

Quantifying soil erosion and sediment yield in a catchment in southern Brazil and implications for land conservation

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Received: 20 January 2015 / Accepted: 16 May 2015 / Published online: 12 June 2015
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Abstract

Purpose Although agriculture represents about 30 % of Brazil's GDP, there are few data at the catchment scale on land use, soil management, hydrology, and water quality.

Materials and methods This study aimed to investigate the connections between current soil management practices in the southern Brazilian Plateau and their impacts on soil erosion, sediment yield, and streamflow. The monitoring was performed in a rural catchment with significant evidence of soil erosion and surface runoff despite widespread use of no-till. Streamflow (Q) and suspended sediment concentration (SSC) were measured over 2 years (2011 and 2012).

Results and discussion The study shows that elevated gross erosion values in the catchment are associated with areas of potentially high surface runoff and low soil infiltration, possibly caused by inadequate soil management practices and excessive soil compaction. It was also noted that a large area in the catchment had higher soil loss rates than the limits considered acceptable for both the region and the tillage system.

Conclusions Results indicate that there are significant environmental problems associated with surface runoff and sediment yield under the no-till system of soil conservation as currently practiced in this catchment.

Keywords Catchment · Modeling · Monitoring · No-tillage system · Sediment yield · Southern Brazil

1 Introduction

Worldwide, the no-tillage (no-till) system is utilized to reduce soil erosion on 105 million hectares, of which 49.5 million can be found in Latin America, 70 % of which occur in Brazil (Derpsch and Friedrich 2009). Despite the large number of studies about soil erosion in Brazil, there are few studies on the effectiveness of conservation agriculture at the catchment scale. The study of soil erosion has been restricted to natural rainfall erosion plots (Basic et al. 2004; Bagarello et al. 2008; Sasal et al. 2010), with differences in soil type, land use, soil management, and precipitation. However, more studies at the catchment scale are needed to better extrapolate soil erosion/sediment yield across scales (Lal 1978; Slaymaker 2006; Walling and Collins 2008; de Vente et al. 2013; Lee et al. 2013) and to assess and quantify the impacts of agriculture on water resources (Kaiser et al. 2010; Tiecher et al. 2014).

Although Brazil cultivates almost 50 million hectares of land using the no-till system, there is no national program promoting soil conservation (Merten et al. 2013), and hydrological and soil erosion processes at the catchment scale are not well documented. Currently, the farming systems have failed in controlling soil erosion during high-magnitude storm events (2-year or greater floods). Large rainfall events can produce a large volume of surface runoff due to reduced infiltration rate (caused by soil compaction), insufficient cover crops (especially in soybean crops), and downhill farming without terraces. As a consequence, soil erosion in no-till crop fields has been observed more frequently than when compared with a few years ago, when no-till was accompanied by cover crops, crop rotation, contour farming, and terraces (Didoné

Responsible editor: Rajith Mukundan

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et al. 2014). A better understanding of these hydrologic and soil erosion aspects would help demonstrate the real impact of current farming systems on soil and water resources and serve as a starting point toward establishing a national soil and water conservation program.

The quantification of erosion processes at the catchment scale can be established when distributed erosion models are combined with streamflow and sediment flux monitoring at the catchment outlet (Park et al. 2006; Knapen et al. 2007). Erosion models are an important tool not only in identifying “erosion hot spots” in a catchment but also in estimating gross erosion (Kinnell 2010; Okoro et al. 2013; Barros et al. 2014), whereas discharge (Q) and suspended sediment concentration (SSC) monitoring at the catchment outlet is important to quantify the sediment yield (Horowitz 2003; Merten et al. 2006). The sediment delivery ratio (SDR) can also be estimated based on the total erosion in the catchment—including interrill, rill, gullies, roads, and streambanks (hereinafter called gross erosion)—compared to the sediment yield data. The SDR represents a percentage of gross erosion that is transferred from fields to waterways, with its value dependent on several factors such as catchment size and geomorphology, soil degradation stage, and connectivity between fields and waterways (de Vente et al. 2007; Moreno-de las Heras et al. 2010). Foster et al. (1980), for example, state that approximately 70 % of sediments mobilized in fields can be deposited before reaching the waterways. However, this is dependent on catchment size and the geomorphology of the landscape—both past and present, natural and anthropogenic (de Vente et al. 2007)—soil degradation stage (Moreno-de las Heras et al. 2010), and the connectivity between fields and streams. This percentage can vary considerably with the presence of riparian zones and buffer strips.

