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Soil loss prediction in Guaraíra river experimental basin, Paraíba, Brazil based on two erosion simulation models

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ABSTRACT

In this study, two hydrological models to estimate soil losses and sediment yield due to sheet and channel erosion, at the basin outlet, are applied to Guaraíra River Experimental Basin, located in Paraíba State, northeastern Brazil. The soil erosion models are (a) the classical Universal Soil Loss Equation (USLE), which is used to simulate annual and monthly soil losses; and (b) Kineros model, which is used to simulate the sediment yield within the basin. Kineros model is a physically-based distributed model that uses a cascade of planes and channels to represent the basin and to describe the processes of interception, infiltration, surface runoff and erosion within the basin. The USLE is computed using land use, soil erodibility, topographic digital maps, as well as observed rainfall data. It was found that Guaraíra river experimental basin has a low potential for soil losses; however, specific areas which are susceptible to the erosion process in the basin could be detected by the modeling techniques coupled to a GIS (Geographic Information System).

Keywords: USLE; Kineros model; ungauged basin.

Predição de perdas de solo na bacia experimental do rio Guaraíra, Paraíba, Brasil usando dois modelos de simulação de erosão

RESUMO

Neste estudo, dois modelos hidrológicos são aplicados para estimar as perdas de solo e a produção de sedimentos devido à erosão laminar e à erosão nos canais, na Bacia Experimental do Rio Guaraíra, localizada no Estado da Paraíba, região nordeste do Brasil. Os modelos usados são (a) a clássica Equação Universal de Perda de Solo (EUPS), usada para simular perdas de solo mensais e anuais; e (b) o modelo Kineros, usado nas simulações da produção de sedimentos na bacia. O Kineros é um modelo de base física, distribuído que usa uma cascata de planos e canais para representar a bacia e descrever os processos de interceptação, infiltração, escoamento e erosão na bacia. A USLE é calculada a partir de mapas digitais da bacia de uso do solo, erodibilidade, topografia e de dados diários observados de chuva. Ao final, verificou-se que a bacia experimental do rio Guaraíra tem um potencial baixo para perdas de solo; entretanto, áreas específicas susceptíveis ao processo erosivo na bacia puderam ser detectadas através de técnicas de modelagem acoplada a um SIG (Sistema de Informação Geográfica).
Palavras-chave: EUPS; modelo Kineros; bacia não-instrumentada.

1. INTRODUCTION

Soil erosion by water is the most important land degradation problem worldwide, and it is a serious problem that stems from a combination of agricultural intensification, soil degradation, and intense rainstorms.

Actually, a large number of erosion models exists, which can be basically divided in two categories: empirical and physically-based models (Morgan, 1995). Empirical models have a statistical basis, whereas physically-based models intend to describe the acting processes on a storm event basis. Nevertheless, many models contain both empirical and physically-based components. A recent review of several current erosion models is provided by Merritt et al. (2003).

The empirical models are simple, but they do not penetrate into the mechanisms of the physical processes. In the case of physically-distributed models, the soil surface is subdivided into rills and interrill areas, while the soil erosion process is also analyzed into physical subprocesses.

Empirical models have been and are still used because of their simple structure and ease of application, but as they are based on coefficients computed or calibrated on the basis of measurement and/or through observed field data, as digital map or field trip, they have limited applicability outside the range of conditions for which they have been developed. Adaptation to a new environment requires a major investment of resources and time to develop the database required to drive them.

The Universal Soil Loss Equation (USLE) is the most widely used empirical erosion model (Wischmeier; Smith, 1978). It estimates soil erosion from an area simply as the product of empirical coefficients, which must therefore be accurately evaluated. Original values of such coefficients were derived from field observations in different areas within the eastern U.S., but they have been expanded with time using information gathered by researchers who have applied the USLE (and derived models) in different countries in the world e.g., El-Swaify; Dangler (1976); Dissmeyer; Foster (1981); Renard et al. (1997).

On the other hand, physically-based models simulate the individual components of the entire erosion process by solving the corresponding equations; and so it is argued that they tend to have a wider range of applicability (Amore et al., 2004). Such models are also generally better in terms of their capability to assess both the spatial and temporal variability of the natural erosion processes.

Kalin et al. (2003) investigated the effect of geomorphologic resolution on runoff hydrographs and sedigraphs over two small USDA experimental watersheds using Kineros model with ArcView interface, and they revealed that the basin geometric simplification for rainfall-runoff-erosion studies may be acceptable under right combinations of rainfall events and basin properties.

Martínez-Carreras et al. (2007) simulated badland erosion with Kineros in small microbasins in order to test the performance of the physically-based soil erosion model. Results are intended to better understand the role of summer rainstorms in annual and interannual catchment sediment yield rates, and the relevance of temporal sediment stores in the drainage network.

Prediction of runoff and erosion in ungauged hydrological basins is one of the most challenging tasks anywhere and especially a very difficult one in developing countries where monitoring and continuous measurements of these quantities are carried out in very few basins either due to the costs involved or due to the lack of trained personnel in sufficient number. Therefore, the aim of this study was the evaluation of the soil loss and sediment yield by the application of two models, the empirical USLE and the physically-based Kineros model, to Guaraíra river experimental basin, using a distributed approach, for further uses in ungauged basin in northeastern Brazil.

2. MATERIAL AND METHODS

2.1. Study Area

The studied area is the Guaraíra river experimental basin, which is located within Gramame river basin (Figure 1), in northeastern Brazil. This basin was chosen for the implantation of equipments in order to monitor the hydrological variables. Guaraíra river basin has an area of 5.84 km² and it is located between the coordinates 9,190,000 mN, 9,195,000 mN and 274,000 mE, 277,000 mE.

