Revista Brasileira de Cartografia (2013) N^0 65/5: 881-894
Sociedade Brasileira de Cartografia, Geodésia, Fotogrametria e Sensoriamento Remoto
ISSN: 1808-0936

IDENTIFICATION OF CRITICAL EROSION PRONE AREAS AND ESTIMATION OF NATURAL POTENTIAL FOR EROSION USING GIS AND REMOTE SENSING

Identificação de Áreas Críticas de Erosão e Estimativa do Potencial Natural de Erosão Mediante SIG e Sensoriamento Remoto

Richarde Marques da Silva[1]; Celso Augusto Guimarães Santos[2] & Suzana Maria Gico Lima Montenegro[3]

[1]Universidade Federal da Paraíba – UFPB
Departamento de Geociências – Centro de Ciências Exatas e da Natureza
Cidade Universitária – João Pessoa – PB – Brasil – CEP – 58051-900
richarde@geociencias.ufpb.br

[2]Universidade Federal da Paraíba – UFPB
Departamento de Engenharia Civil e Ambiental – Centro de Tecnologia
Cidade Universitária – João Pessoa – PB – Brasil – CEP – 58051-900
celso@ct.ufpb.br

[3]Universidade Federal de Pernambuco – UFPE
Departamento de Engenharia Civil – Centro de Tecnologia e Geociências
Av. Acadêmico Hélio Ramos, s/n, Cidade Universitária. 50741-530 Recife, PE, Brazil
suzanam.ufpe@gmail.com

Recebido em 11 de Junho, 2012/ Aceito em 1 de Setembro, 2012
Received on June 11, 2012/ Accepted on September 1, 2012

ABSTRACT

A GIS-based method has been applied for the determination of soil loss and prioritization of critical sub-watersheds in the Tapacurá watershed, Pernambuco state. Mapping the erosion risk areas is an important tool for the planning of natural resources management, allowing researchers to propose modification of land-use properly and implement more sustainable long-term management strategies. Thus, the objective of this study was to assess and identify critical sub-catchments for soil conservation management using the USLE and C factor derived by NDVI. Maps of the erosivity (R), erodibility (K), slope (LS), land cover (C), and support practice (P) factors were derived from the climate database, digital elevation model, soil map and satellite images. In order to validate the simulation process, total sediment delivery ratio (SDR) was estimated. The results showed a mean SDR of around 11.5% and a calculated mean sediment yield of 0.108 t/ha/yr, which is close to the observed one, 0.169 t/ha/yr. The obtained soil loss map could be considered as a useful tool for environmental monitoring and water resources management. The methodology applied showed satisfactory result ($R^2 = 0.81$) and allowed identification of the most susceptible areas to soil erosion, constituting an important predictive tool for soil and environmental management in the watershed, therefore, this approach can be applied to other areas for simple, reliable identification of critical areas of soil erosion in watersheds.

Keywords: Geoprocessing, Erosion, Tapacurá Watershed.

RESUMO

Um método baseado em SIG foi aplicado para identificar as sub-bacias que mais contribuem para a erosão dos solos e para determinar as perdas de solo na bacia Tapacurá, Estado de Pernambuco. O mapeamento de áreas de risco de erosão é uma importante ferramenta para o planejamento da gestão dos recursos hídricos, permitindo aos pesquisadores modificarem o uso do solo de forma adequada e implantar estratégias mais sustentáveis a longo prazo. Assim, o objetivo deste estudo foi avaliar e identificar sub-bacias críticas quanto à erosão dos solos mediante a USLE e o fator C derivado de NDVI. Foram utilizados mapas da erosividade (fator R), erodibilidade (fator K), declividade e comprimento de rampa (fator LS) e cobertura e manejo do solo (fator CP), obtidos a partir de dados de precipitação, modelo de elevação digital do terreno, mapa dos tipos de solo e NDVI derivado de imagens de satélite. Para analisar o processo de simulação das perdas de solo foi calculada a Taxa de Entrega de Sedimentos (SDR). Os resultados mostraram que o valor médio da SDR foi de 11,5%, e a perda de solo média calculada para a bacia foi de 0,108 t/ha/ano, enquanto a observada foi de 0,169 t/ha/ano. A metodologia aplicada apresentou resultado satisfatório ($R^2 = 0,81$) e permitiu identificar na bacia as áreas mais susceptíveis à erosão, constituindo uma importante ferramenta preditiva para a gestão ambiental nessa região, assim, essa metodologia pode ser aplicada na identificação de áreas críticas de erosão do solo em outras bacias.

Palavras chaves: Geoprocessamento, Erosão, Bacia Tapacurá.

1. INTRODUÇÃO

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).

The most commonly used model for predicting the average soil loss rate from agricultural land is the Universal Soil Loss Equation (USLE). The USLE is the most widely used empirical erosion model, and estimates soil erosion of an area simply as a product of empirical coefficients, which must therefore be accurately evaluated. It has been used all over the world either in its original or modified form (e.g., FISTIKOGLU & HARMANCIOGLU, 2002; ERDOGAN *et al.*, 2007; PANDEY *et al.*, 2007; DABRAL *et al.*, 2008; TERRANOVA *et al.*, 2009).

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 (SILVA *et al.*, 2012).

Several studies on soil loss simulation have been conducted with the combination among distributed hydrological models, GIS and Remote Sensing (SILVA *et al.*, 2007; JAIN & DAS, 2009). The GIS and Remote Sensing has been extensively applied in numerous fields, principally, water resources and hydrologic modeling, during the last two decades. However, the integration of GIS and Remote Sensing within watershed erosion models receives little attention primarily because of the complexity of sediment routing.

In Brazil, water soil erosion contributes significantly to food insecurity of rural households and constitutes a real threat to sustainability of the existing subsistence agriculture (CASTRO & QUEIROZ NETO, 2009). Brazil extends from the equatorial to the subtropical belt. Environmental characteristics are highly changeable along Brazilian territory due to large territorial size. The country is characterized by a large diversity of soil types, resulting from the interaction of the different relieves, climates, parent material, vegetation, and associated organisms. This diversity and the consequent potential uses are reflected in the regional differences (SILVA *et al.*, 2011).

This paper presents a case-study at a watershed scale and the objective is to evaluate and identify the critical sub-watersheds on the basis of soil loss based on remote sensing and GIS techniques for the purpose of developing the effective management plan in the Tapacurá watershed.

2. MATERIAL AND METHODS

2.1 Study area description

The Tapacurá watershed covers an area of about 470 km², and is located in the Zona da Mata region in the state of Pernambuco, northeastern Brazil, between coordinates 226000 mE, 270000 mE, and 9090000 mN, 9120000 mN, Fuse 25 (Figure 1).

The Tapacurá watershed is one of the last major sources of adequate water supply in the state and is one of the water resource management planning units for the Recife Metropolitan Region. The watershed is responsible to 9.5% of the water supply to Recife Metropolitan Region. The Tapacurá watershed is divided into 14 sub-watersheds: Rio Tapacurá, Várzea do Una, Gameleira, Itapessirica, Miringaba, Pacas, Riacho Tapacurá, Bacia do Meio, Jurubeba, Pororoca, Água Azul, Natuba, Bento Velho, and Tamata-Mirim.

