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Research Article

Development of Daily Rainfall Erosivity Model for Dehradun, Uttarakhand, India

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Abstract

The main objective of present study was to develop an erosivity model for Dehradun district of Uttarakhand State of India to estimate the erosivity index values and to find the most effective relationship between erosivity index and daily rainfall values for Dehradun. Two types of relationships viz. linear and exponential relationships between erosivity index and daily rainfall values have been developed in this study. The relationships are: Linear relationship: $EI_{30} = 17.2410\ P - 305.09$ ($R^2 = 0.987185$), *Exponential relationship:* $EI_{30} = 0.569\ P^{1.702} - 0.00065$ ($R^2 = 0.968175$). *The performance of the models was also evaluated using statistical indices such as absolute prediction error and coefficient of efficiency. From this study, absolute prediction error was found to be 13.09 % and 19.58 % for linear and exponential relationship respectively. Coefficient of efficiency was found to be 99.24 % and 98.54 % for linear and exponential relationship respectively. Both the developed models are valid for Dehradun region. However, the linear model was found to be better on the basis of evaluation criteria. The model developed by Central Soil and Water Conservation Research and Training Institute is not applicable as per the recent trend of rainfall pattern for Dehradun.*

Keywords: *Daily rainfall erosivity model, Soil conservation, Erosivity index, Dehradun.*

1. Introduction

India is a country with more than fifty percent of its population, depends upon agriculture for their livelihood, but the contribution of agriculture in GDP is just 14 percent, which is causing underemployment or disguised employment. Over-dependence on agriculture is resulting in over exploitation of agricultural land, which is making soil more vulnerable to erosion, along with other natural and anthropogenic (human induced) causes **(Rawat *et al.*, 2013)**.

Progressive degradation of soil leading to soil erosion is the major cause for low productivity in agriculture. Soil erosion involves two processes which are as follows: The detachment of individual particles from the soil mass, and their conveyance by erosive agents such as flowing water and wind **(Neto, 1979; Ram Babu *et al.*, 1978)**.

Four basic steps in erosion process (**Wischmeier, 1959; Wischmeier and Smith, 1958)** are detachment by raindrop splash, transportation by raindrop splash, detachment by surface runoff and transportation by surface runoff. Scientific planning for soil conservation and water management requires knowledge of the relationship among those parameters that cause the soil loss or reduce it. These parameters are found by cautious study of the controlled experimentation **(Raghunath and Erasmus, 1971)**.

The reasons for modeling erosion are:

1. Erosion models can be used as prediction tool for conservation planning, project planning and management.
2. Erosion models give the idea of erosion process as well as the time and amount of possible erosion at the area of interest so as to follow planner to reduce erosion.

USLE is a prevalent prediction model to estimate long term average annual sheet and rill erosion. Universal Soil Loss Equation (USLE) was established to enable planners to estimate and predict the average annual rates of soil erosion. Storm erosivity index values besides other factors are required as an input for the equation to determine soil erosion. Some other important uses of erosion index (EI) values are as follows: (i) the accurate classification of rain storms according to their soil eroding potential is greatly facilitated by the use of EI. This is an efficient tool in analysis of accumulated data for the effects of slope cover and management. (ii) Accurate evaluation of the erosivity of different soils from the soil loss data. (iii)

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Factors describing cover and management effects can be evaluated by using the average erosivity index values during the year.

The conventional methods used to compute erosivity index requires a continuous recording of rainfall event which can be done only with the help of recording type rain gauges **(Ateshian, 1974; Bullock *et al.*, 1990)**. However, there is only few number of stations in the country where such gauges are installed. Moreover, they are costly to install and involve the aid of trained staffs. The process for estimating erosivity index from the data of these rain gauges is also quite multifarious **(Cecilio *et al.*, 2013)**. But there is a network of standard non recording gauges all over the country. In the present study, an attempt has been made to establish a relationship between observed daily rainfall amount and erosivity index for Dehradun, Uttarakhand.

2. Materials and Methods

This section describes the collection and formulation of rainfall data, determination of erosivity index, development of relationships between erosivity index and rainfall and quantitative performance of the models based on statistical indices.

