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A stochastic estimation of sediment production in an urban catchment using the USLE model

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ABSTRACT
The goals of this study were to map the spatial distribution of sediment production and to estimate the probability of this production at the waterline based on a high potential of silting. The RUSLE-GIS model and Monte Carlo simulation were used. A sensitivity analysis of stochastic factors was performed by calculating the simple correlation coefficient. This procedure was applied to the Estrada Nova catchment, located in the city of Belém, northern Brazil, which has been subject to channel improvements and the construction of a detention basin. The results indicate that, following the urbanization and drainage improvements, there was a reduction in the annual sediment production probability, which is consistent with the dynamics in land use. The erodibility was the most sensitive factor in the sedimentation estimates. The methodology was considered an alternative to estimate sediment production in an urban catchment.

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1 Introduction

Intense urbanization and modification of watercourses can produce physical, chemical and biological impacts that affect sediment production in hydrological catchments. The sediments may modify the water quality, aquatic biota, fluvial morphology and hydrological regime by contributing to the eutrophication of water bodies. Sedimentation may lead to silting of channels, thereby reducing the hydraulic efficiency and causing floods. Therefore, it is important to identify areas of potential sediment production that could eventually compromise the function of hydraulic channels in urban catchments. The result could be better water resource management that includes preventive actions (e.g. dredging of channels) to alleviate the above impacts.

The quantification of sediment production, which originates from the processes of erosion, is commonly performed using two types of models: empirical models and those based on processes. Process-based models are based on physical principles and have served as excellent tools for estimating soil losses. These include the WEPP (Flanagan and Nearing 1995), EUROSEM (Morgan *et al.* 1998) and SWAT (Arnold *et al.* 2005) models. However, these require large amounts of computational power and data, which limits their applicability. The empirical models, in contrast, are commonly derived from adapted versions of the universal soil loss equation (USLE), in particular the revised USLE (RUSLE) model (Bingner and Theurer 2001, Kinnell 2005, Lightle 2007). However, these empirical models are imperfect when used to predict sediment production in large catchments (Renard *et al.* 1997). Two disadvantages, in particular, are the stochastic bias in the factors that make up the RUSLE model, especially those associated with spatial and temporal variability, and the assigning of uncertainties in the estimation of sediment production. Recently, work on stochastic bias has been presented by Veihe and Quinton (2000), Sohrabi *et al.* (2003), Van Griensven and Meixner (2006) and Arabi *et al.* (2007), who studied uncertainties and sensitivities associated with input parameters of the process-based models by introducing the technique of Monte Carlo simulation.

Furthermore, provisions for addressing the limitations and uncertainties of the RUSLE model were added to a spatial disaggregation model of the delivery of sediment; the result is referred to as the sediment delivery distributed (SEDD) model, which was tested via Monte Carlo simulation by Di Stefano *et al.* (1999). This same stochastic simulation technique was used by Biesemans *et al.* (2000) to yield an error propagation technique for predicting the average sediment accumulation.

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Rompaey and Govers (2002) proposed the establishment of the most favourable level of complexity of their empirical model for regional scale application if there are no available values to assign to the factors. In contrast, Lim *et al.* (2005) developed a GIS-based assessment tool for effective sediment erosion control (SATEEC) to estimate soil loss and sediment yield using the RUSLE model. This estimate by the RUSLE method was spatially distributed by the SATEEC model. The studies by Lim *et al.* (2005) also provided a simulation of the sediment yield.

Nevertheless, the application of simulations to the RUSLE model to estimate the production of sediment has not included specific studies of the probability that sediment production will cause silting, for example. Generally, such applications are limited to studies associated with water quality changes.

Thus, one aim of this study was to take advantage of the simplicity of the RUSLE model through the use of geographic information; in addition, Monte Carlo simulation was used to stochastically treat the erosivity and erodibility factors of the respective models. Although the factors related to physiography, land use and conservation practices are spatiotemporally variable, their baseline measurements can be obtained via topographic analysis and from remotely acquired images (which reflect the temporal geomorphological dynamics), respectively. These factors can then be treated in a deterministic way based on the intrinsic and physical characteristics of a given catchment. This approach was applied to the Estrada Nova catchment, an urban catchment located in the city of Belém, State of Pará, in northern Brazil. The hydraulics and mechanics of sediment transportation in this catchment are described below.

1.1 Hydraulics and mechanics of sediment transportation in an urban catchment

The Estrada Nova catchment is one of 14 catchments that make up the hydrography of the city of Belém and it is partly characterized by low slope gradients. The predominant effect of a water-level rise in relation to the kinetic head, as well as the combined occurrence of heavy precipitation and tidal oscillation in the Guajarino estuary, constitute a particular feature that could cause flooding along the banks of the catchment's drainage channels.

The tidal influence can be explained by the work of Gregório and Mendes (2009), who found the existence of sedimentary deposits in the sandy and muddy banks, and muddy plains formed by the dissipation of energy from tidal currents. These feature the South Bank of Belém, and the area that skirts the Estrada Nova catchment, along the entrance to the Quintino Bocaiuva channel (CQB) (Fig. 2).

Using the method of Pejrup (1988), Gregório and Mendes (2009) revealed that the water bodies that influence the amount of water in the CQB have hydrodynamics classified as high and very high, corresponding to an intense circulation system with the interaction between the channel and the tidal river. Due to the deposition of sediments, characterized as sandy silt, Gregório and Mendes (2009) found that the south bank of the city, which lies in the southern part of the Estrada Nova catchment, is the most problematic for shipping, since the average maximum depth did not exceed 4 m, and closer to the river bank it came to less than 2 m.

Similarly, the tidal effect may favour entrainment of sediment particles to the CQB and the other channels that drain the catchment. This drag can be enhanced by the flow rate of tidal currents, which according to Barros *et al.* (2011) is between 1.35 m/s (spring tide) and 0.97 m/s (neap tide), flowing south of Guajará Bay and east of the mouth of the Guamá River.

Although low-flow velocities are greater than those of the tides (between 1.84 and 0.83 m/s; Pinheiro 1987), Blanco *et al.* (2013) observed that the time for this phenomenon to complete is about 8 h, but it takes around 5 h for a rising tide (flooding). Thus, there are greater chances of particles in suspension becoming the sedimentary material. This phenomenon was confirmed by Gregório and Mendes (2009), who concluded that increased sediment deposition zones occur along the south bank of the city of Belém.

So, due to the high hydrodynamics, as the tide rises, the water at the mouth of the Guamá River advances into the CQB and other channels that drain the catchment, bringing with it suspended particles. Therefore, it is considered that the concentration of sediment along the channel is enhanced by virtue of its low slope (elevation: $\leq$4 m a.s.l.) and backwater effect (tidal pumping), with the channel's hydraulic operation resembling that of a container. This hydraulic feature and the low slope, as well as the predominant effect of the rising water level in relation to the kinetic load, together with the occurrence of intense rainfall and fluctuation of tides, causes flooding in the channels of the Estrada Nova catchment.

In addition to the catchment's natural aspects, the use and occupation of the land in the catchment can contribute to the generation of sediment, which obstructs the channels and intensifies flooding. To moderate the impacts of floods, some of the channels in the catchment drainage network have received improvements. For this purpose, Engesolo (2007) divided the catchment into four sub-catchments. Sub-catchment II was selected for this study because it includes the most extensive drainage channels in the catchment. This choice was also

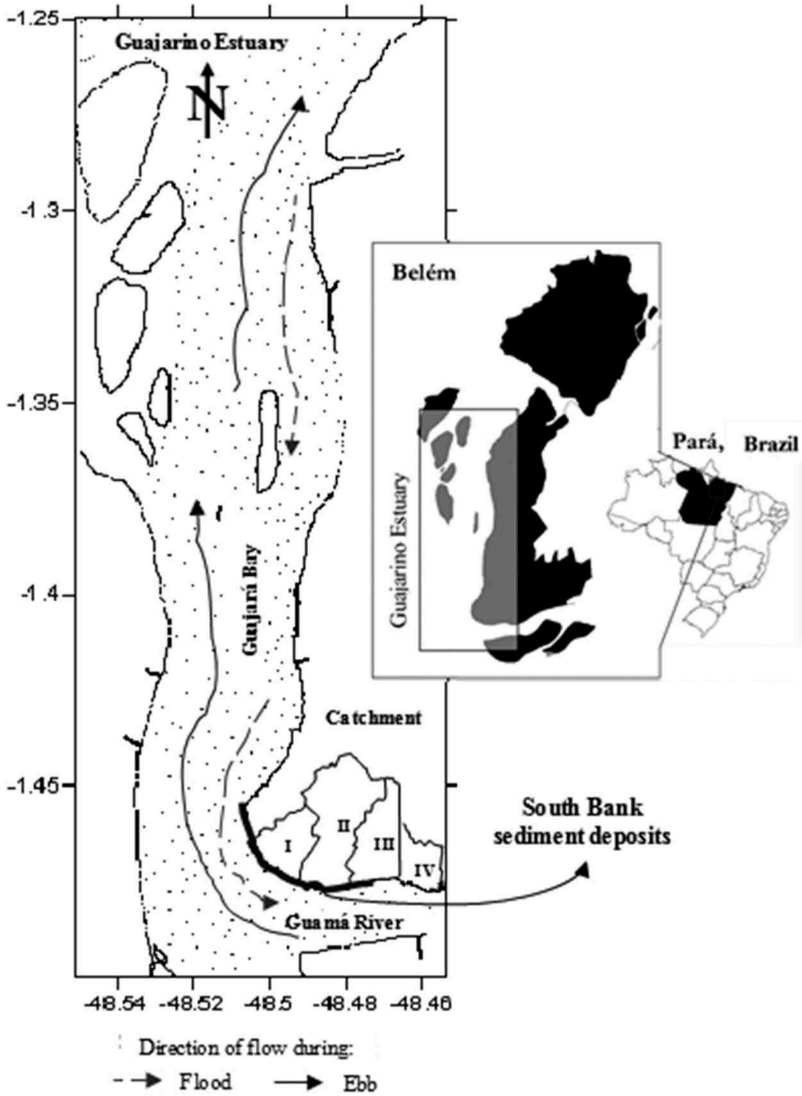

Figure 1. Hydraulics and mechanics of sediment transportation in the urban catchment: Estrada Nova.

prompted by the fact that a detention basin is to be built in this area. Sub-catchment II is drained by five channels: the CQB, the 14 de março (CQM), Dr Moraes (CDM), Caripunas (CCR) and Bernado Sayão (CBS) channels.