The Tapacurá watershed has high hills, deep valleys, large plateaus and gullies are not present. The major land covers in the watershed are agriculture, Livestock, sugar-cane, poultry farms and urban areas. Agriculture is the main activity of the people in the area. The rainfall in this region is characterized by an annual precipitation ranging from 800 to 1,800 mm with the rainy season between March and August. The climate is tropical, hot, and humid. The maximum daily rainfall in the area is 175 mm. The annual average temperature is 27°C, with a daily temperature range of 25–32°C (SILVA *et al.*, 2010).

The main sediment storage components in the Tapacurá watershed are the floodplain, alluvial fans and colluvium on lower slopes and tributary valleys, whereas the main sediment sources are the various hillslope erosion processes. In order to construct a coherent sediment budget for the Tapacurá watershed, all these components should be quantified.

2.2 The Universal Soil Loss Equation – USLE

The USLE (WISCHMEIER & SMITH, 1978) was used to determine the average annual soil loss and its spatial distribution. The USLE predicts soil loss for a given site as a product of five major erosion factors, whose values at a particular location can be numerically expressed. The USLE can be expressed as follows:

$$A = R*K*LS*C*P \qquad (1)$$

where A is the average annual soil loss per unit of area (t/ha/yr), R is the rainfall erosivity factor (MJ.mm/ha/h/yr), K is the soil erodibility factor (t.h/MJ/mm), LS is the topographic factor (%), which includes slope length factor (dimensionless) and slope steepness factor (dimensionless), C is the cover management factor (dimensionless), and P is the support practice factor (dimensionless).

2.3 Rainfall erosivity factor (R)

Erosivity is the potential of rainfall to cause erosion in given soil with no protection. The R factor takes into account both the total precipitation and kinetic energy of raindrops that fall onto the soil,

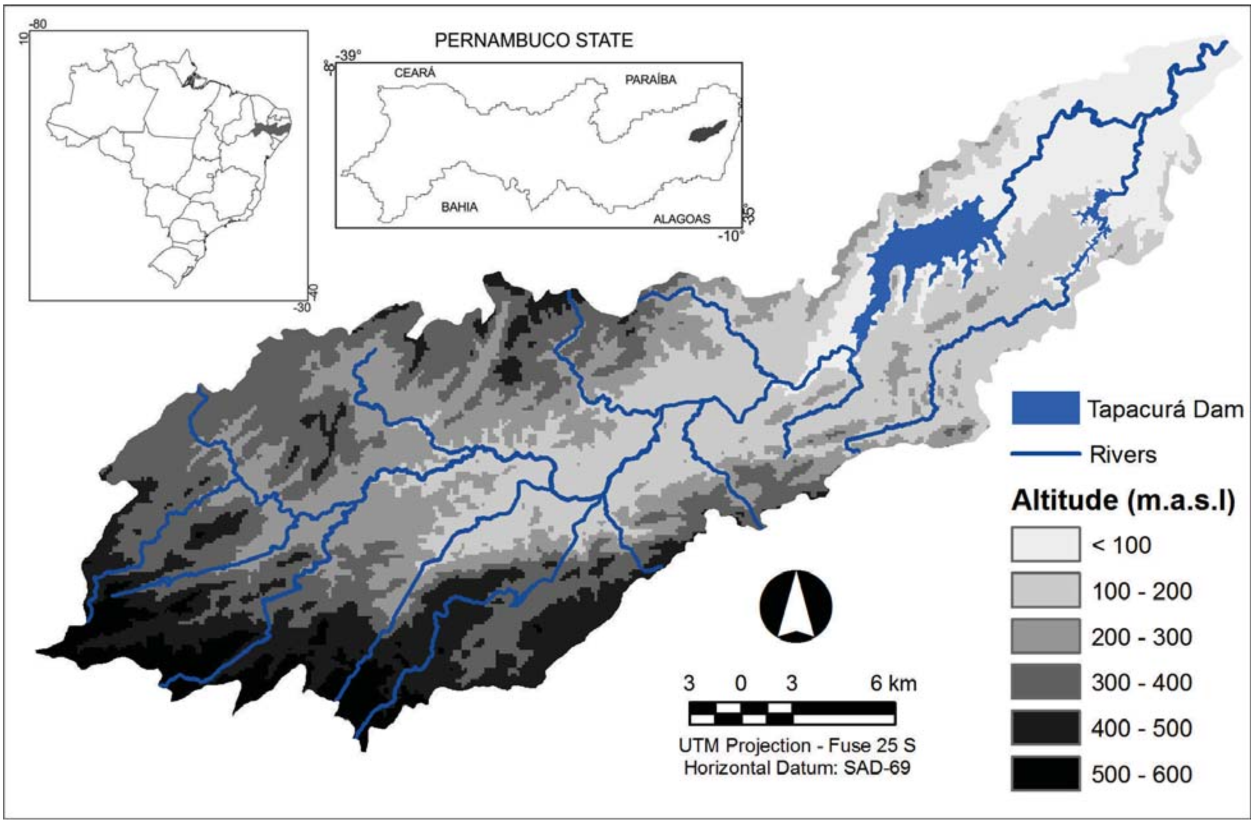


Fig. 1 – Location of Tapacurá watershed in the Pernambuco State.

and is affected by rainfall intensity and raindrop size. Monthly rainfall data between 1970–2000 from 10 rain gauges were used in this study, and the monthly rainfall erosivity of each station was computed for all the studied years by equation:

$$R = \sum_{i=1}^{12} 89.823(P_m^{2} / P_a)^{0.759} \qquad (2)$$

where R is rainfall erosivity factor (MJ.mm/ha/hr/yr), P_m is monthly rainfall (mm), and P_a is annual mean rainfall (mm).

2.4 Topographic factor (LS)

The LS factor depends on the slope steepness and slope length. It is an essential parameter to quantify the erosion generated due to the influence on surface runoff speed. There are different approaches found in the literature for determining the LS factor in a grid-based Digital Elevation Model – DEM. In this study, a DEM of Tapacurá watershed was obtained with 30 m of resolution and was used to generate the slope length and slope steepness factor for each grid cell on the map. This technique for estimating the LS factor was applied by MOORE & BURCH (1986) and ZHANG *et al.* (2009):

$$LS = \left(\frac{V}{22.13}\right)^{0.4} \left(\frac{\sin\theta}{0.0896}\right)^{1.3} \qquad (3)$$

where LS is slope length and slope steepness factor (%), V is the product of flow accumulation and cell size, q is the slope in degrees, both are directly derived from the DEM.

