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REVIEW PAPER

Utility of Modelling Approach in Simulating the Runoff, Soil Loss and Sediment Yield in Shivalik foothills of India: A Review

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ABSTRACT

Degradation of land due to soil erosion is very crucial problem which cause a huge loss to productivity and human lives. The Shivalik foothills of outer Himalaya region possess some characteristics such as uncertain and heavy rainfall, steep slope and undulating topography, inadequate vegetative cover, frequent landslides, lacking vegetative cover, poor soil fertility which are responsible for making this area very friable and erosion prone zone. Further deforestation and huge biotic pressure accelerate the erosion problem in this area. This area is a transitional zone between high hills and planes and locally known as *Kandi* area. In the Shivalik foothills, annually, 16 t ha^{-1} $year^{-1}$ soil is lost which may exceeds to 80 t ha^{-1} $year^{-1}$ in certain catchment area. To combat with these losses, a significant measurement and prediction of runoff, soil loss and sediment yield is important. Modelling approach provides a suitable tool for simulating and measuring the runoff and soil erosion. Several models are available like conceptual, physically based and empirical that are selected according to the data availability and location suitability. When combined with remote sensing and GIS, empirical and semi-empirical models such as the Morgan–Morgan–Finney model, USLE, MUSLE, RUSLE and SCS curve number technique have proven to be more effective in predicting runoff and soil loss at both the field and watershed scales. Deterministic models such as ROMO2D, DREAM, and WEPP, which were evaluated in several parts of the lower Shivalik, also produced satisfactory results. So, the purpose of this review is to describe the applicability of such Models in Shivalik foot hills for simulating the runoff and soil loss which help in adopting better conservation management policy.

HIGHLIGHTS

- Modelling approaches provide effective tools for assessing runoff, soil loss and sediment yield in the Shivalik foothills.
- Integration of erosion models with remote sensing and GIS improves identification and mapping of erosion-prone areas.
- Appropriate model selection, calibration and validation are essential for reliable assessment and effective soil and water conservation planning.

Keywords: Shivalik foot hills, runoff, sediment yield, soil loss, modeling

Next to climate change, land degradation is a serious hazard to the agricultural sustainability and welfare of manhood. Globally existing rate of land degradation due to various causes leading to an irretrievable damage to nature. The data from the Indian government revealed that land degradation led to an approximately 2.5 % loss of the nation's GDP during 2014-2015 (Sethi, 2015) Soil, a friable covering of Earth is the utmost vital exhaustible and

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non-replenish able natural resource that Nourish all growing lives upon it. Natural calamities along with man triggering events result in soil loss which adversely influences not only the ecosystem but also the economy of a state (Lal, 1998). Most responsible factor consider for land degradation is Soil degradation as it severely destructs the land in all three aspects such as physically, chemically biologically (Chemeda, 2007; Nungula *et al.* 2023; Otieno *et al.* 2023). Land degradation from soil loss issue rising very rapidly at an alarming stage. Out of all continents, the highest soil erosion rate i.e. 165.8 Ton/ hectare/ year was estimated from Asia with 80% sediments accumulation in the global oceans through the rivers of this continent (El-Swaify, 1997). Worldwide several researchers have reported soil loss causing land degradation (Foster and Meyer 1972; Renard *et al.* 1997; Van der Knijff *et al.* 1999; Millward and Mersey 1999; Sadiki *et al.* 2004; Hasim *et al.* 2005; Prasannakumar *et al.* 2012; Ghosh and Guchhait 2012; Aiello *et al.* 2015; Belasri and Lakhouili 2016; Kirui *et al.* 2021). In India, 187.8 million ha (about 57% of the geographical area) area is under various forms of degradation (Sehgal and Abrol, 1994) and it is estimated that about 3.975 million hectors land in India have been degraded due to soil loss (Ghosh *et al.* 2010).

Soil erosion mainly includes two phases; one is the detachment of soil separates from upper soil followed by second phase of transportation of that particle by any active agent like wind and water (Bhandari *et al.* 2015; Bhattacharya *et al*. 2023; Mwakidoshi *et al*. 2023). Soil erosion by water has primary concern for land degradation and deteriorating soil productivity. Globally, Soil of 56 % area degraded due to water erosion whereas 28% of the degraded area has been contributed by the wind erosion (Oldeman, 1994). While in Indian condition, as reported in Wastelands Atlas of India area of around 55.77 million ha is under water erosion causing threatening loss of fertility and productivity of the soil (Kumar, 2004; Zaman *et al*. 2017). Various processes are involved in water erosion like splash erosion, sheet erosion, tunnel erosion, rill and formation of gully which are the extreme forms of degradation of land resources (Ghosh *et al.* 2016). The effects of soil erosion go beyond the loss of fertile land. Soil erosion has both on-site and off-site detrimental impacts and these impacts include less agricultural production due to nutrient degradation, loss of soil structure, compaction, and soil salinity, poor water quality because of increased pollution, hydrological systems imbalance as a result of sedimentation in streams and rivers, and environment contamination (Lal, 1998).

High rainfall induced runoff cause water erosion that led to exclusion of soil sediments from one site and its accumulation to other site and consequently dumping into the river network by watershed outlets. (Rawat and Singh, 2017; Rawat and Singh, 2018a; Edon and Singh, 2019). Along with the other deleterious effects of soil erosion, it also causes mutilation problem in stream channels, shrinking the capacity of stream channels, lakes, and reservoirs via sediments deposition and further increase the maintenance cost of these water ways constructions (Rawat and Singh, 2017; Pradhan *et al.* 2018). It is reported that rivers of Himalayan region contribute a large amount of sediment disposal as compare to other Asian rivers Stoddart (1969).

