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EVALUATION OF SOIL LOSS IN GUARAÍRA BASIN BY GIS AND REMOTE SENSING BASED MODEL

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Abstract: Environmental degradation, and specifically erosion, is a serious and extensive problem in many areas in Brazil. Prediction of runoff and erosion in ungauged basins is one of the most challenging tasks anywhere and it is 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. The erosion processes and land use in the Guaraíra River Experimental Basin, located in Paraíba state, Brazil, are evaluated using remote sensing and a runoff-erosion model. WEPP is a process-based continuous simulation erosion model that can be applied to hillslope profiles and small watersheds. WEPP erosion model have been compared in numerous studies to observed values for soil loss and sediment delivery from cropland plots, forest roads, irrigated lands and small watersheds. A number of different techniques for evaluating WEPP have been used, including one recently developed in which the ability of WEPP to accurately predict soil erosion can be compared to the accuracy of replicated plots to predict soil erosion. WEPP was calibrated with daily rainfall data from five rain gauges for the period of 2003 to 2005. The obtained results showed the susceptible areas to the erosion process within Guaraíra river basin, and that the mean sediment yield could be in the order of 3.0 ton/ha/year (in an area of 5.84 ha).

Keywords: Ungauged basin; sediment yield; hydrological model

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INTRODUCTION

The suspended sediment loads in a stream are the result of processes of soil erosion and transport within the drainage basin area. The estimation of sediment yield is a great help to managers and engineers, who lead to the proper investment in, and the design of hydraulic structures. Among available soil erosion and sediment yield models, the Universal Soil Loss Equation (USLE), the revised (RUSLE) and modified versions (MUSLE) are used in hydrology and environmental engineering for computing the amount of potential soil erosion and sediment yield (Sadeghi & Mizuyama, 2007).

Evaluation of the applicability of soil erosion models for a watershed is not easy. In contrast, sediment yield models are easier to be applied because the output data from these models can be determined at the watershed outlet.

Recently, it was developed by USDA-ARS a new generation of runoff-erosion models, titled Water Erosion Prediction Project (WEPP), which is regarded as one of a new generation of soil erosion models since it is process based and predicts soil erosion at spatial and temporal scales. WEPP model represents a new generation of erosion prediction technology based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics and erosion mechanics (Flanagan & Nearing., 1995). It is a natural resource model developed to replace the Universal Soil Loss Equation (USLE), fundamentally based on soil erosion prediction technology.

WEPP is applicable to both hillslopes and watersheds. An advantage of WEPP over other existing models such as the popular USLE (Wischmeier & Smith, 1978) is that soil loss is estimated spatially at a minimum of 100 points along a profile and deposition of sediment also can be predicted. In other words, soil loss and deposition on a complete continuous hillslope profile can be calculated, which is important in watershed modeling because it enables the sediment yield prediction in planes, channels and outlet.

In WEPP model the erosion can be divided into two components: rill and interrill erosion. Interrill erosion is caused by soil particles which are detached by raindrops and transported by overland flow. Rill erosion, however, is the detachment and transport of soil particles by concentrated flow: it is a function of the shear of the water flowing in the rill (Romero *et al.*, 2007).

Additionally, runoff and soil loss are predicted for every rainfall event, allowing detailed temporal analyses and development of probability distributions.

WEPP model has been used in different countries in the world (e.g., Risse *et al.*, 1992; Flanagan *et al.*, 2000; Pudasaini *et al.*, 2004; Santos & Silva., 2007). The present paper aims to evaluate the use of WEPP model for the studies in the Guaraíra River Experimental Basin, as an attempt to solve the problems concerning the lack of data in ungauged basin.

METHODOLOGY

Satellites and sensors applied in erosion research

A large number of earth observation satellites has orbited, and is orbiting our planet to provide frequent imagery of its surface and subsurface. Several of these satellites can potentially provide useful information for assessing erosion, although few of them have actually been used for this purpose (Vrieling, 2006). The sensors can be divided in those which measures reflection of sunlight in the visible and infrared part of the electromagnetic spectrum and thermal infrared radiance (optical systems), and those which actively transmit microwave pulses and recording the received signal (imaging radars).

