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Soil erosion prediction in the Grande River Basin, Brazil using distributed modeling

S. Beskow [a,b,*], C.R. Mello [b], L.D. Norton [c], N. Curi [d], M.R. Viola [b], J.C. Avanzi [a,d]

[a] National Soil Erosion Research Laboratory, 275 South Russell Street, Purdue University, 47907-2077, West Lafayette, IN, USA
[b] Department of Agricultural Engineering, Federal University of Lavras, C.P. 3037, 37200-000, Lavras, MG, Brazil
[c] USDA-ARS National Soil Erosion Research Laboratory, 275 South Russell Street, Purdue University, 47907-2077, West Lafayette, IN, USA
[d] Department of Soil Science, Federal University of Lavras, C.P. 3037, 37200-000, Lavras, MG, Brazil

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ABSTRACT

Mapping and assessment of erosion risk is an important tool for planning of natural resources management, allowing researchers to modify land-use properly and implement management strategies more sustainable in the long-term. The Grande River Basin (GRB), located in Minas Gerais State, is one of the Planning Units for Management of Water Resources (UPGRH) and is divided into seven smaller units of UPGRH. GD1 is one of them that is essential for the future development of Minas Gerais State due to its high water yield capacity and potential for electric energy production. The objective of this study is to apply the Universal Soil Loss Equation (USLE) with GIS PCRaster in order to estimate potential soil loss from the Grande River Basin upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir (GD1), allowing identification of the susceptible areas to water erosion and estimate of the sediment delivery ratio for the adoption of land management so that further soil loss can be minimized. For the USLE model, the following factors were used: rainfall–runoff erosivity (*R*), erodibility (*K*), topographic (LS), cover-management (*C*) and support practice (*P*). The Fournier Index was applied to estimate *R* for the basin using six pluviometric stations. Maps of the *K*, *C*, LS and *P* factors were derived from the digital elevation model (DEM), and soil and land-use maps, taking into account information available in the literature. In order to validate the simulation process, Sediment Delivery Ratio (SDR) was estimated, which is based on transported sediment (TS) to basin outlet and mean soil loss in the basin (MSL). The SDR calculation included data (total solids in the water and respective discharge) between 1996 and 2003 which were measured at a gauging station located on the Grande River and a daily flow data set was obtained from the Brazilian National Water Agency (ANA). It was possible to validate the erosion process based on the USLE and SDR application for the basin conditions, since absolute errors of estimate were low. The major area of the basin (about 53%) had an average annual soil loss of less than 5 t ha^{-1} yr^{-1}. With the results obtained we were able to conclude that 49% of the overall basin presently has soil loss greater than the tolerable rate, thus indicating that there are zones where the erosion process is critical, meaning that both management and land-use have not been used appropriately in these areas of the basin. The methodology applied showed acceptable precision and allowed identification of the most susceptible areas to water erosion, constituting an important predictive tool for soil and environmental management in this region, which is highly relevant for prediction of varying development scenarios for Minas Gerais State due to its hydroelectric energy potential. This approach can be applied to other areas for simple, reliable identification of critical areas of soil erosion in watersheds.
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1. Introduction

Water erosion is one of the most significant environmental degradation processes, and is made up of rill and interrill erosion. Interrill erosion occurs when soil particles are detached by raindrops and transported by shallow overland flow, whereas, rill erosion is the detachment and transport of soil particles by concentrated flow. This detached soil is then transported and delivered as sediment downstream. In areas where the erosion process is advanced, a reduction of soil productivity can occur and the transported sediments, nutrients and agrochemicals contaminate and fill up water bodies.

Minas Gerais is the second most important Brazilian State in terms of economic development and population (second in Brazilian GDP and greater than 18,000,000 inhabitants). The State has an area of 586,000 km^2 and is divided into Planning Units for Management of Water Resources, known as "UPGRHS" which are defined according to the main watershed, e.g. Grande River, São Francisco River, Doce River, Jequitinhonha River and Paraíba do Sul River. These UPGRHS have been extremely important in establishing strategies for development according to the peculiarities of the respective watershed.

* Corresponding author. Department of Agricultural Engineering, Federal University of Lavras, C.P. 3037, 37200-000, Lavras, MG, Brazil.
E-mail address: samuel_beskow@yahoo.com.br (S. Beskow).

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The Grande River Basin is divided into seven smaller UPGRHS, identified by acronym GD. GD1 is one of them, representing a headwater basin with both a high water yield capacity and potential for electric energy production. These are fundamental for the future development of Minas Gerais State. In this basin, the Grande and Aiuruoca Rivers are the main tributaries which feed into the reservoir of the Itutinga/Camargos hydroelectric plant. Hydroelectric potential of the GD1 is visible since other stretches in the Grande River have been studied to design new hydroelectric power plants. Within the scope of this discussion, environmental management of GD1 presents notable importance for Minas Gerais State and deserves greater attention, especially for the current and changing land-use which is mainly characterized by forest, agriculture and livestock.

According to De Roo et al. (1996), quantitative results related to the soil loss rates and conservation strategies are not usually available for areas with erosion problems. However, quantitative erosion assessments and possible strategies for management of basins are necessary for both local planning and governmental agencies associated with sustainable development. Thus, erosion simulation models, especially distributed models, are useful to evaluate different strategies for land-use and soil management improvement in these watersheds.

Several physically-based models have been developed in order to quantify erosion in basins, such as WEPP (Flanagan and Nearing, 1995; Flanagan et al., 2007), LISEM (De Roo et al., 1996), and SWAT (Arnold et al., 1998; Gassman et al., 2007).

The WEPP model (Water Erosion Prediction Project) is capable of simulating climate, plant growth and residue decomposition, tillage, infiltration, water balance, surface runoff, soil loss, deposition, and sediment delivery for different time steps (Flanagan and Nearing, 1995). In order to easily deal with data in WEPP, a Graphical User Interface was developed for the WEPP model, which is called GeoWEPP (Renschler, 2003, 2008). An advantage of the GeoWEPP is that it allows a user to process Digital Elevation Models (DEM), orthophotos, soils surveys, and land use maps (Yüksel et al., 2008).

The Limburg Soil Erosion Model (LISEM) is a physically based model that was written in a raster Geographical Information System, and allows simulating the hydrology and sediment transport during and immediately after a single rainfall event in catchments (Jetten, 2002). According to De Roo et al. (1996), the processes incorporated in the LISEM model are rainfall, interception, surface storage in micro-depressions, infiltration, vertical movement of water in the soil, overland flow, channel flow, detachment by rainfall and throughfall, detachment by overland flow, and transport capacity of the flow. In addition, De Roo et al. (1996) point out that it is able to simulate the influence of machine tracks and small paved roads on the hydrological and soil erosion processes. As a disadvantage, Jetten (2002) reported that the LISEM model has been used so far only in small catchments.

The Soil and Water Assessment Tool (SWAT) is a physically based, continuous-time model and was developed to simulate the impact of management on water, sediment, and agricultural chemical yields at a basin-scale (Gassman et al., 2007). The same researchers report that the main model components are weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. An ArcGIS–ArcView extension, named as ArcSWAT, was created for the SWAT model (SWAT, 2008).

The three models discussed above have the following disadvantages: (a) need extensive data sets as input and many calibration parameters; (b) require either complex laboratory analyses or hard and expensive field data collection, which may be unfeasible to use in many developing countries; and (c) in spite of having some calibration parameters, the models (except SWAT) don't have an optimization method embedded in the software. Some strength of these models can be emphasized: (a) they are physically based models, basic processes are incorporated in them; and (b) they take into account spatial variability of input and output, thus better representing the real world.

