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ESTIMATION OF SOIL EROSION AND SEDIMENT YIELD USING GIS

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CONTENTS

List of Figures

List of Tables

ABSTRACT

In the present study, a GIS based method is proposed and validated for prediction of sediment yield during isolated storm events. Data from Nagwa in Bihar (India) have been used. The ILWIS-GIS package has been used for catchment discretization into grid or cell networks and for evaluation of spatial variation in topographic characteristics and generation of travel time map and for carrying out other geographic analysis. ERDAS Imagine image processing software has been used for digital analysis of IRS-1C and LANDSAT TM digital data to derive land use and soil map of the catchment. The gross soil erosion in the watershed is calculated using Universal Soil Loss Equation (USLE) by carefully assigning various USLE parameters based on soil and land use of the watershed. To arrive at the total sediment yield of the watershed from an isolated storm event, the concept of sediment delivery ratio (SDR) have been used. The SDR of a grid cell is hypothesized to be dependent on travel time to nearest stream channel for over land flow cells and equal to unity for channel cells. The proposed method is found to satisfactorily estimate the sediment yield of the watershed for isolated storm events.

1 INTRODUCTION

Soil erosion is among the most critical environmental hazards of modern times. Vast areas of land now being cultivated may be rendered unproductive or atleast economically unproductive if erosion continues unabated. Information on the sediment yield at the outlet of a river basin can provide a useful perspective on the rate of soil erosion and soil loss in the watershed upstream. Soil erosion involves detachment, transport and subsequent deposition (Meyer and Wischmeier, 1969). Soil is detached both by raindrop impact and the shearing force of flowing water. Sediment is transported down slope primarily by flowing water, although there is a small amount of downslope transport by raindrop splash. Runoff and downslope transport does not occur until rainfall intensity exceeds infiltration rate. For this reason soil erosibility decreases as infiltration rate increases. Once runoff starts, the quantity and size of material transported increases with the velocity of runoff water. At some point downslope, slope may decrease, resulting in a decreased velocity and transport capacity. At this point, sediment will be deposited, starting with the large particles and aggregates. Smaller particles and aggregates will be carried further downslope, resulting in what is known as enrichment of fines.

Models available in the literature for sediment yield estimation can be grouped in to two categories (a) physically based models (b) lumped models. Generally in physically based models the ground surface is separated into inter-rill and rill erosion areas. Detachment over inter-rill areas is mainly caused by the impact of raindrop because flow depth is shallow, while runoff is considered to be the dominant factor in rill detachment and sediment transport over both rill and inter-rill areas. The physically based models include AGNPS (Young et al., 1987), ANSWERS (Beasley et al., 1980), WEPP (Nearing et al., 1989) and SHETRANS (Wicks and Bathrust, 1996). The physically based models are expected to provide reliable estimates for the sediment yield. However, these models require the coordinated use of various sub-models related to meteorology, hydrology, hydraulics and soil. As a result, the number of input parameters for some of these models is high. Therefore, practical application of these models are still limited because of such uncertainty in model parameters and also due to difference between the scale of application i.e. a catchment and that of the development i.e. a field (Hadley et al., 1985; Wu et al., 1993).

Alternatively, the lumped models such as 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., 1993), combine the erosion from all processes over a catchment into one equation. Rainfall characteristics, soil properties, and ground surface conditions are represented by empirical constants in these methods. The lumped methods of sediment yield estimation are in frequent use in many parts of the world (Bogardi et al., 1986; Julien and Tango, 1994; Kothyari et al., 1996). The catchment can be divided into sub-areas for representing the spatial heterogeneity. Surface erosion as computed using the lumped procedure in the sub-area can be routed to the catchment outlet using any appropriate procedure.

Geographic Information Systems (GIS) link land cover data to topographic data and to other information concerning processes and properties related to geographic location. When applied to hydrologic systems, nontopographic information can include description of soils, land use, ground cover, ground water conditions, as well as man-made systems and their characteristics on or below the land surface. A number of studies have been carried out in the past wherein the soil rates were determined using the USLE and the GIS (Bocco et al., 1988; Omakupt, 1989; Jurgens et al., 1993; Jain et al., 1995).

Present study is envisaged to (i) Use GIS techniques for spatial discretization of a catchment into small homogeneous grids; (ii) Generation of land use and soil map from digital classification of satellite data; (iii) Determination of those physical parameters of individual grids that are related to the soil erosion; (iv) Computation of surface erosion within the individual grid using lumped procedure, namely Universal Soil Loss Equation; (v) Generation of sediment delivery ratio map of the watershed; and (vi) routing of eroded sediment to the catchment outlet by rationally accounting for the process of sediment delivery.

2 METHODOLOGY

Apart from rainfall and runoff, the erosion rates from an area are also strongly dependent upon its soil, vegetation and topographic characteristics. In real situations, these characteristics are found to greatly vary within the various segments of the catchment. Therefore, a catchment can be discretized into various smaller homogeneous units before making the computations for soil loss. The grid or cell based discretization is found to be most commonly used procedure in both the physically based models as well as in the lumped models (Beven et al., 1984). Therefore for the present study, grid based discretization procedure has been adopted. Grid size to be used for discretization should be small enough so that the grid encompasses a hydrologically homogeneous area. There is ample evidence in literature that the USLE produces realistic estimation of surface erosion over small size areas (Wischmeier and Smith, 1978). Therefore, soil erosion within each grid (or cell) is estimated as per the USLE. The USLE can be expressed as:

$$S = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad (1)$$

where, S = computed soil loss ($MT.ha^{-1}$); R = rainfall-runoff erosivity factor ($MJ.mm.ha^{-1}.hr^{-1}$); K = soil erodibility factor ($MT.ha.hr.ha^{-1}.MJ^{-1}.mm^{-1}$); L = slope length factor (dimensionless); S = slope steepness factor (dimensionless); C = cover management factor (dimensionless) and P = supporting practice factor (dimensionless).

For calculation of R-factor, different approaches can be followed based on precipitation analysis relative to a relevant period of observation. In this study the approach given by Brown and Foster (1987) have been used. In case of K, C and P factors, the values shown in tables of the USLE application manuals (Wischmeier and Smith, 1978) can be used. A separate analysis must be carried out for estimation of LS-factor.

