Arab J Geosci (2012) 5:797–805
DOI 10.1007/s12517-010-0265-4

ORIGINAL PAPER

An assessment of soil erosion probability and erosion rate in a tropical mountainous watershed using remote sensing and GIS

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Received: 4 March 2010 / Accepted: 14 December 2010 / Published online: 8 January 2011

Abstract Remote sensing data and Geographical Information System (GIS) has been integrated with the weighted index overlay (WIO) method and E_{30} model for the identification and delineation of soil erosion susceptibility zones and the assessment of rate of soil erosion in the mountainous sub-watershed of River Manimala in Kerala (India). Soil erosion is identified as the one of the most serious environmental problems in the human altered mountainous environment. The reliability of estimated soil erosion susceptibility and soil loss is based on how accurately the different factors were estimated or prepared. In the present analysis, factors that are considered to be influence the soil erosion are: land use/land cover, NDVI, landform, drainage density, drainage frequency, lineament frequency, slope, and relative relief. By the WIO analysis, the area is divided into zones representing low (33.30%), moderate (33.70%), and high (33%) erosion proneness. The annual soil erosion rate of the area under investigation was calculated by carefully determining its various parameters and erosion for each of the pixels were estimated individually. The spatial pattern thus created for the area indicates that the average annual rate of soil erosion in the area was ranging from 0.04 mm yr^{-1} to 61.80 mm yr^{-1}. The high soil erosion probability and maximum erosion rate was observed in areas with high terrain alteration, high relief and slopes with the intensity and duration of heavy precipitation during the monsoons.

Keywords Soil erosion · WIO · E_{30} model · Landform · Manimala · Kerala

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Introduction

Sediment-related processes and associated hazards in mountain basins encompass a wide range of processes, from erosion and shallow landsliding on basin slopes to sediment transport and deposition in the channel network. The management of mountain basins requires reliable methods for the analysis of sediment dynamics (Jain and Kothyari 1997; Mitasova et al. 1996; Jain et al. 2003; Marchi and Fontana 2005; Dabral et al. 2008; Hlaing et al. 2008: Singh et al. 2008; Ande et al. 2009; Tian et al. 2009). Land degradation and topological changes within watersheds are accomplished by weathering processes, stream erosion patterns, and sediment transportation by surface runoff. In these, soil erosion and surface runoff have always been problems concomitant with intensive agricultural land use in hilly areas. Soil erosion is a complex dynamic process of land denudation by which productive surface soils are detached, transported, and accumulated at a distant place and is considered as the one form of soil degradation along with soil compaction, low organic matter, loss of soil structure, and poor internal drainage problems (Das et al. 1981; Rao et al. 1994; Jain et al. 2001; Jianrong et al. 2008). These forms of soil degradation, serious in themselves, usually contribute to accelerated soil erosion. Soil erosion and degradation of land resources are significant problems in a large number of countries. The problem has far-reaching economic, political, social, and environmental implications due to both on-site and off-site damages (Thampapillai and Anderson 1994; Baba and Yusof 2001; Ashish Pandey et al. 2007; Yuksel et al. 2008). Numerous human-induced activities, such as mining, construction, and agricultural activities, disturb land surfaces, resulting in erosion. Soil erosion from cultivated areas is typically higher than that from uncultivated areas. Each year, 75 billion tons of soil is removed due to erosion, with most of it coming from agricultural land and as a result, around 20 Mha of land is lost. Soil erosion is very high in Asia, Africa, and South America averaging 30–40 t ha^{-1} $year^{-1}$. In India, about 53% of the total land area is prone to erosion and has been estimated that in India about 5,334 m-tonnes of soil is being detached annually due to various reasons (Narayana and Babu 1983).

Assessment of erosion status of a watershed is an essential prerequisite of integrated watershed management. Due to the complexity of the variables involved in erosion it becomes difficult to measure or predict the erosion in a precise manner. The latest advances in remote sensing and geographical information technologies have provided very useful methods of surveying and identifying various aspects of watershed terrain behavior and also the integrated modeling approach utilizing the parameters controlling soil erosion is the effective means of practical assessment of soil erosion hazard. Several studies carried out in different parts of the world has demonstrated capability of GIS technique for quantitatively assessing soil erosion hazard based on various approaches and equations (Millward and Mersey 1999; Sharma et al. 2001; Ma et al. 2002; Zhao et al. 2002; Onyando et al. 2005; Ashish Pandey et al. 2007; Ismail and Ravichandran 2008; Jianrong et al. 2008; Singh et al. 2008; Kouli et al. 2009; Krishna Bahadur 2009; Naik et al. 2009; Tian et al. 2009).