The Universal Soil Loss Equation (USLE) is the simplest model for erosion prediction, which estimates long-term average annual soil loss with acceptable accuracy. The USLE estimates soil loss per unit of area and takes into account the following parameters: rainfall-runoff erosivity, soil erodibility, topography, cover-management and support practices (Wischmeier and Smith, 1978). Ozcan et al. (2008) pointed out some limitations of the USLE as a prediction model, because this equation predicts the total soil loss (rill erosion and interrill erosion) without differentiating between each of these components. Furthermore, it does not include soil loss as a result of gully formation nor estimates sediment deposition in specific areas. An additional limitation of the USLE is that it requires long-term data to develop the parameters for climate (R factor) and erodibility (K) factor for locations and soils outside the original dataset. In developing countries in particular, these long-term erosion plot data are often not available. Although these are negative aspects, the USLE has been used in simulations on basins with varying drainage area (Jain et al., 2001; Fistikoglu and Harmancioglu, 2002; Onyando et al., 2005; Erdogan et al., 2007; Pandey et al., 2007; Dabral et al., 2008; Ozcan et al., 2008), so that researchers can compare simulated soil loss with acceptable values for the same kinds of soil.

For application of the USLE to simulate soil erosion distribution on basins, it is necessary to utilize mapping and interpolation techniques in order to create a suitable database for soil erosion simulation. The database must include all necessary input for the model taking into account homogeneous cells as small as possible, thus allowing erosion to be characterized with a good resolution. Presently, USLE application with the support of Geographical Information System (GIS) and geostatistical techniques has received special attention of researchers, mainly in developing countries, such as Turkey, India and Thailand (Bhattarai and Dutta, 2007; Irvem et al., 2007; Pandey et al., 2007; Ozcan et al., 2008). All of these authors have demonstrated relevant potential of this approach as a soil management tool.

As reported by De Roo and Jetten (1999), the main reason for using a GIS is that the erosion process varies spatially and, thus, grid cells must be used so that this spatial variation can be taken into account. According to the same researchers, another important consideration is the amount of data necessary for a great quantity of cells that is required for accurate representation of the basin. Since it is unfeasible to input data manually, GIS can be used to gather and access databases.

The PCRaster Program is a dynamic and distributed environmental modeling system (van Deursen, 1995; Wesseling et al., 1996), which provides an excellent GIS modeling environment. Dynamic modeling language is a powerful tool for development of environmental models and it can be modified for a specific situation. For implementation of the USLE in a GIS framework, the PCRaster GIS Program has been used by Verbist et al. (2002).

The objective of this study is to apply the Universal Soil Loss Equation (USLE) with GIS PCRaster in order to estimate potential soil loss from the Grande River Basin upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir (GD1), allowing identification of the susceptible areas to water erosion and estimate of the sediment delivery ratio for the adoption of land management so that further soil loss can be minimized. This basin is strategic for future development of the Minas Gerais State, in southeast Brazil, due to its capacity for electric energy generation, with more than 200 MW of power installed which must also be protected.

2. Material and methods

2.1. Location and description of studied area

The Grande River Basin, upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir–GD1, has the following characteristics (Araújo, 2006): (a) it is located in southern Minas Gerais State

(southeast Brazil) between parallels 21°14′S and 22°22′S and meridians 43°53′W and 44°44′W, covering about 6273 km^2 (Fig. 1); (b) according to the Köppen climate classification, Cwa occurs in major part of the basin and Cwb in regions around Mantiqueira Mountain which is over 2000 m above sea level; and (c) the temporal distribution of precipitation has two different seasons—a hot and rainy summer (85% of precipitation) and dry and cold winter with the overall basin receiving the influence of cold fronts and frost formation. Average annual precipitation ranges from 1600 mm to over 2300 mm near Mantiqueira Mountain.

2.2. PCRaster GIS environmental simulation

PCRaster has been developed at Utrecht University, The Netherlands, and now is supported by PCRaster Environmental Software Company (Jetten and De Jong, 2006). It is a dynamic modeling system for distributed simulation (raster format) and it is a free GIS which consists of several tools for storage, analysis and access of geographical data. The main advantages of PCRaster are the flexibility, power and the possibility of having an open and extendable library; in other words, programmers can use any mathematical expressions already known or even create their own routines without having the mastery of a conventional programming language.

This GIS consists of a modular structure with six main modules (Jetten and De Jong, 2006): (a) "PCRCalc", which is a PCRaster calculator for functions and operations; (b) "Display", a two-dimensional visualization software; (c) "Aguila", a three-dimensional visualization software; (d) "Timeplot", a graphical tool for time series data; (e) Algorithm to convert data; and (f) "Mapedit" is designed for editing of maps in raster format. In addition, the PCRaster package has two extra modules (Jetten and De Jong, 2006): (a) "GStat" for geostatistical modeling, kriging, conditional simulation and generation of random numbers; and (b) "ADAM" to estimate errors of propagation in GIS.

The main applications of the PCRaster are associated with environmental modeling, such as geography, hydrology, ecology, and soil science. Many research projects have been based on the PCRaster programming language, namely: LISFLOOD (De Roo et al., 2006), EUROSEM (van Dijck, 2000), LISEM (De Roo et al., 1996), etc.

2.3. The Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) was used to evaluate the potential of water erosion on the Grande River Basin using a database constructed over the last 10 years. This model was described by Wischmeier and Smith (1978) and can be expressed by the following equation:

$$A = R \times K \times \mathrm{LS} \times C \times P \quad (1)$$

where A is the average annual soil loss per unit of area (t ha^{-1} yr^{-1}), R is the rainfall–runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), LS is the topographic factor (dimensionless) 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).

The PCRaster GIS programming language was applied to implement the USLE model based on the spatial data for the Grande River Basin, with 30 m-resolution maps. The following will describe how data has been collected for mapping of the parameters in Eq. (1).

2.3.1. Rainfall–runoff erosivity factor (R)

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

For estimation of the monthly rainfall–runoff erosivity, the equation developed by Renard and Freimund (1994), which is also

