Review Article

Rational insightson the extent of soil erosion and its management in India

Abstract

Continuous soil erosion from all parts of world through water and winds have become a serious concerns for soil scientists and geologists due to its adverse effect on soil productivity, water bodies siltation and deterioration of water quality. Therefore, we may more readily locate erosion-prone regions in any landscape and take the best measures to solve the issue if we understand the factors contributing to the soil erosion.USLE and its modified models i.e. RUSLE (Revised UniversalSoil Loss Equation) versions and MUSLE (ModifiedUniversal Soil Loss Equation) are most commonly used for estimation of soil erosion.In India, soil erosion is a major serious concern which varies in its intensity depending on the country's agro-climatic zones.USLE aswell known model for evaluating soil deterioration is used in this review to evaluate the extent of soil erosion in various locales. An overview of the situation of erosion status in several states is given at the outset of the analysis, which then looks at regional variations influenced by climate and land uses. The efficiency including afforestation, contour farming and watershed management are found effective in reducing the soil loss and assesses the management strategies being used by the states. Literature also dictates and discusses the potential advantages of better erosion control, such as increased agricultural output and long-term land sustainability and looks at what might be possible in the future if the things get managed. Depletion mechanism of nutrients from soil pools through erosion is also addressed in the article along with the detrimental effects of nutrient insufficiency on soil production. The study also looks at crop selection and land use systems, emphasizing how crucial it is to choose crops that are suitable for the land's vulnerability to erosion in order to prevent the furtherdeterioration. Lastly, it emphasize ona thorough explanation of the USLE's parameters, which are essential for precise erosion prediction including slope factors, soil erodibility, rainfall erosivity and conservation techniques. Study summarizes the knowledge on soil erosion in India and the necessity of customized, area specific soil conservation plans to guarantee long term agricultural outputsand sustainable agricultural goals.

Keywords: Soil erosion, sustainability goal, crop selection,USLE, RUSLE

Introduction

India, encompassed by different rivers and seasonal monsoons, has a huge variety of soils that have been formed through various natural processes such as precipitation, weathering, climate influences, and various complex soil geo-morphological interactions (Pal *et al.,* 2021). In India, more than 60 percent of people depend on agriculture for fulfilling their needs and to keep their socio-economic status up to a threshold level. So, it becomes quite obvious that higher dependency on agriculture for making returns will exploit the land areas and marine systems, thus cause serious problems like soil erosion, land degradation, mineral mining and polluted water bodies. In India, the national average erosion is estimated at 21 tons per hectare per year. In total, the erosion phenomenon affects nearly 30 per cent of the total area in a milder form.

However, 3 percent would be affected by catastrophic soil loss (IIT New Delhi, 2024).This devastating loss can be directly attributed to anthropogenic interventions such as deforestation and intensive agricultural practices.

Controlling the extent of soil erosion is crucial in India, because of the dependency of the country on agricultural sector, which employs around 158 million people, and therefore, it is vital for the economy. Generally, when the soil erodes initially, the fertile topsoil is being lost which reduces the crop yields and threatens the food security in the country. In the past, natural erosion by wind and water has produced some of the World's most fertile soils, such as those in the Indo-Gangetic Plains, Nile Deltas and China Plateaus. However, the accelerated erosion caused by anthropogenic activities has severely triggered the ecosystem services and led to landscape fragmentation (Bhattacharyya *et al.,* 2016). Soil erosion causes sediments accumulation in river basins and reservoirs every year, thus lowering their capacity to store the water and also affecting power generation efficiencies and irrigational facilities. Soil erosion occurs in various forms, such as sheet erosion, water erosion, mass erosion, landslides and terrace failures. The intensification of landslides due to human-based activities has been driven by numerous factors like vegetation removal, road or building construction, illegal mining and the development of hydropower projects (Mishra*et al.,* 2022). India's varying climatic features and landscapes variability, from mountains to coastal plains createsa challenging situation for soil conservationists who are deliberately working on land and natural resources reclamation projects.Additionally, engaging communities and encouraging stakeholder collaboration are vital to support the participatory erosion control methods and for building resilience in specific vulnerable landscapes. Therefore, the present review discusses and highlights the extent of soil erosion and its assessment in different agro-climatic regions of India.