2.1 Measurement and Collection of Data

Rainfall is the main form of precipitation, and it is measured with recording and non-recording rain gauges. Non-recording rain gauges measure only the total depth of rainfall, whereas automatic rain gauges record the depth of rainfall as well as its distribution with time. The recording rain gauge data can be obtained from the rain gauge chart or by data logger. The rain gauge charts are changed every year. The hourly rainfall data from recording type raingauge for Dehradun was collected from National Data Centre, India Meteorological Department, Pune. Dehradun is located between latitudes 29 °58' N and 31°2'N and longitudes 77° 34' E and 78°18'E, at the foothill of Himalaya's Shivalik range. Elevation of Dehradun is 640 m above mean sea level. Eight rainfall events, having magnitude greater than 17.7, were selected from a period of 6 years viz.2002-2007.

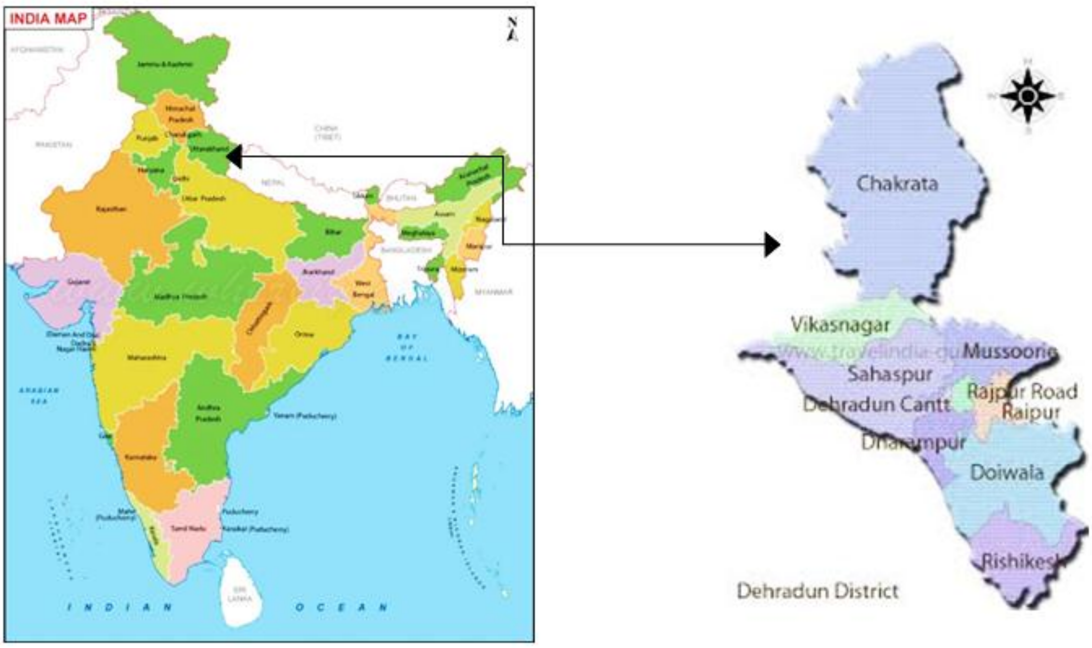

Fig. 2.1 Map showing the location of Dehradun in Uttarakhand, India

2.2 Classification of Models

There are dozens of erosion prediction models. Some models focus on long-term (natural or geological) erosion, as a component of landscape evolution. However, many erosion models were developed to quantify the effects of accelerated soil erosion i.e. soil erosion as influenced by human activity **(Haith and Merill, 1987; Kusre, 1995).**

These models can be categorized into three types based on the mechanism considered in the development of the model. These are: Empirical Models, Conceptual Models and Physically Based Models.

Empirical models are developed with the help of the inductive logic, experiences and experimental results. These models, in most cases, are valid over the region and the conditions for which these are developed. Also, more expensive and time-consuming experiments are required to collect the data necessary to calibrate these models. USLE **(Wischmeier and Smith, 1978)** and Sediment Delivery Ratio Method **(Renfro, 1975; Tiwari, 1986)** are examples of empirical models. Questionable validity of empirical models on the area outside North America, where it was developed, and requirement of large experimental and field data in estimation of erosion forced soil scientists to work for physically based models **(Selker *et al.*, 1990; Singh *et al.*, 1981)**.

Physically Based Models are intended to represent the essential mechanisms controlling erosion process. These models are the synthesis of individual component that affect the erosion process **(Zhang *et al.*, 2005)**. CREAMS, SWRRB and WEPP are examples of process based models.

