Assessment of permissible soil loss in India employing a quantitative bio-physical model

Debashis Mandal* and V. N. Sharda

Central Soil and Water Conservation Research and Training Institute, 218, Kaulagarh Road, Dehradun 248 195, India

Soil degradation in all its nefarious forms has serious repercussions on crop and biomass productivity. Assessment of soil loss tolerance limits (SLTLs) (permissible soil loss) serves as a tool to gauge the potential erosion risk in a given area with regard to long-term sustainability. In this communication, SLTLs in different states of India and at the national level have been quantitatively estimated by employing a bio-physical model based upon integration of relevant attributes. The analysis has indicated that soil loss tolerance or *T*-value varies from 2.5 to 12.5 Mg ha^{-1} yr^{-1} depending upon soil quality governing soil resistibility to erosion and depth at a particular location. About 57% area in the country has permissible soil loss of less than 10.0 Mg ha^{-1} yr^{-1}, which needs to be treated with appropriate conservation measures. Highest priority needs to be accorded to about 7.5% area where the *T*-value is only 2.5 Mg ha^{-1} yr^{-1} due to soil quality constraints. The methodology and framework developed for estimating *T*-values has the potential to be applied in different regions or countries of the world. The relative efficacy of the present method was tested with productivity index-based approach. Case study evidences in different watersheds revealed that soil productivity can be maintained at sustainable levels by bringing the erosion rate within tolerance limit.

Keywords: Biophysical model, conservation planning, permissible erosion, soil degradation, soil sustainability.

THE soil resources of the world are finite, functionally non-renewable and prone to different forms of degradation due to over-exploitation and faulty management practices. Soil degradation has reached alarming proportions in many parts of the world, especially in the tropics and sub-tropics. Soil erosion caused by water is a major factor contributing to land degradation in India and many other countries, as it far exceeds the natural soil formation rates. The estimates suggest that globally about 24 bt of soil is lost annually through water erosion in excess of the natural rate of soil regeneration[1]. The balance between soil-forming and depleting processes is of utmost importance for attaining long-term sustainability in any production system. According to FAO, about 18% of the arable lands in the world could be lost forever if no measures are taken to preserve them[2]. India loses about 16.4 t of soil ha^{-1} yr^{-1}, of which 29% is lost permanently into the sea, 10% gets deposited in the reservoirs reducing their capacity by 1–2% every year and the remaining 61% gets displaced from one place to another[3]. About 30–50% of the world's arable lands are substantially degraded due to soil erosion[4], which directly affects rural livelihood[5,6]. Soil erosion also affects aquatic resources[7], lake/river sediment dynamics[8,9], global carbon cycling[10], aquatic and terrestrial biodiversity[11,12] and ecosystem services[13,14].

Soil being a non-renewable resource and the basis for 97% of all food production[4], strategies to prevent soil depletion are critical for sustainable development. For developing suitable soil conservation strategies, knowledge of the prevailing and permissible rates of soil erosion is an essential prerequisite. The acceptable rate of soil erosion (*T*-value) is defined as the maximum amount of erosion at which the quality of a soil as a medium for plant growth can be maintained. Quantifying the acceptable soil loss without affecting crop productivity is a major challenge for researchers, planners, conservationists and environmentalists. If the erosion exceeds the *T*-value, it adversely affects productivity and must be brought down within the permissible rate to ensure sustainability of a production system. Conservation objectives for soil loss tolerance are based on maintaining a suitable seedbed and nutrient supply in the surface soil, maintaining adequate depth and quality of the root zone, and minimizing unfavourable changes in water availability throughout the soil[15]. The *T*-value concept does not attempt to limit allowable soil loss to the absolute rate of soil regeneration, but it is based on the assumption that desirable top soil (primarily A horizon) properties are regenerated more rapidly. It also implicitly allows some deeper soils to erode at higher rates than shallower soils. Soil physical degradation and loss of nutrients within the permissible rates of erosion are usually not enough to significantly reduce the crop yields. Thus the concept of *T*-value is compatible with the current thinking on the sustainability of agricultural systems. It is known that a given erosion rate is not equally serious on all soils. On shallow soils, a *T*-value of 5 Mg ha^{-1} yr^{-1} and prevailing erosion rate of 12.5 Mg ha^{-1} would result in rapid loss of productivity. In contrast, a *T*-value of 12.5 Mg ha^{-1} yr^{-1} in a deeper soil with similar erosion may not have much impact on crop productivity[16].

In India, a default *T*-value ranging from 4.5 to 11.2 Mg ha^{-1} yr^{-1} is generally assumed in the absence of specific criteria to compute it in different regions based upon soil quality with regard to resistance to water erosion. It is important to distinguish the intrinsic susceptibility of the soil to erosion. Potential soil indicators required to assess the intrinsic susceptibility of the soil to erosion depend on sensitivity analysis. Sensitivity analysis of the Water Erosion Prediction Project indicated infiltration rate, bulk density, erodibility factor, organic

*For correspondence. (e-mail: demichael@rediffmail.com)

