Soil erosion management at a large catchment scale using the RUSLE-GIS: the case of Masinga catchment, Kenya

B. M. Mutua & A. Klik
Institute of Hydraulics and Rural Water Management,
Universität für Bodenkultur (BOKU), Austria

Abstract

Kenya is one country suffering heavily from land degradation due to increasing anthropogenic pressure on its natural resources. As is common to many tropical countries, Kenya suffers from a lack of financial resources to research, monitor and model sources and outcomes of environmental degradation for large catchment domains. In order to evaluate viable management options, soil erosion modelling at the catchment scale needs to be undertaken. This paper presents a comprehensive methodology that integrates an erosion model, the Revised Universal Soil Loss Equation (RUSLE) with a Geographic Information System (GIS) for estimating soil erosion at Masinga catchment, which is a typical rural catchment in Kenya. The objective of the study was to map the spatial mean annual soil erosion for the Masinga catchment and identify the risk erosion areas. Current land use/cover and management practices and selected, feasible, future management practices were evaluated to determine their effects on average annual soil loss. The results can be used to advice the catchment stakeholders in prioritising the areas of immediate erosion mitigation. The integrated approach allows for relatively easy, fast, and cost-effective estimation of spatially distributed soil erosion and sediment delivery. It thus provides a useful and efficient tool for predicting long-term soil erosion potential and assessing erosion impacts of various cropping systems and conservation support practices.

Keywords: ArcView GIS, RUSLE, catchment, soil erosion, modelling, Masinga, Kenya.

Management Information Systems, C. A. Brebbia (Editor)
ISBN 1-85312-728-0

1 Introduction

Expansion of subsistence farming practices in the form of field crop agriculture and pasture within rural areas is contributing significantly to ecological alteration in many tropical countries. One of the most destructive and insidious processes, steadily increasing as a result of anthropogenic activity in these areas, is soil erosion (Landa *et al* [1]).

Kenya is one country suffering heavily from land degradation due to increasing anthropogenic pressure on its natural resources. This is more so mainly in the catchment where the rural communities encroach to open up new land for agricultural activities and settlement.

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 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 and 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 a lack of financial resources to research, monitor and model sources and outcomes of environmental degradation. 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 geographic information systems (GIS) technology as a tool in catchment management planning at Masinga. The general objective is to develop readily transferable 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, identify and prioritise areas with high erosion risk in order to direct the implementation of viable management options.

2 Study area

The Masinga catchment area is some 6,255 km^2 in extent, lying to the east of the Aberdares mountains and south of Mount Kenya. It lies between latitudes 0° 7' South and 1° 15' South and longitudes 36° 33' East and 37° 46' East. Its location on the Kenyan map is shown in fig.1.

The geology of Masinga area can be broadly divided into volcanic rocks in the north and west, and pre-cambrian basement complex in the south-east. The

Management Information Systems, C. A. Brebbia (Editor)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-728-0

landform in the catchment ranges from steep mountainous terrain with strong relief in the west, to undulating plains with subdued relief in the south-east. The elevations above means seal level (asl) 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. On the basement complex, the soils are mostly coarser textured and shallower and are classified as Acrisols, Luvisols and Ferralsols.

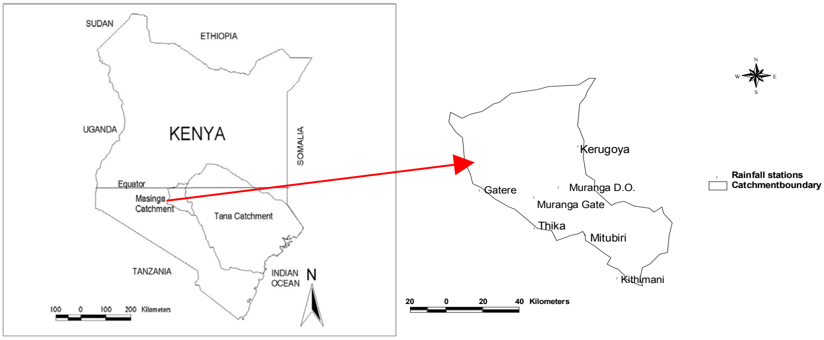

Figure 1: Location of the study area in Kenya.

