

LAND DEGRADATION MODELLING IN INACCESSIBLE MOUNTAINOUS AREAS IN THE TROPICS

D. P. Shrestha

University of Twente, Faculty of Geo-Information Science and Earth Observation (ITC)

P. O. Box 217, 7500 AE Enschede, The Netherlands

Email: d.b.p.shrestha@utwente.nl

KEY WORDS: Land cover and topographic parameters, critical areas for gully initiation, erosion modelling

ABSTRACT

Land degradation processes in hilly areas are often directly related to land cover changes. At the same time, many hilly areas in the tropics are inaccessible and thus lack proper data. As a result, data scarcity is a crucial problem when trying to assess soil erosion. In this paper a method is described showing the use of digital elevation, remote sensing and field measurement techniques for deriving necessary land cover and topographic parameters as required for erosion modelling. The study shows that field measurements help in accurate estimation of cover factor. Similarly, the incorporation of DEM-derived parameters such as upslope catchment area and flow direction network in erosion modelling helps to identify the dominant erosion process active in the area. This makes the formulation of sound conservation measures for minimising soil losses and reducing off-site erosion effects in low lying areas much easier.

1. INTRODUCTION

Driving forces of land degradation processes on hill slopes in the tropics are often directly related to changes in land cover or to extreme climatic conditions. Conversion of natural forest to agricultural land to support growing population is reported to cause major changes in soil physical properties such as increase in bulk density, destruction of soil structure, and decrease of organic carbon content (Matson et al., 1997). These changes not only affect soil fertility but also soil hydraulic properties and water retention characteristics (Prachansri, 2007; Suriyaprasit, 2008; Zhou et al., 2008). In inaccessible mountainous areas data scarcity is often the crucial problem. Necessary data for analysing land degradation problem may not be easily available. In view of these problems, remote sensing techniques have become very important not only for generating land cover parameters but also for getting information on surface topography, both of which are important parameters for modelling degradation processes. For an example, classification techniques are applied for mapping land cover or cover factor (C factor) (Wischmeier and Smith, 1978) is generated for application in modelling erosion process. Moreover, for understanding the driving forces responsible for land degradation in the rugged terrain it is essential to know the role of topography, surface conditions and land cover. The main objective of the study is to study the application of remote sensing technique in inaccessible areas for assessing erosion processes. Specific objectives are (i) deriving land cover parameters and (ii) identifying erosion processes so that planning for implementing conservation measures can be made (more) effective.

2. MATERIAL AND METHODS

2.1 Study area

The study area is located in the Nam Chun watershed in Petchabun Province, about 400 km north of Bangkok, Thailand (Fig. 1). It lies between 16° 40' and 16° 50' North latitudes and between 101° 02' and 101°15' East longitudes covering 67 km². The climate is tropical with distinct differences between dry (Oct-April) and wet

(May-September) seasons. Average annual rainfall based for the period 1953 - 2006 is 1,095 mm, of which 80% falls during the monsoon period (May to Sept). Elevation varies from 185 to 1,490 m asl. The soils are mainly in the clay loam to silty clay loam texture classes. Main land use types consist of forest, degraded forest, cropland, grassland and orchard. Slash and burn is the common approach to clear forest area by the local population. Main agricultural crops are maize and beans in the upland sloping area and rice and vegetables in the lowland area. The dominant fruit tree type is tamarind but other fruit types grown are mango, papaya and banana.