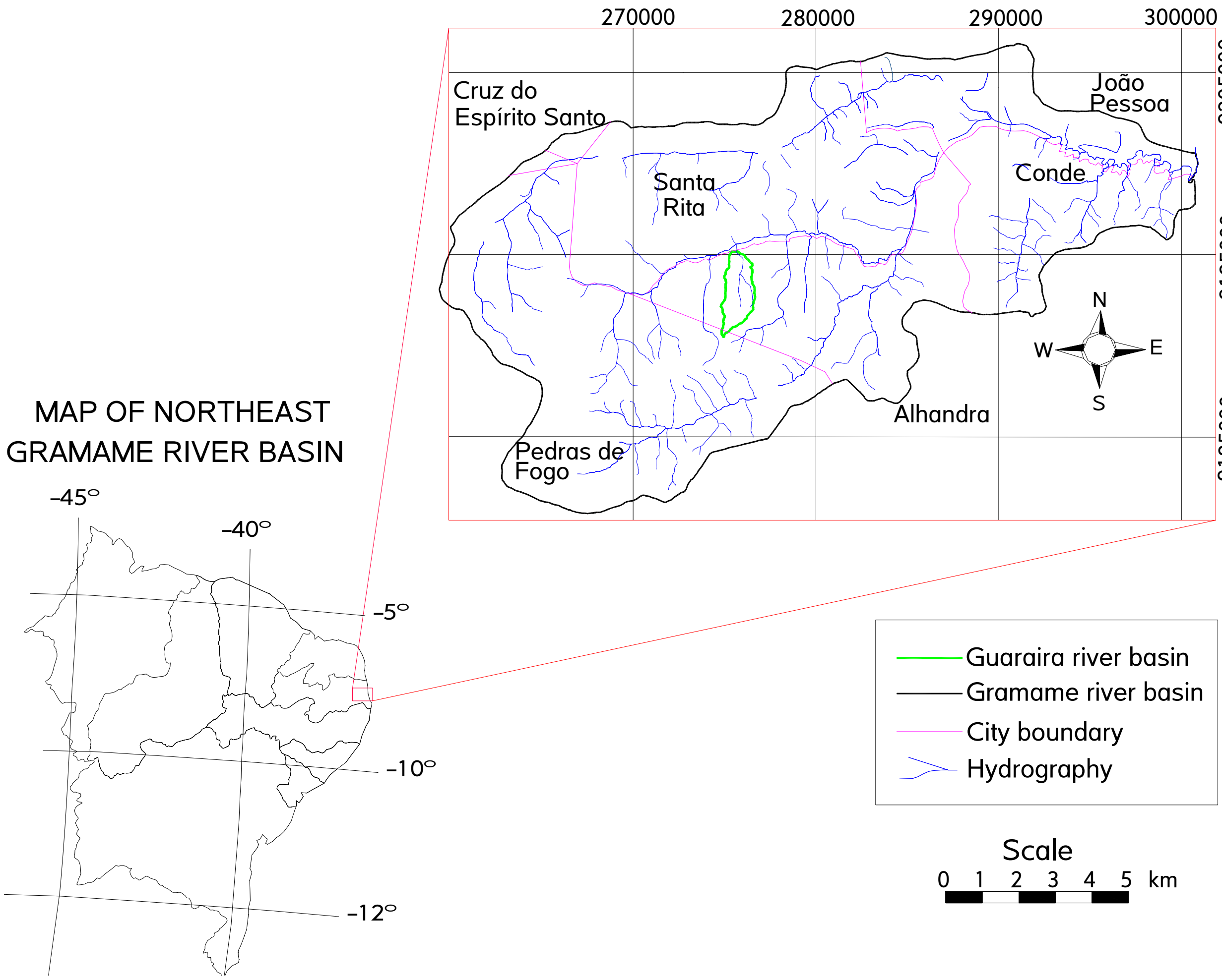


Figure 1. Location of Guaraíra river experimental basin and Gramame river basin in northeastern Brazil.

2.2. The USLE

Universal Soil Loss Equation (USLE) is an empirical model that was developed to predict the long term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, crop system and management practices. USLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses that might occur from gully, wind or tillage erosion.

This erosion model was created for use in selected cropping and management systems, but is also applicable to nonagricultural conditions such as construction sites. The USLE can be used to compare soil losses from a particular field with a specific crop and management system to tolerable soil loss rates. Thus, alternative management and crop systems may also be evaluated to determine the adequacy of conservation measures in farm planning. This soil loss equation is as follows:

$$A = R \times K \times LS \times C \times P \quad [1]$$

where A is computed soil loss per unit area (usually in tons/hectare/year); *R* is rainfall and runoff factor; *K* is soil erodibility factor; *LS* is the topographic factor (slope degree and length); *C* is cover and management factor (ratio of soil loss from an area with specific cover and management to an identical area in tilled continuous fallow); *P* is support practice factor (ratio of soil loss with a support practice factor such as contouring, terracing, etc, to a straight-row farming up and down slope).

Derivation of the factors required by USLE is well-documented in the literature (e.g., Williams; Berndt, 1976; Wischmeier; Smith, 1978; Foster et al., 1983; Desmet; Govers, 1996; Kinnell, 2005). However, the recent advent of GIS and remote sensing technology has enabled more accurate estimations of some the USLE factors, specifically those of slope length and steepness.

