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PREDICTING SOIL EROSION AND SEDIMENT YIELD IN THE TAPACURÁ CATCHMENT, BRAZIL

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Abstract: The EPM is a model for qualifying the erosion severity and estimating the total annual sediment yield. The EPM uses empirical coefficients (erodibility coefficient, protection coefficient and erosion coefficient) and a matrix of the basin physical characteristics. The EPM gives a quantitative estimation of erosion intensity as well as the estimation of sediment yield and transportation. To analyze the suitability of the Gavrilovic method for use with GIS techniques, we prepared cartographic data on geology, pedology, slope, temperature and land use in digital form. A raster-based Geographic Information System (GIS) was applied to generate the erosion-severity and sediment yield maps. In order to validate the EPM estimated erosion, data annual sediment yield were collected between 1999 and 2007. The results showed a mean sediment delivery ratio (SDR) of around 8% and a calculated mean sediment yield of 0.108 t/ha/year, which is close to the observed one, 0.169 t/ha/year. The obtained soil loss map could be considered as a useful tool for environmental monitoring and water resources management.

Keywords: EPM model, GIS, Tapacurá catchment

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INTRODUCTION

Soil erosion is a physical process of degradation caused by losing particles from soil surface due to raindrop impact and runoff events. Mapping and assessment of erosion risk are important tools for planning of natural resources management (de Vente & Poesen, 2005). During the last decades many different models, methods and relationships have been proposed to describe and predict soil erosion by water and associated sediment yield, varying considerably in their objectives, time and spatial scale involved, as well as in their conceptual basis. A major problem concerning the modeling of erosion process with physically based models is the optimization of erosion parameters that cannot be directly measured in the field. Several optimization methods have been tested in the past during the calibration of such erosion models, but it is difficult to assure that the final values are not trapped in a local minimum (Santos *et al.*, 2003).

Soil erosion is one of the most significant environmental degradation processes and has been accepted as a serious problem arising from agricultural intensification, land degradation and possibly due to global climatic change (Bhattarai & Dutta, 2007). One of the biggest challenges of distributed erosion modeling is the prediction of soil loss over a range of spatial scales, *e.g.*, at basin interior locations. To address this challenge, a distributed model should reasonably well represent the heterogeneities of basin properties through its model structure and parameters. Unfortunately, spatial data limitations reduce model evaluation to a simple comparison of observed and calculated soil loss at the gauged outlet and greatly impede an evaluation of the spatial correctness of model parameters (Reed *et al.*, 2004).

In addition to the scarcity of spatial data, many runoff-erosion models do not represent basin states such as soil moisture state but rather soil water storages which also limit comparison of simulation to available data (Koren *et al.*, 2006). Since all these factors vary in both space and time, the use of Geographical Information Systems (GIS) offers considerable potential (de Roo, 1998). Several examples illustrate simple GIS techniques to produce erosion hazard indices or erosion estimates using USLE-type models and can also be loosely coupled to a GIS, such as the KINEROS and WEPP models. Furthermore, models can be fully integrated into a GIS by embedded coupling, such as the WATEM-SED, LISEM and SWAT models.

Presently, erosion models are extensively used by water resources planners, water quality managers, engineers, and scientists to understand the important processes and interactions that affect the sediments in water bodies, to evaluate the effectiveness of various control strategies, and to perform cost-benefit analysis (Kalin & Hantush, 2006). Several studies have presented qualitative and quantitative comparisons of watershed models that may help in the initial screening of models (Hantush & Kalin, 2005; Hrissanthou, 2005; Winchell *et al.*, 2008).

Estimating the soil loss risk and its spatial distribution are the one of the key factors for successful erosion assessment. Thus it can be possible to develop and implement policies to reduce the effect of soil loss under varied geographical conditions. The accuracy of estimating soil risk depends on model and its factors. Researchers have developed many predictive models that estimate soil loss and identify areas where conservation measures will have the greatest impact on reducing soil loss for soil erosion assessments (Sılva *et al.*, 2012).

Quantification of sediment yield is one of the greatest challenges in environmental modeling and computer simulation models are becoming increasingly popular in predicting soil erosion for scale basin. This research was conducted in the Tapacurá catchment using Remote Sensing and GIS techniques and Erosion Potential Method (EPM) to estimate erosion-potential mapping and sediment-yield assessment. The paper shows application of the EPM method in assessing of land use change and estimating erosion in Tapacurá catchment.