There are many relationships available for the estimation of LS-factor (Wischmeier and Smith, 1978; Moore and Burch, 1986; McCool et al., 1987; Moore and Wilson, 1992; Desmet and Grovers, 1996). Among them, the ones that seem best suited for integration inside the GIS are the equations proposed by Moore and Wilson (1992) in a form like:

$$L \cdot S = \left[\frac{A_s}{22.13}\right]^n \cdot \left[\frac{Sin\beta}{0.0896}\right]^m \qquad (2)$$

Where, A_s is the specific catchment area (=A/b), defined as the up slope contributing area (A) per unit width normal to flow direction (b); β is the slope gradient in degrees; n = 0.4; and m = 1.3. The use of eq. (2) in the estimation of the LS-factor allows the introduction of the (3-D) hydrological and topographic effect of converging and diverging terrain on soil erosion.

Use of equation (1) allows for estimation of gross soil erosion in the watershed or grid cell. However the models such as USLE or RUSLE assumes no deposition. It is a wellestablished fact that only a fraction of eroded material reaches watershed outlet and rest of the eroded material deposit back in the watershed. To account for this phenomenon, the concept of sediment delivery ratio as described below is used.

2.1 Sediment Delivery Ratio

In case of a catchment, part of the eroded soil is deposited within the catchment before reaching its outlet. The ratio of sediment yield to total surface erosion is termed as the sediment delivery ratio (D_R). Empirical formulae have been developed for D_R of a catchment in terms of the catchment area, length or relief by various investigators (Maner, 1958, Roehl, 1962, Williams and Berndt, 1972, Walling, 1983, 1993, Richards, 1993). In a cell based approach for determination of sediment yield the D_R value for individual cells is defined first. Kling (Hadley et al. 1985) considered the D_R for two adjacent cells as the ratio of average land slope of the given (draining) cell to that of the adjacent (receiving) cell. Kothyari et al. (1994 and 1996) considered the D_R to be a combined function of slope ratio, area ratio, and the ratio of percent forest cover in the corresponding segments.

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 is assumed herein for D_{r_i} of a cell size area.

$$D_{r_i} = \exp(-\beta t_{i,j}) \quad (3)$$

Here $t_{i,j}$ is the travel time (hr) of i^{th} cell of j^{th} drainage path to the nearest stream reach. β is a coefficient which is assumed constant for a given basin. Since the D_{r_i} of a grid cell is hypothesized as a function of travel time to nearest channel, it implies that gross erosion in that cell multiplied by D_{r_i} of the cell become sediment yield contribution of that cell to the nearest stream channel.

The effect of varying land uses over the catchment on D_{r_i} is accounted for by using, spatial variability of land use in computation of flow velocity using appropriate flow velocity computation methodology.

Now let S_i be the amount of erosion produced within the i^{th} cell of the catchment estimated using Eq (1), then sediment yield for the catchment S_y during the storm event is obtained as below:

$$S_y = \sum_{i=1}^{N} D_{r_i} S_i \quad (4)$$

Here N is the total number of cells in the catchment, and the term D_{r_i} is the fraction of S_i that ultimately reaches the nearest channel. The sum of all the sediment yield reaching to nearest channel is termed as the total sediment yield from the watershed due the storm event. This hypothesis is based on the Playfair's law of stream morphology which states that over a long time a stream must essentially transport all sediment delivered to it (Boyce, 1975). Based on this hypothesis, the sediment delivery ratio of all channel cells is assumed as unity.

3 THE STUDY AREA

For the present study a watershed situated in Damodar-Barakar river basin in Bihar has been selected. The stream named upper Sewani traverses through this catchment and finally joins the Konar river, a tributary to river Damodar. The watershed of Nagwa is being monitored under Indo-German bilateral project on watershed management (S&WCD, 1991).

3.1 Location

Geographically the catchment of Nagwa lies at a longitude of 85°24′ East and at a latitude of 24°03′ North. This catchment is also known as Sewan 7A in some other publications (Das et al., 1984). The catchment lies about 7 km away from Hazaribagh town in Bihar. Figure 1 shows the location of the catchment.

3.2 Climate

The climate of the region is tropical sub-humid with the average rainfall of 1076 mm (SCD, 1983). About 90% of the rainfall occur during monsoon season from July to September. The maximum temperature in the catchment varies between 40° to 44°C and the minimum temperature ranges between 10° to 20°C. Evaporation during the months of April-May is very high with a mean value of 21 mm (SCD, 1983).

Fig. 1 Location map of Nagwa watershed

3.3 Topography

The catchment has rectangular shape and undulating topography with irregular slopes. Figure 2 shows drainage characteristics of the catchment. The average slope of the catchment is 1.25%. Length of main channel is 21.25 km with an average slope of 0.234%. Length-width ratio of the watershed is 1.53 and the bifurcation ratio 5.04.

3.4 Soils

Major soils of the area belong to a group of red loamy soils which are light in texture, have moderately heavy sub soils and are moderately acidic in nature. To account the spatial variability of soils in the watershed, digital classification of Landsat TM scene of area of interest of May, 1991 have been carried out on ERDAS Imagine image processing system. Figure 3 shows the classified soil map of the study watershed.

3.5 Land Use

The land use of this catchment can be divided into four categories viz. agriculture, forest, scrub and waste land. Agricultural land includes the area under paddy cultivation and other mixed cultivation. Most of the cultivated lands have been treated by soil and water conservation measures like terracing, grade stabilization structures, sediment control structures and farm ponds. To account the spatial variability of land use in the watershed, digital