To estimate the average annual soil loss from an area, RUSLE is often used. To adopt the RUSLE, large sets of data starting from rainfall, soil, slope, crop, and land management are needed in detail. In developing countries all the necessary data are often not available or require ample time, money, and effort to prepare such data sets. In the present study, an attempt has been made to assess the spatial distribution of potential soil erosion zones and rate of soil erosion at a of scale 1:50, 000, covering upper catchment of Manimala river by an efficient, fast, and simple methodology using the remote sensing and GIS data integration and analysis, despite the lack of direct observation data. Indirect ways were used to collate the required data of the watershed and this has been discussed in the methodology section.

Study area

The study area constitute mountainous sub-watershed of the Manimala River, falling in the eastern portion in Kottayam district of Kerala, India. The sub-watershed area is 99 km^2, and falls between 9° 30′ to 9° 40′ north latitudes and 76° 50′ to77° 00′ east longitudes (Fig. 1). Study area presents a typical mosaic of moderate to highly undulating rugged topography with numerous mountain peaks over 1,000 m above msl and shows an average slope of 39° with a maximum of >72°, along with a maximum elevation of 1,200 m. Sub-watershed is composed of hard crystalline rocks, mainly charnockite (more than 95% of the area), quartzite and dolerite, and the soil type varies from forest loam to lateritic soil with change in elevation. Drainage patterns in this area resemble to a combination of dendritic and trellis with a dominance of dendritic pattern. Climate of the area is humid tropical with a mean annual rainfall of 3,750 mm and more than 50% of which is received during the south-west monsoon (June–September), the mean monthly temperature ranges from a minimum of 19°C during December to the maximum of 35°C in May. Land use/land cover of the area comprises 66% rubber plantations followed by tea plantation, mixed forest, grassland, cleared areas etc. The major characteristics of the sub-watershed area are undulating highlands with slided (landslide) and eroded slopes surface with varying land practices.

Methodology

Occurrence of soil erosion in general is largely a function of the interaction of natural phenomena and human activities, such as rock types, structural makeup, geomorphological setting, soil conditions, land use practices, rainfall, etc. It is believed that the accuracy of susceptibility mapping increases when all controlling parameters are included in the analytical process and it is usually difficult to get so, because, detailed data are hard to find. In this study, seven types of soil erosion affecting factors are selected and defined. In the present study Resource Sat (IRS P6 LISS III) data acquired on 19th February 2004 (P100/R67), Survey of India toposheets 58 C/14 of scale 1:50,000 of year 1969 were used for the preparation of spatial databases and they are land use/land cover, normalized difference vegetation index (NDVI), landform, drainage density, drainage frequency, lineament frequency, and the topographic attributes of the region such as slope and relative relief. Each category is subdivided into different classes by its value or feature for the identification of soil erosion probability zones. The exact methods used for the soil erosion prone area mapping and the estimation of annual soil erosion rate are explained in the following sections and