Optical satellite systems have most frequently been applied in erosion research. The parts of the electromagnetic spectrum covered by these sensors include the visible and near-infrared ranging from 0.4 to 1.3 Am, the shortwave infrared between 1.3 and 3.0 Am, and the thermal infrared from 3.0 to 15.0 Am. **Table 1** shows sensor characteristics of the some systems.

Generation of the thematic layers

Landsat 7 data and collateral data have been used for preparation of various thematic maps as spatial data base. The GIS database created for the Guaraíra Basin focused on attributes and data necessary to run the WEPP model.

Thematic layers such as watershed boundary, drainage network, soil, and digital elevation data on 1:50 000 scale maps have been digitized, transferred and encoded as GIS layers in Geographic Information System. The process of computerization is a complex procedure involving manual data entry, map digitization or scanning followed by vectorization, editing, labeling

Table 1. Overview of satellite sensors applied in erosion research

Satellite	Sensor	Spatial resolution	Spectral bands
Landsat 1, 2, 3	MSS	80 m	4
Landsat 4, 5	TM	30 m	6
Landsat 7	ETM	30 m	6
SPOT 1, 2, 3	HRV	20 m	3
SPOT 4	HRVIR	20 m	4
IRS 1A, 1B	LISS-1	72.5 m	4
IRS 1C, 1D	PAN/LISS-3	23.5 m	3
Terra	ASTER	30 m	6
CBERS 2	CCD	120 m	4
NOAA/TIROS	AVHRR	1.1 km	5
Ikonos	Panchromatic	1 m	1
	Multispectral	4 m	4
QuickBird	Panchromatic	0.6 m	1
	Multispectral	2.4 m	4

cleaning of digital maps, topology building, and attachment of attribute data with maps. All encoded digital data, coverages, and model variables in the GIS were spatially organized with the same resolution and coordinate system.

Vegetal cover to remote sensing

Vegetation cover provides protection of the soil against erosion processes. In many regions of the world, vegetation cover shows a high temporal dynamics. Long-term dynamics can be related to land use conversions or gradual depletion of resources. Short-term dynamics are caused by rainfall characteristics, and by human activities such as crop harvesting or burning practices.