Based on the hypothesis that the no-tillage system currently being used is less effective at reducing erosion and sediment yield, this study aimed to verify this by monitoring sediment yield and modeling gross erosion at the catchment scale. This information is important in determining the real impact of current farming systems on the degradation of soil and water resources in southern Brazil. Only by being aware of the real impact of such farming systems are we able to suggest better soil conservation and management practices.

2 Material and methods

2.1 Description of the study area

The study was conducted in southern Brazil in the Conceição River catchment (Fig. 1), located in the northwest part of the state of Rio Grande do Sul, with a drainage area of 800 km². The monitoring section is located at 28° 27' 22" S and 53° 58' 24" W. According to Köppen, the climate is Cfa, humid

subtropical with no dry season, with an annual rainfall variation between 1750 and 2000 mm, and an average temperature of 17 °C. The local geology is basalt with the formation of deep and highly weathered soils. The local soil classes are oxisols, ultisols, entisols, and alfisols, with the first two being the most prevalent in the catchment. The relief is characterized by long slopes 300 to 600 m in length, gentle (6–9 %) at the top, and hilly (10–14 %) near the river.

In summer, monoculture of soybeans (*Glycine max* L.) is predominant, although there are small areas of soybeans in rotation with corn, sunflower, and sorghum. In the winter, there is widespread crop rotation of wheat (*Triticum* spp.), oats (*Avena strigosa* S.), and ryegrass (*Lolium multiflorum*), with oats and ryegrass being used as cover crops and pasture. Soil management consists mainly of no-till farming with little increase in biomass (less than 3 Mg ha⁻¹ year⁻¹ of dry matter) despite the official recommendation according to Denardin et al. (2009) of 6 Mg ha⁻¹ year⁻¹ of dry matter. There are no runoff control measures such as terraces, strip farming, vegetated ridges, or contour farming. Other land uses (approximately 15 % of the catchment) consist of native and planted forests as well as wetlands, paddocks, roads, and urban areas.

2.2 Hydrology and sediment flux monitoring

Regardless of the scale, erosion studies require the monitoring of soil and water loss to assess sediment sources as well as its controlling factors, a task that becomes even more complex at the catchment scale. In this study, surface runoff and SSC were monitored from February 2011 to January 2013. The surface runoff was estimated from gauge height readings with a rating curve. The water level was measured every day by both a local observer and using a limnigraph (pressure sensor) at 10-min intervals.

The SSC was estimated based on a combination of daily sampling and sampling carried out during several rainfall–runoff events (rising and falling streamflow). Additionally, in situ turbidity data collected at 10-min intervals were used to estimate SSC using a correlation equation between turbidity in nephelometric turbidity units (NTU) and SSC (mg l⁻¹) based on data from rainfall–runoff events. It is important to emphasize that during this period, there were several rainfall events of significant duration, frequency, and intensity (Figs. 2 and 3).

The sediment discharge (kg s⁻¹) was obtained by multiplying the instantaneous Q (l s⁻¹) by the SSC (mg l⁻¹), which, integrated over time, provided the sediment yield (SY) (t year⁻¹).

2.3 Estimates of gross erosion

The Revised Universal Soil Loss Equation (RUSLE) equation model enabled gross erosion (the sum of rill erosion and

