WATER AND WIND INDUCED SOIL EROSION ASSESSMENT AND MONITORING USING REMOTE SENSING AND GIS

S.K. Saha
Agriculture and Soils Division
Indian Institute of Remote Sensing, Dehra Dun

Abstract : Water and wind induced soil erosion has adverse economic and environmental impacts. Large area in Asia-Pacific region is affected by soil erosion. This paper discusses various satellite remote sensing and GIS based modelling approaches for soil erosion hazard assessment such as empirical, semi-empirical and process based. Few case examples of soil erosion modelling by integrated use of remote sensing and GIS are included in this article.

INTRODUCTION

Soil degradation by accelerated water and wind-induced erosion is a serious problem and will remain so during the 21st century, especially in developing countries of tropics and subtropics. Erosion is a natural geomorphic process occurring continually over the earth's surface. However, the acceleration of this process through anthropogenic perturbations can have severe impacts on soil and environmental quality.

Accelerated soil erosion has adverse economic and environmental impacts (Lal, 1998). Economic effects are due to loss of farm income due to on-site and off-site reduction in income and other losses with adverse impact on crop/ animal production. The on-site and off-site effects of soil erosion on productivity are depicted in Figure 1 and Figure 2, respectively. Off-site economic impact of soil erosion is presented in Figure 3. Table 1 shows regional food production statistics for 1995 with and without soil erosion in the world. The data in Table 1 indicate total loss of food production at 31 M Mg for Africa, 190 M Mg for Asia and 18 M Mg for tropical America.

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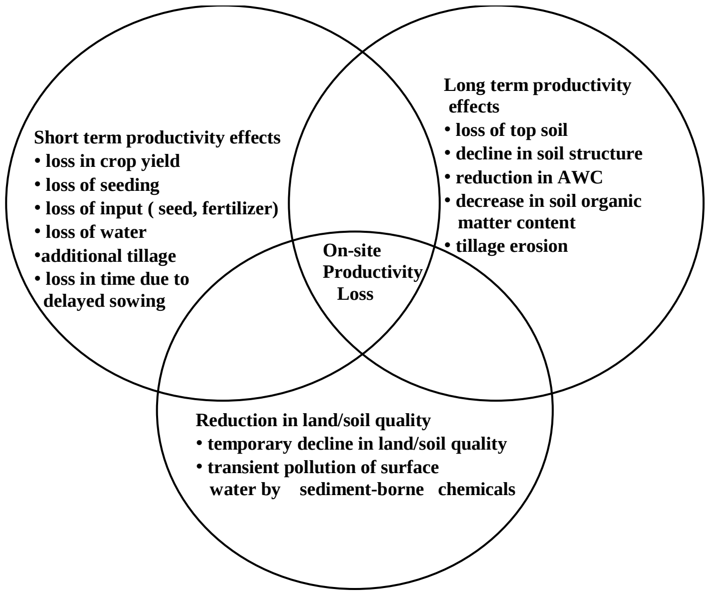

Figure 1: On-site effects of soil erosion on productivity are due to short-term and long-term effects, and on decline in soil quality (Lal, 2001)

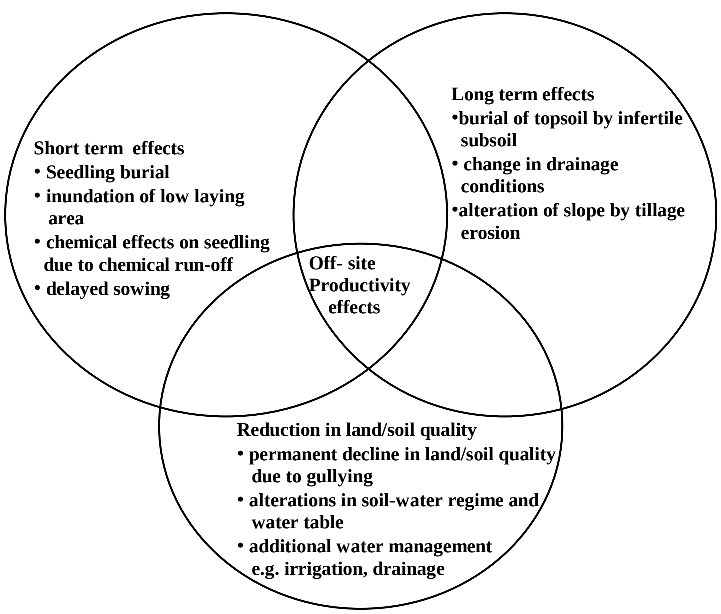

Figure 2: Off-site effects of soil erosion on productivity may be due to short-term or long-term and due to decline in land/soil quality (Lal, 2001)