The catchment falls within four agro-climatic 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 vary from about 600 mm on the easterly boundary to over 2000 mm on the Aberdares Mountains. The maximum temperatures vary from 25.5° C to 31.0° C generally being experienced in February or March, prior to the onset of the main rain season (long rains). Minimum mean temperatures of 21.0° C to 24.0° C occur in the month of July.

The catchment has an estimated population of 2 million people (1998 census) with most people engaged in agricultural activities. Almost all the cultivation takes place in the south-east, north-west and generally in the western areas. There is scattered cultivation in the eastern half of the area with slopes of 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 with very little cover.

3 Materials and methods

3.1 GIS and soil erosion modelling

In evaluation of viable management options, soil loss modelling at the catchment scale needs to be undertaken. While soil loss data gathered from experimental plots can be extrapolated over the entire catchment, 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 variation 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 limiting. Modelling is therefore preferred since soil loss under alternative management scenarios can be rapidly estimated at minimal cost.

In the present 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 Masinga catchment was estimated under the current land use/cover and management practices.

3.2 The soil erosion model structure

The Revised Universal Soil Loss Equation (RUSLE) is among the most extensively used empirical soil erosion models. 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. RUSLE 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 is expressed as:

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

Where A is the estimated average annual soil loss (t ha^{-1} yr^{-1}); LS is the combination of the slope steepness and slope length factors (unitless); R is the rainfall erosivity factor (KJ mm m^{-2} h^{-1} yr^{-1}); K is the soil erodibility factor (t 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 a 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 digital elevation model (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 was required to develop the rainfall erosivity (R) factor. The soil type coverage was required to develop the soil erodibilty (K) factor and the land use coverage was used to develop 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 to establish among others the land use and management practices. The survey was carried out between July and September 2003. In addition to the survey and the field data collection, more data was collected from relevant Ministries, Departments, Research Centres and Agencies in Kenya. Other data was acquired from relevant existing databases.

3.3.1 The Digital Elevation Model (DEM)

A DEM of scale of 1: 250,000 and grid resolution of 90 metres covering the study area was purchased from the United States Geological Surveys (USGS). The DEM was projected using the Universal Transverse Mercator 37 North (UTM-37N) reference system. Most digital elevation models often contain pits or local depressions. These pits can reflect real life conditions but are often the results 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 was created using the "Fill the Sink" command from ArcView "Hydro" extension menu that allows the removal of the sinks or pits from the DEM.

The GIS technology allows calculation of the Slope length and steepness, 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 (Mitasova *et al* [2]). Generation of the L-factor for this study was conducted using the upslope drainage area substitution method suggested by Desmet and Govers [3]. The unit contributing area for the slope length value was substituted as the slope length within the equation provided by Foster and Wischmeier [4], 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 [4] equation gives the slope length L component as:

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

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)($\mathrm{m}^2\ \mathrm{m}^{-1}$), and m is the slope length exponent of the RUSLE S-factor.

In reality, a zone of deposition or concentrated flow would generally occur when a slope becomes long. The limiting slope length for interrill and rill erosion is about 120 to 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 constraining the maximum flow accumulation to a given number of cells. To determine the number of cells, an upper bound slope length of 150 m was assumed and the DEM resolution of 90m x 90m was used.

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 equation:

$$LS = \left(FAccum * CS / 22.13 \right)^{0.4} * \left(\sin slope / 0.0896 \right)^{1.3} * 1.6 \tag{3}$$

Where *FAccum* is the flow accumulation expressed as the number of grid cells; *CS* is the cell size (resolution of the DEM (90m)); *Sin slope* is the slope grid that had to be converted into radians; 0.4 and 1.3 are slope exponents and 1.6 a multiplying factor adapted from the values estimated by Mitasova *et al* [2].

