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Research Article

Spatial Variability of Satellite Derived Rainfall Erosivity Factors (R-Factors) for a Watershed near Allahabad

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ABSTRACT

Rainfall erosivity, depending upon amount and intensity of rainfall, is an important parameter for soil erosion risk assessment. Despite its importance, rainfall erosivity is usually implemented in models with a single numeric value. The need for satellite-estimated precipitation arises because of the non-dependable and poor spatially distributed ground rainfall data. Hence, the objective of this study was to assess the spatio-temporal distribution of rainfall erosivity (R) factors in the selected study area, based on available free satellite rainfall data and to develop an erosivity map. The precipitation data for the entire duration of study and area were derived from daily precipitation data provided by the NOAA climate prediction center. The spatial resolution of rainfall data is 0.1 by 0.1 degree and temporal resolution is one day. Accordingly, the rainfall data were analyzed for deriving the rainfall erosivity factor (R) which plays a very important role in the soil erosion process as well as in RUSLE, USLE and MUSLE models using the derived EI_{30} maps. The results revealed that the mean value of one year rainfall erosivity was 17.79 MJ mm ha^{-1} h^{-1} yr^{-1} with lowest values of 17.29 MJ mm ha^{-1} h^{-1} $yr^{-1}$and highest values for study area is found 18.13 MJ mm ha^{-1} h^{-1} yr^{-1}. The most important advantage of R-factor derived from satellite rainfall data is that spatial variations in R-factor can be incorporated with USLE, RUSLE or MUSLE models to capture spatio-temporal variations in soil erosion.

Key words: Rainfall Erosivity, Smith Method, Soil Erosion

Introduction

One major concern in landscape management and conservation planning is the reduction of the risk of erosion, which requires a correct assessment of the potential transport capabilities of runoff generated by erosive storms. A preliminary step is to map the rainfall erosivity in the area under management (Meusburger *et al*., 2011; Goovaerts, 1999). Rainfall erosivity (R) is one of the six factors in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al*., 1997) for erosion prediction. It quantifies the ability of rainfall to cause soil loss from the watersheds including any landforms and hillslopes. Soil loss may be estimated using either the USLE or RUSLE by multiplying R together with the other five factors: soil erodibility (K), slope length (L), slope steepness (S), crop type and management (C), and supporting conservation practices (P) (Bartsch *et al*., 2002).

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The rainfall erosivity factor (R) in RUSLE is generally recognized as one of the best indicators of the erosive potential of raindrops impact (Renard *et al*., 1994; 1993). Since rainfall erosivity is not distributed uniformly through the year, the assessment of soil erosion requires knowledge of the seasonal distribution of R; hence, there is great need of rainfall measurements with high temporal resolution. Daily-read raingauge stations are expensive, and so the rainfall erosivity is typically known only at a limited number of locations. It is therefore critical to capitalize on any source of information to predict rainfall erosivity values at unmonitored locations with high temporal frequencies.

So, the study was undertaken to develop average annual rainfall erosivity for the study area in year 2006 by using satellite estimated daily rainfall product.

Material and Methods

Study Area

The study was carried out for the Jhagrabaria watershed situated in Allahabad district of Uttar Pradesh State, India. It is bounded by latitudes 25°12' N to 25°20' N and longitudes 81°33' E to 81°44' E (Figure1) falling in Survey of India (SOI) topographical sheets 63G/11 and 63G/12, respectively. Geologically the area comprises of