Table 1. Regional food production statistics for 1995 with (a) and without (b) soil erosion (Lal, 2001)

Region	Cereals X 1000000		Soybeans X 1000000		Pulses X 1000000		Roots and tubers X 1000000	
	A	B	A	B	A	B	A	B
North Central America	358	376(5)	61	64(5)	6	65(b)	28	29(5)
Europe	268	281(5)	1	1(5)	6	6(5)	80	84(5)
Oceania	27	28(10)	-	-	2	2(15)	3	3(10)
Africa	100	110(10)	0.5	0.6(20)	7	8(20)	135	155(15)
Asia	929	1068(15)	21	23(10)	27	31(15)	248	293(18)
South America	90	99(10)	41	45(10)	4	4(10)	46	51(12)
Others	124	130(5)	3	3(5)	4	4(5)	69	72(5)
Total	1896	2092	126	136	50	61	609	687

GLOBAL EXTENT OF SOIL DEGRADATION BY EROSION

The total land area subjected to human-induced soil degradation is estimated at about 2 billion ha (Table 2; Lal, 2001). Of this, the land area affected by soil degradation due to erosion is estimated at 1100 Mha by water erosion and 550 Mha by wind erosion (Table 2). South Asia is one of the regions in the world where soil erosion by water and wind is a severe problem (Venkateswarulu, 1994 and Singh *et al.*, 1992) (Table 3).

Table 2. Global extent of human–induced soil degradation (Lal, 2001)

World Regions	Total Land Area (10 ha)	Human induced soil degradation (10 ha)	Soil erosion (10 ha)	
			Water	Wind
Africa	2966	494	227	186
Asia	4256	748	441	222
South America	1768	243	123	42
Central America	306	63	46	5
North America	1885	95	60	35
Europe	950	219	114	42
Oceania	882	103	83	16
World Total	13013	1965	1094	548

Table 3. Land area affected by soil erosion by water and wind in South Asia (Lal, 2001)

Country	Water erosion (Mha)	Wind erosion (Mha)	Total land area (Mha)
Afghanistan	11.2	2.1	65.3
Bangladesh	1.5	0	14.4
Bhutan	0.04	0	4.7
India	32.8	10.8	328.8
Iran	26.4	35.4	165.3
Nepal	1.6	0	14.7
Pakistan	7.2	10.7	79.6
Sri Lanka	1.0	0	6.6
Total	81.74	59.0	677.4

SOIL EROSION AND PROCESSES

Soil erosion is a three stage process : (1) detachment, (2) transport, and (3) deposition of soil. Different energy source agents determine different types of erosion. There are four principal sources of energy: physical, such as wind and water, gravity, chemical reactions and anthropogenic, such as tillage. Soil erosion begins with detachment, which is caused by break down of aggregates by raindrop impact, sheering or drag force of water and wind. Detached particles are transported by flowing water (over-land flow and inter-flow) and wind, and deposited when the velocity of water or wind decreases by the effect of slope or ground cover.

Three processes viz. dispersion, compaction and crusting, accelerate the natural rate of soil erosion. These processes decrease structural stability, reduce soil strength, exacerbate erodibility and accentuate susceptibility to transport by overland flow, interflow, wind or gravity. These processes are accentuated by soil disturbance (by tillage, vehicular traffic), lack of ground cover (bare fallow, residue removal or burning) and harsh climate (high rainfall intensity and wind velocity).

FACTORS OF SOIL EROSION

The soil erosion process is modified by biophysical environment comprising soil, climate, terrain and ground cover and interactions between them (Figure 4). Soil erodibility – susceptibility of soil to agent of erosion - is determined by inherent soil properties e.g., texture, structure, soil organic matter content, clay minerals, exchangeable cations and water retention and transmission properties. Climatic erosivity includes drop size distribution and intensity of rain, amount and frequency of rainfall, run-off amount and velocity, and wind velocity. Important terrain characteristics for studying soil erosion are slope gradient, length, aspect and shape. Ground cover exerts a strong moderating impact on dissipating the energy supplied by agents of soil erosion. The effect of biophysical processes governing soil erosion is influenced by economic, social and political causes (Figure 4).