3.3.2 Rainfall runoff factor R

The rainfall erosivity factor R was estimated by first calculating the storm erosivity indices using the product of the measured rainfall kinetic energy and its 30-minute intensity (EI_{30}) (Renard *et al* [5]). The method documented by Wischmeier and Smith [6] was applied to generate the erosivity indices for the few stations with autographic records within Masinga catchment. The storm erosivities were then accumulated for each year to give the R-factor for each of these few stations. A regression equation relating the R-factor and mean annual rainfall was developed.

Data for seven rainfall stations in Masinga with mean monthly rainfall amounts recorded over more than 20 years was collected from the Department of Meteorological Station, Dagoretti corner, Kenya. These seven rainfall stations are randomly distributed over the catchment, fig.1. A data file for each of the seven stations presenting mean annual rainfall was generated by averaging recorded amounts of rainfall over consecutive years. The R values were then estimated using the developed regression equation:

$$R = 0.56896 * P - 1.011 \tag{4}$$

Where R represents the rainfall erosivity factor (KJ mm m^{-2} h^{-1} yr^{-1}) and P is the measured mean annual precipitation (mm).

To enable the mapping of the R-factor in a spatial domain, it required first to prepare the precipitation surface for the catchment. The data from the seven stations was geo-referenced using their latitudes and longitudes and presented in an excel table. The data was converted into a "dbaseIV" and then exported to the ArcView software. A point theme was created using the ArcView GIS software and the exported data was joined to the attribute table of this point theme. 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 created by interpolating the rainfall point grid using the Inverse Distance Weighting (IDW) interpolation method, a procedure supported by ArcView. Using the Analysis tool and the map calculator in the ArcView, eqn (4) 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 digitised. To enable mapping of different soil types and their associated parameters in a spatial domain, the soil map of Masinga catchment was clipped from the digitised 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. The map obtained thus contained the major soil mapping units based on FAO-UNESCO [7] 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 existing literature from previous studies carried out in Kenya by Sombroek *et al* [8]. 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 was generated. The K-factor shape file was converted to a grid file.

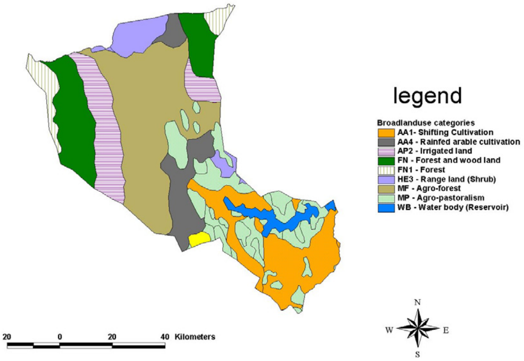

Figure 2: Broad land use /cover categories based on FAO-UNESCO classification.

3.3.4 Cover management factor C

In RUSLE, the C factors represent weighted average soil loss ratios (SLRs) that are determined from a series of sub-factors that include prior land use, canopy cover, surface cover and surface roughness (Renard *et al* [9]). However, it was not possible in this study to determine the magnitude of these sub-factors because the land use/cover data available for Masinga catchment only defined broad land use categories, fig. 2. The land use map for the catchment was

Management Information Systems, C. A. Brebbia (Editor)

generated by clipping it from the main 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 assigned. The C-factor for each land use/cover category was estimated based on values determined for similar crops and land cover for Kenya (Angima *et al* [10]). The C-factor map was converted from a shape file to a grid file.

3.3.5 Support practice factor P

To create a spatial map for the P-factors in this study, the digitised map of the soil units and land use/cover polygons was used. A spatial percent slope map was created and each of the polygon units was assigned a P value based on its percentage slope. The P values for contour cultivation and their corresponding percent slopes from results of Wenner [11] were assumed. The forestland was assigned a P-factor of 1. The P-factor shape file was then converted into a grid file.