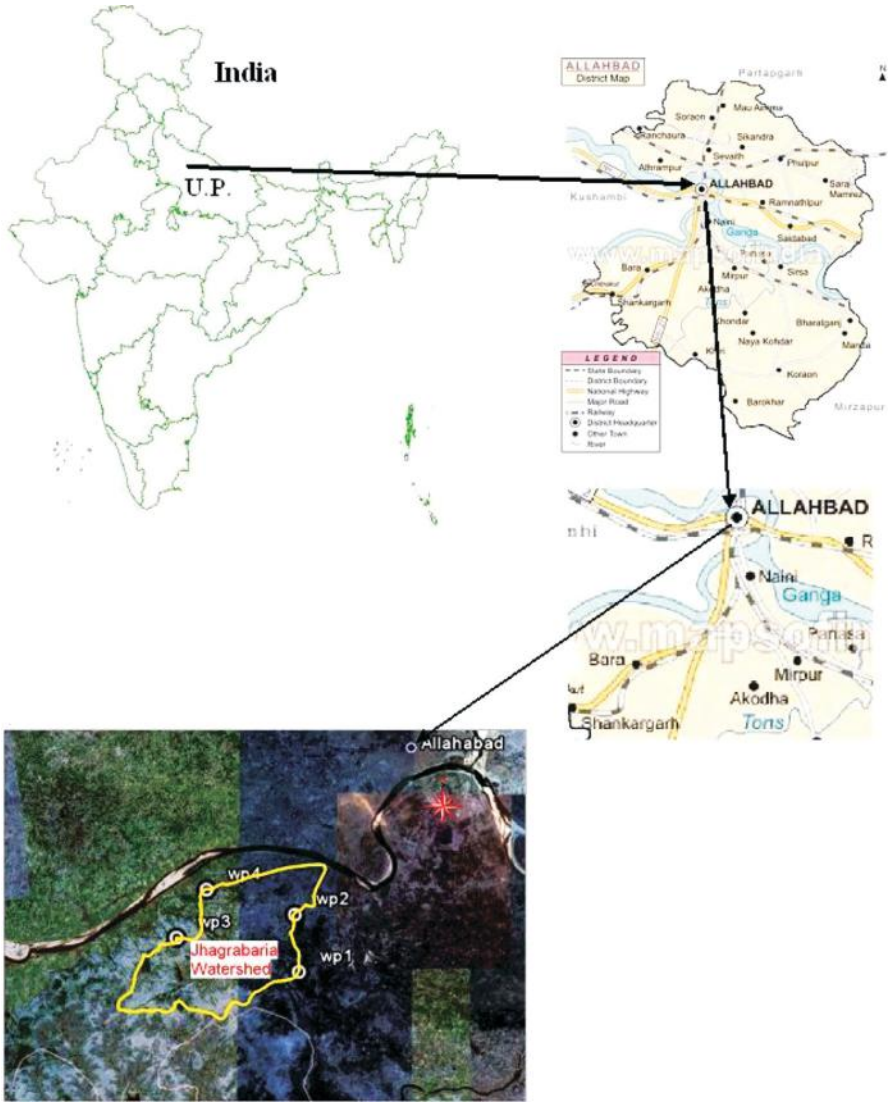

Fig. 1. Location of the study area (Jhagrabaria Watershed) in the state of U.P. (India)

Table 1. Ten (1994-2006) years Average Maximum and Minimum Temperature and Rainfall

Month/ Year	Max. Average Temp (°C)	Min. AverageTemp. (°C)	Average Rainfall (mm)
JANUARY	22.03	7.75	15.8
FEBRUARY	26.54	11.17	19.0
MARCH	33.09	15.79	3.8
APRIL	38.88	22.9	5.4
MAY	41.41	26.72	9.4
JUNE	39.40	27.84	103.8
JULY	34.55	26.27	281.0
AUGUST	33.18	25.78	266.0
SEPTEMBER	32.66	24.49	216.3
OCTOBER	33.23	20.37	39.1
NOVEMBER	30.02	14.05	10.1
DECEMBER	24.78	8.61	11.0

Source: Air Force Station, Bamrauli, Allahabad (U.P), India

Upper Vindhayan formations mainly consisting of the sandstone and shale. The watershed is about 45 km southwest of the Allahabad district and is situated on the right bank of river Yamuna. The watershed shows a nearly flat to a gently undulated topography with occasional small hillocks. The minimum and maximum elevations of this watershed are 90 m (above msl) and 180 (above msl), respectively.

The climatic condition in the region is semi-tropical in which the summers are very hot and the winters are very cool. The south western winds directly affect the climatic condition of the region. However, in the most of the time the climate is found to be very pleasant, the winters are rainless and dry. There is continuous increase in temperature from March to May, which is also the hottest month with the mean daily maximum temperature at about 41°C and the mean minimum at about 27°C (Table 1). The weather is appreciably hot in summer and in individual days during May and the early part of June. The day temperature rises up to 46°C or more in June. With the onset of the monsoon in the region by about the middle of June, there is an appreciable drop in the day temperature. After the withdrawal of the monsoon, the nights become progressively cooler. February is generally the coldest month with a mean daily maximum temperature of about 24°C (Table 1). About 91 percent of the annual rainfall in the study area is received during the southwest monsoon in the months from June to September. The variation in the annual rainfall from year to year is appreciable. The relative humidity is high during the Southwest monsoon. During the rest of the year the air is dry (Table 1).