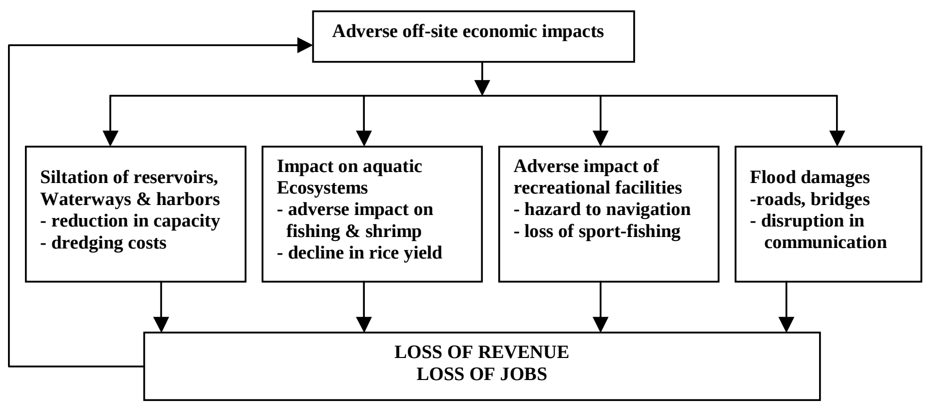

Figure 3: Off-site economic impact of soil erosion (Lal, 2001)

MODELLING SOIL EROSION

Field studies for prediction and assessment of soil erosion are expensive, time-consuming and need to be collected over many years. Though providing detailed understanding of the erosion processes, field studies have limitations because of complexity of interactions and the difficulty of generalizing from the results. Soil erosion models can simulate erosion processes in the watershed and may be able to take into account many of the complex interactions that affect rates of erosion.