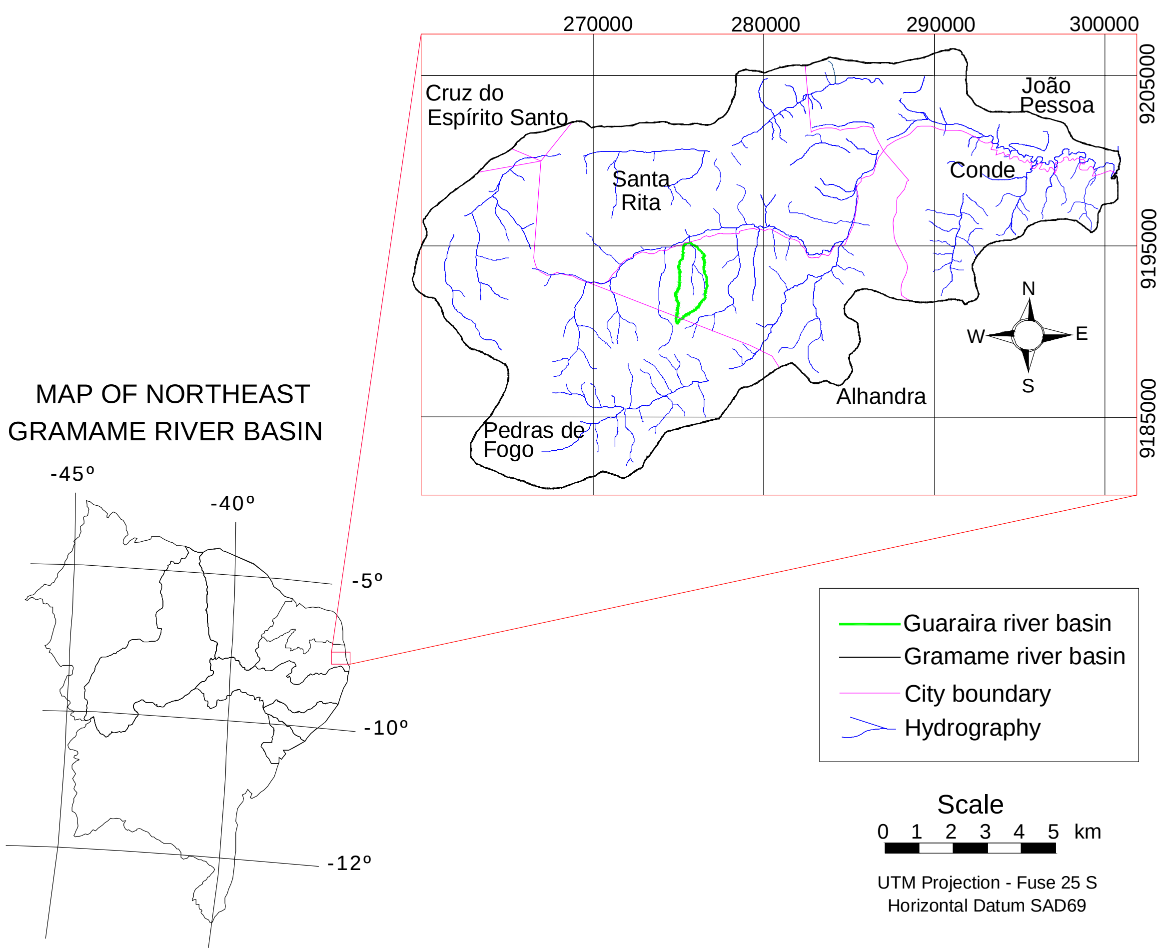
Many satellite remote sensing studies of soil erosion focus on the assessment of vegetation cover. These studies need to account somehow for the temporal variation, and consequently image timing is highly important, although not always sufficiently highlighted (Vrieling, 2006).

Depending on the purpose of the study, sometimes a mono-temporal assessment can be sufficient. However, especially for physically-based models careful matching of satellite imagery with rainy periods and crop development is required, which demands a time series of remote sensing images to account for seasonal variability (Cyr *et al.*, 1995).

Land use classification is often used to map vegetation types that differ in their effectiveness to protect the soil. After classification, a qualitative ranking of vegetation types is made. For erosion studies, land use classification has been performed with optical satellite systems through visual interpretation of image composites (e.g. Mati *et al.*, 2000; Khan *et al.*, 2001; Sharma & Singh, 1995) or automated classification approaches. The most common ones are unsupervised classification, in which pixels are grouped according to their relative spectral similarity (e.g. Jakubauskas *et al.*, 1992; Feoli *et al.*, 2002) and supervised classification, where pixels are allocated to predefined classes that are generally established based on ground-truth data (e.g. Millward & Mersey, 1999; Jürgens & Fander, 1993).

Study area

Guaraíra River Experimental Basin is located within Gramame river basin (**Fig. 1**), in northeastern Brazil. 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, 274,000 mE, and 277,000 mE.



Runoff-erosion model

The Water Erosion Prediction Project (WEPP) model was developed from 1985–1995, by the United States Departments of Agriculture and Interior to succeed the USLE and provide a “new generation of water erosion prediction technology”, and was publicly released in 1995 for application on cropland, rangeland, forestland, and other managed lands (Flanagan & Nearing, 1995). WEPP simulates the important physical processes that result in soil erosion by water.

The WEPP erosion model computes soil loss along a slope and sediment yield at the end of a hillslope, where interrill and rill erosion processes are considered. Interrill erosion is described as a process of soil detachment by raindrop impact, transport by shallow sheet flow, and sediment delivery to rill channels. Sediment delivery rate to rill flow areas is assumed to be proportional to the product of rainfall intensity and interrill runoff rate. Rill erosion is described as a function of the flow’s ability to detach sediment, sediment transport capacity, and the existing sediment load in the flow (Flanagan & Nearing, 1995).