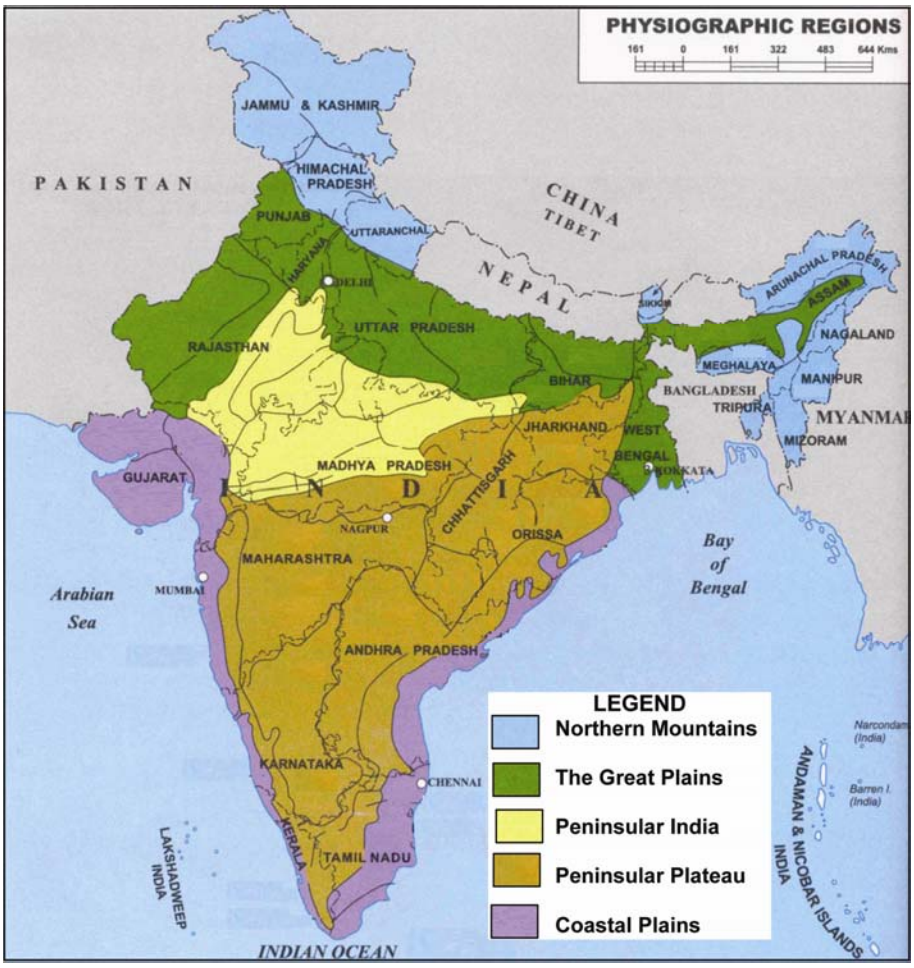

Figure 1. Physiographic regions of India[27].

carbon (OC) and soil pH as minimum dataset[16]. Assignment of site-specific *T*-value would help in understanding the vulnerability of soil erosion in a particular region. About 39% area in the country is estimated to have erosion rates of more than 10.0 Mg ha^{-1} yr^{-1} (ref. 17). Hence, it is imperative to treat such lands on priority and bring the erosion, estimated by employing a systematic and scientific procedure, within permissible limits.

Evaluation of soil loss tolerance for an area requires judgement about rates of soil formation and the timescale over which land use is to be sustained. In a strict sense, tolerance with the soil loss rate equal or less than the soil formation rate would allow production to continue indefinitely. Soil formation rates at undisturbed sites are estimated[18] to be generally about 0.1–0.2 mm yr^{-1} (i.e. about 1.3–2.6 Mg ha^{-1} yr^{-1}). Some researchers suggested that a soil renewal rate of 1.1 Mg ha^{-1} yr^{-1} is a useful average. On normal agricultural lands, it is suggested that the rate of soil development may range from 8 mm yr^{-1} in ideal circumstances, which may decline to 2.5 mm yr^{-1} in more severe environments[19]. However, numerous criteria should be considered in establishing the *T*-value.

Several attempts have been made in India[16,20,21] and elsewhere to refine the computation of soil loss tolerance[22–24]. The *T*-value should be assessed in terms of specific range with an acceptable degree of risk associated with a given soil type. A typical range of *T*-values in integer steps from 2.5 to 12.5 Mg ha^{-1} yr^{-1} was proposed by USDA–NRCS (http://www.statlab.iastate.edu/soils/nssh/). Information on quantitative assessment of soil loss tolerance is rather scanty in the literature. Thus a default *T*-value ranging from 4.5 to 11.2 Mg ha^{-1} yr^{-1} is generally assumed[25]. The objective of the present study was to develop a framework and methodology for quantitative assessment of permissible limits of soil loss based upon soil quality attributes and the related erosion risks in different regions of India. The current approach follows a quantitative model to sum up overall soil performance with respect to resistance to water erosion.

India is endowed with rich diversity in terms of climate, geology, landforms and vegetation. It lies to the north of the equator between 8°4′N and 37°6′N lat. and 68°7′E and 97°25′E long.[26]. It is the seventh largest country in the world, with a total geographical area of about

Table 1. Indicators for each function with weights

Function	Indicator and reference	Weight
Accommodate water entry and facilitate water transfer	Infiltration rate; 35	0.35
Water transport and retention	Bulk density ; 44–46	0.10
Resist physical degradation	Soil erodibility (*k*); 46–48	0.25
Resist biochemical degradation	Organic carbon; 44, 45	0.15
Sustain plant growth	pH; 45	0.15
Total score		1.00

329 m ha (3,287,263 km^2). The country is bounded by the Arabian Sea, Bay of Bengal and Indian Ocean to the southwest, southeast and south respectively. It is broadly divided into five physiographic regions, viz. Northern Mountains, The Great Plains, Peninsular India, Peninsular Plateau and Coastal Plain[27]. Spatial distribution of these regions is shown in Figure 1.