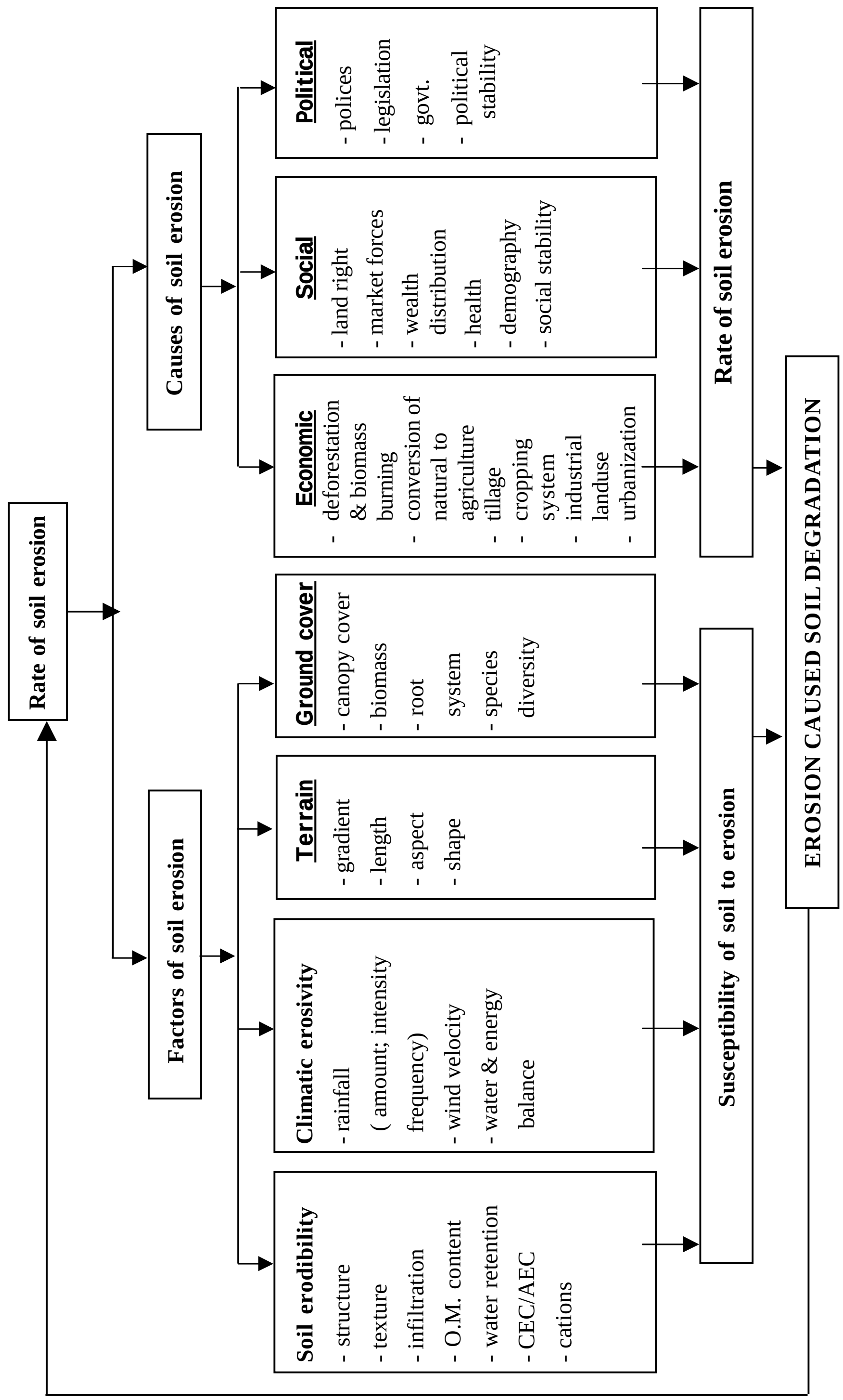

Figure 4: Factors of soil erosion; causes of soil erosion and interactions between them (Lal, 2001)

Soil erosion prediction and assessment has been a challenge to researchers since the 1930s' and several models have been developed (Lal, 2001). These models are categorized as empirical, semi-empirical and physical process-based models. Empirical models are primarily based on observation and are usually statistical in nature. Semi-empirical model lies somewhere between physically process-based models and empirical models and are based on spatially lumped forms of water and sediment continuity equations. Physical process-based models are intended to represent the essential mechanism controlling erosion. They represent the synthesis of the individual components which affect erosion, including the complex interactions between various factors and their spatial and temporal variabilities.

Some of the widely used erosion models are discussed below:

Empirical Models

Universal Soil Loss Equation (USLE)

USLE is the most widely used empirical overland flow or sheet-rill erosion equation. The equation was developed to predict soil erosion from cropland on a hillslope. The equation is given by –

$$A = R.K.L.S.C.P$$

Where, A is the average annual soil loss (mass/area/year); R is the rainfall erosivity index; K is the soil erodibility factor; L is the slope length factor; S is the slope gradient factor; C is the vegetation cover factor, and P is the conservation protection factor.

Revised Universal Soil Loss Equation (RUSLE)

The RUSLE updates the information on data required after the 1978 release, and incorporates several process-based erosion models (Renard *et al.*, 1997). RUSLE remains to be a regression equation –

$$A = R.K.L.S.C.P$$

A principal modification is in R factor which includes rainfall and run-off erosivity factor (run-off erosivity also includes snow melt where run-off is significant). There are also changes in C factor which is based on computation of sub-factor called soil loss ratios (SLR). The SLR depends on sub-factors : prior landuse, canopy cover, surface cover, surface roughness and soil moisture (Renard *et al.*, 1997).

Semi-empirical Models

Modified Universal Soil Loss Equation (MUSLE)

Williams (1975) proposed a modified version of USLE that can be written as–

$$Sye = Xe.K.L.S.Ce.Pe$$

Where, Sye is the event sediment yield

$$Xe = \alpha. (Qe.\ qp)\ 0.56$$

Where, α is an empirical co-efficient; Qe is the run-off amount and qp is the peak run-off rate obtained during the erosion event and K.L.S.Ce & Pe are as defined for USLE.

