Mathematical model for predicting soil erosion by flowing water in ungauged watersheds

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Abstract A model was developed for estimating soil erosion by flowing water in ungauged watersheds from four parameters: slope; annual rainfall; clay content; and vegetation cover. The mathematical model is: soil erosion (t ha^{-1}) = 41.73 + 0.181 × slope (%) + 0.046 × rainfall (cm) – 0.387 × clay (%) – 8.125 × vegetation cover factor. The vegetation cover was ranked on a scale of 1 to 5, 1 being bare soil surface, and 5 the extremely dense forests with trees, bushes and grasses. The model was applied to the data obtained from gauged watersheds during subsequent years for validity and was found quite effective in estimating soil erosion by water. However, further investigations are required to refine the model. Furthermore, because the gauged watersheds comprise only a minute fraction of the total ungauged area of the region, estimating soil erosion estimation necessitates spatial extrapolation on a spatial and temporal basis.

Key words mathematical model; partial regression; prediction; soil erosion; vegetation cover

INTRODUCTION

The northeastern region of India, with an area of 255 090 km^2, is predominantly hilly. Even though the region is endowed with rich natural resources of soil, water and vegetation, it has remained economically backward due to gross misuse and mismanagement of these resources. A prevalence of shifting cultivation, the land ownership pattern, heavy precipitation, low accessibility due to hilly terrain, and a lack of proper infrastructure and marketing facilities are the major socio-economic constraints hindering judicious management of natural resources. Shifting cultivation alone results in deforestation and an annual loss of 88.3 million tonnes of soil and 10620, 370 and 6050 tonnes of available N, P_2O_5 and K_2O, respectively. The practice was acceptable when the shifting cycle was 25 to 30 years and the land was rejuvenated with vegetation, but with the reduction in the cycle to 2 to 10 years, the surface soil is washed away during rainfall due to constant human activity on hillslopes. With an increase in population from 10.5 million in 1951, to 40.0 million in 2001, there is tremendous pressure on land, water and forests, and crops are seeded on hillslopes of 10% and more. The heavy annual rainfall of 250 cm has caused unabated soil erosion in the hills, and silting of riverbeds and flooding in the plains. Since it is difficult to monitor soil erosion everywhere, a model was developed to estimate soil erosion from ungauged basins under different agro-climatic conditions.

METHODS

The soil erosion prediction model involves a partial regression equation of the form:

$$SE = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 \quad (1)$$

where SE is the soil erosion (t ha^{-1}) and b_1, b_2, b_3 and b_4 are the partial regression coefficients for slope (x_1) in %, annual rainfall (x_2) in cm, clay content (x_3) in % and vegetation cover (x_4), respectively. Equation (1) was developed using the Dolittle method as described by Goulden (1952), which gave a reasonably high degree of accuracy in prediction or estimation of soil erosion. The vegetation is the only independent variable for which the values (1–5) have to be based on visual estimates. For uniformity, the classification used for the vegetation values is: 1, bare soil surface with soil stirred or ploughed; 2, scrub or effective covered area below 25%; 3, cropped soil surface or effective covered area of 25 to 50%; 4, open forest vegetation or effective covered area of 50 to 75%; and 5, dense forest vegetation, including bushes and grasses, or effective covered area more than 75%. Even though the data used for developing the model were obtained from several studies undertaken at various places by different workers (Singh, 1978–1990; Singh & Singh, 1978; Pratap Narain *et al.*, 1994; Sharma & Prasad, 1995; Sharma, 1999), the required range of values was not available for some variables. Further systematic studies can improve the validity of the model. Equation (1) is a multiple regression equation, and represents a method of predicting soil erosion from individual values of four variables. More available data for calculating the values of the coefficients may result in an increase in the predictive power of the equation. In principle, the model can be used for predicting soil erosion under a wide range of conditions.

FIELD AREA

Topography

The northeastern region is predominantly hilly. About 57% of the area has elevations of >300 m a.m.s.l. (above mean sea level) while 43% of the area is <300 m (Table 1). The states of Arunachal and Manipur have >90% of their geographical area at elevations of >300 m a.m.s.l. Assam is the only state having about 90% of its area as plains. The data in Table 1 summarize the topographical situations prevalent in the different states of the region. Except for the Assam plains, cultivation is done on hillslopes. Poor agricultural practices prevalent in the region, coupled with heavy rainfall and the undulating topography of the region, result in heavy losses of soil and nutrients, which can be reduced by efficient management of rainwater and by following soil conservation measures.

Climate

The average annual rainfall in the region is about 2500 mm. The distribution, however, is uneven, varying both in time and in space (Table 2). On average, Meghalaya, Arunachal and parts of Nagaland receive more than 3000 mm of annual rainfall. The

Table 1 Elevation distribution in different states of northeastern region (km^2 and %).

State	Below 300 m	300–600 m	600–1200 m	Above 1200 m
Arunachal	7414 (8.9)	8943 (10.7)	13732 (16.4)	53489 (64.0)
Assam	70479 (89.8)	4633 (5.9)	3146 (4.0)	259 (0.3)
Manipur	1491 (6.7)	2792 (12.5)	11954 (53.4)	6119 (27.4)
Meghalya	7342 (32.6)	4284 (19.0)	6962 (31.0)	3899 (17.4)
Mizoram	8998 (42.6)	5225 (24.8)	6664 (31.6)	203 (1.0)
Nagaland	2639 (15.9)	2922 (17.6)	5054 (30.5)	5965 (36.0)
Tripura	10395 (99.2)	85 (0.8)	–	–
NE Region	108758 (42.6)	28884(11.3)	47512 (18.7)	69934 (27.4)

Table 2 Average rainfall in northeastern region (mm).