The model contains a climate generator, simulates surface and subsurface hydrology, irrigation, plant growth, residue decomposition, effects of tillage, soil detachment by raindrop impact and flowing water, sediment transport and deposition. Original aims were to provide a hillslope, catchment and grid cell version of the model, though the latter has yet to be realized. For the purpose of the study we have concentrated solely upon use of the hillslope model.

The WEPP model was intended to replace the USLE family models and expand the capabilities for erosion prediction in a variety of landscapes and settings. It is a physically-based model with distributed parameters that can be used in either a single event or continuous time scale and calculates erosion from rills and interrills, assuming that detachment and deposition rates in rills are a function of the transport capacity.

Infiltration in WEPP is calculated using a solution of the Green-Ampt equation for unsteady rainfall developed by Chu (1978). It is essentially a two-stage process under steady rainfall. Initially, infiltration rate is equal to the rainfall application rate and after ponding occurs infiltration rate is calculated with the **Eq. (1)**:

$$f = K_e\left[1+\frac{N_s}{F}\right] \qquad (1)$$

where f is infiltration rate (mm/h), N_s is effective matric potential (mm), F is cumulative infiltration (mm), and K_e effective hydraulic conductivity (mm/h). Effective matric potential is given by **Eq. (2)**:

$$N_s = (\eta_e - \theta_i)\psi \qquad (2)$$

where η_e is available porosity, θ_i is soil water content, and ψ is average wetting front capillary potential. Available porosity is calculated as the difference between total porosity corrected for entrapped air and antecedent water content. Average wetting front capillary potential is determined with an equation developed by Rawls & Brakensiek (1983) which states that

$$\psi = 0.01e^{b} \qquad (3$$

where

$$b = 6.531 - 7.33\eta_e + 15.8C_l^2 + 3.81\,\eta_e^2 + 3.4C_lS_a - 4.98S_a\,\eta_e + 16.1S_a^2\,\eta_e^2 + 16C_l\,\eta_e^2 - 14S_a^2C_l - 34.8C_l^2\eta_e - 8S_a^2\eta_e \qquad (4)$$

where S_a and C_l are decimal amounts of sand and clay.

Soil erosion in hillslope is represented as two components in the WEPP model: soil particle detached by raindrop and transported by thin sheet flow, known as interrill erosion component and soil particle detached by shear stress and transported by concentrated flow, known as rill erosion components. The steady state sediment continuity equation used to estimate net detachment in the hillslope is expressed as (Foster *et al.*, 1995):

$$\frac{dG}{dx} = D_f + D_i \qquad (5)$$

where G is sediment load (kg/m²/s) at distance x from the origin of hillslope, x is distance down slope (m), D_i is interrill sediment delivery rate to rill (kg/m²/s) and D_f is rill detachment rate (kg/m²/s). Interrill erosion function of above equation (D_i) is given as (Foster *et al.*, 1995):

$$D_i = K_{iadj} I_e \sigma_{ir} SDR_{RR} F_{nozzle}\left(\frac{R_s}{w}\right) \qquad (6)$$

where K_{iadj} is adjusted interrill erodibility (kg s/m^4), I_e is effective rainfall intensity (mm/h), σ_{ir} is interrill runoff rate (mm/h), SDR_{RR} is interrill sediment delivery ratio, F_{nozzle} is the adjustment factor for sprinkler irrigation nozzle impact energy variation, R_s is rill spacing (m), w is width of rill (m) and rill erosion function (D_f) is given as (Foster *et al.*, 1995):

$$D_f = K_{radj}\left(\tau_f - \tau_{cadj}\right)\left(1-\frac{G}{T_c}\right) \qquad (7)$$

where K_{radj} is adjusted soil erodibility parameter (s/m), τ_f is flow shear stress (kg/m s²), τ_{cadj} is adjusted critical shear stress of the rill surface (kg/m s²) and T_c is sediment transport capacity of the rill flow (kg/m s) which is given by the following relation (Foster *et al.*, 1995; Huang & Bradford, 1993)

$$T_c = K_{tr} q_w s \tag{8}$$

where K_{tr} is constant parameter, q_w is flow discharge per unit width (m²/s) and s is slope (%).