Overview of USLE & RUSLE

This model soil erosion measurement wasproposed by Wischmeier & Smith in 1978, and is a globally acceptable approach and being used as a tool in soil erosion research, as it is offering a systematic approach to measuring the erosion rates and identifying thematic areas susceptible to erosion. By integrating the meteorological data, soil properties, land use patterns, and agriculture conservation practices, USLE helps to evaluate the soil loss potential and also pinpoints various key areas for erosion control and land management. Addressing the soil erosion extent is crucial for achieving sustainable development goal and environmental stewardship. Reducing erosion risks demands a comprehensive strategy comprise of land-use planning, soil conservation techniques, reforestation projects and sustainable farming practices. USLE approach primarily used at plot scale for agricultural plots in the United States of America in 1978, and since then, this approach is providing promising results on erosion measurement.

Soils are the most basic and crucial natural resource that are essential to daily life as they provide numerous ecosystem services and goods. For instance, a) producing food, fiber and other biomass; b) interacting with the environment through water filtration, carbon storage and nutrients transformation; c) serving as a biological habitat; d) supplying raw materials; e) contributing to physical and cultural heritage; e) serving as a foundation for human-made structures like buildings and roads (Poesen, 2018). Soil erosion is a severe and escalating issue in India with its far-reaching consequences on agriculture, environment and the economy.

Implementing effective soil erosion control measures is crucial to mitigate such previously addressed issues.

RUSLE, an updated version of USLE was introduced and this model included detailed soil erosivity maps for precise erosion estimation. This model also added the variations in soil erodibility caused due to moisture imbalances caused through precipitation and freezing actions. RSULE method is a computer based model basically programmed to handle complex datasets from farm and measures the soil loss occurred per unit area in a yearly period. The MUSLE is an extension to work at finer resolution by using the runoff and peak flow rate to estimate event based soil loss (Sadeghi *et al.*, 2014). RUSLE method is globally known for its low data requirements and simple result interpretations. These simpler interpretations encourage the policy makers to think and retaliate for maximum possible solutions from both agricultural and non-agricultural point of view. The RUSLE as an empirical model, briefly discussed in numerous reviews of soil erosion modelling and model types that have been published. Components of this model are frequently integrated into more intricate conceptual or physics based soil erosion models (Aksoy and Kavvas, 2005).

USLE parameters

Soil erosion models aids in land use planning and management by elucidating the areas vulnerable to soil erosion, estimation of potential erosion rates and identifying possible causes of soil erosion. The Universal Soil Loss Equation estimates the long-term average annual soil loss (tons per unitarea) from sheet and rill erosion by considering six basic factors related to climate, soil, topography, vegetation and management practices (Pham*et al.*, 2018).).
USLE is given as:

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

Where,A = Average annual soil loss (tons/ha/year); R = Erosivity caused by rainfall (It represents the effect that rainfall has on soilerosion and was included after observing sediment depositsafter an intense storm); K = Soil erodibility factor (It represents the influence of different soil propertieson the slope’s susceptibility to erosion); L = Slope length factor; S= Slope steepness and topographic factor (L and S factor, which is the ratio of the anticipated soil loss from a field slope to the initial USLE unit plot, shows how the slope's length and steepness affect sheet, rill, and inter-rill erosion by water); C = Crop management factor (Ratio of soil loss between a field under "clean-tilled continuous fallow" and one with a specific cover and management); P = Practice support factor (Ratio of soil loss in a field with upslope and downslope tillage to that under a certain soil conservation technique (such as terracing or contouring).

Although USLE was initially used for agricultural land at the small farm plot scale, but now, it has now been applied in numerous nations under a wide range of geo-climatic zones. The original USLE is more accurate for soils comprised of medium in texture and slopes (<400 fts in length) with a gradient ranging between 3-18 per cent.Despite the name suggesting that the model can be applied to all soils, it is maintained with regular cropping practices which are well represented in plot-scales (Wischmeier and Smith, 1978). Therefore, it is necessary to carefully parameterize the model and be aware of the increased uncertainty in model predictions when applying the USLE family of models to soils and sites that exceed these boundaries. Factors used by USLE are geographic in nature. These factors can be easily and efficiently calculated using a geographical information system (GIS), which incorporates various data layers such as watershed boundaries, slope, rainfall distribution, land use, management practices and soil types. By combining these data layers, GIS enables the calculation of soil erosion for each pixel (Chandramohan and Durbude, 2002). The USLE was originally developed to estimate the soil erosion on gently sloping cultivated land in the Mid-West, USA (Renard*et al.*, 1997). The RUSLE has been developed with a structure similar to the USLE, incorporating several enhancements in identifying input factors using an updated database in the United States.