The Indian Himalayan Region (IHR) is the segment of the Himalayas inside India, spreading over 11 Indian states and association domains, in particular the locales of Jammu and Kashmir and Ladakh directed by India as UTs, and territories of Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, Assam and West Bengal. The Physiographic division of IHR begins from the foothills of south (Shivaliks) and stretches out up to the Tibetan plateau on the north (Trans-Himalaya). Three significant topographical constituents, the Himadri (greater Himalaya), Himanchal (lesser Himalaya) and the Shiwaliks (outer Himalaya), spread out almost in continuation all through its length and are isolated by major geographical separation points. Himalayas were one of the most ecologically delicate and financially weak regions (Tiwari *et al.* 2000). The outer Himalaya area known as Shivalik foothills or Churia Hills one of the eight most degraded eco-frameworks of the state (Singh and Khera, 2011). Shivaliks constituting the north-western foothills of the Himalayas in Jammu and Kashmir (9410 km^2), Himachal Pradesh (8170 km^2), Punjab (5360 km^2), Haryana (1970 km^2), Chandigarh (110 km^2), Uttarakhand (6690 km^2) and Uttar Pradesh (1470 km^2) (Kumar *et al.* 2012; Yadav *et al.* 2015;

Bhardwaj *et al.* 2020). In Submontane Punjab, the area of transitional zone between the Shivalik and plains locally recognized as Kandi area. The area of *kandi* region is approx. 3.93 lakh hectares which comprises approximately 7.8 per cent of total geographical area of the State. This zone is located between 30044′ and 32032′ N latitude and 75052′ and 76043′ E longitude at an elevation of 300-500 m above mean sea level (Sharma *et al.* 2016). Due to deforestation and immense biotic stress on natural resources of this area, reduced its dense forests to devastated terrain and scrubs. Further, these deforested belts with steep slope and undulating relief having uncertain distribution of precipitation, inadequate vegetative cover, frequent landslides, little landholdings, shortage of irrigation system, lacking vegetative cover, poor soil fertility and frequent crop failures resulting in scarcity of food, fodder and make this area more prone to heavy soil erosion (Singh *et al.* 2017; Arora and Hadda 2016; Maitra *et al*. 2024). Annually, 16 t ha^{-1} $year^{-1}$ soil is lost which may exceeds to 80 t ha^{-1} $year^{-1}$ in certain catchment area of this region (Yousuf *et al.* 2016). Water erosion is mainly responsible for soil degradation in this area. A big amount (35-45 percent) of monsoon rainfall runs downstream in the torrents causing severe runoff and soil erosion. For example, runoff and soil loss varied from 20% to 45% and 25 to 225 tons ha $year^{-1}$, respectively, on a small to large watershed in the area (Hadda *et al.* 2000; Sur and Ghuman 1994). Kukal and Sur (1992) estimated that about 20% of the area in kandi region is affected by sever water erosion and turned into gullies. The severity of the problem highlights the need to assess runoff, soil loss, and sediment yield in this region. Numerous methods are available in the literature for estimating and measuring these parameters. Traditionally, conventional techniques were employed for quantifying runoff and soil loss; however, these methods were time-consuming, complex, and labour-intensive. With the development of simulation models, the process has become significantly more efficient, accurate, and less time-consuming. Mathur and Kukal, 2002, studied about the shape of the catchments on the basis of lemniscate ratio, form factor and compactness coefficient. Lemniscate ratio was calculated as the ratio of square of maximum length (L) of the catchment and four times its area (A), whereas form factor was determined as the ratio of average width to the maximum length of the catchment and compactness coefficient as the ratio of catchment perimeter (p) to the area (A) of the catchment as P/2 (π A) 0.5. Contour length method was used to determined average slope of the catchments as Σ CL × CI/A, where CL is contour length (m) and CI is contour interval (m) and n is the number of contours. Average fall in gully slope was determined as the ratio of the difference of elevation at the highest and lowest points of the main gully to the distance between the two points. The runoff rate is measured manually with the help of stage level recorders fitted in each catchment. Kukal and Bawa, (2013) estimate runoff by using conventional method in which stage level recorders installed at the outlet end of each studied catchment. Total runoff amount and volume were determined by the analysis of obtained Hydrograph. In storage tank the sediments are mixed in the runoff by Coshocton wheel samplers and then runoff samples were collected at different time intervals on the onset of rainfall. These runoff samples were then mixed together to get a composite sample for an individual rain event to measure sediment load to monitor the variation in runoff and soil loss in four differentially treated catchments located in lower shivalik region of Punjab and reported that in initial years soil loss during the initial years (1989-1995) of imposition of the treatments was lowest (25.2 t ha^{-1}) in catchment I but during the later period (1996-2006) the trends reversed, i.e. catchment IV recorded the lowest (14.1 t ha^{-1}) soil loss whereas catchment I recorded the highest (23.4 t ha^{-1}) soil loss. The initially reported runoff from untreated catchment was 71 percent higher when compared with treated catchments whereas in later period this alteration reduced to 27 percent.

Singh *et al.* (2017), Evaluate the vegetative barriers for runoff, soil loss and crop productivity in Kandi region of Punjab and for this runoff and soil loss was measured with daily rainfall data that was collected from the nearby rain-gauge installed at the research farm of the RRS, Ballowal Saunkhri. After every shower the depth of water collected from the runoff experimental plots in the collection-tanks with a capacity of 200 litres was measured to calculate the total Runoff. To determine the soil loss, runoff samples were taken after thoroughly churning the runoff collected in collection tank with

a rod, in one litre capacity glass bottles. Similarly, in another study Singh *et al.* (2008) measured the runoff and soil loss from shivalik foothill of Punjab through Plots method in which after each rainstorm, depth of runoff in drums situated in plots was measured using meter rod and was converted to runoff volume. Amount of rainfall received during a rainstorm was deducted from the runoff depth before converting it to runoff volume. PVC containers are used to store a 2L of thoroughly mixed representative sample from each drum and was allowed dried for further calculation of soil loss. Sran *et al.* (2011) also measure runoff and soil loss from micro-catchments of Shiwaliks in the lower Himalayas by conventional method in which all four studied catchments were installed with stage-level recorders for continuous monitoring of run-off at the outlet. Run-off sub-samples were collected in 2-L containers at the outlet end of the catchment at 15-min intervals during a particular rainstorm. These sub-samples collected during a rainfall event were mixed to give a composite sample. The sediment yield from each rainfall event was measured in the composite run-off sample. The run-off water was treated with 50 ml phosphoric acid to cause flocculation and sediment settling. The clear water was then decanted and the settled sediment dried in an oven at 105.8C for 24 h.

Currently, the model approach for estimating Runoff, Soil loss and rainfall fetching more interest comparatively with other approaches as they are economically feasible tools, consume less time and easy to run. Throughout the world, Modelling and prediction of soil erosion is used from more than seven decades (Alewell *et al.* 2019; Bennett, 1939). The major factor responsible for increased utility of modelling approaches in present day is the development of more reliable earth observations data, climatic datasets, remote sensing technologies, and increased big datasets (Alewell *et al.* 2019). However, there is a gap in understanding the validation of soil erosion models with time especially in Indian Himalayan region, because of the non-availability of field observations of erosion in hilly areas (Meraj *et al.* 2017; Pandey *et al.* 2009; Amin and Romshoo, 2018.