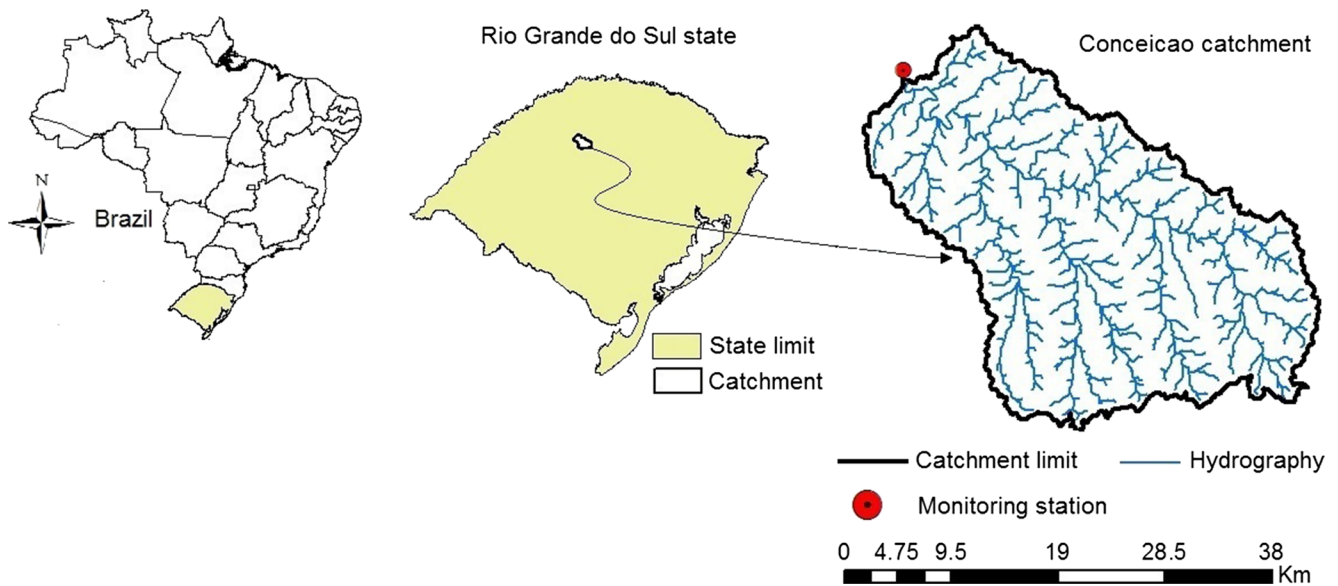


Fig. 1 Location and stream network of the Conceição River catchment, southern Brazil

interrill erosion) to be estimated (Renard et al. 2011). This equation is defined by:

$$A = R * K * L * S * P * C \quad (1)$$

where A is the soil loss ($\text{t ha}^{-1} \text{ year}^{-1}$), R is the rainfall erosivity ($\text{MJ mm ha}^{-1} \text{ h}^{-1}$), K is a soil erodibility factor ($\text{t ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$), LS is the combined length of the ramp with the slope factor, C is a factor of cover crop management, and P is the support practice factor. With the exception of urban areas, roads, and the drainage network, the equation was applied to all other areas of the catchment (i.e., crops, pastures, and forests). The soil loss estimated by RUSLE represents the long-term annual average established by the 40-year records of existing climate data used when calculating

erosivity and by the 10 years of soil use and land management data.

It is important to highlight that, whenever possible, factors were calculated following specific local selection criteria parameters and equations. In the calculation of R and K factors, equations developed for the study site were used. The L factor included the current complexity in the catchment, and data from the cover crops used in the catchment were used to determine the C factor.

The RUSLE model was run within a geographical information system (GIS) environment. Individual GIS files were created for each factor in the RUSLE and combined by cell grid modeling to predict gross erosion in a spatial domain.

Fig. 2 Average monthly rainfall over a long-term period (40 years) and for the years of monitoring (2011 and 2012)