Limitations of (R)USLE

The (R)USLE models limited application to areas outside of the United States of America is the most frequently mentioned drawback (Sadeghi et al., 2014). Soil erosion research conducted on US agricultural land served as the foundation for the original USLE. However, estimates of average annual soil loss may become more imprecise when applied to various climatic regimes and land cover situations other than US region (Kinnell, 2010). Upscaling the original USLE to the catchment or regional scale is not without its uncertainties (Naipal*et al.*, 2015). Additionally, Wischmeier and Smith (1987) cautioned that extrapolation error could result from applying the (R)USLE under circumstances that are very dissimilar from the agricultural conditions under which the model was developed. The incapacity of models to capture the intricate relationships involved in soil loss, the scarcity of long-term, trustworthy data for modelling and the absence of soil erosion observational data for model validation particularly in data-scarce environments are the main causes of the uncertainties surrounding the (R)USLE and, it can be argued, soil erosion modelling in general.

Nutrients depletion through erosion

Deterioration of soil attributes associated with soil productivity and the quality of natural resources is commonly called land degradation (Shubham *et al.*, 2023). Furthermore, soil compaction, erosion, loss of biodiversity, acidification, alkalization, depletion of soil nutrients and decrease in soil organic matter (SOM) are some of the typical examples (Acharya *et al.*, 2009). There are numerous physic-chemical and biological processes which are either directly or indirectly brought on by anthropogenicactivities cause land degradation. One of the biggest problems facing land managers is land degradation, which includes soil erosion, and it affects around 60 per centof the world's land surface. For instance, soil erosion is a severe issue that have raised serious worries all around the world (Guerra *et al.*, 2017). Over the years, agricultural soils have been continuously degrading to severe extent and the necessity to use the forest resources to meet the people demandfor basic food has grown. As per the reports global population is projected to outreach 9.6 billion people by 2025, and to full fill the basic food requirement of such outnumbered population, agricultural production would needed to increase by 70 per cent (Shubham *et al.*, 2023). However, soil fertility has been severely weakened by farming practice like intensive farming and overuse of synthetic chemicals and as result soil erosion has beenbecome a persistent issue for both the environment and agricultural sector (Gardner *et al.*, 2003).

According to an estimate, soil erosion causes 1.7 mm of topsoil to be lost annually, yet it takes nearly 100 years for formone centimetre of soil (Gautam, 1993). Different rates of soil erosion are caused by variations in topography, changes in land use and cover, uneven rainfall distribution and demographic differences within the nation. The majority of soil minerals for plant nourishment are concentrated in the surface layers, and also impacted the most (Quansah *et al.,* 2000). Planning for the implementation of adaptive measures is necessary because the increased risks of soil erosion hazards brought on by climate change would have comparable detrimental effects on the crop growth and yields, particularly in the tropics and sub-tropics where the effects of climate change would be more severe and small landholders with limited resources would not be able to adjust to the sudden changes in climate (Cline, 2007).

Extent of erosion through water and wind in India

There are several ways that nutrients might be lost. While less soluble nutrients like phosphorus are more likely to be lost with sediments moving in eroding soil and runoff water, soluble nutrients like potassium and nitrate can be lost in runoff and drainage water. The growth and life cycle of plants depend on the majority of the 17 basic nutrients. The primary nutrients that replenish soil fertility are N and P, which are lost due to water erosion together with Ca, Mg, K, and organic matter (Bertol &Miquelluti, 2003). Although total erosion prevention is unachievable, it can be reduced, and erosion management methods typically preserve or boost soil production. Transport of productive soil or erosion-induced reduction in productivity. Usually removing around three times as much nutrients from the soil as are still present. The average nitrogen content of a ton of fertile surface soil is 1-6 kilogram, 1-3 kg of phosphorus, and 2-30 kg of potassium; in contrast, the average nitrogen content of soil on eroded land is 0.1-0.5 kg per ton (Hopkins *et al.,* 2001).

Organic matter, clay partials, or soil in sand, silt, and clay ratio is disturbed with reduced fertility due to negligible loss from wind erosion (Mandal *et al.,* 2012). There are three distinct ways that silt is transported in wind erosion: creep, saltation, and suspension. The saltating grain bombardment starts the particles moving in creep, yet they are big enough to stay in constant contact with the soil surface. Since creep mostly moves coarse sand, which is low in nutrients, it is thought to not produce appreciable nutrient losses. Additionally, creep transit distances range from a few centimetres to several meters. The majority of saltating particles bounce just over the soil's surface before rising to a height of two meters. They can be moved between a few hundred and several hundred meters. From Bielders et al. (2002), we discover that the nearby bush acts as a sink for the majority of the silt and, consequently, the majority of the nutrients when wind erosion takes place in farmed areas. When the fallow is replanted for farming, water erosion may cause this sediment and the nutrients it contains to return, depending on the local terrain. Nitrogen dynamics and soil organic carbon (SOC) are impacted by topsoil loss that ultimately impacts the soil's capacity to sequester carbon (Mendez *et al.,* 2006). One of the most important steps in preserving soil quality and production is the conservation and maintenance of SOC contents. The small SOC pool of desert soils has also declined more quickly as a result of progressive land use trends shifting from natural rangeland ecosystems to arable farming in dryland areas and this decrease will only accelerate in the context of desertification processes linked to global climate