Conceptual models lie somewhere between physically based models and empirical models. These models use the concept of unit hydrograph to predict sediment yield. **Rendon-Herrero (1974)** was probably the first to use unit hydrograph concept to derive Unit Sediment Graph (USG) for a small watershed. Sediment Concentration Graph **(Johnson, 1943; Elangovan and Seetharaman, 2011)** is an example of conceptual model.

2.3 Determination of Erosivity Index

Rainfall erosivity (R factor) describes the soil loss potential caused by rainfall. It is calculated from two rainfall characteristics; total kinetic energy (E) of the storm times its 30 minutes intensity (I_{30}). This product tells the combined potential of rainfall impact and turbulence of runoff to transport dislodged soil particles from the field **(Das *et al.*, 1967; Wischmeier and Smith, 1978)**.

The erosivity index is given by:

$$EI = E.\ I_{30} \quad (2.1)$$

where, E is the Kinetic energy in MJ/ha and I_{30} is the 30 minutes maximum energy in mm/h.

EI is an abbreviation for energy time's intensity and the term should not be considered simply as an energy parameter. The data show that only rainfall energy is not a good indicator of erosive potential **(Erasmus *et al.*, 1970; Satapathy, 2000)**. The storm energy indicates the volume of rainfall and runoff, but rain of lower intensity occurring for a longer duration may have the same energy value as a short duration rain of much higher intensity. The I_{30} components specify the prolonged peak rates of detachment and runoff. Thus, the term erosivity index is a statistical interaction that shows how total energy and peak intensity are combined in each particular storm. Technically, it indicates how particle detachment is combined with transport capacity **(ARS, 1961; Jaiswal, 1982)**.

In practice, the total of the storm energy is calculated for time intervals of equal intensity with the help of the following equation (**Foster, 1981**).

$$E=\sum ej\ .\ pj \quad (2.2)$$

in which,

$$ej= 0.119 + 0.0873 \log_{10} Ij \ ; \quad Ij \leq 76mm/h$$
$$ej= 0.283; \quad Ij > 76mm/h \quad (2.3)$$

where, ej is the Kinetic energy for time interval j in MJ/ha-mm, Ij is the intensity of rainfall for time interval j in mm/h, E is the energy for the event in MJ/ha and Pj is the rainfall for time interval j in mm.

A limit of 76mm/h is imposed on intensity 'I' because medium drop size, which directly affects the rain intensity, does not continue to increase when intensities exceeds 76 mm/h **(Laws and Parson, 1943; Das *et al.*, 1966)**.

Rainfall of less than 17.7 mm is not included in the computation of erosivity index in the present study in reference with the observations made by **Wischmeier and Smith (1978)**, who observed that rains lower than 15 mm are usually very less for practical significance and have very little effect on monthly percentage of erosivity index **(Gordon and Madramootoo, 1989; Meusburger *et al.*, 2011)**.

The storm wise erosivity index values are calculated by using the continuous record charts of self-recording rain gauge installed at the site. The procedure for estimating erosivity index is described as given below:

1. The storm is subdivided into the time intervals of uniform intensity.
2. The Kinetic energy of rainfall per millimeter of rainfall for the j^{th} time interval is calculated using Eq. 2.3.
3. The total storm energy is obtained using equation 2.2.
4. The 30 minute maximum intensity 'I_{30}' of rainfall is determined by selecting that 30 minute period during which the slope is maximum in the rain gauge chart.
5. The obtained storm energy (step 4) and the 30 minute maximum intensity I_{30} multiplied to get the erosivity index for that storm as in Eq. 2.1.

2.4 Development of Relationship between Erosivity Index and Daily Rainfall Amount

Linear and exponential relationships were derived between erosivity index and daily rainfall values for Dehradun.

Daily rainfall is not always tantamount with an event. A daily rainfall amount may include only one event, multiple events or only part of an event. However, since the objective of this study was to develop a method for estimating erosivity index from daily rainfall amount, daily rainfall values were treated as individual storm events **(Elsenbeer *et al.*, 1993; Jain and Narain, 1995)**.

