Chapter 13
Satellite-Based Soil Erosion Mapping

Kishor Kumar Sahu, Satyajeet Kar, and Sandeep Rout

Abstract Soil erosion has long been recognised as a significant process of soil destruction, affecting millions of hectares of land worldwide, resulting in loss of fertility and biodiversity, decreased stability of marine and terrestrial ecosystems and enhanced exposure to climate change. In semi-arid zones, the highest rate of deforestation occurred in wooded grassland, bushland and shrubland systems, while the lowest rate occurred in woodland. Satellite remote sensing technology for tracking and modelling soil erosion has exploded in popularity worldwide over the last decade. More precisely, renewed emphasis has been placed on recent advances in remote sensing technologies and the availability of these data at various resolutions, as well as on the critical need for up-to-date knowledge on soil loss levels, soil erosion monitoring and modelling, in particular, to ensure that viable agricultural fields are available to ensure food security. GIS research delivers adequate results when developing erosion surveys and risk maps using GIS data layers such as DEM, slope, aspect and land use. The Revised Universal Soil Loss Equation (RUSLE), the Water Erosion Prediction Project (WEPP) and Environmental Information Coordination are the most widely used scientific erosion prediction models that are combined with remote sensing and GIS (CORINE). Remote sensing techniques and the universal soil loss equation were established as the primary tools for mapping and tracking soil erosion in this chapter. It consists of four components: baseline sheet and rill erosion mapping, real-time rill and gully erosion monitoring, future sheet and rill erosion change forecast and long-term pattern determination.

Keywords Satellite imagery · Remote sensing · Geographic information system · Soil erosion · Erosion mapping

K. K. Sahu
Department of Soil Science and Agricultural Chemistry, CSK HPKV, Palampur, Himachal Pradesh, India

S. Kar
Department of Forestry, JNKVV, Jabalpur, Madhya Pradesh, India

S. Rout (✉)
Faculty of Agriculture, Sri Sri University, Cuttack, Odisha, India

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13.1 Introduction

Soil is a vital natural resource because it performs critical economic, social and environmental roles. The global economy is primarily dependent on the soil as a natural resource for the supply of goods and services (Blum, 2005). However, due to the high demand for soil-generated products, commodities and services, there has been a considerable strain, especially from developing countries heavily reliant on primary sectors such as agriculture and forestry (Wessels et al., 2004).

Soil depletion by runoff is a primary ecological concern that covers 56% of the world's land. The depletion of soil is exacerbated by soil degradation triggered by human activities (Bai et al., 2008). Rill and inter-rill erosions are the recurrent forms of water erosion, including separation, transport and accumulation of soil particles into a new deposition area, deteriorating soil quality and decreasing land productivity (Fernandez et al., 2003). Soil erosion-related problems include loss of productive crop topsoil, sedimentation, infrastructure destruction and biodiversity loss contributing to global change (Morgan, 2005; Nearing et al., 2004; Onyando et al., 2005).

Although geomorphological processes can cause soil erosion, accelerated soil erosion is mainly encouraged by human activities. Accelerated soil erosion has resulted from rapid population growth, deforestation, unsuitable land production and unregulated grazing (Reusing et al., 2000; Tamene et al., 2006; Zemenu & Minale, 2014). Soil loss is often caused by an amalgamation of slope length steepness, climate change, patterns of land cover and soil's intrinsic properties, making the soil particles more vulnerable to erosion.

Owing to the lack of ability to withstand it and also to substitute the nutrients, the economic impact of soil depletion in some countries is more severe (Tamene et al., 2006). These countries have been marked by high population growth, leading to the excessive use of already harassed resources and the expansion of development on marginal and vulnerable lands. Such a mechanism exacerbates deforestation and loss of productivity, resulting in a cycle of population-poverty-land degradation.

Soil erosion is primarily influenced by topographic features, vegetation cover, soil characteristics and climatic factors. Human movements and large-scale schemes change the vegetation cover, thus affecting the rate of soil erosion. Drill and inter-rill erosions are primarily influenced by topographic features such as field slope, slope length and shape. The two critical climatic factors are the amount of precipitation and the intensity of precipitation, which is referred to as rainfall erosivity. Additionally, the temperature is a significant climatic aspect since it influences the vegetative materials used in mulching to manage erosion. Aggregate stability, texture, depth, organic matter and stoniness are primarily affected by soil erodibility.

Assessing the rate of soil erosion is critical for developing effective erosion prevention techniques for sustainable land and water resource management. Geographic Information System (GIS) technologies, through their advanced data storage, analysis, management and display functionality, are valuable resources in creating environmental models. Remote sensing (RS) technology, using digital image processing techniques, has provided land use/cover information. Many types of research on modelling soil erosion using RS and GIS technologies have been performed.

These capabilities of such technologies are enhanced further when paired with empirical erosion prediction models. While soil erosion models estimate soil loss and offer geographic erosion distributions, integrated erosion prediction models using RS and GIS estimate soil loss and offer spatial erosion distributions. As a result, it is critical to create accurate erosion risk maps in GIS to identify areas at high risk of erosion and implement appropriate erosion prevention techniques. Sazbo et al. (1998) successfully used RS and GIS technology to chart land loss and deterioration. Another study conducted by Bojie et al. (1995) showed that when GIS data layers such as DEM, aspect, slope and land use create erosion surveys and risk charts, GIS analysis produces adequate results.

The Revised Universal Soil Loss Equation (RUSLE), the Water Erosion Prediction Project (WEPP) and the Coordination of Information on the Environmental (CORINE) are the most frequently used empirical erosion prediction models combined with RS and GIS for mapping erosion threats. The RUSLE was established based on erosion factors like soil erodibility, topography, rainfall and vegetation cover to estimate the annual soil loss per unit area. Based on a particular erosion variable, sediment yield and erosion rates can be calculated over multiple periods in the WEPP model.