States	May–October	November–April	Total
Arunachal, Meghalaya, Nagaland, Assam hills	2484	1586	4070
Manipur, Tripura, Mizoram	1267	784	2051
Central & lower Brahmputra Valley (Assam)	1195	644	1839
Upper Brahmputra Valley (Assam)	2291	688	2979

Cherrapunji–Mawsynram range receives about 11 500 mm of annual rainfall, which is the highest in the world. The region receives 12.7% of the country's rainfall in only 8.7% of the geographical area. The large amounts and intensity of the rains result in frequent landslides and severe soil erosion.

Land use

In the northeastern region, shifting cultivation is practiced on about 3869 km^2 each year (Table 3). The age-old practice involves deforestation and burning of forest material, land preparation and seeding of various crops. Loosening of the surface soil on the hillslopes makes it susceptible to erosion during high intensity rains. Sharma & Prasad (1995) estimated annual losses from shifting cultivation areas alone in the region as 88.3 million tonnes of soil and 10.61, 0.37 and 6.05 thousand tonnes of available N, P_2O_5 and K_2O, respectively. The extent of shifting cultivation, however, varies from 3% of the total cultivated area in Assam, to about 97% in Mizoram. The problem of soil erosion is further aggravated by the prevailing land tenure system in the region. The farmers have usufructuary right over land as it belongs to either the community or the village chief, and consequently have no interest in soil conservation measures.

RESULTS AND DISCUSSION

In the northeastern region, slope, depth and intensity of rainfall, soil texture and vegetative cover are the most important factors determining soil erosion rates, and

Table 3 Area under shifting cultivation in northeastern region (km^2).

State	Annual area under shifting cultivation	Total seeded area	Area under shifting cultivation as % of cultivated area
Arunachal	700	1490	46.9
Assam	696	27060	2.6
Manipur	900	1400	64.2
Meghalaya	530	2020	26.2
Mizoram	630	650	96.9
Nagaland	190	1900	10.0
Tripura	223	2700	8.2

were therefore used for estimating the soil erosion from a particular area. In addition, crop geometry, soil conservation measures, management practices and human and animal activities also contribute towards erosion of the soil. Singh & Singh (1978), for overall slopes of 70%, reported rates of soil erosion of 146.0, 17.2, 30.2, and 8.2 t ha^{-1} $year^{-1}$ from the land under the first and second year of shifting cultivation, abandoned land after shifting cultivation, and bamboo forest, respectively. Improper land management generates very high erosion rates of up to 80 t ha^{-1} $year^{-1}$, compared to the national average of 16.3 t ha^{-1} $year^{-1}$ (Singh *et al.*, 1992).

The main factors determining the rate of soil erosion: slope, rainfall, clay content and vegetation, were considered in the model. Using the method described earlier in this paper, the equation developed was:

$$SE = 41.73 + 0.181 \times \text{slope} + 0.046 \times \text{rainfall} - 0.387 \times \text{clay content} - 8.125 \times \text{vegetative cover} \quad (2)$$

Observed and predicted values of soil erosion are given in Table 4. The cases for comparison are from studies undertaken by different researchers under different conditions of slope, rainfall, soil texture and vegetation cover. Correlation of the observed and predicted soil erosion data in Table 4 result in a correlation coefficient of 0.946, which is highly significant. The R^2 is 89.5%, and the proposed model therefore can be safely and reliably used for estimating soil erosion in ungauged basins under a wide range of conditions.

LIMITATIONS

The proposed model can be used for predicting soil erosion by flowing water resulting from rainfall. The model may not be valid under extreme values of the parameters considered in the equation. The amount of water received during the monsoon season (May to September) is important since this is the period of maximum rainfall. Conversely, rainfall received during the winter season is less significant because it does not cause soil erosion due to the small amounts and low intensity. There may be several other factors, in addition to those considered above, that could play a significant role in soil erosion. These factors, such as land configuration and management practices, can cause a deviation in estimated soil erosion values under certain conditions.

Table 4 Observed and predicted values (using the proposed model) of soil erosion from different watersheds.

Watershed	Slope (%)	Rainfall (cm)	Clay (%)	Vegetation value	Soil erosion ($t\ ha^{-1}\ year^{-1}$) Observed	Predicted	Reference for observed soil erosion
1	32	170	20.8	5	1.2	6.6	Singh(1989)
2	53	170	20.5	5	8.0	10.5	Singh(1989)
3	30	87	15.0	3	27.0	20.9	Simukaban *et al.* (1998)
4	30	115	16.0	2	37.7	30.4	Simukaban *et al.* (1998)
5	4	95	17.1	4	8.5	7.7	Pratap Narain *et al.* (1994)
6	8	95	15.0	3	17.4	17.3	Pratap Narain *et al.* (1994)
7	2	95	15.0	3	16.3	16.3	Pratap Narain *et al.* (1994)
8	4	95	15.0	3	16.6	16.4	Pratap Narain *et al.* (1994)
9	70	180	12.0	4	30.2	25.6	Singh (1978)
10	70	180	12.0	5	8.2	17.4	Singh (1978)
11	70	180	12.0	1	130.0	50.0	Singh (1978)

CONCLUSIONS

The northeastern region of India is predominantly hilly and receives heavy rainfall. Varying degrees of soil erosion has been reported under different situations. Monitoring soil erosion in watersheds by installing gauges in different places is difficult for a variety of reasons. The model developed here can be used for predicting soil erosion reliably, with certain limitations as mentioned above. There is need to improve and refine the model by including observed data from recent studies as well as by additional systematic studies of the factors that control soil erosion.

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