2.5 Soil Erodibility Factor (K)

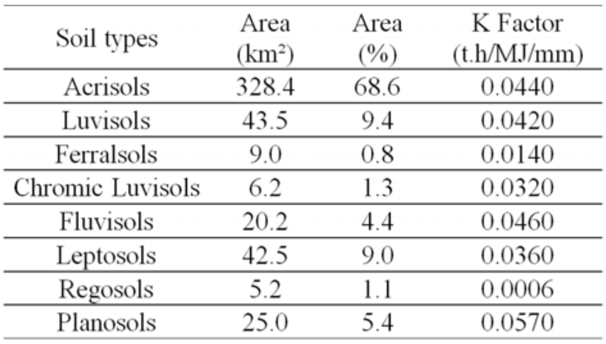
The determination of the soil erodibility factor was based on soil texture in the Tapacurá watershed, using a soil map (SILVA *et al.*, 2012). The erodibility was calculated indirectly through the method proposed by Boyoucos, called clay-ratio method (SILVA *et al.*, 2011) (Eq. 4). Soil distribution in the watershed and the K factor values are shown in Table 1.

$$\text{Erodibility} = [(\text{sand} + \text{silt}) / (\text{clay})] / 100 \qquad (4)$$

2.6 Land cover (C) and support practice (P) factors

The C and P factors are related to land cover and are reduction factors to soil erosion vulnerability. These factors represent the ratio of soil loss from a given vegetal cover and support practice. These are important factors in the USLE, since they

Table 1: Soil distribution in the Tapacurá watershed and soil erodibility values



Soil types	Area (km²)	Area (%)	K Factor (t.h/MJ/mm)
Acrisols	328.4	68.6	0.0440
Luvisols	43.5	9.4	0.0420
Ferralsols	9.0	0.8	0.0140
Chromic Luvisols	6.2	1.3	0.0320
Fluvisols	20.2	4.4	0.0460
Leptosols	42.5	9.0	0.0360
Regosols	5.2	1.1	0.0006
Planosols	25.0	5.4	0.0570

represent conditions that can be easily changed in order to reduce erosion. In this study, the vegetation cover was estimated using vegetation indices derived from satellite images by Normalized Difference Vegetation Index (NDVI).

The NDVI is one of various mathematical combinations of satellite bands (SESNIE *et al.*, 2008), which have been found to be sensitive indicators of the presence and condition of green vegetation and the NDVI has been used widely in remote sensing studies since its development (SADER; WINNE, 1992; JENSEN, 2005; SILVA *et a1.*, 2010). NDVI is based on the reflectance properties of vegetation in comparison with water, snow and clouds on the one hand and rocks and bare soil on the other hand. NDVI values range from -1.0 to 1.0, where higher values are for green vegetation and low values for other common surface materials. Bare soil is represented with NDVI values which are closest to 0 and water bodies are represented with negative NDVI values (SYMEONAKIS *et al.*, 2011).

A time-series of NDVI were derived from Landsat 5 TM images, orbit 214 and path 65, acquired on April, May, June and August 2010. An average NDVI of watershed area was calculated using those NDVI images. Vegetation indices allow delineating the distribution of vegetation and soil based on the characteristic reflectance patterns of green vegetation. The NDVI is one of the most significant vegetation indices and measures the amount of green vegetation and is expressed as:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{IR}) / (\mathrm{NIR} + \mathrm{IR}) \qquad (5)$$

where NIR is reflection of the near infrared portion of the electromagnetic spectrum and IR is reflection in the upper visible spectrum. In a next step NDVI values for forest and bare land were taken from each image. These sample points were used for a linear regression analysis:

$$C = \exp\left(-\alpha \frac{\mathrm{NDVI}}{\beta - \mathrm{NDVI}}\right) \qquad (6)$$

where á and â are parameters determining the shape of the NDVI-C curve adjusted. A á-value of 2 and a â-value of 1 seem to give reasonable results. Since the original C factor of USLE ranges from 0 (full cover) to 1 (bare land) and the NDVI values range from 1 (full cover) to 0 (bare land), the calculated NDVI values were inverted using software ArcGIS 9.3 (Figure 2).

Due to lack of information and maps about conservation practices in the study area, P factor values are assumed as 1 for the watershed. The spatial distributions of the factors R, K, C, P and LS were all converted into grid diagrams with 30 m cells in a uniform coordinate system. The GIS input layers were then multiplied using the USLE to estimate annual soil loss on a pixel-by pixel basis.

2.7 NPE – Natural potential for erosion

The NPE is generated using the factors related to physical environment (rainfall erosivity, soil erodibility and topographic factor). The NPE is:

$$\mathrm{NPE} = R*K*LS \qquad (7)$$

where NPE is natural potential for erosion (t/ha/yr) and R, K, LS are same of Eq. 1.

2.8 Sediment delivery ratio and USLE validation

Sediment yield is defined as the total sediment outflow from a watershed, measurable at a point of reference and for a specific period of time (DE MOOR; VERSTRAETEN, 2008). The SDR is defined as the ratio of sediment delivered at a location in the stream system to the gross erosion from the drainage area above that point. The proportion of sediment that is generated by hillslope erosion and that reaches the river is the hillslope sediment delivery ratio. The simulation process was tested on the basis of the SDR (IRVEM *et al.*, 2007; BESKOW *et al.*, 2009), as:

$$\mathrm{SDR} = T_S / \mathrm{MSL} \qquad (8)$$

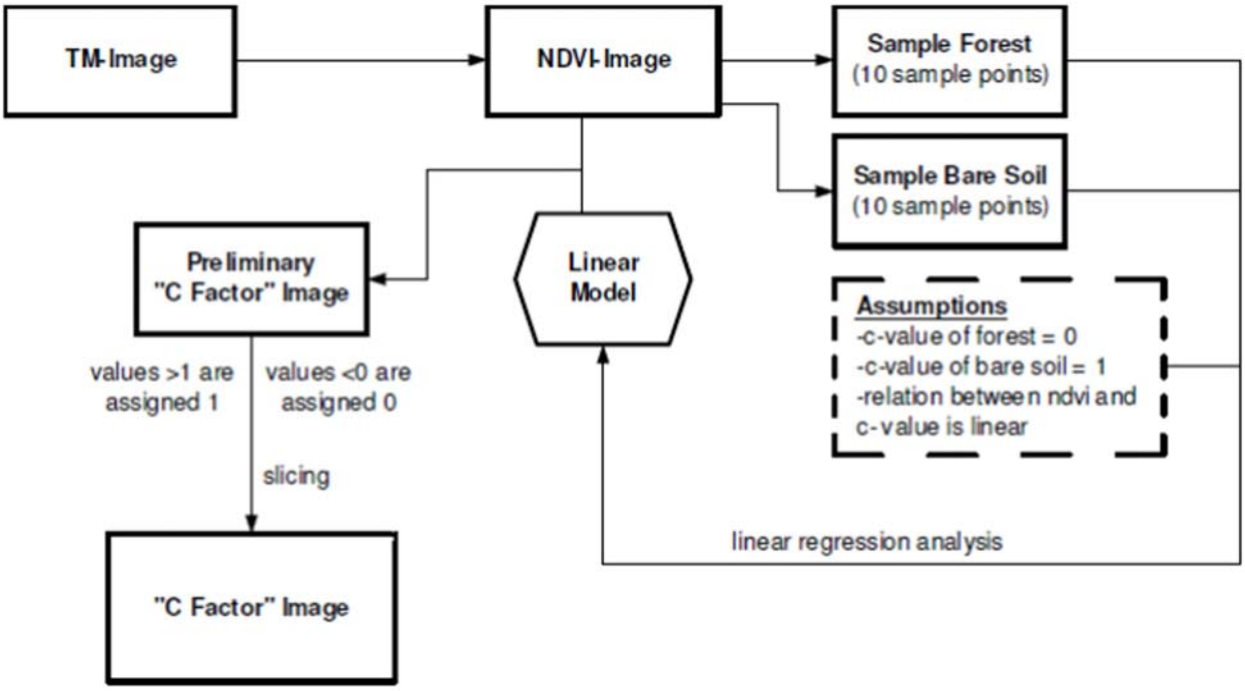


Fig. 2 – Flowchart outlining the procedure of C factor mapping using NDVI.

where T_S is the sediment transported to the watershed outlet (t/ha/yr), and MSL is the mean soil loss within the watershed (t/ha/yr).