Rainfall Erosivity Factor (R)

The erosivity factor of rainfall is a function of the falling raindrops and rainfall intensity. Wischmeier and Smith (1965) found that the product of the kinetic energy of the raindrop and the maximum intensity of rainfall over duration of 30 minutes, in a storm was the best estimator of soil loss (Diana, 2011). This product is known as the EI value. It has been established that this value gives a very good correlation for estimation of soil loss, and is the most reliable single estimate of potential of rainfall erosivity.

The EI values are determined from the recording of rain guage data of each storm. The rainfall mass curve is divided into small increments, and for each increment the values for intensity of rainfall and their raindrop-kinetic energy (E) are calculated. From these a value, of the maximum intensity of rainfall, during 30 minute continuous duration (I_{30}), is then determined. A product of this value with E, gives the EI_{30} value. The erosivity of rain is calculated for each storm, and these values are summed up for the desired

periods, namely weeks, months, years, etc. The kinetic energy of rainfall (E) is calculated by using the following formula (Wischemeier and Smith, 1978):

$$E = \sum E_i \quad \ldots(1)$$

$$E_i = \sum \left(200 + 87 \log_{10} I_i\right) P_i \quad \ldots(2)$$

where,

E_i = kinetic energy of the i^{th} rain increment, J/m^2,

I_i = average intensity of rainfall intensity in the i^{th} increment, cm/h

P_i = depth of rainfall in the i^{th} increment, cm

R = Σ Erosion index = Σ $E_i I_{30}$, J-cm/m^2-h …(3)

Rainfall Erosivity factor (R) is also expressed as,

$$R = \frac{\sum_{n=0}^{i} \left(E_i . I_{30}\right)}{100} \quad \ldots(4)$$

where,

E_i = rainfall kinetic energy, kg-m/(m^2-mm)

I_{30} = maximum intensity of rainfall during a continuous period of 30 min, mm/h

n = number of rainstorms per year

Rambabu *et al*. (1979) developed a relationship between EI_{30} and daily and monthly rainfall amounts for Dehradun (India) region as given below:

EI_{30} = 3.1 + 0.533 * Rd (for daily rainfall in mm) …(5)

EI_{30} = 1.9 + 0.640 * Rm (for monthly rainfall in mm) …(6)

Based on regression equation, R can be determined as follows:

R = 22.8 + 0.6400 * Ra …(7)

where,

R = Rainfall erosivity factor (in metric unit), and

Ra = Annual rainfall (mm)

Rain gauges installed at various meteorological observatories give depth of rainfall at that place. This point information can be converted to spatial distribution by Thiessen polygon method in GIS environment. Once this Thiessen polygon map is derived then by above formula, R factor map can be drawn. However, the spatial resolutions of satellite data often limit the use because of being a coarse resolution one.

Data Products and its Processing

The remote sensing rainfall data products from NOAA satellites were used in the study where in for each day of the 2006 calendar year the satellite data products were used in the present analysis. The processing methodologies are discussed in detail in this section:

Rainfall Data

The remote sensing rainfall data product RFE2.0 from Climate Prediction Centre (CPC), NOAA was used in the study for each day of the 2006. The daily rainfall images are provided for the Southern Asia (70^0-110^0E; 5^0-35^0N) beginning from May 01, 2001. The product is updated three times daily at around 9 am, 1 pm, and 9 pm Eastern Local Time and covers a 24-hour period of accumulated precipitation. Resolution of rainfall estimates is 0.1 by 0.1 degree. The daily rainfall data product is generated by merging four kinds of individual input data sources (Figure 2). The infrared cloud top temperature fields derived from Meteosat, polar orbiting satellite precipitation estimate data from Special Sensor Microwave/ Imager (SSM/I) on board the Defense Meteorological Satellite Program, Advanced Microwave Sounding Unit (AMSU-B) on board the NOAA-15, 16 and 17 and Global Telecommunication System (GTS) station data (Figure 2). The merged analysis presents similar spatial distribution patterns with those of satellite estimates while its magnitude is close to the gauge-based analysis over areas with gauge data.

