Modelling Soil Erosion and Vegetation Change

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Abstract

Soil erosion by water continues to be a major problem that has led to land degradation and adversely has affected the livelihoods in Kenya. This calls for enhanced understanding of the dynamic interactions at play in the soil erosion process. Modelling provides a useful tool in estimation and prediction of soil erosion rates at the watershed level, that can guide planning and allocation of funds in rehabilitation programmes within the watershed.

This paper presents a model developed to simulate the controls on runoff and erosion for a semi-arid watershed. The model is parameterised using data from a semi-arid basin in South-East Spain. The main assumption of this model is that water is the main factor limiting productivity in semi-arid watersheds. The model explores the interactions between vegetation and erosion through available soil moisture. It is designed to simulate the hydrologic behaviour of soil and to estimate the sediment yield in a catchment, with regenerating vegetation.

The overall behaviour of interactions is developed in a series of sub models; hydrology, vegetation growth and sediment yield. In the hydrology component, the infiltration and storage models are combined to generate both hortonian and saturated overland flow. Plant growth is computed as the accumulation of dry matter biomass using water use efficiency and evapotranspiration is input data. The vegetation therefore interacts dynamically with soil moisture regime through the actual evapotranspiration and hence controls the possibility of runoff generation and production of sediment yield. The generated runoff is routed within the catchment using a single direction routing algorithm, together with a Strahler network-ordering scheme to sequence the flow. This approach requires a regular gridded digital elevation model of the catchment and considers the elevation of

each cell relative to its surrounding neighbours. The flow is routed by transferring the overland flow along a predefined network of pathways. The sediment yield is estimated using this outflow together with the slope gradient; soil factor and the corresponding vegetation cover characteristics, which vary spatially and temporally due to selected scenarios.

The model is parameterised from field data and a variety of weather conditions over 30 years and subject to different scenarios. The results indicate that it can be used in providing indicators to guide decision-making. Modelling, however, does have shortcomings related to validation and data requirements. Indeed the model can be improved by incorporating other sub models depending on the objectives. However, models do remain abstractions of reality and can only be as good as the data used and the linkages used in explaining the interrelationships between the variables.

Introduction

Soil erosion caused by rainfall and runoff is a serious problem affecting both the agricultural land in Kenya’s high rainfall areas (17% of total land area), upon which more than 80% of the rural population depend for livelihood, as well as in the semi-arid areas which support more than 60% of the livestock and wildlife. Furthermore, the natural forest cover in the country has continued to decline to less than 2% of land cover, resulting in high rates of erosion. These factors are having serious repercussions on the economy, currently about one-third of Kenyans are suffering from food insecurity. In order to plan the use of land and water resources, modelling becomes a useful tool at the watershed level in enhancing understanding of the dynamic interactions among the biophysical and other variables and in estimating of rates of erosion and predicting rates of erosion.

Basis of Watershed Modelling

Studies in Kenya (Lewis, 1985; Kilewe, 1985; Okoth and Omwega, 1989; Mati, 2000 and Hai, 2000) indicate that significant amounts of soil and water losses occur in these high rainfall areas. In semi-arid areas high rates of erosion have been noted (Dunne, 1978; Dunne, 1978 and Moore, 1979). Soil erosion rates have proven almost impossible to estimate over large areas with any degree of precision due to its highly variable nature, both spatially and temporally, and as the differences in techniques of field data collection vary from erosion plots and river yield sediments.

The relationship between erosion and vegetation cover have been shown from various researchers (Stocking and Elwell, 1976; Evans, 1980) that erosion declines exponentially as vegetation in cover increases. This reduction is most marked when plants cover more than 30%. Erosion plot studies in humid areas of Kenya (Obando, 1991) also found that different types of agricultural crops vary in their effectiveness in reducing erosion and runoff. In semi-arid areas of Spain, erosion was also shown to decrease with increasing vegetation cover as it regenerates (Obando, 1995; Thornes ,1990; and Francis and Thornes, 1990). This well-established relationship forms the basis of the model development.

Model Development

The model operates in a series of interacting sub models (Figure 1).