13.2 Assessing Land Degradation

1. Expert opinion: Subjective appraisal based on semi-quantitative definitions (e.g. GLASOD survey).
2. Remote sensing is the ground-based radiometry wherein satellite images and aerial photographs correlate with field measurements.
3. Field observations: This includes stratified soil sampling and analysis and long-term field studies of plants and habitats in particular locations.
4. Productivity changes: Keeping an eye on improvements in crop yields and opinions of landowners.
5. Level field criteria: Studies at the farm level are deemed necessary to ascertain the severity of deterioration and its causes and possible remedial steps.
6. Modelling: Modelling is used to estimate the danger of deterioration based on data collected from other approaches (GIS-based models), thus expanding the spectrum of applicability of observed degradation effects.
7. None of these is a singular methodology, and their synergistic applications are widespread.

13.2.1 Land Degradation Mapping and Modelling

Satellite imagery and aerial photography are highly recommended for the following purposes:

13.2.2 Assessing the spatio-temporal distribution of features associated with land degradation

13.2.3 Collecting input data for process simulation models that create maps of ground cover, plant cover and bare soil.

13.2.4 Spatio-Temporal Distribution Assessment

Surveying: To determine the land's present condition in terms of continuing erosion processes.

Identifying the spatial diversity and status of the:

- Vegetation in its natural state (structure and coverage)
- Crops used in agriculture (crop performance)
- Floor of the soil (crusting or sealing)
- Existence of soil erosion surface characteristics (rills and gullies)

Monitoring changes over time:

- Crop canopy development throughout a growing season (an indicator of erosion)
- An area's long-term growth of rill and gully formation

13.2.5 Detection and Quantification of Indicators

Numerous methods can be used to identify indicators, including:

- Field measurements
- Laboratory research
- Data gathered by remote sensing
- A combination of the above

13.2.6 Modelling Input Data

Variables that influence the process include the following:

- Interception of rainfall.
- Storage of water canopy.
- Agricultural land use changes during the growing season are deduced from airborne or satellite-borne photographs and used in process simulation models.

13.3 Soil Erosion Modelling Techniques

13.3.1 Estimation of Soil Loss

Erosion management is essential for preserving soil fertility and enhancing or sustaining the quality of water downstream. Reducing soil erosion to tolerable limits requires sufficiently designed cropping practices and soil conservation initiatives. To calculate soil loss from various land units, many methods exist, including measuring every landform and land use from drainage plots of different sizes, small unit source watersheds and sizeable mixed land use watersheds. Nevertheless, analytical and process-dependent models (equations) are used to predict soil erosion. The Universal Soil Loss Equation (USLE) is empirical. As a feature of most of the significant factors influencing sheet and rill erosion, it estimates the average annual mass of soil loss per unit area. It is considerably more challenging to evaluate soil loss than to assess runoff since several natural factors, such as soil and precipitation and human-made factors, embrace management practices. The loss of soil dramatically depends on the form of erosion.

Significant and valuable sediment yield estimates can be obtained from models for specific purposes. The best example is the Universal Soil Loss Equation (USLE) calculation of long-term average annual soil loss from a catchment.

13.3.2 Erosivity and Erodibility

Degradation of the soil is demonstrated by a drop in fertility status, a decline in the number of nutrients or physical depletion of the topsoil. The latter state is more prevalent in areas prone to soil erosion. During periods of heavy runoff, a large amount of mud, rock waste and organic matter are transferred downslope to rivers and eventually to the oceans. Soil erosion management can be accomplished by considering the susceptibility of soils and other factors. In general, the amount of erosion yield is dependent on the rain's ability to remove soil particles (rainfall erosivity) and, concurrently, on the soil's resistance to rainfall (soil erosivity). Thus, both erosivity and erodibility are essential features of soil erosion that occur when rainfall erosivity exceeds soil erodibility.

13.3.3 Erosivity of Rainfall

The word 'rainfall erosivity' refers to the soil's proclivity to be washed away from disturbed and de-vegetated regions into surface waters during storms. It is determined by the physical characteristics of precipitation, which include the size of raindrops, their propagation, their kinetic energy and their terminal velocity, among others. For a specific soil condition, the tendency of two storms to induce soil erosion may be quantitatively compared. The capacity of overland runoff flow to erode soil is determined in part by rainfall and in part by the soil's surface. The increased erosivity of the overland water flow in the presence of rain indicates a more remarkable erosive ability. Soil erosion occurs when the intensity and length of a downpour exceed the ability of the soil to absorb the rainwater. Erosion is influenced by various conditions, including the state of the soil, the slope and the amount of energy or precipitation force expected during the duration of surface disturbance.

13.4 Factors Affecting the Erosivity of Rainfall

The following variables influence the erosivity of rainstorms:

13.4.1 Intensity of Rainfall

Rainfall strength is a term that refers to the amount at which rain falls on the ground surface. It is a significant factor in the erosive aspect of rainfall. Rainfall strength is described as the force exerted by a single water droplet as it reaches the soil surface. Wischmeier and Smith (1958) suggested the following equation to equate kinetic energy to rainfall intensity:

$$\mathrm{KE} = 210.3 + 89 \log_{10} I$$

Where:

KE = Kinetic energy of the rainfall

I = Intensity of the rainfall

13.4.2 Distribution of Drop Sizes

The drop size distribution within a rainstorm has a combined effect on the rain's energy, velocity and erosivity. Increases in the median drop size result in a rise in the rainfall level. The following equation illustrates the relationship between the rainfall strength and the median drop size (D50) (Laws & Parsons, 1943):

$$D_{50} = 2.23 I^{0.182}$$

Where:
D_{50} = Median drop size in inches
I = Intensity of the rainfall (inch/h)