The drainage area of Sub-catchment II, which measures 4.04 km^2, includes two urban areas (ZAU), which were defined by Belém (2008) and are referred to as ZAU5 and ZAU6(I). Both areas are densely populated and are distinguished by the fact that ZAU5 is more susceptible to flooding than ZAU6(I). This sub-catchment has been almost entirely urbanized, has been intensely modified in terms of its land use, and lacks conservation practices (such conservation actions are generally associated with agriculture, i.e. rural areas) (Fig. 2).

In urban basins the soil change is definitive since the soil is exposed to erosion during the urbanization process, as reported by Dawdy (1967). However, a probabilistic estimation of the sediment production of a catchment before and after urbanization has not been reported to date. To evaluate the effect on erosive processes of urbanization that includes drainage projects, the aims of this study were (1) to map the spatial distribution of sediment production, and (2) estimate the probability that sediment production was high both before and after the respective urbanization projects.

For operational reasons, the city of Belém should schedule the dredging of channels in advance of any flooding to maintain and promote their hydraulic efficiency. Thus, a map of the spatial distribution and estimation of the probability of sediment production in the channels of Sub-catchment II is a relevant issue in infrastructure management.

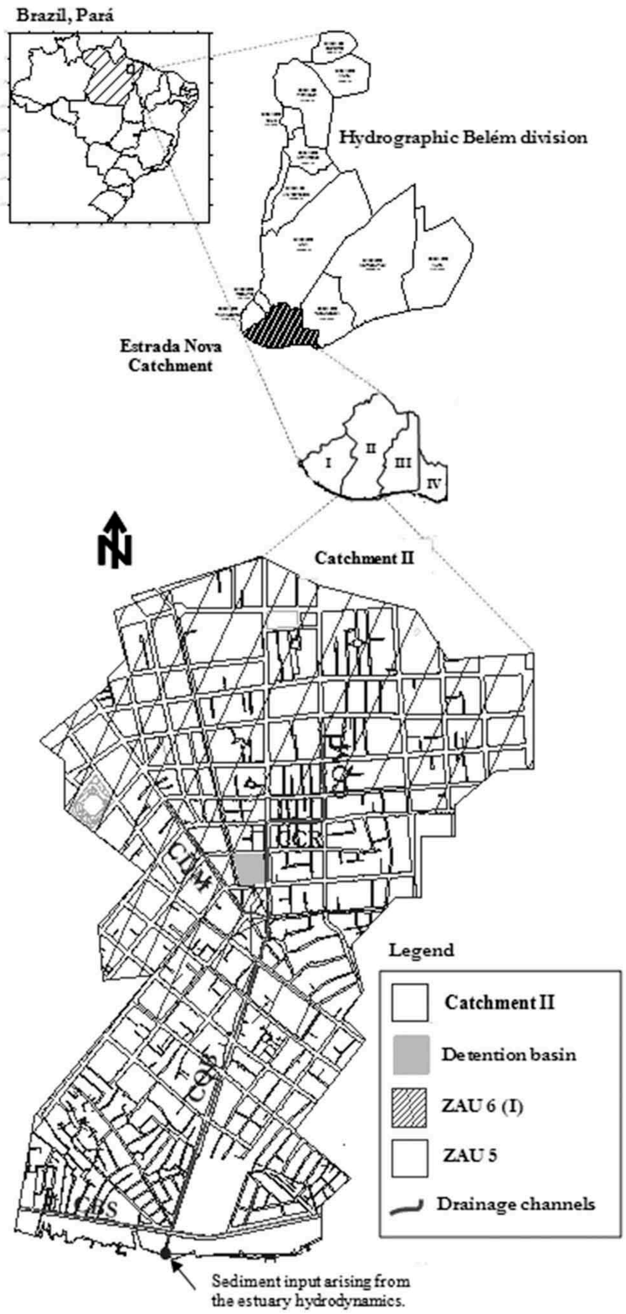

Figure 2. Location of Sub-catchment II and urban environment zones (ZAU).

2 Methodology

2.1 Sediment production

The universal soil loss equation (USLE) (Wischmeier 1965) and its revised version, the RUSLE model (Renard *et al.* 1997), were designed for estimating the average annual loss of soil (A) over a certain period of time. Both models are expressed by a formula that combines six factors:

$$A = R \times K \times LS \times CP \tag{1}$$

where R is the power factor of rainfall ($\mathrm{MJ\,h\,ha^{-1}\,mm\,h^{-1}}$); K is related to the soil erodibility ($\mathrm{t\,h\,MJ^{-1}\,mm^{-1}}$); LS is the physiographic factor; C represents the land use and soil management; and P is the factor representing conservation practices. Factors L, S, C and P are dimensionless and are calculated as the ratio of the soil loss in a specific location to the soil losses in the USLE unit (22.1 m long, with 9% inclination, without vegetation, with growing areas along the slope). However, the value of A does not take into account the soil deposition. Thus, to estimate the deposition, the delivery of sediment in the drainage area, i.e. the production of sediment (Y), needs to be accounted for based on a sediment production coefficient (SPC):

$$Y = A \times \mathrm{SPC} \tag{2}$$

Fu *et al.* (2005) explained that the SPC of a particular catchment is dependent on the geomorphological, hydrological and environmental factors associated with the catchment itself, and may be quantified by:

$$\mathrm{SPC} = a(A_d)^{-b} \tag{3}$$

where A_d is the drainage catchment area, and a and b are coefficients whose values, as suggested by Vanoni (1975), are 0.473 and 0.125, respectively. Therefore, Y is constrained by the estimated values of the variables that constitute the RUSLE model, which are stochastic in nature, although a few were considered deterministic. The uncertainty and variability of these variables suggest that the value of Y of a particular catchment can be estimated stochastically using the Monte Carlo simulation (MCS) method.

2.2 Definition of deterministic factors

The lack of information and the level of uncertainty regarding the behaviour of certain variables have led to their deterministic analysis. The length of the hillside (G), the average slope of the land (S), the land use and soil management (C), and conservation practices (P) are considered to be variables of this type. Although these factors display strong spatial and temporal variability, the dynamics of land use and management can be estimated based on a data matrix in a cell (pixel). This definition is linked to a square portion of the region in such a way that each pixel contains the values of the respective factors.

2.2.1 Length of hillside (L) and average slope of land (S)

The length L can be obtained, as recommended by Paiva *et al.* (1995), from the quarter of the equivalent rectangle width (L_e), once the parcel is replaced by the river catchment, in which L_e is expressed as:

$$L = L_e = \frac{k_c\sqrt{A_b}}{1.128}\left[1 - \sqrt{1 - \left(\frac{1.128}{k_c}\right)^2}\right] \quad (4)$$

where A_b represents the area of the catchment (m^2), and k_c is the compactness coefficient, which is obtained by:

$$k_c = 0.282\frac{P_b}{\sqrt{A_b}} \quad (5)$$

where P_b is the perimeter of the catchment (m). The slope can be obtained as a function of the slope of each cell (θ) for slopes less than 9%, as given by (Renard *et al.* 1997):

$$S = 10.8 \times \sin(\theta) + 0.03 \quad (6)$$

The combination of these two variables produces the physiographic factor, LS (Wischmeier and Smith 1978):

$$LS = \left(\frac{L}{22.1}\right)^m (0.065 + 0.0454 \times S + 0.0065 \times S^2) \quad (7)$$

in which m is the slope-length exponent, which, as described by Mills (1985), takes the following values according to the slope: 0.2 ($S < 1\%$), 0.3 ($1 > S < 3\%$), 0.4 ($3 < S < 5\%$) and 0.5 ($S > 5\%$). Using topographic data with a resolution of 10 m, a digital terrain model (DTM) consisting of cells, 30 m on a side, can be developed. This model can be used to estimate the inclination, direction, accumulation and length of the flow for each mesh cell.

2.2.2 Land use and occupation of soil (C) and conservation practices (P)

The factor C was conceived of by Wischmeier (1965) as the expected relationship between the soil losses of land cultivated under specific conditions and the corresponding loss of soil that is continuously cultivated. The factor P is the ratio between the loss of soil that occurs with certain conservation practices and the loss that occurs on agricultural land that is at the maximum inclination (downhill cultivation). These factors, when analysed individually, may be used to develop a more appropriate interpretation of conservation-minded agricultural production.