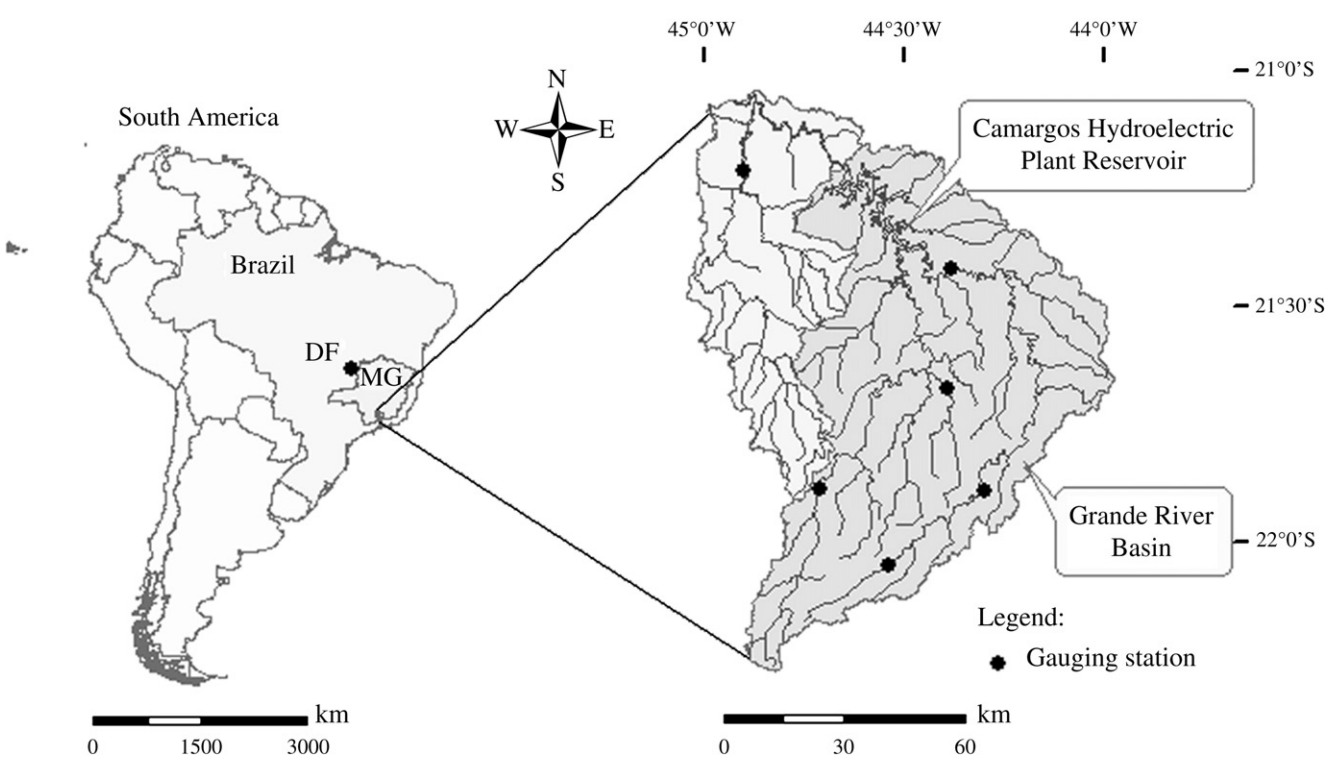

Fig. 1. Location of the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir.

Table 1
Mean annual rainfall-runoff erosivity factor (R) for the pluviometric stations applied in this study.

No.	Pluviometric station	Latitude	Longitude	R (MJ mm ha^{-1} h^{-1})
1	Bocaina de Minas	−22° 07′ 40″	−44° 24′ 30″	8531.7
2	Aiuruoca	−21° 58′ 47″	−44° 36′ 09″	7802.8
3	Bom Jardim de Minas	−21° 56′ 52″	−44° 11′ 05″	6947.1
4	Andrelândia	−21° 44′ 19″	−44° 18′ 20″	7189.5
5	Madre de Deus	−21° 29′ 03″	−44° 19′ 36″	7503.2
6	Itumirim	−21° 19′ 16″	−44° 52′ 23″	7625.9

known as Fournier Index, was applied. This Index has been used widely in several studies of soil loss and erosivity mapping, as in Irvem et al. (2007), Mello et al. (2007) and Pandey et al. (2007).

$$\mathrm{EI}_i = \frac{125.92 \times \left(\frac{r_i^2}{P}\right)^{0.603} + 111.173 \times \left(\frac{r_i^2}{P}\right)^{0.691} + 68.73 \times \left(\frac{r_i^2}{P}\right)^{0.841}}{3} \tag{2}$$

where EI_i is the average monthly erosivity (MJ mm ha^{-1} h^{-1} month^{-1}) for month i, r is the average monthly rainfall (mm) for month i, and P is the mean annual precipitation (mm). The annual rainfall-runoff erosivity factor is obtained by summing the respective monthly values. The daily precipitation data for each of the pluviometric stations used were obtained from the Brazilian National Water Agency (ANA).

The Thiessen Polygon Methodology was employed in order to determine the spatial mean of rainfall–runoff erosivity factor for the basin, using six pluviometric stations (Table 1), distributed throughout the basin as shown in Fig. 1, considering the area of influence of each one using GIS tools.

Table 2
Soil classification on the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir and soil erodibility (K) values and their respective sources.

No.	Soil[1]	K (t h MJ^{-1} mm^{-1})	Source
1	CXbd	0.024	Silva (2003)
2	LVd	0.017	Cabral et al. (2005)
3	GXbd	0.0362	Batalha (2006)
4	RLd	0.050	Cabral et al. (2005)
5	LVAd	0.010	Silva (1997)
6	LAd	0.057	Mannigel et al. (2002)
7	RYbd	0.0249	Batalha (2006)
8	CHd	0.0433	Mannigel et al. (2002)

[1]CXbd: Dystrophic Tb haplic cambisol; LVd: Typic dystrophic red latosol; GXbd: Dystrophic Tb haplic gleisol; RLd: Dystrophic litholic neosol; LVAd: Typic dystrophic yellow-red latosol; LAd: Dystrophic yellow latosol; RYbd: Dystrophic Tb fluvic neosol; CHd: Dystrophic haplic cambisol.

2.3.2. Soil erodibility (K)

Erodibility means intrinsic susceptibility of soil to water erosion and depends on many pedologic factors, such as mineralogical, chemical, morphological and physical attributes (Pérez-Rodríguez et al., 2007). The K factor represents the rate of soil loss per unit of rainfall erosion index for a specific soil, for a clean-tilled fallow condition at 9% slope (Renard et al., 1997). Values for this factor can be determined through experiments carried out in field plots; however, field trials for estimating the K factor are expensive and time-consuming, therefore, it is normally estimated from a nomograph.

The soil map used in this study was adapted from Araújo (2006) (Fig. 2), who mapped soils in the basin for hydrological studies, taking into account similarity among soil classes and respective properties. The K-factor map was developed based on values published from several studies carried out in different areas of Brazil for the same soil

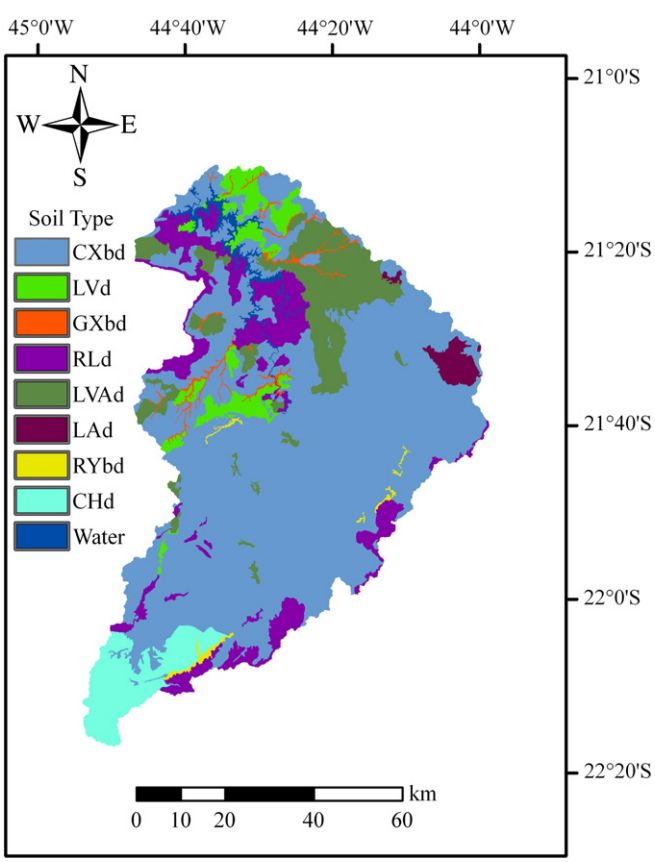

Fig. 2. Soil map of the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir.

