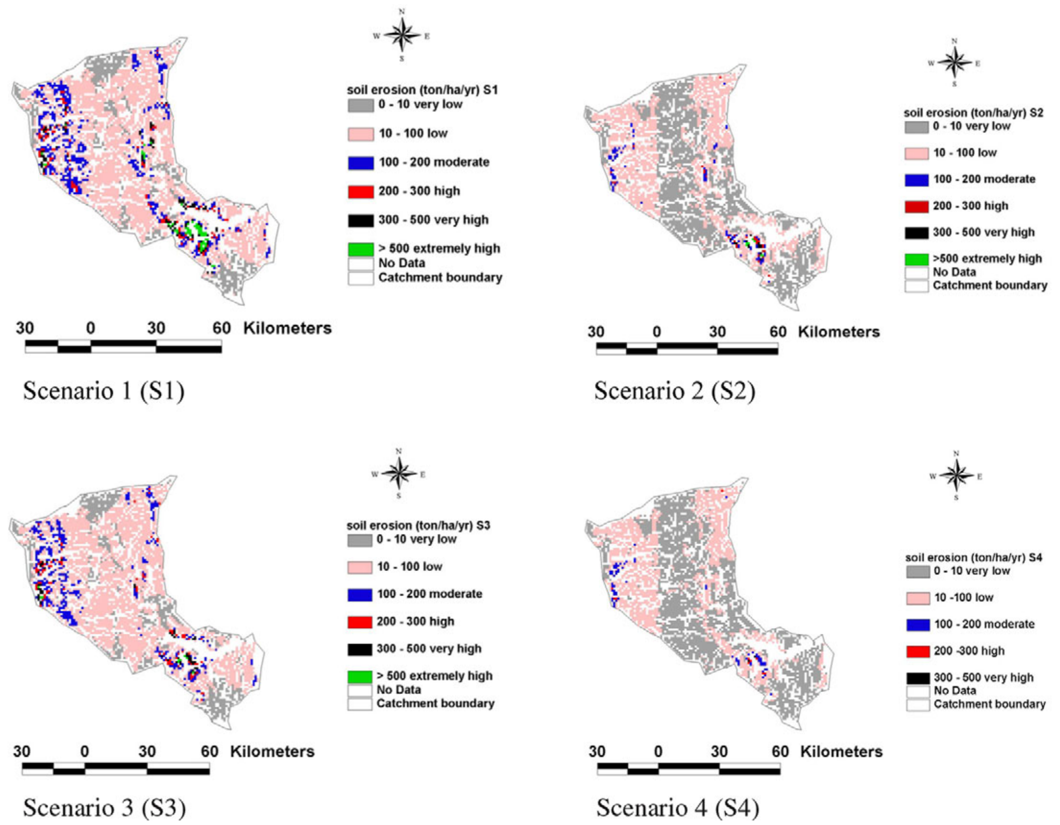

Figure 10: Spatial soil erosion for all simulation scenarios: S1, S2, S3 and S4.

Table 2: Area under different spatial soil erosion range for each of the four simulation scenarios.

Soil loss range	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
(ton ha^{-1} year^{-1})	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
0–10	582	9.3	2068	33.1	708	11.3	2280	36.5
10–100	2628	42.0	1766	28.2	2731	43.7	1611	25.8
100–200	522	8.3	99	1.6	392	6.3	72	1.2
200–300	116	1.9	29	0.5	94	1.5	10	0.2
300–500	101	1.6	14	0.2	55	0.9	2	0
>500	57	0.9	7	0.1	9	0.1	0	0

erosion rates could be increased to 33.1 and 11.3% in scenarios 2 and 3, respectively. By combining the recommended land use/cover and conservation support practices (scenario 4), the results show that the area experiencing a tolerable soil erosion rate could be increased to 36.5%. Likewise, the area experiencing soil erosion within 10–100 ton ha^{-1} year^{-1}, which is greater than the allowed tolerable rates is 42.0, 28.2, 43.7 and 25.8% in scenarios 1, 2, 3 and 4, respectively. Again the results show that by combining the recommended land use/cover and conservation support practices (scenario 4), the area experiencing soil loss greater than the allowed rates could be reduced from 42.0 to 25.8%. Scenario 4 is thus recommended as the viable BMP for the Masinga catchment.