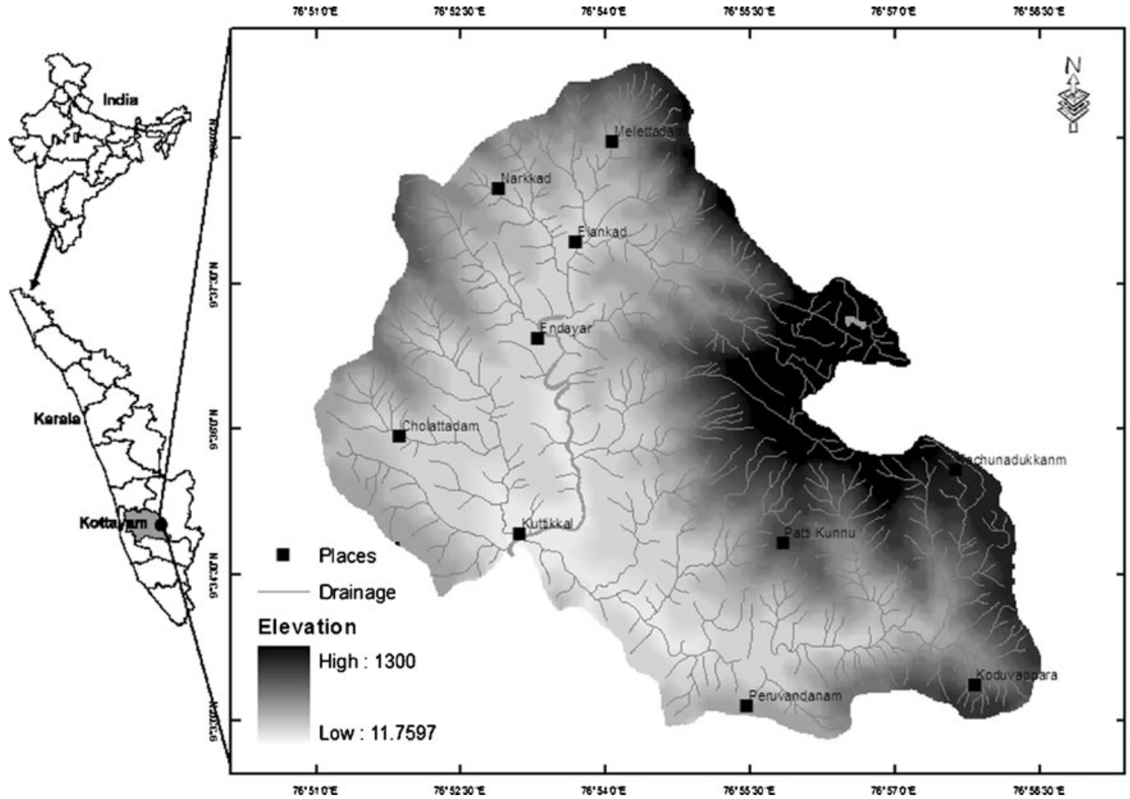

Fig. 1 Study area location map

a discussion on the parameters which are used for the assessment with regard to their effect on the process of soil erosion is given below.

Land use/land cover

The land use/land cover pattern of the area was very important because, the Western Ghats are identified as the biodiversity hot spots in the world. Besides, this area is prone to the landslides, a phenomenon of debris flow associated with torrential rain falls during the monsoons. In the present study, the standard methods of visual interpretation of remote sensing data were adopted to demarcate the various zones of natural and manmade patterns. The various land use/land cover classes delineated include mixed forest, cleared area, grass land, crop land, tea, and rubber (plantations), built-up land, escarpment, and water body. The spatial statistics of land use/land cover shows that out of the total area studied, 66% is occupied by rubber plantation.

Normalized difference vegetation index (NDVI)

NDVI is calculated from the visible and near-infrared light reflected by vegetation and the healthy vegetation absorbs most of the visible light that hits it, and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation reflects more visible light and less near-infrared light. Calculations of NDVI for a given pixel always result in a number that ranges from minus one (−1) to plus one (+1); however, no green leaves give a value close to zero. A zero means no vegetation and close to +1 (0.8–0.9) indicates the highest possible density of green leaves.

IRS P6 LISS 3 multispectral image was used with the vegetation index function available in the ERDAS Imagine 9.2 software to derive the NDVI image. To avoid the negative values and for easy handling of digital data, NDVI value obtained for IRS—P6 L3 data (23.5 m spatial resolution) were rescaled as shown in Eq. 1

$$\text{NDVI} = [(\text{Band 4} - \text{Band 3}/\text{Band 4} + \text{Band 3}) + 1] \quad (1)$$

Thus produced rescaled NDVI map shows a range of values between 0.63 and 1.75, in which the low values are characteristics of cleared areas and zones with sparse vegetations and the higher values indicate densely covered areas.

Landform

Landform mapping involves the identification and characterization of the fundamental units of landscape. It was found that the underlying lithology, slope, and the type of existing drainage pattern influence the genesis and processes of different landform units. The study area has a dominant rocky terrain, which is manifested by hills and undulating surfaces. Based on NRSA (1995) three distinct landform units, i.e., side slope plateau, denudational hill, and valley fill, which are promoting the soil erosion in the area have been identified and delineated from the study area. These distinct landform features are resulted from the complexity of geomorphic evolution and the distribution and extent of these features were varying from place to place.

