

Process-based modelling of soil erosion: scope and limitation in the Indian context

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The conservation and sustainability of natural resources, particularly soil and water, are crucial for agricultural yield and livelihood. Soil erosion models simulate the influence of existing farm management patterns as well as soil conservation interventions affecting soil erosion rates and accordingly recommend appropriate management techniques. The erosion models might be helpful for forecasting soil erosion, sediment load and evaluating the effectiveness of conservation measures. Although numerous empirical, conceptual or physical process-based models are used to study soil erosion, they differ in respect of input data requirements, representation of physical processes, sediment yield, and limitations due to their spatial and temporal variations. Due to limitations in empirical models in describing the erosion process, some process-based models may be used to quantify the state of soil erosion in a region. Before use, the available erosion models must be evaluated and validated for local circumstances. In this respect, the present study has been carried out to provide a critical review of various soil erosion models used worldwide, having different climatic parameters for determining soil erosion rate, run-off and sediment yield status.

Keywords: Conservation measures, natural resources, process-based models, run-off, sediment yield, soil erosion.

The scenario of soil erosion

GLOBALLY soil erosion is the primary source of land deterioration, as water erosion affects 1094 million hectare (Mha) of land, with 751 Mha severely impacted. About 549 Mha land is influenced by wind erosion, of which 296 Mha is severely affected¹. In India, from a total geographical area of 329 Mha, about 120.4 Mha of land has been degraded (68% owing to water erosion)², resulting in an annual loss of 5.3 giga tonnes of soil³. In the Eastern Himalayan zone of India, about one-third area is degraded because of soil erosion by water^{2,4,5}. The first

approximation shows India's average soil erosion rate as 16.35 t ha⁻¹ yr⁻¹ (ref. 3), whereas the permissible erosion rate is 4.5–11.2 t ha⁻¹. According to estimates, 29% of the total soil eroded is completely lost to the sea, 10% is collected in reservoirs and 61% is shifted from its original location³. Another study⁶ revealed that the gross erosion rate of India is 15.59 t ha⁻¹ yr⁻¹, out of which about 22.9 ± 29% is lost to the oceans, 34.1 ± 12% is collected in the reservoirs, and the rest 43.0 ± 41% is relocated from the provenance. India has committed at the 14th Conference of Parties (COP-14) meeting that it will work to achieve land degradation neutrality by 2030 by rehabilitating 26 Mha of degraded land. In the rainfed regions of the country, productivity loss owing to water erosion is 13.4 million tonnes, which is observed in major rainfed crops like cereals, oilseeds and pulses, amounting to ₹ 111.3 billion in monetary loss⁷.

Process and factors of soil erosion

Soil erosion is a complicated phenomenon driven by soil properties, land slope, vegetation, rainfall amount and its intensity. Soil erosion rates that exceed soil production rates reduce agricultural production⁸. Soil erosion and sedimentation processes involve detachment, entrainment, transportation and deposition of soil and other earth materials. It is due to shear stress generated by the raindrop and surface run-off on land surface and may be described in terms of the type of erosion (as rain splash, sheet, interrill, rill, etc.) and based on location (hill slope and channel erosion) and various causative agents (water and wind erosion)⁹. Soil erosion is a multidimensional phenomenon in which fertile surface soils are detached from the parent material and transported by eroding agents to a distant location, exposing the underlying soil¹⁰. The erosion from an area occurs through two distinct processes, i.e. interrill and rill erosion. The former occurs due to rain splash and the soil is transported by the sheet or overland flow. The overland flow down the slope concentrates into rills or small channels to cause rill erosion. Usually, the rate of rill erosion is higher than the interrill erosion. However, development of rills can be checked by plowing action.

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The severity of these erosion processes is often determined by the amount of material provided by the detachment and transit capabilities of the eroding agents. When eroding agents have greater power to carry material than the quantity delivered by detachment, the erosion process is referred to as detachment limited. It is called transport-limited if more material is provided in comparison to the transport capacity of the eroding agent¹¹. Human activities have intensified soil erosion, which is a destructive process as it degrades soil structure and fertility level, decreases the effective rooting depth and depletes the natural and organic resources¹.