2.2.1. Erosivity factor (*R*)

The *R* factor represents the erosivity of the rainfall at a particular location. An average annual value of *R* is determined from historical records and is the average annual sum of the erosivity of individual storms. The *R* factor is the average annual summation of (EI) values, and it was obtained using the Equation [2] developed by Lombardi Neto and Moldenhauer (1980), and using observed data from 2003 to 2005 from five rain gauges.

$$EI_{monthly} = 89.823 \, (Pm^2 / Pa) \, 0.759 \quad [2]$$

where $EI_{monthly}$ is the monthly average of the erosion index (MJ/ha×mm), for the considered month; Pm is the monthly precipitation (mm) also for the considered month; and Pa is the annual mean precipitation (mm). The precipitation in the basin, computed by the Thiessen method (Equation 3), and the results of the rain energy factor ($EI_{monthly}$) were computed for each month. Table 1 presents the locations and data range of the selected rain gauges.

$$\overline{P} = \frac{\sum_{i=1}^{n} A_i P_i}{A_T} \quad [3]$$

where is the mean precipitation in the basin (mm); Ai is the polygon area assigned to i^{th} gauge (km^2); *Pi* is the precipitation recorded at the i^{th} gauge (mm); and AT is the basin area.

Table 1. Location and data range for the used rain gauges.

Identification	Latitude	Longitude	Period of data
Rain gauge 1	7° 17' 40"S	35° 02' 34"W	2003 - 2005
Rain gauge 2	7° 17' 55"S	35° 01' 51"W	2003 - 2005
Rain gauge 3	7° 18' 51"S	35° 01'57"W	2003 - 2005
Rain gauge 4	7° 17'51"S	35° 01' 17"W	2003 - 2005
Rain gauge 5	7° 17' 71"S	35° 01' 25"W	2003 - 2005

2.2.2. Soil erodibility factor (*K*)

The determination of the soil erodibility factor was based on the soil textures which exist in Guaraíra basin by using the soil map. A spatial soil distribution in the basin is shown in Figure 2 and the *K* factor values used in the present work are presented in Table 2.

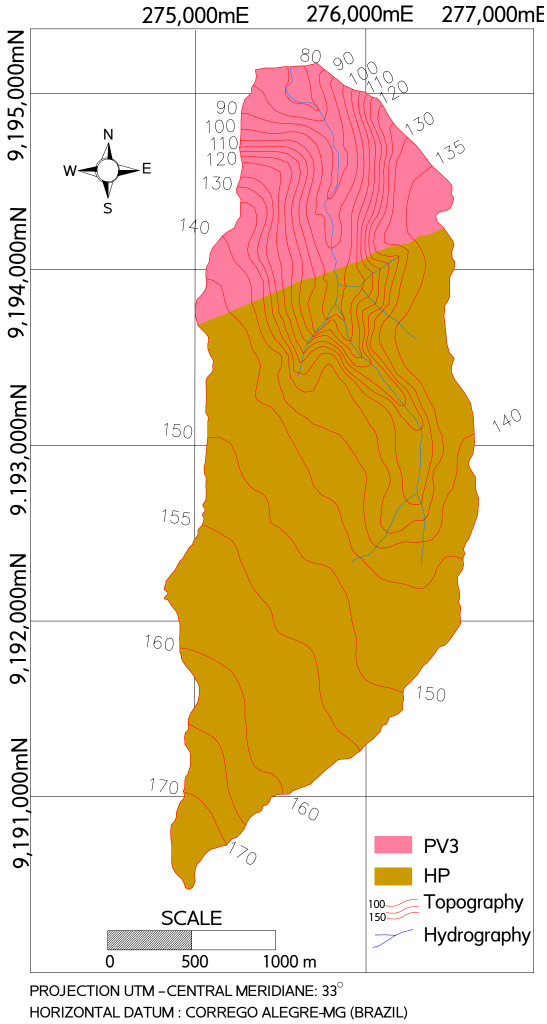


Figure 2. Topography and soil types in thee experimental basin.
Source: SUDENE (1972).

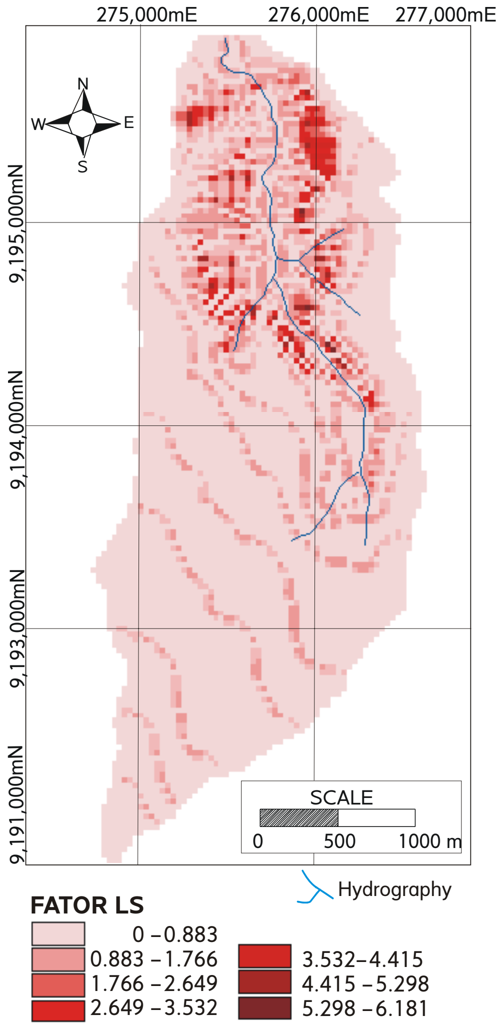


Figure 3. *LS* factor map computed by Equation [4] in SIG.

Table 2. Values of *K* factor according to the soil types in Guaraíra river experimental basin.