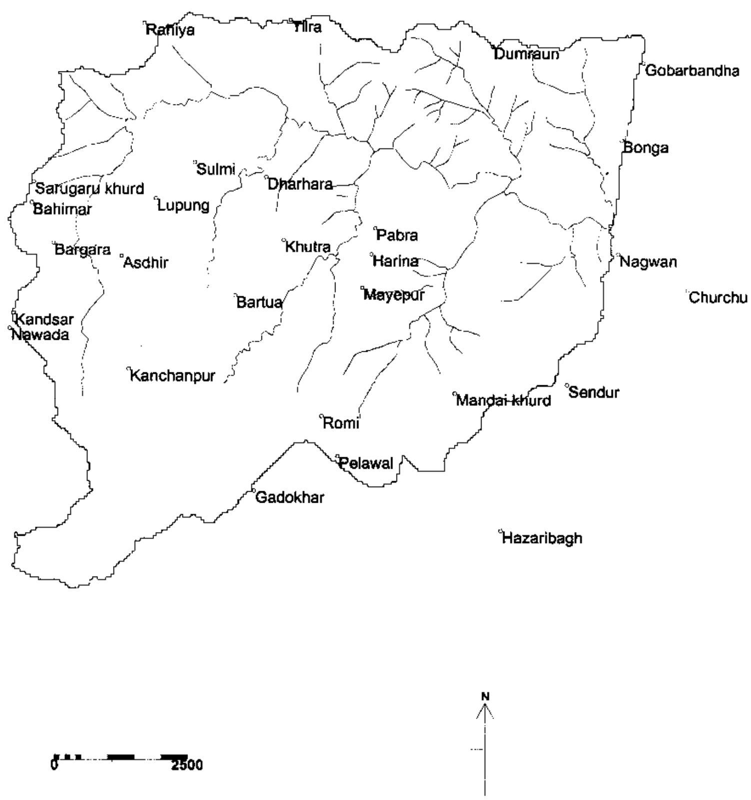

Fig. 2 Drainage map of Nagwa watershed

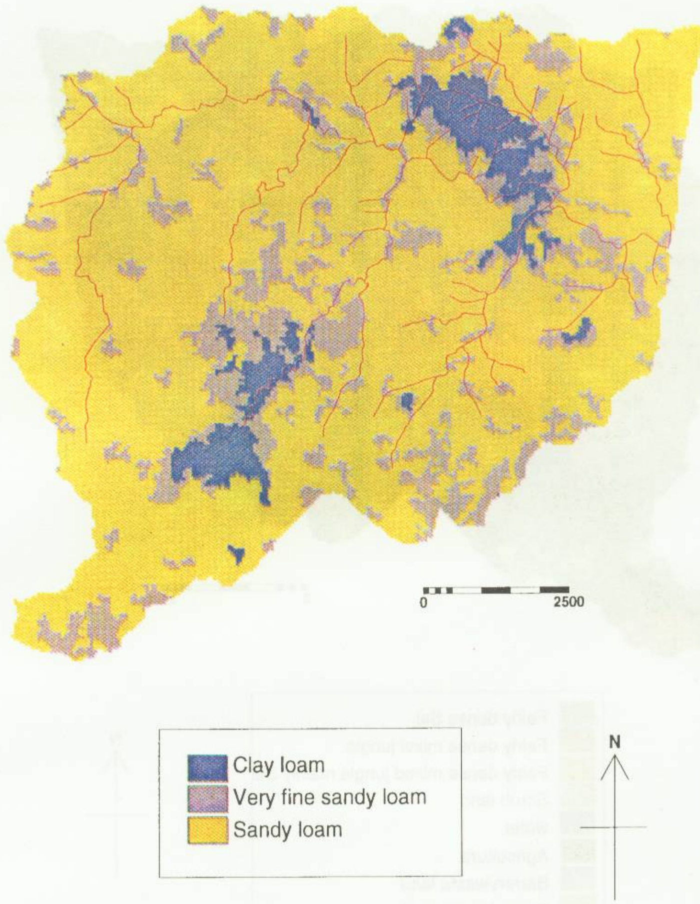

Fig. 3 Soil map of Nagwa watershed

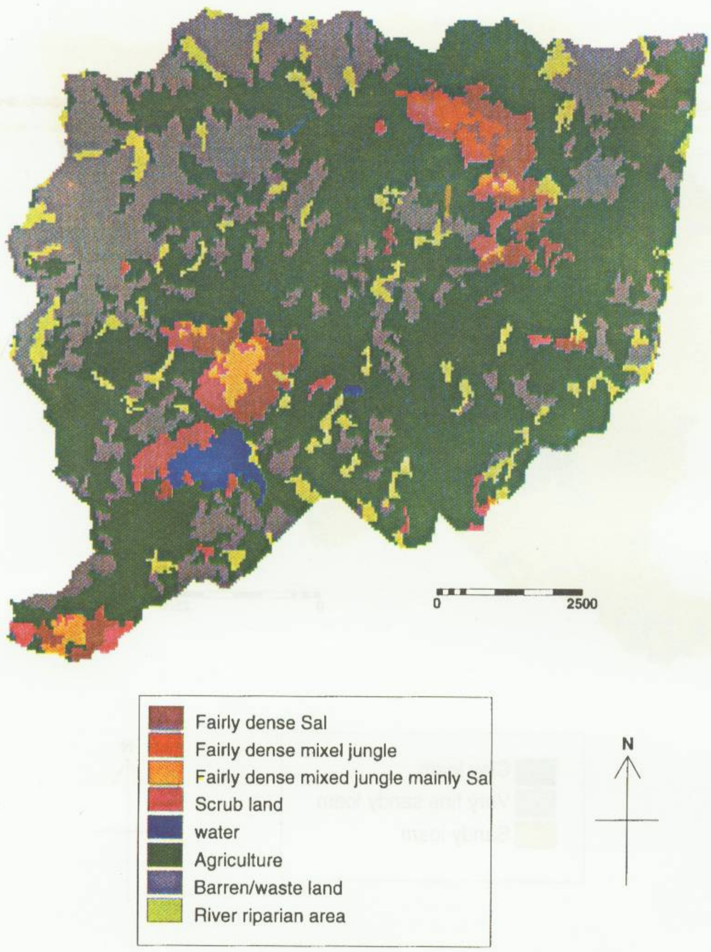

Fig. 4 Landuse map of Nagwa watershed

classification of IRS 1C LISSIII scene of area of interest of November, 1996 have been carried out on ERDAS Imagine image processing system. Figure 4 shows the classified land use map of the study watershed.

3.6 Data collection

The catchment is being gauged under the Indo-German bilateral project. Records of rainfall, runoff and sediment yield area available for the catchment. Rainfall data was collected by automatic tipping bucket type recording rain gauge and runoff was observed using velocity-area method. The USDH-48 sampler was used to collect the sediment samples. Sediment load samples were taken for every 15-cm rise and fall of water level.