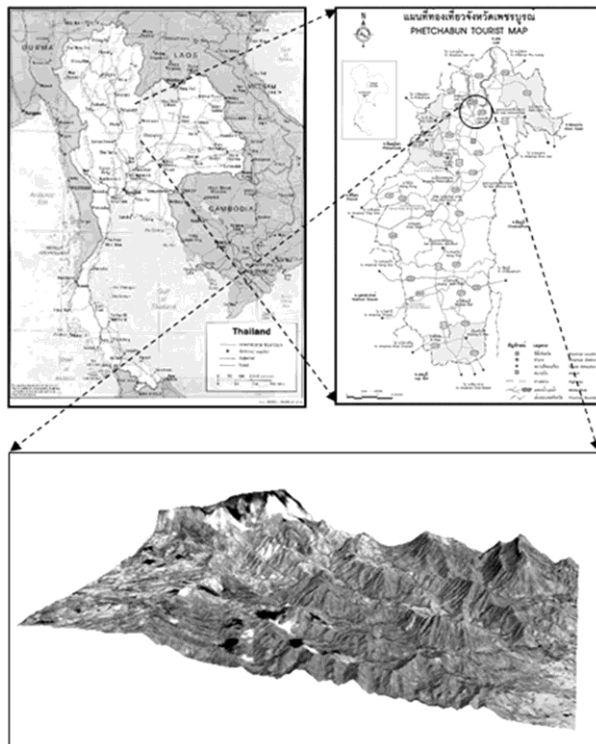


Fig. 1. The study area

2.2 Deriving land cover parameters

2.2.1 Estimation of cover factor. The USLE cover factor, C (Wischmeier and Smith, 1978), which reflects the effect of cropping and management practices on erosion rates, is the factor used most often to compare relative impacts of management options on conservation plans. In order to derive C factor, Normalized Difference Vegetation Index (NDVI) is often used based on empirical equations (De Jong, 1994; Van der Knijff et al., 1999). It will be interesting to see if the described methods are also applicable in the tropics. For this purpose the NDVI derived C factor is compared with the field estimated factor based on 138 sample locations during fieldwork in September 2007. C factor is derived based on prior land use (PLU), canopy cover percentage assessed for different cover types (CC), surface cover percentage (SC) and surface roughness (SR) as explained in the method for RUSLE (Renard et al., 1997). The prior-land-use subfactor (PLU) expresses the influence on soil erosion of subsurface residual effects from previous crops. For agricultural area the value is

adjusted to 0.90 considering the effect of crop residue. Canopy cover and surface cover were estimated in the field in terms of the fraction of land surface covered by canopy (F_c) and the percentage of land area covered by soil surface cover (S_p). Finally, the cover factor (C_f) was calculated as follows:

$$C_f = PLU.CC.SC.SR \quad (1)$$

An ASTER data of the area acquired on 6 November 2007 was available. The ASTER data was processed to remove illumination variation caused by topography in the mountainous areas. Normalized Difference Vegetation Index was generated from the topography-corrected ASTER data using its near infrared (NIR) and red band (R) and following the conventionally applied equation (Rouse et al., 1974):

$$NDVI = (NIR - R)/(NIR + R) \quad (2)$$

The NDVI was used to generate C factor maps based on the established methods. The NDVI-derived C values were plotted against 138 field estimates in order to test in how far NDVI derived C values correspond to field estimates and to determine if NDVI can be used in generating C values in the tropics.

2.3 Topographic parameters

Apart from the computation of slope gradient and aspect from the digital elevation data, flow accumulation-based terrain parameters were used to describe flow of runoff water over a gridded surface. Flow accumulation in combination with local slope gradient describes the accumulation or erosion potential of the location. In order to accumulate the surface runoff, flow direction needs to be estimated for each cell. The flow direction was defined according to direction of the steepest slope, as this was considered the natural pathway of runoff water. Once the flow direction was defined, a local drainage direction network was generated and the total flow-contributing area was calculated for each cell. The accumulated flow was used not only for assessing soil detachment by runoff water but also for assessing critical area for gully erosion.

2.4 Erosion modelling

Erosion is the detachment of soil particles by raindrop impact and/or by surface runoff, and the transportation of the sediments down the hill. Several factors e.g. surface condition, topography, land cover and soil type play a role in the erosion process. Erosion models are designed to simulate the processes. Several models are available for assessing soil losses but it is difficult to see which erosion process e.g. sheet, rill or gully erosion, is dominant in an area. In the present study the revised MMF model (Morgan, 2001) was selected because of its simplicity, flexibility, strong physical base and because it has proven to be applicable in similar mountainous environments (Shrestha et al., 2004). If conditions for surface runoff generation is optimal it is normal to have concentric surface flows in sloping areas. This results in more scouring of the soil surface by runoff water, thus forming rills or initiating gullies which can be modelled using the critical slope gradient and the critical contributing areas (Vandaele et al., 1996). (Desmet and Govers, 1997) found that most gullies were initiated in agricultural fields located in the Belgian Loess Belt when:

$$S \cdot \left(\frac{A^{0.4}}{W} \right) > 0.72 \quad (3)$$

Where S is slope ($m \cdot m^{-1}$), A is upstream contributing area (m^2) and w is flow width (m) along the contour which equals the cell length in case that the flow is along the four cardinal directions (N, E, S and W). In case of inter-cardinal directions (NE, SE, SW and NW) the flow width is the diagonal length along the cell center. For rills, the threshold is different. Rill initiation starts when the value of the index is more than 0.22. A map of critical zones for ephemeral gully incision was generated for the Nam Chun watershed to see if areas with high erosion hazard coincide with the critical zones identified.