Morgan, Morgan and Finney (MMF) Model

Morgan *et al.* (1984) developed a model to predict annual soil loss which endeavors to retain the simplicity of USLE and encompasses some of the recent advances in understanding of erosion process into a water phase and sediment phase. Sediment phase considers soil erosion to result from the detachment of soil particles by overland flow. Thus, the sediment phase comprises two predictive equations, one for rate of splash detachment and one for the transport capacity of overland flow. The model uses six operating equations for which 15 input parameters are required (Table 4). The model compares predictions of detachment by rain splash and the transport capacity of the run-off and assesses the lower of the two values as the annual rate of soil loss, thereby denoting whether detachment or transport is the limiting factor.

Physical Process-based Model

Empirical models have constraints of applicability limited to ecological conditions similar to those from which data were used in their development.

Further, USLE cannot deal with deposition; its applicability limits large areas and watersheds. Based on these considerations, several process-based models have been developed (e.g. WEPP, EUROSEM, LISEM (Lal, 2001)).

Table 4. Operative functions and input parameters of Morgan, Morgan & Finney Soil erosion model

Operative functions	Input parameters
Water phase: $E = R * (11.9 + 8.7 * \log I)$ (1) $Q = R * \exp(- R_C / R_0)$ (2) Where, $R_C = 1000 * MS * BD * RD * (E_t / E_0)^{0.5}$ (3) $R_0 = R / R_n$ (4) *Sediment phase:* $F = K * (E * e^{-0.05*A}) * 10^{-3}$ (5) $G = C * Q^2 * \sin S * 10^{-3}$ (6)	*E* - *kinetic energy of rainfall (J/m^2)* *Q* - *volume of overland flow (mm)* *F* - *rate of detachment by raindrop impact (kg/m^2)* *G* - *transport capacity of overland flow (kg/m^2)* *R* - *Annual rainfall (mm)* R_n - *Number of rainy days in the year* *I* - *Intensity of erosive rain (mm/h).* *A* - *Percentage of rainfall contributing to permanent interception and stream flow (%) .* E_t/E_0 - *Ratio of actual (E_t) to potential (E_0) evaporation.* *MS* - *Soil moisture content at field capacity or 1/3 bar tension (% w/w).* *BD* - *Bulk density of the top layer (Mg/m^3)* *RD* - *Top soil rooting depth (m) defined as the depth of soil from the surface to an impermeable or stony layer, to the base of A horizon; to the dominant root base.* *K* - *Soil detachability index (g/J) defined as the weight of soil detached from soil mass per unit of rainfall energy.* *S* - *Steepness of the ground slope expressed as slope angle.* *C* - *Crop cover management factor. Combines C and P factors of the USLE*

Water Erosion Prediction Project (WEPP) Model

WEPP is an example of widely used physically process-based erosion model (Renard *et al.*, 1996). It was developed as a system modeling approach for predicting and estimating soil loss and selecting catchment management practices for soil conservation. Basic erosion and deposition equations in WEPP are based on the mass balance formulation that uses rill and inter-rill concept of soil erosion, which is a steady-state sediment continuity equation. The WEPP model computes erosion by rill and inter-rill processes. The sediment delivery to rill from inter-rill is computed by following equation –

$$Di = Ki.\ Ie^2.\ Ge.\ Ce.\ Sf$$

Where, Di is the delivery of sediment from inter-rill areas to rill ($kg/m^2/sec$); Ki is the inter-rill erodibility ($kg/m^4/sec$); Ie is the effective rainfall intensity (m/sec.); Ge is the ground cover adjustment factor and Sf is the slope adjustment factor calculated as per equation given below –

$$Sf = 1.05 - 0.85 \exp(-4 \sin \alpha)$$

Where, α is the slope of the surface towards nearby rill. In comparison, rill erosion is the detachment and transport of soil particles by concentrated flowing water -

$$Dc = Kr.\ (T - Tc)$$

Where, Kr is the rill erodibility (sec/m); T is the hydraulic shear of flowing water (Pa) and Tc is the critical hydraulic shear that must be exceeded before rill detachment can occur (Pa).

Wind Erosion Model

Comparable to the USLE, a wind erosion model was proposed by Woodruff and Siddoway (1965) as shown in equation given below –

$$E = f(I, K, C, L, V)$$

Where, E is the mean annual wind erosion; I is the soil erodibility index; C is the climatic factor (Wind energy); L is the unsheltered median travel distance of wind across a field; V is the equivalent vegetative cover. This equation has been widely adopted and used for estimating erosion hazard in dry lands.