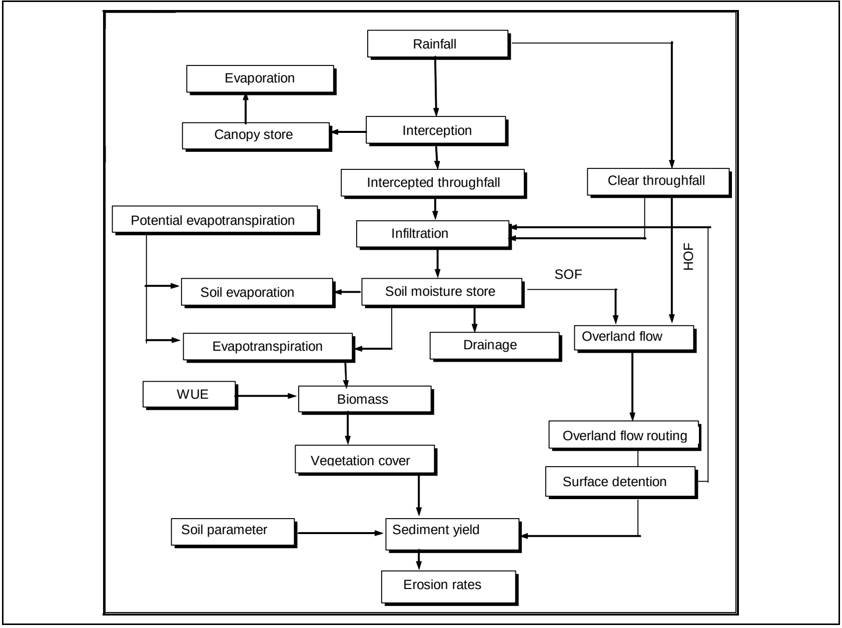

Figure 1: Flow-charts of the model

The Hydrology

The basis of the soil moisture described as a simple water balance equation (*Equation 1*) of the form;

$$S_t = S_0 + P - E - Q - Q_d$$

Where all the units are in mm/day

S_t is the current moisture content of the soil and S_0 is the previous moisture.

P is the daily rainfall amount and forms the main input

E is the evapotranspiration (This includes the bare soil evaporation E_s and plant transpiration that is assumed to be equal to the actual evapotranspiration E_t. It also includes the interception loss)

Q is the total runoff, which is the sum of the Hortonian and saturation overland flow (H_{of} and S_{of}).

Q_d is the drainage beyond the rooting zone.

The units of *Equation 1* are given in mm/day, thereby indicating an overall daily soil moisture budget, however, the specific processes within the model are computed for hourly time steps, for given rainfall events. The infiltration and storage models are combined to generate both hortonian and saturated overland flow respectively. In addition, rainfall interception is computed for both vegetation and bare ground (Brandt, 1989). Infiltration rates are differentiated for bare and vegetated surfaces, and are calculated using the Green and Ampt Equation. Drainage is considered to occur beyond the rooting zone. The soil surface evaporation is considered separately from the actual evapotranspiration, thus enabling the latter to be used for driving the plant growth model.

Computing Vegetation Change

The plant cover characteristics play an important role in the hydrology through interception, evaporation and drainage. The plant growth sub-model deals with the long-term growth of plants driven by fluctuations in soil moisture and actual evapotranspiration. Plant growth is computed as the accumulation of dry matter biomass using water use efficiency (Fischer and Turner, 1978; Szareck, 1979; Lauenroth ,

1986) for the particular plant type and the evapotranspiration. The biomass is used to estimate vegetation cover using and empirical formula (Whittaker and Marks, 1975). The vegetation therefore interacts dynamically with the soil moisture regime through the actual evapotranspiration and hence controls the possibility of runoff generation and production of sediment yield.