3. RESULTS AND DISCUSSION

3.1 Deriving land cover parameters

The field estimations of land cover parameters such as canopy cover, plant height and the cover factor are given for each land cover type (Table 1). The lowest C-factor is estimated for the land use class forest (0.001). Degraded forest has C-values of around 0.028. The estimated average C factor in the agriculture fields is 0.32 which varies from 0.21 to 0.69. For orchard the estimated average C value is 0.12. Consequently, the former cultivated lands in steep slope areas were left abandoned and were replaced by fallow grasses and shrubs (thus named grassland). In this land use class, the estimated C-factor is 0.28 which shows some improvement as compared to the agriculture land.

Table 1: Land cover parameters

Land cover types	Canopy cover	Surface cover	Plant height (m)	Cover factor (C)		ET_Eo ratio	Manning's n
				Average	range		
Forest	0.79	0.26	17.5	0.001	0.00 – .002	0.95	0.40
Deg. Forest	0.59	0.17	7.5	0.028	0.00 – 0.04	0.80	0.30
Grassland	0.37	0.12	0.8	0.28	0.21- 0.43	0.70	0.06
Agriculture	0.51	0.34	0.8	0.32	0.21 - 0.69	0.85	0.24
Orchard	0.63	0.15	7.5	0.12	0.07 – 0.32	0.80	0.06

In order to see how far the NDVI-based C-factor estimation is close to field derived C values, both the established linear (De Jong, 1994) and the exponential method (Van der Knijff et al., 1999) were applied to generate C factor maps. The results were tested with a set of 138 field derived C values. A scatter plot of the field estimated C values and the C values estimated by the linear model does not show any pattern or any sign of correlation (R^2 of 0.003). Similar results are shown in the C values estimated by the exponential model (Fig.2). The linear method over estimated vegetation cover (Fig. 2a) while the exponential method under estimated it, which is shown by the fact that most estimated C values plot close to the vertical axis for the field estimated value in the range 0-0.1 (horizontal axis, Fig. 2b). In the tropics vegetation can grow very rapidly because of favourable soil moisture and climatic conditions. The field estimates of C factor was carried out in September while the NDVI is from November. Also, there is the effect of local land use practices. For example, due to the practice of leaving plant residues the land is often not bare after crop harvest. Different cropping systems such as mixed or inter-cropping, relay cropping and multiple cropping or combinations are often practiced in order to grow more than one crop on the same plot of land (Beets, 1975). This is mainly because of favourable climatic conditions, the availability of abundant labour and a lack of capital for mechanization. Thus, generating average annual C-values from a NDVI image –derived from data captured in a certain satellite over pass - is not a straightforward exercise. For erosion assessment in the tropics the best alternative method at the moment seems to be application of image classification to map major land cover types in the area followed by field-based C-factor estimation.

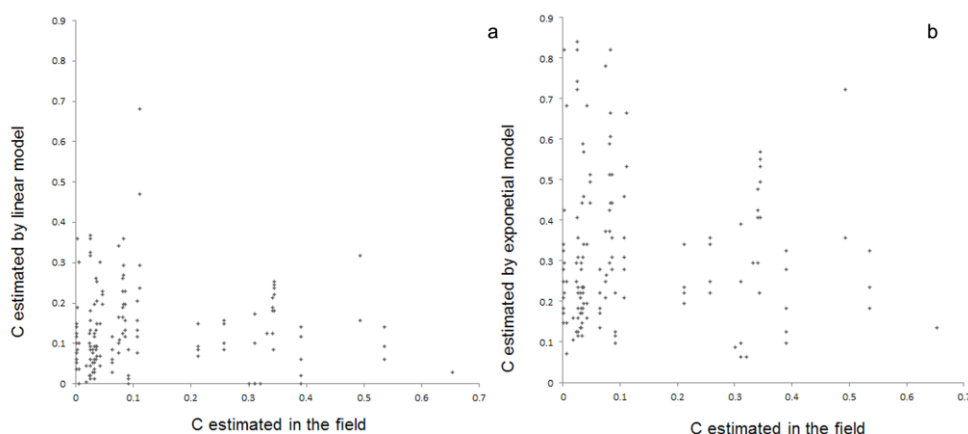


Fig. 2. Cover factor estimation in the field versus established methods (linear (a) and exponential (b))

3.2 Modelling results

3.2.1 Soil erosion. Annual soil loss for the whole watershed, estimated using the revised MMF model is 6 t.ha^{-1} . The rate is close to the acceptable limit in this area with high intensity rain (Verheijen et al., 2009; Wakatsuki and Rasyidin, 1992). Highest soil loss is found in agricultural areas with an average soil loss of 10 t.ha^{-1} and with a standard deviation of 36.6; and the lowest in orchard (3 t.ha^{-1}) and with standard deviation of 17.2). In grassland it is slightly higher (4 t.ha^{-1}). In forest and degraded forest erosion rates are within the tolerable limit (5 t.ha^{-1}). Assessment of critical zones for ephemeral gully formation shows that the critical areas are located in slope gradients higher than 20 per cent. During field work 20 gullies were studied and their locations were recorded using Garmin GPS. They were used to validate the concept of critical zones for ephemeral gully formation (equation 3). The result shows an accuracy of 65 per cent (Table 2) with soil losses of more than 10 t.ha^{-1} . In steep slope areas rill and gully erosion are dominant over sheet erosion especially when surface cover is lower and when there is sufficient surface runoff coming from up-slope areas.