The rainfall images were georeferenced using coordinates for first pixel and pixel size. The daily rainfall images were converted into weekly rainfall by adding up the 7 day rainfall starting

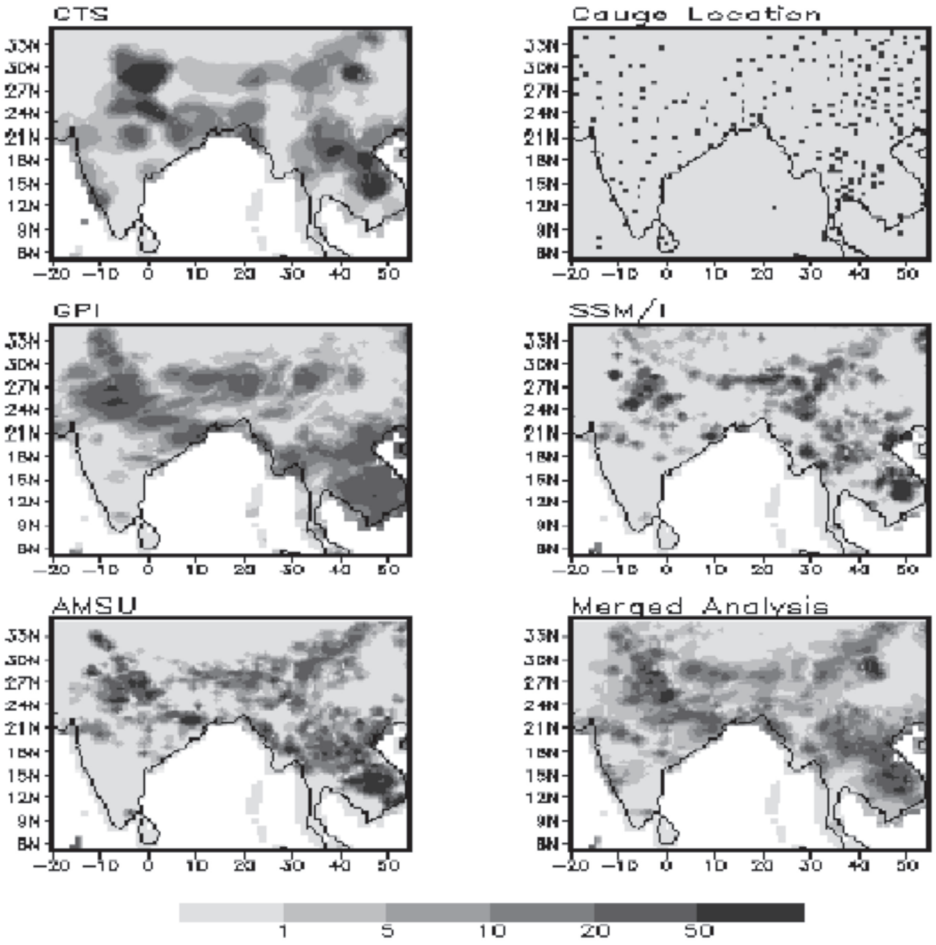

Fig. 2. Daily precipitation (mm/day) for July 20, 2001, obtained from GTS gauge-based analysis, satellite estimates of GPI, SSM/I and AMSU-B, and the merged analysis. Also displayed is the distribution of GTS gauge stations over the target domain. (*Source:* CPC, NOAA)

from 1st of January 2006. The weekly rainfall was an input for calculation of EI_{30} which is the product of kinetic energy of raindrop (KE) and maximum intensity of rainfall over duration of 30 minutes (I_{30}). The relation for calculation EI_{30}, for U.P. region is given by Singh, 1990 and is as follows:

$$EI_{30} = 0.6235 \times Weekly \text{ rainfall } + 12.3 \quad \ldots(8)$$

The weekly EI_{30} values for the whole year were calculated using the above equation. The weekly EI_{30} values were summed up for the one year duration study and extracted for the study region. The EI_{30} map derived for the study region was used in the computation of rainfall erosivity map.

Results and Discussion

Derivation of the Rainfall Erosivity Factor (R) image

As discussed in the previous section, daily rainfall image was converted into weekly rainfall data by adding up the 7 day rainfall starting from 1st January 2006. The weekly rainfall formed an input for calculation of EI_{30} which was the product of kinetic energy of raindrop and maximum intensity of rainfall over duration of 30 minutes. The relation for calculation EI_{30}, for study area using equation 9. After of estimates the weeks EI_{30}, a cumulative EI_{30} was estimated. The EI_{30} value for the 52 weekly periods for the whole year was also calculated using the equation 9.