USE OF SATELLITE REMOTE SENSING AND GIS IN SOIL EROSION MODELING

The potential utility of remotely sensed data in the form of aerial photographs and satellite sensors data has been well recognized in mapping and assessing landscape attributes controlling soil erosion, such as physiography, soils, land use/land cover, relief, soil erosion pattern (e.g. Pande *et al.*, 1992). Remote Sensing can facilitate studying the factors enhancing the process, such as soil type, slope gradient, drainage, geology and land cover. Multi-temporal satellite images provide valuable information related to seasonal land use dynamics. Satellite data can be used for studying erosional features, such as gullies, rainfall interception by vegetation and vegetation cover factor. DEM (Digital Elevation Model) one of the vital inputs required for soil erosion modeling can be created by analysis of stereoscopic optical and microwave (SAR) remote sensing data.

Geographic Information System (GIS) has emerged as a powerful tool for handling spatial and non-spatial geo-referenced data for preparation and visualization of input and output, and for interaction with models. There is considerable potential for the use of GIS technology as an aid to the soil erosion inventory with reference to soil erosion modeling and erosion risk assessment.

Erosional soil loss is most frequently assessed by USLE. Spanner et al. (1982) first demonstrated the potential of GIS for erosional soil loss assessment using USLE. Several studies showed the potential utility of RS and GIS techniques for quantitatively assessing erosional soil loss (Saha *et al.*, 1991; Saha and Pande, 1993; Mongkosawat *et al.*, 1994). Satellite data analyzed soil and land cover maps and DEM derived and ancillary soil and agro-climatic rainfall data are the basic inputs used in USLE for computation of soil loss. Kudrat and Saha (1996) showed the feasibility of GIS to estimate actual and potential sediment yields following Sediment Yield Prediction Equation (SYPE) using RS derived soil and land use information, DEM derived slope and ancillary rainfall and temperature data. MMF model was used for quantification of soil loss by water erosion in Doon Valley, Dehra Dun, India, in GIS environment using various satellite remote sensing derived inputs (ASD, 2002).

The availability of GIS tools and more powerful computing facilities makes it possible to overcome difficulties and limitations and to develop distributed continuous time models, based on available regional information. Recent development of deterministic models provides some spatially distributed tools, such as AGNPS (Young *et al.*, 1989); ANSWERS (Beasley *et al.*, 1980), and SWAT (Arnold *et al.*, 1993). The primary layers required for soil erosion modeling are terrain slope gradient and slope length which can be generated by GIS aided processing of DEM. Flanagan *et al.* (2000) generated the necessary topographic inputs for soil erosion and model simulations by linking WEPP model and GIS and utilizing DEM.

CASE EXAMPLES OF SOIL EROSION MODELING BY INTEGRATED USE OF REMOTE SENSING AND GIS

Soil Erosion Inventory in part of Bhogabati Watershed using RS & GIS following USLE

The study area is part of Bhogabati watershed which is located in Kolhapur district of Maharashtra, India. The area is characterized by warm, sub-humid tropical climate and the average annual rainfall is 1215 mm. The methodology adopted in this study for soil erosion modeling is depicted in Figure 5 (ASD, 2001). Soil and Land Use/Land Cover maps were prepared by analysis of IRS-1D : LISS III satellite data. Topographic factor (LS) was derived from DEM generated by GIS analysis. Various USLE factors and model derived erosional soil loss of the watershed are presented in Figure 6.

Regional Soil Erosion Inventory using RS & GIS following MMF model – a case study of Doon Valley

MMF modeling approach was tested for soil erosion inventory in Doon Valley, Dehra Dun district which is a part of northern India. The average annual rainfall ranges between 1600 to 2200 mm. The climate of the area is sub-tropical to temperate. The methodology adopted for this study for soil erosion modeling following MMF model is presented in Figure 7 (ASD, 2002). The various parameters of MMF model and model predicted erosional soil loss of the study area are presented in Figure 8.