Drainage density and drainage frequency

Drainage network is acting as the major agent for shaping the landscape by eroding and transporting the materials out of the drainage basin. Hill slope evolution in an area is controlled by the sediment transport processes which changes in response to the evolving topography and by their interaction with stream processes at the slope base (Rajkumar et al. 2007). In mountainous regions, drainage density provides an indirect measure of groundwater conditions, which have an important role to play in landslide and other erosional activities. (Nagarajan et al. 2000; Sarkar and Kanungo 2004; Saha et al. 2005a). Drainage density is a measure of stream spacing and a higher drainage density represents a relatively higher number of streams per unit area and thus a rapid storm response. It also represents conditions favorable for higher erosion from the catchment.

Drainage density is defined as the ratio of sum of the drainage lengths in the cell and the area of the corresponding cell. A drainage density map is prepared after computing density for each cell using GIS for 1 km^2. The values obtained range from 150 to 3,959 m/km2, which is finally classified into three classes of high (>3,000 m/km^2), moderate (1,501–3,000 m/km^2), and low (<1,500 m/km^2) density.

Drainage frequency of the area represents the number of drainages present in the unit area. In the analysis the unit area was set to be 1 km^2 and frequencies of the drainages were assessed. The resultant drainage frequency map was has shown a frequency value ranging from 0 to 5, which was then reclassified into low (2 nos./km^2), moderate (2–4 nos./km^2), and high (>4 nos./km2).

Lineament frequency

Lineaments, i.e., topographic features that are thought to represent hidden crustal structures, generally associated with high infiltration rates. Lineaments were extracted from geological maps and through visual interpretation of georeferenced IRS P6 LISS 3, 23.5 m satellite imagery. These data provide important information about fractured nature of the terrain, which indirectly gives the indication of rapid erosion potential. The study area is crisscrossed by major and minor lineaments. They vary in length from a few meters to kilometers in dimension. General trend shown by the lineaments present in the study area are NNE–SSW and NE–SW. The lineament frequency map was generated using the Spatial Analyst extension of ArcGIS. The raster layer obtained was reclassified into two classes on using the reclassification tool.

Slope and relative relief

Slope is the angle formed between any part of the surface of the earth and a horizontal datum. The most important factor controlling the stability of slopes is the slope angle (Anbalagan 1992; Pachauri and Pant 1992; Maharaj 1993). It is the means by which gravity induces stress in the slope rocks, flux of water, and other materials; therefore, it is of great significance in hydrology and geomorphology. In fact, slopes affect the velocity of both surface and subsurface flow and hence soil water content, soil formation, erosion potential, and a large number of important geomorphic processes. Digital elevation model (DEM) is derived using contour information from the topographical map for estimation of slope in degrees. The identified slope category varies from 0^o to >35^o degree in the study area and are classified into five classes like, 0–5^o (gentle), 5–10^o (moderate), 10–25^o (high), 25–35^o (very high), and >35^o (steep).

Elevation is useful to classify the local relief and locate points of maximum and minimum heights within terrains. Relative relief portrays the difference in elevation at a given point. The factor of safety decreases with increase in height. Thus, for two slopes having identical geomechanical and geometrical parameters except for height, the higher slope will be more susceptible to erosion and landslide. Run-off is higher and infiltration is lower in areas of steeper topography. In addition, saturation of a slope reduces the shear resistance of the regolith and increases the shear forces through drag (Thampi et al. 1997; Nagarajan et al. 2000; Saha et al. 2005a, b; Pandey et al. 2008). The relative relief map was generated from the IRS using the neighborhood range function available in the Spatial Analyst extension. The relative relief map thus generated shows a value ranging between 0 and 788 m/km^2 and reclassified into class 1 (<200 m/km^2); class 2 (201–400 m/km^2); class 3 (401–600 m/km^2), and class 4 (>600 m/km^2).