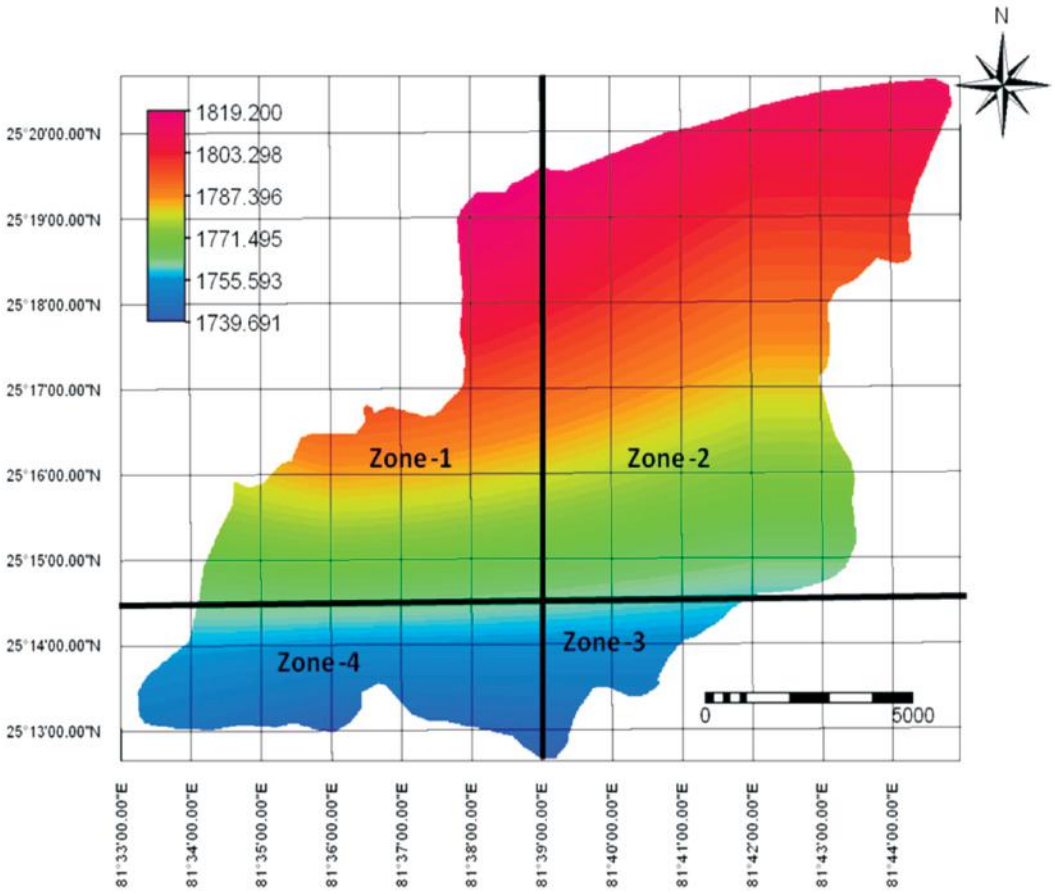

Fig. 3. EI_{30} map for study area (Jhagrabaria Watershed) in year 2006

The weekly EI_{30} values were summed up for the one year duration of the study and were extracted out from the large map for the study region. The EI_{30} map derived for the study region is shown in figure 3 and used in the computation of rainfall erosivity map (Figure 4). Rainfall erosivity values were calculated by using Equation (4). The weekly EI_{30} were computed (Eq. 8) and summed up for the whole year. The annual EI_{30} value for the one year duration was divided by 100 to get rainfall erosivity values, where, EI_{30} is the product of kinetic energy of raindrop and maximum intensity of rainfall over duration of 30 minutes.

The figure 4 is showing distribution of R-values over Jhagrabaria watershed. The minimum and maximum R-values are slightly increasing from lower to upper basin depending on precipitation characteristics. R-values for the study area were found to vary from 7.29 MJ mm ha^{-1} h^{-1} $yr^{-1}$to 18.13 MJ mm ha^{-1} h^{-1} yr^{-1}, respectively. R-values of the RUSLE, USLE and MUSLE models for any point of the watershed can be located from this spatial map.

It is evident from the figure 4 that the rainfall intensity remained fairly uniform over the entire watershed and hence, the EI_{30} varied only marginally from a minimum of 1739.69 to 1819.2 JM^{-2}. On the basis of EI_{30}; the entire watershed can be divided into four distinct zones A, B, C and D (Figure 3). Accordingly, the rainfall erosivity map was also been divided into four distinct zones (Figure 4) on the lines of the EI_{30} map of the watershed. In absolute terms, the EI_{30} of the order of 1740 may be considered as a relatively high and capable of eroding substantially. However, the cumulative effects of higher EI_{30} and consequently R gets nullified due to highly dense vegetation which is encountered in the watershed, thus, the resultant erosivity is not so predominant.