Modelling Approach

Conservational management planning of a site requires quantitative estimation of rate and magnitude of soil erosion and the mapping of the susceptible area to know the vulnerable region to soil erosion (Gelagay and Minale, 2016; Zaman and Maitra, 2018). Accurate assessment of soil erosion is a challenging task as it involves the interaction of numerous factors such as climate, soil, relief, land cover and anthropogenic activities. There are mainly three methodologies were categorized for spatial assessment of soil erosion. The first method comprises of computing erosion from experimental erosion plots. The second method is to plot a map of all erosional features captured through satellite images. The third and most widely used method involve integration of spatial data with the different erosion feature with erosion models (Vrieling, 2007). A number of models are presented in the literature for measuring soil erosion and sediment yield but their efficiency varies with each other depending up on the procedures involved, model complexity, data requirement and their utilization. So, prior to selection of any model, it is necessary to have a knowledge of some aspects such as watershed features, goals, data availability, model capacity and efficiency, hardware requirement and input and output variables.

Requirement and Limitation of Models

Measurements of exact rate of soil erosion in any catchment area is very challenging and have a constrain of field data availability for every portion of the catchment over spatial and time scales. It is necessary to generate a sufficient data base based on long term observation to avoid any error caused due to incidence of unusual heavy rainfall only for a short period of few years or any extreme event are also needed in order to investigate the response of erosion rates to alterations in climate and land use or the efficiency of erosion control actions. The impact of climate change, land use and land cover as well as erosion control activities on erosion rates can be observed with a continuous measurement for a long period of time. To deal with these issues, technology-based computer-operated physical models can be utilised to anticipate erosion under a variety of circumstances. For a precise sediment yield modelling, simulation of runoff along with its associated processes is necessary. A rational estimation /quantification of runoff is helpful in

water resource management, minimising the risk of injuries and death rate of people due to prevalence of any calamity. The efficiency of a model depends upon its calibration and, validation (if possible) for a specific condition in terms of temporal and spatial dimensions (Govers, 2011). The calibration of a model with the field data enhances its utility for simulation of erosion in other areas having comparable characteristic. A Model is consider to be valid after comparing the simulation results with actual field outcomes. An ideal model must meet the following criteria: general acceptability, reliability, natural resilience, ease of use with minimal data, and the ability to account for changes in land use, climate, and conservation policies (Pandey *et al.* 2021).

Categorization of Models

Models are classified into three categories based on their use in physical process simulation, data dependency, and model algorithm and equation used: empirical, conceptual, and physically based. Empirical models are mainly dependent on data response characterisation and observations (Wheater *et al.* 1993). In contrast to physically based and conceptual models, which require a huge data set and a complex computational technique, empirical models can work with simple measurements and less data (Jakeman *et al.* 1999). Depending upon the associated processes, the models can further be categorised as stochastic, deterministic, or mixed type (Singh, 1988). As empirical models mainly required experimental plots observations or experience which limits its applicability in other regions. Whereas, conceptual models define numerous diverse viewpoints of associative combination between field studies and spatial data. Therefore, the conceptual models are usually used in the shortage of real-world data availability. However, Physical models are based on fundamental equations that define water and sediment movement (Pandey and Palmete, 2019).

Use of Models in Estimation and Measurement of Soil Loss, Sediment Yield and Runoff

Many investigators have utilised a number of model to estimate soil erosion around the world, including physical models, empirical models, statistical models, and process-based models (Dimotta, 2019). In Fig. 1, the percent use of 18 diverse models including statistical, physical, process based and empirical models to assess soil erosion risk according to their suitability to the location throughout the world are shown (Pandey *et al.* 2021).

The Physical based soil erosion and sediment yield models first invented after the 1970s, when availability of processer computers became very easy. And till now a wide range of very simple to very complex Model are developed with fresh advances continually going on. Recently, several physically based soil erosion and sediment yield models can accurately predict soil erosion and can be used to solve a variety of water resources and environmental concerns.

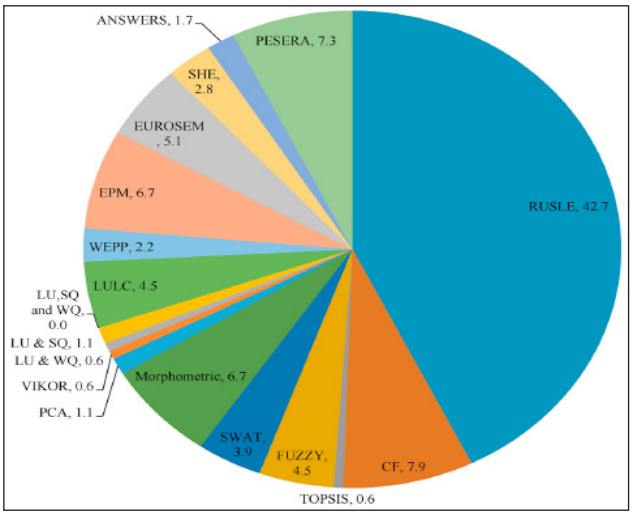


Fig. 1: Percentage of model used for assessing soil erosion vulnerability in various researches (n = 160) (***Source:*** Pandey *et al.* 2021)

For many physical models' soil, topographical, hydro meteorological, and land use data are primary input to work. Some other physical model e.g APEX, EPIC, AGNPS, ANSWERS, MEDALUS, OPUS, GLEAMS, GSSHA, CREAMS, KINEROS, PALMS, PERFECT, SWAT, SWIM, SMODERP, TOPOG and WEPP also need crop management related data. However, few more models, comprise all the three key mechanisms, viz., sediment, hydrological, and chemical, in simulation watershed Characteristic such as ANSWERS, ANSWERS-continuous, AGNPS, AnnAGNPS, CREAMS, DWSM, HSPF, GLEAMS, IDEAL, LASCAM, SWIM, WEPP, OPUS, PRMS, etc. However, EROSION-2D/3D, EPIC, EUROSEM, WATEM and KINEROS like models were designed

exclusively to simulate and predict erosion process in different region (Pandey *et al.* 2016).

Some Physical methods like ANSWERS and SHE have become less popular over time, whereas the use of physical and process approaches like RUSLE, SWAT, WEPP, and PESERA become more popular. It also highlights the fact that a few models, such as PESERA, EUROSEM, and WEPP, are primarily used in a single region.