4 ANALYSIS AND DISCUSSION OF RESULTS

4.1 Generation of Digital Input Maps

The river network and contour map of the study area has been derived from Survey of India toposheets in 1:25,000 scale. Derived contour and drainage maps were then digitized on Integrated Land and Water Information System (ILWIS). Digitized segment contour map is then interpolated at 50m-pixel size using interpolation function available in ILWIS to generate a Digital Elevation Model (DEM) of the area. This DEM was further analyzed to remove pits and flat areas in it using neighborhood functions available in ILWIS. The corrected DEM can then be used to delineate watershed area draining to the outlet. To delineate watershed of Nagwa, the watershed outlet location was marked and using neighborhood analysis, watershed boundary was generated using ILWIS. The corrected DEM was further analyzed by using ILWIS operations to generate slope and flow direction maps of the watershed. Figs. 5 shows the DEM of the basin.

As reported in section 3.0, the land use and soil map of the study area has been derive by digital classification of satellite data. The scene corresponding to the area of interest was first cut from entire path/row scene and further it was geo-coded as per standard practice at 30 and 24 meter pixel resolution for TM and LISSIII scenes respectively. The geo-coded scene is then masked by the boundary of the basin derived earlier to delineate area lying within the basin. Land use map is then generated from

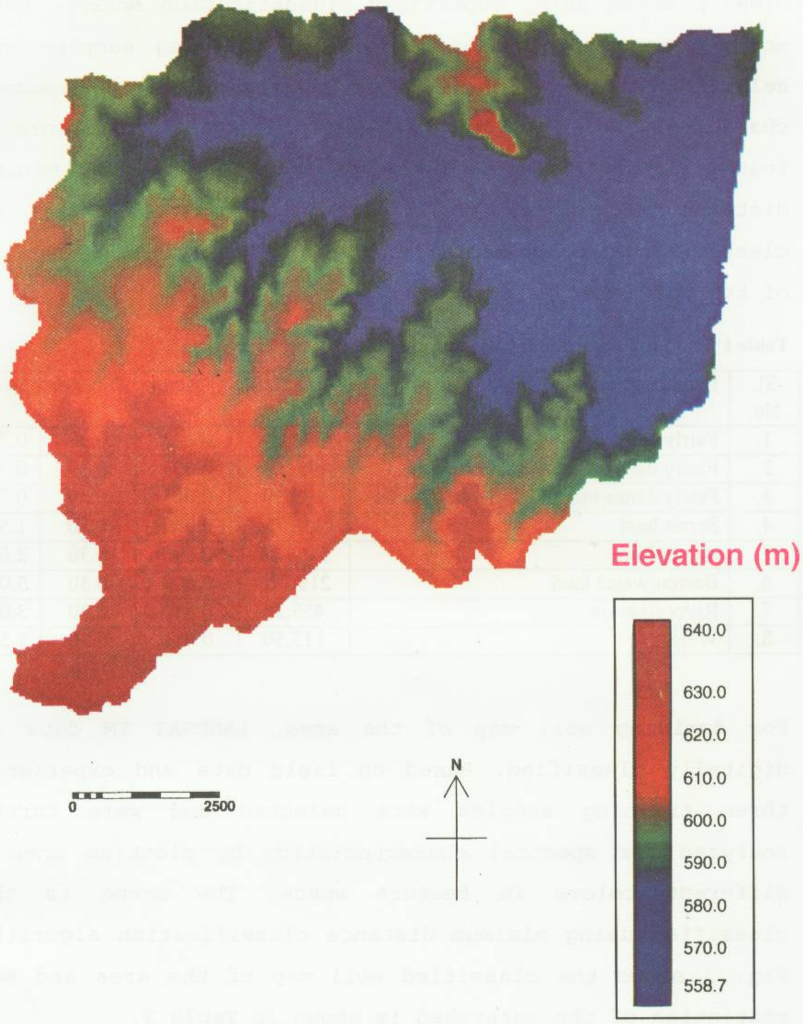

Fig. 5 DEM of Nagwa watershed

LISSIII scene using supervised classification scheme. Based on experience and field data, nine training samples were selected and were further analyzed for spectral characteristics by plotting them in different colors in feature space. The scene is then classified using minimum distance classification algorithm. Fig. 4 shows the classified land use map of the area and land use statistics of the watershed is shown in Table 1.

Table 1 Land use statistics of Nagwa watershed

Sl. No.	Land use	Area (ha)	C-factor	P-factor	a-value
1.	Fairly dense Sal	392.25	0.003	0.30	0.7625
2.	Fairly dense mixed jungle	75.25	0.009	0.30	0.7625
3.	Fairly dense mixed jungle mainly Sal	105.50	0.003	0.30	0.7625
4.	Scrub land	256.75	0.040	0.30	1.5555
5.	Agriculture	5404.25	0.290	0.30	2.6230
6.	Barren/waste land	2190.25	0.400	0.30	3.0805
7.	River riparian	455.25	0.450	0.30	3.0805
8.	Water	113.50	0.001	0.30	1.5555

For deriving soil map of the area, LANDSAT TM data was digitally classified. Based on field data and experience, three training samples were selected and were further analyzed for spectral characteristics by plotting them in different colors in feature space. The scene is then classified using minimum distance classification algorithm. Fig. 3 shows the classified soil map of the area and soil statistics of the watershed is shown in Table 2.

Table 2. Soil type statistics of Nagwa watershed

Sl.no.	Soil type	Area (ha)	K-factor (MT.ha.hr.ha^{-1}.MJ^{-1}.mm^{-1})
1.	Clay loam	561.50	0.042144
2.	Very fine sandy loam	1566.50	0.048729
3.	Sandy loam	6856.00	0.056631

4.2 Generation of USLE Parameter Maps

Based on the soil and land use maps of the area, various parameters such as USLE K, C and P were determined from tabulated values and values reported by Kothyari & others (1996). Attribute maps for USLE K, C and P was generated at 50-m grid size using attribute map facility available in ILWIS package. For calculation of L and S factors, equation (2) has been used. Use of equation (2) requires computation of up slope contributing area at each grid. Since the catchment has been discretized in to cell size of 50 m, therefore entire watershed has a total of 35972 cells (total area 89.93 km^2). To calculate up slope contributing area of each grid cell, capabilities of ILWIS software were utilized as described in following section 4.2.1.