Generation of Runoff and Sediment Yield

The surface runoff is generated either as hortonian overland flow occurs which when the rainfall intensity exceeds the infiltration rate, or as saturation overland flow. The generated runoff is routed within the watershed using a single direction routing algorithm (Quinn , 1993), together with a Strahler network-ordering scheme to sequence the flow. This approach requires a regular gridded digital elevation model of the watershed (Grayson and Moore, 1992; Beven , 1993; Moore,1993) and considers the elevation of each cell relative to its surrounding neighbours. The flow is routed by transferring the overland flow along a pre-defined network of pathways until the channel mouth is reached. The velocity of the flow and the resulting discharge are determined for each cell on the basis of the stream network. Figure 2 illustrates the resulting effects of this weighing - the largest amount of discharge is transferred in the direction of the steepest gradient. The remaining overland flow is distributed in the surrounding cells in proportion to the gradient, thereby diffusing the flow. The discharge is calculated as a function of the surface roughness, depth of flow and the velocity.

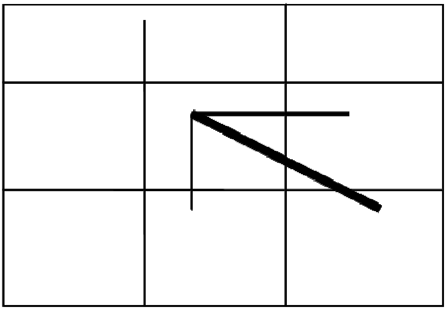

Figure 2: Diffusion of flow to neighbouring cells

The erosion rate (E) (*Equation 2*) combines the power function for overland flow and slope, and an exponential reduction of erosion due to vegetation cover.

$$E = Kq^{m}S^{n}e^{-bVc}$$

Where;

K (dimensionless) is a soil parameter, which describes the erodibility of the soil.

q is the discharge (m^3/s)

S is tanβ where β is the slope in degrees

V_c is the percent vegetation cover

E is the erosion (mm/m)

b m and n are dimensionless parameters, b relates to the reduction in erosion due to vegetation cover.

Equation 2 accounts for the hydraulic effects of vegetation. Stocking and Elwell (1976) found an exponential relationship between the mean annual soil loss and runoff and vegetal cover. Dunne (1978), Moore (1979) and Francis and Thornes (1990) have obtained similar results. The sediment yield is estimated using this outflow together with the slope gradient; soil factor and the corresponding vegetation cover characteristics, which vary spatially and temporally due to different patterns and percentages of vegetation cover. The sediment yield in the cells is then summed daily and annually to provide the values for the watershed. Daily and annual estimates of the overland flow, sediment yields and erosion rates are calculated for the watershed under different scenarios. The sediment yield from each cell on days when overland flow is generated provides a sum that can be compared with values for various patterns and percentages of vegetation cover.

Performance of the Model

Table 1 summarized the model inputs and outputs. The model inputs (Table 1) were obtained from the field measurements during different seasons to provide characteristics over changing rainfall and climate conditions. The rainfall data over 30 years and the corresponding potential evapotranspiration provide the main inputs in the model.

Initially, a repeated rainfall series for south east Spain representing 300mm annual rainfall is used to assess the sensitivity of the model. The field data analysis also enabled relationships indicating the complex and numerous interactions and variability over seasons due to lithology, aspect, and topography; and along the slope profile. Rainfall simulation experiments were carried out to examine the factors, which influence the hydrological aspects, since the infrequent, short lived storm event render it difficult to observe these processes. Variations in the infiltration rates were found to be due to the antecedent soil moisture, aspect, surface characteristics and vegetation cover. Highly significant positive correlations were obtained between the observed and predicted time to runoff and storage. The key parameters identified as having a bearing on the interactions between regeneration of vegetation and erosion, during the field measurements and experiments formed the basis of the model.

Table 1: Model inputs and outputs

Model inputs	**Model outputs**
Daily rainfall (mm)	Biomass (g/m^2)
Potential monthly evapotranspiration (mm)	Vegetation cover (%)
Digital elevation model (x, y co-ordinates, z height (m))	Litter (g/m^2)
Day length (hours)	Soil moisture storage (mm)
Storm length (hours)	Evapotranspiration (mm)
Ksat (mm/hr)	Bare soil evaporation (mm)
Soil moisture capacity (mm)	Drainage beyond rooting zone (mm)
Initial soil moisture (mm)	Overland flow (mm)
Infiltration parameters A (mm/hr), B (mm)	Detention storage (mm)
Interception storage (mm)	Sediment yield (g/m^2)
Water use efficiency (g DM per kg H_20)	Erosion rates (mm/m^2)
Initial biomass (g/m^2) (Vegetation %)	
Ratio of above ground/below ground biomass (dimensionless)	
Respiration coefficient (g DM/day)	
Manning’s n (dimensionless)	
Soil parameter *K* (dimensionless)	