The Tapacurá catchment is located between coordinates 230 000 mE, 270 000 mE, and 9 090 000 mN, 9 120 000 mN (**Fig. 1**). The Tapacurá catchment is located in Pernambuco State, northeastern Brazil and is one of the planning units for management of water resources of Recife Metropolitan Region, an important area of Brazil, with approximately 2 million of inhabitants. This basin is 72.6 km long, and has a 470 km² drainage area. It is a tributary of Capibaribe catchment, which is one of the main rivers in Pernambuco State. The climate is tropical, hot and humid. The annual precipitation is around 1200 mm/year, the maximum daily rainfall is 175 mm and the annual average temperature is 27°C, with a daily temperature range of 25–32°C.

MATERIAL AND METHODS

Erosion Potential Method

The Erosion Potential Method (EPM) is a model for qualifying the erosion severity and estimating the total annual sediment yield, developed initially from the investigation of data in Yugoslavia by Gavrilovic (1972). The EPM involves a parametric distributed model, and is used for predicting annual soil erosion rates and annual sediment yield. It uses empirical coefficients (erodibility coefficient, protection coefficient and erosion coefficient) and the matrix of physical characteristics of the basin. The EPM gives a quantitative estimation of erosion intensity as well as the estimation of sediment yield and transportation (Tangestani, 2006).

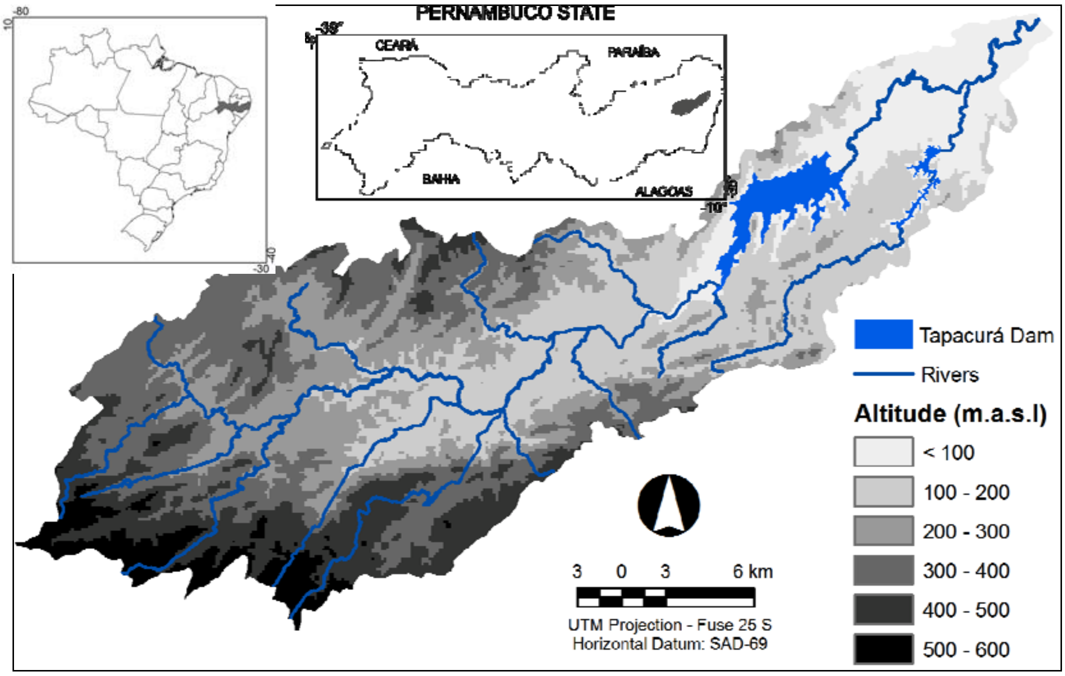

Fig. 1 Location of Tapacurá catchment in the Pernambuco State.