However, Stein *et al.* (1987) analysed the factors C and P together and thereby established values for various groups and types of vegetation. They concluded that C and P are strongly correlated, which prevents their individual analysis. The reported values of CP (Stein *et al.* 1987) resemble those of the analysed catchment. These values were adapted to an urban catchment in which ground movements are more common due to the dynamics of land use and occupation of the soil that can make it more susceptible to erosion. So this adaptation, which was based on the proposition of Stein *et al.* (1987), took into account the most common features of Sub-catchment II (Table 1).

Table 1. Values of factor *CP* adapted for Sub-catchment II.

Description	*CP*
Urban area/water bodies – rivers and lakes	0
Green areas (squares, forests, etc.)	0.25
Treeless areas/propitious for ground movements	1

The problems of obtaining the values of CP are addressed by the use of remote images, which were obtained from the City Planning Department of Belém (SEURB) for the year 2008 and from Google Earth® for the year 2013, all of which are at a scale of 800 m.

2.3 Definition of stochastic factors

In addition to the lack of data, the stochastic nature was a criterion used to determine which variables affect the average annual soil loss. The variables under consideration were pluviometric (precipitation) and morphological (chemical and physical soil properties); these are independent variables that are the factors R and K.

2.3.1 Pluviometric precipitation

Pluviometric precipitation is a continuous hydrological variable and is of a stochastic nature, with spatial and temporal variability. Based on this assumption, the quantile of the Pearson type-III distribution was used to estimate the maximum annual precipitation. Its contribution to the large drainage project in Sub-catchment II was 182, 198 and 215 mm in 24 h, with return periods of 25, 50 and 100 years, respectively, according to Engesolo (2007). The Pearson type-III and the log-Pearson III and Gumbel distributions are often used to describe events in hydrology, such as the annual maximum precipitation (i.e. extreme events).

However, the annual loss of soil in a catchment is influenced both by the amount of rain during the relevant month and by the average annual precipitation (P_{ma}); the final product of these two values yields the power factor of the rain (R). For the area that includes Sub-catchment II, determination of R was performed based on the work of Kim *et al.* (2005), who found that the average annual precipitation (P_{ma}) controlled R in tropical countries:

$$R = 587.8 - 1.219(P_{ma}) + 0.004105(P_{ma})^2 \quad (8)$$

Table 2. Historical precipitation series.

Station code	Time period (years)	Distance from Sub-catchment II (km)
00148019	1974–1981 (7)	2.43
00148001	1982–1988 (6)	3.64
00148002	1989–2013 (24)	5.98

Therefore, the distribution that best fits the annual precipitation is the regular one. In addition to these, the daily, weekly and monthly precipitation can be best described by a gamma distribution. To define the distribution that best fits P_{ma}, continuous historical series of pluviometric stations near Sub-catchment II were processed based on the catalogue from the hydrological information system of the National Water Agency (HIDROWEB), as presented in Table 2.

Thus, the normal distribution was identified as the one that provides the best fit, as verified using the Kolmogorov-Smirnov test ($t_{\text{k-s}}$), with a significance level of 0.05 ($t_{\text{k-s}}$ = 0.258). The calculated $t_{\text{k-s}}$ was equal to 0.120 with the distribution of P_{ma} between 1974 and 2013 (Fig. 3).

The normal distribution yielded an average and standard deviation of 262.12 mm and 166.83 mm, respectively. Note that spatial issues still remain, specifically the distance between the pluviometric stations and Sub-catchment II; there are also temporal issues, specifically the 39 years of the historical series. To generate pseudorandom numbers of the average annual precipitation, NtRand® was used in the Microsoft Excel® program.

2.3.2 Morphological, chemical and physical soil properties

The focus of the geological history of the region containing Sub-catchment II is on two layers: the first is the soft soils (recent sediments), which are located at lower elevations; and the second is the region of higher elevations, where there are common variably coloured clays with ferruginous concretions (laterite). These characteristics were studied by Alencar and De Souza (2006) based on undisturbed soil block samples taken at a depth of 2 m below the ground surface. The particle size distribution indicated the presence of a fine-grained soil with an absence of certain ranges of grain sizes, which could be explained by a possible leaching process that occurred during the genesis of the lateritic soils.

Grain-size analysis carried out by Engesolo (2007) on samples from granular layers of the bodies of the pavements and from the sub-grade floor of Sub-catchment II led to an estimated set of grain-size ranges. These tests were performed in accordance with NBR-7181 (ABNT 1988), in proximity to the surface, and resulted in 40–45% coarse sand (>0.2 mm diameter), 25–30% fine sand (0.05–0.2 mm), 8–10% silt (0.002–0.05mm), and 15–17% clay (<0.002 mm). Therefore, a uniform distribution was considered the most suitable for the generation of pseudorandom values using NtRand®.

This same distribution fits the data regarding the amount of organic matter. This variable takes on values

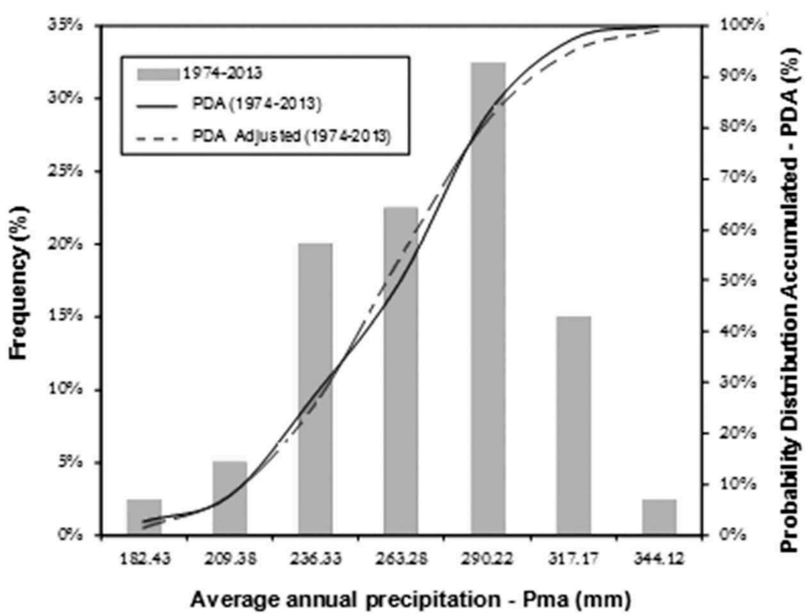

Figure 3. Probability distribution of P_{ma}.

ranging between 0.19 and 0.23%, based on a standard deviation of 10% around the average value of 0.21%. Thus, the conjunction of variables related to the morphology and chemical properties produces dependent terms, including M and r, which are components of Equation (9) that quantify the factor K. This equation is the result of the work of Levy (1995), which was based on an indirect estimation of the "Wischmeier nomogram"; its proposed representation is:

$$K = 7.5 \times 10^{-6} M + 44.8 \times 10^{-4} p - 6.3 \times 10^{-2} DMP + 10.4 \times 10^{-3} r \quad (9)$$

The value of the term M is derived from grain-size values, specifically the sum of the silt and the fine sand fractions multiplied by the sum of the silt, fine sand and coarse sand fractions. The term r is related to the product of the percentage of organic matter and the coarse sand fraction, divided by 100. The term p, obtained by the aforementioned nomogram, is related to five classes of permeability: 1 – fast; 2 – moderate to fast; 3 – moderate; 4 – moderate to slow; 5 – slow; and 6 – very slow. In this study, a moderate permeability (i.e. p = 3) was adopted. This adoption suggests that moderate permeability is likely in the region containing Sub-catchment II. Therefore, based on the geological features and the lack of information regarding this term, a uniform distribution was adopted as the best considering the minimum (p = 2) and maximum (p = 6). The DMP (the weighted average diameter of the fraction smaller than 2 mm (mm)) term for particles <2 mm in diameter is obtained by:

$$\text{DMP} = \sum C_i \times P_i \quad (10)$$

in which C_i refers to the midpoint of each texture range (in mm). The term P_i is related to the proportion of the textural class (g/g). The work by Zaroni (2006) yielded DMP values of 0.65 (coarse sand), 0.150 (fine sand), 0.0117 (silt) and 0.00024 (clay). Although the soil of Sub-catchment II typically consists of sandy silt, the soil variability indicated that the most appropriate distribution for that variable was a uniform one such that the maximum and minimum values of DMP were 0.65 and 0.58, respectively. Therefore, the adoption of uniform distributions for these variables in the stochastic simulation was due to the lack of information regarding such parameters as the amount of organic matter and the permeability; there was also the premise that the morphological soil properties are equiprobable values found in the intervals under consideration, as determined by texture tests.

It is emphasized that, although factor K estimates are different for a given soil type and draining condition, such as cited by El-Swaify and Dangler (1976) for dry soil and Lima *et al.* (1990) for saturated soil, the data available were not sufficient to evaluate their values before and after the drainage works. By this condition, the Levy (1995) proposition was adopted to estimate the factor K.