Delineation of soil erosion probability zones—weighted index overlay method

In order to identify and map areas vulnerable to soil erosion, various thematic maps prepared were integrated in ArcGIS 9.3. The major factors that are considered to be influencing soil erosion include land use/land cover, land form, drainage density, drainage frequency, lineament frequency, slope, and relative relief. Thus the major processes involved are theme weightage fixing and their further analysis in GIS platform. The weightages of individual themes and feature score were fixed and added to the layers by considering its role in the soil erosion. The process involves raster overlay analysis and is known as weighted index overlay (WIO). Of several methods available for determining interclass/inter-map dependency, a probability weighted approach has been adopted that allows a linear combination of probability weights of each thematic map (W_t) and different categories of derived thematic maps have been assigned scores (W_f), depending upon their role in making the terrain susceptible to soil erosion. The maximum value is given to the feature with highest susceptibility and the minimum being to the lowest susceptible feature (Table 1). The procedure of weighted linear combination dominates in raster-based GIS software systems. Spatial analyst extension of ArcGIS 9.3 was used for converting the features to raster and also for final analysis. Then using raster calculator, all the themes are added and the soil erosion prone area map is prepared. In this method, the total weights of the final integrated map were derived as sum or product of the weights assigned to the different layers according to their susceptibility.

Assessment of annual soil erosion rate—E_{30} model using NDVI and slope

The methodology used in the present analysis was proposed by Honda et al. (1996, 1998) and Hazarika and Honda

Table 1 Theme and feature class weights

Theme	Theme weight (W_t)	Feature class	Feature class weight (W_f)
Land use/land cover	15	Waterbody	0
		Escarpment	0
		Tea	1
		Mixed forest	1
		Grass land	1
		Built-up land	2
		Crop land	7
		Rubber	7
		Cleared area	9
Landform	12	Denudational hill	8
		Side slope plateau	5
		Valley fill	10
Drainage density	10	1,500 m/km^2	3
		1,500–3,000 m/km^2	4
		>3,000 m/km^2	10
Drainage frequency	15	2	2
		2–4	5
		>4	10
Lineament frequency	10	2	3
		>2	8
Slope	20	0–5°	0
		5–10°	3
		10–25°	7
		25–35°	10
		>35°	10
Relative relief	18	200 m/km^2	0
		201–400 m/km^2	5
		401–600 m/km^2	8
		>600 m/km^2	10

(2001). The proposed method provides a greater flexibility in estimating the soil erosion rate for any location within the study area, because by this method the soil erosion rate for each of the pixels could be estimated individually.

The soil erosion model given in Eq. 2 was used to estimate the annual rate of soil erosion in the areas under investigation. This model is mainly governed by slope gradient and vegetation index and the annual soil erosion rate (E) is defined as :

$$E = E_{30}(S/S_{30})^{0.9} \tag{2}$$

Where S = gradient of the point under consideration, S_{30}= tan (30°), and E_{30}=rate of soil erosion at 30° slope and defined as given in Eq. 3:

$$E_{30} = \mathrm{Exp}\,[(\mathrm{Log}\,0.562 - \mathrm{Log}\,22.25/\mathrm{NDVImax} - \mathrm{NDVImin}) \times (\mathrm{NDVI} - \mathrm{NDVImin}) + \mathrm{Log}\,22.25] \tag{3}$$

The maximum and minimum (average) rate of soil erosion at 30° slope in the study areas collected from the field stations were 22.25 mm/year and 0.562 mm/year in the study area as shown in Eq. 3. By calculating the E_{30} value for each pixel using Eq. 3, soil erosion from each pixel with a different slope was calculated using Eq. 2. A raster map of slope gradient was prepared with the pixel size of 20 m, using a DEM to provide the slope information for Eq. 2. The final map thus produced has given a continuous raster with values varying from pixel to pixel indicates the soil erosion rate in the study area. Thus by using the GIS-based proposed methods, soil erosion probability zones and soil erosion rate map were prepared and the results are discussed in the following sections.