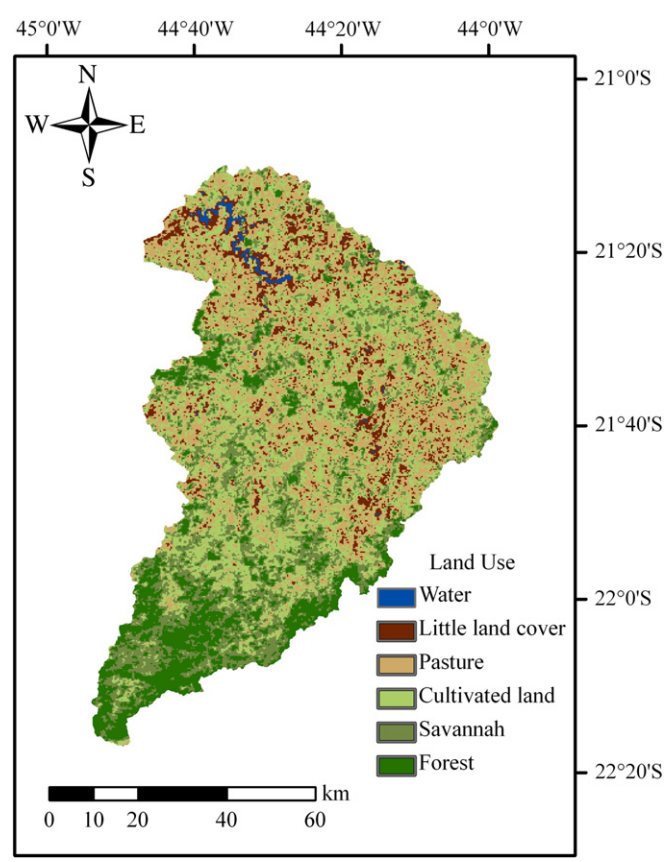

Fig. 3. Current land-use map of the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir.

Table 3
Values of the cover-management factor (*C*) used from literature sources.

No.	Land-use	*C*	Source
1	Little land cover	0.404	Ruhoff et al. (2006)
2	Pasture	0.0075	Oliveira et al. (2007)
3	Cultivated land	0.290	Ruhoff et al. (2006)
4	Savannah	0.001	Santos et al. (1999)
5	Forest	0.01	Ruhoff et al. (2006)

types as found in this work (Silva, 1997; Mannigel et al., 2002; Silva, 2003; Cabral et al., 2005; Batalha, 2006). The *K* values for each soil type of this basin can be found in Table 2.

2.3.3. Cover-management factor (C)

The *C* factor is related to the land-use and is a reduction factor to soil erosion vulnerability. This factor represents the ratio of soil loss from an area with a given cover and management to that from an identical area in tilled continuous fallow on the same soil and slope. This is an important factor in USLE, since it represents the conditions that can be easily changed to reduce erosion. Therefore, it is very important to have good knowledge concerning land-use in the basin to generate reliable *C* factor values.

In this work, satellite images (ETM$^+$ Landsat sensor) of 2003 were used to classify land cover according to supervised classification method of Maximum Likelihood (van der Meer et al., 2006). For development of this map, training samples were selected for six land cover categories (Fig. 3): water, little land cover, pasture, cultivated land, savannah and forest. The *C*-factor map was developed based on values published from several studies carried out in different areas of Brazil with the same land-use as in this study (Santos et al., 1999; Ruhoff et al., 2006; Oliveira et al., 2007). The *C* values for each land use of this basin can be found in the Table 3.

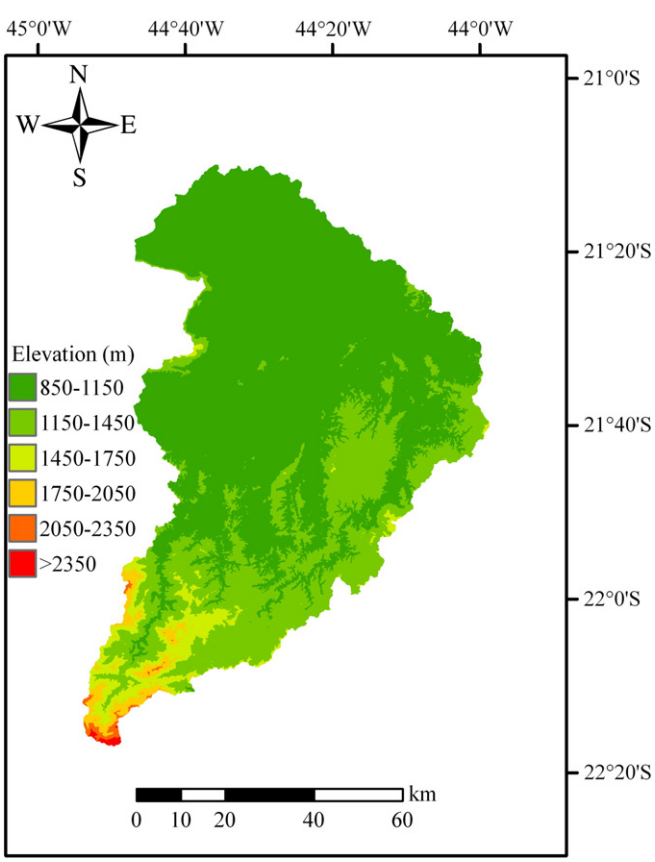

Fig. 4. Digital Elevation Model (DEM) of the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir.

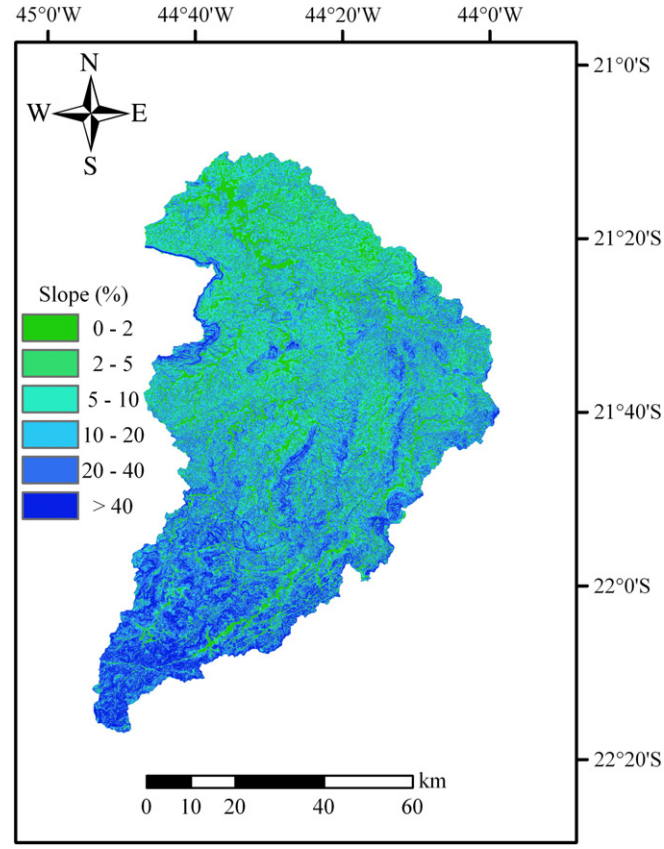

Fig. 5. Slope steepness categories (%) of the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir.

2.3.4. Topographic factor (LS)

The LS factor is used in the USLE to consider the effect of topography on erosion (Renard et al., 1997). The topographic factor depends on the slope steepness factor (*S*) and slope length factor (*L*) and 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 *L* factor in a grid-based DEM. One of them is based on the upslope contributing area of each cell, which can be calculated with the equations described by Desmet and Govers (1996), and Winchell et al. (2008), and another approach described in this study.