Importance of soil erosion research

Soil degradation is a grave problem for India's rainfed and irrigated areas. It is associated with considerable capital loss due to declining crop productivity, soil fertility, shifting cropping patterns, excessive input consumption and diminishing profit¹². Unfortunately, in many regions, the rate of soil erosion surpasses the rate of soil formation. Environmental conditions like climate, topography, soil, etc. regulate the type and rate of erosion in a region. Extensive human interference has caused the degradation of soil resources and their production potential. This is a global issue requiring local, site-specific erosion control measures⁹. Numerous onsite and offsite effects of soil erosion can be observed at various localities¹¹. The onsite impacts of soil erosion include soil loss, collapse of soil structure, decline in soil organic matter (SOM) and nutrient content, which lead to reduced cultivable soil depth, soil fertility, loss of productivity, limitation in crop growth, and eventually abandonment of agricultural lands. Offsite effects occur as a result of sedimentation downstream, which diminishes the carrying capacity of rivers and channels, interrupts irrigation canals and reduces the storage capacity of reservoirs, enhancing flood risk. Moreover, the chemical substances adsorbed to the sediment are released, which may cause eutrophication in the water bodies.

Erosion-influenced soil movement affects the directional distribution of soil carbon stocks, hence disrupting the net flow of carbon between soil and atmosphere as carbon dioxide (CO₂) (refs 1, 13). There is still some disagreement on whether soil erosion leads to net carbon acquisition¹⁴⁻¹⁶ or net carbon release^{1,17}. Some scientists argue that soil erosion serves as a source of 0.8–1.2 Pg C y⁻¹ of atmospheric carbon^{1,18}. The mechanisms that promote net C loss as a result of erosion are accentuated mineralization during the breakdown of aggregates and increase in the emission of CO₂. Other scientists argue that human-induced soil erosion causes a global sink of 0.12–1.5 Pg C y⁻¹ (refs 16, 19). This is based on the dynamic partial substitution of SOC with fresh photosynthate in the eroding areas by continuous crop growing with ade-

quate inputs²⁰. A significant portion of the eroded, carbon-rich topsoil is buried in different depositional sites and is subject to reduced rate of decomposition^{21,22}. Visualization of spatial variation of SOC at the watershed scale is possible by integrating an appropriate process-based hydrological model and a process-based biogeochemical model. This would help develop carbon management and credit policies²³.

Soil erosion may have a role in climate change by releasing CO₂ into the atmosphere, which increases the greenhouse effect. Adopting best management practices may thus help in mitigating climate change by increasing carbon sequestration in eroded landscapes. Soil erosion is a major challenge for sustainable agricultural production. It gradually removes the fertile topsoil and makes it unsuitable for cultivation purposes, besides causing several offsite environmental damages. Hence, a focused study is necessary to identify sources of soil erosion, agents causing erosion, its mechanism and prioritization of erosion-prone areas to adopt suitable management practices to cope with the ill-effects of erosion.

Basic types of soil erosion models

Soil erosion models quantitatively reflect the process of soil particle separation, movement and deposition on the soil surface as a result of various causative factors and their interaction based on laws governing the surface runoff, and their detachment and transport capacity²⁴. Soil erosion models simulate the effect of current farming patterns, including soil conservation measures, on soil erosion rates and provide suitable approaches. They are used to develop effective erosion control techniques, evaluate land-use management practices and manage the environment^{24,25}. Soil erosion models consider various complex interactions within the soil, land use, climate and topography, which influence the rate of soil erosion by simulating the erosion processes in a watershed²⁶.

As explained below, empirical, conceptual and physical process-based models available for projecting sediment generation and accumulation on hillslopes and small watersheds^{24,25,27}. Empirical models may be used when all of the required data are available though they do not describe the mechanisms of soil erosion. They are often based on a statistical relationship between the causal factors and the rate of soil erosion. Physical models describe the basic soil sediment-producing processes and the spatio-temporal variation of sediment detachment, transport and deposition of soil particles by overland flow. They are employed to study the effects of various management practices. When sediment-producing parameters like rainfall and run-off are available, conceptual or semi-empirical models are utilized based on spatially lumped water and sediment continuity equations. Conceptual or semi-empirical models exist between the empirical and physical