Taxonomically, soils of the country are classified into eight orders, viz. Alfisol (14.1%), Inceptisol (41.4%), Aridisols (4.5%), Entisols (28.2%), Vertisols (8.8%), Ultisols (2.6%), Mollisols (0.4%) and Histosols (0.1%)[28]. Among different soil resource regions, the highest erosion rate occurs in the black soil region (23.7–112.5 Mg ha^{-1}) followed by the Shiwalik region (80 Mg ha^{-1}), north-eastern region with shifting cultivation (27–40 Mg ha^{-1}) and the least in the north Himalayan forest region (2.1 Mg ha^{-1}). The annual erosion rates in the coastal region of the Western Ghats vary from 20 to 30 Mg ha^{-1}, whereas in the red soils of Chhota Nagpur Plateau, they vary from 10 to 15 Mg ha^{-1}. About 11% area in the country falls in the very severe category with erosion rates of more than 40 Mg ha^{-1} yr^{-1} (ref. 29). Some states in northwest and northeast Himalayas are the worst affected, with more than 30% of their geographical area falling in the very severe (40–80 Mg ha^{-1} yr^{-1}) category.

Soil information on texture, OC content and soil fertility status was collected from existing sources. About 1649 soil mapping units were studied representing various physiographic regions of India[27]. Detailed state-wise soil information was collected from NBSS publications on 'Soils of India' series. The value of basic infiltration rate and bulk density was derived using appropriate pedotransfer function (SSWATER). Soil erodibility factor (*k*) was computed based upon texture and organic matter content[30].

Five indicators (Table 1) representing soil functions related to erosion and selected on the basis of sensitivity analysis[31] were used for developing an integrated index for assessing the soil loss tolerance limits (SLTLs). Basic relationships were developed among various indicators by giving due priority to soil functionality. The functional integrity of a soil depends on its regeneration capacity to accommodate perturbations of erosive forces. After identifying various primary soil functions related to resistance to water erosion, the most relevant indicators representing these functions were selected (Table 1). The next step was the transformation of measured values of indicators into a dimensionless score having value between 0 and 1. Different scoring curves[32] were used to convert the measured values of attributes to a common membership grade (0 to 1), according to the class limits specified by McBratney and Odeh[33].

The basic model used was:

$$\mathrm{MF}(x_i) = [1/(1 + \{(x_i - b)/d\}^2)], \tag{1}$$

where $\mathrm{MF}(x_i)$ represents individual membership function (MF) values for the *i*th soil property *x*, *b* the central concept and *d* the width of the transition zone.

As there are *n* characteristics of soils to be rated and combined using a convex combination function to produce a joint membership function (JMF) of all attributes, JMF(*Y*) is given as follows:

$$\mathrm{JMF}(Y) = \sum_{i=1} \lambda_i \mathrm{MF}(x_i), \tag{2}$$

where *Y* is the convex membership function (JMF) of all attributes, λ_i the weighting factor for the *i*th soil property *x*.

Model functions used for fuzzy membership classification of soil attributes are based on the semantic import approach, which utilizes a bell-shaped curve[34]. This approach consists of two basic functions, viz. symmetric and asymmetric. The first function, also called an 'optimum range'[32], distinguishes two variants: one uses a single ideal point (model 1), and the other employs a range of ideal points (model 2), as in case of pH, where there are two different ideal points, viz. 6.5 and 7.5. For example, an ideal level of soil pH for agricultural purposes may range from slightly acidic to slightly alkaline (6.5–7.5), and very low and very high pH values are limiting for agricultural crops. Therefore, a symmetric function may be with an ideal point (model 1) or it may be with a range of ideal points (model 2).

The following forms were applied to models 2–4:
For optimum range (model 2):

$$\mathrm{MF}(x_i) = 1 \quad \text{if } (b_1 + d_1) < x_i < (b_2 - d_2). \tag{3}$$

Table 2. Categorical ranking of soil characteristics used to convert into unit-less score (0 to 1)

Soil attribute		Category 1	2	3	4	5	Model no.
Infiltration rate (cm h^{-1})	Range	0.5–1.0	1.0–2.0	2.0–3.5	3.5–5.0	> 5.0	3
	Score	0.2	0.3	0.5	0.8	1.0	
Bulk density (Mg m^{-3})	Range	< 1.40	1.40–1.47	1.48–1.55	1.56–1.63	> 1.63	4
	Score	1.0	0.8	0.5	0.3	0.2	
Erodibility factor	Range	< 0.10	0.10–0.29	0.30–0.49	0.50–0.69	> 0.70	4
	Score	1.0	0.8	0.5	0.3	0.2	
Total organic carbon (%)	Range	< 0.50	0.50–0.75	0.75–1.00	1.00–1.50	> 1.50	3
	Score	0.2	0.3	0.5	0.8	1.0	
pH	Range	< 5.0 > 9.0	5.0–5.5 8.5–9.0	5.5–6.0 8.0–8.5	6.0–6.5 7.5–8.0	6.5–7.5	2
	Score	0.2	0.3	0.5	0.8	1.0	

Values in brackets are the converted unit-less score (0 to 1 scale) of soil characteristics determined through models 2–4.