2.4 Monte Carlo simulation (MCS)

In addition to the information regarding the distributions of a particular variable and their statistical attributes (e.g. average, standard deviation), the MCS method requires a random sampling method. For the statistical attributes, the simple random sampling method (SRS) was used for the simulation of R and K. However, other methods such as Latin hypercube sampling (LHS) have been used; details can be found in Vose (2008).

In the SRS method, a random value is sampled at a particular distribution for each stochastic variable under study, which consisted of the annual average precipitation and the physical, chemical and morphological soil properties. The output value calculated on a deterministic basis, as expressed by Equation (2), is obtained by the combination of the distributions resulting from R and K – $f(R)$ and $f(K)$, respectively – and the factors considered to be deterministic, particularly CP and LS.

The MCS method allowed us to determine the sediment production allocation, $f(Y)$, via the following process:

(a) Production of random numbers for the variables considered to be stochastic, e.g. P_{ma}, to obtain R and the percentages of coarse and fine sand (CS and FS), silt (SIL), and organic matter (OM), and the values of p and DMP to obtain K; and
(b) Obtaining $f(Y)$ based on the probability distributions $f(R)$ and $f(K)$ combined with the average of CP and LS, which results in the estimate of the sediment production probability (additional details are presented below) based on the deterministic model of the universal soil loss equation.

Although it is beneficial to estimate the full range of characteristics of the distribution of the dependent variable using other methods, such as those of finite order, Gates and Al-Zahrani (1996) discussed the cost and computational disadvantages of the MCS method when analysing the real size and complexity of the problems. These disadvantages have been overcome by computational advances.

Sensitivity analysis is one of the advantages of the MCS method, and this analysis can be performed to determine the degree of influence of each factor on the uncertainty of the results. In this study, a sensitivity analysis was performed to quantify the stochastic factors that are most relevant to the uncertainty when quantifying Y (this quantification required the combination of deterministic factors CP and LS). Thus, a simple correlation coefficient (SCC) was calculated for the association between the jth stochastic ($x_1^j, x_2^j, \ldots, x_n^j$) and the corresponding vector response $\mathbf{Y}_1, \mathbf{Y}_2, \ldots, \mathbf{Y}_n$, which is given by:

$$\mathrm{SCC}(x^j, Y) = \frac{\sum_{i=1}^{n}\left(x_i^j - \mu_x^j\right)\left(Y_i - \mu_Y\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i^j - \mu_x^j\right)^2 \sum_{i=1}^{n}\left(Y_i - \mu_Y\right)^2}} \quad (11)$$

in which μ_x^j refers to the sample average of the stochastic factor x_j, associated with R and K; μ_Y is the average value of Y_i, associated with the production of sediment, Y; and n is the sample size. Thus, the factors that contribute most to the uncertainty response produce higher values of the SCC, as proposed by Salas and Shin (1999).

2.5 Procedure for estimating sediment production

After defining the stochastic factors as simulated by the MCS, and the deterministic factors that make up Equation (1), the production of sediment (Y) in Sub-catchment II was estimated for the periods before and after the improved urbanization and drainage construction. For this purpose, Equation (3) was applied to obtain the SPC. Based on the proposal of İrvem *et al.* (2007) for classifying the potential annual soil loss, the value of Y was qualified based on the value of A (t/ha) (Table 3).

In the first of the four stages of the adopted methodology, and based on the variability in the average annual precipitation simulated by a normal distribution, the morphological and chemical soil properties simulated by a uniform distribution, $f(R)$ and $f(K)$, respectively, were obtained.

The second stage consisted of a stochastic simulation to obtain the distribution resulting from the probability of Y, $f(Y)$, for the years 2008 and 2013. This distribution was used to characterize the interaction between the distributions $f(R)$ and $f(K)$, and the average values of $LS(\mu_{LS})$ and $CP(\mu_{CP})$. Thus, the probability of

Table 3. Degrees of classification of A (t/ha). VL: very low; L: low; M: moderate; S: severe; VS: very severe; and ES: extremely severe.

	Potential sedimentation classification					
	VL	L	M	S	VS	ES
A	<5	5–12	15–50	50–100	100–200	>200

Y may be classified in degrees. Also at this stage, the sensitivity of R, K, LS and CP to the estimates of Y based on Equation (11) was analysed for the period 2008–2013. A schematic diagram of these steps is shown in Figure 4.

The third phase of the methodology consisted of quantifying the value of A for each cell for the years 2008 and 2013 such that, as applied to Equation (2), the value of the spatial distribution of Y is obtained; this value characterizes the level of sediment production in the given catchment. Then, it is a spatial distribution of difference between $Y_{(2008)}$ and $Y_{(2013)}$, whose purpose is to indicate the reduction and/or increased production of sediment in Sub-catchment II. The procedure used in this step was based on the conjunction of the spatial distribution of CP and LS and average values of R and K (μ_R and μ_K, respectively), for the years considered.

The input values of the deterministic factors complemented the quantification of A and were obtained by assigning the CP factor (Table 1). This process was made possible by the development of a data matrix in which each pixel was associated with a square portion of the region (grid-cell size: 30 m × 30 m) such that each pixel contains the value of CP for the years 2008 and 2013 based on satellite images. The development of this data matrix also provided the LS factor. Thus, from the application of Equation (4), the value of L for each area of Sub-catchment II was obtained.

The ratio of the difference in elevation among the cells, which was obtained from the topographic contours, and the base of the cells, allowed us to calculate S, which was obtained by calculating the slope of each cell via Equation (6). The spatial distribution of the deterministic factors and the average value of Y (μ_Y) were obtained using the inverse-distance-to-a-power interpolation method (non-geostatistical).

3 Results and discussion

The stochastic simulation using the Monte Carlo method provided a deterministic response to the estimation of Y for the years 2008 and 2013, which was obtained in two ways. The first involved a simulation using 10 000 values of P_{ma} and the morphological, chemical and physical soil properties. The factors R and K were quantified, which resulted in certain statistical values: μ, the standard deviation (σ), the coefficient of variation (CV), tendency (MOD), and the distribution of probability (f). The second was the result of a deterministic consideration in which the values of LS and CP were estimated. Thus, A was obtained, and then the spatial distribution of Y, the distribution of $f(Y)$ and,

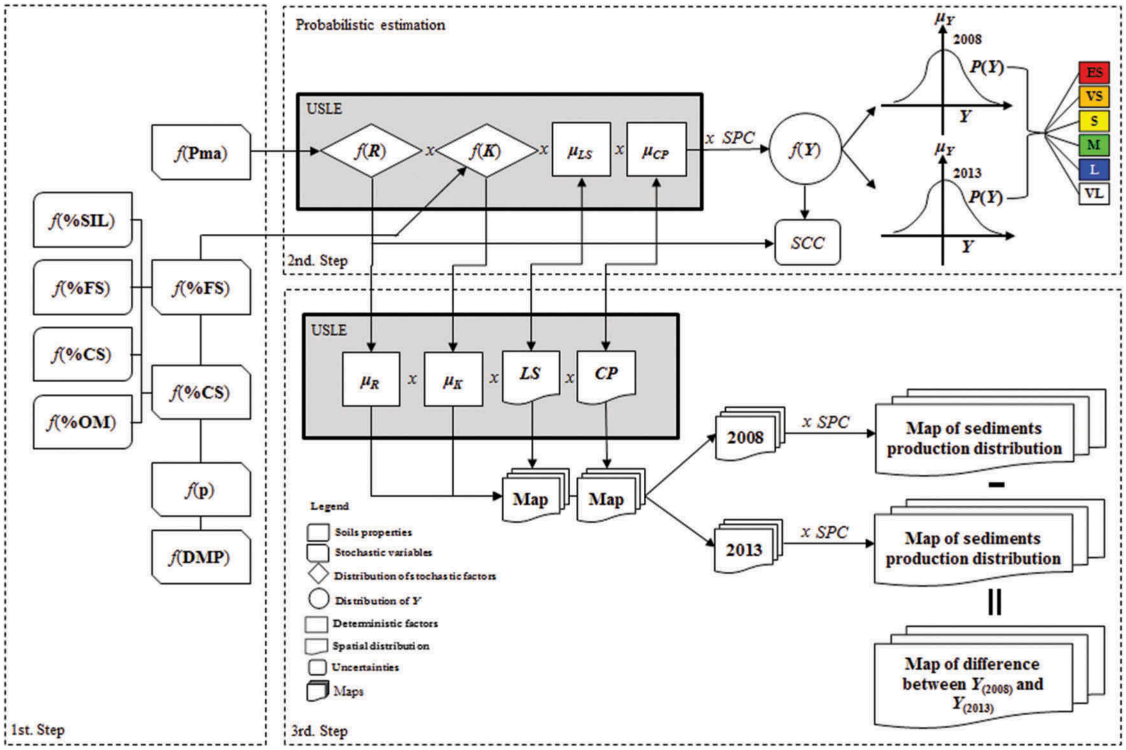

Figure 4. Scheme of the methodological process adopted.

subsequently, the sensitivity of the stochastic factors were obtained from the calculation of the SCC.