Result and discussion

In the present study, an attempt has been made to assess and explain the two aspects related to the soil erosion in the upper catchment of River Manimala: delineation of soil erosion probability zones and rate of soil erosion. The evaluation of soil erosion probability zones and soil loss at the watershed scale is necessary for sustainable agricultural/land use and comprehensive local and regional development. To account the integrated effect of all the parameters considered in this study, the choice among a set of features for the identification of soil erosion probability, based upon multiple criteria were developed, which gives linear combination of probability weights for land use/land cover, land form, drainage density, drainage frequency, lineament frequency, slope, and relative relief. The composite map represents regions with weight factors as values. The integrated final map has generated a range of values from 1.25–9.35, which is reclassified into three zones (Fig. 2), based on the quantile classification method available in the spatial analyst option. In quantile classification, the range of possible values is divided into unequal-sized intervals so that the number of values is the same in each class. Classes at the extremes and middle have the same number of values. Because the intervals are generally wider at the extremes, this option is useful to highlight changes in the middle values of the distribution. The soil erosion probability of the area is classified as high, moderate, and poor. The high erosion probability zones occupies 33.00% of the total area; moderate and low soil erosion prone zones occupy 33.70% and 33.30% of the study area, respectively. After generating the soil erosion probability zones, it is very important to identify the type of individual feature classes, which play a vital role in the making the area vulnerable to soil erosion. In the present analysis it was found that land use/land cover types such as cleared areas, crop land, and rubber plantations, particularly in replanting time present in the slide slope plateau, highly elevated areas with high slope and high drainage density make the terrain more prone to soil erosion. The rate severity and nature of the erosion will be more unpredictable in the time of monsoon seasons.

A quantitative assessment of average annual soil loss on grid basis was made using a new methodology known as E_{30} model using the NDVI and slope of the area. Lack and non-availability of data needed to process the RUSLE method necessitated the application of the proposed methodology in the study area to assess the spatial distribution of rate of soil erosion in the studied sub-watershed. The use of remote sensing data and digital elevation model in GIS and ERDAS enabled the determination of the spatial distribution of the parameters needed for the analysis. An appraisal of soil erosion rates were carried out, and the spatial characteristics of soil erosion rate within the sub-watershed was computed (Fig. 3). The overall estimated soil erosion rate in the study area was varying from 0.04 mm year^{-1} to 61.80 mm year^{-1} with an average of 30.92 mm year^{-1}. The spatial patterns of soil erosion rate were overlaid with soil erosion probability map of the area to crossvalidate the accuracy of both the maps, and it was observed that areas with high soil erosion rate and high erosion probability zones were showing a similar spatial domains and patterns. The result of crossvalidation of both maps indicates the accurate choice of parameters and methodology for the present study.

Conclusions

In the present study, remote sensing and GIS-based soil erosion assessment techniques (both WIO and E_{30}) were effectively implemented to characterize and evaluate soil

