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Soil erosion and sediment yield modeling using GIS

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Abstract
A Geographical Information System (GIS) based method is discussed and demonstrated for prediction of storm sediment yield from catchments. In the method discussed herein the catchments are discretized into hydrologically homogeneous grid areas for capturing the heterogeneity present in them. The gross soil erosion in each grid of the catchment is calculated using the universal soil loss equation (USLE). The concept of sediment delivery ratio is used for determination of the total sediment yield of the catchment during an isolated storm event. Temporal variation of the sediment yield during the storm event is also calculated.

INTRODUCTION

Studies on soil erosion in catchment areas and their sediment yields are required to be made for assessment and control of reservoir sedimentation, design of efficient erosion control structures, water quality and river morphologic modeling etc. The process of soil erosion by rainfall and runoff mainly consists of the soil detachment and transport by raindrops and runoff. The ground surface is generally separated into inter-rill, rill and channel areas for modeling this process. Detachment over inter-rill areas is considered to be by impact of raindrops because flow depths are shallow, whereas runoff is considered to be dominant factor in rill-detachment and channel scour and also in sediment transport over inter-rill, rill and channel areas (Kothyari et al., 1997). Therefore the process of soil erosion and sediment yield are affected by the variables that relate to hydrology, topography and land use in the catchment. Most of these variables are found to have significant spatial variation in a catchment. Also the control of upland erosion does not always reduce the sediment yield immediately, because decreasing upland sediment load increases the erosivity of channel flow. Therefore, for obtaining realistic estimates of catchment sediment yield and its temporal variation the entire system of catchment drainage should be studied.

The Geographical Information System technique hence after referred as GIS is found to be best suited for quantification of the heterogeneity present in topographic, drainage and land use features of a catchment (Walling, 1988). The GIS technique offers data management facility that is useful in distributed modeling of sedimentological and hydrological processes (Shamsi, 1996). Therefore, the application of GIS in studies on soil erosion and sediment yield of catchment areas is illustrated in the present paper. A demonstration of the application of GIS is also made in identification of erosion prone areas within a catchment.

BRIEF REVIEW

Methods available in literature for modeling of soil erosion and sediment yield can be grouped as (i) empirical methods (ii) process-based methods. Empirical methods which include the universal soil loss equation (USLE) (Wischmeier and Smith, 1978), modified universal soil loss equation (MUSLE) (Williams, 1978), or revised universal soil loss equation (RUSLE) (Renard et al., 1991), combine the soil erosion from all processes in the catchment into one equation which makes use of empirical coefficients for representing the rainfall characteristics, soil properties, ground surface conditions etc. These methods are simple in application and hence frequently used in different parts of the world. The process-based methods attempt to solve the fundamental equations for transport of water and sediment. Some of the process-based models for soil erosion include ANSWERS (Beasley et al., 1980), WEPP (Nearing et al., 1989). AGNPS (Young et al., 1987) and SHE (Wicks and Bathrust, 1996). These models are expected to realistically simulate the process of rainfall-runoff-soil erosion. However, due to temporal variations in rainfall inputs and pronounced spatial heterogeneity prevalent in catchment areas, even the process-based models are found to produce unsatisfactory results (Wu et al., 1993). The effect of temporal variations in rainfall on sediment yield can be approximately simulated by analysing the isolated rain-storm events (Kothyari et al., 1997) while, GIS technique is found to be best suited for quantification of the spatial variation in topographic and drainage features of a catchment (Shamsi, 1996).

Recently, GIS techniques have been interfaced with some standard hydrologic models, either distributed type or empirical parameter type, to capture the spatial variation in computed quantities. The Agricultural Non-Point Source Pollution Model (AGNPS) for computation of soil erosion rates is interfaced with the GRASS GIS system (Srinivasan and Engel, 1994). Likewise, Rewarts and Engel (1991) interfaced ANSWERS model and GRASS system. Marchrigni and Cruise (1997) interfaced a GIS with the SLURP model for sediment yield modeling based upon homogeneous hydrological and sediment response units. Kothyari and Jain (1997) have used a GIS for estimation of sediment yield resulting from isolated storm events. Jain and Kothyari (2000) further studied the sediment yield modeling using GIS. Only a simplified view of the complicated process of soil erosion was considered in these studies. The components of rill erosion, inter-rill erosion, gulley erosion and channel scour and deposition are not studied individually. Thus the term, sediment yield used herein essentially means the total suspended sediment load carried by the stream to the catchment outlet.