For asymmetric left (model 3), 'more is better':

$$\mathrm{MF}(x_i) = [1/(1 + \{(x_i - b_1 - d_1)/d_1\}^2)] \quad \text{if } x_i < (b_1 + d_1). \tag{4}$$

For asymmetric right (model 4), 'less is better':

$$\mathrm{MF}(x_\mathrm{i}) = [1/(1 + \{(x_i - b_2 + d_2)/d_2\}^2)] \quad \text{if } x_i > (b_2 - d_2). \tag{5}$$

Model parameters include lower crossover point (LCP), central concept (b), upper crossover point (UCP) and width of transition zone (d)[35]. LCP and UCP represent the situation where a soil attribute is examined at the marginal level for a given purpose, whereas b is for an ideal level[36].

In the case of OC and infiltration rate, 'more is better' concept was used since resistance to erosion would be better with a higher value of OC or higher infiltration rate. On the other hand, for bulk density and erodibility factor (k), 'lower is better' concept (model 4) was followed for the purpose of ranking. The model used along with converted score and range of indicators is presented in Table 2. It is evident that score 1 represents the highest potential function for that system, i.e. the indicator is non-limiting to pertinent soil functions and processes within the inherent capability of the soil. A general relationship was assumed between the indicators representing a particular soil function. The relationship determines the shape of an indicator scoring curve. Some shapes include 'more is better' (upper asymptotic curve), 'lower is better' (lower asymptote) and 'mid is optimum' (Gaussian function)[35,37]. OC and infiltration rate are the ascending logistic, i.e. 'more is better' function based on their role in water entry, water partition and structural stability and soil fertility[38,39]. A lower asymptotic or 'less is better' function was used in case of bulk density and soil erodibility (k) because of its inhibitory effect on root growth, soil porosity and soil erosion[40].

Weights were assigned to the indicators depending on their relative importance. In relation to water erodibility, entry of water into the soil profile, i.e. infiltration rate was considered the most important and assigned maximum weight. Soil erodibility (resistance to physical degradation) was assigned the second highest weight of 0.25. Bulk density was assumed to be complementing the water entry function and was assigned a low weight of 0.10. The remaining weights of 0.30 were distributed equally between the functions resisting biochemical degradation (OC; 0.15) and sustaining plant growth (pH; 0.15) (Table 1). The converted values on the '0 to 1' scale were multiplied by the weights assigned to them. Summing the values of the weighted parameters, a quantitative value (Q) indicating the state of soil condition was obtained. This model used to assign the performance of the soil may be described as:

$$Q = q_{\mathrm{rir}}w_{\mathrm{wir}} + q_{\mathrm{rk}}w_{\mathrm{wk}} + q_{\mathrm{rbd}}w_{\mathrm{wbd}} + q_{\mathrm{roc}}w_{\mathrm{woc}} + q_{\mathrm{rpH}}w_{\mathrm{wpH}} \tag{6}$$

or, more generally, $Q = \sum q_i w_i$, where Q defines the state or condition of the soil in terms of structural and functional integrity, q_{rir} the rating for infiltration rate, q_{rbd} the rating for bulk density, q_{rk} the rating for soil erodibility, q_{roc} the rating for OC and q_{rpH} the rating for pH of soils, whereas W denotes the weight factor for each function. A sensitivity index was calculated using the concept of a relative comparison of the method (weighted additive model) employed in this study with that of the productivity index (PI)-based method. The parametric paired t-test showed that the overall mean of the sensitivity index was

Table 3. Matrix of soil depth and soil group for soil loss tolerance limit (SLTL) estimation

	Annual soil loss tolerance (Mg ha^{-1} yr^{-1})		
Soil depth (cm)	Group 1 (Q < 0.33)	Group 2 (Q = 0.33–0.66)	Group 3 (Q > 0.66)
0–25	2.5	2.5	7.5
25–50	2.5	5.0	7.5
50–100	5.0	7.5	10.0
100–150	7.5	10.0	12.5
> 150	12.5	12.5	12.5

Table 4. Characteristics of soils in different physiographic regions

Physiographic region	Infiltration rate (cm h^{-1})	Organic carbon (%)	Bulk density (Mg m^{-3})	K-factor	pH	Soil group	Soil depth (cm)	SLTL (Mg ha^{-1} yr^{-1})
North Mountains	0.3–10.8 (0.2–1.0)	0.40–2.75 (0.2–1.0)	1.30–1.76 (0.2–1.0)	0.09–0.46 (0.5–1.0)	4.5–8.4 (0.2–1.0)	2, 3	< 25–150	2.5–12.5
The Great Plains	0.2–15.5 (0.2–1.0)	0.40–2.8 (0.2–1.0)	1.16–1.94 (0.2–1.0)	0.08–0.65 (0.3–1.0)	5.5–0.5 (0.2–0.0)	1–3	10– >200	2.5–12.5
Peninsular India	0.2–11.6 (0.2–1.0)	0.04–2.31 (0.2–1.0)	1.20–1.52 (0.2–1.0)	0.11–0.68 (0.3–0.87)	5.0–10.0 (0.2–1.0)	2, 3	10–>150	2.5–12.5
Peninsular Plateau	0.2–7.5 (0.2–1.0)	0.3–3.40 (0.2–1.0)	1.26–1.74 (0.2–1.0)	0.06–0.65 (0.3–1.0)	4.9–8.5 (0.3–1.0)	2, 3	25–150	2.5–12.5
Coastal Plains	0.3–7.2 (0.2–1.0)	0.28–1.70 (0.2–1.0)	1.22–1.68 (0.2–1.0)	0.09–0.55 (0.3–1.0)	5.0–9.0 (0.3–1.0)	2, 3	25–150	2.5–12.5