13.4.3 Terminal Velocity

The effect of falling raindrops' terminal velocity (a function of the drop size) is quantified in terms of their kinetic energy upon contact with the soil surface. A rainstorm with a high proportion of larger raindrops would have a higher terminal velocity and vice versa. The relationship between the kinetic energy and terminal velocity of a rainstorm is as follows:

$$E_{\mathrm{k}} = \frac{IV^2}{2}$$

Where:
E_{k} = Energy of rainfall
I = Intensity of the rainfall
V = Terminal velocity of the rainfall before impact

Ellison (1947a) developed the following empirical connection between terminal velocity, drop diameter and rainfall intensity in order to determine the volume of soil removed by rainfall:

$$E = KV^{4.33} d^{1.07} I^{0.65}$$

Where:
E = Relative amount of soil detached
K = A constant (depends upon the characteristics of the soil)
V = Velocity of the raindrops
d = Diameter of the raindrops
I = Intensity of the rainfall

13.4.4 Wind Speed

Wind speed impacts the ability of runoff to detach soil by affecting the kinetic energy of a rainstorm. As tropical areas are often subjected to windy storms, they are more potent at dislodging aggregates than predicted.

13.4.5 Slope Direction

The slope of the soil also has a significant impact on the erosivity of rainfall. Gradients in the path of the rainstorm have the effect of altering the raindrop's natural kinetic energy. It increases the raindrop's impact force as the velocity factor in the slope direction increases.

13.5 Erosivity Estimation Using Rainfall Data

The erosivity of rainfall is proportional to its kinetic energy, and the following two techniques are commonly used to determine the erosivity of rains:

1. EI_{30} Index method
2. KE > 25 Index method

13.5.1 EI_{30} Index Method

Wischmeier and Smith (1965) developed this technique because the result of the storm's kinetic energy and the maximum rainfall intensity of 30 minutes give the best estimate of soil loss. The highest average intensity encountered in any 30 minutes during the storm is determined by finding the maximum amount of rain that falls in the 30 minutes and later translating the same to intensity in mm/hour from tracking rain gauge maps. This erosivity measure is the EI_{30} index and can be measured for individual storms and weekly, monthly or annual erosivity values.

The value of the precipitation erosivity factor EI_{30} is determined as follows:

$$\mathrm{EI}_{30} = \mathrm{KE} \times I_{30}$$

Where:

KE = Kinetic energy of the rainfall

I_{30} *= Maximum intensity of the rainfall for 30 minutes*

Kinetic energy for the storm is computed from equation

$$\mathrm{KE} = 210.3 + 89\log_{10} I$$

Limitation

The EI_{30} index system was developed in the United States and has been considered unsuitable for estimating erosivity in tropical and subtropical areas.

13.5.2 KE > 25 Index Method

This is a new approach proposed by Hudson for calculating the erosivity of tropical storms' rainfall. This approach is based on the premise that erosion happens only when the rainfall level reaches a specific threshold value. Studies determined that rainfall intensities less than 25 mm/h cannot result in substantial soil erosion. As a result, this approach only considers rainfall intensities more significant than 25 mm/h. That is why the process is referred to as the KE > 25 index method. It is used in the same way as the EI_{30} index and has a related measurement technique.

13.6 Procedure for Calculation

Both techniques use the same calculation practice. However, the KE > 25 approach is more beneficial since it eliminates several data points with a value less than 25 mm/h, resulting in fewer rainfall data. Both methods include data on rainfall volume and severity.

The method entails multiplying rainfall quantities by the measured kinetic energy values for each strength class. Then, all of these values are taken together to obtain the storm's overall kinetic energy. The resulting KE value is then multiplied by the actual 30-minute rainfall rate to derive the rainfall erosivity value.

13.6.1 Erodibility of the Soil

Soil erodibility is a measure of a soil's resistance to erosion depending on its physical characteristics. By and large, soils with increased penetration rates, higher organic matter levels and improved soil composition withstand erosion better. Sandy loam and soils with a loam texture are less erodible than fine sand, silt and certain clay-textured soils. A soil's erodibility can be quantitatively compared to that of other soils under a given rainfall environment. Bouyoucos (1935) proposed that soil erodibility is proportional to the mechanical composition of the soil, which includes silt, clay and sand:

$$E = \frac{\%\text{sand} + \%\text{silt}}{\%\text{clay}}$$

Where:

E = Erodibility of soil

The range of particle diameter of silt, clay and sand is

Clay = < 0.002 mm
Silt = 0.002–0.006 mm
Sand = 0.06–2.0 mm

Tillage and cropping activities that deplete soil organic matter contribute to low soil composition, soil compactness and erodibility. Compacted subsurface soil layers can have the effect of reducing penetration and increasing runoff. Additionally, forming a soil crust that appears to 'seal' the surface may result in a decrease in infiltration. A soil crust may reduce soil loss in specific locations due to sheet or rain splash erosion, but a rise in runoff water may exacerbate rill erosion problems.

There may be three different soil types with varying degrees of disturbance severity, for example:

- Low
- Moderate
- High

Stocking rates or the responses of three different soils, for example, are as follows:

- A clay
- A loam
- A sand

13.6.2 Determination of Erodibility

The term 'erodibility' refers to the soil's resistance to detachment and transport. It varies according to the aggregate stability, infiltration capability, soil texture, shear strength, infiltration performance and organic and chemical content. The soil erodibility element 'K' is used to describe the soil's erodibility. There are numerous methods for determining K, and three of the most common are discussed below.

13.6.2.1 In Situ Erosion Plots

Erosion plots allow for the determination of 'K' under field conditions. They use a normal state of bare soil with no maintenance practices and a 7° slope along the length of the plots, which is 22.13 metres. This is an expensive and time-consuming process.

13.6.2.2 Measuring K Under a Simulated Rainstorm

This technique is less time-consuming but reasonably expensive. The primary downside is that all the properties of natural rain cannot be recreated by any of the rainfall simulators designed to date. Nevertheless, in erosion research, this approach is more commonly used.