A Digital Elevation Model (DEM) of Grande River Basin (GD1) was obtained with 30 m-resolution (Fig. 4) and was used to generate a slope map (Fig. 5), the slope length factor (*L*) and slope steepness factor(*S*) for each grid cell on the map. Different algorithms have been created for calculating grid-based slope using GIS. For this work a PCRaster slope algorithm was employed, which calculates the slope at a central cell on the basis of the elevation DEM of its eight nearest neighbours in a 3×3 cell window applying a third-order finite difference method. Methods like the one used in this study, which use all the nine points within the 3×3 window elevation matrix for the estimate, tend to perform better than the methods based on simple trigonometry that use only two points for the estimate (Warren et al., 2004). It is unusual to have DEMs available with resolutions better than 30 m for watersheds of this size in Brazil; therefore we had to use a 30 m-resolution DEM in this study. This coarse DEM caused us to underestimate the slope gradient (*S*) and soil loss values at some points of the watershed, therefore it is a source of underprediction.

Table 4
Slope steepness categories for the Grande River Basin (GD1).

Categories (%)	Relief classification	Area (%)
0–2	Flat	19.95
2–5	Gently undulating	5.38
5–10	Moderately undulating	10.40
10–20	Undulating	28.50
20–40	Strongly undulating	27.52
≥40	Mountainous	8.26

L factor value may be expressed as (Jain et al., 2001; Fistikoglu and Harmancioglu, 2002; Onyando et al., 2005; Dabral et al., 2008):

$$L = \left(\frac{\lambda}{22.13}\right)^m \tag{3}$$

where λ is the field slope length (m), and *m* is a dimensionless exponent that depends on slope steepness, being 0.5 for slopes greater than 5%, 0.4 for slopes between 3% and 5%, and 0.3 for slopes less than 3% (Wischmeier and Smith, 1978; Dabral et al., 2008).

The *L* value was calculated by taking the field slope length equal to grid size (30 m), a procedure similar to field slope length that was used by several other researchers with successful results for this size basin (Jain et al., 2001; Fistikoglu and Harmancioglu, 2002; Onyando et al., 2005; Dabral et al., 2008). This assumption, for calculation of *L* factor in this size watershed, has been successfully applied in these studies; however, it is worthwhile to point out that soil loss prediction might be underestimated in some parts of the watershed, since actual slope length may be longer (50, 100 or 200 m).

The *S* factor was calculated based on the relationship given by McCool et al. (1987) and used in several studies like Pandey et al. (2007) and Dabral et al. (2008) for slopes greater than 4 m:

$$S = 10.8 \times \sin\theta + 0.03 \text{ for slopes} < 9\% \tag{4}$$

$$S = 16.8 \times \sin\theta - 0.50 \text{ for slopes} \geq 9\% \tag{5}$$

where θ is the slope angle (°).

Slope steepness categories are shown in Table 4 according to categories recommended by Ramalho Filho and Beek (1995). Average slope of the Grande River Basin was 17.21%. It is possible to notice considerable variation in these values, since a large part of the basin has gradients less than 10%, but on the other hand an extensive area has slope greater than 20%. The latter is probably a high risk area for erosion, depending on soil type and land cover.

2.3.5. Support practice factor (P)

The *P* factor is the relationship between the soil loss in a soil cropped with a given support practice and the corresponding loss with up and down slope cultivation (Pandey et al., 2007). Practices of soil conservation (*P*) also have an influence on a reduction of erosion processes, therefore, soil loss values range according with practices adopted (Ruhoff et al., 2006).

The values for *P* factor were assigned to be 1.0 for the entire area, since there were no erosion control practices in the studied area, according to the procedure also adopted by Ozcan et al. (2008).

2.4. Validation

The simulation process was tested on the basis of Sediment Delivery Ratio (SDR) calculated according to Bhattarai and Dutta (2007) and Irvem et al. (2007) where:

$$\text{SDR}(\%) = \frac{\text{TS}}{\text{MSL}} \times 100 \tag{6}$$

where TS is the transported sediment (t ha^{-1} yr^{-1}) to basin outlet and MSL is the mean soil loss in the basin (t ha^{-1} yr^{-1}).

In order to estimate annual sediment transport, a discharge curve relating total sediments transported with water discharge was constructed. To construct this, we used data (total solids in the water and respective discharge) monitored between 1996 and 2003 from a Gauging Station at Madre de Deus County, located in Grande River (operated by the Minas Gerais Water Resources Management Institute — IGAM). Afterward, we calculated the annual sediment transported by the Grande River taking into account the discharge curve and daily water flow data set, the latter of which was obtained from the Brazilian National Water Agency (ANA). Data from subsequent years to 2003 were not used due to discontinuation of monitoring after this date at the gauging station.

A histogram, which was divided into soil loss classes, was created on the basis of annual mean spatial soil loss (from 1996 to 2003) for the watershed. Results from 1996 to 2000 were used to relate TS and MSL and this relation was applied for the period between 2001 and 2003 in order to estimate TS. Aforementioned, TS values were compared to the observed values and a curve fitting the data was obtained (Fig. 6). The same procedure was adopted by Irvem et al. (2007) and Pandey et al. (2007) for USLE application in their basins in Turkey and India, respectively.

3. Results and discussion

3.1. Sediment delivery ratio (SDR)

Mean SDR value for the Grande River Basin was 0.016, meaning that we estimated that 1.62% of the soil loss generated in the basin was transported to the outlet. For the studied period, average sediment transport was equal to 0.813 t ha^{-1} yr^{-1}, however, values ranged between 0.34 and 1.39 t ha^{-1} yr^{-1}.

Irvem et al. (2007) applied the same procedure for a basin of 21,000 km^2 in Turkey and reported values similar to the ones found in this work (varying between 0.27 and 1.51 t ha^{-1} yr^{-1}). However, their mean value of SDR was 6%, showing a much greater potential of sediment delivery as compared to the Grande River Basin. This difference was due to a variation in mean soil loss found by the authors, which was equal to 16.38 t ha^{-1} yr^{-1}, whereas, in this work it was 55.45 t ha^{-1} yr^{-1}. This fact can be explained based on different soil erodibility values applied in simulations. The Grande River Basin has 60% of the overall area with Cambisols, which have greater soil erodibility values (Araújo, 2006). Another important difference is related to the mean rainfall-runoff erosivity value calculated in this study which was about 7600 MJ mm ha^{-1} yr^{-1}, whereas, in the work

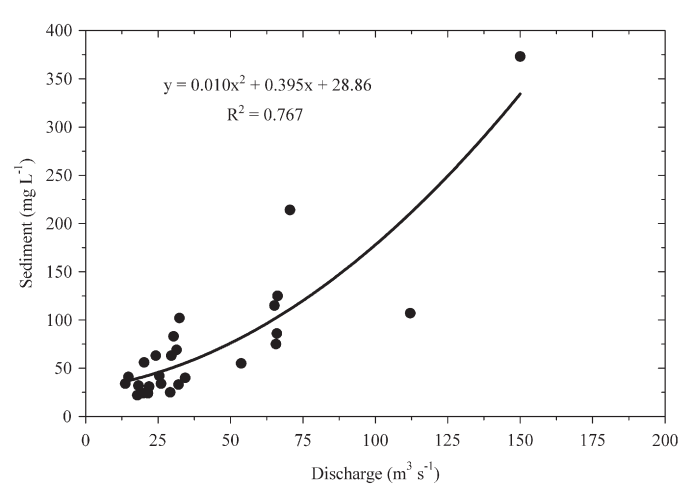

Fig. 6. Water discharge curve (sediment transported × water discharge) for the Grande River, outlet at Madre de Deus, Grande River Basin, Minas Gerais State.