Selection of erosion resistant cropping systems

The soil serves as a reservoir of water and nutrients, meeting the demands of plants throughout their growth and serving as a vital substrate for animal activity and plant growth. Additionally, one of the soil's key roles is to collect water and hold onto it so that the plant roots may use it. The plants need a steady flow of water for photosynthesis, turgor maintenance, cooling and nutrient transportation (Bazilevskaya*et al.*, 2013). The unique properties of soil are derived from a combination of minerals and organic matter found across the earth's surface. India's varied soil types have produced a wide range of agricultural techniques, with various crops and cropping systems tailored to certain soil types and climates (table 1). For the nation to maintain agricultural production and food security, soil conservation and management techniques are essential. India's huge geographical and climatic variances result in a broad spectrum of soils.

Table 1. Selection of Crops according to Soil types in different states of India

Types of Soils	States where found	Rich in	Lacks in	Crops grown
Alluvial soils	Mainly found in the plains of Gujarat, Punjab, Haryana, UP, Bihar, Jharkhand, etc.	Potash and Lime	Nitrogen and Phosphorous	Large variety of *rabi* and *kharif* crops such as wheat, rice, sugarcane, cotton and jute
Black soils/Regur soils	Deccan plateau: Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, Tamil Nadu, Valleys of Krishna, and Godavari.	Lime, Iron, Magnesia, Alumina and Potash	Phosphorous, nitrogen and organic matter	Cotton, sugarcane, jowar, tobacco, wheat and rice
Red soils	Eastern and Southern parts of the Deccan Plateau, Orissa, Chattisgarh, and Southern parts of the middle Ganga Plains	Iron and Potash	Nitrogen, phosphorus, sulphur and humus	Wheat, rice, cotton, sugarcane and pulses
Laterite soils	Karnataka, Kerala, Tamil Nadu, Madhya Pradesh, Assam and Orissa hills	Iron oxide and potash	Organic matter, nitrogen, phosphate and calcium	Cashew nuts, tea, coffee and rubber

Arid and Desert	Western Rajastan, North Gujarat and Southern Punjab	Soluble salts and phosphate	Humus and Nitrogen	Only drought resistant and salt-tolerant crops such as barley, rape, cotton, millets maize and pulses
Saline and Alkaline soils	Western Gujarat, Deltas of Eastern Coast, and Sunderban area of West Bengal, Punjab and Haryana	Sodium, potassium, and magnesium	Nitrogen and calcium	Barley, cotton, sugar beet, sugarcane, sorghum and rice,

Scenario of soil erosion extent in Indian agro-climatic zones

In India, soil erosion is a pervasive environmental issue that varies in intensity among states due to a variety of anthropogenic, climatic and geographic causes. Water erosion makes up the largest percentage of the estimated 147 Mha of land in India that are degraded to varying degrees. Deforestation, unsustainable farming methods, heavy monsoon rains, and other natural causes are all directly related to the problems caused by soil erosion (Anonymous, 2024). Because of the high rainfall erosion during the monsoon season, soil erosion is particularly severe in North- Eastern states like Assam, Meghalaya, and Arunachal Pradesh (table 2). Heavy rainfall in these areas erodes the nutrients-rich topsoil, resulting in severe soil loss. The problem is made worse by the steep slopes and the common loamy and silt loamy soils, which are more prone to erosion. According to district-level data, Meghalaya's East Khasi Hills and other regions see some of the nation's highest erosivity levels as a result of heavy rains (Mongabay, 2024). Because of the steep terrain and seismic activity, the soil in the Himalayan region—which includes states like Jammu and Kashmir, Himachal Pradesh and Uttarakhand is extremely vulnerable to erosion. The issue is made worse by landslides and slope instability, which cause soil displacement, especially during the monsoon season. Deforestation and uncontrolled development further jeopardize the delicate ecosystems in these regions by upsetting the natural soil structure and making them more susceptible to erosion (Anonymous, 2023).