Table 5. Area under different SLTLs of India

SLTL (Mg ha^{-1} yr^{-1})	Area (m ha)	Total geographical area (%)
2.5	24.24	7.37
5.0	16.09	4.90
7.5	61.98	18.85
10.0	85.86	26.12
12.5	105.41	32.07
Non-soil	35.15	10.69
Total geographical area	328.73	100

statistically insignificant at $P < 0.05$. Hence, the estimation of soil loss tolerance by weighted additive approach was generally in good agreement with the results of PI-based approach[21]. This validation test suggests that the weighted additive approach could well be used by soil managers and policy planners for assigning T-values. The PI-based approach requires a complicated depth-wise dataset, including available water capacity, bulk density and pH, which at present is not available for most of the agro-ecological regions. Generating such a dataset would require huge time and monetary investment. On the other hand, the weighted additive model requires a minimum dataset of six soil attributes, which are readily available for all the locations.

Soil grouping (1–3) was done on the basis of an aggregated score (Q) obtained from the above model (Table 3). A general guideline developed at the Iowa State University Statistical Laboratory[21] was followed for assigning the SLTLs.

Characteristics of dominant soils in each physiographic region of India are presented in Table 4. Analysis of the data indicated that infiltration rate varied from 0.2 to 15.5 cm h^{-1} and the corresponding converted score varied between 0.2 and 1.0. Bulk density varied from 1.20 to 1.94 Mg m^{-3}, depending upon the variation in soil texture, and the corresponding score ranged between 0.2 and 1.0. These results showed that infiltration rate and bulk density had a common range of normalized score between 0.2 and 1.0. The variation in resultant converted score (0.2 to 1.0) of infiltration rate and bulk density is ascribed to the variations in texture and OC. A considerable difference was observed in OC content among the physiographic regions with values ranging between 0.04% and 3.4%, and hence the converted score fluctuated widely between 0.2 and 1.0 indicating a high degree of heterogeneity even within a physiographic region. Lower OC content was commonly observed in semi-arid and arid regions. Erodibility factor, derived from soil organic matter and soil texture relationships, varied from 0.06 to 0.68. According to the classification of soil reaction, soils of the country were moderately acidic to highly alkaline in nature, with soil pH ranging from 4.5 to 10.0. Hence, the corresponding converted score varied between 0.2 and 1.0.

Considering the entire dataset of the country, soils were classified into three groups (1–3) based on the total