In order to estimate annual sediment transport, a discharge curve comparing total sediments transported to the water discharge was developed. In order to develop this curve, annual total solids in the water and the respective discharge collected between 1999 and 2007 from a gauging station at Vitória de Santo Antão, located in the Tapacurá watershed between coordinates -8°06’49’’ Latitude and -35°17’02’’ Longitude, were used. In addition, the annual sediment transported by the Tapacurá watershed was calculated, taking into account the discharge curve and the daily water flow data set, the latter of which was obtained from the Agência Nacional de Águas (2011).

Data from years subsequent to 2007 were not used because the monitoring at the gauging station was discontinued after this period. The same procedure was adopted by Irvem *et al.* (2007) and Pandey *et al.* (2007) to apply the USLE to watershed in Turkey and India, respectively. The T_S values were compared to the observed discharge values and a curve fitting the data was obtained (Figure 3).

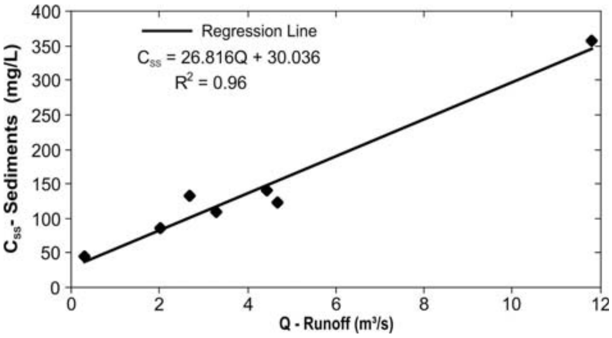


Fig. 3 - Relationship between suspended sediment and water discharge for the Tapacurá watershed.

Figure 4 shows the annual rainfall variability for Tapacurá watershed. These discrepancies in annual rainfall are due to high coefficient of variations (> 40%) of annual rainfall amounts. This area has hot climate and sub-humid with annual rainfall ranging from 1,000 to 1,200 mm (SILVA *et al.*, 2010) with a well-defined rainy season between April and July.

In order to analyze the rainfall variability, the most amount of raingauges with the largest number of existing data within the basin (1970–2010) was selected. The monthly rainfall is around of 90 mm. In Tapacurá watershed yearly average precipitation reach 1,200 mm and average yearly temperatures are ~26°C; such average values are caused by strong seasonal contrasts and by high variability of these values over region. In tropical climate, precipitation presents high spatial variability and, consequently, this variation directly influences surface runoff and sediment yield.

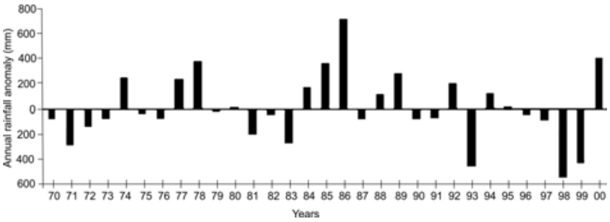


Fig. 4 - Annual rainfall anomaly between 1970 and 2000 for Tapacurá watershed.

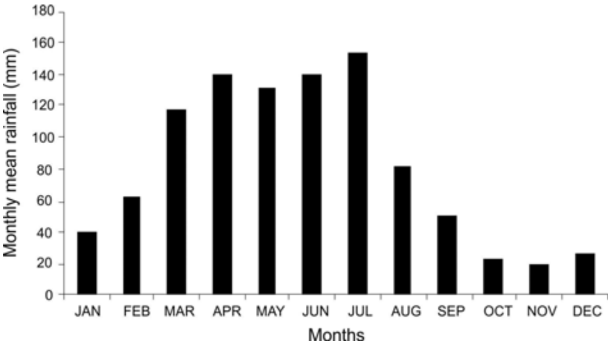


Fig. 5 - Monthly mean rainfall for Tapacurá watershed between 1970 and 2000.

The precipitation regime in the region is highly irregular and is composed of few isolated and intense rainfalls along with the presence of many low intensity events. Monthly mean rainfall distribution for Tapacurá watershed is shown in Figure 5.

2.9 Prioritization for sub-watershed treatment

The USLE was applied for the identification and prioritization of the critical sub-watersheds of the Tapacurá watershed on the basis of average annual soil loss. Simulations were performed using solid and water discharge data collected (1999–2007) from a gauging station at Vitória de Santo Antão. This is the only data series existents in the watershed.

Table 2 shows the six erosion risk classes based on Irvem *et al.* (2007). According to this classification, an erosion risk map based on the distribution of soil loss over the Tapacurá watershed, was prepared. The ranges of the erosion rates and their suggested classes were inferred for identification of the critical sub-watersheds. Mean annual soil loss was simulated for each sub-watershed of the Tapacurá watershed and priorities were identified

The critical sub-watersheds were then prioritized related to management scenarios for reducing soil loss. A particular sub-watershed may get top priority due to various reasons, but often the intensity of land degradation is used as the basis. This approach of prioritizing watersheds based on actual soil loss rates is possible only when the number of sub-watersheds to be prioritized is low and the necessary data are available. Furthermore, this method is helpful when the soil loss potentials of different sub-watersheds do not have considerable variations.

Table 2: Soil loss, erosion risk and critical classes

Soil loss (t/ha/yr)	Erosion risk classes	Critical classes
< 5	Very low	VI
5–12	Low	V
12–50	Moderate	IV
50–100	Severe	III
100–200	Very severe	II
> 200	Extremely severe	I

3. RESULTS AND DISCUSSION

The mean SDR value for the Tapacurá watershed was 0.115, which means that 11.5% of the soil loss generated in the watershed was transported to the outlet. Pandey *et al.* (2007) and Beskow *et al.* (2009), applying a similar methodology, found errors that ranged from 1.37% to 13.85%, for watersheds with similar soil and precipitation regime in India and Brazil, respectively. According to those authors, errors less than 20% are acceptable, and it is possible to validate the erosion simulation process based on the USLE application for the watersheds conditions. An important role, however, is played by the internal diversity of the watershed by landforms and land cover in the basin.

The transported sediments in the channels are originated largely from bank erosion and in higher parts are transported more effectively through the drainage network. Initially, supplied sediment may be transported in suspended mode in streams with a high flow velocity, but a part may become bedload transport when flow velocities reduce downstream. Under high flow velocity, a larger part of the sediment delivered to the streams remains in suspension.

The sediment transport regime of large drainage basins is determined by the amount of sediment supplied to the drainage network, by the capability and efficiency of the drainage network to transport this material, and by the amount of deposition along the river. The ratio between the amount of material eroded from the hillslopes and the material transported out of the watershed is referred to as the sediment delivery ratio

(SDR). In Table 3, it is possible to evaluate both observed and estimated sediment yields. For the period studied, the mean sediment transport was equal to 0.11 t/ha/yr, with values ranging between 0.05 and 0.4 t/ha/yr. For 2004, it was observed that there was a considerable error, equal to -0.29 t/ha/yr. On the other hand, for the years 2002 and 2007, the errors were -0.05 and -0.04 t/ha/yr, respectively. These values, above the satisfactory criteria levels, indicate that the USLE performed well for sediment yield prediction, with $R^2 = 0.81$.