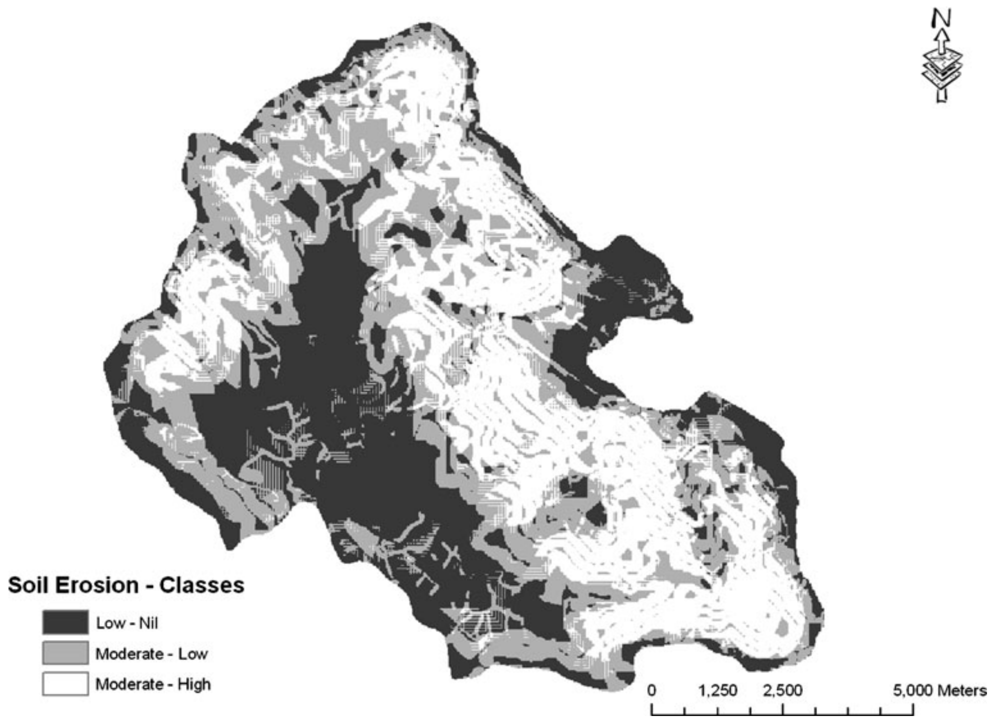

Fig. 2 Classes of soil erosion

erosion potentials, its spatial pattern and the influence of different land use/land cover types and other terrain variables in the study area. The implementation of WIO and E_{30} method, enable to classify the area in to different zones on the basis of probability of soil erosion and the rate of soil erosion in each pixel, which ultimately helpful to derive suitable protection measures. The maximum rate of soil erosion is estimated to be 61.80 mm year^{-1} and this corresponds to areas with high soil erosion probability (33.00% of the total area). The generated soil erosion probability image, predicted amount of soil erosion rate, and its spatial distribution can provide a basis for comprehensive and sustainable land management for the study area. Once the land use types and associated soil erosion severity are known, such information becomes extremely valuable as these can be used to formulate a plan

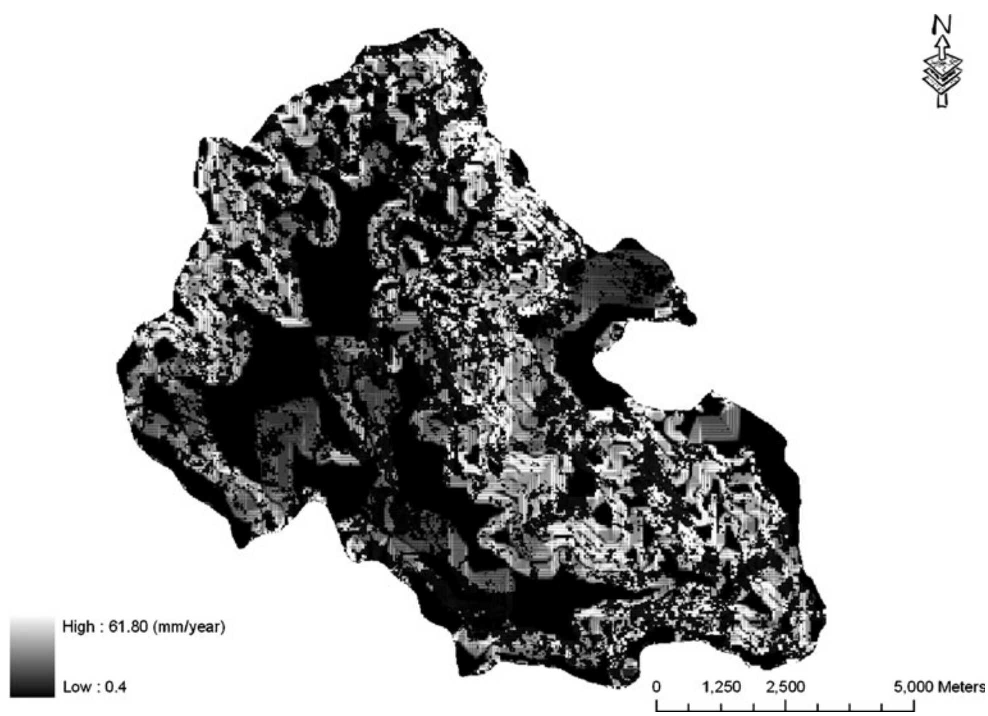

Fig. 3 Spatial characteristics of soil erosion rate assessed by E_{30} method

focusing conservation measures in those areas. Therefore, the ways of evaluating soil erosion zones and rate of losses even with the lack of direct observation data presented in this study could be useful for the land use decision makers in other part of the world.

Acknowledgments The authors are thankful to the Director of the School of Environmental Sciences, Mahatma Gandhi University for providing the spatial data sources and necessary lab facilities.

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