The deposition equation is given as (Foster & Meyer, 1972; Foster *et al.*, 1995):

$$\frac{dG}{dx} = \frac{\beta_r V_f}{q_w}\left(T_c - G\right) + D_i \tag{9}$$

where V_f is effective fall velocity of the sediment (m/s) and β_r is raindrop induced turbulence coefficient (0–1). Parameters in **Eqs 5** and **9** are normalized with corresponding parameter values of uniform hillslope condition. The equations are then solved to find soil erosion and deposition at particular point of interest at distance x from the top of the hillslope at desired time interval (Pudasaini *et al.*, 2004).

The soil physical and chemical property analysis were performed to determine important soil properties as shown in **Table 2**.

The uncalibrated WEPP model parameters were estimated from physical observations or from text-book values. Particle size distribution and organic matter were obtained in Cavalcante (2005). The observed interrill erodibility (K_i) values were calculated using the **Eq. 10**.

$$D_i = K_i I^2 S_f \tag{10}$$

where D_i is interrill erosion rate (kg/m^2 s), K_i interrill erodibility (kg/s m^4), I the rainfall intensity (m/s) and S_f slope factor (dimensionless = 1.05 – $0.85e^{-0.85\sin\theta}$, where θ is expressed in degrees). At each of the sites K_i was also estimated using the equation used by the WEPP model:

$$K_i = 2\ 728\ 000 + 19\ 210\ 000 vfs \tag{11}$$

where *vfs* is very fine sand fraction.

Table 2. Soil properties used in the WEPP simulation

Soil properties	Values
Coarse sand, % weight	6.8
Fine sand, % weight	32
Clay, % weight	35
Organic matter, % weight	1.5
Albedo	0.3
Initial soil saturation	0.75
Interrill erodibility (kg/s m^4)	8.8–10^6
Rill erodibility (s/m)	1.4–10^2
Critical shear (N/m^2)	2.4
K_h of surface soil (m/s)	0.8

Whereas WEPP allows the user to input up to ten soil layers and uses these layers in the water balance component of the model, the infiltration routine uses a single-layer approach. The harmonic mean of the soil properties in the upper 100 cm is used to represent the effects of multilayer systems. Effective porosity, soil water content, and wetting front capillary potential are all calculated based on the mean of these soil properties.

Sensitivity analysis on the hydrologic component of WEPP has indicated that predicted runoff amounts are most sensitive to rainfall parameters (depth, duration, and intensity) and hydraulic conductivity (Nearing *et al.*, 1990).

Others studies concluded that proper determination of hydraulic conductivity is critical to obtaining reliable estimates of runoff from WEPP (Van der Sweep, 1992; Risse *et al.*, 1992; Risse, 1995). Current versions of WEPP allow for two methods of hydraulic conductivity input. In the first method, the user inputs an average effective value of hydraulic conductivity that remains constant throughout the simulation.

Nearing *et al.* (1996) developed a procedure for estimating these average effective values based on soil properties, and Risse (1995) showed that this method produced reliable event estimates of runoff on natural runoff plots at 11 locations. The second method allows for temporal variation of hydraulic conductivity. In it, the user inputs a 'baseline' value of hydraulic conductivity that is then adjusted to account for temporal changes in effective hydraulic conductivity.

RESULTS AND DISCUSSION

In the basin, four raingauges and one climatologic station were installed (**Table 3**) with data range of 2003–2006. WEPP requires detailed breakpoint data for parameters such as rainfall in order to characterize the shape of the daily hyetograph and daily input data for all other climate variables.

In this example, a 3-year time series generated from climate data for the microbasin has been used as model input, and the soil data were obtained from SUDENE (1987). This was collected from soil survey maps at 1:10 000 scale for the whole basin. The soil data were inserted to the WEPP model in its hillslope form either directly as in the case of textural parameters or organic matter content, for example, or indirectly via regression based relationships as in the case of the erodibility parameters, for all combinations of soil, slope and land use needed.