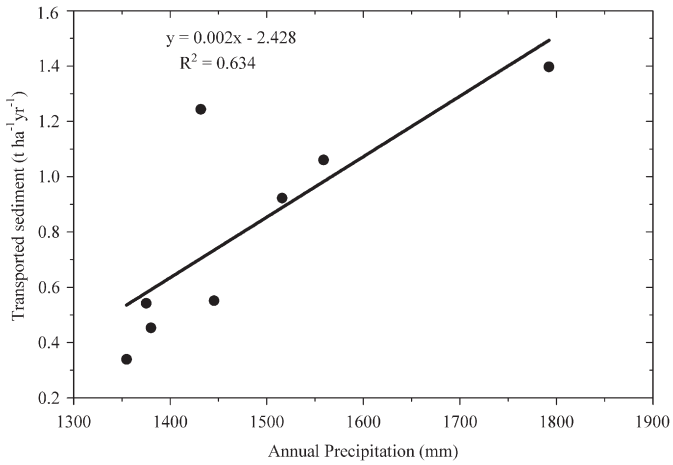

Fig. 7. Correlation between annual sediment delivery and annual rainfall.

carried out by Irvem et al. (2007), R was only 2091 MJ mm ha^{-1} yr^{-1}. This difference means that the erosive rainfall potential in the Grande River Basin is considerably higher. This erosivity behavior is associated with the rainfall characteristic typical of southeastern Brazil, which is affected by important climatic phenomena during the summer, such as the South Atlantic Convergence Zone, where there is a concentration of warm and cold systems, the first from the humid Amazonia region and the second from Antarctica, especially in December and January, thus often generating daily rainfall amounts greater than 100 mm (Mello et al., 2007).

Fig. 7 shows the relationship between annual sediment delivery and total annual rainfall and the acceptable correlation ($R^2 = 0.63$) between these data for the Grande River Basin. Physically, the deeper the rainfall depth, the greater erosive potential of rainfall, implicating a greater capacity for surface runoff generation which its reduction is an important mechanism to help control sediment delivery. In tropical and sub-tropical climates, the distribution of precipitation depth over time, characterizing mean rainfall intensity, is highly relevant and needs to be considered in evaluations like this, especially due to some rainfall events occurring during summer, known as convective rainfall events with high intensity and high erosivity, but small depth when compared to frontal events of rainfall. According to Mello et al. (2007), this situation is common in the studied region, and the sediment transport can be affected by other rainfall characteristics. Unfortunately, the monitoring of sediment transport, carried out by IGAM, has not presented a sufficient frequency necessary to follow the entire hydrologic year (just four or five times per year due to high costs involved), thus resulting in rainy days without values of sediment transport.

In Table 5, it is possible to evaluate both the observed and estimated sediment delivery as a function of the relationship between TS and MSL from 1996 to 2000, which is a linear relationship with a coefficient of determination equal to 0.96. For the 2001 year it was possible to observe that there was a considerable error of 0.232 t ha^{-1} yr^{-1} (absolute error of 48.41%). On the other hand, for the years 2002 and 2003, the errors were −0.018 t ha^{-1} yr^{-1} and 0.065 t ha^{-1} yr^{-1}, which, in terms of the absolute errors, correspond to only 3.38% and 7.05%, respectively. Pandey et al. (2007), applying similar methodology, found errors that ranged from 1.37% to 13.85%. According to the authors, errors less than 20% are acceptable, and it is possible to validate the erosion simulation process based on the USLE application for the basin conditions. Using this criterion the results of the validation process presented errors considerably low and acceptable, except for 2001. A possible reason for this greater error is that, for 2001, annual rainfall was considerably lower than mean annual precipitation in the region (1356 mm compared to 1750 mm). Thus, a reduction of sediment delivery (0.48 t ha^{-1} yr^{-1}) was expected due to lower surface runoff and peak discharges. However, there was a great concentration of precipitation from January to March in this year, generating high rainfall–runoff erosivity factor values and soil loss of 52 t ha^{-1} yr^{-1}, different from the expected values for this amount of annual precipitation which should have been about 48 t ha^{-1} yr^{-1}. Therefore, this caused a greater error of estimate for this year.

It is worthwhile to mention that there might be some major sources of error in this study, such as the estimation of L as stated before. Main sources of error in this kind of study are associated with the estimation and determination of the spatial mean of rainfall–runoff erosivity factor and characterization of land-use (C factor values). Although the Fournier Index is widely used and accepted, it consists of an estimate of rainfall–runoff erosivity factor due to the difficulty in obtaining pluviograph data, which are desired but not normally available or processed for many regions in Brazil. In addition, satellite image interpretation can also induce errors due to uncertainties associated with the process of land-use determination. According to Diaz-Ramirez et al. (2008) remote sensing techniques are extremely relevant, but these may result in an important source of

Table 5
Observed and estimated sediment delivery and errors of estimate for the Grande River Basin (GD1).

Year	Estimated SD (t ha^{-1} yr^{-1})	Observed SD (t ha^{-1} yr^{-1})	Error (t ha^{-1} yr^{-1} and %)
2001	0.712	0.48	0.232 (48.41)
2002	0.533	0.551	−0.018 (3.38)
2003	0.987	0.922	−0.065 (7.05)

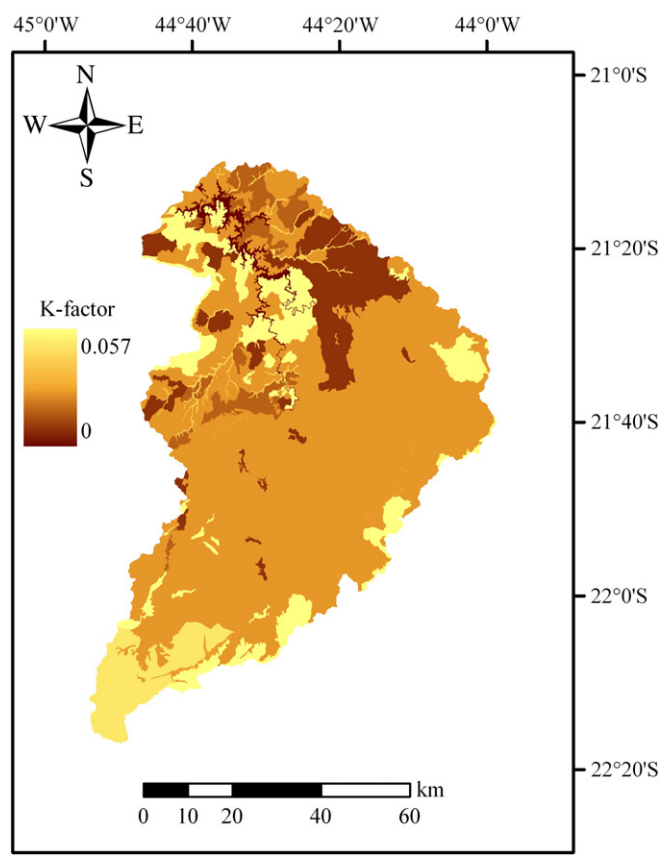

Fig. 8. Map of the soil erodibility factor (K) for the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir derived from PCRaster GIS tools.

error that can affect the land cover mapping and its relationship with hydrology and sediment transport in basins, especially, ones with thousands of km^2. In this context, the cover-management factor (C), applied in the simulation, can be another significant source of error. The methodology applied for calculation of the L factor can possibly cause an underprediction of values at some points of the watershed due to longer slope lengths, such as 50, 100 or 200 m, resulting in underestimate of soil loss. Other approaches, based on upslope contributing area (Desmet and Gover, 1996; Winchell et al., 2008), were also used to compute the L factor; however, these approaches gave unrealistic results for the study watershed. A 30 m-resolution DEM was used for computation of both slope gradient and L factor map, which tends to underestimate such variables, therefore DEMs with better resolutions would be preferable if available for assessments like this. In Brazil, this kind of resolution is found only in small monitored watersheds, where researchers are able to survey the watershed in detail because of a lower expense involved when compared to large basins. Even though channels in this watershed present considerable slope gradients and may experience some soil loss, these were not taken into account to compute soil loss using the USLE approach since it does not consider channel processes.