2.4.1 Development of linear relationship

A regression analysis is performed between erosivity index 'EI" and daily rainfall amount 'P' with the help of following form of the linear equation:

$EI = a + b.P$ (2.4)

Where, EI is the dependent variable and P is independent variable. a and b are regression parameters and can be obtained as below:

$$a = \frac{\sum EI - b . \sum}{n} \quad (2.5)$$

$$b = \frac{n\sum EI. P - \sum P. \sum EI}{n \sum P^2 - (\sum P)^2} \quad (2.6)$$

Coefficient of correlation

$$r = \frac{n\sum EI . P - \sum P . \sum EI}{\sqrt{(n \sum P^2 - (\sum P)^2)} . \sqrt{(n \sum EI^2 - (\sum EI)^2)}} \quad (2.7)$$

2.4.2 Development of exponential relationship

The exponential form of equation as given by **Richardson (1983)** has been incorporated in the present study:

$EI = a P^b + ε$ (2.8)

Where, EI is the erosivity index in MJ-mm/ha-h and P is the daily rainfall amount in mm.

In this equation a P^b is the deterministic component with a and b as equation parameters and ε is the random error component with zero mean and unit variance. It is the difference between computed erosivity index and the deterministic component aP^b for the given storm. The random error component is the result of rainfall intensity that can occur within an event of a given rainfall amount.

Now, the equation is linearized by logarithmic transformation as

$\log EI = \log a + b \log P + \acute{ε}$ (2.9)

and thus the equation parameters can be estimated by the least square method as described above through Eq.3.5 to 3.6.

The random component $\acute{ε}$ is determined by rearranging the Eq. (3.9) as

$\acute{ε} = \log EI - (\log a + b \log P)$ (2.10)

2.5 Quantitative Performance of Developed Relationship

The acceptability of the model is judged by the goodness of fit between observed and estimated values by a model. For quantitative performance between observed and estimated values, the following statistical measures are employed in this study.

2.5.1 Absolute prediction error

The absolute prediction error values are determined by the following equation as proposed by the **World Meteorological Organization Statistics (1975)** as:

$$APE = \frac{\sum(Oi - Pi)}{\sum Oi} \times 100 \quad (2.11)$$

Where, APE is absolute prediction error in percentage, Oi and Pi are calculated and predicted values respectively.

2.5.2 Coefficient of efficiency

The use of another goodness of fit parameter known as coefficient of efficiency (CE) for evaluating model performance has been recommended by many researcher in the field of hydrology. The coefficient of efficiency as defined by **Nash and Sutcliffe (1970)** is the proportion of the initial variance accounted by that model. The coefficient of efficiency is determined by the following equation:

$$CE = \frac{\sum (Oi - O)2 - \sum (Oi - Ei)2}{\sum (Oi - O)2} \times 100 \quad (2.12)$$

Where, CE is coefficient of efficiency in percentage, Oi and Ei are respectively calculated and predicted values at corresponding time, and O is the mean of computed values.

Relationship proposed by Central Soil and Water Conservation Research and Training Institute (CSWCRTI), Dehradun

Ram Babu *et al.* (1969) proposed the following relationship between erosivity index and rainfall amount which can be written as:

$EI = 0.533 P + 3.1$ (2.13)

Where, EI is the erosivity index in t.m.cm/ha. h and P is the rainfall amount in mm.

3. Results

In this study, effort has been made to develop erosivity models. The models developed viz. linear and exponential relationships in which the erosivity index is developed as a function of rainfall and evaluation of performance of the model based on statistical indices will be discussed in this chapter.

Data analysis has been done with the help of standard software Microsoft excel 2010 on a personal computer.

3.1 Determination of Erosivity Index

The values of erosivity index (EI) for various storm events have been predicted as per the procedure detailed under Art.2.3. The computational tables for estimating erosivity index based on storm events have been prepared. It was found that I_{30} and EI values ranges from 18.8 mm/h to 63.51 mm/h and 92.01 MJ-mm/ha-h to 1822.4 MJ-mm/ha-h respectively.

3.2 Development of Relationship between Erosivity Index and Rainfall Amount

The linear and exponential relationships have been developed between erosivity index and rainfall values for Dehradun.

3.2.1 Development of linear relationship

Linear relationship between erosivity index (EI) as dependent variable and rainfall (P) as independent variable has been developed as per the procedure discussed in Art.2.4.1 and the following equation has been obtained with correlation coefficient equal to 0.993572.

$$EI_{30} = 17.24104\ P - 305.099 \qquad (3.1)$$

where, EI_{30} is the erosivity index in MJ.mm/ha.h and P is the daily rainfall amount in mm.