Table 3. Description of the used rain gauges

Type	Longitude (m)	Latitude (m)	Period
Rain gauge 1	275 402	9 194 296	2003–2006
Rain gauge 2	275 788	9 192 719	2003–2006
Rain gauge 3	275 608	9 190 997	2003–2006
Rain gauge 4	276 824	9 192 848	2003–2006

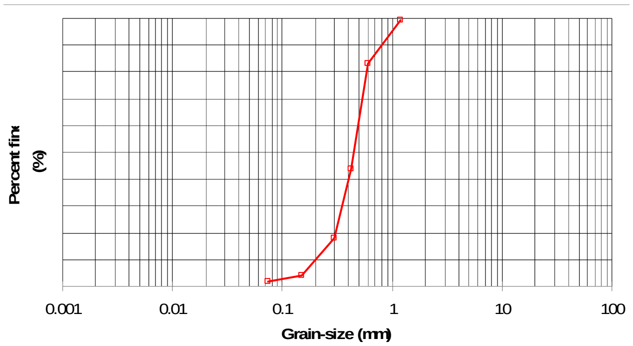


Fig. 2 Grain-size distribution curve for the bed material.

Three locations within the main water stream were selected for the soil samples, whose results are shown in **Fig. 2**, and the **Table 4** presents the grain-size distribution curves for each sample. The mean sediment diameter (d_{50}) varied between 0.45 and 0.71 mm.

The available images for the study were obtained by sensor ETM, of Landsat 7 satellite, of the orbit 214 and Point 65, year 2007. The color composites generated from bands R1G4B3 were visually interpreted through on screen digitizing. The image was georeferenced in GIS software, establishing a relationship between the coordinates of the image and the acquired coordinates in the field, in order to get a larger precision for the image interpretation. The image was transformed in UTM coordinate system by the average of 1:25 000 scaled standard topographic maps by using the first order polinomial and nearest neighbour resampling method.

The supervised classification technique using Maximum Likelihood was applied to classify the Landsat images of the microbasin. The aim of the image classification process is converting image data into thematic data. **Fig. 3** presents the spectral interpretation and analysis of the geo-objects. Seven main types of land use classes were identified within the basin: sugarcane, roads, grass, high *capoeira*, low *capoeira*, exposed soil, pineapple culture, and grass.

Model simulation

For simulations, the WEPP watershed version was used. WEPP required climate, slope, management and soil input files, which were assembled using the gathered information. For the climate input file, breakpoint data (precipitation) and daily averages (temperature) were used.

Table 4. Soil samples to determine the grain-size distribution curves

Grain -size (mm)	Sample 1 (%)		Sample 2 (%)		Sample 3 (%)	
	coarser	finer	coarser	finer	coarser	finer
1.20	0.6	99.4	10.7	89.3	3.3	96.7
0.60	16.8	83.2	60.2	39.8	41.0	58.9
0.42	56.3	43.7	87.5	12.5	79.4	20.6
0.30	81.8	18.1	95.6	4.4	93.3	6.6
0.15	95.9	4.1	99.2	0.7	99.9	0.1
0.074	98.3	1.7	99.7	0.3	100.0	0.0

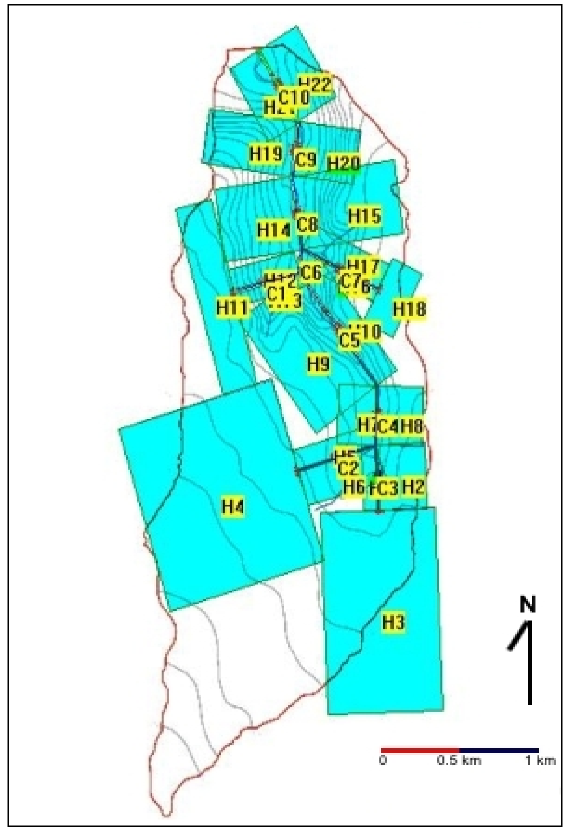


Fig. 4 Discretization of Guaraira river experimental basin for the WEPP model.