3.1 Stochastic factors R and K

The value of factor R was obtained from Equation (8) based on the annual average precipitation. The result was an annual average value of 553.12 MJ h ha mm h^{-1}, and the most frequent result was 538.66 MJ h ha mm h^{-1}, with a standard error of 32.52 MJ h ha mm h^{-1}. Figure 5(a) shows the histogram and cumulative probability distribution of R for a series spanning 39 years. The resulting distribution displayed positive asymmetry, with a Pearson index of 0. Although there is a small deviation between the simulated and adjusted cumulative distributions, an approximately log-normal (LN) trend was observed. A statistical summary of the simulation of this factor and the factor R is presented in Table 4.

Furthermore, the simulation of K (Fig. 5(b)) displayed a cumulative density that essentially overlaps the adjusted simulation produced by a normal distribution. This distribution was the result of K, i.e. the product of Equation (7) simulated by a uniform distribution of the variables M, r, p and DMP. Thus, the average value of K was 0.0116 t h MJ^{-1} mm^{-1}, and the standard error was 0.0077 t h MJ^{-1} mm^{-1}. The asymmetry was characterized by a Pearson index of 0.159 such that the distribution of K was classified as substantially symmetrical. A statistical summary of the simulation of factor K is also presented in Table 4.

In addition to providing the stochastic factors for estimating the sediment production of Sub-catchment II, the Monte Carlo method allowed us to estimate the probability of occurrence of certain values of the respective factors while taking into account the uncertainties and variability. Therefore, after having added the deterministic factors, it is possible to predict the result of future preventive actions, e.g. the dredging of the improved channels and construction of the detention basin, and to develop an understanding of the potential risks associated with the rainfall erosivity and soil erodibility in compromising the hydraulic performance of the respective channels.

3.2 Deterministic factors CP and LS

The spatial distribution of CP allowed the prediction of the changes associated primarily with two aspects of the catchment: the chronology of the large-scale drainage works and the urbanization dynamics. Before the large-scale drainage system was installed, slightly more than 78% of the land in Sub-catchment II was developed, and approximately 5% of the area's ground movements were concentrated along the banks of the canals, where there were unpaved roads (Fig. 6(a)).

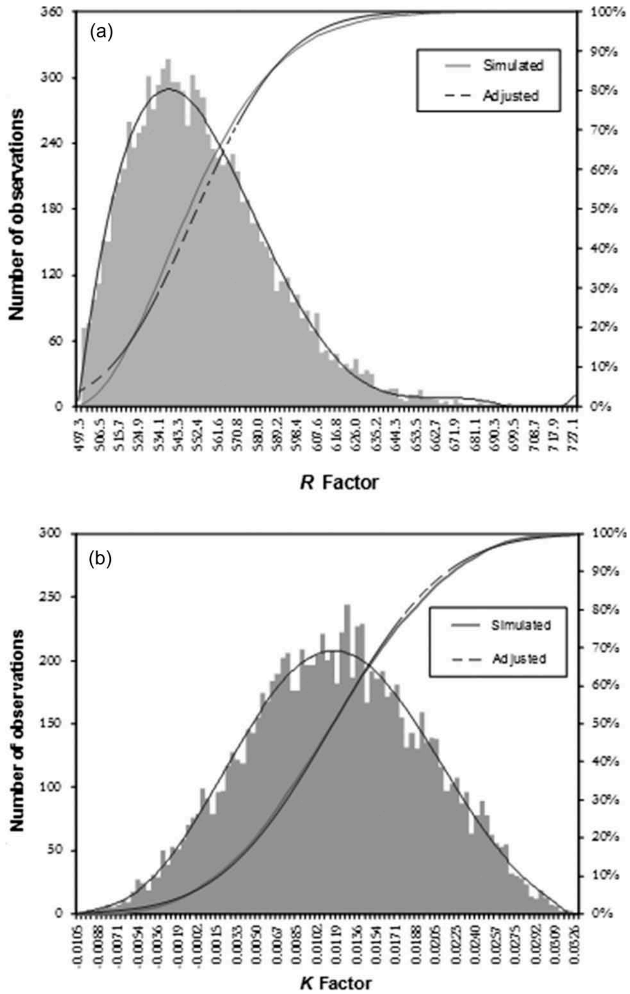

Figure 5. Graphs of (a) $f(R)$ resulting from R factor and (b) $f(K)$ resulting from K factor.

Table 4. Statistical summary of the R and K factors. μ: average; σ: standard deviation; CV: coefficient of variation; MOD: tendency; f: probability distribution. LN: log-normal; N: normal.

Stochastic factor	μ	σ	CV (%)	MOD	f
R (MJ h ha mm h^{-1})	553.12	32.52	5.88	538.66	LN
K (t h MJ^{-1} mm^{-1})	0.0116	0.0077	66.65	0.0128	N

Green areas covered slightly more than 16% of Sub-catchment II; these areas included squares, museums, parks, gardens and thickets of vacant lots. Such areas, especially at the edges of the channels, produced a prediction of greater intensity of erosion and, consequently, production of sediment delivered into the water bodies. In 2008, when μ_{CP} was equal to 0.593, at the location where the detention basin is currently being built, there was less potentially erodible area than in 2013. Furthermore, with a value of μ_{CP} of 0.456 in 2013, a reduction in potential erosion areas was verified.

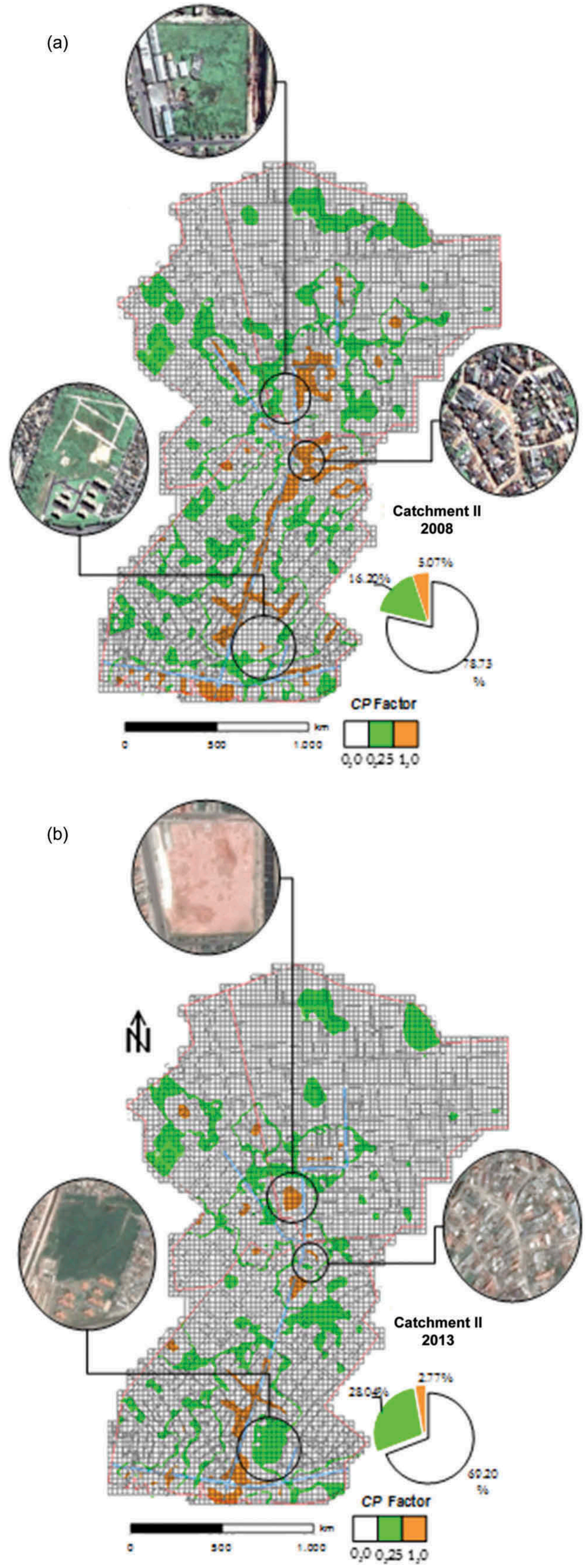

Figure 6. Spatial distribution of factor CP in (a) 2008 and (b) 2013.

This change can be explained by the partial paving of roads along the banks of the canals, which reduced the area susceptible to ground movement (Fig. 6(b)): in 2013, less than 3% of the catchment was susceptible to ground movement. This observation may be related to the fact that there are still areas susceptible to soil loss along the banks of CQB channel, farther downstream, where earthwork is still in progress. This may also be more evident in the area where the detention basin is under construction.

When compared to 2008, 2013 recorded a decrease in erodible areas. But, there was an increase in green areas due to thickets that developed near the QCL channel. Thus, 28.04% of Sub-catchment II was characterized by a forecast of potential erosion related to the dynamics of land use and soil conditions. In the context of the spatial distribution of *CP*, the predictions of erosion intensity of a particular type of soil may be more severe when associated with slope. Accordingly, there is proportionality between the *LS* factor and the increase in erosive force: greater values of these factors are associated with higher flow velocities.

Based on the topography of Sub-catchment II (Fig. 7), the steepest slopes were located upstream of the drainage channels, and the flow direction and flow accumulations converged in an area where the detention basin will be built.

However, the DTM (Fig. 8(a)) predicted nearly flat topography in Sub-catchment II, based on the most frequently estimated values of between 0% and 2%. The area of the detention basin contained a few slopes exceeding 5%. These areas are characterized as having potential for greater water velocities and jumps and, thus, greater erosive forces, which depend on the slope. The evaluation of L yielded a value of 561.76 m, and the value of k_c was equal to 2.23, thus indicating susceptibility to flooding and confirming the findings of Belém Municipal Law nº 8.655/08, de 30 de julho de 2008.