A possible reason for this higher error is that, for 2004, annual rainfall was considerably lower than the mean annual precipitation in the region (1200 mm compared to 1067 mm), undermining for 2004 the rainfall-runoff-erosion relationship compared to other years. The high level of discrepancy between the observed and computed long-term average sediment yields might be a result of the different dynamic processes occurring within the watershed.

Figure 6 shows the annual rainfall erosivity in the watershed obtained by Equation 2. The mean erosivity factor of all investigated stations range of 4400–7400 MJ.mm/ha/h/yr. In general, eastern region have the highest rainfall erosivity and medium level erosivities are observed in the middle part of watershed. The regions with the lowest rainfall erosivities are the western part.

The average erosivity factor values found for Tapacurá watershed are similar to the ones published by Nascimento & Chaves (1996) for Alagoinha (close to the studied watershed), which range from 3500 to 6500 MJ.mm/ha/h/yr for different years at one station. However, the Tapacurá watershed values are twice as high as the maximum value observed for Alagoinha, which can be explained by higher annual precipitation means (i.e., > 1200 mm in Tapacurá and 1100 mm in Alagoinha) and by the strong influence of orographic rainfall. Small erosivity values occur in the middle and western parts of watershed, which is mainly due to a very high annual rainfall in combination with a high topography. These values indicate that, climatologically, the watershed had very high erosion potential. However, in spite of showing very high erosivity values, it has been long recognized that the climatic characteristics of these regions together with topographic, soil, and land use factors have enhanced soil erosion by water.

Table 3: Observed and estimated sediment yield and estimation errors for the Tapacurá watershed

Years	Sediment Yield (t/ha/yr)		
	Estimated	Observed	Estimation Error
1999	0.04	0.05	-0.01
2000	0.17	0.16	0.01
2002	0.08	0.13	-0.05
2004	0.13	0.42	-0.29
2005	0.17	0.16	0.02
2007	0.06	0.10	-0.04
Average	0.11	0.17	-0.06

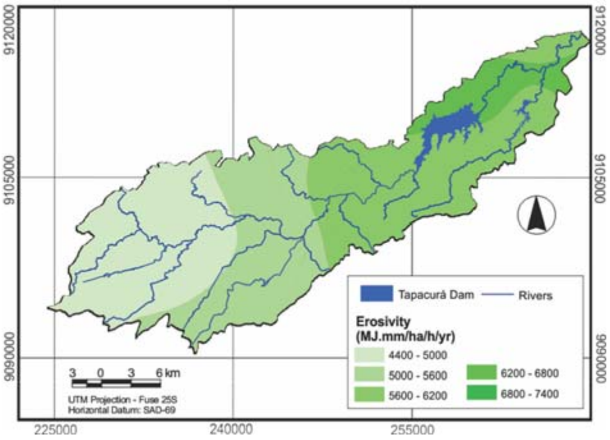


Fig. 6 - Map of erosivity factor in the Tapacurá watershed.

Figure 7 shows soil types and the spatial distribution of soil erodibility K factors. This map was obtained using Equation 4. The K values in the study area varied from 0.00060 to 0.057, with the mean value being 0.029 t/h/MJ/mm. It is noted that 68% of the Tapacurá watershed's overall area has Acrisols, which have higher soil erodibility values. Figure 8 shows the spatial distribution of LS factor obtained by Equation 3 . The Tapacurá watershed has LS factor values which ranged from 0–2.3 to

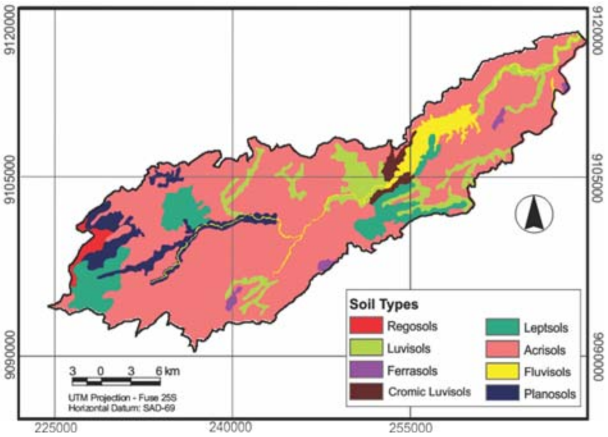


Fig. 7 - Map of main soil types in the Tapacurá watershed.

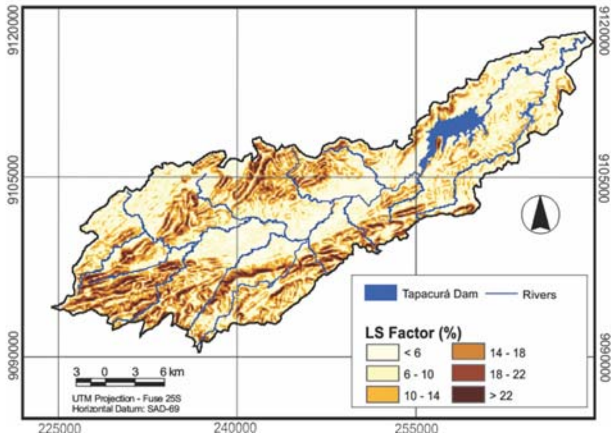


Fig. 8 - Map of topographic factor in the Tapacurá watershed.

22.3–25.6%. Spatial analysis of the LS factors suggested that the topography of the watershed mostly favored less erosion, which means that only in a very small part of the watershed with steeper slopes there is an increase of water production.

The C factor map derived by NDVI is shown in Figure 9. The C factor values varied from -1 to 0.80, with the mean value being 0.20. The highest C factor values occurred in the hillside areas, due to the agricultural presence in those areas. Owing to the larger agricultural area located in the hillside edge of the valley, higher C factor values occur in that area as well.

The distribution of average annual soil loss predicted for the Tapacurá watershed is showed in Figure 10. The annual soil loss was obtained based by multiplying all maps (erosivity, erodibility, topographic and NDVI maps, using map algebra techniques). It can be observed that the majority of land use in the watershed (agriculture and livestock are predominant land use classes) is expected to have an average annual soil loss of around 12–14 t/ha/yr, which is considered to be high for these areas and the southwest part of the watershed has more erosion yield than the other parts. This situation occurs due to the high C factor value presented in a large part of the area. The soil erosion hazard map clearly shows that nearly the entire watershed requires implementation of different types of soil and water conservation measures for sustainable land use.

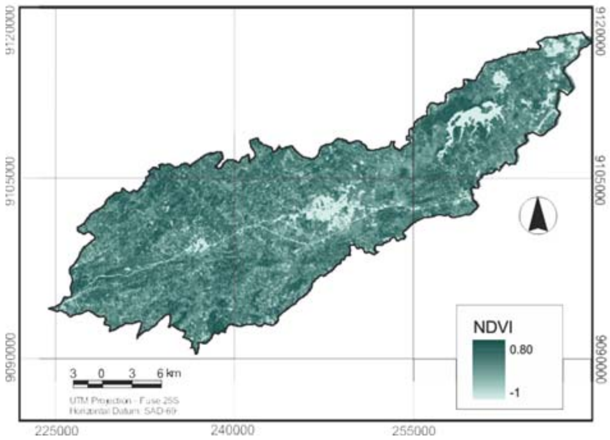


Fig. 9 - C factor map derived by NDVI for Tapacurá watershed.