CONCLUSIONS

Soil erosion involves complex, heterogeneous hydrological processes and models can only simulate these processes. USLE model is simple to use and conceptually easy to understand, but the greatest criticism of this model has

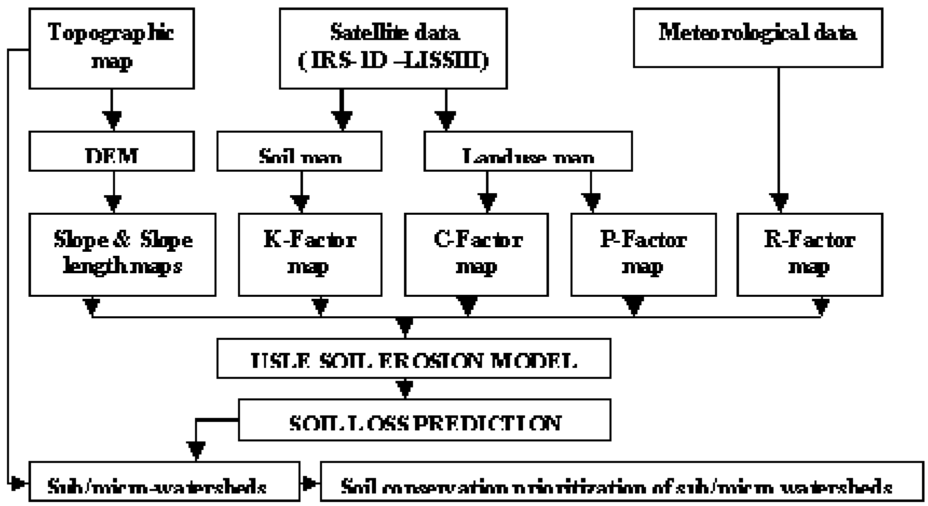

Figure 5: Flow diagram of methodology of soil erosion modeling using USLE

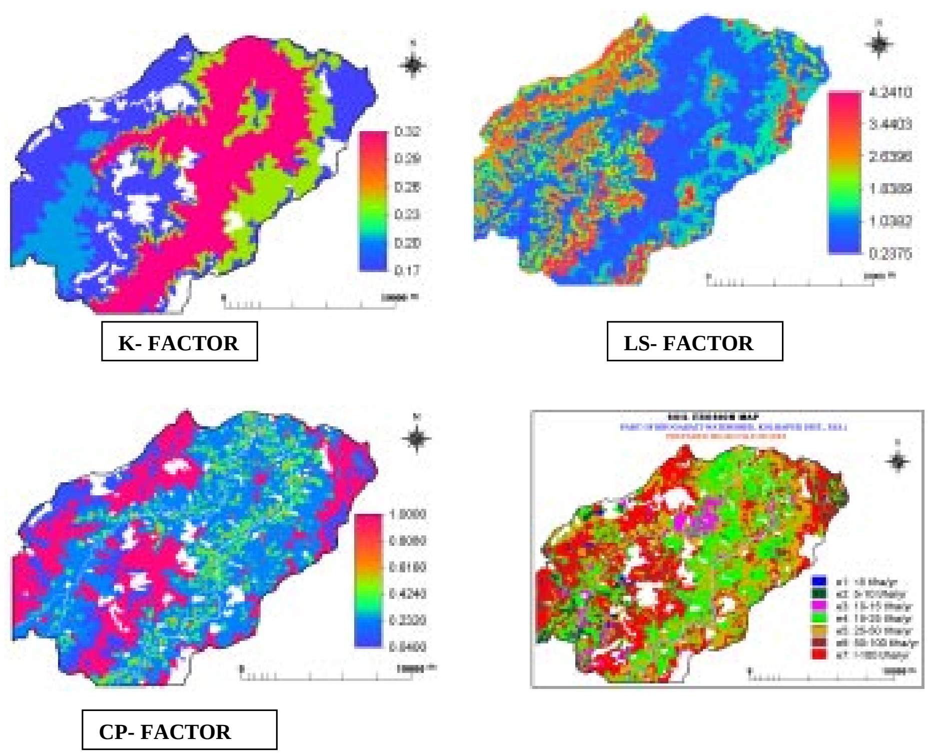

Figure 6: Factors of USLE and model predicted erosional soil loss (Bhogabati Watershed, Kolhapur District, Maharashtra, India)