The values of L and S that result in the spatial distribution of LS are shown in Figure 8(b). The values of LS ranged between 2 and 3.5, and were concentrated in certain areas, particularly upstream of the main channels, yielding a value of μ_{LS} of 2.132. These results are close to the values obtained in the work of Gomide (2012), who obtained a value of μ_{LS} = 1.70.

Figure 7. Spatial distribution of altimetry in Sub-catchment II.

3.3 Spatial distribution of sediment production

Figure 9 show the spatial distribution of *Y*, which is the product of the SPC function. Prior to the work on the drainage system, slightly more than 83% of the Sub-catchment II area was classified as having a VL (Table 3) level of sediment production. Areas representing approximately 3 and 12% of the catchment were classified as having average and low degrees of sediment production, respectively (Fig. 9(a)).

After the partial construction of channel improvements, with the partial paving of roads, areas classified as M and L decreased as percentages of the Sub-catchment II area, i.e. 1.50 and 11.51%, respectively. More than 87% of Sub-catchment II was classified as VL in terms of *Y* (Fig. 9(b)). During both periods, most of Sub-catchment II showed sediment values of less than 237 t/km^2.

However, between the years 2008 and 2013, 8.5% of the space domain showed a reduction of over 100 t/km^2, while in 3.96% of Sub-catchment II, sediment production increased by up to 300 t/km^2. Figure 10 illustrates the spatial distribution of reduced/increased sediment production. The possible deposition of sediment in Sub-catchment II resulting from the intense estuarine hydrodynamics referred to in Section 1.1 should be noted; however, sediment yield between 2008 and 2013 remained unchanged. In the vicinity of the area where the construction of the detention basin was under way, there was an increase of sediment yield in 2013 compared to 2008.

These results are consistent with the values reported by Ellis (1996), who estimated values of annual sediment production of nearly 272 t/km^2 in certain European and North American cities, specifically in commercial areas, high-density residential areas and parks.

3.4 Probability of sediment production

The interaction of the probability distributions $f(K)$ and $f(R)$, average values of μ_{CP} and μ_{LS} and the SPC value of 0.397 (A_d = 4.04 km^2) resulted in a normal probability distribution of estimates of Y for the years 2008 and 2013 (Fig. 11).

The probability distributions for 2008 and 2013 remained essentially symmetrical, with a Pearson index of 0.102 for both distributions. The simulated and adjusted cumulative distributions nearly overlap, indicating a normal style of behaviour (N). The statistical summary for the Y simulation corresponding to the respective years is presented in Table 5.

In addition to providing the estimate of Y in Sub-catchment II, the MCS yielded classifications of VL to ES for the estimated probability. For example, the probability $P(Y)$ that Y would be classified as L in 2008 was 61.54%, and 59.83% for 2013 (Table 6). The probability that Y would be classified as M decreased after the partial execution of the drainage improvements. The value of $P(Y)$ was 6.10% in 2008, i.e. a classification of M, which then decreased to 1.75%. The probability that Y would be rated as S, VS or ES was zero. With respect to the areas of Sub-catchment II, the normal distribution was the result of the estimation of Y and the probability of sediment of this value of Y delivered to the water body.

It was observed that the increase in $P(Y)$ in terms of the sediment production in VL and L was related to the reduction of ground movement and soil cover between the two periods, i.e. they were associated with the changing dynamics in Sub-catchment II. Furthermore, the paving of roads and the control of water flow via drainage works contributed to this evaluation. Based on this estimated probability, it is possible to predict the need for dredging, i.e. the areas where sediment production is likely to silt the drainage channels and thereby affect their hydraulic function.

It is noteworthy that, even following the channel improvements, sediment production in the catchment can cause negative impacts, such as those mentioned earlier, e.g. changes in water quality, the hydrological regime and, in particular, flooding. The Estrada Nova catchment, specifically Sub-catchment II, is an area

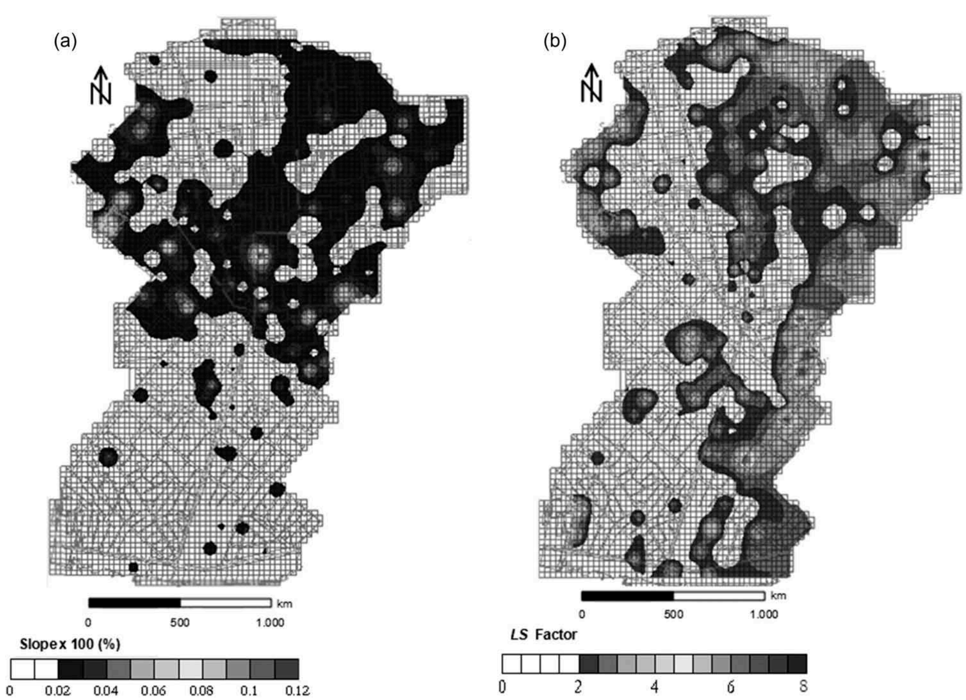

Figure 8. Spatial distribution of (a) slope and (b) *LS* factor.

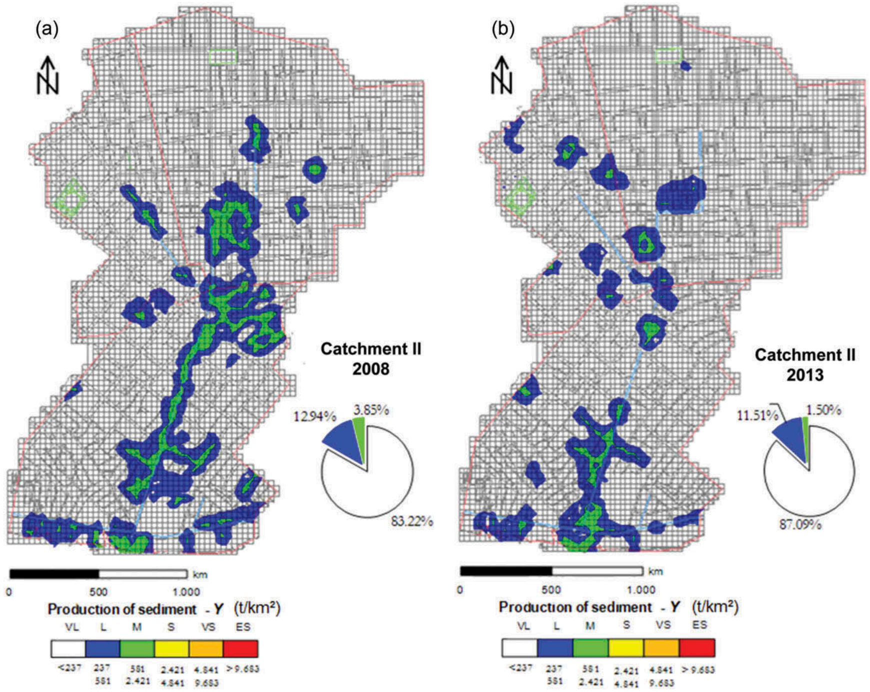

Figure 9. Spatial distribution of Y in (a) 2008 and (b) 2013.

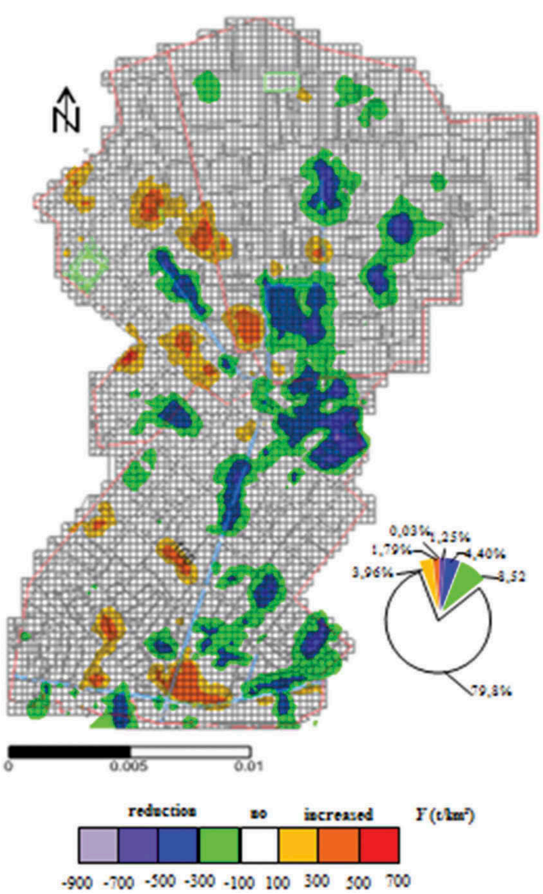

Figure 10. Spatial distribution of the difference between $Y_{(2008)}$ and $Y_{(2013)}$.