13.6.2.3 Predicting K

K can be predicted by using regression equations that describe the relationship between K and the physico-chemical properties of the soil. Wischmeier et al. (1971) developed a nomograph to express the relationship between K and soil properties. It is based on the following equation:

$$100\mathrm{K} = 2.1\times 10^{4}\times\left(2-OM\right)\times m^{1.14}+3.25\times\left(St-2\right)+2.5\times\left(Pt-3\right)$$

Where:

OM = Organic matter content

m = Silt plus fine sand

St = Soil structure code (1 for very fine granular, 2 for fine granular, 3 for coarse granular, 4 for massive, blocky or platy)

Pt = Permeability class (1 for rapid, 2 for moderate to rapid, 3 for moderate, 4 for slow to moderate, 5 for slow, 6 for very slow).

K is predicted using the monograph devised by Wischmeier et al. (1971).

13.7 Correlation of Soil Erosion and Rainfall Energy

It is widely established that the volume of soil removed by a particular depth of rainfall is related to the pace at which it occurs. Numerous tests and various measurements of raindrop fall velocity (Ellison, 1947b) demonstrate that soil splash rate is a function of rainfall intensity:

$$S \infty V^{4.3}.D^{1.07}.I^{0.65}$$

Where:

S = Quantity of soil splashed in 30-minute duration

V = Velocity of a raindrop

D = Diameter of the raindrops

I = Intensity of rainfall

Raindrop diameters can be found in storms with different intensities within each area, resulting in regressions such as the energy of a storm being equal to the energy of each segment of rain falling at a given intensity compounded by the number of millimetres falling at this Intensity (Bisal, 1960).

The expression is given by

$$G = K.D.V^{1.4}$$

Where:

G = Weight of the soil splashed

D = Diameter of the raindrops

V = Impact velocity

K = A constant depending on the soil type

Mihara (1959) claimed that splash erosion is directly proportional to the kinetic energy of raindrops based on their mass and velocity. He established the following relationship between two distinct soil types:

For sandy soil, splash erosion ∞ K.E.0.9

For clay soil, splash erosion ∞ K.E.1.46

13.8 The Universal Soil Loss Equation (USLE)

In 1940, the United States began developing equations for estimating soil erosion. Zingg (1940) proposed that soil loss and slope length had a power-raised relationship. Later in 1947, a committee headed by Musgrave proposed a soil loss equation that bore some resemblance to the current USLE. Wischmeier and Smith (1965) developed the universal soil loss equation using data from runoff plots; the equation was later modified using more recent data from runoff plots, rainfall simulators and field observations. Controlling erosion is the most often used method for measuring soil depletion from rural watersheds. The USLE is an erosion prediction model that allows for the measurement of long-term soil erosion averages from sheet and rill erosion on a given land surface under specified conditions (Wischmeier & Smith, 1978).

It estimates the long-term average annual loss of soil from arable land segments under different cropping conditions. This estimate aims to encourage farmers and soil conservation advisors to choose combinations of land use, cropping and soil conservation practices to keep soil loss to an appropriate level. The equation (USLE) is as follows:

$$A = R \times K \times L \times S \times C \times P$$

Where:

A = Soil erosion per unit area per unit time
R = Rainfall erosivity index
K = Soil erodibility index
L = Slope length
S = Slope steepness
C = Cover management factor
P=Supporting practice factor

13.9 Parameters of Universal Soil Loss Equation

13.9.1 The Factor of Rainfall (R)

To account for the erosive force of rainfall, the volume and strength of rain over a year (erosivity index unit) are associated with the erosivity component. The word 'erosivity of runoff' refers to the ability of storms to wash the soil from disturbed and de-vegetated areas onto surface waters. Erosion is influenced by various conditions, including the state of the soil, the slope and the amount of energy or precipitation force expected during the duration of surface disturbance.

13.9.2 Factor of Soil Erodibility (K)

Soil erodibility factor is a unit of erosion index defined as the soil loss from a plot 22.1 m in length on a 9% slope under a continuous bare cultivated fallow. It varies by less than 0.1 for the least erodible soils and almost 1.0 for the most erodible soils.

13.9.3 The Factor of Topography (LS)

LS denotes the slope length-gradient factor. The topographic factor is used to calculate the slope's length and steepness. The longer the slope, the larger the amount of surface runoff; the steeper the slope, the greater the velocity of surface runoff.

13.9.4 The Factor of Crop Management (C)

C is the crop/vegetation management part and is the ratio of soil loss caused by a specific crop management strategy to the equal loss caused by continuous fallow and tilled soil. It is used to determine the relative effectiveness of soil and crop control schemes in preventing soil degradation. The C factor can be determined by choosing the crop type and tillage method.

13.9.5 The Factor of Support Practices (P)

P denotes the help practice aspect, representing the results of various activities that minimise the volume and rate of runoff, thus reducing erosion. The P factor quantifies the soil depletion caused by a support practice compared to straight row farming up and down the hill. Cross slope planting, contour forestry and strip cropping are the most often used supportive cropland activities. P should be zero in an environment with absolute support practices, suggesting no sediment loss. P should be 1.0 in an area with no support practices, indicating the highest potential sediment loss.

13.10 USLE Parameter Estimation

13.10.1 Rainfall Erosivity Factor (R)

It references the rainfall erosion index, which quantifies rainfall's tendency to erode soil particles in an exposed area. The amount of soil loss from a barren field has been determined to be directly proportional to the product of two rainfall characteristics: the storm's kinetic energy and its 30-minute maximum intensity. The outcome of these two characteristics is termed EI or EI_{30} or rainfall erosivity. It is equal to the amount of rainfall erosion index units (EI_{30}) that fell on the study site during a given time. A storm's rainfall erosion index unit (EI_{30}) is calculated as follows:

$$\mathrm{EI}_{30} = \frac{\mathrm{KE} \times I_{30}}{100}$$

Where:

KE = Kinetic energy of the rainfall

I = Intensity of the rainfall

$$\mathrm{KE} = 210.3 + 89 \log_{10} I$$

The duration of the research maybe a week, a month, a season or an entire year. Annual EI_{30} values are typically computed using data from various meteorological stations, and lines linking equivalent EI_{30} values (referred to as iso-erodent lines) are drawn for the area covered by the data stations to facilitate their use in USLE.