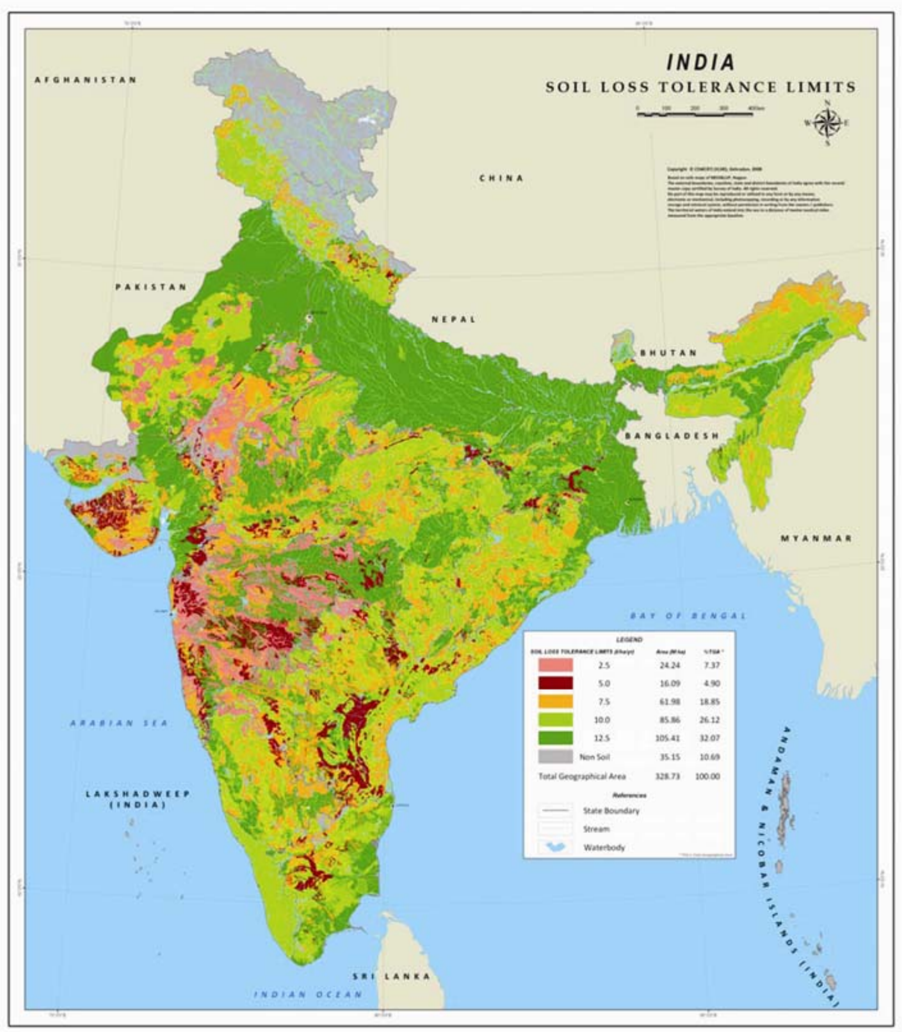

Figure 2. Soil loss tolerance limits in different states of India.

aggregated score (Q). Overall performance of the soils with respect to erosion resistance and tolerance for all physiographic regions of India is shown in Table 5. T-values were computed on the basis of soil group versus depth matrix. T-values in each physiographic region ranged from 2.5 to 12.5 Mg ha^{-1} yr^{-1}, indicating wide variation in soil function to resist the impact of water erosion on crop productivity. The spatial distribution of tolerance limits of the entire country is shown in Figure 2. Priority zones can be delineated by comparing the prevailing erosion rates with the computed T-values in a given region or location. Among all the physiographic regions, The Great Plains are better placed with higher T-values (12.5 Mg ha^{-1} yr^{-1}) followed by the Coastal Plains. The regions of utmost concern are Peninsular India and Peninsular Plateau, where a considerable area can only afford soil loss ranging from 2.5 to 5.0 Mg ha^{-1} yr^{-1}. Analysis of tolerance limit data (Table 5) indicated that about 42.8% of the total geographical area can tolerate a soil loss more than the default T-value of 12.5 Mg ha^{-1} yr^{-1}. The remaining 57.2% area had T-value ranging between 2.5 and 10.0 Mg ha^{-1} yr^{-1}, including about 7.4% area with T-value of 2.5 Mg ha^{-1} yr^{-1}. The area with T-value of 2.5 Mg ha^{-1} yr^{-1} is most sensitive from the conservation point of view as with its shallow soil depth and poor resistivity to erosion, it is vulnerable to loss of crop productivity if erosion exceeds the T-value.

Estimation of site-specific SLTLs would help in judging the vulnerability of soils to water erosion in different regions of the country. Based on limited experimental data available on the loss of crop productivity vis-a-vis degree of erosion, it was observed that productivity of maize decline by 5.0% annually when soil loss exceeded the T-value in alluvial soils of humid sub-tropical regions[41]. Similar results were also reported from the semi-arid region of Bellary where reduction in yields of sorghum and Bengal gram was more pronounced as the soil loss exceeded the estimated T-value of the region[42]. Analysis of the data generated in these experiments also revealed that the reduction in yields was insignificant at erosion levels below the *T*-value. Results of various soil and water-conservation programmes on watershed basis in different agro-climatic regions of the country revealed increase in productivity by bringing the soil loss near or below tolerance limit[43]. Permissible soil loss (*T*-value) and its comparison with the prevailing potential erosion rate would decide the priority for treatment of a given area. Where the erosion rate far exceeds the *T*-value, intensive conservation measures are needed to bring the former within permissible limits.

The concept of tolerance limit or permissible soil loss was evolved to prevent land degradation which may otherwise impact the livelihood of the people due to landlessness. A framework (model) has been developed for determining soil loss tolerance (*T*-value) that ensures long-term sustainability of the soil resource, by preventing excessive erosion through appropriate conservation measures. The framework or the methodology for computing the *T*-value has been applied and tested using data from representative benchmark soils of India. The *T*-value varied from 2.5 to 12.5 Mg ha^{-1} yr^{-1} depending on the soil quality and soil depth in different physiographic regions of the country.

This model has the potential to be applied and validated in other countries for further modifications and refinements to improve its predictive power. Site-specific *T*-values would help in devising a suitable strategy for identifying the best management practices to bring soil loss within permissible limits in a given area or region.