Sub-division of hillslopes were carried out by overlaying different thematic layers such as slope coverage, soil coverage and land use coverage, so that each hillslope is characterized by topography, soil, and land use. Parameters of the watershed such as overland and channel slope, channel length and hillslope length were extracted from different thematic layers (i.e. contour, slope and drainage map). The number of channels identified for each sub-watershed is presented in **Fig. 2** and **Table 5**

Crop characteristics required for hydrological calculation were taken from the WEPP crop database and supplemented with site-specific data. Soil erodibilities were calculated according to the WEPP recommendation.

Based on the field layout and topography, the watershed area was divided into 22 sub-basins, which were connected through 10 channels. For each sub-basin, a representative hillslope was selected and then, if necessary, it was divided into different overland flow elements according to the existing soil-vegetation condition (**Fig. 3**).

Table 5 presents the simulation results for each basin channel element, and **Table 6** shows the simulation results for each basin plane element. The predicted soil loss values using WEPP model were reasonably good, based on the range of the observed values as published by Santos & Silva (2007) and Silva *et al.* (2007) to the

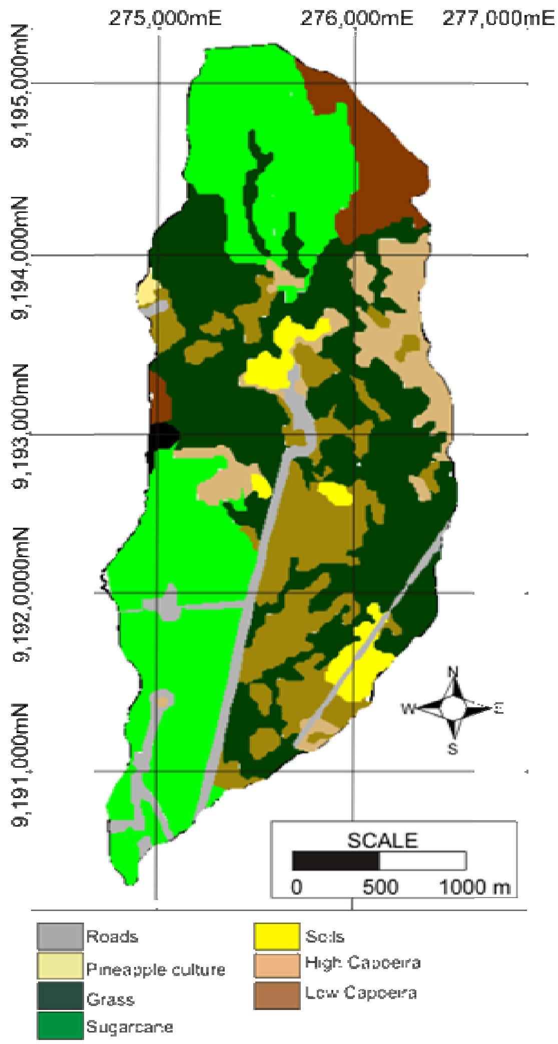


Fig. 3 Land use in Guaraíra River Experimental Basin.

Table 5. Channel characteristics

Channel	Runoff (m^3/year × 10^5)	Sediment yield (ton/year)	Contributing	
			channel	hillslope
C1	0.5	137	6	11, 12, 13
C2	1.8	353	4	4, 5, 6
C3	1.4	250	4	1, 2, 3
C4	3.6	792	5	7, 8
C5	4.4	1,314	6	9, 10
C6	4.9	1,536	8	-
C7	0.3	126	6	16, 17, 18
C8	6.1	2,024	9	14, 15
C9	6.6	2,297	10	19, 20
C10	7.0	2,655	-	21, 22

Further, the model parameters could be optimized using a genetic algorithm as presented by Duan *et al.* (1992), Sorooshian *et al.* (1993), and Santos *et al.* (2003).