The sensitivity analysis and the validation of the model were carried out using repeated rainfall series, and on the basis of hypothetical and actual catchments. The results from the model runs indicate that the sediment yield in the catchment increases with increasing slope. Secondly, the sediment yield increases with increasing rainfall intensity. However, for low rainfall events there is less runoff generated due to low rainfall intensities and high infiltration rates, resulting in low or no sediment, such that it becomes difficult to compare results for varying slope gradient. The sediment yield production depends on slope geometry, vegetation and slope gradient. The percent cover simulated increases slightly with soil depth; likewise the moisture increases slightly with soil depth. Vegetation cover has been shown by the model to be an important factor in the control of erosion by influencing the soil hydrology through interception, increased infiltration, and evapotranspiration.

Model Results

The results obtained from running the model using an average annual rainfall of 330 mm for a period representing a total of 140 years in semi-arid Spain, indicate that runoff and sediment yield generally decrease with increasing vegetation cover over a long term period. Large magnitude events tend to produce high sediment irrespective of the vegetation cover in the watershed. For long dry periods, correspondingly low sediment yield is produced implying that increasing aridity will not necessarily lead to higher erosion rates. A positive relationship exists between the annual rainfall amount and the modelled sediment yield for annual rainfall of up to 350 mm. These results are consistent with the Langbein and Schumm (1958) curve.

Relevance of the Model

It is important to estimate extent, severity, as well as economic and environmental impacts. Indeed data from models and also field collection on soil loss rate can guide decisions on allocation of funds for mitigation purposes in a watershed. The model provides comparative sediment yield for different percentage and spatial pattern of vegetation cover. This would give some indication of the order of magnitude of the erosion and enables selection of appropriate vegetation cover in a watershed. The model is flexible and can operate at slope or watershed level, for selected sub routines. This model can be used to advance the understanding of and to predict interactions in semi-arid watersheds in Kenya and ultimately in sustainable management of land and water resources.

Models can, however, become complicated due to many variables, particularly when the relationships cannot be adequately and accurately quantified, thus increasing the errors. Another shortcoming is related to validation of the model due to data requirements. Up scaling of the model results from a single cell to a watershed level can also increase errors. With changing technologies and ideas, modelling can never be completed. It must be remembered that models are abstractions of reality and therefore shortcomings in the model will be a reflection of the current state of knowledge. The exclusion of some processes in the model is because they are not quantifiable or on the basis of pre-existing evidence rather than a result of restrictions due to scale, time and lack of data on several processes; and also because of shortcomings in understanding the linkages. There are always ways of further developing the model structure to either improve the results or enable a wider applicability. Model development can be continued in order to improve its usefulness. Validation of the model for other semi-arid watersheds will improve the understanding of arid and semi-arid watersheds, where lack of proper management could ultimately lead to land degradation.

Conclusions

The model is capable of simulating interactions between vegetation regeneration and erosion through the available soil moisture. The predicted values of biomass and erosion rates have been shown to be consistent with those in a wide range of literature and with file experiments from Spain. There is need however, to test this model in semi-arid areas with the East Africa region.

From the model results, it has been shown that the spatial vegetation cover can be planned such that the least possible erosion occurs in the watershed. The selection of patterns in which the most vulnerable areas are vegetated, can enable the sediment yield in the watersheds to be reduced. The importance of modelling the effect of vegetation cover is that it provides an opportunity to compare several possibilities such that those, which provide the most effective measure against soil erosion, are recommended.

The use of models can be instrumental in explaining as well as supporting theoretical advances such land evolutions, in examining the sensitivity of landscapes in responses to changes at different scales. At the watershed level both modelling and field collection methods should be used in continuously understanding the soil erosion phenomenon. These models are useful depending on the several factors including the quality of input data. In many circumstances, relative results from models are more reliable than absolute results.

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