4.2.1 Model results verification

The mean annual soil loss generated by the RUSLE–GIS model is subject to error due to inaccuracies inherent in each data layer and the limitations of the methods used to derive the component factor values. Therefore, verification is essential to gain an appreciation of the model's predictive capabilities. A visual and qualitative field survey was conducted within the study area. The field verification by visual observations and through questionnaires indicated that locations of very low soil loss potential were well estimated by the model, while locations of low potential were not as accurate. However, areas of moderate, high and extreme soil loss potential were the most successfully identified by the model. From the field validation, the RUSLE model's ability to predict soil erosion potential within the Masinga catchment is viewed as effective, when considering the purpose of this model as a conservation tool.

5 CONCLUSIONS

This study presents a first attempt in the application of GIS technology to model soil erosion in the Masinga catchment. It demonstrates the integration of an empirical model, RUSLE within the GIS environment to estimate average annual soil losses in a spatial domain. GIS was used to prepare the required spatial data, extract input parameters for the model, execute the model computations, query and display results.

Refinements to the slope length and rainfall erosivity factors of the RUSLE model were introduced to improve its applicability in an area of varied terrain under a tropical climatic regime. By employing the upslope drainage substitution method to generate *LS*-values, the RUSLE model is adapted to function on a semi-distributed basis, which more comprehensively considers the cumulative effects of overland flow on erosivity.

The model is based on modest data requirements, a common limitation in developing nations. Its practical utility is based upon providing a means for evaluating and comparing factor changes among alternative land areas, rather than on its prediction of absolute soil erosion for a particular grid cell. It provides a means to isolate and describe areas that are vulnerable to soil erosion thereby lending immediate application to conservation planning.

The database that was established for the benchmark scenario was extended to formulate alternative soil and water conservation scenarios whose results were used to formulate the BMPs. Among the four simulation scenarios carried out, a combination of recommended feasible land use/cover and conservation support practices (scenario 4) was perceived as the BMP for the catchment.

The GIS database and soil erosion potential maps generated in this study provide valuable planning aids for managers in the Masinga. The tool can be operated locally by land managers in the Masinga catchment, with available software and data. With limited financial resources for land restoration or the implementation of the BMPs, it is imperative that each activity be undertaken in an area where the greatest impact can be made on mitigating soil erosion.

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REFERENCES

[1] Landa, R., Meave, J. & Carabias, J., Environmental deterioration in rural Mexico: an examination of the concept. *Ecological Applications*, **7(2)**, pp. 316–329, 1997.

[2] Lal, R., Review of soil erosion research in Latin America. *Soil Conservation and Management in the Humid Tropics*, eds D.J. Greenland & R. Lal, Wiley: New York, pp. 331–340, 1977.

[3] Atkins Land and Water Management in Association with African Development and Economic Consultants Ltd., Soil and Water Conservation Programme. Masinga Dam Catchment Areas. *Final and Main Report, Volume I*, 1984.

[4] Grunblatt, J., Ottichilo, W.K. & Sinange, R.K., A GIS approach to desertification assessment and mapping. *Journal of Arid Environments*, **23**, pp. 81–102, 1991.

[5] Mati, B.M., Morgan, R.P.C., Gichuki, F.N., Quinton, J.N., Brewer, T.R. & Liniger, H.P., Assessment of erosion hazard with the USLE and GIS: a case study of the Upper Ewaso Ng'iro North Basin of Kenya. *International Journal of Applied Earth Observation and Geoinformation*, **2(1)**, pp. 78–86, 2000.

[6] Angima, S.D., O'Neill, M.K. & Stott, D.E., On-farm assessment of contour hedges for soil and water conservation in Central Kenya. *Sustaining the Global Farm*, eds D.E Stott, R.H. Mohta & G.C. Steinhardt, pp. 390–394, 2001.

[7] Millward, A.A. & Mersey, J.E., Adapting the RUSLE to model soil erosion potential in a mountainous tropical watershed. *CATENA*, **38**, pp. 109–129, 1999.

[8] Moore, I.D. & Wilson, J.P., Length-slope factors for the revised universal soil loss equation: simplified method of estimation. *Journal of Soil and Water Conservation*, **47(5)**, pp. 423–428, 1992.

[9] Desmet, P.J.J. & Govers, G., A GIS procedure for automatically calculating the USLE LS factor for topographically complex landscape units. *Soil and Water Conservation*, **52(5)**, pp. 427–433, 1996.