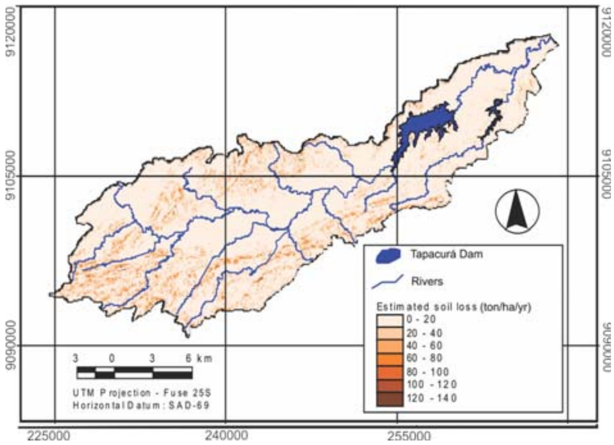


Fig. 10 - Spatial distribution of soil loss rate in the Tapacurá watershed.

The obtained results show the areas susceptible to the process of erosion within the Tapacurá watershed. Annual soil loss ranged from 0–20 t/ha/yr in the central part of the watershed to 20–40 t/ha/yr downstream, and to more than 110 t/ha/yr in some critical erosion areas. Average annual soil loss for the entire watershed was estimated at 70 t/ha/yr. The estimated soil loss rate and the spatial patterns are generally realistic, when compared to what can be observed in the field as well as to results from previous studies. It can also be observed that the areas with higher soil loss contribution have LS factor higher than 12.3% and land use classified as agriculture and livestock. In fact, the topography plays a critical role in controlling the soil movement in the Tapacurá watershed.

The results showed that about 12% of the watershed area is classified as severe erosion areas, where the average soil loss rate is higher than 81–92 t/ha/yr, and that about 88% of the area is classified as very severe erosion areas. In addition, due to the existing human activities in the watershed, it is speculated that the sediment yield in the area is likely to increase further more in future, which could be controlled with reforestation of areas near to the rivers, mainly in areas with average soil loss rate higher than 100 t/ha/yr. Therefore, this watershed needs immediate attention from the soil conservation point of view.

3.1 Results of the natural potential for erosion

The integration of the three factors early described (R, K and LS) outcomes the NPE map, shown in Figure 11. Possibly due to relief influences, the predominant class was "< 200 t/ha/yr", with approximately 34%. Surprisingly, the classes larger than 800 t/ha/yr have 12.8% of total area (Table 4). It can be observed that the major part of the watershed (about 34%) is predicted to have an average annual soil loss of less than 200 t/ha/yr and the second major class was 200–400 t/ha/yr (25%) (Table 4).

Besides the occurrence of soils highly erodible along Tapacurá catchment, the geographical distribution of high values of NPE has two notable distinct influences. The first one is an evident influence of very high erosivity values (R factor). The second one is a major influence of relief (LS factors) in the eastern portion. This information takes an important role on the establishment of land use politics in order to promote a sustainable land use, as rural or urban zone.

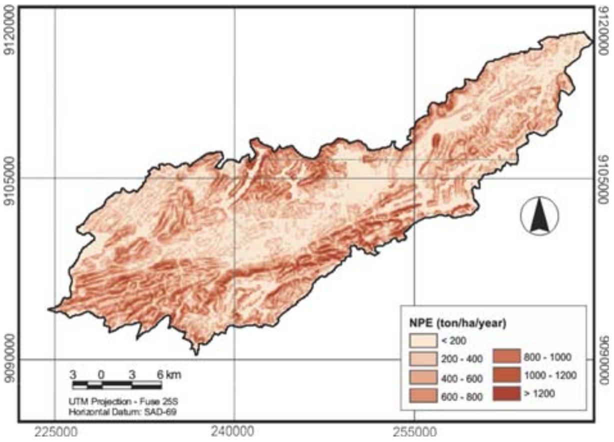


Fig. 11 - NPE map for Tapacurá watershed.

Table 4: Intervals of the natural potential for erosion in the Tapacurá watershed (SILVA *et al*., 2011)

Soil loss intervals (t/ha/yr)	Area (%)
< 200	33.7
200–400	24.8
400–600	17.3
600–800	11.3
800–1000	7.3
1000–1200	4.1
> 1200	1.4

This situation is because possibly due to relief influences and high NDVI-C factor value for a large part of the area. This high value represents unfavorable soil protection from the direct impact of raindrops (Fig. 9). Besides of the occurrence of soils erodibility along watershed, the geographical distribution of high values of natural potential for erosion has two notable distinct influences. The first one is an evident influence of very high erosivity values (R factor) and the second one is major influence of topographic factor. This information takes an important role on the establishment of land use politics in order to promote a sustainable land use, as rural or urban.

The pressure of population, among other factors, is leading to increased cultivation of tropical steeplands, generally defined as land with slope exceeding 20% (TERRANOVA *et al.*, 2009). Tapacurá watershed is a typical case of this problem, where the land use is more intensive. In rural context, many crops have been cultivated in hilly areas and favoring the erosion process, as sugar-cane cultivated in steep lands.

3.2 Identification of critical sub-watershed

Prioritization of sub-watersheds involves ranking the different sub-watersheds according to the order in which they ought to be taken up for conservation management, by taking into consideration the amount of soil loss occurring. Figure 12a shows soil erosion critical classes map for Tapacurá watershed.

In this work, a total of 14 sub-watersheds were delineated based on drainage systems and the erosion hazard map were reclassified based on prioritization (Figure 12b). The 14 sub-watershed in the two erosion severity classes were classified as (a) severe, and (b) very severe. Soil erosion risk maps and critical classes based on distribution of soil loss for the Tapacurá watershed were accomplished.

Based on the spatial distribution of erosion hazards, 11 (Tamata-Mirim, Natuba, Pacas, Miringaba, Água Azul, Itapessirica, Jurubeba, Bento Velho, Tapacurá river, Pororoca, and Várzea do Una) out of 14 sub-watersheds fell under the very severe soil erosion category (100–200 t/ha/yr) (Figure 12). Three of the sub-watersheds in the severe soil loss category account for about 12%