13.10.2 Soil Erodibility Factor (K)

The element of soil erodibility (K) in the USLE refers to the rate at which various soils erode. Due to inherent soil characteristics, some soils can erode more quickly than others under conditions of an equal slope, precipitation, vegetative cover and soil management practices. On unit runoff plots, the direct calculation of 'K' reflects the cumulative effects of all variables that substantially affect the ease with which soil is eroded or the primary slope other than 9% slope. Soil permeability, infiltration rate, soil texture, size and stability of the soil structure, organic content and soil depth are soil properties that primarily affect soil loss. These are typically calculated by unique experimental runoff plots or by using empirical erodibility equations related to factor 'K' with several soil properties. The soil erodibility factor (K) is expressed as tonnes of soil loss per hectare per unit of rainfall erosivity index, with a slope of 9% and a field length of 22 m (in some instances, 22.13 m). The soil erodibility factor (K) is calculated by taking into account, without the effect of crop cover or management, the soil loss from continuous cultivated fallow lands.

The formula used for estimating K is as follows:

$$K = \frac{AO}{S \times \left(\sum \mathrm{EI}\right)}$$

Where:

K = Soil erodibility factor
AO = Observed soil loss
S = Slope factor
ΣEI = Total rainfall erosivity index

13.10.3 Topographic Factor (LS)

The slope length factor (L) is the ratio of soil loss under identical conditions from the field slope length under consideration to 22.13 m length plots. The size of the slope has a direct relationship with the loss of the soil, i.e. it is roughly equal to the square root of the length of the slope for soils on which the size of the slope does not affect the runoff rate (Zingg, 1940).

The gradient of the land slope factor is defined as the soil loss ratio from the field slope gradient to that from the 9% slope under otherwise identical conditions (S).

Since runoff velocity increases as field slope increases, causing more soil to be detached and carried along with the surface flow, increased slope steepness results in increased soil erosion.

Typically, the two variables L and S are merged into a single topographic component called LS. This factor is defined as the ratio of soil loss from a field with a specified steepness and slope length (i.e. 9% slope and 22.13 m length) to soil loss from the continuous fallow property. The value of LS can be determined using the formula given by Wischmeier and Smith (1962):

$$LS = \frac{\sqrt{L}}{100}\left(0.76 + 0.53S + 0.076S^2\right)$$

Where:

L = Length of field slope

S = Percent slope of the land

Wischmeier and Smith (1978) again derived the following equation for *LS* factor in MKS system, based on the observations from cropped land on slopes ranging from 3 to 18% and length from 10 to 100 m. The derived updated equation is

$$LS = \left(\frac{\lambda}{22.13}\right)^m \left[65.41\sin^2\theta + 4.56\sin\theta + 0.065\right]$$

Where:

Λ = Length of field slope

θ = Angle of slope

M = Exponent varying from 0.2 to 0.5

13.10.4 Crop Management Factor (C)

Factor C, crop management, can be described as the estimated soil loss ratio from cultivated versus fallow land. The surface form, slope and precipitation regimes are all the same. According to crops and cropping practices, soil erosion is influenced in many ways, such as the type of crop, cover quality, root growth, water use by plants, etc. The difference in rainfall distribution during the year also affects crop management, which involves the loss of soil. Given all these variables, the effectiveness of each crop and cropping practice in erosion control is assessed based on five suggested crop stages implemented by Wischmeier (1960):

- Period F (rough fallow): This period encompasses summer ploughing and seedbed planning.
- Phase 1 (seed bed): This corresponds to the period beginning with seeding and ending 1 month later.
- Period 2 (establishment): This phase lasts between 1 and 2 months after seeding.

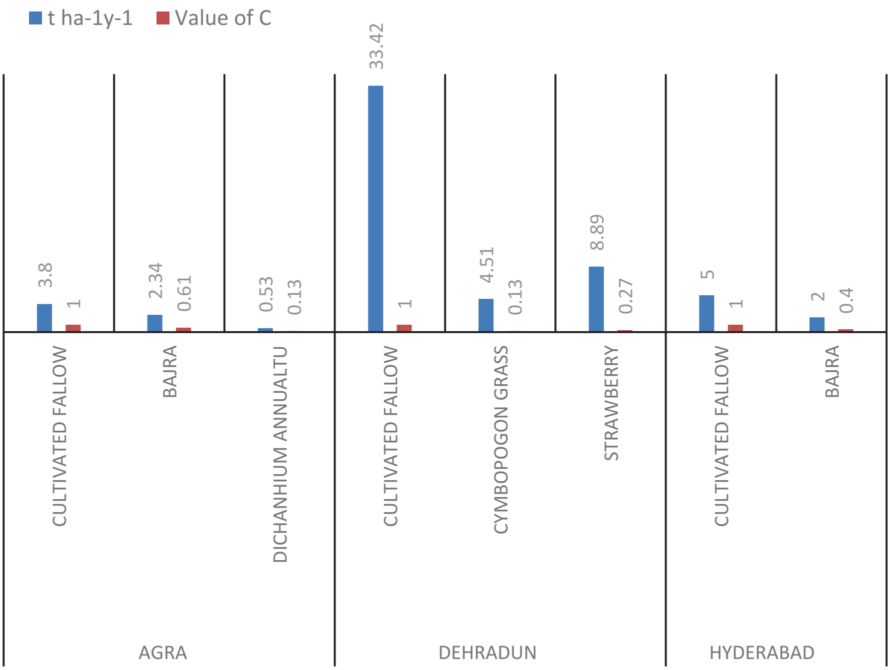

Fig. 13.1 Values of crop management factors for different stations in India. (Source: Modified from K Subramanya, 2008)

- Phase 3 (growth period): It begins with period two and ends with crop harvesting.
- Stage 4 (residue or stubble): This period encompasses everything from grain processing to summer ploughing or seedbed preparation.