SWAT (Soil and Water Assessment Tool) MODEL

The USDA Agricultural Research Service (ARS) designed the SWAT model to estimate the influence of land management techniques on hydrology, sediment, and pollutant transport in large river basins over extended time periods (Neitsch *et al.* 2002). The SWAT, an event-based model, is commonly used to simulate hydrologic components of a watershed in order to develop long-term management strategies. It has also been proven to be applicable universally, as it has been examined in a number of countries. SWAT-CUP (SWAT-Calibration and Uncertainty Programs) a decision-making framework was developed for calibration of SWAT models which enables sensitivity and uncertainty analysis (Abbaspour, 2007; Arnold *et al.* 2012; Abbaspour *et al.* 2015, Fu *et al.* 2014). A version SWAT-G was also developed for application to low mountain range catchments of Germany (Eckhardt and Arnold, 2001; Eckhardt *et al.* 2002). The SWAT model was discovered to be the highly adaptable model for a variety of applications, including easy calibration, highly receptive and sensitive for uncertainty prediction (Abbaspour *et al.* 2015; Murty *et al.* 2014; Cibin *et al.* 2014; Arnold *et al.* 2012), climate change (Uniyal *et al.* 2015; Wu *et al.* 2014); pollutant cycling/loss and transport (Zhai *et al.* 2014; Pandey *et al.* 2005); land use change (Nie *et al.* 2011; Quyen *et al.* 2014; Pandey and Palmate, 2019)

For estimating the runoff in Sitlarao watershed situated in Shivalik region of Doon valley of Dehradun three different models SWAT, SWAT-VSA and modified SWAT-VSA (SWAT-Him) were used. The primary mechanism for SWAT is infiltration excess response for runoff other two expected saturation excess. All three models varied in Hydrological Response Units (HRUs) consideration and distribution of Curve Number (CN). Soil Wetness Index (SWI), which signifies the saturation level in the area was combined in runoff modelling by the SWAT-VSA and SWAT-Him. But both the Model have difference in incorporation of land use in runoff modelling; SWAT-Him reflect the influence of land use whereas, SWAT-VSA disregarded land use factor during runoff estimation. SWAT Him better simulated the hydrological processes in the watershed as it took into account two major factors (topographic and land use) for runoff calculation. So out of all three model SWAT Him better simulated the hydrological processes in the watershed since it calculated runoff based on two primary elements: topography and land use (Singh, 2009). Walia *et al.* (2020), simulate the runoff and soil loss by Arc-SWAT and remote sensing for selected upper Patiala-Ki-Rao watershed having ungauged watershed, sub-watersheds and four gauged micro-watersheds situated in Shivalik foothill region of Punjab. Detailed manual calibration and validation followed by statistical analysis evaluate that the SWAT model can significantly simulate the runoff and sediment yield.

WEPP (Watershed Erosion Prediction Project) MODEL

The WEPP model has been widely utilised in simulations of sediment yield and water erosion, and it is one of the most widely used tools in this field. Several scholars have tested and analysed the model in various geographic regions around the world, including (Cochrane and Flanagan, 1999; Yu and Rosewellm, 2001; Renschler. 2003; Pieri *et al.* 2007; Savabi *et al.* 2011; Onsamrarn *et al.* 2020) for estimating runoff and soil loss from different land use and crop management practices. The WEPP hill slope version are further modified as Water Erosion Prediction Project Climate Assessment Tool (WEPPCAT) for controlling and accessing possible climate change impacts on sediment loading to streams (Bayley *et al.* 2010). WEPP deals with a number of other components applicable for various purposes such as WEPP Road is used to forecast road erosion and sediment delivery during road building and maintenance. Disturbed-WEPP is a model for predicting soil erosion after a slope has been disturbed by forest operations. Rock:Clime will create climatic datasets for use with WEPP and other applications (Elliot, 2004). Few studies have

been conducted in India for quantification of runoff and sediment yield using WEPP model (Pandey *et al.* 2008 (karso watershed, Bihar); Singh *et al.* 2011 (Umroi watershed, Megalaya) and Kumar *et al.* 2021 (Dal lake, Jammu and Kashmir). In Shivalik foot-hills Sharma, 2012 evaluate the performance of WEPP model to simulate runoff under heavy rainfall and steep slope conditions. Yousuf *et al.* (2015) also use the WEPP model to simulate runoff and sediment yield from the watershed situated near the Chandigarh within the shivalik foot hill. The model accurately predicted storm runoff, as evidenced by low RMSE (4.59 mm), percent error (11.36), and strong correlation coefficient (0.96) values, as well as high model efficiency (87.54 percent). The model also performed well enough in simulating sediment yield, with an RMSE of 0.33 Mg ha^{-1}, a percent error of 13.83, a correlation coefficient of 0.85, and a model efficiency of 83.18 percent. In quantifying total runoff and sediment yield, the percent simulation error was well within the acceptable limits which stipulate the acceptability of the WEPP model for its imminent use in Shivalik foot-hills. Integrated approach of remote sensing and GIS technologies with the WEPP modelling system in Kaneli watershed situated in Shivalik foothills of Kumaon Himalaya is used to simulate surface runoff and sediment. The model parameters were calibrated using measured data on runoff volumes and sediment yield. Measured data on runoff volumes and sediment output were used to calibrate the model parameters. The distributed pattern of model outcomes can help to identify the zones inside the watershed that may be more susceptible to soil erosion. (Ramsankaran *et al.* 2009). In another study, Sharma and Bhardwaj, 2017 calibrated and validated the WEPP model for a narrow rangeland watershed with an area of 15.55 ha in the Shivalik foothills of Punjab. The model's sensitivity analysis reveals that it is extremely sensitive to the soil's hydraulic conductivity. The model was developed using recorded runoff data from four years (1994-1997, 1998-2001, and 2000-2001). For a study period of validation (1998-2001), statistical parameters to check the performance of model was analysed and found RMSE of 0.56, percent error of 4.9%, high correlation coefficient of 0.93 and model efficiency of 81% which signify the practical accuracy of the WEPP model in simulation of runoff at the watershed scale of Shivalik foothill. When simulation runs were undertaken without two extreme periods of rainfall more than 100 mm, the effectiveness of the WEPP model was significantly increased with (R = 0.99 and model efficiency 97 %). Similarly, Yousuf *et al.* (2017) performed calibration and validation of the Water Erosion Prediction Project (WEPP) watershed model to simulate the runoff and sediment yield from a small forest watershed with an area of 1.85 ha positioned in Shivalik foothills. The outcomes revealed that among all sensitive parameters such as hydraulic conductivity, rill erodibility, inter-rill erodibility and critical shear model is extremely responsive to hydraulic conductivity during the simulating runoff whereas it is sensitive to all identified parameters while simulating sediment yield. So, the model must be calibrated accurately for these delicate parameters. The model simulated storm runoff with model efficiency of 94 (calibrated) and 87% (validated) and sediment yield with efficiency of 86.56 (calibrated) and 82.78%(validated). However, smaller storms, are better simulated by the model than larger storms. Therefore, the WEPP model performed well in terms of runoff and sediment yield simulation and measurement, and hence may be utilised with certainty within that location (Yousuf *et al.* 2017). In another study, Singh *et al*. (2020) quantified daily runoff and sediment yield from a small watershed in the Lesser Himalayas using the GeoWEPP model. The model utilizes input data such as land use/land cover (LULC), slope, climate, soil characteristics, and land management practices. Calibration was conducted using observed data from 2015, while validation was performed for the years 2016 and 2017. Sensitivity analysis identified effective hydraulic conductivity, critical shear stress, inter-rill erodibility, and rill erodibility as the most influential parameters. Model calibration yielded strong results, with correlation coefficients of 0.92 and 0.94, and Nash–Sutcliffe efficiency (NSE) values of 0.67 and 0.85 for daily runoff and sediment yield, respectively. The model demonstrated good performance, with high coefficients of determination (R^2 = 0.85 for runoff and R^2 = 0.95 for sediment yield) and low root mean square error (RMSE) values of 4.35 mm and 2.53 t ha^{-1}, respectively. Using a geographic information system (GIS) in combination with the water erosion prediction project (WEPP) model, major erosion prone regions in the Patiala-ki-Rao watershed in the Shivalik foothills were