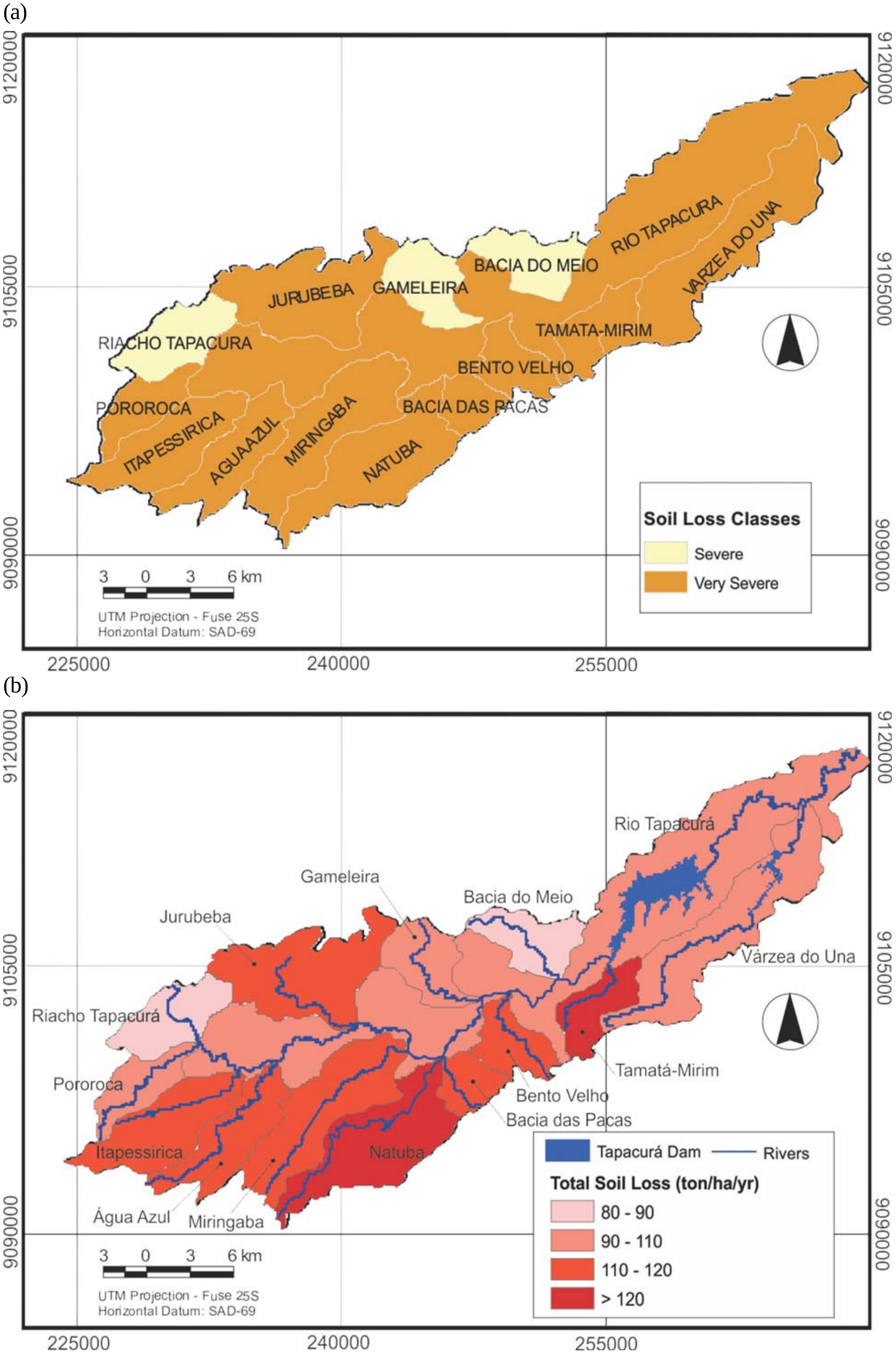


Fig. 12 – (a) soil erosion critical classes and (b) soil erosion hazard in the Tapacurá watershed.

of the total soil loss from the watershed, while accounting for only about 17% of the total area.

None of the sub-watersheds fell under extremely severe erosion class. This may be due to the fact that the studied watershed has a mean slope of 3.6% only. Out of the 14 sub-watersheds, three (Tamata-Mirim, Natuba, and Pacas) were predicted to experience annual soil loss of more than the average within the watershed (117 t/ha/yr), whereas in one other sub-watershed (Miringaba), estimated annual soil losses were close to the average in class II. Gameleira, Bacia do Meio, and Riacho Tapacurá watersheds that are predicted to experience severe soil loss correspond together to about 12% of the watershed area, but account for only 17% of the total watershed soil loss. In prioritizing for conservation intervention, Gameleira, Bacia do Meio and Riacho Tapacurá sub-watersheds can be considered to be in class III.

Numerous studies have indicated that, for many watersheds, a few critical areas are responsible for a disproportionate amount of sediments that are carried to drainage network (TRIPATHI *et al.*, 2003; BEWKET & TEFERI, 2009). Critical areas of soil loss can be defined from the land resource perspective. From the land resource perspective, critical areas are those land areas where the soil erosion rate exceeds the soil loss tolerance value.

4. CONCLUSIONS

Soil erosion is a serious problem in northeastern Brazil and the evaluation of soil loss risk is necessary for sustainable land use and comprehensive soil conservation management. Owing to the spatial and temporal variability of landscape and land use, and the time needed for that data collection, there are difficulties in estimating soil erosion over large areas. However, these problems can be partially overcome by the use of predictive models, remote sensing, and GIS techniques, which was the main goal of the present study.

The USLE, GIS and remote sensing techniques were very effective in assessing soil loss and erosion risk in this study. The results showed an annual estimated sediment yield of 0.108 t/ha/yr, and estimated soil loss of 70 t/ha/yr, which indicates that soil losses are high on approximately half of the area in the Tapacurá watershed. Sediment yield calculations indicate that only a small portion of the total sediment input leaves the watershed as suspended load, giving a SDR of 11.5% for the period.

The results obtained by the present study demonstrated the importance of land cover for the watershed management. The Tapacurá watershed has soils with high vulnerability to erosion, high slope steepness, and high rainfall erosivity factor, which ranges from 4400 to 8200 MJ.mm/ha/h/yr. In this study, it was observed that slope (LS) and land cover (C) factors are the most significative ones to estimate the soil loss within the area. Overall 20% of the area is undergoing high erosion rates which are the major contributors to the watershed sediment yield; i.e., the sediment yield of those areas represents 78% of the total sediment yield. This can be due to the high slope degree, the presence of agriculture and livestock, and the considerable vegetation removal by human activities. Those areas could be considered as high-priority areas for management in order to reduce soil losses, which are mostly found in the upstream part of the watershed.

ACKNOWLEDGMENTS

The authors are supported by CNPq, FACEPE and MCT/CT-HIDRO/FINEP. ANA (Brazilian National Water Agency) is acknowledged for providing the database.

REFERENCES

AGÊNCIA NACIONAL DE ÁGUAS. **HIDROWEB –Dados hidrológicos**. Available in; http://hidroweb.ana.gov.br. Accessed: 26 November 2011.

BESKOW, S.; MELLO, C. R.; NORTON, L. D.; CURI, N.; VIOLA, M. R.; AVANZI, J. C. Soil erosion prediction in the Grande River Basin, Brazil using distributed modelling. **Catena**, v. 79, n. 1, p. 49-59, 2009.

BEWKET, W.; TEFERI, E. Assessment of soil erosion hazard and prioritization for treatment at the watershed level: case study in the Chemoga watershed, Blue Nile Basin, Ethiopia. **Land Degradation and Development**, v. 20, n. 7, p. 609-622, 2009.

BHATTARAI, R.; DUTTA, D. Estimation of Soil Erosion and Sediment Yield Using GIS at Catchment Scale. **Water Resources Management**, v. 21, n. 10, p. 1635-1647, 2007.

CASTRO, S. S.; QUEIROZ NETO, J. P. Soil erosion in Brazil from coffee to the present-day soy bean production. **Developments in Earth Surface Processes**, v. 13, p. 195-221, 2009.

DABRAL, P. P.; BAITHURI, N.; PANDEY, A. Soil erosion assessment in a hilly watershed of North Eastern India using USLE, GIS and remote sensing. **Water Resources Management**, v. 22, n. 12, p. 1783-1798, 2008.