The soil loss data for the above stages are collected from the runoff plot for determining the crop management factor. C is computed as the ratio of soil loss from cropped plot to the corresponding soil loss from a continuous fallow land for each of the above five crop stages separately, for a particular crop, considering various combinations of crop sequence and their productivity levels. This factor reflects the combined effect of different crop management practices. Values of factor C for some selected stations of India are shown in Fig. 13.1.

13.10.5 Support Practice Factor (P)

This element is the ratio of soil erosion caused by a support practice and straight row farming up and down the hill. Contouring, terracing and strip cropping are the primary management practices. The amount of soil lost varies according to the techniques used. The table shows the factor P for various types of support activities in different parts of India (Fig. 13.2).

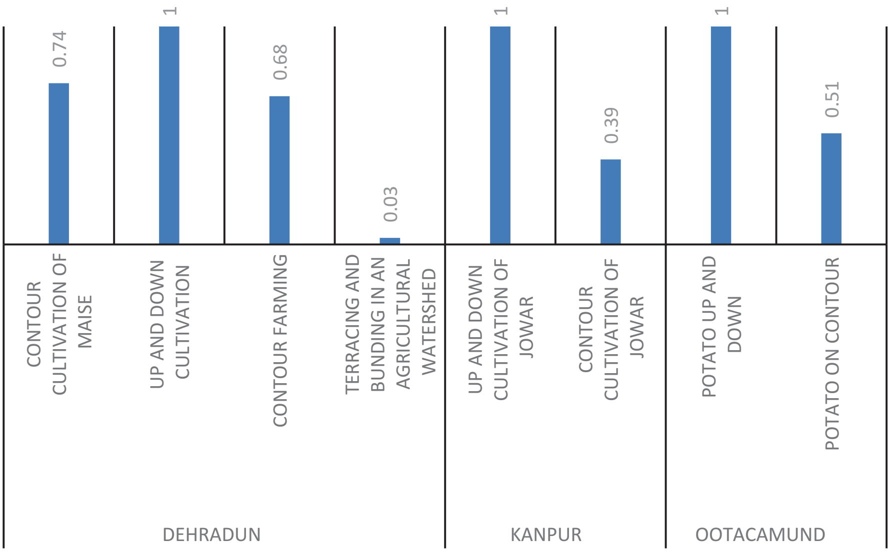

Fig. 13.2 Different values of support practice factor (P) for some Indian locations. (Source: Modified from K. Subramanya, 2008)

13.11 Applications of Universal Soil Loss Equation

USLE is an erosion prediction model, and its effectiveness is contingent upon its ability to forecast its multiple variables accurately. It is focused on a sizable experimental database relating to a variety of factors affecting USLE. The universal soil depletion equation has three critical applications:

- It forecasts land loss.
- It aids in the detection and selection of agricultural practices.
- It makes crop management recommendations.

13.12 Limitations of Universal Soil Loss Equation

The equation involves the procedure for assigning the values of different associated factors based on the practical concept. Therefore, there is a possibility to introduce some errors in selecting the appropriate values, particularly those based on the crop concept. Typically R and K factors are constant for most of the sites/regions in the catchment, whereas C and LS vary substantially with the erosion-controlled measures used.

The following are some of the limitations of the USLE:

1. *Empirical*

The USLE is an abstract equation that does not mathematically reflect the actual mechanism of soil erosion. By using observational coefficients, the probability of including predictive errors in the equation is eliminated.

2. *Prediction of Annual Soil Loss on an Average Basis*

Since this equation was constructed primarily using average annual soil loss data, its applicability is restricted to estimating the average annual soil loss for a given region. This equation produces less than the calculated value, mainly when the rainfall is intense. For each heavy flood, the storage basin whose sediment area was computed using USLE should be examined to ensure that the sedimentation amount in the storage basin remains within acceptable limits.

3. *Gully Erosion Is Not Calculated*

This equation is used to determine the extent of sheet and rill erosion but cannot forecast gully erosion. The calculation does not account for gully erosion caused by concentrated water flow, although it increases soil erosion.

4. *Non-computation of Sediment Deposition*

Only soil depletion, but not soil deposition, is calculated in the equation. Sediment accumulation at the bottom of the river is smaller than the overall loss of soil from the watershed as a whole. Nevertheless, the USLE can quantify the amount of sediment storage needed for sediment retention structures. The USLE equation can also be used as a conservative measure of potential storage needs for sediment, mainly where sediment basins usually range from 2 to 40 ha and runoff has not travelled further. The basin is intended to serve as the settlement area. Again, if the drainage is poorly managed on any site and gully erosion is in extensive form, this equation underestimates the retention structure's sediment storage requirement.

13.13 Revised Universal Soil Loss Equation (RUSLE)

Over the last few decades, a cooperative effort between scientists and users to update the USLE has resulted in the development of RUSLE. The modifications incorporated in USLE to result in the RUSLE are mentioned as under (Kenneth et al., 1991):

- Automating the equations to aid in the computations.
- A new definition for rainfall-runoff erosivity (R) in the Western United States, based on the data from over 1200 gauge locations.
- Specific revisions and additions have been made for the Eastern United States, including adjustments for regions with elevated R factors and flat slopes to account for splash erosion caused by raindrops landing on ponded water.

- The establishment of a seasonally variable definition for soil erodibility (K).
- A novel method for measuring the cover management term (C) using sub-factors for accounting for previous land usage, crop canopy, soil cover and surface roughness.
- New slope length and steepness (LS) algorithms that take into account the ratio of rill to inter-rill erosion.
- Capacity for calculating LS products for slopes with a variety of shapes.
- Rangeland restoration techniques, strip crop rotations, contour factor values and subsurface irrigation are all new conservation practices (P).