This method considers four factors that depend on erosion coefficient, drainage area, mean annual rainfall, and mean annual temperature. According to the method, average annual basin degradation W (m³/km²/year), represents the average annual soil loss is calculated using the following equation:

$$W = \sqrt{E^3} \times S_t \times P_m \times A \times \pi \qquad (1)$$

where A is the catchment size (km²), Pm (mm) denotes average annual rainfall, St is land surface temperature, E is erosion coefficient. The erosion coefficient (E) depends of four factors control erosion development (exposed rock and soil, topography, and vegetal cover/land use, which can be calculated as:

$$E = Y \times X_a \times \left(\varphi + \sqrt{j}\right) \qquad (2)$$

with Y, X_a, φ as the coefficients dependent on geology, land use, and the basin's erosive degree, respectively, and j as the average slope in percent. EPM method suggest that the average slope could be computed as the total contour line length in the analyzed basin multiplied by the contour interval divided by the drainage area. If a digital elevation model is available, the average slope is simply calculated as the average slope of the cells in the basin. When the drainage basin is not uniform with respect to the erosion coefficients, EPM method suggests that the basin should be divided into smaller sub areas (pixel). After the annual soil erosion rates W are calculated for each pixel, they are summed to obtain the soil erosion rate for the whole basin.

Tables 1 and **2** present coefficients of rock resistance to erosion (*Y* factor) and the coefficient of observed erosion processes (φ factor) of the study area, used in EPM method. The coefficients of observed erosion processes (*Y* and φ factors in EPM method) required visual estimation in the field. Data for estimating the geology coefficient (*Y* factor) was obtained by examining the geological map of study area (CPRM, 2005) and field survey, and the erosion process coefficients are classified into five categories, ranging from 0.10 (Hard rocks resistant against erosion) to 0.55 (Soils and soft rocks).

Data for estimating the soil resistance to erosion (φ factor) was obtained using the methodology proposed by Tangestani (2006), and the name of soil categories were assigned according to experimental data from field observation and sampling. For Tapacurá catchment were determinates four classes of φ factor: (a) minimal erosion, (b) moderate erosion, (c) high erosion, and (d) very high erosion, ranging from 0.2 to 0.9.

Table 1. Values of Y factor for Tapacurá catchment

Description	Geological Periods	*Y* Value	Area (km²)	%
Soils and soft rocks	Mesoproterozoic	0.55	56	11.7
Deposits, clays, sandstones	Neoproterozoic	0.40	5	1.10
Rocks moderately resistant to erosion	Neoproterozoic	0.20	19	3.90
Fragmented of granitic rocks	Paleoproterozoic	0.25	280	58.3
Hard rocks resistant against erosion	Neoproterozoic	0.10	120	25.0

Table 2. Values of φ factor for Tapacurá catchment

Description	φ Value	Area (km²)	Area (%)
Minimal erosion	0.2	20	4.2
Moderate erosion	0.4	107	22.3
High erosion	0.6	157	32.7
Very high erosion	0.9	196	40.8

Table 3. Values of X_a coefficient for Tapacurá catchment

Land Use	Area (km²)	Area (%)	X_a Value	Source
Agriculture	180.71	38.23	0.7	Tangestani & Moore (2001)
Livestock	147.08	31.14	0.9	Tangestani (2006)
Rainforest	23.43	4.56	0.1	Globevnik *et al.* (2003)
Capoeira vegetation	6.25	1.12	0.3	Estimated
Caatinga (native vegetation)	8.09	1.06	0.5	Estimated
Sugar cane	52.67	11.20	0.4	Estimated
Poultry farms	37.85	8.06	0.6	Haghizadeh *et al.* (2009)
Urban area	12.51	2.37	0.2	Estimated
Water	11.40	2.26	0.0	Emmanouloudis *et al.* (2003)

Table 3 shows the land use coefficient (X_a) related to each land use class. In order to determine the X_a factor value utilized by the EPM, land use map was generated using Landsat 5/TM satellite images acquired from orbit 214/point 65, dated 19 August 2009, with spatial resolution 30 × 30 m, and false color composite R5G4B7. The vegetation cover was obtained by Maximum Likelihood Classification and pseudo-color satellite image of the area.

Also several enhancements and classification techniques were used, related to ground truth data from field trip carried in 2010, to delineate training areas of identified land cover categories for Tapacurá catchment. Some land use changes which occurred between the satellite data collection and the field surveys were not considered. EPM method classifies land uses in categories and evaluates the coefficient Xa from 0.1 (for high-density woodland) to 1.0 (for badlands). The study area was classified into nine categories and the land use coefficient was evaluated for each map class (**Table 3**).

The land surface temperature coefficient (S_t) denotes the annual land surface temperature coefficient, which is calculated by:

$$S_t = \sqrt{0.1 + \frac{T_p}{10}} \tag{3}$$

where T_p is land surface temperature in °C, which is the result of the equilibrium thermodynamic state dictated by the energy balance between the atmosphere, surface and subsurface soil and the efficiency by which the surface transmits radiant energy into the atmosphere (surface emissivity). For annual rainfall were used monthly rainfall data from 1070–2000 of ten rain gauges, six rain gauges obtained from the Brazilian National Water Agency – ANA, and 4 from the Meteorology Laboratory of Pernambuco State.