investigated. The simulated sediment yield obtain through WEPP appears to be moderate (16.80 t ha^{-1}) at the watershed channel, However, sediment yields at the slopy foothills are quite high, varing from 0.03 and 165.53 t ha^{-1}. The GIS based sediment yield data of hill slope area of watershed was analysed and a detailed distribution of significantly eroded areas within the watershed was derived in the form of different erosion classes. According to the findings, around 35.96 percent area of the Patiala-ki-Rao watershed is prone to critical erosion (Sushanth *et al.* 2019a). Sushant and Bhardwaj, (2019b) also used WEPP model to quantified and simulate Runoff and sediment yield in *Patiala-ki-Rao* watershed. The model was successfully simulate the runoff and sediment yield, with an efficiency of more than 85%.The WEPP model was used to estimate runoff and sediment yield for the years 2006 and 2016 using two climate scenarios (2006 and 2016). Due to changes in land use over a ten-year period, the simulated runoff, sediment output, and sediment delivery ratio increased by 18.62 percent, 48.04 percent, and 32.23 percent under Climate-2006 and 26.78 percent, 30.23 percent, and 16.09 percent under Climate 2016.

USLE, MUSLE and Revised Universal Soil Loss Equation (RUSLE)

The RUSLE was advanced version of USLE developed by Renard *et al.* (1997) with a special advantage over the USLE as it includes empirical approach in addition to process-based characteristics (Maqsoom *et al.* 2020; Yoder *et al.* 2004). Due to its spatial characteristics and simplicity the RUSLE model has become an extensively recognised model and effective method for assessing soil loss all around the world (Tsegaya and Bharti, 2021). The development of RUSLE model helpful in predicting long term average annual rate of soil erosion on slopes using data on rainfall, soil type, topography, crop system and management practices on a large area (Mondal *et al.* 2016; Maitra *et al*. 2026) The RUSLE model's implementation necessitates the computation of the many parameters influencing erosive processes, as well as their spatialization in the form of thematic maps. Further, with the integration of these data with GISit become feasible to superimpose them and calculate the rate of water erosion using the formula $A = R*K*LS*C*P$ where, A = soil loss (t ha^{-1} yr^{-1}), R = rainfall erosivity (MJmm ha^{-1} h^{-1} yr^{-1}), K = soil erodibility (tha MJ^{-1} mm^{-1}), LS = topographic factor (dimensionless), C = soil use and management factor (dimensionless), P = soil conservation practice factor (dimensionless). RUSLE also have capability of simulating Sediment yield in a watershed receiving data inputs from GIS and RS (Bera, 2017). Because of its ease of use and compatibility with GIS, RUSLE has been widely used throughout world to estimate soil loss in addition to assessing soil erosion and figure out the effective soil erosion management plans. (Millward and Mersey, 1999; Jain *et al.* 2001; Dabral *et al.*2008; Pandey *et al*. 2009; Zhou *et al.* 2014; Shivhare *et al.* 2018; Borrelli *et al.* 2020; Benchettouh *et al.* 2021; Fu *et al.* 2021). Chauhan *et al.* (2020) use RUSLE model and GIS for assessing the average annual soil erosion quantitatively in Ghaggar river basin a parts of lower Shivaliks has been made using the GIS RUSLE model outcomes revealed that the areas having higher LS- Factor and rainfall were more prone to soil erosion. The area about 64.70 percent in Ghaggar river basin comes under the category of very severe soil erosion (>40 t ha^{-1} y^{-1}) of the total area.

The Ratmau-Pathari Rao watersheds situated in Haridwar district of Uttarakhand includes middle Shiwalik hill slope. The RUSLE (Revised Universal Soil Loss Equation) with Geographic Information System (GIS) technique used for predicting the various factors related to soil loss and the spatial patterns of soil erosion risk required for land degradation assessment. Soil erodibility (K) factor in the sub-watershed ranged from 0.30 to 0.42 (Lal *et al.* 2017).

Goerge *et al.* (2021) in their study used different high-resolution geospatial data layers such as Global rainfall erosivity database, SOILGRIDS, CartoDEM, and LULC data to predict the average annual soil erosion and risk area in the Uttarakhand State of the Indian Himalayan region using the Revised universal soil loss equation (RUSLE) model in a GIS framework. These data layers give spatially distributed information related to the factors responsible for erosion. The average annual soil erosion rate was estimated to be 27.45 t ha^{-1} yr^{-1}, resulting in a potential soil loss of 119 Mt yr^{-1} in the state. In different physiographic regions of Himalayan total soil loss amounts were predicted