4 Results and discussion

The RUSLE data themes and their associated attribute tables were integrated in the Arcview 3.2 GIS to determine the average annual soil loss for the catchment. The grid themes were overlaid together to generate a spatial mean annual soil erosion map, fig.3, using the ArcView's map algebra calculation. From the results, it can be depicted that the present land utilisation with lack of soil conservation measures, a rather low standard of husbandry on arable land, gross overstocking and lack of management on range areas is resulting in high soil erosion. The critical areas that require urgent soil and water conservation management are easily identified from the spatial erosion map.

The mean annual soil loss generated by the RUSLE 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. Verification was essential to gain an appreciation of the model's predictive capabilities.

The field verification indicated that locations of very low soil loss potential were well estimated, while locations of low potential were not as accurate. However, areas of moderate, high and extreme soil loss potential were the most successfully identified. From this 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.

The GIS database and soil erosion potential map generated in this study provide valuable planning aids for managers in Masinga. With limited financial resources for land restoration or the implementation of best management practices (BMPs), it is imperative that each activity be undertaken in an area where the greatest impact can be made on mitigating soil erosion.

The database created in this research can be queried to identify those land areas currently under agriculture, with a high or extreme soil erosion potential ranking. The model can be re-run, adjusting the *C*- or *P*-value for these areas, to assess the effects of implementing BMPs leaving crop residue on the fields after harvest, or employing contouring or terracing techniques on the resulting soil erosion potential values. Financial resources can then be allocated accordingly. Similar scenarios, such as assessing the effects of clearing forested lands to meet increasing agricultural needs, can be readily accommodated with the model.

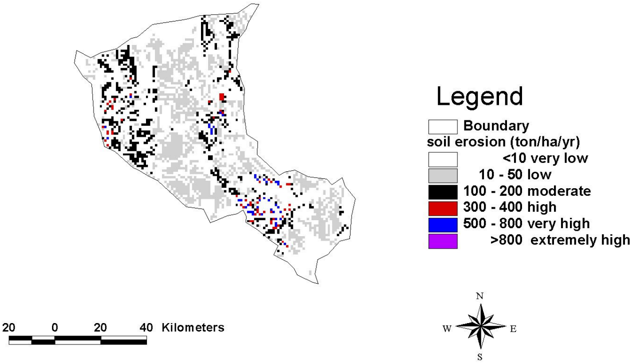

Figure 3: Spatial mean annual soil erosion within Masinga based on current land use and management practices.

5 Conclusions

This study presents a first attempt in the application of GIS technology to model soil erosion in Masinga catchment. It demonstrates the integration of an empirical model, the RUSLE within the GIS environment to estimate average annual soil losses in a spatial domain. The GIS was used to prepare required spatial data, extract input parameters for the model, execute the model computations 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 mountainous terrain and a tropical climatic regime. By employing the upslope drainage substitution method to generate LS-values, the RUSLE 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 lending immediate application to conservation planning. The tool can be operated locally by land managers in Masinga catchment, with available software and data.

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] 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.

[3] 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.

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

[5] 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). U.S. Department of Agriculture-Agriculture Handbook No. 703, 1997.

[6] Wischmeier, W.H. & Smith, D.D., (eds). *Predicting rainfall erosion losses,* USDA Agricultural Research Service Handbook 537. USDA, Washington, D.C., 1978.

[7] FAO-UNESCO, *Soil Map of the World, Revised Legend*, FAO World Soil Resources Report No. 60. Food and Agricultural Organisation of the United Nations, UNESCO, Rome, Italy, 1998.

[8] 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.

[9] 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.

[10] 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.

[11] Wenner, C.G., Soil Conservation in Kenya, SWC Branch, MoALDM, Nairobi, Kenya.