Soil types	Texture	Class	*K* (t·ha·h/ha·MJ·mm)
Podzolic Red-Yellow	Clay-Sand	PV3	0.032
Podzol Hidromorfic	Clay	HP	0.021

2.2.3. Topographic factor (*LS*)

For direct application of the USLE, a combined slope-length and slope-steepness (*LS*) factor was evaluated for Guaraíra basin. There are several methods to determine this factor, e.g, Williams and Berndt (1976), Moore and Burch (1986), Desmet and Govers (1996), and Kinnell (2005). In this study, the *LS* factor was estimated from the digital elevation model (DEM). This technique for estimating the *LS* factor was proposed by Moore and Burch (1986), which was also used by Engel and Mohtar (2007) and tested to the Brazilian conditions by Lima et al. (2006) and Souza et al. (2006), using Equation [4].

$$LS = \left(\frac{V}{22.13}\right)^{0.4}\left(\frac{\sin\theta}{0.0896}\right)^{1.3} \quad [4]$$

where V is runoff depth times the cell size, q is the slope angle in degrees.

The technique to compute *LS* requires the values of the flow accumulation and the slope steepness. Thus, the flow accumulation and slope steepness were computed from a DEM using watershed delineation techniques. Topographic factor is one the main factors responsible for the final soil erosion caused by water when evaluated by USLE. To model the topographic factor for a watershed is necessary to quantitatively spatialize it for the entire watershed. This can be done in a GIS environment. Figure 3 shows the *LS* factor map of Guaraíra river experimental basin, obtained in this study.

2.2.4. Cropping (*C*) and support practice (*P*) factors

The Cropping and Management Factor (*C*) for the USLE is defined as the ratio of soil loss from a particular cropping and management to soil loss from a continuously tilled fallow area. Earlier, *C* values had been defined as the ratio for a particular cropping and management to soil loss from a continuously tilled fallow area or to soil loss from a conventionally tilled row cropped area. Figure 4 presents the topography and land uses founded in Guaraíra basin.

The conservation practices factor (*P*) is the ratio of soil loss for a specific practice to the soil loss with up-and-down hill culture. The initial practices considered for the USLE were contouring, strip-cropping, contour strip-cropping, and terraces. These were expanded to include contour listing, controlled-row grade ridge planting, contoured residue strips, and several types of terraces. Most *P* values were recognized to have slope-length limits and to have values that varied according to the land slope.

Finally, USLE equation basically expresses soil loss per unit area due to rainfall. It does not include wind erosion, and it does not give direct sediment yield estimates (Fistikoglu; Harmancioglu, 2002). Since all factors in the USLE equation have a spatial distribution in a watershed, a GIS-based evaluation gives more accurate results. In the GIS assisted approach (Figure 5), each equation factor is described in the form of digital maps, and five digital layers of the equation are overlaid in order to obtain spatially distributed soil loss in a watershed.

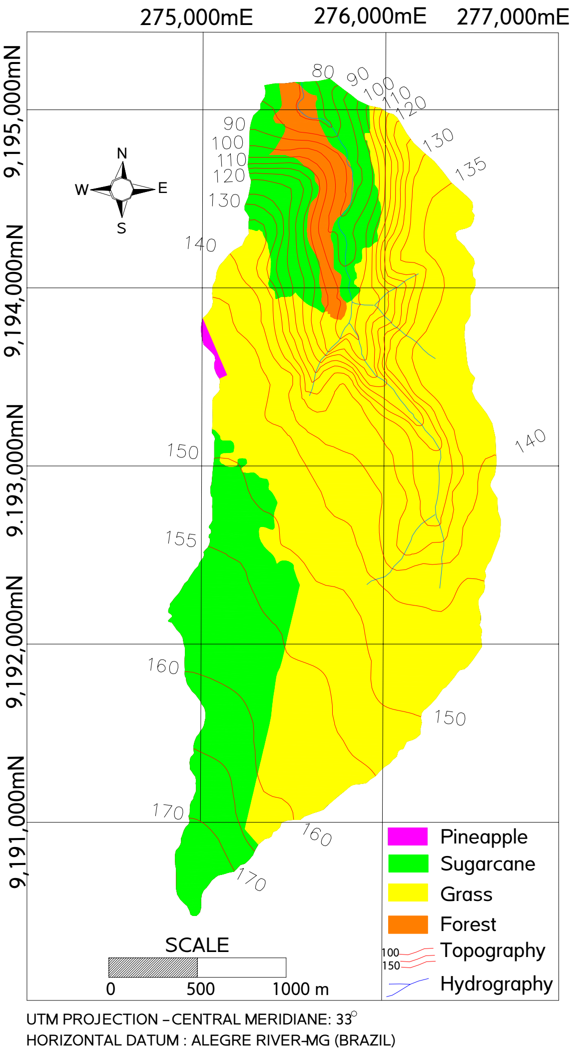


Figure 4. Topography and land use in basin.