to be 2.94, 5.08, 5.35, 7.48, 15.55, and 82.88 Mt yr^{-1} from Tarai, Trans-Siberian, and Trans-Himalayan Bhabhar (foothills), Shivalik, Greater Himalaya and Middle Himalaya, respectively. About 20.34% of the total considered area is fall under very severe erosion class (>40 t ha^{-1} yr^{-1}). The soil loss and the spatial patterns of soil erosion risk in Pathri Rao sub-watershed located in the Shivalik physiographic area of Haridwar, Uttarakhand was estimated to plan the conservation strategy. For this the RUSLE-3D (Revised Universal Soil Loss Equation-3D) model was assimilated with remote sensing and GIS. Soil erodibility factor and soil Maps were prepared with the help of high-resolution data (IKONOS and IRS LISS-IV) and three-dimensional topographic factor was produced by Digital Elevation Model (DEM). Soil erodibility (K) factor varied from 0.30 to 0.48in the sub watershed of the area. The highest average soil loss was estimated in open forest while, lowest in the very dense forest in the hilly area. The area about 15 percent of the sub-watershed has a 'moderate' to 'moderately high' risk of soil erosion, whereas 26 percent area has a high to extremely high risk. (Kumar and Kushwaha, 2013). Similarly, Kushwaha and Bhardwaj, (2016) use RUSLE model to predict average annual soil loss in micro-watersheds of Takarla-Ballowal watershed lies in Shivalik foot-hills of Punjab, India for prioritization of this watershed. The range of average annual soil loss was lying between5.73 tons ha^{-1} yr^{-1} in MWS-8 to 63.46 tons ha^{-1} yr^{-1} in MWS-1 among all selected micro-sheds (MWS-1 to MWS-8). The micro shed having soil loss greater than 50 tons ha^{-1} yr^{-1} fall under very high priority category while micro-watersheds having 35.30- and 30.34-tons ha^{-1} yr^{-1}soil erosion rates lies in high priority categories. Revised universal soil loss equation (RUSLE) model with sediment delivery ratio (SDR) was integrated with high resolution remote sensing (RS) and geographic information system (GIS) to estimate Soil Erosion and sediment loss in a watershed located in north-western Shivalik region of Himalayan, Uttarakhand, India. In the watershed, a soil erosion risk map based on the RUSLE model found that 36.4 percent of the region is at high to extremely high risk of Soil Erosion. Cropland Soil Erosion ranges from 10.61 to 16.08 ton $ha^{-1}yr^{-1}$, while dense forest and open scrub cover were expected to be 4.14 and 26.04 $tonha^{-1}yr^{-1}$, respectively. The use of soil and sediment clay ratio found most appropriate method for calculating SDR and sediment loss for sub-watershed prioritization. Singh *et al.* (2019) and Bhat *et al.* (2012) develop a sediment yield model using the event wise historical observations on runoff and sediment yield of a forest micro- watershed in Shivalik foothill. The model can be utilized for predicting the event wise sediment yields by MUSLE. The estimated values of sediment yield by MUSLE were found very close to observed values which makes the use MUSLE model feasible for similar watershed in the region. One more study was carried out in Kandi area lies in shivalik foothills of Punjab to quantify and map the potential soil erosion by the application of Universal Soil Loss Equation (USLE). The estimated and calculated values of soil erosion shows a positive correlation with each other (Saluja and Alam, 2017).

Duggal *et al*. (2000) used historical observations of a micro-watershed situated in the Patiala-Ki-Rao catchment, along the Shivalik foothills, to create runoff and sediment yield models. MSEDIMENT, a computer software, was created to calculate peak runoff rates based on runoff depths and sediment output. The calibration and validation of peak runoff rate, runoff depth and sediment yield models were done for micro-watershed II using (Modified Universal Soil Loss equation). However, in most of the storms the simulated sediment yields and peak runoff rates are strongly agreed with the historic values while simulated runoff depths differ about 30% from the historic values. Further the same models were used to predict the peak runoff rate, runoff depth and sediment yield for micro-watershed I and the outcomes assured the validity of models for *Pariala-Ki-Rao* region of Kandi area of Punjab.

The study was conducted in the Bino watershed under river Ramganga, a major tributary of the river Ganga that originates in the and drains into river Bino Erosion tolerance index (ETI) was computed by integrating potential annual soil loss by Rusle and soil loss tolerance limits by Fuzzy technique for each landscape unit for the Bino watershed of Ramganga catchment situated in Chamoli district of Uttarakhand comes under outer Himalayas (Shivalik region) in Uttarakhand. Digital elevation models (DEMs), remote sensing, and geographic information systems were used to create the thematic maps (GIS). Potential annual soil loss varied from 0.49-3.64, 1.93-8.83, 4.07-55.49 Mg

ha^{-1}and calculated soil loss tolerance limit (SLTL) values from 3.1-10.0, 5.0-10.0 and 6.7-10.0 Mg ha^{-1} in the lower, middle and higher slopes, area of watershed, respectively. The in the study ranged for lower, middle and high slopes varies, respectively. However, the highest (0.38) weighted ETI value has been observed for Syalde and refer as least priority area for sub-watershed and the lowest (0.212) for Gaya Gadhera sub-watershed denoted as highest priority area. This method of computing ETI and developing prioritization map could be used by policymakers to decide on an appropriate watershed management plan (Sudhishri *et al.* 2014).

Fuzzy Model

Zadeh in 1965 first time proposed the concept of fuzzy logic modeling, in which instead of numerical values the linguistic variables are considered to simplify the expression of instructions and evidences. Fuzzy logic is a formal mathematics theory that permits the determination of a realistic solution to complex, indeterminate, and formless issues (Bojorquez-Tapia *et al.* 2002). Fuzzy sets, membership functions (MFs), and fuzzy production rules are the three key modules of a common fuzzy system Cohen *et al.* (2008). Through fuzzy modelling and a scoring scheme, the indicator values were converted into dimensionless scores ranks ranging from 0 to 1 (McBratney and Odeh, 1997). A fuzzy rule-based system (FRBS) using the Takagi-Sugeno-Kang approach has been developed for Rainfall Runoff Modeling (Casper, *et al.* 2007). In past also fuzzy logic modelling has been used to solve a variety of engineering problems, including traffic junction management, water treatment, water level forecasting, stream flow prediction, and rainfall-runoff modelling Chang, 1996; Chau *et al.* 2005; Tayfur and Singh, 2006; Altunkaynak and Şen 2007; Özger 2009; Altunkaynak 2010; Lohani *et al.* 2011; Wang and Abdusselam, 2012). It was observed that the use of this method has increased from 2011 to 2019 (Pandey *et al.* 2021).