Table 1. Soil erosion models used in India

Model	Region	Purpose	Climate	Data source	Remarks
USLE ²⁹	Gumti River Basin (Tripura), area 2492 km ²	To assess the amount of soil loss ³⁰ .	Humid sub-tropical (rainfall 335.27 mm)	Rainfall data (IMD), soil data (NBSSLUP), ASTER DEM (30 m resolution) and LISS III	LULC has a greater influence on soil erosion compared to rainfall. The field-measured soil-loss data should be used to validate the predicted soil loss.
RUSLE ³¹ and TLSD ³²	Pambar River Basin (Idukki district, Kerala), area 288.53 km ²	To predict average annual soil erosion and deposition, and identify critical erosion or deposition areas ³³ .	Tropical mountainous river basin (rainfall 1533 mm (U/S) to 852 mm (D/S))	Rainfall data (meteorological stations), soil properties (field sampling), elevation data (Survey of India toposheet, 1 : 50,000 scale), and vegetation characteristics (IRS-P6 LISS-III)	Loamy sand and sandy loam texture soil have relatively low 'K' values compared to silt loam textured soil. Semiarid sub-basins having less vegetative cover show higher soil erosion compared to humid regions. So climate-specific management plans should be formulated.
USLE and MUSLE ³⁴	Sarada River basin (Andhra Pradesh), area 1252.99 km ²	To find vulnerable soil erosion-prone regions, computation of sediment yield and to suggest best management practices ³⁵ .	Rainfall 1105 mm	ASTER DEM (30 m), LISS III, Survey of India toposheets (1 : 50,000), Suspended-sediment concentration (for 28 storm events by DH-48), discharge (1 yr data)	In MUSLE, the sediment yield produced from the MNRCS-CN model outperforms the NRSC-CN model.
MUSLE ³⁴	Karso watershed of Hazaribagh (Jharkhand), area 28 km ²	To estimate sediment yield ³⁶ .	Sub-humid, tropical (rainfall 1300 mm)	Daily rainfall (automatic rain-gauge station), run-off and sediment yield data (gauging station), IRS-1C LISS-III	This model does not predict well the sediment yield for small and large rainfall events, but is good for intermediate events.
MMF ³⁷	Shiwalk hills region (Saharanpur district, Uttar Pradesh), area 205.95 km ²	To evaluate soil erosion risk and land capability categorization for watershed management ²⁶ .	Sub-tropical, semi-arid climate (rainfall 1170 mm)	ResourceSat LISS IV (5.8 m resolution), soil map (1 : 50,000), SRTM DEM	Soil erosion database can be effectively classified into different land-use systems and conservation measures suggested accordingly.
MMF and USLE	Sitla Rao sub-watershed (Dehradun district, Uttarakhand), area 52 km ²	To estimate soil erosion ¹⁰ .	Western part of the Doon Valley	Toposheet (1 : 50,000), rainfall data and IRS-1C, LISS III	MMF model predicts well the soil erosion compared to USLE in hilly terrains like the Himalaya.
RUSLE-3D ³⁸	Pathri Rao sub-watershed (Haridwar district, Uttarakhand), area 44 km ²	To predict soil loss and spatial distribution of soil erosion hazards for soil conservation planning ³⁹ .	Sub-tropical, semi-arid climate (rainfall 1044 mm)	ResourceSat-1 LISS-IV (5.8 m resolution), IKONOS (1 m resolution) and toposheet (1 : 25,000), field survey of farmers and rainfall data	Topographic factor (LS) is dominant in controlling soil erosion.

USLE, Universal soil loss equation; RUSLE, Revised universal soil loss equation; TLSD, Transport limited sediment delivery; MUSLE, Modified universal soil loss equation; MMF, Morgan, Morgan and Finney; K, Hydraulic conductivity of soil.

process-based models. Integrating remote sensing (RS) and geographical information system (GIS) with various erosion models effectively assess the severity of erosion and geographical extent. Since the models help predict soil erosion rates under various soil and land management practices, they are used for soil conservation planning²⁶. Because quantifying bed load is challenging, and the spatial distribution of erosion and deposition in larger basins is varied, an empirical method to model the erosion rate

from larger basins is favoured^{6,28}. Table 1 shows the major soil erosion models used in various regions of India²⁹⁻³⁹.

Process-based models

Due to some limitations of empirical models, several process-based models have been proposed to forecast the spatial variation of run-off and sediment across the land surface, and estimate the total run-off and soil loss¹¹.