1. *The State of World Population*, United Nations Population Fund, 2000, p. 13.
2. Leisinger, K. M. and Schmitt, K., *All Our People: Population Policy With a Human Face*, Island Press, Washington DC, 1994, p. 267.
3. Dhruvanarayana, V. V. and Rambabu, Estimation of soil erosion in India. *J. Irrig. Drain. Eng.*, 1983, **109**, 419–434.
4. Pimentel, D., *World Soil Erosion and Conservation*, Cambridge University Press, Cambridge, UK, 1993.
5. Lal, R., Soil erosion and sediment transport research in tropical Africa. *Hydrol. Sci. J.*, 1985, **30**, 239–256.
6. Kerr, J., The economics of soil degradation: from national policy to farmers' needs. In *Soil Erosion at Multiple Scales: Principles and Methods for Assessing Causes and Impacts* (eds Penning de Vries, F. W. T. *et al.*), CABI Publishing, Wallingford, UK, 1997, pp. 21–38.
7. Eggrerment, H. and Verschuren, D., Impact of soil erosion in disturbed tributary drainages on the benthic invertebrates fauna of Lake Tanganyika, East Africa. *Biol. Conserv.*, 2003, **113**, 99–109.
8. Kelley, D. W. and Nater, E. A., Historical sediment flux from three watersheds into Lake Pepin, Minnesota, USA. *J. Environ. Qual.*, 2000, **29**, 561–568.
9. Walling, D. E., Linking land use, erosion and sediment yields in river basins. *Hydrobiologia*, 2000, **410**, 223–240.
10. Lal, R., Soil erosion and the global carbon budget. *Environ. Int.*, 2003, **29**, 437–450.
11. Harrey, C. A. and Pimentel, D., Effects of soil and wood depletion on biodiversity. *Biodivers. Conserv.*, 1996, **5**, 1121–1130.
12. Alin, S. R., O'Reily, C. M., Cohen, A. S., Dettman, D. L., Palacios-Fest, M. R. and Mckee, B. A., Effects of land use change on aquatic biodiversity: a view from the Paleorecord at Lake Tanganyika, East Africa. *Geology*, 2002, **30**, 1143–1146.
13. Tinker, P. B., The environmental implications of intensified land use in developing countries. *Philos. Trans. R. Soc. London*, 1997, **B352**, 1023–1033.
14. Pimentel, D. and Kounang, N., Ecology of soil erosion in ecosystems. *Ecosystem*, 1998, **1**, 418–426.
15. USDA-SCS (Soil Conservation Service). Advisory notice. Soils-6, US Department of Agriculture, Washington DC, 1973.
16. Mandal, D., Dadhwal, K. S., Khola, O. P. S. and Dhayni, B. L., Adjusted *T* values for conservation planning in Northwest Himalayas of India. *J. Soil Water Conserv*., 2006, **61**, 391–397.
17. Sharda, V. N. and Mandal, D., Land resources: food and livelihood security. In *Looking Back to Change Track*, TERI, New Delhi, 2010.
18. Loomis, R. S. and Connar, D. J., *Crop Ecology*, Cambridge University Press, Cambridge, UK, 1992, p. 552.
19. Piemental, D. E. *et al.*, Land degradation: effect on food and energy resources. *Science*, 1976, **194**, 149–155.
20. Bhattacharyya, T., Rambabu, Sarkar, D., Mandal, C., Dhyani, B. L. and Nagar, A. P., Soil loss and crop productivity model in humid subtropical India. *Curr. Sci*., 2007, **93**, 1397–1403.
21. Mandal, D., Sharda, V. N. and Tripathi, K. P., Relative efficacy of two biophysical approaches to assess soil loss tolerance for Doon Valley soils of India. *J. Soil Water Conserv*., 2010, **65**, 42–49.
22. Bork, H. R. and Frielinghaus, M., *Zur Tolerierbarkeit von Bodenabtrag. Mitt. Dtsch. Bodenkdl. Ges*., 1997, **83**, 83–86.
23. Lal, R., Agronomic consequences of soil erosion. In *Soil Erosion at Multiple Scale: Principles and Methods for Assessing Causes and Impacts* (eds Penning de Vries, F. W. T. *et al.*), International Board for Soil Research and Management, CABI Publishers, Wallingford, UK, 1998, pp. 149–160.
24. Renschler, C. S. and Harbor, J., Soil erosion assessment tools from point to regional scales – the role of geomorphologists in land management research and implementation. *Geomorphology*, 2002, **47**, 189–209.
25. Pawar, S. N., Kalbande, S. R., Bhuibhar, B. J. and Jadhav, S. B., Effect of nala bund on groundwater recharge. *J. Agric. Eng*., 2007, **44**, 21–25.
26. Ministry of Human Affairs, Department of Border Management. Government of India, 2008.
27. NBSSLUP, Soils of India. National Bureau of Soil Survey and Land Use Planning, Nagpur, 2002, Publ. No. 94.
28. Velayatham, M. and Bhattacharya, T., Soil resource management. In Natural Resource Management for Agricultural Production in India, International Conference on Managing Natural Resources for Sustainable Agricultural Production in the 21st century, New Delhi, 14–18 February 2000.
29. Maji, A. K., Assessment of degraded and wastelands of India. *J. Indian Soc. Soil Sci*., 2007, **55**, 427–435.
30. Kirkby, M. J. and Morgan, R. P. C., *Soil Erosion*, John Wiley, 1980, p. 312.
31. Nearing, M. A., Deer-Ascough, L. and Laflen, J. M., Sensitivity analysis of the WEPP hillslope profile erosion model. *Trans. Am. Soc. Agric. Eng*., 1990, **33**, 839–849.
32. Wymore, A. W., *Model-based Systems Engineering: An Introduction to the Mathematical Theory of Discrete Systems and to the Tricotyledon Theory of System Design*, CRC Press, Boca Raton, FL, 1993.
33. McBratney, A. B. and Odeh, I. O. A., Application of fuzzy sets in soil science: fuzzy logic, fuzzy measurements and fuzzy decisions. *Geoderma*, 1997, **77**, 85–113.
34. Burrough, P. A., MacMillan, R. A. and van Deursen, W., Fuzzy classification methods for determining land suitability from soil profile observations and topography. *J. Soil Sci*., 1992, **43**, 193–210.
35. Karlen, D. L. and Sott, D. E., A framework for evaluating physical and chemical indicators of soil quality. In *Defining Soil Quality*