13.14 Modified Universal Soil Loss Equation (MUSLE)

Williams updated the USLE in 1975 to create the MUSLE by substituting a 'runoff factor' for the rainfall energy factor (R). The MUSLE is denoted by

$$Y = 11.8\left(Q \times q_{\mathrm{p}}\right)^{0.56} K\left(LS\right)CP$$

Where:

Y = Yield of sediment from an individual storm

Q = Volume of storm runoff

q_p = Peak rate of runoff

K,L,S,C,P = Different factors of universal soil loss equation

Appropriate runoff models can be used to determine Q and q_{p} values. Q is taken to reflect the detachment phase in this model, while q_{p} represents sediment transport. A sediment yield model does not require calculating the sediment delivery ratio separately, and it applies to individual storms. Additionally, it improves the precision of sediment yield estimation. From a modelling perspective, it benefits from the simulation of a watershed's constant, weekly and annual sediment yields by integrating suitable hydrological models with MUSLE.

13.15 Spatial Erosion Assessment

Three distinct methods exist for assessing the spatial extent of soil erosion:

- The first step is to determine soil erosion rates at different locations using measurement instruments or erosion plots (Hudson, 1993; Loughran, 1989). However, accurate measurements are typically expensive and time-consuming, essential equipment is scarce (Stroosnijder, 2005) and measuring results can be highly unpredictable even under comparable circumstances (Nearing et al., 1999). Field measurements are often used to determine the role of a specific erosion element, the development of models and their validity, but not for erosion spatial assessment.

- The second solution is to conduct erosion field surveys through which erosion-related characteristics such as pedestals or rills are identified (Herweg, 1996). Although quantitative data can be collected by continuously calculating the dimensions of a feature, most surveys are conducted qualitatively, with the volume of erosion classified according to the characteristics encountered. Due to management practices such as ploughing, survey timing is critical, as some features can be undetectable during the year. Surveys can map spatial erosion in small catchments of around 2 km^2 (Vigiak et al., 2005), but this becomes more complex in more expansive areas. However, systematic visual recognition of specific characteristics from aerial photos is another form of erosion survey that could be conducted for wider regions up to 50 km^2 (Bergsma, 1974).
- Integrating spatial data on erosion causes is the third and the most often used method for assessing spatial erosion. While the Universal Soil Loss Equation (Wischmeier & Smith, 1978) is frequently used, numerous other erosion models exist that allow spatial mapping of erosion (Merritt et al., 2003).

However, erosion models are designed for a specific area and size, and moving them to other scales or regions is not straightforward and may result in suboptimal or incorrect results (Brazier et al., 2000; Jetten et al., 2003; Kirkby et al., 1996; Schoorl et al., 2000). Additionally, specific erosion models include extensive data on a wide range of rainfall, soil, vegetation and slope parameters. These statistics are often unavailable or only accessible at very coarse scales in data-scarce areas such as developed countries. Qualitative data integration techniques that allow flexible selection and a combination of erosion factors can be an excellent complement to erosion models. The choice of erosion variables will be region-specific, based on the existing processes and the main parameters that account for the region's heterogeneity in these processes. Local or specialist expertise can contribute significantly to developing such qualitative approaches (De la Rosa et al., 1999; Sonneveld, 2003). The outcomes of these approaches are typically a numerical assessment of erosion risk, which is the relative likelihood of erosion occurring at a particular location compared to other sites in the mapped area.

13.16 Mapping Erosion From Space

Satellite remote sensing can provide essential input to erosion assessments at different spatial scales through various space-borne sensors currently orbiting the earth. Satellite data can aid in the rapid mapping of erosion over large areas, especially for data-poor regions. At the same time, otherwise, this could only be achieved through costly and time-consuming survey methods.

Several types of satellite images and image-derived items are available to the general public obtained from earth-observing space missions. While certain kinds of images are still costly, much data is inexpensive or free of charge, making it easier for a broader audience to use it. Therefore, satellite imagery is increasingly being used for studies of regional erosion. This can be achieved by identifying erosion characteristics and eroded areas or measuring erosion factors such as the cover or slope of vegetation.

In some instances, degraded areas, larger than 1 ha, can be distinguished from their habitat due to reduced plant cover (Pickup & Nelson, 1984), altered soil properties (Hill et al., 1995) or natural changes in the earth's surface (Lee & Liu, 2001). However, successful use of satellite remote sensing to detect degraded areas is typically limited to (semi-)arid natural and rangeland landscapes, as well as areas of extensive gully erosion (badlands). In more tropical environments, vegetation cover often obscures the visibility of the earth, and farming practices may have a direct effect on vegetation cover, soil resources and surface roughness. As a result, these variables cannot be directly linked to soil degradation in wet and agricultural fields. Along with eroded areas, satellite imaging may reveal individual erosion features such as gullies and large rills. This is partly due to distinct characteristics such as proximity to the subsoil and reduced vegetation cover but even more fundamentally due to the rills and gullies' basic spatial structure. The spatial resolution of the imagery, on the other hand, should correspond to the scale of the elements. Visual interpretation has been a widely used technique for distinguishing individual gullies from aerial photos (Martínez-Casasnovas, 2003; Nachtergaele & Poesen, 1999) and satellite imagery (Bocco & Valenzuela, 1993). Although some scholars questioned the viability of this exercise due to the spectral heterogeneity of gullies and their atmosphere, automatic gully retrieval from satellite images provides fast insight into the magnitude of gully erosion and the resulting lack of productive land for vast areas (King et al., 2005; Zinck et al., 2001).