4.2.1 Grid-based Flow Pattern

Most of the raster based GIS systems contain routines which determine the flow direction over land surface terrain using pour point model. Water on grid cell is permitted to flow to one of its eight neighboring cells. By taking a grid of terrain elevations, determine the slope of the line joining each cell with each of its neighboring cells, a grid of flow directions is created with one direction for each cell which represents the direction of steepest descent among the eight permitted choices. The concept of grid based flow pattern is represented in Figs. 6(a), 6(b), 6(c) and 6(d). The grid in figure 6(c) is shown as a set of arrows but infect is stored in GIS as a grid of numbers where each flow direction has a unique identifying number. By assigning water flow to one of

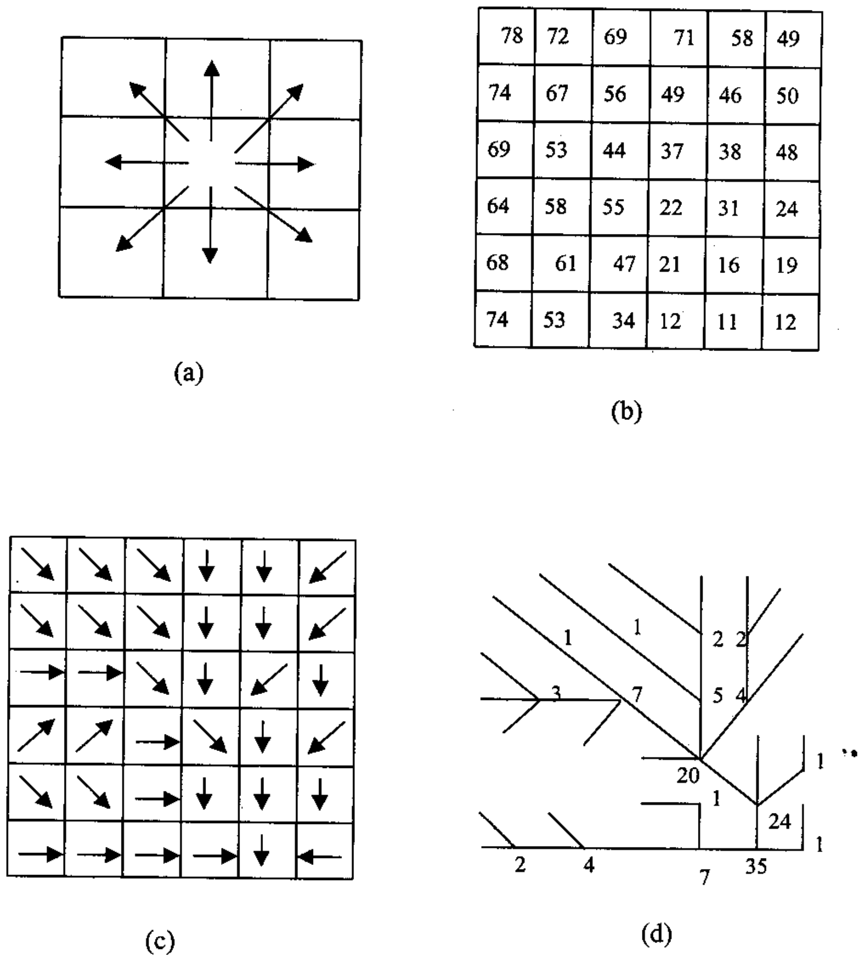

Fig. 6 Watershed terrain analysis using grid GIS method: (a) the eight direction pour point model; (b) a grid of terrain elevations; (c) the corresponding grid of flow directions, (d) the equivalent network showing flow accumulation.

its eight neighboring cells, equivalent one dimensional flow network is constructed by connecting the cell centers in the direction of flow as shown in Fig. 6(d). There is thus a duality between the grid and equivalent flow network and one might call the network so created a hybrid grid-network.

4.2.2 Calculation of LS factor

As described in section 4.2.1, equivalent flow network for the Nagwa watershed has been generated using neighborhood operators of ILWIS. Generated equivalent flow network is shown in figure 7. Each pixel value of this equivalent network represents number of up slope contributing cells to a particular grid using pour point algorithm. Now if we multiply this number with cell area, we get up-slope-contributing area in each cell. If we work similarly up to the outlet of the basin, the cell representing outlet of the watershed has up slope contributing area equal to the total drainage area of the watershed.

Based on this up slope contributing area, an equivalent channel network for the watershed can be generated by assigning a threshold channel initiation area. Various values of channel initiation threshold were tried and generated channel network was compared with digitized channel network. It was observed that a channel initiation threshold of 5 hectare gives a good reproduction of channel network. Generated channel network and digitized channel network are shown in figure 8.