METHODOLOGY

There is ample evidence that the USLE and/or RUSLE yield a good estimate of the amount of detached soil (surface erosion) at the plot scale (Wischmeir and Smith 1978, Renard et al., 1991). In a larger sized catchment, part of the soil eroded in upland areas gets deposited within the catchment before reaching the outlet. The catchments are, therefore, divided into sub areas to account for spatial heterogeneity. Time – area based sub-division was adopted by Kothyari et al. (1996, 1997) for obtaining unique drainage directions in different segments of a catchment. However, the grid or cell approach of catchment sub-division has been used more extensively (Hadley et al., 1985, Beasley et al, 1980). The grid or cell approach is quite adaptive to collection of input data on a regular pattern with the use of GIS and it accounts for the variation in topographic characteristics over a catchment in detail (Kothyari and Jan. 1997). Therefore, a grid-based procedure for discretization of the catchment as depicted in Fig. 1 is adopted in the studies on Soil Erosion and Sediment Yield Modeling using GIS (Jain and Kothyari 2000). Also, for application of RUSLE, one requires such information as prior land use, crop canopy, surface cover and surface roughness, which are not always available. Therefore, the USLE is adopted in these studies for estimation of gross erosion rates in the different cells of a catchment. The eroded sediment is routed from each cell to the catchment outlet using the concept of the sediment delivery ratio as described below.