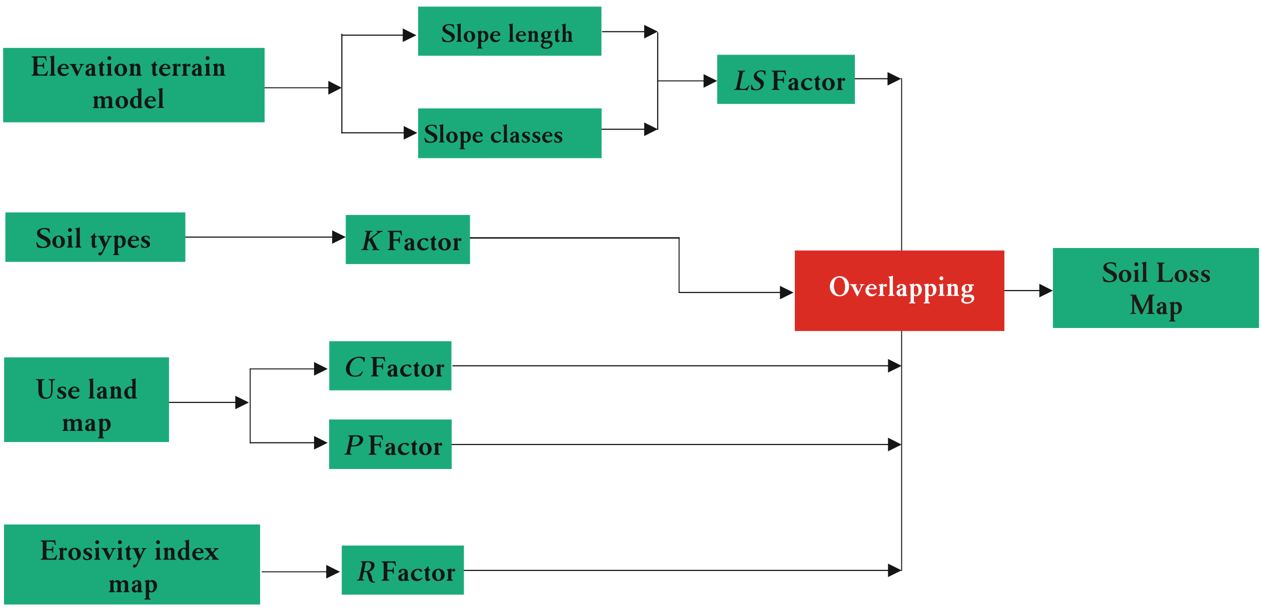


Figure 5. Steps in estimation of soil loss by USLE.

2.3. The Kineros model

Kineros model (Woolhiser et al., 1990) is a distributed kinematic physically-based runoff-erosion model that uses a cascade of planes and channels to represent the water path in the basin. Kineros model inputs assume rectangular hillslope areas being laterally contributed by water and sediment and/or to the top of channel segments (Figure 6).

This model is also an event-oriented model which describes the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban basins. As stated before, the basin is represented by a cascade of planes and channels, in which the partial differential equations describing overland flow, channel flow, erosion and sediment transport are solved by finite difference techniques. Furthermore, the spatial variation of rainfall, infiltration, runoff, and erosion parameters can be also accommodated.

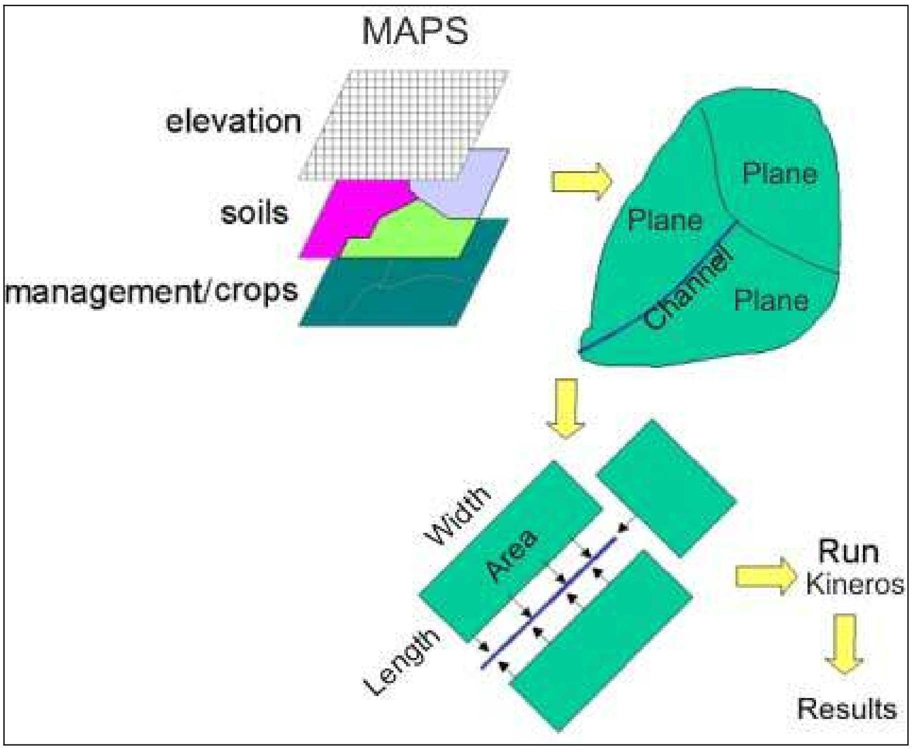


Figure 6. Steps in discretizing a watershed for a Kineros model simulation.

Thus, the Kineros model was selected as the physically-based model to be used during this study. This model is primarily useful for predicting surface runoff and erosion over small agricultural and urban watersheds. Runoff is calculated based on the Hortonian approach and infiltration is calculated by Smith and Parlange (1978) infiltration model. It requires the watershed to be divided into homogeneous overland flow planes and channel segments, and it models water movement over these elements in a cascading fashion. One-dimensional flow discharge per unit width, q, is expressed in terms of the storage of water per unit area, h (equal depth for a plane surface), through the kinematic approximation:

$$q = ah^m \quad [5]$$

where a and m are parameters related to the slope roughness and nature of flow. The continuity equation for upland areas is:

$$\frac{\partial A}{\partial t}+\frac{\partial q}{\partial x}=q_c(x,t) \qquad [6]$$

where t is time, x is the spatial coordinate, and qc is the net lateral inflow rate. The upstream condition is determined by the flow entering at the upstream end. The continuity equation for one-dimensional flow in channels is:

$$\frac{\partial A}{\partial t}+\frac{dQ}{dA}\frac{\partial A}{\partial x}=q_c(x,t) \qquad [7]$$

where A is flow cross-sectional area, Q is the channel discharge, and qc is the net lateral inflow per unit length of channel. Under the kinematic wave approximation.