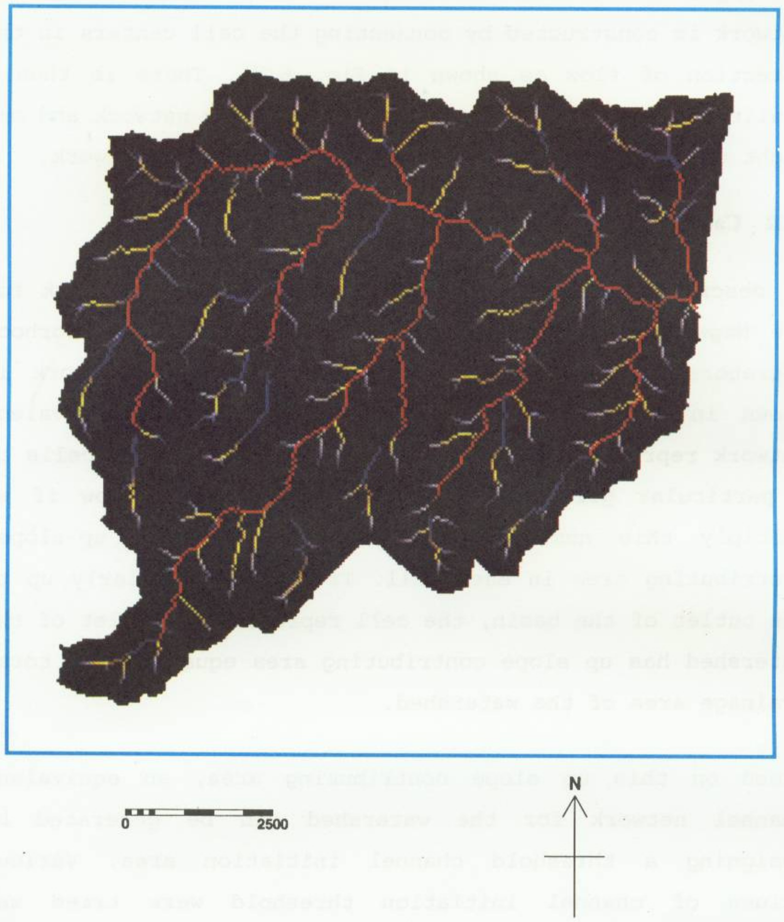

Fig. 7 Generated flow network of Nagwa watershed

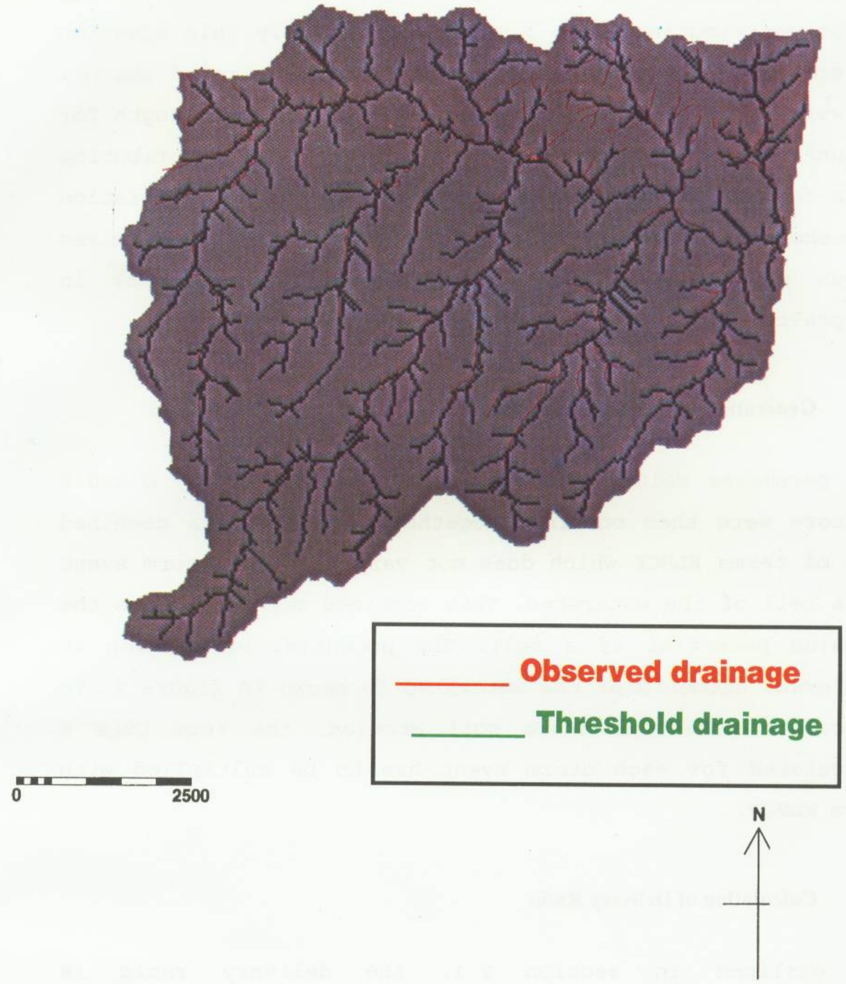

Fig. 8 Threshold channel network of Nagwa watershed

As per equation (2), the slope length is a function of up slope contributing area. However, if we apply this equation directly for both overland flow zones and generated channel network, it will give a very high value for slope length for channel cells. To avoid this problem, up slope contributing area for all channel cells is assumed as channel initiation threshold value calculated above. After calculating required input maps, the computation of LS factor was done in "mapcalculation" facility of ILWIS using equation (2).

4.3 Generation of erosion potential map

The parameter values maps of the USLE viz. K, L, S, C and P factors were then combined together to generate a combined map of terms KLSCP which does not vary with the storm event in a cell of the watershed. This combined map represents the erosion potential of a cell. The potential of erosion in different segments of the watershed is shown in figure 9. To calculate potential storm soil erosion, the term USLE R calculated for each storm event has to be multiplied with term KLSCP.

4.4 Calculation of Delivery Ratio

As outlined in section 2.1, the delivery ratio is hypothesized as a function of travel time to nearest channel. The travel time from a cell to nearest channel can be calculated if we have flow path length and flow velocities for all cells localizing in a flow path. Velocity is a vector quantity specified my magnitude and direction of