3.2.4 Mapping erosion processes. Although the estimated average soil loss rates in the whole watershed is not that high (6 t.ha^{-1}), the erosion problem can be locally severe with annual soil loss rates of more than 50 t.ha^{-1} especially in cultivated fields located on steep slopes. The concept of critical value derived from using terrain slope and contributing area, originally developed for Loess soil in Belgium, is thus also applicable in steep mountainous areas with other soil types. From the results of the assessment of critical areas for rill and gully initiation and in

combination with soil erosion assessment of the area, it is possible to generate a map showing areas susceptible to sheet, rill and gully formation (Fig. 3). Areas susceptible to gully erosion were separated if the estimated soil loss rates are higher than $10 \text{ t}\cdot\text{ha}^{-1}$ and the critical value is more than 0.72 (equation 18). Similarly, the areas susceptible to rill erosion were mapped if the critical value is within the range 0.22 to 0.72 and soil loss rates are below $10 \text{ t}\cdot\text{ha}^{-1}$ (Table 3). Areas susceptible to sheet erosion are the ones with lower soil loss rates (less than $10 \text{ t}\cdot\text{ha}^{-1}$) and with the critical value lower than 0.22.

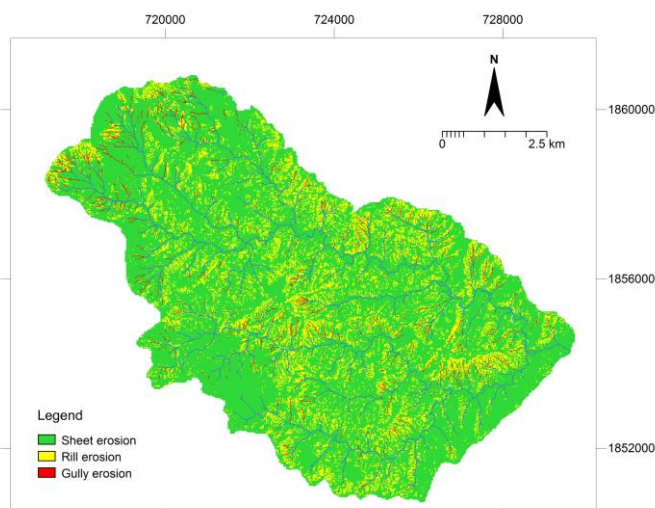


Fig. 3. Map showing erosion types

Generally, sheet erosion occurs due to rain splash effect and in shallow overland flow with estimated average soil loss rate of $2 \text{ t}\cdot\text{ha}^{-1}$. These are typically the summits and the shoulder complex and gently sloping areas which cover together 79 percent of the area. The rill erosion susceptible area covers nearly one fifth of the watershed (18 percent). In the area which is dominated by rill erosion higher soil losses usually occur due to the combined effect of sheet and rill erosion. Here, the estimated average erosion rate is $3 \text{ t}\cdot\text{ha}^{-1}$ which can go up to $20 \text{ t}\cdot\text{ha}^{-1}$ on steeper slopes. In very steep areas with high surface runoff potential due to larger upslope catchment area soil erosion is mainly in the form

of gully formation.

Table 2: Contingency table of critical zones for ephemeral gullies and field data

Threshold value	Reference gully (field location)	Accuracy
Critical zones (> 0.72)	Gully	13 65%
Critical zones (< 0.72)	No gully	7
Total		20

Table 3: Determining soil erosion types

Erosion type	Critical value	Erosion rates $\text{t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$
Gully erosion	> 0.74	> 10
Rill erosion	$0.22 - 0.74$	< 10
Sheet erosion	< 0.22	< 10

Based on surface area affected, the results show that sheet erosion plays dominant role in the watershed. Since soil losses due to sheet erosion seem to be in agreement with soil formation rate it cannot be considered a major problem. In the watershed one fifth of the surface area is estimated to be susceptible to rill formation. Erosion processes influence cultivation and land use practices. Since normal cultivation practices usually remove rills developed in previous rainy season, rill erosion can still be considered as not very alarming. However, conservation measures e.g. vegetative protective measures or terracing will be needed to minimise soil loss. In steeper areas having high surface runoff potential due to larger upslope catchment area and with high soil loss rates, soil erosion is mainly attributed to gully formation for which both mechanical (terracing, construction of check dams, etc.) as well as vegetative protective measures would be necessary to protect the land from further degradation.