State	Area (*in hectare*)
Andhra Pradesh (including Telangana)	8093
Arunachal Pradesh	666
Assam	3248
Bihar	851
Chhatisgarh	3733
Delhi	28
Goa	1
Gujarat	984
Haryana	306
Himachal Pradesh	982
Jammu and Kashmir	1369
Jharkhand	3219

Karnataka	7522
Kerala	490
Madhya Pradesh	12262
Maharashtra	8799
Manipur	122
Meghalaya	302
Mizoram	-
Nagaland	46
Orissa	2227
Punjab	229
Rajasthan	19029
Sikkim	45
Tamil Nadu	2308
Tripura	109
Uttar Pradesh	13075
Uttarakhand	1018
West Bengal	1332
Total	92400

(Source: Anonymous, 2023)

Table 2.Indian states cultivable area impacted by soil erosion

Management practices of soil erosion in India

Because it is necessary for all life on Earth, soil is nature's most valuable resource. Prosperous agriculture, which is the cornerstone of economic growth and a higher standard of living in a community, can only be ensured by a fertile soil base. Therefore, soil management and conservation are essential to ensuring that economic development is a sustainable process. All such actions that aid in preventing soil erosion and depletion are included in soil conservation. There are many different approaches that can be used to preserve this important resource.

Management practices:

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1. **Contour tillage:** Water erosion processes are accelerated on sloping farms by conventional tillage, which involves ploughing up and down the hill. The use of cultivation and tillage direction in respect to a field's contour lines, also known as contour farming, is a conservation method for lowering water erosion. The method is predicated on the idea that ridges created by tillage and seeding create an oriented roughness. Oriented roughness is improved by lowering the angle (0–90°) between contour lines and agricultural direction, which can lessen soil erosion and surface runoff (Stevens et al., 2009)
2. **Contour bunding:** For hilly, sloping, and marginal terrain where soil erosion is a concern, contour bunding is a tried-and-true sustainable land management technique (ICIMOD, 2013). In many areas, contour bunding significantly lowers soil erosion and surface runoff in agricultural watersheds. Runoff observations on a 55 hectares agricultural watershed treated with contour bunds in the Dehradun region revealed that

the volume and peak of runoff were decreased by 62 and 40 per cent, respectively (Ram Babu *et al.*, 1980). Strip planting in a 2:1 maize to cowpea ratio was just as successful as graded contour bunding in reducing runoff by 43 to 37 per cent and soil loss by 21 to 11 t/ha (Bhardwaj, 1994).

3. **Strip cropping:** It is generally acknowledged that strip cropping is crucial for reducing runoff erosion and preserving soil fertility. Several good agricultural techniques, such as crop rotation, contour cultivation, appropriate tillage, stubble mulching, and cover crops, are used in strip cropping. In order to increase productivity and net return, soybeans grown as a strip crop (2:8 rows of maize and soybean) at a 4 per cent slope with maize decreased runoff by 42 per cent and soil loss by 54 per cent. Since soybeans are a crop that effectively resists erosion, they should either be cultivated in strips with maize in a ratio of two rows of maize to eight rows of soybeans, or they should be grown in place of maize (Singh *et al.*,1979).
4. **Afforestation:** Forests are the most effective technique to preserve soil for future growth. Trees should not be cut down carelessly, and efforts should be made to replace trees in new locations. The five-year plan increased the minimum amount of forest land that is deemed healthy for soil and water conservation nationwide from 20 to 25 per cent to 33 per cent. It is advised that 20 per cent of plain areas have forest cover, whereas 60 per cent of hilly and mountainous areas should have forest cover (Saroha, 2017).

Conclusion

Assessment throughUSLE assesses the serious status of soil erosion in India's various agro-climatic zones. The significance of elements such as crop cover, slope length, rainfall erosivity and soil erodibility in determining erosion rates is shown by the examination of several USLE characteristics. Because of India's diverse agro-climate, erosion patterns vary with wind erosion being more common in arid areas and water-induced erosion predominating in humid ones.Because eroded soils lose vital elements that are necessary for crop productivity, nutrient depletion from soil erosion is still a major concern. In order to support sustainable land use, our review also emphasizes how crucial it is to choose crops that are appropriate for the soil type and erosion susceptibility in various zones. Crop rotation, mulching, terracing, contour farming, and other efficient management techniques have demonstrated promise in reducing erosion and preserving soil health. Future USLE applications can greatly enhance soil erosion estimation and facilitate focused interventions if they are improved to account for local differences and real-time monitoring technology. To protect soil resources and guarantee long-term agricultural viability, ongoing work toward adaptive soil conservation solutions catered to India's varied agro-climatic zones are essential.

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