Validation of Model

The actual sediment yield is then calculated by **Eq. (4)**. The simulation process was tested on the basis of sediment delivery ratio calculated according to Irvem *et al.* (2007) and Beskow *et al.* (2009) using **Eq. (5)**. The actual sediment yield is then calculated as **Eq. (6)**.

$$T_s = \mathrm{SDR} \times W \tag{4}$$

$$\mathrm{SDR} = \frac{T_s}{W} \tag{5}$$

$$S_y = \mathrm{SDR} \times T_s \tag{6}$$

where T_s is the average sediment yield to basin (t/ha/year), SDR is sediment delivery ratio, W is average soil loss in the basin (t/ha/year), and S_y is the actual sediment yield total in the outlet. In order to estimate annual sediment transport, a discharge curve relating total sediments transported with water discharge was constructed. To construct this, data of total solids in the water and respective discharge, monitored between 1999 and 2007 from a gauging station at Vitória de Santo Antão, located in basin between coordinates -8°06′49″ Latitude and -35°17′02″ Longitude were used.

Afterward, it was calculated the annual sediment transported by the Tapacurá catchment taking into account the discharge curve and daily runoff data set, the latter of which was obtained from the Brazilian National Water Agency – ANA. Data from subsequent years to 2007 were not used due to discontinuation of monitoring after this date at the gauging station.

RESULTS AND DISCUSSION

In Tapacurá catchment high rates of suspended sediment loads occur along the hydrographic network during intense rainfall events. **Figure 2a** shows water

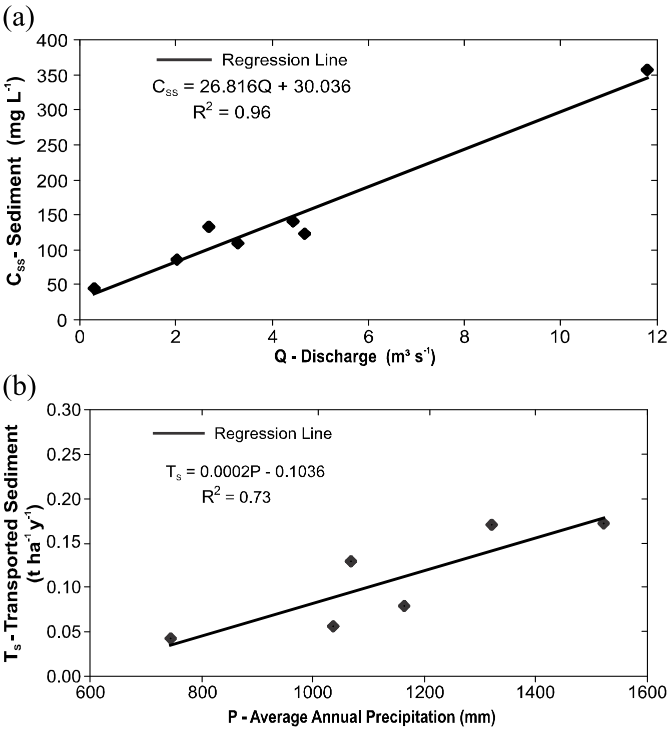

Fig. 2 (a) Suspended sediment versus water discharge, and (b) correlation between annual sediment delivery and annual rainfall for Tapacurá catchment.

discharge curve, *i.e.*, suspended sediment versus water discharge, for the Tapacurá catchment with correlation ($R^2 = 0.96$). A regression between load and flow can be used to estimate long term loads.

The best fit of a theoretical function to this data can be obtained with equations of the potential type or with quadratic polynomials. **Figure 2b** shows the relationship between annual sediment delivery and annual rainfall and the satisfactory correlation ($R^2 = 0.73$) between these data for the Tapacurá catchment. The transported sediment to basin outlet (T_s) values was compared to the discharge observed values and a curve fitting was obtained. The same procedure was adopted by Irvem *et al.* (2007), Pandey *et al.* (2007) and Beskow *et al.* (2009).