4. Conclusions

The study shows that processing of satellite data in combination with field measurements helps in determining land cover parameters required for erosion modelling. In inaccessible mountainous areas data scarcity often hinders proper assessment of the status of land degradation. Crucial input data e.g. land cover parameters are often not available or insufficient for running hydrological models. Satellite data is very useful in getting spatial variation of land cover information in inaccessible area, but it will not be very meaningful if it is not combined with field data. Field data is required not only to take samples for spectral classification and for its accuracy assessment, but also to

fine-tune land cover parameters used in erosion modelling. Moreover field assessment of cover factor helps incorporate local land use practices. Field data helps to incorporate plant residues left after crop harvest which would not be incorporated if only NDVI derived C value is used. Crop residues help in minimising soil loss by creating obstruction for surface flow.

The study shows that application of an erosion model alone in a watershed may not be sufficient in addressing the localized erosion problem since average soil loss rates may be lower or within the tolerable limit but the problem may be locally severe. For making conservation plans it is essential to know not only which land cover unit has high erosion rates but it is also important to know the underlying causal factors and processes in soil erosion. The use of topography-derived contributing area for runoff estimation and slope gradient relationship appeared to be an efficient method for assessing the type of erosion process in inaccessible areas. This helps in planning conservation measures.

References

- Beets, W.C., 1975. Multiple-cropping practices in Asia and the Far East. *Agriculture and environment*, 2: 219 - 228.
- De Jong, S.M., 1994. Applications of reflective remote sensing for land degradation studies in a Mediterranean environment. Published Thesis, Utrecht University, Utrecht, 237 pp. pp.
- Desmet, P.J.J. and Govers, G., 1997. Two-dimensional modelling of the within-field variation in rill and gully geometry and location related to topography. *CATENA*, 29(3-4): 283-306.
- Matson, P.A., Parton, W.J., Power, A.G. and Swift, M.J., 1997. Agricultural Intensification and Ecosystem Properties. *Science*, 277(5325): 504-509.
- Morgan, R.P.C., 2001. A simple approach to soil loss prediction: a revised Morgan-Morgan-Finney model. *Catena*, 44(4): 305-322.
- Prachansri, S., 2007. Analysis of soil and land cover parameters for flood hazard assessment: a case study of the Nam Chun Watershed, Petchabun, Thailand. Unpublished MSc. Thesis, International Institute for Geo-Information Science and Earth Observation (ITC), 92 pp.
- Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. and Yonder, D.C., 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE), USDA, Washington, DC.
- Rouse, J.W., Haas, R.H., Schell, J.A. and Deering, D.W., 1974. Monitoring vegetation systems in the Great Plains with ERTS, Third Earth Resources Technology Satellite - 1 Symposium. NASA, Goddard Space Flight Center, Washington DC, pp. 309 - 317.
- Shrestha, D.P., Zinck, J.A. and Van Ranst, E., 2004. Modelling land degradation in the Nepalese Himalaya. *CATENA*, 57(2): 135-156.
- Suriyaprasit, M., 2008. Digital terrain analysis and image processing for assessing erosion prone areas. Unpublished MSc. Thesis, International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, The Netherlands, 85 pp.
- Van der Knijff, J.M.f., Jones, R.J.A. and Montanarella, L., 1999. Soil Erosion Risk Assessment in Italy, European Commission Directorate General JRC Joint Research Centre Space Applications Institute European Soil Bureau.
- Vandaele, K., Poesen, J., Govers, G. and Wesemael, B.v., 1996. Geomorphic threshold conditions for ephemeral gully incision. *Geomorphology*, 16(2): 161-173.
- Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J. and Smith, C.J., 2009. Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews*, 94(1-4): 23-38.
- Wakatsuki, T. and Rasyidin, A., 1992. Rates of weathering and soil formation. *Geoderma*, 52(3-4): 251-263.
- Wischmeier, W.H. and Smith, D.D., 1978. Predicting rainfall erosion losses. A guide to conservation planning, Agricultural Research Service Handbook no. 537. USDA, pp. 58 pp.
- Zhou, X., Lin, H.S. and White, E.A., 2008. Surface soil hydraulic properties in four soil series under different land uses and their temporal changes. *CATENA*, 73(2): 180-188.