Table 2. Process-based models used worldwide

Model	Region	Objective	Remarks
WEPP, ANSWER and EPIC ⁴⁷	Experimental field, Kansas State University, Ottawa, Kansas, USA; elevation 271.3 m, 27 plots of size 3.05 m by 15.24 m	To forecast soil loss due to interrill erosion (using WEPP, EPIC, and ANSWERS model) from small plots under three different tillage systems ⁵⁴ .	The WEPP model prediction was superior to the EPIC and ANSWERS models for event-based, annual and average soil loss for all tillage techniques considered. The most sensitive parameters for the WEPP model are effective hydraulic conductivity, interrill erodibility and critical hydraulic shear stress.
WEPP watershed model	Hermada watershed (Boise National Forest, Northern Idaho); elevation 1760–1880 m, area 9 ha	To correct and improve the WEPP model algorithm in order to accurately predict the hydrology and erosion process of forest watersheds ⁵⁶ .	By modifying the algorithm for water infiltration in the soil profile, the WEPP model predicts soil erosion from the forest watershed more accurately. It has improved ability to differentiate the infiltrated water into percolation and subsurface lateral flow and better represent the forest hydrology.
WEPP hillslope model	Scrub-bearing hillslopes (Northwest Spain), elevation 350 m	To study the impacts of farm fire on run-off and soil erosion from scrub-bearing hillslopes ⁵⁷ .	The WEPP model predicts run-off and soil erosion with reasonable accuracy.

Process-based erosion models have several benefits over empirical-based models, including the ability to estimate spatio-temporal variation in net soil loss or gain on various timescales. It can also interpret a wide range of conditions where field experimentation is not possible. It includes several components, namely soil erosion, climate, hydrology, daily water balance, plant growth, residue decomposition and irrigation to represent the spatio-temporal distribution of soil loss and its deposition in the watershed for visualization of the adoption of appropriate soil and water conservation measures⁴⁰. Moreover, process-based models, which essentially simulate soil erosion in much smaller regions, complement empirical models using the universal soil loss equation (USLE) and revised universal soil loss equation (RUSLE) approach over much larger areas, and lend further insight into the local erosion factors and dynamics⁴¹. The use of physical process-based models for run-off and soil erosion estimation at the field and watershed level has gained popularity due to their ability to assess the effects of various interventions and management practices^{5,42}. However, one of the significant limitations of these models is the absence of credible field data for calibration and validation^{5,42}.

Process-based models worldwide

Understanding the many hydrologic and physical processes that lead to soil erosion and their interactions with the soil type(s), cropping pattern(s), land use and management strategies is necessary to control or minimize soil erosion⁴³. Different methods are being followed to quantify soil erosion, such as erosion plot studies and fallout radionuclide-based tracer techniques⁴⁴. Models can

predict how conservation measures may influence soil productivity spatially. In this context, hydrological modelling can be a valuable tool for forecasting the run-off and erosion for successful land-use planning in hilly watersheds and detecting crucial regions to adopt proper soil conservation measures⁴⁵. The Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS)⁴⁶, Erosion Productivity Impact Calculator (EPIC)⁴⁷, Morgan, Morgan and Finney (MMF)³⁷, Watershed Erosion Simulation Program (WESP)⁴⁸, Agricultural Non-point Source model (AGNPS)⁴⁹, Kinematic run-off and Erosion model (KINEROS)⁵⁰, European Soil Erosion Model (EUROSEM)⁵¹, Water Erosion Prediction Project (WEPP)⁵², Agricultural Policy Environmental Extender (APEX)⁵³, etc. are all well-validated erosion modelling approaches and are commonly used by various researchers^{24,54,55}. MMF is a conceptual, spatially distributed model used to determine annual soil loss from field-sized areas on hillslopes³⁷. In hilly watersheds having high spatio-temporal variability, watershed models like CREAMS, ANSWERS, AGNPS, EPIC and SWAT are the most relevant and extensively utilized for hydrologic modelling of the produced run-off and sediment⁵. Table 2 presents the various process-based soil erosion models used worldwide^{54,56,57}.