Hadda *et al.* (2017) tried toassess the soil loss tolerance in submontane Punjab using five factors *viz*., infiltration rate, bulk density, erodibility, organic carbon and soil pH through Fuzzy techniques in Sub montane Punjab. In order to turn each indicator into a unit less scale in the form of 0 to 1 integers, a link was constructed between five variables and corresponding indications. As a result of the aggregated score, the soils were divided into three groups: I, II, and III. The finding revealed that Ballowal-Saunkhari were more tolerant to soil loss compare to other sites Binewal, Dallewal, Bhadiar and Kokowal. Whereas, tolerance to soil loss was less in Majari soils having low aggregate score and fit to soil group I.

Morgan Morgan Finney (MMF)

Morgan-Morgan Finney model is an intermediate semi-empirical erosion model (Morgan *et al.* 1984). The Morgan–Morgan–Finney model has been used effectively in various environmental zones such as, hills lope, field plot and micro watershed level in Malaysia (Morgan and Finney, 1982), the Rocky Mountains of the USA (Morgan, 1985), Indonesia (Besler, 1987), Nepal (Morgan, 2001), Kenya and Tanzania (Vigiak *et al.* 2005), UK (Morgan and Duzant, 2008), Northwest Tunisia (Strek 2021). The model along with GIS is used to assess erosion in Mediterranean Europe (Paracchini *et al.* 1997 and De Jong *et al.* 1999). Amin and Romshoo (2018) use Morgan Morgan Finney (MMF) along with universal soil loss equation (USLE), in GIS environment to evaluate the soil erosion, influenced by soil type, topographical features and land use/ land cover, in a hilly watershed situated in the Kashmir in Shivalik Himalayan region, India. From both the model, sensitivity analysis categorises the equal region of the watershed under the class having erosion > 10 kg m^{-2} year^{-1}. MMF model were used with geospatial approach to evaluate the actual soil erosion as well as sediment yield with reliable accuracy of a sub watershed of Sutlej River basin located in Shivalik region. The model provides significant evaluations of sediment yield from sub-watershed with maxi. ±36.5 and mini. ±3.93 percent deviation from actual observations. (Rajtantra *et al.* 2013). Similarly, Jasrotia and Singh (2006) figure out the annual spatial soil loss estimation by using the Morgan– Morgan–Finney mathematical model in combination with remote sensing data and GIS systems in Jammu lying-in North-west Himalaya region of Shivalik foothills. From the north western part of catchment about 31 km^2 area, the maximum average soil loss greater than 20 t ha^{-1} was recorded.

SCS CN

An attempt has been made to estimate the runoff due to rainfall occurred in Koshiallia watershed; located in Haryana rises in the lower Shivaliks at the foot of the Himalayas and joins river Ghaggar. Modified version of SCS-CN Model which also comprises some more parameters such as – catchment area, drainage map, land use/ land cover is used in conjugation with Remote sensing data for predicting runoff using land cover, soil type and predicted rainfall value. ERDAS Imagine software is used to test the classification accuracy assessment and classification Model calibration and validation performance between the observed and simulated surface runoff data were evaluated using graphical and statistical methods. Estimated runoff is compared with the runoff calculated with the actual rainfall data for the year 2010, a good correlation (R^2 = 0.973) has been found between observed and computed runoff (Soni, 2013). Chandel and Hadda (2017a) used soil conservation service-curve number (SCS-CN) approach and their modifications with the aim to choose the best model of the 8-different employed models in estimation of surface runoff for *Patiala-Ki-Rao* watershed, district SAS, Nagar, Punjab. The on the basis of Root Mean Square Error (RMSE), Coefficient of Determination (R^2), Nash- Scutcliffe Efficiency (NSE), and Percent Bias (PB)the model's performance was evaluated. The NRCS model (M5), which used mean and median values of the soil moisture retention, worked best among the analysed and tested models, with a score of 32 and 31 in *Patiala-Ki-Rao* watersheds. In similar way again Chandel *et al.* (2017b) compute the surface runoff from Saleran and *Patiala-Ki-Rao* watershed employing five different empirical methods including the original SCS-CN method. Based upon various statistical performance tools a score was define for each method. Proposed empirical method (M5) when compared with original SCS-CN and other methods based on RMSE, NSE, PB, residual error and coefficient of determination show best performance in Saleran as well as in *Patiala-Ki-Rao* watershed. In Rupnagar (Punjab) during 2019 floods, SAR interferometry-based flood mapping and Soil Conservation Service curve number (SCS-CN) runoff modelling employs Sentinel-1A satellite data in the C-band with VV (vertically emitted and vertically received) and VH (vertically emitted and horizontally received) polarisation channels along with DEM application. The predicted runoff reasonably interrelated with the rainfall occurrence having R^2 = 0.93. On August 18, 2019, the highest runoff recorded was 350 mm, with an average daily rainfall of 120 mm. (Tripathi *et al.* 2021).

Other Model

ROMO-2D a physically based distributed numerical model, established to estimate event-based runoff from minor agricultural watersheds. The model simulates infiltration and soil moisture dynamics in the vadoze zone under variable rainfall conditions using the 2-D Richards equation,while runoff is predicted by employing the stage-discharge Manning's equation along with 2-D Saint-Venant equations under the kinematic wave approximation. To simulate runoff from a 1.45 ha agricultural watershed located in the Shiwalik foothills region of India, the performance of the developed model was evaluated. The results indicated that the model effectively simulated runoff from small agricultural watersheds during individual storm events (Bhardwaj and Kaushal, 2009a; Bhardwaj and Kaushal, 2009b). In Lower Shivaliks of India Parameterization of EROSION-3D Model was designed under Simulated Rainfall Conditions to evaluate prediction techniques in which four rainfall experiments, each with a dry and wet run, were undertaken on a research farm of the Regional Research Station Ballowal Saunkhri under various land use conditions. For resistance to erosion and surface roughness estimated by two different methods for experimental conditions produced the values having a good relation with experimentally determined values. So, existing estimating methods, are assumed to be suitable to the Shivalik mountain situations (Lenz *et al.* 2018). Kaundal *et al.* (2020) design soil erosion vulne *Rabi* litymodel based on rank sum rule method to interpret the soil vulnerability of Bist Doab in Punjab. The model use main six parameters of the region *e.g.* Rainfall, Vegetation, Slope, Soil, Drainage and land Use and land cover change for a simple and calculation based combined analysis of multi class maps. The very slight vulnerable zone covers about 10.86 percent of the whole research area, whereas the slight susceptible zone covers 31.98

percent. 20.45% of the area was in the moderate susceptible zone, 23.43 percent was in the high vulnerable zone, and the rest was in the extremely high vulnerable zone. The areas about 12.40 percent lies along Shivalik Hills in the blocks *e.g.* Talwara, Bhunga, eastern side of Hoshiarpur-II, Hazipur and small patches in Mahilpur, Garhshankar, Saroya and Balachaur comes under Very High soil erosion vulnerability zone.