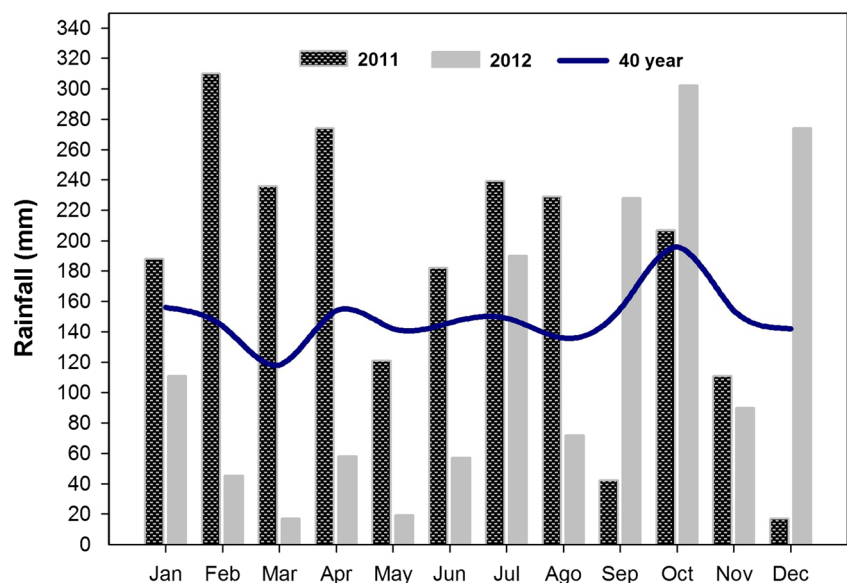
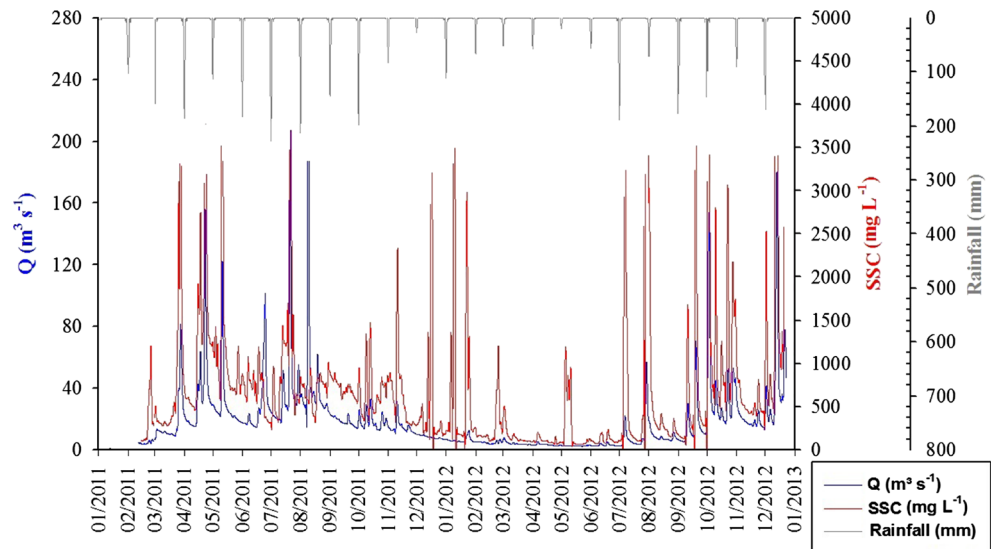


Fig. 3 Streamflow (Q) and suspended sediment concentration (SSC) from March 2011 to December 2012 in the Conceição River



2.3.1 Erosivity factor (R)

Data (40-year records) from a National Water Agency (ANA) rainfall monitoring station and a National Institute of Meteorology (INMET) monitoring station, both situated within the catchment, were used to estimate the annual average rainfall. The amount of rainfall erosivity (R) was calculated with an equation developed by Cassol et al. (2007) specifically for the region:

$$EI_{30} = 109.65 * Rc^{0.76} \tag{2}$$

where EI_{30} is the rainfall erosivity index ($MJ\ mm\ ha^{-1}\ h^{-1}$) and Rc is the rainfall coefficient in millimeters ($Rc = p^2/P$, where p is the monthly precipitation in mm and P is the total annual precipitation in mm). The calculated value for erosivity was $8978\ MJ\ mm\ ha^{-1}\ year^{-1}$, which is close to the $8825\ MJ\ mm\ ha^{-1}\ year^{-1}$ annual average estimated by Cassol et al. (2007) for the same region.

2.3.2 Erodibility factor (K)

The K factor represents the susceptibility of soil to erosion by splash and runoff detachment. Soil texture, organic matter, structure, oxides, and permeability determine the erodibility of a particular soil. The erodibility (Table 1) was calculated with equations developed by Roloff and Denardin (1994) for Brazilian soils. Soil erodibility in the catchment was calculated by determining physical and chemical parameters measured in different soils present in the catchment. Therefore, 150 samples representing the spatial variability of soil in the catchment were collected and analyzed.