Characteristics of process-based models

Among all the advanced models reported, WEPP, EUROSEM, KINEROS, ANSWERS and WESP are fully process-based, compared to others which use some empirical models to predict parameters. The ANSWERS model was introduced to explore the impact of land use,

management and conservation strategies on the hydrological and erosion response in agricultural watersheds, but it may also be used in ungauged watersheds during and after a rainfall event⁴⁶. It is an event-based and distributed parameter model which requires complex data files to describe a watershed. The modified equation of Holtan and Overton is used to describe infiltration⁵⁸. The detachment of soil particles by raindrop impact and overland flow was computed using the derived relationship⁵⁹, and the modified Yalin's equation was used to quantify the transport of particles of different sizes. The EUROSEM model estimates soil loss based on a numerical solution of the dynamic mass balance equation⁵¹. It cannot model ephemeral gullies or erosion due to saturated overland flow⁶⁰. Moreover, WESP is a distributed and event-based physical model that simulates the erosional and depositional behaviour of small watersheds⁴⁸. An infiltration component based on the modified Green-Ampt equation was included in the model to compute rainfall excess rates⁶¹.

Importance of process-based models in the Indian context

Several empirical, conceptual or physical process-based models are available worldwide for studying run-off, soil erosion and sediment yield. However, these models vary significantly in terms of input data requirements, representation of various physical processes involved as well as spatial and temporal variations, limitation of area and their capacity to accurately predict erosion and sediment yield⁵⁵. Nowadays, process-based models are gaining popularity as research tools for predicting run-off, soil erosion and sediment yield under different climatic and management conditions. Among them, the WEPP model has been used by several researchers, mostly abroad and by a few researchers in India, to conserve and utilize important natural resources effectively^{4,52,62,63}. India's topography, climatic scenario, cropping pattern, etc. are different from many other areas in the world where the WEPP model has been used to provide various outputs. Therefore, it is essential to evaluate the applicability of the WEPP model in different agro-climatic regions of India for its wider use⁶². Table 3 shows several process-based models used in India⁶³⁻⁷⁰.

Discussion

WEPP model is a continuous simulation and distribution model that demonstrates soil detachment, transport and deposition by the impact of raindrop, overland flow, and channel flow rather than the average net soil loss as provided by the initial USLE model^{25,52}. The basic coding for the WEPP model was done in Arizona and Indiana, USA, between 1985 and 1995 (ref. 52). The reported and validated hill slope and watershed WEPP model was re-

leased at Iowa, USA in July 1995 (ref. 52). Although the WEPP model could not predict gully erosion, it can effectively identify the sediment source and sink within a catchment due to interrill and rill erosion⁷¹. For small agricultural watersheds (less than 260 ha), the WEPP model can identify sediment detachment and deposition zones, and spatio-temporal variability due to various agricultural management practices. It also considers the effects of backwater on detachment and deposition within channels and sediment impoundment effects⁵². The WEPP model can compute run-off and soil loss using stochastic weather generation, infiltration theory, hydrology, soil physics, plant science and erosion mechanics⁵.

The WEPP model is available to function in a hillslope and on a watershed basis. The hillslope version involves nine parts: climate generation, hydrology, winter processes, irrigation, soils, plant growth, residue decomposition, overland flow hydraulics and erosion. In contrast, the WEPP watershed version consists of an additional three parts, viz. channel hydrology and hydraulics, channel erosion and impoundments^{5,52,62,64}. The watershed version is the extension of the hillslope version. It is used for soil-loss assessment at the catchment scale, and ideally, a catchment consists of several hillslopes, channels and impoundments. Inside a catchment or watershed, one or more hillslopes drain into one or more channels or impoundments^{45,66}.

The modified Green-Ampt-Mein-Larson equation determines the infiltration component, whereas the peak run-off rate at the channel outlet is estimated using a modified rational equation^{52,72}. The three soil erodibility parameters used in the model are interrill erodibility, rill erodibility and critical hydraulic shear, which define the respective erosion phenomena⁶².

The WEPP model simulates overland flow, sheet erosion, rill erosion and erosion from small channels (ephemeral gullies)⁷². It employs a steady-state sediment continuity equation for estimation of net detachment or deposition as follows⁴⁰

$$\frac{dG}{dx} = D_f + d_i,$$

where G is the sediment load (kg/s/m), x the distance downslope (m), D_f the rill erosion rate (kg/s/m²) and D_i is the interrill erosion rate (kg/s/m²).