Remote Sensing and GIS

In mapping of soil erosion risk in agriculture, forest, and degraded land, remote sensing (RS) technology plays a significant role (Kushwaha and Yousuf, 2017) Different models can also successfully be integrated with remote sensing data, geographic information system (GIS) and digital elevation model (DEM), and provide a rapid and detailed assessments of erosion threats (Jain *et al.* 2001; Kouli *et al.* 2009). Therefore, presently models with remote sensing and GIS integration capabilities are usually preferred to get more significant outcomes. Kudrat, 1997 described the utility of remote sensing and GIS techniques in quantitative modelling of actual and potential sediment yields and the Erosion Index of Watershed in Song Watershed (Doon valley, Dehradun district, India). Sushant and Bhardwaj, (2019), were used remote sensing and Geographic Information System (GIS) to attain the characteristics of *Patiala-Ki-Rao* watershed, located in *Shivalik* foot-hills of Punjab, for identifying the suitable runoff potential zones. For this, multi criteria decision making techniques integrated with thematic layers of slope, land-use and soil texture data obtained from GIS. High, moderate, and low runoff potential zones, respectively, covered 13.74 km^2 (26.73%), 21.87 km^2 (42.55%), and 15.79 km^2 (30.72%) of the total area. The upstream area possessed moderate to high runoff potential, while the downstream portion had the least runoff potential. Through scalogram modelling, super imposition of geo morphological maps, lithology, land and use slope, was done to delineate Erosion intensity zones in Dabka watershed located in outer part of Lesser Himalaya (Shivalik group) in Kumaun, Himachal Pradesh. In this modelling approach, Erosion Hazard Index (EHI) is used to assess soil erosion hazard Five major factors such as slope, geology, land use pattern, soil types and geomorphic features have been identified by comprehensive field data and GIS mapping, whereas stream discharge and sediment load modelling were used to estimate two main factors, i.e. soil erosion intensity and run-off from four sample micro-watershed in terms of slope, soil type and land use pattern. The estimated erosion rate for a period of 3 years (2006–08) is estimated as 0.92 mm/year (302 tons km^{-2} yr^{-1}) in the agricultural land, 1.21 mm/year (398 tons km^{-2} yr^{-1}) in the barren land, while in the forest land, it varies between 0.20 mm/year (66 tons km^{-2} yr^{-1}) under dense forest land and 0.40 mm/year (132 tons km^{-2} yr^{-1}) under open forest/shrubs land. Least disturbed dense forest has 5–6 times less erosion intensity as compare to most disturbed agricultural and barren land (Rawat *et al.* 2011). Singh and Singh (2020) employ the IRS data of LISS IV, Cartoset-1 merged satellite data, ASTER DEM and ArcGIS-10.2 software in Dholbaha watershed, located in the *Kandi* region of Punjab for morphometric analysisof the watershed area. The watershed's circularity ratio (0.412), form factor (0.51), and elongation ratio (0.72) signifying that it is less elongated in shape, associated with medium to high relief, moderately permeable subsoil conditions leading in moderate peak discharge, and moderate runoff volume resulting in significant soil erosion.(LPU)Similarly, Walia *et al.* (2018) and Walia *et al.* (2020) also used Remote sensing and geographic information system (GIS)along with ArcGIS 10.3 to enumerate the watershed characteristics through morphometric parameters with hypsometric and erosion aspects, located in upper *Patiala-Ki-Rao* catchment lying on Shivalik hills of SAS Nagar district of Punjab and Panchkula district of Haryana, India. Soil, slope, and land use thematic layers were prepared using a 9-year data of runoff and sediment yield for all these micro watersheds and with the help of GIS overlay technique, erosion vulnerable areas were identified and further classified into high, medium and low priority areas susceptible to erosion. This analysis becomes very useful for comparing, planning, implementing, and controlling soil erosion in similar watersheds. With the application of Geospatial-statistical techniques about 52 % area of sub watersheds of Suketi watershed was found to lie in moderate to high erosion and runoff susceptible zones which needs soil and water conservation on priority basis (Singh and Singh, 2018). Remote sensing and GIS techniques, principal component

analysis (PCA) and metamorphic characteristics are consider to check the runoff potential and soil erosion risk from selected six basin catchments that are Chohal dam (C1), Dholbaha dam (C2), Thana dam(C3), Janauri dam(C4), Damsal dam(C5) and Patiaria dam (C6), situated in Shivalik foothills of North-West India. Prioritization time can be decreases by the application of PCA as it considered only highly correlated parameters. In ArcGIS 10.4.1 software (Archydro tool), high-resolution ALOS PALSAR digital elevation model (DEM) was used to demarcate the selected catchments. The lower values of the form factor (0.28–0.64), elongation ratio (0.59–0.79) and circularity ratio (0.23–0.36), specified the higher risk of soil erosion in the catchments. Furthermore, higher drainage density, drainage texture, bifurcation ratio and stream frequency values indicate the increased runoff potential, which would exacerbate soil erosion. Storage capacities of these reservoir catchments considerably decrease due to sediment inflow which emphasizing the adoption of suitable land and water conservation practices to maintain the maximum reservoir storage volumes. (Singh *et al.* 2021).

In Naula watershed of Ramganga reservoir of Himalayan from India, a simple spatially distributed model was framed in GIS environment for mapping vulnerability of areas to soil erosion and sediment deposition. Using eight years of historical sediment yield data, the model's spatial distribution capacity was tested at the outlet as well as three upstream gauging locations. The model estimation value of seasonal sediment yield have an error <30%. (Rawat *et al*. 2017) Sediment yield was estimated the Randigad catchment located in Pauri district of Uttarakhand situated in Shivalik range with the integrated application of remote sensing and GIS techniques and sediment yield index. The whole catchment area possesses a very low annual sediment yield i.e. 0.147 M $m^3/yr \times 10^3$ (Kandpal and Joshi, 2018).

CONCLUSION

The review highlighted the wide scope of modelling approach in computing runoff and soil loss and the need to increase the frequency of researches to compare efficacy of some new hydrological models with accurate input data in this fragile *Shivalik* foothills. The integration of remote sensing and GIS with the different models also helpful in accessing the erosion prone area in spatial and temporal scale. The integrated approach of hydrological models along with remote sensing and GIS provide a promising solution to decision makers to design a better soil and water conservation structures along with best management strategy for reducing the problem of soil erosion in the *Shivalik* foothills.

GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

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