2.3.3 Topographic factor (LS)

The LS factor is composed of length (L) and slope (S). The LS factor (Eq. 3) was calculated based on the work of Moore and Burch (1986). This method for spatial representation of the LS factor calculation enabled us to estimate the spatial distribution of the topographic factor considering the influence of hillslope forms in the slope length at the catchment scale (Minella et al. 2010).

$$LS = \left(\frac{A_s}{22.13} \right)^{0.4} \left(\frac{s}{0.0896} \right)^{1.3} \tag{3}$$

where LS represents the topographic factor, A_s is the cumulative drainage area divided by the width of the cross section of the hydrological unit at the river outlet, and s is the slope gradient (%). This was calculated with the aid of a GIS software from the digital elevation model of the catchment.

2.3.4 Land use and soil management factor (C)

The C factor indicates the long-term combined effects of land use and soil management. It is used to express how the crops affect erosion rates. Thus, the calculation of the C factor depends on the seasonal effect of agricultural crops and is balanced by the temporal variability of erosivity, using:

$$C = \sum_{i=1}^{i=n} (RPS_i * EI_{p_i}) \tag{4}$$

where the subscript i refers to the rotation period (month), EI_p is the fraction of total erosivity for the period i , and RPS is the

Table 1 Erodibility index and area of the soils of the Conceição catchment

Main soil class		Erodibility ^a	% area ^b
FAO	Embrapa (2006)		
Ferralsols	Latossolo Vermelho distrófico típico	0.0115	23.6
Ferralsols	Latossolo Vermelho distroférico típico	0.0134	52.1
Ferralsols	Latossolo Vermelho aluminoférrico húmico	0.0159	4.7
Nitisols	Nitossolo Vermelho eutroférico típico	0.0035	17.6
Acrisol, lixisols	Argissolo Vermelho distrófico típico	0.0375	2.0

FAO Food and Agriculture Organization

^a t ha h ha⁻¹ MJ⁻¹ mm⁻¹

^b % area of the total catchment

ratio of soil loss. The RPS is calculated by multiplying the four subfactors: CD_i , CS_i , UA_i , and RS_i .

$$RPS_i = CD_i * CS_i * UA_i * RS_i \quad (5)$$

where CD is the effect of soil cover by areal vegetation, CS is the effect of cover crop residue, UA is the effect of previous use, and RS is the random surface roughness. The C factor values and the respective subfactors for the different scenarios are shown in Table 2.

Soil cover was used to determine stages during the crop cycles. Five crop cycle stages were then determined: stage 1 corresponds to the period from sowing to 10 % soil cover, stage 2 from 10 to 30 % soil cover, stage 3 from 30 to 50 % soil cover, stage 4 from 50 to 75 % soil cover, and stage 5 from 75 % soil cover to harvest. The values of all subfactors were obtained by considering the characteristics of each crop as well as soil management and the agricultural calendar. Due to the large area of the catchment (800 km²), it is impossible to determine each subfactor in Eq. 5 for all areas of the catchment. Thus, three scenarios (Table 4) that match the different patterns of soil use and land management commonly used by farmers were defined.

Scenario I corresponds to the best case scenario: continuous use of conservation practices, crop rotation (soybean/turnip/oats/corn), and cover crops for most of the year. Scenario II represents an intermediate condition most commonly found in the catchment: partial use of conservation practices and continued crop rotation repeated annually (soybean/oats/wheat/soybean). Scenario III represents the worst case scenario: no or insignificant use of conservation practices, sparse soil cover, and the predominance of monocrop farming (soybean/

fallow/soybean). Thus, three values for the C factor were calculated in detail for each scenario.