The prediction ability of the physical process-based WEPP model for run-off and sediment yield from the Karso watershed (2793 ha) of Jharkhand, India, was studied. The findings of the study were used for watershed prioritization, based on the severity of erosion and further appraisal of best cropping management practices⁶³. For the Karso watershed, sensitivity analysis was performed to identify the factors that must be carefully determined to anticipate watershed run-off and sediment yields

Table 3. Process-based models used in India

Model	Region	Objective	Remarks
WEPP watershed model ⁵²	Umroi watershed (Eastern Himalayan region, Ribhoi, Meghalaya), area 239.44 ha, climate humid subtropical, rainfall 2842.5 mm, elevation 900 to 1240 m, data of two years were used	To simulate run-off and sediment yield, and sensitivity analysis of watershed characteristics with high rainfall and steep slope ⁵ . To develop integrated crop, tillage and structural management practices in order to reduce sediment yield ⁵ .	Results of the WEPP model have been improved using the climate input files generated by the Break Point Climatic Data Generator (BPCDG). It underpredicts the high run-off events and sediment yield.
WEPP watershed model	Karso watershed (Damodar Barakar catchment), area 2793 ha, climate sub-humid tropical, rainfall 1300 mm, elevation 390–650 m amsl	To evaluate the WEPP model for estimation of run-off and sediment yield, and its sensitivity analysis ⁶⁴ .	Run-off is sensitive to changes in the physical environment, i.e. effective hydraulic conductivity value, whereas interrill erodibility and effective hydraulic conductivity affect sediment yield.
WEPP watershed model	Karso watershed (Damodar Barakar catchment), area 2793 ha, climate sub-humid tropical, rainfall 1300 mm, elevation 390–650 m	To classify and prioritize vulnerable sub-watersheds based on erosion and assessment of optimal management practices ⁶³ .	This model was found suitable for use as a decision-making tool to assess erosion hazards and prioritization purposes.
WEPP watershed model	Kaneli watershed (middle Himalayan region, Uttarakhand), area 0.67 km ² , elevation 1220–1540 m, rainfall 2840 mm	To validate and evaluate the WEPP model for estimating run-off and sediment in data-scarce areas ⁶² .	The model failed to account for less severe rainfall events with less than 1 mm discharge and sediment yields of less than 0.02 t/ha.
WEPP, MUSLE and unit sediment graph (USG) ⁶⁵	Kozhy Thodu watershed, area 37.49 km ² , Valiya Thodu watershed (area 41.15 km ²) and Kiri Thodu watershed (area 36.55 km ²) in the Pamba River basin, Central Kerala	To evaluate the soil erosion models (WEPP, MUSLE and USG) for sediment yield prediction with the help of measured rainfall, run-off and sediment yield data ²⁷ .	The USG model predicts better than WEPP in data-scarce conditions.
WEPP hillslope model	Sub-catchment of Sitlarao (Dehradun), area 0.57 km ² , rainfall 1753 mm, elevation 920–1200 m	To study the impact of soil hydrological properties on spatial variation of run-off and soil loss ⁶⁶ .	The WEPP model is used to understand the relationship between infiltration, surface run-off and soil erosion process along the hillslope.
WEPP watershed model	Sitlarao watershed (Doon Valley, Dehradun), area 5300 ha, rainfall 1753 mm, elevation 960–1480 m	To evaluate the simulated surface run-off and soil loss data using the WEPP watershed model with the observed data ⁶⁷ .	The surface run-off produced from higher intensity rainfall events (>50 mm/h) is poorly simulated, but surface run-off from low to medium intensity rainfall (<50 mm/h) is well simulated.
WEPP watershed model	Experimental farm (ICAR-NEH, Meghalaya), area 2.19 ha, rainfall 2232 mm, elevation 952–1082 m	To simulate run-off and soil loss from three different conservation practices using the WEPP model ⁴⁵ .	The model overpredicts small run-off values and under-predicts large run-off values. Run-off is highly sensitive to Manning’s roughness coefficient, initial saturation level and effective hydraulic conductivity.
WEPP watershed model	Patiala-Ki-Rao (Ropar, Punjab, Shivalik foothills), area 15.55 ha, rainfall 910 mm	To simulate run-off from a small watershed using the WEPP model ⁶⁸ .	Run-off is sensitive effective hydraulic conductivity followed by slope.
ANSWERS model	Three small agricultural watersheds (Bandi river basin), area 326.82 km ² , 450.33 km ² and 1024.02 km ² , rainfall 300–600 mm, arid climate	To assess the significance of the ANSWERS model in predicting run-off and soil loss in agricultural watersheds ⁶⁹ .	Total soil loss is under-predicted by this model. It gives better run-off prediction on sloping watersheds than on level watersheds.
ANSWERS model	Banha (Upper Damodar Valley, Hazaribagh, Jharkhand), area 1613 ha, rainfall 1255 mm, humid subtropical climate elevation 450–406 m	To simulate run-off, peak flow and sediment yield under various soil moisture and rainfall conditions ⁷⁰ .	Run-off and peak flow are most sensitive to antecedent soil moisture, followed by control zone depth and Manning’s roughness coefficient. Run-off, peak flow and sediment yield are under predicted for small storms (25–50 mm) of medium intensity rainfall (30–45 mm/h).