The obtained results showed the susceptible areas to the erosion process within Guaraíra River Basin, and that the mean sediment yield could be in the order of 21 t/ha/year (in an area of 574 ha). The results also showed that the computed soil losses was considered moderate based on the four classes of basin soil loss as proposed by FAO (1967) in ton year/ha: (a) < 10 = very low; (b) 10–50 = moderate; (c) 50–200 = high; and (d) 50–120 = very high.

The results demonstrate that reliable assessment of the available sediment yield models requires accurate sediment data collection which is most confidently obtained through development of sediment graphs. Moreover, preparation of input data for the model requirements may also lead to better and reliable judgment.

Table 6. Simulation results for each sub-basin

Hillslopes	Element area (ha)	Runoff volumes (m^3 year × 10^4)	Soil losses (ton year)	Sediment yield (ton year)
H1	4.13	0.6	1.13	0.76
H2	14.47	1.7	14.00	2.65
H3	108.29	12.0	101.23	19.79
H4	142.32	16.0	133.49	26.05
H5	7.18	0.8	7.34	1.32
H6	13.4	1.5	13.09	2.45
H7	10.08	1.6	2.77	1.85
H8	12.48	2.0	3.43	2.29
H9	48.16	5.4	45.87	8.81
H10	14.89	1.7	14.77	2.73
H11	32.25	3.7	31.46	5.90
H12	6.58	1.0	1.81	1.21
H13	4.21	0.5	4.30	0.77
H14	26.56	4.2	7.30	4.86
H15	34.78	3.9	32.87	6.37
H16	4.46	5.2	4.56	0.81
H17	10.44	1.2	10.34	1.92
H18	10.77	1.7	2.95	1.97
H19	22.89	2.6	21.70	4.20
H20	15.44	2.5	4.24	2.83
H21	12.87	2.0	3.53	2.35

Conclusion and recommendations

The present research was conducted in the Guaraíra River Experimental Basin in Brazil, located in northeastern Brazil to assess the applicability of the well-known WEPP model, remote sensing and GIS techniques for sediment yield prediction and the basin land use.

The use of geoinformation techniques was very successful in addressing the study objectives. Through these techniques, it was possible to identify and map the erosion areas and classify the land cover types within the studied area. Therefore, this study showed that remote sensing and hydrologic modeling could be a useful tool for identification and analysis of soil loss and runoff in the Guaraíra river basin.

The soil loss results, simulated by the WEPP model, showed that these losses within the basin could be considered moderate, around 21 ton/year ha, and that the planes H3 and H4 presented the largest losses (approximately 100 t/year ha).

The presented simulation procedure are according to the comments of Lakshmi (2004): the satellite remote sensing could be used to address to (a) advance the ability of hydrologists worldwide to predict the fluxes of water and associated constituents from ungauged basins, along with estimates of the uncertainty of predictions; (b) predict the fluxes of water by using vegetation, surface air temperatures as inputs to hydrological models and surface temperature and soil moisture as validation variables in the intermediate step to calculation of overland flow and stream flow; (c) advance the knowledge and understanding of climatic and landscape controls on hydrological processes to constrain the uncertainty in hydrologic predictions, since the spatial mapping of land surface areas helps to identify regions of saturation/high vegetation content along with surface flow characteristics, infiltration dominated and/or runoff dominated; and (c) advance the scientific foundations of hydrology, and provide a scientific basis for sustainable river basin management.

Future estimation of water resources requires an accurate prediction of sources of surface and subsurface water, both of which can be mapped in space with the use of satellite remote sensing. Tracking fresh water estimates from space is a challenging problem that can be solved by a combination of satellite sensors and existing gauge networks (Lakshmi, 2004; Vrieling, 2006).

Indeed, prediction of ungauged water resources is fast becoming a well-defined and important problem in satellite hydrology.

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