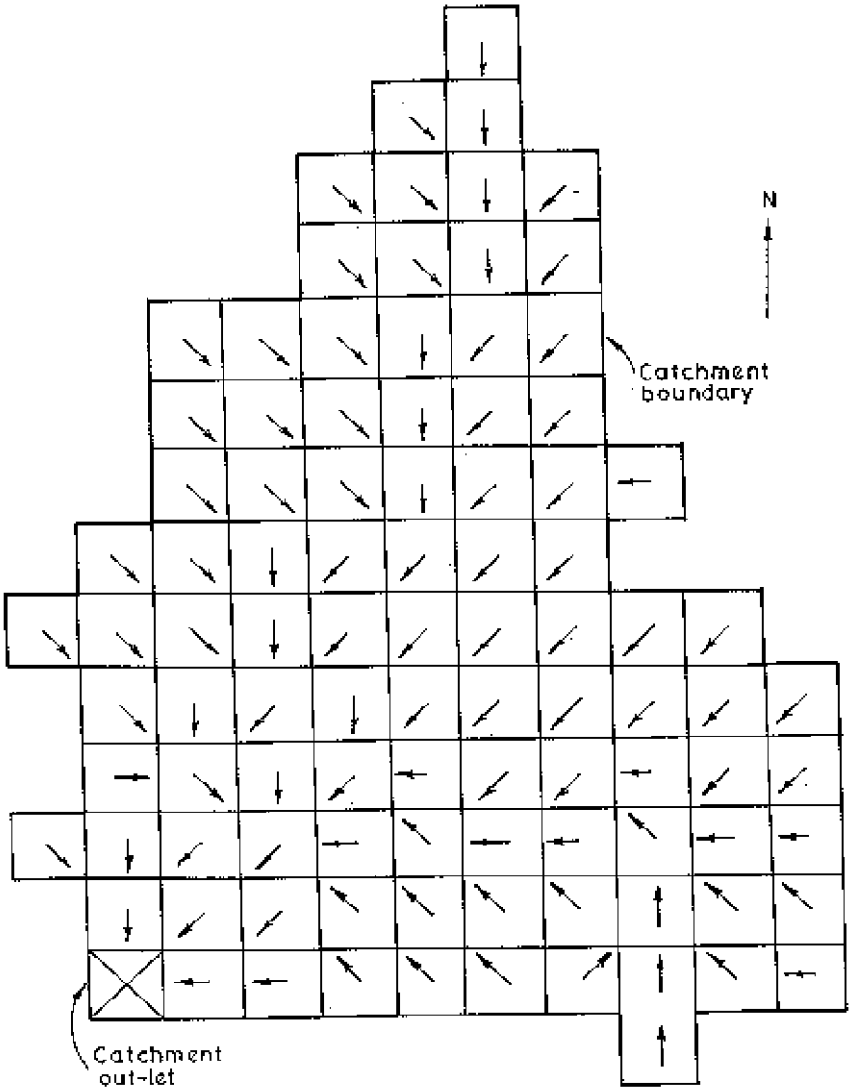

Figure 1. Grid discretization and flow directions for Kharkari catchment.

SEDIMENT DELIVERY RATIO

The ratio of sediment yield from a cell or grid to gross erosion within that cell of the catchment is termed here as sediment delivery ratio D_r. The magnitude of sediment delivery ratio for any area is influenced by catchment physiography, sediment source, transport system, texture of eroded material, land use etc. (Walling, 1988). Mainly catchment area, land slope and land use have been used as parameters for estimating D_r (Hadley et al. 1985, Kothyari et al., 1996).

Ferro and Minacapilli (1995) hypothesized that D_r is a function of travel time of overland flow in the cell. The travel time is strongly dependent on topographic and land use characteristics of a cell and therefore, its relation with D_r is justified. Based on these, the following empirical relation was assumed by Yoseph (1998) for D_r of a cell size area.

$$D_r = \left\{ \exp\left(-\beta \frac{l_i}{\sqrt{\theta_i}} \right) \right\}^{\alpha} \qquad (1)$$

Here l_i is the length of drainage path for the i^{th} cell of the catchment and θ_i is its slope, α and β are coefficients that were considered to remain the same for cells lying in a homogeneous sub-area of the catchment. Time of travel is proportional to length of cell/velocity of flow which can be taken as $l/\sqrt{\theta}$ if one uses the fact that velocity is proportional to $\theta^{1/2}$ according to Manning's or Chezy's equation. Thus, indeed as per Eq.(1), D_r becomes dependent on the travel time. The effect of varying land uses over the catchment on D_r can be accounted for by using, in different sub-zones, different sets of values of coefficients in Eq. (1). Jain and Kothyari (2000) considered $\alpha = 1$ in Eq. (1).

Now let S_{Ei} be the amount of soil erosion produced within the i^{th} grid of he catchment estimated using an appropriate relation such on the USLE, then the sediment yield for the catchment S_y during the storm event can be obtained as below (Kothyari and Jain, 1997).

$$S_y = \sum_{i=1}^{N} D_{ri} S_{Ei} \qquad (2)$$

Here N is the total number of grids in the catchment

TEMPORAL VARIATION OF SEDIMENT YIELD

The time of travel of overland flow through drainage path of a cell in the catchment can also be obtained by using Kirpich relation (Kirpich 1940) which is given below:

$$t_{ci} = 0.0078 \left(\frac{l_i}{\sqrt{\theta_i}} \right)^{0.77} \qquad (3)$$

Here t_{ci} is the time of travel in minutes for the i^{th} cell, l_i is the drainage length in m in the cell and θ_i is the drainage slope. The time of travel of surface flow from each of the cells to the catchment outlet can be obtained by following the respective drainage paths downstream of these cells (See; Fig. 1). The travel time thus obtained from the N number of cells to the catchment outlet can be grouped into different classes of magnitude and these can be presented in the form of a histogram.