Satellite imagery may obtain information on a range of erosion factors. Significant climate parameters for erosion studies are the volume and intensity of rainfall, measured on coarse scales, e.g. Tropical Rainfall Measuring Mission (TRMM) spaceborne data. Digital elevation models (DEMs) that can be obtained from stereo images (Toutin, 2001) or specialised techniques such as radar interferometry (Toutin & Gray, 2000) typically determine terrain attributes such as slope. Satellite data can be used to determine the spatial distribution of different soil properties, but this is mainly limited to arid or semi-arid regions due to the alarming effect of vegetation (Huete, 2004). Satellite data for the classification of land use or the extraction of continuous measurements of vegetation abundance and structure can be applied to determine vegetation cover (Hall et al., 1995). Erosion factors are not static, but over time they shift. Rainfall and vegetation are the most complex variables, while soil properties can also be altered due to, for example, tillage or crusting on short time scales. One way or another, the temporal variability of erosion variables needs to be accounted for satellite-based erosion evaluations. One alternative is to measure the variables using multi-temporal satellite imagery at various moments of the year (e.g. De Jong et al., 1999). A second choice is to decide that a mono-temporal satellite image reflects the conditions of the factor being analysed when the most significant risk of erosion is analysed. Image timing may be essential to obtain precise spatial erosion patterns, although rationales for image selection are often not established in erosion studies.

13.17 Satellites and Sensors Applied in Erosion Research

Numerous earth observation satellites orbit our earth, providing periodic images of the surface. Many of them can provide valuable information for measuring erosion, but they have been used for this purpose less often. Sensors are classified into those that measure sunlight reflections in the visible and infrared portions of the electromagnetic spectrum, thermal infrared radiance (optical systems) and those that continuously relay microwave signals and monitor the received signal (microwave systems).

In most cases, optical satellite systems have been used in erosion studies. These sensors operate in the visible and near-infrared (VNIR) range of 0.4–1.3 Am, the shortwave infrared (SWIR) range of 1.3–3.0 Am and the thermal infrared (TIR) range of 3.0–15.0 Am.

13.18 Detection of Erosion

Satellite data may be used to track erosion either directly or indirectly by the detection of erosion effects. Direct detection has been accomplished by identifying significant erosion features, the discrimination of eroded zones and the estimation of erosion rate using observational relationships. Detectable consequences include disruption caused by important erosion events and reservoir sedimentation.

13.19 Geographic Information Systems (GIS) and Simulation of Soil Erosion

Ultimately, the effectiveness of every soil erosion model is contingent upon its integration with GIS. SOMs have been implemented at the field scale as a cost-effective method for organising and managing soil protection. However, their implementation at the watershed scale has been constrained until recently by the difficulties of handling and controlling a vast amount of data and model parameters at such a spatial scale. The implementation of robust spatial hydrological tools within GIS, as well as the integration of various lumped parameter models (LPMs) and distributed parameter models (DPMs) with GIS, has allowed modellers to resolve these constraints and expand model capabilities to the watershed scale (Tim & Jolly, 1994). The ability to produce topographic parameters from digital elevation models (DEMs) enables the modelling of three-dimensional erosion in areas with complex topography (Desmet & Govers, 1995). Coupling GIS and soil erosion models has the added advantage of standardising modelling procedures in user-defined model parameters, cost and time savings associated with modelling processes and visualising modelling performance (Greene & Cruise, 1995). As a result, many existing models, such as RUSLE, WEP, EUROSEM and ANSWERS, have been successfully connected to GIS, while new models, such as LISEM and SWAT, have been built based on GIS.

13.20 Satellite Remote Sensing

Environmental factors must be observed to determine the state of the earth's wealth and monitor its dynamics. At the moment, space technology, especially satellite remote sensing, is making a significant contribution to the comprehensive and timely evaluation of large-area natural resources (Colwell, 1983). Remote sensing is primarily used to gather, store and analyse data collected by sensing systems mounted on aircraft or satellites. Currently, satellite remote sensing is a critical source of information for environmental research, including the atmosphere, seas and land surfaces. Simultaneously, military goals have fuelled its expansion. There are hundreds of artificial satellites orbiting our planet, each equipped with various sensors to capture and relay valuable data about our environment.

However, information must be gleaned from the recorded image evidence. Onboard satellites and sensors monitor electromagnetic radiation, which is sent to the ground and stored electronically. Radiation can be analysed at various wavelengths depending on the sensor's properties (e.g. visible light, infrared, thermal). The sun is the most common source of radiation. Nonetheless, in some instances, such as radar imaging, the satellite structure generates radiation by sending energy beams to the earth's surface. Thus, satellite photographs merely depict spatial differences in how electromagnetic radiation interacts with the atmosphere and the earth's crust at a given point in time. Physical models or computational methods may be used to extract information about environmental factors from the recorded imagery. In a particular study, the vector of interest dictates the image form to be used (sensor or satellite).

Along with the wavelength(s) recorded, additional sensor characteristics such as spatial and temporal resolution may be necessary. Temporal resolution refers to the frequency at which an image with the same features may be recorded and is usually inversely proportional to spatial resolution. The spatial resolution is determined by the sensor and the height of the satellite's orbit.

As a result, removing environmental variables from satellite data varies according to the image type used. Independent in situ measurements of the variable of interest are needed to create and evaluate these methods (Jensen, 2004). The variables extracted from satellite data will then be paired with additional spatial data to develop new or more accurate data (He et al., 1998; Lubczynski & Gurwin, 2005; Saha et al., 2002).

13.21 Conclusions

Soil erosion adversely affects millions of land areas, resulting in production losses, increased food insecurity, reduced ecosystem resilience and increased climate change vulnerability. In general, its spatial reach is not well known, and erosion mitigation interventions have had limited success due to the lack of adequately focused interventions, hampering progress towards preventing further property degradation. Therefore, more comprehensive and extensive work is required to evaluate the spatial variability and extent of soil erosion within given regions. Furthermore, for sustainable and efficient soil erosion control, remedial and preventive strategies are to be established, and the discrimination of soil erosion over different land management practices is needed. Although the temporal soil degradation paths and landscape innovations were examined on various aspects of soil erosion, little attention was received. An overview of the progress of remote sensing applications in mapping soil erosion over time and space is given in this chapter.

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