Erosion and sediment transport rates are determined by solution to the sediment balance relation:

$$\frac{\partial(AC_s)}{\partial t}+\frac{\partial(QC_s)}{\partial x}-w_e(x,t,C_s)=q_c(x,t) \qquad [8]$$

in which *Cs* is the sediment concentration (m^3/m^3), e is the local rate of erosion or deposition ($m^3/s/m^2$), q is the rate of sediment inflow, as for lateral inflow to a channel.
Erosion rate e is composed of rainsplash erosion, es (r, h), and hydraulic erosion, eh. Splash erosion is a function of rainfall energy, often related to the square of rainfall intensity. Kineros relates es to the rainfall rate, r, the fraction of covered soil, , and mean runoff depth :

$$e_s=S_{pl}(1-\gamma)\exp\left(-c_d\bar{h}\right)r^2 \qquad [9]$$

Parameter Spl represents soil vulnerability to rainfall detachment, and cd represents the effect of water depth in damping splash energy. The exponent function expresses a reduction in es with increasing depth of surface water, reflecting its dampening effect on splash energy.

Hydraulic erosion may be positive or negative (deposition), depending on the local transport capacity. Transport capacity is assumed to represent a concentration, *Cm,* in which erosion and deposition rates are in balance and eh is 0, assuming there is no resistance to particle entrainment. Deposition is theoretically related to settling velocity, vs, and thus a relation for eh may be found:

$$e_h=C_h v_s\left(C_m-C_s\right) \qquad [10]$$

in which, the coefficient *Ch* is inversely related to soil cohesion or any other restriction on soil entrainment by flowing water, and is 1 during deposition (*Cs* > *Cm*). *Cm* is estimated in Kineros by a modified form of the Engelund and Hansen transport relation (Kalin et al., 2003).

2.4. Kineros model calibration

The parameters that have the strongest influence on runoff from a land cover perspective for Kineros are saturated hydraulic conductivity (*Ks*), porosity (*f*), canopy cover, and Manning's roughness coefficient. These parameters were adjusted for each layer, according to the soil types found in the basin and also based on the mean values proposed by Green-Ampt (Rawls et al., 1991). Other parameters such as mean soil capillarity drive (*G*), mean microtopographic spacing (S_p), volumetric rock fraction (*R*) were based on either field observation or digital maps, as shown in Tables 3 and 4. After that, the obtained simulation results were inserted into a GIS.

Table 3. Parameters for the soil upper layer used in the calibration process.

Parameters	Symbol	Upper layer
Thickness of upper soil layer	H	400 - 550 mm
Mean microtopographic spacing	S_p	0.1 - 0.3 m
Rainfall splash coefficient	c_f	50
Soil cohesion coefficient	c_o	0.5
Fraction of surface covered by canopy	C_s	2 - 4
Initial degree of soil saturation	θ_{si}	0.4 - 0.7
Manning roughness coefficient	n	0.02 - 0.005

Table 4. Parameters for the two-layers soil profile used in the calibration process.

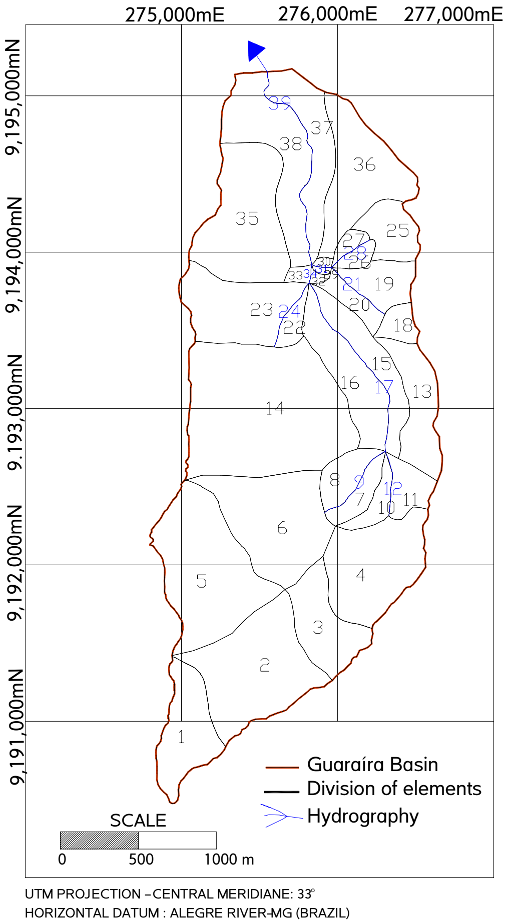
Parameters	Symbol	Upper layer	Lower layer
Mean capillary drive	G	20 - 25 mm	12 - 16 mm
Saturated hydraulic conductivity of the soil	K_s	2.2 - 3.0 mm/h	1.8 - 2.0 mm/h
Pore size distribution index	λ	0.29 - 0.32	0.16 - 0.18
Volumetric rock fraction	R_o	0.0 - 0.0	0.0 - 0.1
Porosity	ϕ	0.32 - 0.40	0.16 - 0.24