For rain occurring during the selected unit duration, the sediment yields from N number of cells can be computed for unit value of the rainfall erosivity factor R to be used in the USLE. The suspended sediment load of the catchment is expected to travel to the catchment outlet with the same speed as the overland flow. Therefore, sediment yields of those cells which belong to the same group of travel times are summed up. The graph between the thus-summed up sediment yield values and their corresponding travel times would denote the translation curve for temporal variation of sediment yield called herein as translated sediment graph; See; Fig. 2. The translated sediment graph is then routed through a conceptual reservoir to account for the time delay due to storage effects on overland flow (Singh, 1988). Consider that the translated sediment graph is input S_I to the conceptual reservoir, which has sediment storage S_S at given time t (See; Fig.2). Then

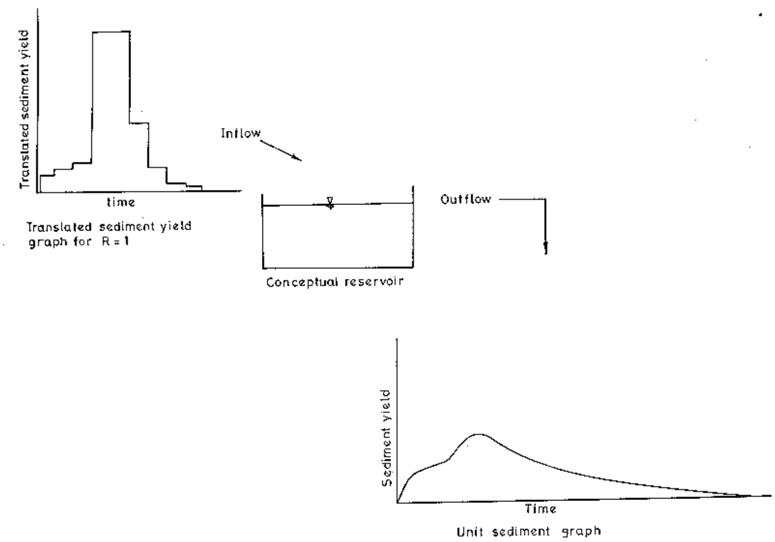

Figure 2. Routing of translated sediment yield graph through a linear reservoir.

Sediment outflow S_0 of such a reservoir is obtained by using the continuity equation

$$S_I(t) \quad - \quad S_O(t) \quad = \quad \frac{dS_s(t)}{dt} \tag{4}$$

The sediment outflow of the conceptual reservoir is considered to be related to its storage as

$$S_s(t) \quad = \quad k_r S_o(t) \tag{5}$$

Here k_r is storage coefficient. Simultaneous solution of Eqs. (4) and (5) produces the temporal variation of S_0 values, which is termed as unit sediment graph of the catchment. Unit sediment graph of the catchment represents the temporal variation of sediment yield generated from excess rainfall (total rainfall – abstractions) uniformly occurring over the unit duration and having such magnitude that corresponds to unit value of R-parameter of the USLE.

The unit sediment graph thus obtained can be convoluted with values of R-factor of the USLE corresponding to all the unit duration excess rain blocks of the given storm event. Superimposition of such convoluted graphs produces the temporal variation of sediment yield for the catchment during the given storm-event. Note that spatial variation in rainfall can also be accounted for by using different R-values in different cell areas of the catchment.

GENERATION OF INFORMATION THROUGH GIS

The GIS package used in the studies mentioned here was ILWIS (Integrated Land and Water Information, ITC, 1992), which was developed at the International Institute of Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands. The parameters needed for estimation of surface erosion, sediment delivery ratio and sediment yield were generated and stored in ILWIS (Kothyari and Jain 1997, Yoseph, 1998, Jain and Kothyari, 2000). The base map depicting drainage pattern, land use and elevation contours of the study areas were prepared using the Survey of India topographical maps for these at a scale of 1:25000. These were converted into digital form using a digitizer. The catchments were discretized into grid networks using ILWIS by adopting square grids having different sizes for different catchments. The contour maps were rasterized using interpolations from isolines and converted into digital elevation model (DEM) for each of the catchments studies.

In ILWIS, water from any grid cell is permitted to flow to one of its eight nearest neighbouring cells. Using the DEM's, grids of flow directions were created for all the catchments with unique flow direction for each cell which represents the direction of steepest descent amongst the eight permitted choices. The grid map showing thus obtained drainage directions for Kharkari catchment in Rajasthanis shown in Fig. 1.