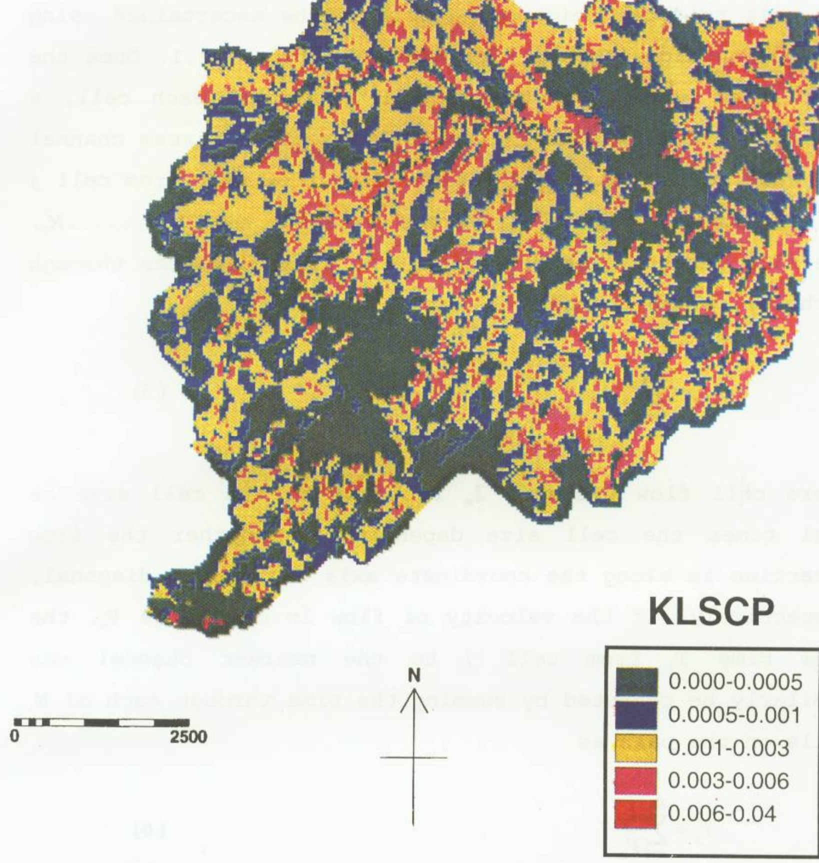

Fig. 9 Erosion potential (KLSCP) map of Nagwa watershed

flow. In grid based GIS analysis, the direction of flow from one cell to other neighboring cell can be ascertained using pour point algorithm as reported in section 4.2.1. Once the pour point identified the flow direction in each cell, a cell to cell flow path exists to the nearest stream channel and thus to the watershed outlet. If a flow path from cell j to the nearest channel traverses m cells, $m = 1,2,.....M_j$, the flow length L_j is defined as the flow distances through each cell along the path

$$L_j = \sum_{m=1}^{M_j} l_m \quad (5)$$

where cell flow distance l_m is equal to the cell size or 1.41 times the cell size depending on whether the flow direction is along the coordinate axis or along a diagonal, respectively. If the velocity of flow in cell m is V_m, the flow time T_j from cell j to the nearest channel can similarly be computed by summing the time through each of M_j cells on the path as

$$T_j = \sum_{m=1}^{M_j} \frac{l_m}{V_m} \quad (6)$$

Determination of flow time by the method described above requires the specification of the velocity for each cell on the watershed. This velocity is a typical or representative value for conditions during the types of events under simulation. There are a number of methods by which this can be done. However for the present study, method proposed by US Soil Conservation Service for overland flow velocity as a function of land surface slope and land cover is chosen for its simplicity and availability of information. In mathematical form

$$V_m = a\,S_m^b \qquad (7)$$

where S_m is slope of cell *m* and a and b are coefficients related to land use taken from McCuen (1982). Equation (7) was used by Sircar *et al.* (1991) for computation of time-area curve. Parameter "a" of the area was derived based on land use map obtained from satellite data and is tabulated in Table 1 for Nagwa watershed. The parameter b is kept constant and equal to 0.5.

Since for each cell both flow direction and flow velocities are now known, and the paths from each cell to the nearest channel has been specified, it follows that one can create a grid of flow travel times where the value in each cell is the time taken for water from that cell to flow to the nearest stream reach. The value of sediment delivery ratio is then calculated using equation (3). The coefficient β is assumed as unity for simplicity. However if sufficient data on observed storm events are available, the coefficient β can be optimized. In present application since only three storm event data was available therefore the proposed model was applied without calibration. Figure 10 shows delivery ratio map from cell to nearest stream channel. As can be seen from figure 10, the delivery ratio of channel cells are assigned a value equal to 1.0 due to reasons described in section 2.1.

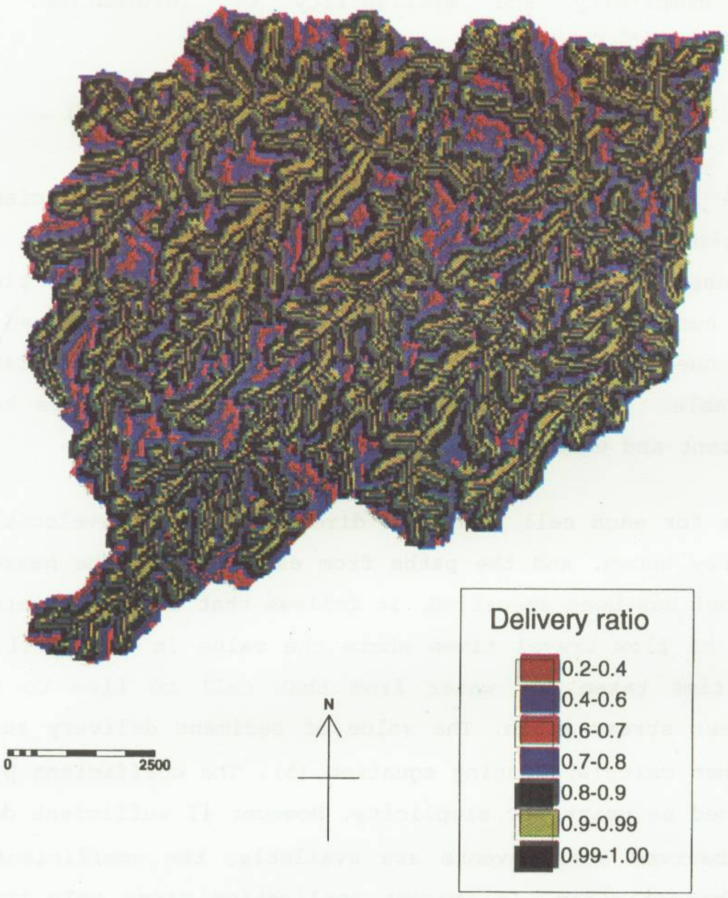

Fig. 10 Sediment delivery ratio map of Nagwa watershed

4.5 Calculation of Soil Erosion and Sediment Yield

Gross soil erosion from each pixel due to a storm event can be generated by multiplying erosion potential map shown in figure 9 with R-factor tabulated in Table 3 for each storm event as per equation (1). Figure 11 shows for illustration gross soil erosion of the watershed during storm event dated July 28, 1989.

The soil loss equation described earlier is useful tool for predicting the amount of soil loss from a field, referred to as gross erosion. However, the models, such as USLE, assume no deposition. Between the field and outlet, sediment will normally have numerous opportunities to be deposited, reducing the sediment yield accordingly. To quantify the amount of deposition occurring, the concept of sediment delivery ratio is used.