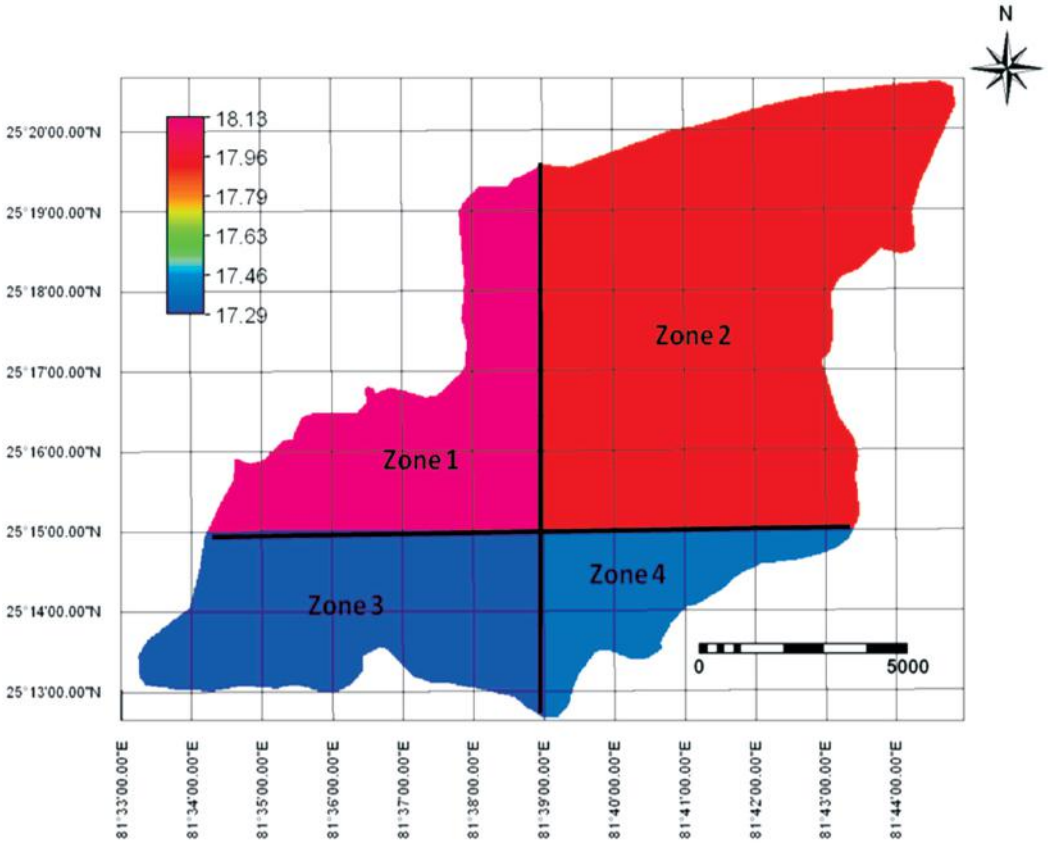

Fig. 4. Rainfall erosivity map for study area (Jhagrabaria Watershed), year 2006

Conclusions

It is evident from the above discussion that the satellite driven rainfall data can be successfully utilized for developing the EI_{30} as well as rainfall erosivity map of any watershed following the above methodology. In India where the density of rain gages is very poor this technology as discussed can help the land and water management professionals to a great extent for arriving at the most crucial information such as R which is the basic parmeter in estimation of soil loss using the USLE, MUSLE or RUSLE. The daily rainfall data provides the researcher the temporal information and the map the much required spatial information because in the absence of such data from meteorological stations, the applications and use of distributed models were restricted to a great extent.

From the above case study it can be concluded that although the rainfall erosivity in the selected watershed was high, the corresponding dense land use has played a major role in controlling the resultant soil loss from the watershed. If the other factors required for estimation of soil loss such as K, LS, C and P could be estimated at required finer resolution, the soil erosion from the watershed, its temporal and spatial extents could also be determined with very high accuracy. This information, if generated will not only facilitate the researchers but also the planners for undertaking watershed conservation restoration work.

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