3. RESULTS AND DISCUSSION

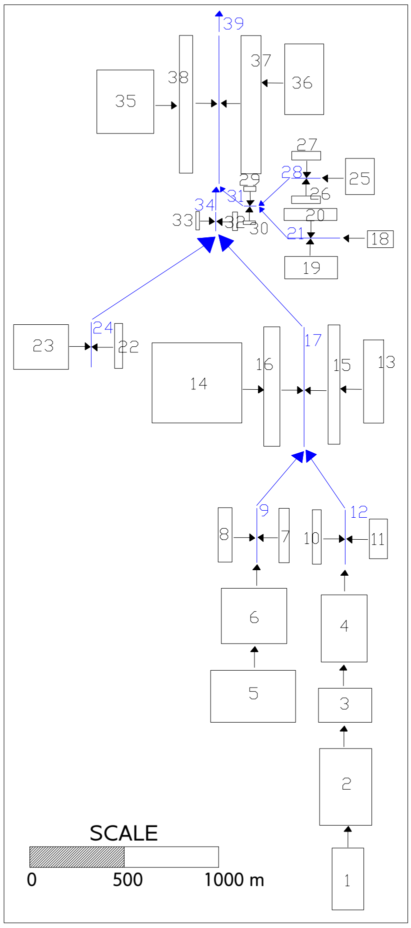
3.1. Application of Kineros model to the Guaraíra basin

Figure 7 illustrates the geometric abstraction of a watershed into channel and plane elements, which are 30 overland flow subareas and 9 channel sections for simulation purposes. As the illustration suggests, this subdivision was performed along streamlines, and the elements were selected to distinguish and conserve the management areas indicated in the furnished maps through the geoprocessing techniques. These subareas were treated as rectangles of equivalent area, when the length and mean slope were preserved.

This subdivision was a compromise, in so far as some local slope variations could have been represented only by using far more elements. It was later learned that furrow directions in some cases did not match the topographic trend, which would affect the derivation of slope and flow length for areas with significant furrow depths. The data did not specify furrow geometries, which were assumed according to crop type.



(a)



(b)

Figure 7. (a) Lateral boundaries of the elements in which the Guaraíra basin was subdivided for Kineros, and (b) basin scheme in plane and channel elements. It was assumed, in the absence of detail on furrow depth and direction, that flow follows topographic directions.

3.2. Estimation of soil loss and sediment yield in Guaraíra basin

The estimation of soil loss was calculated through overlapping of all the maps of *R*, *K*, *LS*, *C* and *P*, which were integrated to generate the erosion map to find out the spatial distribution of soil loss within GIS environment for the Guaraíra river basin. The average rainfall erosivity factor (*R*) for the years 2003, 2004 and 2005 was found to be 528 (MJ/ha×mm). Thus, Figure 8 shows soil loss in the Guaraíra basin using USLE, expressed in five broad classes and ranging from 0.0 up to 3.2 ton/ha/year, which can be considered as very low risk areas. The mean annual soil loss rate can be assumed as around 1.6 ton/ha/year.

Figure 9 presents the computed sediment yield in Guaraíra basin in four classes, using Kineros model, in which the mean annual soil loss rate can be in the oder of 2.8 ton/ha/year. The sediment yield in the area during those analyzed years can be considered of moderate magnitude, mainly due to the small area of basin.

In addition, Figure 10 presents the mean precipitation and the $EI_{monthly}$, which are monthly computed in the basin. From this relationship, it is observed that the largest values of erosivity and rainfall, in Guaraíra basin, were observed from May to July (around 57%). Even taking into account the wide spatial diversity and limitations in the data, it was found that, in general, the USLE can be used to predict soil loss in the basin. As the Figure 11 shows, the erosion depends mainly on the precipitation depth and a relationship could be done as shown in the same Figure.

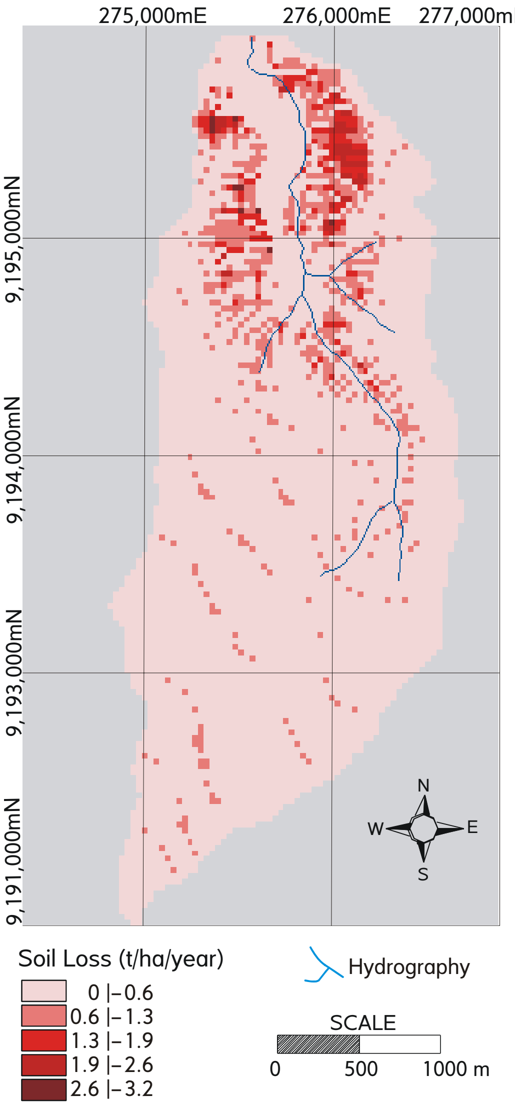


Figure 8. Estimation of soil loss using USLE in Guaraíra basin.