Knowing the gross erosion due to each storm event in different grid cells and their D_r values, the sediment yields at the outlet of the watershed were computed using equation (5). Comparisons between observed and computed storm sediment yields are given in Table 3. As can be seen from Table 3, the present method produces sediment yield with a reasonable accuracy without any calibration. The prediction accuracy of the proposed methodology can be rated as very good particularly considering the fact that no parameter was optimized and prediction from some of the process based models show still large scatter in plots between measured and computed sediment yields (Wu et al.,

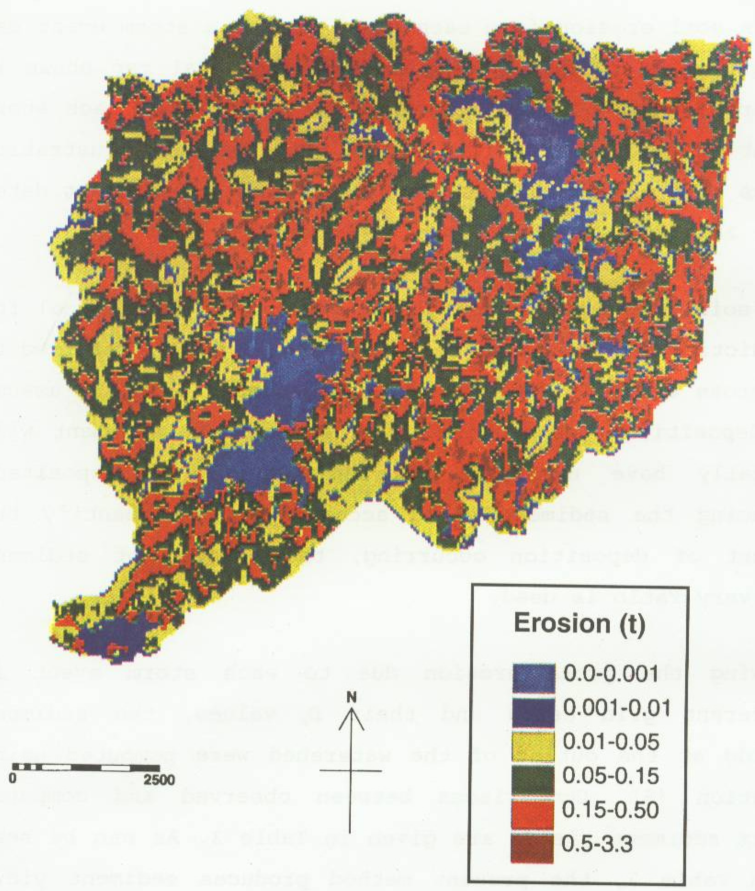

Fig. 11 Gross erosion in Nagwa watershed during event no. 3

1993). It is to emphasize here in this study no parameter optimization has been used and all parameters used were derived from literature based on satellite observations. Therefore, this method has the potential to predict impact of future changes in catchment land use and climate.

Table 3. Computed and observed values of sediment yield.

Date of event	R-value ($MJ.mm.ha^{-1}.hr^{-1}$)	Sediment yield (MT)		% error (obs-comp)/obs
		Observed	Computed	
July 06, 1989	533.06	2172.81	3791.41	74.44
July 20, 1989	574.99	7143.23	4097.66	42.63
July 28, 1989	419.60	3246.84	2983.85	08.09

4.6 Identification of Sediment Source Areas

Figures 9 and 10 were overlaid in ILWIS 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 were identified and are indicated in figure 12. It may be emphasized that these areas would need special priority during the implementation of erosion control measures.

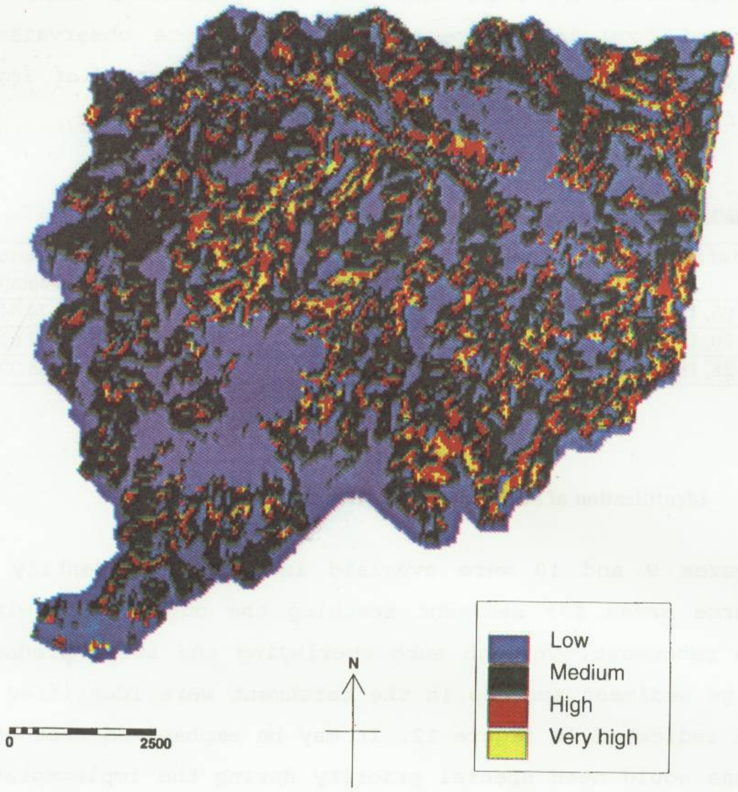

Fig. 12 Sediment source area map of Nagwa watershed

5 CONCLUSIONS

A GIS based methodology is demonstrated for identification of sediment source areas and prediction of storm sediment yield for small watersheds. Using ILWIS GIS package, the Nagwa watershed was discretized in to 50m grid cells and unique drainage directions were obtained using GIS analysis. Also a threshold channel network was generated from DEM of the watershed. Actual observed drainage and generated drainage networks were superimposed and were found identical.

Digital analysis of satellite data was carried out using Imagine 8.3.1 and land use and soil maps of the Nagwa watershed were generated. A GIS based procedure for USLE-LS factor determination for individual grid cells was implemented for the watershed. After assigning various USLE parameters to individual grid cells based on derived land use and soil map of the watershed, gross surface erosion in each cell is calculated. The eroded sediment is then routed to the catchment outlet using the concept of sediment delivery ratio. Reasonable results were obtained for storm sediment yield on Nagwa watershed using proposed concepts without any parameter calibration. However, to draw definite conclusions for applicability of this methodology without any calibration, more watersheds need to be analyzed.

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