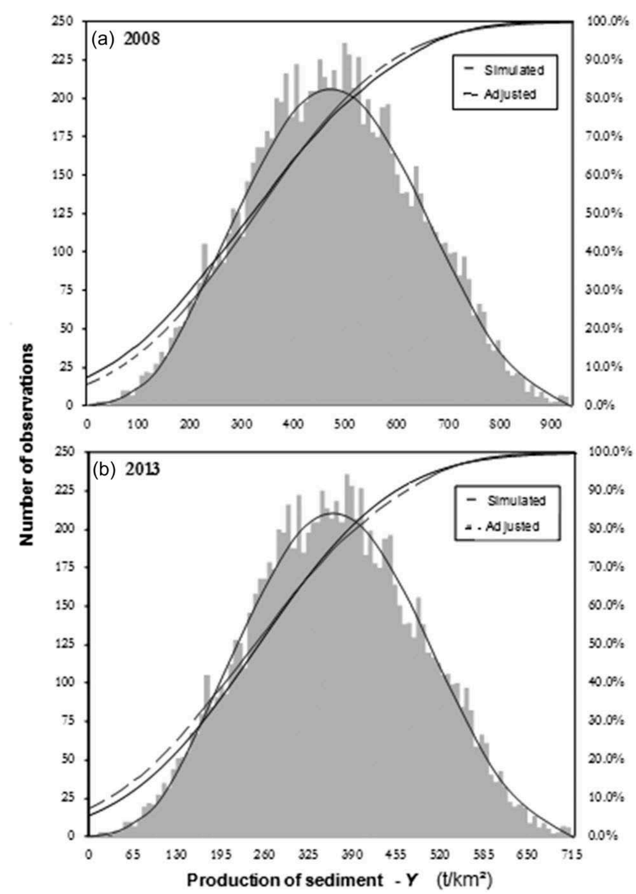

Figure 11. Graphs of $f(Y)$ for Sub-catchment II in (a) 2008 and (b) 2013.

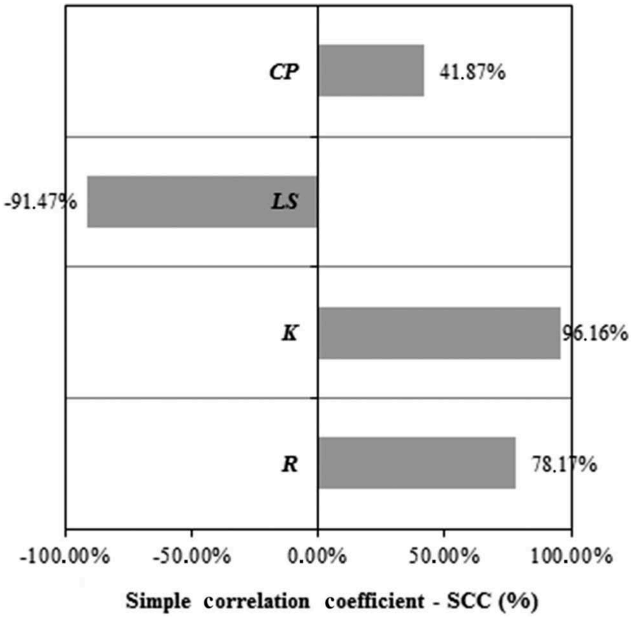

Figure 12. Sensitivity of factors *R*, *K*, *LS* and *CP*.

whose land-use dynamics are highly variable due to the increase in construction of civic works. Ellis (1996) estimated that the annual production of sediments from construction areas can reach 8400 t/km^2.

After estimating the probability, the sensitivity analysis of the stochastic factors indicated that *R* was the least important factor in estimating sediment production, independent of the area and the particular year. Furthermore, *K* exerted the strongest influence on the value of *Y* and is therefore the most important factor in quantifying the sediment production in the catchment (Fig. 12).

These results are in partial agreement with the study of Renard and Ferreira (1993), who stated that *K*, due to its greater variation from place to place, slightly outweighs *R*, which is not as important in predicting soil losses when using the USLE model. In these terms, *K* showed a relative value of SCC equal to 96.16%, while the *R* factor showed a relative sensitivity equal to 78.17%, to quantify the reduction of sediments from 2008 to 2013. The *CP* factor showed a relative influence, demonstrated by a SCC value of 41.87%. However, the smaller influence of the reduction was of the *LS* factor as the study area presents nearly flat conditions, as shown by the small height difference (SCC = −91.47%). Therefore, the *K* factor had the greater influence in the estimation of sediments production.

In addition to providing the values of *R* and *K* in the estimation of *Y* in Sub-catchment II, the MCS provided the average values for the spatial distribution, as well as the probability distribution. Thus,

Table 5. Statistical summary of *Y* in Sub-catchment II. See Table 4 for explanation of abbreviations.

Y (t/km^{-2})	μ	σ	CV (%)	MOD	*f*
2008	320.99	215.03	66.99	358.53	N
2013	246.94	165.42	66.99	275.82	N

estimates of the probability of *Y* could be classified and used to predict the sediment production potential, taking into account the uncertainty and variability of the stochastic factors.

4 Conclusions

Considering the stochastic variability of some of the parameters of the RUSLE model, the probabilistic estimation of sediment in an urban catchment was presented as an alternative to be used in the face of data limitations and in the absence of a sediment measurement network. However, even with these limitations, it should be emphasized that the methodology used is generic to the point of being used in other urban catchments, provided it considers some physical characteristics.

Thus, with the objective of estimating sediment production in an urban catchment, this study was conditioned on parametric uncertainties and data shortage. Therefore, a probabilistic approach was adopted, considering two important moments in the dynamics of the land use: before and after the urbanization process, which included works that artificially drained the channels of the studied catchment.

The results suggest that, for the specific case of the urban catchment analysed, the probability of sediment production before urbanization was relatively higher than the estimates made after urbanization. Although this finding was expected, it was possible to estimate probabilistically by the methodology used. It was also possible to analyse the sensitivity of each of the parameters of the RUSLE model. In the specific case, because it is an urban catchment with almost flat topography, the *LS* factor was considered as having little significance for the estimation of sediment production. However, for the conditions adopted, the factors *K* and *R* are the ones that contribute most to the generation of uncertainties in the estimation of sediment production in relation to the *CP* factor.

Table 6. Estimates of the probability of *Y*, *P*(*Y*), in Sub-catchment II. See Table 3 for explanation of abbreviations.

	P(Y) (%)					
Year	VL	L	M	S	VS	ES
2008	28.40	61.54	10.06	0.0	0.0	0.0
2013	38.42	59.83	1.75	0.0	0.0	0.0

It is emphasized that the results obtained considered only the factors *K* and *R* as stochastic; the other factors were treated deterministically. Nevertheless, the results of the probabilistic estimation can be altered if another type of algorithm is used to generate pseudo-random numbers (e.g. Latin hypercube sampling). In the same way, the sensitivity analysis can also be changed if another type of coefficient is used (e.g. the coefficient of correlation).

Finally, it should be noted that, although probabilistic results are an alternative in the sediment management process in urban catchments, this study should be calibrated and validated by the inclusion of a range of temporal and spatial data, to consider all the parameters as stochastic and to use experimental techniques. Therefore, the obtained results should not be taken as assertive and final, but rather as an indicator or probable estimator of occurrence and that, eventually, these can be altered in the face of the dynamics of the use and occupation of the soil.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

ABNT (Brazilian Association of Technical Standards), 1988. *NBR – 7181: "Granulometric Soil-Analysis"*. ABNT.

Alencar Jr., J.A. and De Souza, R.R., 2006. Geotechnical parameters of a soil structured the metropolitan region of Belém (in Portuguese). *In*: *XIV Brazilian Congress of Soil Mechanics and Geotechnical Engineering*. 1–5.

Arabi, M., Govindaraju, R.S., and Hantush, M.M., 2007. A probabilistic approach for analysis of uncertainty in the evaluation of watershed management practices. *Journal of Hydrology*, 333 (2–4), 459–471. doi:10.1016/j.jhydrol.2006.09.012

Arnold, J.G., *et al.*, 2005. *Soil and water assessment tool theoretical documentation version 2005*. Texas: Agricultur Research Servic US [terhubung berkala]. http://www. http. brc. tamus. edu/swat/document. html.