accurately⁶⁴. The findings of the study demonstrated that run-off is susceptible to changes in the physical environment, such as the effective hydraulic conductivity value, whereas sediment yield is affected by interrill erodibility and effective hydraulic conductivity. The Erosion Database Interface (EDI), in conjunction with the WEPP model was employed to a 1990 ha watershed in southeast Brazil, which allowed the estimation of georeferenced run-off⁷³. Another study on a comparison among three soil erosion models, namely MUSLE, USG and WEPP for small watersheds, concluded that the USG model (conceptual model) assessed better the sediment yield, followed by the WEPP (physical process-based model) and the MUSLE (empirical model) models²⁷. The WEPP model could not predict accurately due to lack of required data and some model parameters related to soil and crop management. This model may be used on hillslope profiles ranging from 100 to 200 m in length and small watersheds of up to 260 ha area⁷⁴.

Data requirement of process-based models

Four input files, viz. climate, topography or slope, soil and management data are required for a process-based model like WEPP. The climate data are generated by CLIGEN (Climate Generator) or Break Point Climatic Data Generator (BPCDG)^{5,27,62,66}. The WEPP watershed model uses climate data such as daily precipitation, maximum and minimum temperatures, dew point temperature, solar radiation, wind velocity and its direction⁶². Channel hydraulic properties like width, depth and their management details, along with various soil properties like soil texture and its composition (percentage of rocks, sand, clay and organic matter), effective hydraulic conductivity, soil layer depth, etc. are also required and need to be collected by field experiments. Also, albedo, cation exchange capacity (CEC), interrill erodibility, critical shear, etc. need to be estimated using the empirical equations^{62,75}.

Major strengths and limitations of process-based models

The WEPP model is a powerful research tool that helps in better understanding of the interaction among land-use pattern, topography and soil condition. Also, it simulates the non-uniformities within the hillslope using several individual overland flow elements, each having uniform or homogeneous soil, slope and management, and a hillslope can be divided up to a maximum of ten units^{56,66,67}. Although process-based models are more scalable than empirical models, model development is hampered by the lack of field observational data on the process parameters and knowledge of the processes across scales^{71,76}. Some of the flaws of the WEPP model include the fact that the

simulated channel processes may only apply at small scales, and erosion processes in traditional gullies and perennial streams are not taken into account⁷². Process-based models often need substantial input data and calibration work, restricting their use to larger areas or those with insufficient observed data^{66,71}. Although WEPP is a physical process-distributed model, it under-predicted soil loss for the Central Kerala region, as it requires a large amount of data and a large number of design variables relating to soil and crop management practices, which are difficult to quantify on a large scale²⁷.

Conclusion

Soil erosion is a challenging issue in India's rainfed and irrigated areas. It is controlled by various parameters like soil properties, land slope, vegetation, rainfall amount, etc. and ultimately affects the agricultural production potential. To minimize the erosion effect, it is essential to comprehend the hydro- and physical dynamics driving soil erosion and its interactions with soil type, cropping pattern and other factors. The various available models may be used to visualize run-off and erosion scenarios in the field, both with and without conservation measures, enabling optimal land-use planning and the identification of sensitive areas. The process-based models may effectively predict run-off, soil erosion, sediment yield under different agro-climatic zones and management conditions. In this direction, WEPP – a continuous simulation and process-based model – is used extensively by various researchers worldwide to determine run-off and erosion. The contextual relevance of this model in various agro-climatic regions of India could be tested to ensure its wide application.

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