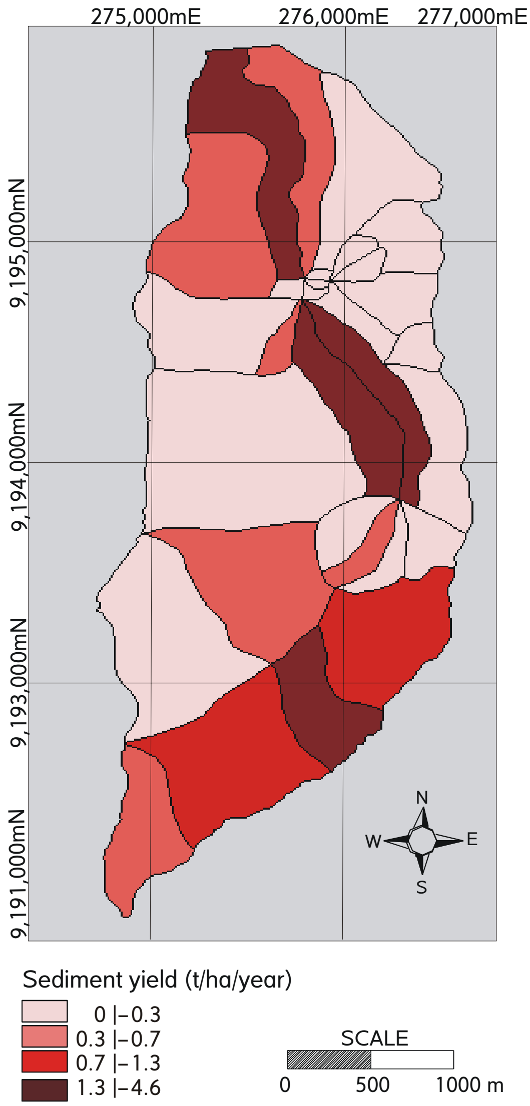


Figure 9. Estimation of sediment yield using Kineros model.

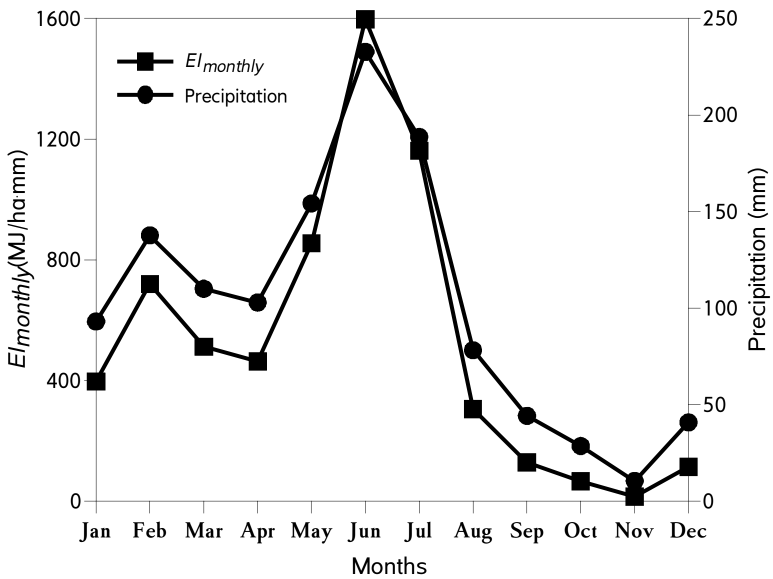


Figure 10. Rainfall erosivity and annual precipitation distribution in Guaraíra basin.

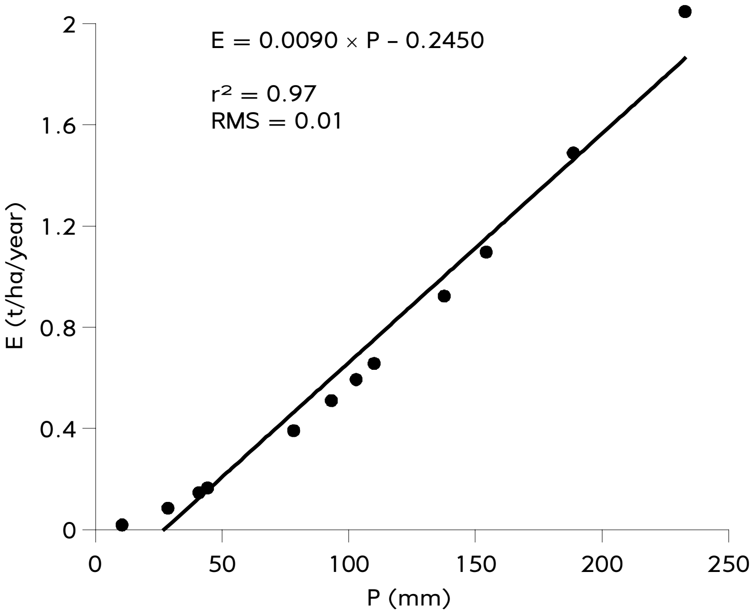


Figure 11. Relationship between mean annual precipitation (*P*) and soil loss computed by USLE (*E*).

4. CONCLUSIONS

In this paper, it was shown the integration of USLE and Kineros model with GIS in order to model the soil erosion potentialities in an ungauged basin named Guaraíra river experimental basin, located in northeastern Brazil. The simulation results have demonstrated the importance of detailed hydrologic information to successful erosion simulation.

Results obtained in this paper are preliminary, thus the models should be calibrated and verified by further field research. However, the study showed that GIS allows more effective and accurate applications of the USLE and Kineros models for basin with available spatial data. The soil loss results, simulated by the USLE, showed that these losses within the basin ranged from 0 to 3.2 ton/ha/year and that the period from May to July presents the greatest losses while the period from September to December shows the smallest ones. In the Kineros modeling, the sediment yield was estimated in the order of 0 to 4.6 ton/ha/year for the same period, and the susceptible areas to the erosion process are well determined. In general, the Guaraíra river experimental basin shows a soil loss potential which could be considered as very low for the studied period; however, special attention must be taken from May to July mainly on those areas indicated by this study.

5. ACKNOWLEDGEMENTS

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