DE MOOR, J. J. W.; VERSTRAETEN, G. Alluvial and colluvial sediment storage in the Geul River watershed (The Netherlands) – Combining field and modelling data to construct a Late Holocene sediment budget. **Geomorphology**, v. 95, n. 4, p. 487-503, 2008.

DE ROO, A. P. J. Modelling runoff and sediment transport in catchments using GIS. **Hydrological Processes**, v. 12, n. 6, p. 905-922, 1998.

ERDOGAN, E. H.; ERPUL, G.; BAYRAMIN, I. Use of USLE/GIS methodology for predicting soil loss in a semiarid agricultural watershed. **Environmental Monitoring and Assessment**, v. 131, n. 2, p. 153-161, 2007.

FISTIKOGLU, O.; HARMANCIOGLU, N. B. Integration of GIS and USLE in assessment of soil erosion. **Water Resources Management**, v. 16, n. 6, p. 447-467, 2002.

HANTUSH, M.M.; KALIN, L. Uncertainty and sensitivity analysis of runoff and sediment yield in a small agricultural watershed with Kineros-2. **Hydrological Science Journal**, v. 50, n. 6, p. 1151-1172, 2005.

HRISSANTHOU, V. Estimate of sediment yield in a basin without sediment data. **Catena**, v. 64, n. 4, p. 333–347, 2005.

IRVEM, A.; TOPALOGLU, F.; UYGU, V. Estimating spatial distribution of soil loss over Seyhan River Basin in Turkey. **Journal of Hydrology**, v. 336, n. 1, p. 30-37, 2007.

JAIN, M. K.; DAS, D. Estimation of sediment yield and areas of soil erosion and deposition for watershed prioritization using GIS and Remote Sensing. **Water Resources Management**, v. 24, n. 10, p. 2091-2112, 2009.

JENSEN, J. R. **Introductory digital image processing: a remote sensing perspective**. Pearson Prentice Hall, New Jersey, 2005. 526 p.

KALIN, L.; HANTUSH, M. H. Comparative assessment of two distributed watershed models with application to a small watershed. **Hydrological Processes**, v. 20, n. 11, p. 2285-2307, 2006.

KOREN, V.; MOREDA, F.; REED, S.; SMITH, M.; ZHANG, Z. Evaluation of a grid-based distributed hydrological model over a large area. **IAHS Publication**, v. 303, p. 47-56, 2006.

MOORE, I. D.; BURCH, G. Physical basis of the length-slope factor in the Universal Soil Loss Equation. **Soil Science Society American Journal**, v. 50, n. 5, p. 1294-1298, 1986.

NASCIMENTO, C. W. A.; CHAVES, I. B. Erosividade e características da chuva correlacionadas com perdas de solo em Alagoinha - PB. **Ciência Rural**, v. 26, n. 3, p. 407-412, 1996.

PANDEY, A.; CHOWDARY, V. M.; MAL, B. C. Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing. **Water Resources Management**, v. 21, n. 4, p. 729-746, 2007.

REED, S.; KOREN, V.; SMITH, M.; ZHANG, Z.; MOREDA, F.; SEO, D.-J. Overall distributed model intercomparison project results. **Journal of Hydrology**, v. 298, n. 1, p. 27-60, 2004.

SADER, S. A.; WINNE, J. C. RGB-NDVI colour composites for visualizing forest change dynamics. **International Journal of Remote Sensing**, v. 13, n. 16, p. 3055-3067, 1992.

SESNIE, S. E.; GESSLER, P.E.; FINEGAN, B. Integrating Landsat TM and SRTM-DEM derived variables with decision trees for habitat classification and change detection in complex neotropical environments. **Remote Sensing of Environment**, v. 112, n. 5, p. 2145-2159, 2008.

SILVA, A. M.; ALVARES, C. A.; WATANABE, C. **Natural potential for erosion for Brazilian territory**. In: GODONE, D. and STANCHI, S. Soil Erosion Studies. Rijeka: InTech – Open Access Publisher. Chapter 1, p. 1-22, 2011.

SILVA, R. M.; SANTOS, C. A. G.; MONTENEGRO, S. M. G. L.; SILVA, L. P. Spatial analysis of vegetal cover and sediment yield in Tapacurá river watershed based on remote sensing and GIS. **Land Reclamation**, v. 42, n. 1, p. 5-16, 2010.

SILVA, R. M.; MONTENEGRO, S. M. G. L.; SANTOS, C. A. G. Integration of GIS and Remote Sensing for estimation of soil loss and prioritization of critical sub-catchments: a case study of Tapacurá catchment. **Natural Hazards**, v. 62, n. 3, p. 953-970, 2012.

SILVA, R. M.; SILVA, L. P.; MONTENEGRO, S. M. G. L.; SANTOS, C. A. G. Análise da variabilidade espaço-temporal e identificação do padrão da precipitação na Bacia do Rio Tapacurá, Pernambuco. **Sociedade & Natureza**, v. 22, n. 2, p. 357-372, 2010.

SILVA, R.M.; SANTOS, C. A. G.; SILVA, L. P. Evaluation of soil loss in Guaraíra basin by GIS and remote sensing based model. **Journal of Urban and Environmental Engineering**, v. 1, n. 2, p. 44-52, 2007.

SYMEONAKIS, E.; CACCETTA, P.; KOUKOULAS, S.; FURBY, S.; KARATHANASIS, N. Multi-temporal land-cover classification and change analysis with conditional probability networks: the case of Lesvos Island (Greece). **International Journal of Remote Sensing**, v. 33, n. 13, p. 4075-4093, 2012.

TERRANOVA, O.; ANTRONICO, L.; COSCARELLI, R.; IANQUITA, P. Soil erosion risk scenarios in the Mediterranean environment using RUSLE and GIS: an application model for Calabria (Southern Italy). **Geomorphology**, v. 112, n. 3, p. 228-245, 2009.

TRIPATHI, M. P.; PANDA, R. K.; RAGHUWANSHI, N. S. Identification and prioritisation of critical sub-watersheds for soil conservation management using the SWAT model. **Biosystems Engineering**, v. 85, n. 3, p. 365-379, 2003.

VERSTRAETEN, G.; ROMMENS, T.; PEETERS, I.; POESEN, J.; GOVERS, G.; LANG, A. A temporarily changing Holocene sediment budget for a loess-covered watershed (central Belgium). **Geomorphology**, v. 108, n. 1, p. 24-34, 2009.

WINCHELL, M. F.; JACKSON, S. H.; WADLEY, A. M.; SRINIVASAN, R. Extension and validation of a geographic information system-based method for calculating the Revised Universal Soil Loss Equation length-slope factor for erosion risk assessments in large watersheds. **Journal of Soil and Water Conservation**, v. 63, n. 1, p. 105-111, 2008.

WISCHMEIER, W. H.; SMITH, D. D. **Predicting rainfall erosion losses**. Admin. U.S. Department of Agriculture. Washington, Agriculture Handbook Science and Education 357, 1978, 58p.

ZHANG, Y.; DEGROOTE. J.; WOLTER. C.; SUGUMARAN, R. Integration of Modified Universal Soil Loss Equation (MUSLE) into a GIS framework to assess soil erosion risk. **Land Degradation and Development**, v. 20, n. 1, p. 84-91, 2009.