for a Sustainable Environment (eds Doran, J. W and Parking, T. B.), Special Publication No. 35. Soil Science Society of America, Madison, WI, 1994, pp. 53–72.
36. Sys, C., *Land Evaluation: Part I*, University of Ghent, Ghent, 1985.
37. Andrews, S. S., Karlen, D. L. and Mitchell, J. P. A., Comparison of soil quality indexing methods for vegetable production systems in northern California. *Agric. Ecosyst. Environ*., 2002, **90**, 25–45.
38. Lal, R., *Methods and Guidelines for Assessing Sustainable Use of Soil and Water Resources in the Tropics*, Scientific Publishers, Jodhpur, 1996.
39. Tiessen, H., Cuevas, E. and Chacon, P., The role of organic matter in sustaining soil fertility. *Nature*, 1994, **371**, 783–785.
40. Grossman, R. B., Harms, D. S., Seybold, C. A. and Herrick, J. E., Coupling use-dependent and use-invariant data for soil quality evaluation in the United States. *J. Soil Water Conserv*., 2001, **56**, 63–68.
41. Singh, R., Shrimali, S. S. and Sharma, N. K., Soil surface management for erosion control, CSWCRTI Annual Report (2003–2004), Dehradun, 2004.
42. Nalatwadmath, S. K., Patil, S. L., Adhikari, R. N. and Reddy, K. K., Erosion productivity relationship for evaluating vulnerability and resilience of soils under different agro-ecological regions. CSWCRTI Annual Report (2009–2020), Dehradun, 2010.
43. Singh, K. D., Participatory watershed management – a key to sustainable agriculture. *J. Indian Soc. Soil Sci*., 2006, **54**, 443–451.
44. Larson, W. E. and Piece, F. J., Conservation and enhancement of soil quality. In *Evaluation for Sustainable Land Management in the Developing World* (eds Dumanski, J. *et al.*), Proceedings of International Workshop, Technical Papers, International Board for Soil Research and Management, Bangkok, Thailand, 1991, vol. 2, pp. 175–203.
45. Doran, J. W. and Parkin, T. B., Defining and assessing soil quality. In *Defining Soil Quality for a Sustainable Environment* (eds Doran, J. W. *et al.*), Special Publication No. 35, Soil Science Society of America, Madison, Wisconsin, 1994, pp. 3–21.
46. Arshad, M. A., Lowery, B. and Grossman, R. B., Physical tests for monitoring soil quality. In *Methods of Assessing Soil Quality* (eds Doran, J. W. and Jones, A. J.), Special Publication No. 49, Soil Science Society of America, Madison, Wisconsin, 1996, pp. 123–141.
47. Harris, R. F., Karlen, D. L. and Mulla, D. J., A conceptual framework for assessment and management of soil quality and health. In *Methods for Assessing Soil Quality* (eds Doran, J. W. and Jones, A. J.), Special Publication No. 49, Soil Science Society of America, Madison, Wisconsin, 1996, pp. 61–82.
48. Karlen, D. L., Parkin, T. B. and Eash, N. S., Use of soil quality indicators to evaluate conservation reserve program sites in Iowa. In *Methods for Assessing Soil Quality* (eds Doran, J. W. and Jones, A. J.), Special Publication No. 49, Soil Science Society of America, Madison, Wisconsin, 1996, pp. 345–356.

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Effect of Himalayan topography on two-dimensional interpretation of magnetotelluric data

G. Pavan Kumar* and A. Manglik

National Geophysical Research Institute (CSIR), Uppal Road, Hyderabad 500 606, India

Magnetotelluric method is a powerful tool for deep crustal studies of tectonically active mountainous regions such as the Himalaya, where logistic constraints severely limit the use of other artificial source electrical and electromagnetic methods. Topographic variations in mountainous regions distort apparent resistivity curves and thus lead to artefacts in interpreted models. In the present work, we have analysed a simplified two-dimensional (2D) model of the subsurface electrical resistivity structure along a profile in the Garhwal Himalaya for the effect of topography. The topography varies significantly along the profile between the foothills and the higher Himalaya. We first computed TE and TM-mode apparent resistivity and phase curves at various stations along the profile for a model with topography and then inverted these datasets for two cases. In the first case the surface of the earth was assumed to be flat, whereas in the second case the actual topography was included in the model. The results suggest that the interpreted model assuming flat earth is similar to the one obtained by including topography in the model. Inclusion of 10% Gaussian noise to the synthetic data does not change these results. Thus, we infer that the effect of 2D topography is not prominent in the 2D interpretation of the selected Garhwal Himalaya profile.

Keywords: Magnetotelluric data, mountainous regions, resistivity curves, topographic variations.

MAGNETOTELLURIC (MT) method is a powerful tool for the delineation of deep crustal structure because electromagnetic (EM) signals penetrate deeper into the earth as the frequency of the signal decreases. Natural EM sources contain a broad range of frequencies, making it possible to scan the crustal structure at various depths and resolutions. The usefulness of the method becomes pronounced in tectonically active mountainous regions, such as the Himalaya, where logistic constraints severely limit the use of other artificial source electrical and EM methods for deep crustal studies. The topographic variations of mountainous regions distort the resistivity curves for recording sites in the vicinity of a topographic feature[1–3]. Inversion of these distorted curves due to the effect of topography yields spurious structural features.

*For correspondence. (e-mail: gayatripavan@ngri.res.in)