3.2. Spatial distribution of erosion within Grande River Basin–GD1

The spatial distributions of the USLE's factors (K, C and LS) were derived from maps of land use, soil type and slope, using the PCRaster GIS environment (Figs. 8, 9, and 10). Considering the maps shown in Figs. 8, 9, and 10, we can identify some important aspects associated with the basin. It should be noted for the soil erodibility map that a considerable area of the basin has a K factor higher than 0.03 t h MJ^{-1} mm^{-1} indicating a high susceptibility to water erosion. This natural behavior can be explained because the greater part of the watershed contains Cambisols. Soils with an incipient B horizon, just like Cambisols, are also very susceptible to water erosion because they contain a loam texture which can produce surface sealing in bare soils which greatly reduces the infiltration capacity. Moreover, these types of soil are linked to the undulating relief and, specifically within the Grande River Basin, are poor in fertility and shallow to impermeable substrate (Araújo, 2006). These characteristics, combined with a greater erosive capacity of rainfall in the region (Mello et al., 2007), make more efficient erosion control techniques desirable. Erodibility values greater than 0.05 t h MJ^{-1} mm^{-1} can be found especially in the headwater of the watershed due to the occurrence of Litholic Neosol which presents coarse texture as well as very shallow depth. Contrary to the headwaters, near the Itutinga/Camargos Hydroelectric Plant Reservoir, the lowest erodibility values were found, which are associated with Oxisols and nearly level relief (Fig. 5).

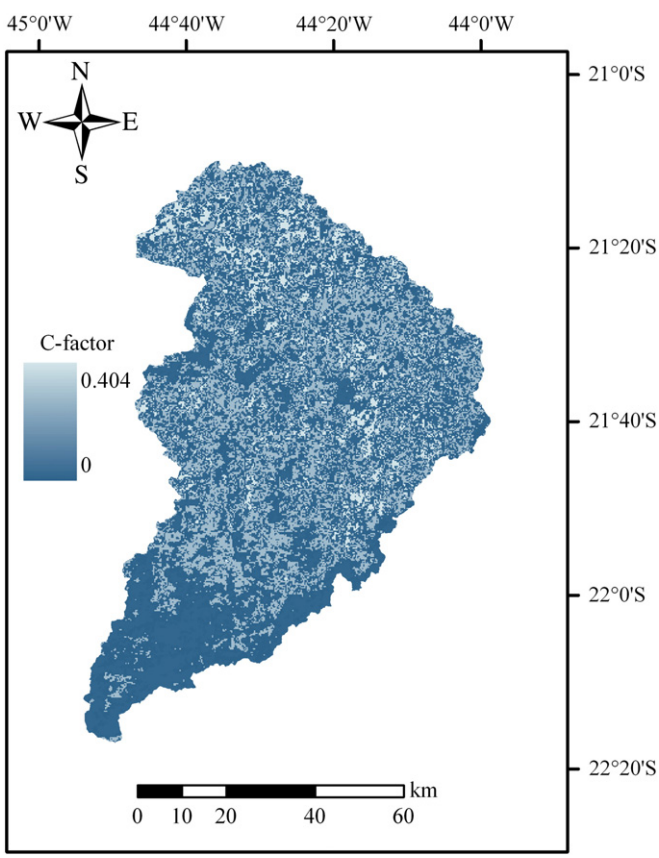

Fig. 9. Map of the cover-management factor (C) for the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir derived from PCRaster GIS tools.

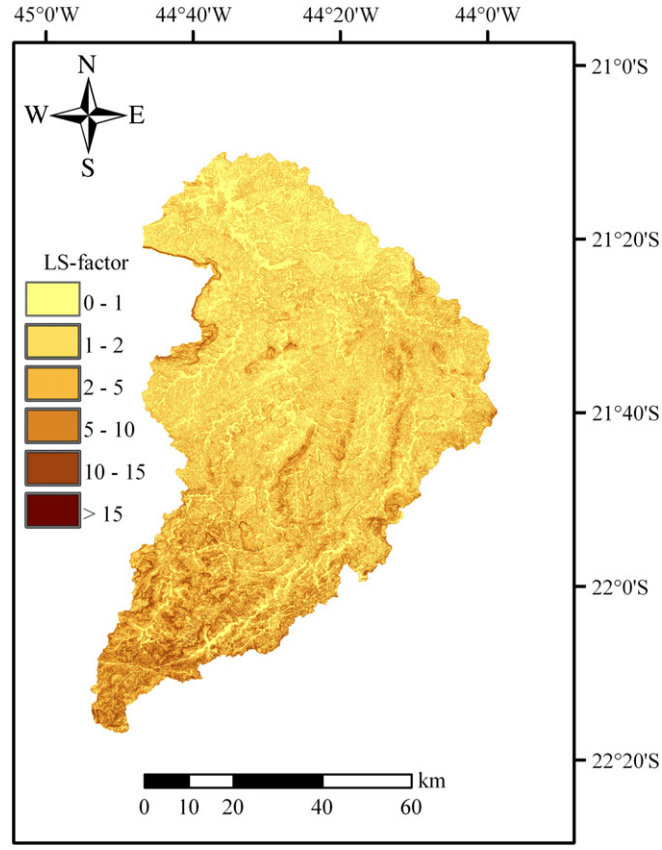

Fig. 10. Map of the topographic factor (LS) for the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir derived from PCRaster GIS tools.

Analysis of the topographic factor (Fig. 10) is very important in USLE application, since this parameter characterizes surface runoff speed and, therefore, it is an indicator of soil erosion risk in watersheds. Table 6 shows the distribution of the area of basin that corresponds to each interval of the topographic factor, showing that

Table 6
Categories of topographic factor (LS) for the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectric Plant Reservoir.

LS interval	Area (%)
0–1	30.6
1–2	15.0
2–5	36.5
5–10	16.9
≥10	1.0

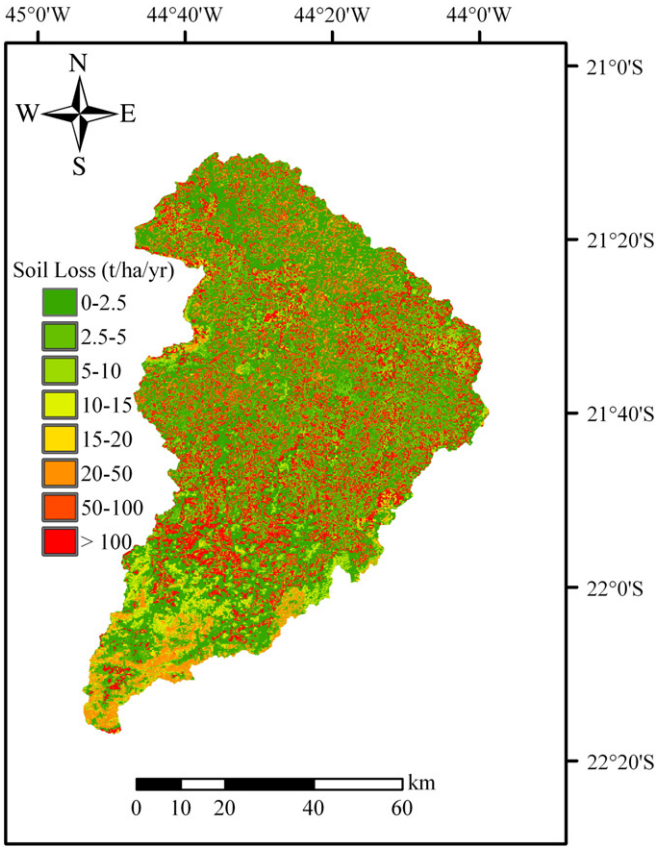

Fig. 11. Map of soil loss rate (t ha^{-1} yr^{-1}) for the Grande River Basin (GD1).

over 82% has a value of LS less than 5, demonstrating moderate vulnerability to water erosion. In contrast, 1% of the area has LS greater than 10, which has a high vulnerability to erosion. In the scope of soil management, it is important to determine whether the same areas having a greater LS value coincides with areas of higher erodibility and low land cover (high exposure of soil) in order to identify the greatest risk areas where conservation efforts need to be intensified.