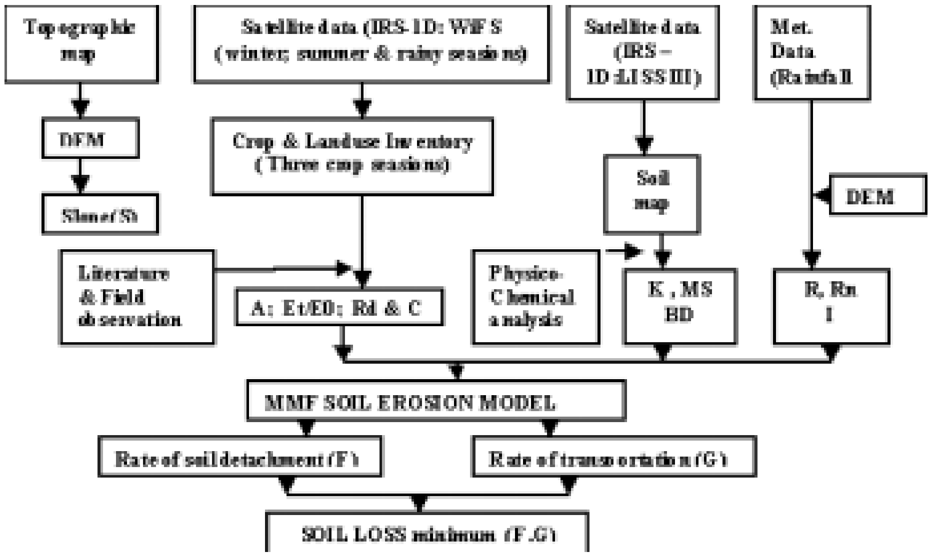

Figure 7: Flow diagram of methodology of soil erosion modeling using MMF model

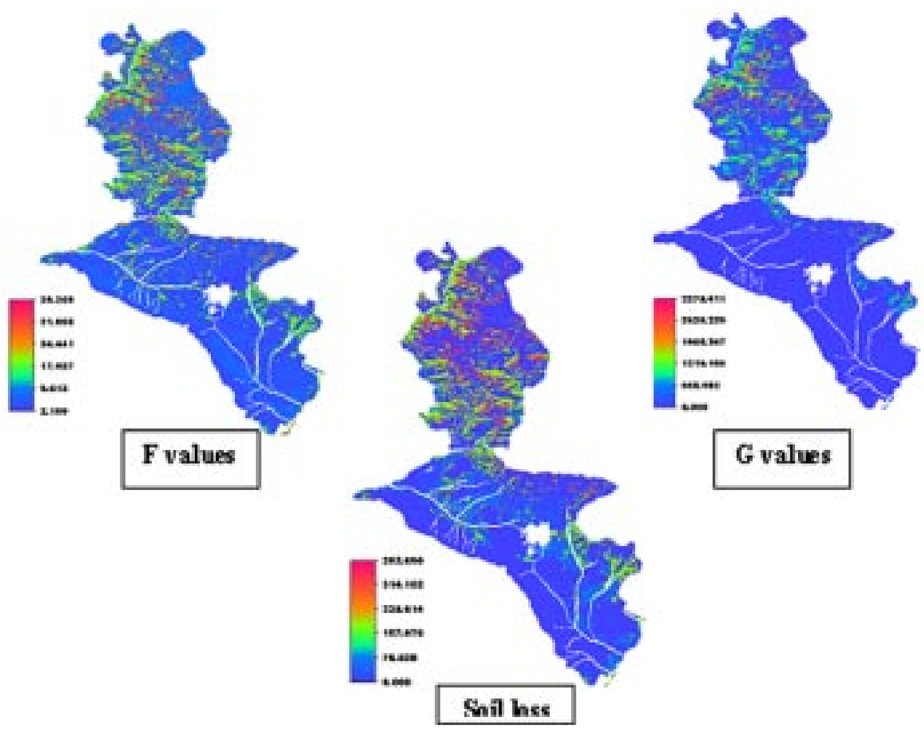

Figure 8: MMF model parameters F & G and model predicted erosional soil loss (Dehra Dun District, Uttaranchal, India)

been its ineffectiveness in applications outside the range of conditions for which it was developed. The process models and physically-based model have an advantage over simple statistical empirical models when individual processes and components that affect erosion are described simply and effectively. The disadvantages of these models are that the mathematical representation of a natural process can only be approximate and there are difficulties in the parameter prediction procedures. RS and GIS techniques are very effective tools for soil erosion modeling and erosion risk assessment.

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