RESULTS AND DISCUSSION

The foregoing concepts of computation of sediment yield and its temporal variation have been applied in the catchment of Nagwa (area 92.46 km^2), Karso (area 27.93 km^2) in Damodar valley region in Bihar and in Kharkari (area 16.22 km^2) in Rajasthan, India . Details on these data are given in Kothyari et al. (1997). A graphical comparison was made between the computed and observed values of sediment yields for the different storm events (Yoseph, 1998). This comparison indicated that the method discussed herein predicted the sediment yield with a maximum of $\pm$40 per cent error for most of the data. The temporal variation of sediment yield computed using the stated method was also compared with the corresponding observed values. Figure 3 shows such comparison for one storm event as illustration (Yoseph, 1998). Satisfactory prediction of sediment yield could be seen in this and similar other figures.

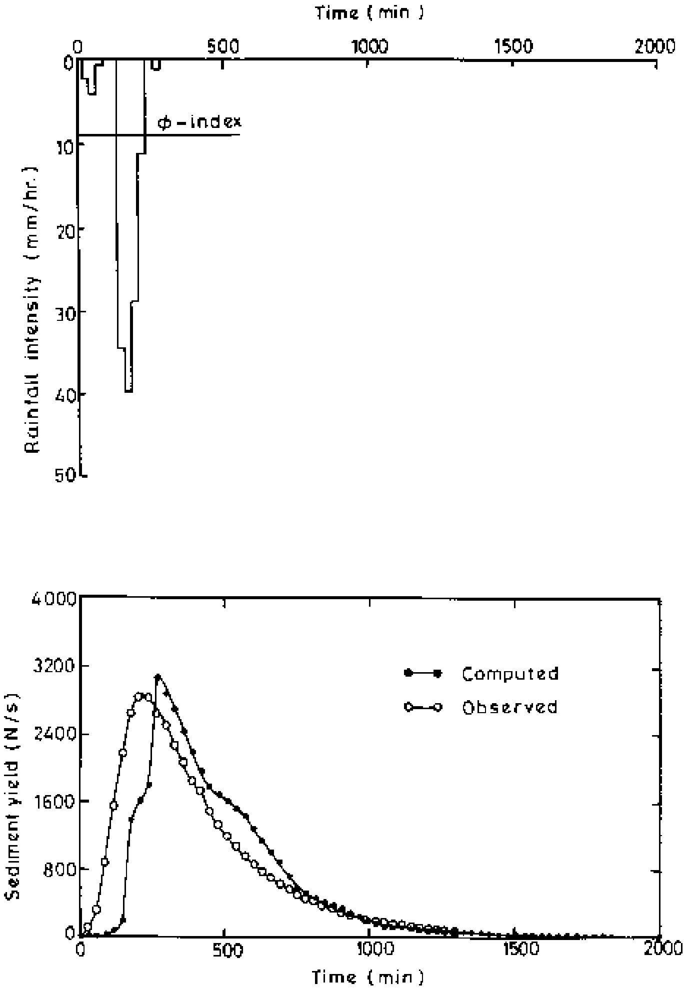

Figure 3. Temporal variation of sediment yield for Nagwa catchment (July 20, 1989).

The gross soil erosion map and sediment delivery ratio maps were overlaid in the ILWIS GIS package to identify the source areas for sediment reaching the outlet from within the catchment. Through such overlaying the areas producing large sediment amounts in the catchment could be identified. The areas producing more sediment would need special priority for the implementation of soil erosion control measures.

CONCLUSION

A GIS based method is discussed and demonstrated for prediction of sediment yield and its temporal variation during isolated storm events. The process of sediment delivery from cell or grid size areas within the catchment to the catchment outlet was found to be well represented by Eq. (1). Total sediment yield from the catchments during storm events is satisfactorily determined by using Eq. (2). Unit sediment graphs for the catchments were derived by first translating the sediment yields from the cell size areas for unit value of rainfall erosivity factor to the catchment outlet and next routing the same through a conceptual linear reservoir. The discussed method herein was found to satisfactorily estimate the temporal variation of sediment yield during the storm events.

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