The Universal Soil Loss Equation allows researchers to quantify soil loss rates (average annual value), in either a lumped or spatially distributed approach. By using the latter approach, it was possible to generate interpretive maps through the PCRaster programming language as well as a map of average annual soil loss rate (Fig. 11) within the Grande River Basin, taking into account current or changing land use.

The distribution of average annual soil loss for the Grande River Basin is presented in Table 7. We can observe that the major part of the basin (about 53%) is predicted to have an average annual soil loss of less than 5 t ha^{-1} yr^{-1} which can be considered low (Pandey et al., 2007). This situation is because of the low *C* factor value (0.10) for a

Table 7
Intervals of the soil losses simulated for current land-use conditions on the Grande River Basin (GD1).

Soil loss intervals (t ha^{-1} yr^{-1})	Area (%)
0–2.5	42.83
2.5–5	10.39
5–10	9.42
10–15	4.17
15–20	2.43
20–50	7.19
50–100	5.49
100–500	16.94
≥500	1.15

Table 8
Soil loss variation (%) for different soils types in the Grande River Basin (GD1) upstream from the Itutinga/Camargos Hydroelectic Plant Reservoir.

Soil	Soil loss rate intervals (t ha^{-1} yr^{-1})								
	0–2.5	2.5–5	5–10	10–15	15–20	20–50	50–100	≥100	Total (%)
CXbd	27.57	7.07	7.32	2.58	1.00	2.03	3.60	14.31	65.49
LVd	2.27	0.46	0.22	0.07	0.05	0.37	0.57	0.47	4.49
GXbd	0.64	0.18	0.06	0.04	0.03	0.05	0.05	0.09	1.13
RLd	2.54	1.23	0.96	0.73	0.54	1.55	0.19	2.24	9.98
LVAd	6.17	0.57	0.39	0.18	0.20	1.26	1.03	0.27	10.07
LAd	0.33	0.14	0.20	0.13	0.06	0.07	0.03	0.37	1.34
RYbd	0.36	0.02	0.03	0.02	0.01	0.02	0.01	0.03	0.49
CHd	1.42	0.71	0.24	0.42	0.54	1.84	0.01	0.31	5.50
Water	1.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.52
Total (%)	42.83	10.39	9.42	4.17	2.43	7.19	5.49	18.09	100.00

large part of the area. This low value represents good soil protection from the direct impact of raindrops (Fig. 9). The greatest area of the watershed has little agriculture and pasturing, a low population density and considerable native vegetated areas, especially on the southern part.

The results from this study demonstrate the importance of land cover for watershed management. The greatest part of the soils in the Grande River Basin has high vulnerability to erosion, high slope steepness and high rainfall–runoff erosivity factor. Therefore, both land cover and support practices factors are important for reducing erosion process, especially on the area around Mantiqueira Mountain, where is possible to obtain high simulated soil loss values in areas that have been deforested.

Table 8 and Fig. 12 were prepared in order to compare soil losses with the tolerance of each pedologic mapping unit. Tolerance value (*T*) of soil loss for each soil type was taken, in t ha^{-1} yr^{-1}, according to Silva (2003), Mannigel et al. (2002), Fujihara (2002), Sparovek and van Lier (1997) and Batalha (2006), resulting in 3.67; 11.34; 5.82; 6.8; 11.53; 12.45; 6.70 and 7.95, for soils classified as CXbd, LVd, GXbd, RLd, LVad, LAd, RYbd and CHd, respectively. With the results presented in Table 8, we can conclude that it is necessary to change the land use in the Grande River Basin only to the extent that erosion is below *T* and the impacts to the environment are minimized.

It can be determined from Fig. 12 that 48.95% of overall basin presently has soil loss greater than the tolerable rate. This value indicates that there are zones where the erosion process is critical, meaning that both management and land-use have not been used appropriately in these parts of the watershed. This kind of identification was only possible due to a computer tool for dynamic and spatial

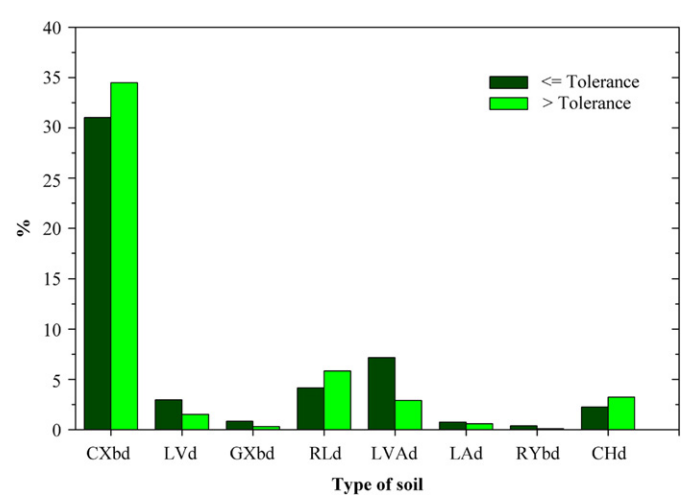

Fig. 12. Percentage of the basin area with soil loss greater and lesser than tolerable for each soil type.

modeling, such as the PCRaster, demonstrating local problems of soil erosion in areas where the general situation appears adequate and controlled. This method can be used to identify where erosion processes are more intense and conservation needs to be concentrated in the not-too-distant future. Within the scope of this discussion, Ozcan et al. (2008) pointed out the importance of the USLE associated with spatially distributed modeling, as a powerful tool for management of agricultural lands, especially in developing countries, which rarely have available database for application of the more advanced physically-based erosion models such as WEPP or SWAT on large watersheds.

4. Conclusion

The results showed that soil losses exceeded the presumed tolerable limits on approximately half of the area in the Grande River Basin. Therefore, it is necessary to change the land-use and add supporting practices in some places in order to reduce the soil loss rates to a tolerable level.

The methodology applied to the study of spatially distributed erosion (USLE with the PCRaster) in the Grande River Basin, showed acceptable precision and allowed for identification of the most susceptible areas to water erosion. It constitutes an important predictive tool for soil and environmental management in this region, which is highly relevant for prediction of varying development scenarios for Minas Gerais State due to its hydroelectric energy potential. In spite of the satisfactory results found in this paper, some sources of error concerning estimated soil loss were discussed, which are associated with: (a) determining of spatial mean of rainfall–runoff erosivity factor by employing Fournier Index; (b) characterization of land-uses using satellite images and estimating the *C* factor; (c) computation of *L*-factor employing the methodology described; (d) computation of slope gradient map using a 30 m-resolution map; and (e) disregard of soil loss in channels. These may have contributed to the low soil delivery ratio found for the studied watershed.

PCRaster was found to be an effective and useful computer tool to implement the algorithms needed to quantify water erosion according to the USLE, since this software permits creation of computer routines (free, fast, effective and simple) embedded in a Geographical Information System. Moreover, by using the PCRaster package for simulation of erosion processes we can generate spatially distributed results within the basin and identify specific areas with serious problems of erosion to target for conservation. Thus, it allows conservationists and planners to implement management strategies more precisely, rationally and sustainably in the long-term while at the same time protecting the environmental quality and longevity of the reservoir.

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