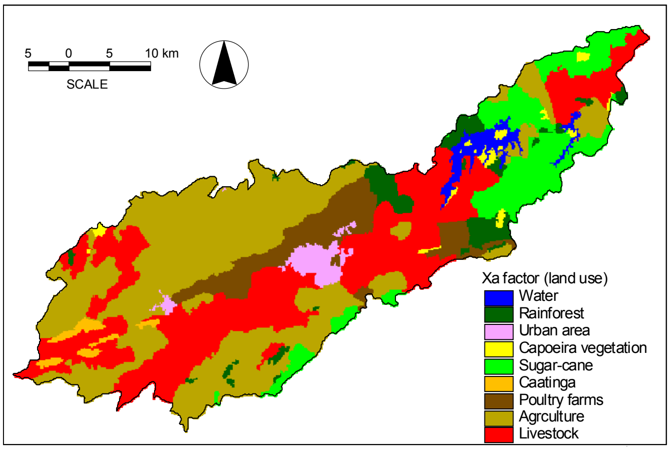

Fig. 3 Map of X_a values for Tapacurá catchment.

The precipitation regime in the region is highly irregular composed of a few isolated and intense rainfalls along with many events of low intensity. Those are major problems that cannot be measured directly in the field to the erosion process in basins. According to Santos *et al.* (2003), this situation is common in the studied region, and the sediment transport can be affected for these rainfall characteristics. Unfortunately, the monitoring of sediment transport, carried out by Brazilian National Water Agency has not presented a sufficient frequency necessary to follow the entire hydrologic year (just four or five times per year due to high costs involved), thus resulting in rainy days without values of sediment transport.

Figure 3 presents each vegetation cover/land cover mapped: water, urban area, caatinga (native vegetation), sugar cane, capoeira vegetation, livestock, agriculture, rainforest, and poultry farms. For example, vegetation categories as agriculture were given value of 0.7, whereas those that belonged to rainforests received value of 0.1. Land degradation processes in the study area are degradation of natural vegetation due to deforestation and the remarkable land use variation during the last decades, due to increase of agriculture and livestock, 72% of total area.

Figures 4 and **5** showed the geological map and erosion degree values used for GIS calculation of the EPM model. In order to obtain the *j* coefficient, contours lines, triangulation points and summits were digitized from the region topographic maps. These data were subsequently interpolated to generate a digital terrain model (**Figure 6**). The slopes were classified into five categories ranging from 0–5.9 to 28–54%. The mean values of each slope class were assigned in decimal system to determine the j parameter. The data layers were finally converted to a raster format with cell-size of 30 × 30 m.

Figures 7 and **8** showed surface temperature annual coefficient (S_t) and the spatial distribution of the mean annual precipitation depth from 197 to 2000 mm, respectively. The hydrological balance in the Tapacurá catchment shows values between 800 to 1200 mm/year, decreasing in directions east–west and south–north, with a multi-annual mean (1970–2000) of 1074 mm and a rainy season between March to August (Silva *et al.*, 2010).

The quantitative output of erosion potential in the EPM method was evaluated mathematically by solving **Eq. (2)** for values of factor classes, and then they were collapsed into four ordinal classes to generate the erosion potential map, using the method described by Gavrilovic (1988). **Figure 9** presents the erosion coefficient map. Results showed that areas with erosion coefficient Classes I, II, III and IV possess 67, 23.3,

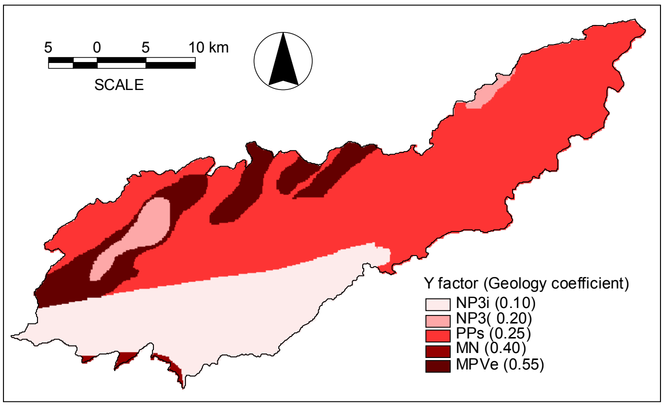

Fig. 4 Map of Y values for Tapacurá catchment.