Barros, M.D.L.C., *et al.*, 2011. A water flow pattern analysis of Guajará Bay: Amazon Estuary – Brazil. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 33 (1), 79–85. The Brazilian Society of Mechanical Sciences and Engineering. doi:10.1590/S1678-58782011000100012

Belém, Municipal Law nº 8.655/08, de 30 de julho de, 2008. Provides for the Master Plan of the city of Belém, and other measures (in Portuguese). *In*: *Diário Oficial [do Estado do Pará]. Pará, v. 03, n. 6, p.70, 30. out. 2008, Seção. 1, pt.*

Biesemans, J., Meirvenne, M.V., and Gabriels, D., 2000. Extending the RUSLE with the Monte Carlo error propagation technique to predict long-term average off-site sediment accumulation. *Journal of Soil and Water Conservation*, 55 (1), 35–42. Available from: http://www.jswconline.org/content/55/1/35.abstract.

Bingner, R.L. and Theurer, F.D., 2001. AnnAGNPS: estimating sediment yield by particle size for sheet and rill erosion. *In*: *Proceedings of the Seventh Interagency Sedimentation Conference*. Reno, NV: US DA-Agricultural Research Service, 1–7.

Blanco, C., *et al.*, 2013. Hydrodynamic evaluation of a flood embankment in the Amazon estuary region, Brazil. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, 166 (6), 49–55. ICE Publishing. doi:10.1680/cien.13.00004

Dawdy, D.R., 1967. Knowledge of sedimentation in urban environments. *Journal of the Hydraulics Division*, 93 (6), 235–245. ASCE.

Di Stefano, C., Ferro, V., and Porto, P., 1999. Linking sediment yield and Caesium-137 spatial distribution at basin scale. *Journal of Agricultural Engineering Research*, 74 (1), 41–62. doi:10.1006/jaer.1999.0436

Ellis, J., 1996. Sediment yield and BMP control strategies in urban catchments. *In*: *Proceedings Erosion and Sediment Yield: Global and Regional Perspectives,* July. Exeter: IAHS.

El-Swaify, S.A. and Dangler, E.W., 1976. *Erodibilities of selected tropical soils in relation to structural and hydrologic parameters.In: National Conference on Soil Erosion, Proceedings,* West Lafayette, IN. Ankeny, IA: SWCS, 105–110.

Engesolo, 2007. *Preparation of studies and basic designs for the preparation of the macro drainage program watershed – PROMABEN (Technical Report in Portuguese).* Belo Horizonte.

Flanagan, D.C. and Nearing, M.A., 1995. U.S. DA-Water Erosion Prediction Project (WEPP) Hillslope Profile and Watershed Model Documentation. *In: NSERL Report No. 10, National Soil Erosion Research Laboratory*. West Lafayette, IN: US DA-Agricultural Research Service.

Fu, B.J., *et al.*, 2005. Assessment of soil erosion at large watershed scale using RUSLE and GIS: a case study in the Loess Plateau of China. *Land Degradation & Development*, 16 (1), 73–85. John Wiley & Sons, Ltd. doi:10.1002/ldr.646

Gates, K.T. and Al-Zahrani, A.-Z.M., 1996. Spatiotemporal stochastic open-channel flow. I: model and its parameter data. *Journal of Hydraulic Engineering*, 122 (11), 641–651. American Society of Civil Engineers. doi:10.1061/(ASCE)0733-9429(1996)122:11(641)

Gomide, I.S., 2012. *Modelling of soil loss in small watershed Amazon by USLE Model. 73f.* Master's thesis. Federal

University of Pará, Postgraduate Program in Civil Engineering, Belém, PA.

Gregório, A.M.D.S. and Mendes, A.C., 2009. Characterization of sedimentary deposits at the confluence of two tributaries of the Pará River estuary (Guajará Bay, Amazon). *Continental Shelf Research*, 29 (3), 609–618. doi:10.1016/j.csr.2008.09.007

İrvem, A., Topaloğlu, F., and Uygur, V., 2007. Estimating spatial distribution of soil loss over Seyhan River Basin in Turkey. *Journal of Hydrology*, 336 (1), 30–37. doi:10.1016/j.jhydrol.2006.12.009

Kim, J.B., Saunders, P., and Finn, J.T., 2005. Rapid assessment of soil erosion in the Rio Lempa Basin, Central America, using the universal soil loss equation and geographic information systems. *Environmental Management. United States*, 36 (6), 872–885. doi:10.1007/s00267-002-0065-z

Kinnell, P.I.A., 2005. AGNPS-UM: agricultural non point source pollution model using the USLE-M. *In*: *User guide, version 4.02*. Australia: University of Canberra.

Levy, M.C.T.C., 1995. *Scenarios of agricultural production evaluation to the sustainability of land use in Piracicaba (SP). 104 f.* Master's thesis. University of São Paulo, Piracicaba.

Lightle, D., 2007. Revised Universal Soil Loss Equation, Version 2 (RUSLE2). *Official NRCS RUSLE2 Program. Official NRCS Database*. Available from: http://fargo. nserl. purdue. edu/rusle2_dataweb/RUSLE2_Index. htm (verified 4-23-07).

Lim, K.J., *et al.*, 2005. GIS-based sediment assessment tool. *Catena*, 64 (1), 61–80. doi:10.1016/j.catena.2005.06.013

Lima, J.M., *et al.*, 1990. Dispersion of soil material in water for indirect evaluation of latosol erodibility. *Revista Brasileira de Ciência do Solo*, 14 (1), 85–90.

Mills, W.B., 1985. Water quality assessment: A screening procedure for toxic and conventional pollutants in surface and ground water. *In*: *Environmental Research Laboratory, Office of Research and Development*. Parts 1 and 2. PB86-122496 and PB86-122504. Athens, GA: US Environmental Protection Agency (US EPA).

Morgan, R.P.C., *et al.*, 1998. The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surface Processes and Landforms*, 23 (6), 527–544. John Wiley & Sons, Ltd. doi:10.1002/(SICI)1096-9837(199806)23:6<527::AID-ESP868>3.0.CO;2-5

Paiva, J.B.D., Paiva, E.M.C.D., and Vilella, S.M., 1995. Sediment discharge review tributary to the capture of the lift station I transposition project of the San Francisco River waters. *RBE – Water Resources Notebook (Brasilian Maganize of Water Resources)*, 13 (2), 47–79.

Pejrup, M., 1988. The triangular diagram used for classification of estuarine sediments: a new approach. *Tide-Influenced Sedimentary Environments and Facies*. doi:10.1007/978-94-015-7762-5_21

Pinheiro, R.V.L., 1987. *Hydrodynamic and sedimentological study of Guajará-Belém (Pará) Estuary. 163f.* Master's thesis. Geosciences Institute, Federal University of Pará, Belém.

Renard, K., *et al.*, 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). *In*: *Agricultural Handbook*. Washington, DC: US Department of Agriculture.

Renard, K.G. and Ferreira, V.A., 1993. RUSLE model description and database sensitivity. *Journal of Environmental Quality*, 22, 458–466. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. doi:10.2134/jeq1993.00472425002200030009x

Rompaey, A.J.J.V. and Govers, G., 2002. Data quality and model complexity for regional scale soil erosion prediction. *International Journal of Geographical Information Science*, 16 (7), 663–680. Taylor & Francis. doi:10.1080/13658810210148561

Salas, J.D. and Shin, H.-S., 1999. Uncertainty analysis of reservoir sedimentation, *Journal of Hydraulic Engineering*, 125 (4), 339–350. American Society of Civil Engineers. doi:10.1061/(ASCE)0733-9429(1999)125:4(339)

Sohrabi, T.M., *et al.*, 2003. Uncertainty analysis of hydrologic and water quality predictions for a small watershed using SWAT2000. *Environmental Forensics*, 4 (4), 229–238. Taylor & Francis. doi:10.1080/714044368

Stein, D.P., *et al.*, 1987. Erosion potential laminar natural and anthropogenic the fish-paranapanema catchment. *National Symposium on Erosion Control*, 4, 105–135.

Van Griensven, A. and Meixner, T., 2006. Methods to quantify and identify the sources of uncertainty for river basin water quality models. *Water Science and Technology*, 53 (1), 51 LP–59. doi:10.2166/wst.2006.007

Vanoni, V.A., 1975. Sedimentation Engineering: American Society of Civil Engineers. *Manuals and Reports on Engineering Practice*, 54, 745.

Veihe, A. and Quinton, J., 2000. Sensitivity analysis of EUROSEM using Monte Carlo simulation I: hydrological, soil and vegetation parameters. *Hydrological Processes*, 14 (5), 915–926. John Wiley & Sons, Ltd. doi:10.1002/(SICI)1099-1085(20000415)14:5<915::AID-HYP978>3.0.CO;2-4

Vose, D., 2008. *Risk analysis: a quantitative guide*. Chichester: John Wiley & Sons.

Wischmeier, W.H., 1965. Predicting rainfall-erosion losses from cropland east of the rocky mountain, guide for selection of practices for soil and water conservation. *In*: *Agricultural handbook*. USDA, 282. Washington, DC: US Department of Agriculture.

Wischmeier, W.H. and Smith, D.D., 1978. Predicting rainfall erosion losses: A guide to conservation planning. *In*: *Agricultural handbook*. Washington, DC: US Department of Agriculture.

Zaroni, M.J., 2006. *Estimation of sediment yield in watersheds from the USLE model and Sediment Transfer Rate (SDR). 143 f.* Master's thesis. Postgraduate Program in Geography of Federal University of Rio de Janeiro (PPGG/UFRJ).