From the above equation, it is clear that the calculated value of erosivity index for rainfall amount less than 17.7 mm comes out to be negative which is physically impossible. Hence, the equation proves to be good for rainfall depth exceeding 17.7 mm only. **Wischmeier and Smith (1978)** also observed through their study that the rainfall amounts less than 15 mm contributes very little to erosivity. Thus, the rainfall amounts less than 17.7 mm have been neglected for the development of the above relationship in this study.

3.2.2 Development of exponential relationship

An exponential relationship has been obtained between erosivity index (EI) as the dependent variable and rainfall amount (P) as the independent variable as per the procedure in Art.2.4.2, with coefficient of correlation equal to 0.983959. The following equation is obtained in the form as:

$$EI_{30} = 0.569\ P^{1.702} + \varepsilon \qquad (3.2)$$

where, EI_{30} is the erosivity index in MJ-mm/ha-h and P is the daily rainfall amount in mm, and ε is the random error component.

The random error component ε is linearized by logarithmic transformation and the predicted storm-wise values of έ have been presented in Table 4.5. It is apparent from the Table that the mean of έ values is zero and the standard deviation is 0.0865. The values of coefficient a, exponent b and residual term ε are within the range according to **Richardson *et al.* (1983)**. The distribution of random component may is thus considered uniform which serves the hypothesis as outlined in Art. 2.4.2.

3.3 Performance of Models

The legitimacy of the developed relationships was checked for eight randomly selected storm events from years 2001-2007. The absolute prediction error and coefficient of efficiency were found to be 13.09 % and 99.24 % for linear relationship and 19.58 % and 98.54 % for the exponential relationship. These values are within the recommended range of below 25 % for absolute prediction error **(World Meteorological Organization Statistics, 1975)** and above 75 % for coefficient of efficiency **(Nash and Sutcliffe, 1970)**. Thus, it is apparent that both the relationships give good results and both of them can be functional for Dehradun in particular and its surroundings in general. However, linear relationship gave better results in comparison to exponential relationship. The linear model is recommended for use because of its simplicity in computational procedure for EI values.

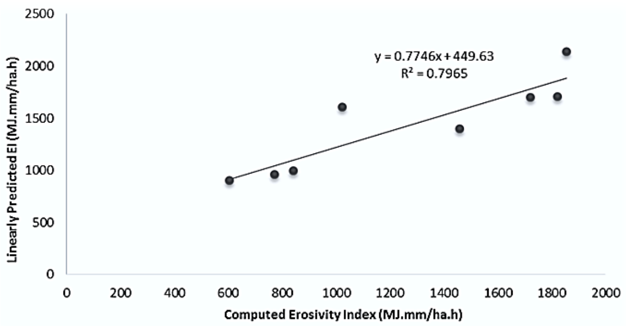

Fig 3.1 Relationship between computed and linearly predicted erosivity index

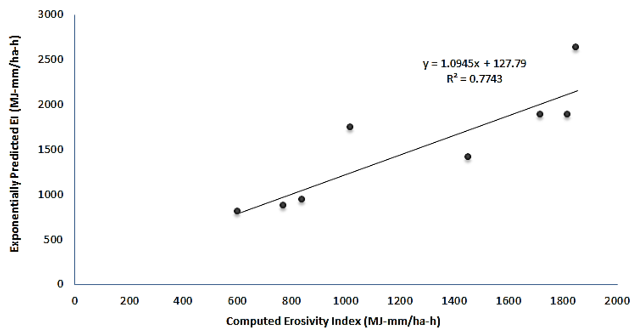

Fig 3.2 Relationship between computed and exponentially predicted erosivity index

3.4 Quantitative Performance of the Central Soil and Water Conservation Research and Training Institute (CSWCRTI), Dehradun model

The performance of the erosivity index relationship proposed by **Ram Babu *et al.* (1969)** has also been studied with a view to establish the applicability of the model for Dehradun and its surrounding region. The predicted values of erosivity index by this model for the same eight storm events were calculated with absolute prediction error of 55.10 % and coefficient of efficiency of 45.37 %. It was found that for this region both the models viz. linear as well as exponential, developed in this study were preferable to the model proposed by Central Soil and Water Conservation Research and Training Institute (CSWCRTI), Dehradun.

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