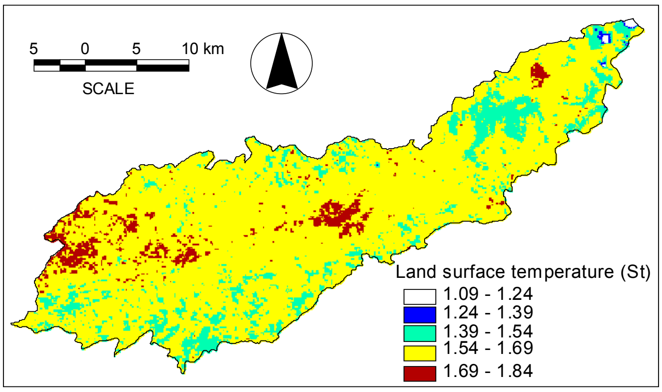

Fig. 7 Map of surface temperature annual coefficient (S_t) for Tapacurá catchment.

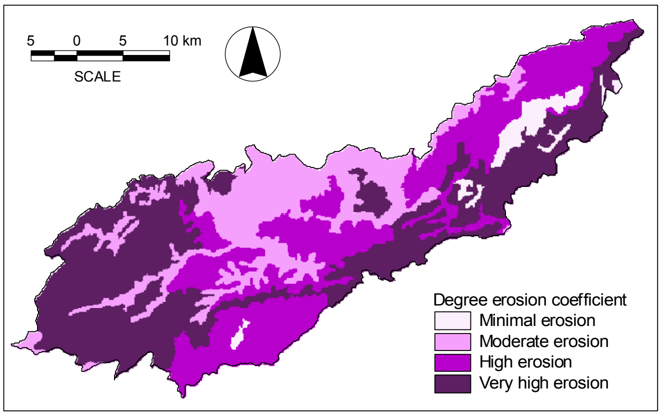

Fig. 5 Map of φ values for Tapacurá catchment.

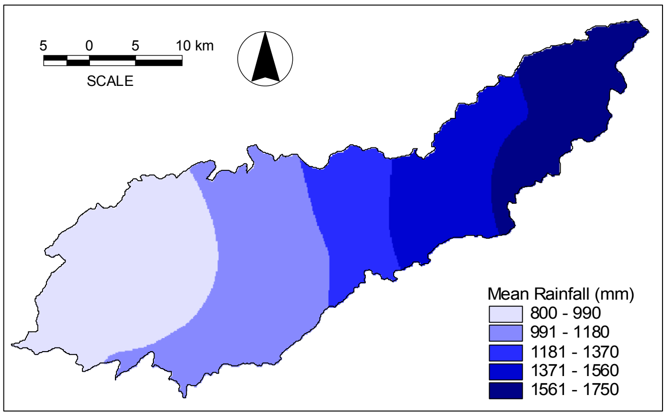

Fig. 8 Map rainfall mean annual (Pm) for Tapacurá catchment.

9.1 and 0.7% of the total area, respectively. The EPM method allows researchers to quantify soil loss rates (average annual value), in either a lumped or spatially distributed approach.

By using the latter approach, it was possible to generate interpretive map through the EPM method as well as a map of average annual soil loss rate (**Fig. 10**) within the Tapacurá catchment, taking into account current land use. Average annual sediment yields were estimated on a cell basis and all the grid cells of the watershed was regrouped into the following scales: slight (0–22 t/ha/year), moderate (22–45 t/ha/year), high

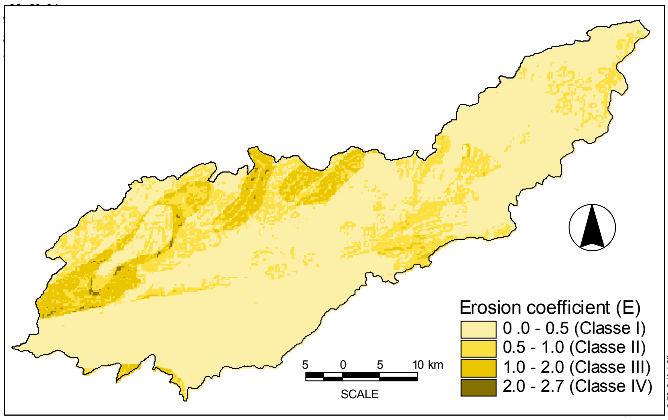

Fig. 9 Map of E coefficient map for Tapacurá catchment.