[10] Mitasova, H., Hofierka, J., Zlocha, M. & Iverson, L.R., Modelling topographic potential for erosion and deposition using GIS. *Geographical Information Systems*, **10(5)**, pp. 629–641, 1996.

[11] Foster, G.R. & Wischmeier, W.H., Evaluating irregular slopes for soil loss prediction. *American Society of Agricultural Engineers*, **17(2)**, pp. 305–309, 1974.

[12] Renard, K.G., Foster, G.R., Weesies, G.A. & Porter, J.P., RUSLE: Revised Universal Soil Loss Equation. *Soil and Water Conservation*, **46(1)**, pp. 30–33, 1991.

[13] Renard, K.G., Foster, G.R., Weesies, G.A. & McCool, D.K., *Predicting Soil Erosion by Water – A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*, Draft, 1992.

[14] Morgan, R.P.C., *Soil Erosion and Conservation*, John Wiley & Sons, Inc.: New York, 1986.

[15] Stocking, M.A. & Elwell, H.A., Rainfall erosivity over Rhodesia. *Transactions of the Institute of British Geographers*, **1**, pp. 231–245, 1976.

[16] Arnoldus, J.M.J., Methodology used to determine the maximum potential average soil loss due to sheet and rill erosion in Morocco. *FAO Soils Bulletin*, **34**, pp. 39–51, 1977.

[17] Roose, E., Erosion et Ruissellement en Afrique de l'ouest—2vingt annees de mesures en petites parcelles experimentales. *Travaux et Documents de l'ORSTOM*, No. 78, OSTROM: Paris, 1977.

[18] Renard, K.G. & Freimund, J.R., Using monthly precipitation data to estimate the R factor in the revised USLE. *Journal of Hydrology*, **157**, pp. 287–306, 1994.

[19] Yu, B. & Rosewell, C.J., A robust estimator of the R-factor for the Universal Soil Loss Equation. *Transactions of the American Society of Agricultural Engineers*, **39**, pp. 559–561, 1996.

[20] Ateshian, J.K.H., Estimation of rainfall erosivity index. *Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers*, **110(IR3)**, pp. 293–307, 1974.

[21] Wischmeier, W.H., New developments in estimating water erosion. *Proceedings of the 29th Annual Meeting of the Soil Society of America*, Madison, pp. 179–186, 1974.

[22] Wischmeier, W.H. & Smith, D.D. (eds). *Predicting Rainfall Erosion Losses*, USDA Agricultural Research Service Handbook 537, USDA: Washington, DC, 1978.

[23] Rosewell, C.J., Estimation of rainfall erosivity. *Erosion Research News Letter*, Technical Handbook No. 11, 2nd edition, Soil Conservation Service of NSW, 1993.

[24] Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. & Yoder, D.C. (eds). *Predicting Soil Erosion by Water, A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*, US Department of Agriculture, Agriculture Handbook No. 703, 1997.

[25] Yu, B. & Rosewell, C.J., An assessment of a daily erosivity model for New South Wales. *Australian Journal of Soil Research*, **34**, pp. 139–152, 1996.

[26] Yu, B. & Rosewell, C.J., Rainfall erosivity estimation using daily rainfall amounts for South Australia. *Australian Journal of Soil Research*, **34**, pp. 721–733, 1996.

[27] Yu, B., Rainfall erosivity and its estimation for Australia's tropics. *Australian Journal of Soil Research*, **36**, pp. 143–165, 1998.

[28] FAO–UNESCO, *Soil Map of the World, Revised Legend*, FAO World Soil Resources Report No. 60, Food and Agricultural Organization of the United Nations, UNESCO: Rome, Italy, 1998.

[29] Sombroek, W.G., Braun, H.M.H. & van der Pouw, B.J.A., *The Exploratory Soil Map and Agro-climatic Zone Map of Kenya*, Report No. E.I, Kenya Soil Survey: Nairobi, 1982.

[30] Angima, S.D., Stott, D.E., O'Neill, M.K., Ong, C.K. & Weesies, G.A., Soil erosion prediction using RUSLE for central Kenyan highland conditions. *Agricultural Ecosystems and Environment*, **97**, pp. 295–308, 2003.

[31] Wenner, C.G., *Soil Conservation in Kenya*, SWC Branch, MoALDM: Nairobi, Kenya, 1981.