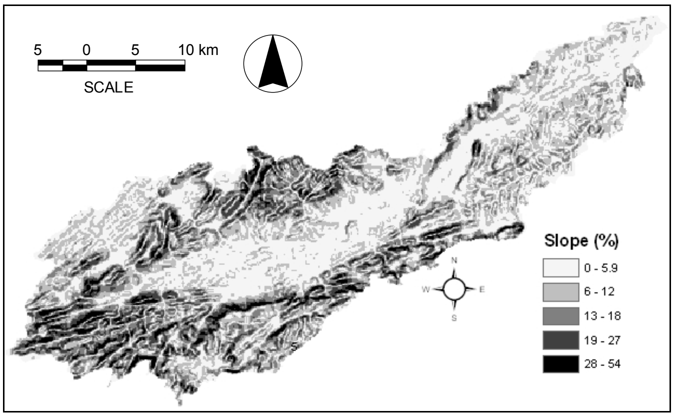

Fig. 6 Map of slope (j parameter) for Tapacurá catchment.

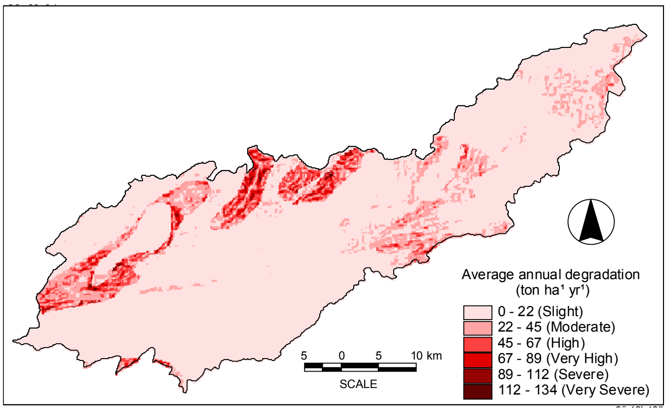

Fig. 10. Map of total degradation for Tapacurá catchment.

(45–67 t/ha/year), very high (67–89 t/ha/year), severe (80–112 t/ha/year), and very severe (112–134 t/ha/year).

Annual average soil loss for Tapacurá catchment was estimated as 14.08 t/ha/year. This number is quite low when compared to the average values obtained in other studies (Emmanouloudis *et al.*, 2003; Tangestani, 2006; Irvem *et al.*, 2007). Thus, the soil loss predicted for Tapacurá catchment can be considered low. This situation is due to the low geological factor value in large part of the area and this low value represents considerable protection against erosion process (fragmented of granitic rocks (58%) and hard rocks resistant against erosion (25%)). Other factors can be that great part of the area of the basin has low population density, and some native vegetated areas, especially on the eastern part. It must be taken into consideration that the Tapacurá catchment is exposed to semiarid and sub-humid climatic conditions and is composed by Acrisols soil type, which indicates a high susceptibility to water erosion in the areas.

The under-prediction or over-prediction limits for the EPM method simulation are within 13 percent from the measured values and are considered as the acceptable levels of accuracy for the simulations as reported by Pandey *et al.* (2007) and Silva *et al.* (2012). The EPM method was also validated by comparing the estimated sediment yield with the observed values (**Fig. 11**). From this study, the potential soil erosion for Tapacurá catchment was found to be 0.08 t/ha/year, however, values ranged between 0.05 t/ha/year to 0.16 t/ha/year. It can be seen from the same figure that the points obtained by plotting the estimated values against the observed values are not very close to 1:1 line indicating that their differences can be significant. However, the best fit line between the above data have satisfactory coefficient of determination of 0.80 and standard deviation of 0.05, which shows that they are closely related by a straight line.

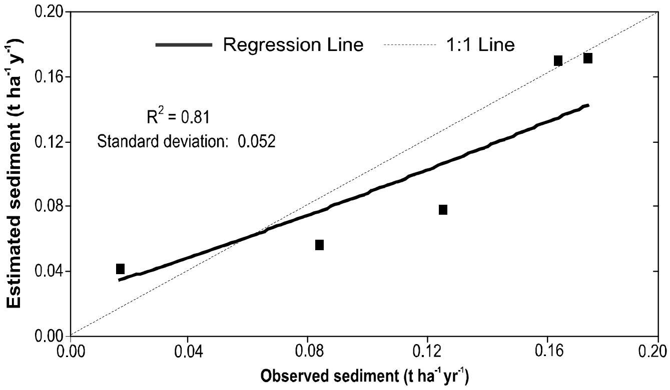

Fig. 11 Comparison between the observed and estimated sediment yields in the study area.

The differences between the predicted and observed sediment yields from EPM method are reinforcement of the knowledge that the erosion predictions in general contain large factors of error. Thus USLE can be successfully used for estimation of sediment yield from Tapacurá catchment. The wide variation in sediment yield is mainly due to the variation of factors mentioned previously. Mean SDR value for basin was 13% by solving **Eq. (5)**. Irvem *et al.* (2007) and Globevnik *et al.* (2003) applied the same procedure for basins within different scales, 23 000 km² and 91 km², respectively, and reported similar values to the ones found in this study.

Figure 12 shows the magnitude and spatial distribution of potential soil erosion in the Tapacurá catchment on a cell basis. Observation of the areas identified as high erosion potential zone, namely more than 3 t/ha/year, indicated that they have already undergone severe erosion due to undulating topography of basin and influence of land cover and geology. From this study, the potential sediment yield total for basin was calculated to be 1.12 t/ha/year.

Another important difference is related to the annual mean rainfall depth in this basin if compared to other studies. The hydrological balance in this basin is characterized by an annual precipitation range between 550 and 1250 mm with a well-defined rainy season between April and July. Spatial distribution of soil loss and sediment yield with area for different land uses in the Tapacurá catchment is given in **Table 4**. It can be observed that the majors land use in the basin are Agriculture (38.2%), Livestock (31%), and Sugar cane (11.2%), with an average annual soil loss estimated around of 0.35, 0.41 and 0.49 t/ha/year, respectively. These land uses are very present and common in a large part of the basin.

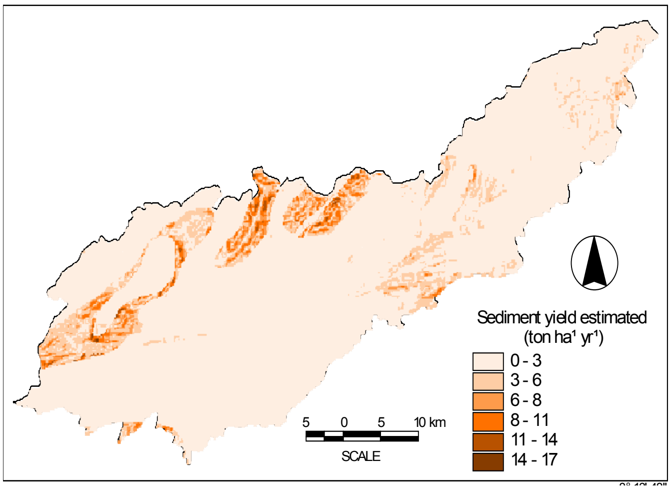

Fig. 12 Spatial distribution of sediment yield in the Tapacurá catchment.

Table 4. Statistical analysis of Soil loss and sediment yield variation for different land uses in the Tapacurá catchment

Land use	Area (km²)	Percent area	Soil Loss Estimated	Sediment Yield Estimated
			Average (t/ha/year)	
Livestock	147.08	30.6	0.41	2.00
Agriculture	180.71	37.6	0.35	2.32
Rainforest	23.43	4.9	1.79	0.24
Capoeira vegetation	6.25	1.3	5.22	0.83
Caatinga vegetation	8.09	1.7	10.91	2.28
Sugar cane	52.67	10.9	0.49	0.86
Poutry farms	37.85	7. 9	1.08	1.53
Urban área	12.51	2.6	1.15	0.25

CONCLUSIONS

The present research was conducted in the Tapacurá catchment, located in northeastern Brazil, in order to assess the applicability of the well-known EPM method, remote sensing and GIS techniques for soil loss and sediment yield prediction in the basin. The use of geoinformation techniques was very successful in addressing the study objectives. Using these techniques, it was possible to identify and mapping the erosion areas and classify the land cover types of the study area. The recent development on GIS and remote sensing technologies permit a more accurate estimation of the EPM method factors. Therefore, this study showed that remote sensing and hydrologic modeling could be useful tools in the identification and analysis of soil loss and sediment yield in Tapacurá catchment.

Factors as land cover, erosion degree and geology are important to control the runoff and, consequently, the erosion process. The results suggest a SDR around 13%, soil loss 14.08 t/ha/year and estimation of sediment yield as 0.08 t/ha/year. Erosion mapping through EPM method showed to be a useful tool for environmental monitoring and water resources management, which could provide satisfactory results when jointly used.

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