2.3.5 Conservation practice factor (P)

The P factor is generally seen as reflecting the positive impacts of management through runoff control, with special emphasis on how management changes the direction and speed of runoff, but also reflecting management practices that control the amount of runoff. Traditionally, the P factor has been used to reflect the impact of agricultural practices such as the various forms of strip cropping (buffer strips, filter strips, rotational strip cropping), terraces, contour farming, and subsurface drainage (Renard et al. 2011). The only conservation practice used, and used rarely, in the Conceição catchment is contour farming, and even when it is used, it is not ongrade. Equation 6 was applied to estimate the influence of contour farming in the catchment:

$$P_g = P_o + (1 - P_o) \left(\frac{s_f}{s_1} \right)^{1/2} \quad (6)$$

where P_g is the P factor for offgrade contour farming, P_o is the P factor for ongrade contour farming, s_f is the slope along the contour seeding row (a mean value of 0.45 was chosen for the croplands of the entire catchment), and s_1 is the slope of the terrain.

2.4 Sediment delivery ratio (SDR)

The sediment delivery ratio represents the portion of the total amount of soil mobilized by erosion (gross erosion) which is

Table 2 Values of the coverage factor (C) and their subfactors for the different scenarios in the Conceição River catchment

Main scenarios ^a	C	CS	CD	UA	RS
Scenario I: soybean/turnip/oats/corn	0.0115	0.1065	0.5053	0.1706	0.9694
Scenario II: soybean/oats/wheat/soybean	0.0208	0.5761	0.1422	0.2362	0.9809
Scenario III: soybean/fallow/soybean	0.1027	0.6152	0.5217	0.2903	0.9807

^a Main simulated scenarios for different uses

transferred to the catchment outlet. According to Walling (1983), the difficulty in producing a generally applicable SDR prediction equation is partly due to the complexity of sediment delivery processes and their interaction, and partly to a lack of definitive assessments of the dependent variable. In this study, SDR was estimated by the ratio of sediment yield measured during the monitoring period and gross erosion estimated by RUSLE. For comparison, the SDR was estimated using equations presented in Table 3. The comparison between the SDR estimated by sediment yield data and the SDR estimated using the catchment’s parameters is important to establish the real ability of empirical relations to represent the SDR of this catchment.

3 Results and discussion

3.1 Streamflow monitoring

The 2 years of monitoring were characterized by two distinct conditions: a long period of drought in 2012 and high-magnitude rainfall events in 2011 (Fig. 2). According to the National Water Agency, the daily average surface runoff in the catchment from 2000 to 2012 was $21.5 \text{ m}^3 \text{ s}^{-1}$. In 2011, the average daily surface runoff measured was $25.0 \text{ m}^3 \text{ s}^{-1}$, while in 2012, the average daily streamflow was $14.4 \text{ m}^3 \text{ s}^{-1}$ (30 %

less than the daily average surface runoff from 2000 to 2012). In both years, there were storm events that generated large volumes of runoff (Fig. 3). However, the storms that occurred in 2011 were of higher magnitude and frequency than the ones in 2012.

The analysis of Q and SSC during rainfall–runoff events during 2011 indicates that just a few storm events contributed most of the total annual runoff volume and sediment yield in the catchment. The mean value for the 2011 runoff events was $40 \text{ m}^3 \text{ s}^{-1}$ with peaks of up to $230 \text{ m}^3 \text{ s}^{-1}$. For 2012, the mean value for runoff events was $14 \text{ m}^3 \text{ s}^{-1}$ with peaks of up to $178 \text{ m}^3 \text{ s}^{-1}$. The mean value of the SSC for 2011–2012 was 95 mg l^{-1} ; however, the mean value for the months with the most rain (September and October) was 800 mg l^{-1} with peaks reaching 4000 mg l^{-1} . The SSC data for the same gauging station monitored by the National Water Agency (ANA) from 2000 to 2012 ranged from 6 to 330 mg l^{-1} , with an average of 35 mg l^{-1} , i.e., much lower than those observed during the monitoring period. This difference can be explained by the difference in sampling frequency. From 2000 to 2012, ANA conducted 36 monitoring campaigns, representing an average of 2.7 measurements per year. This clearly indicates that occasional measurements underestimate the sediment flux because they are unable to capture the variability of the streamflow (Horowitz et al. 2015).

Table 3 Methods for calculating the sediment delivery ratio (SDR), based on physiographic indices of the catchment

Equation	Description of the variables	Area ^a (km ²)	Reference
$\text{Log SDR} = 2.96 + 0.869 \text{Log} R - 0.854 \text{Log} L$	R =difference in catchment elevation L =length of catchment	560	Maner (1958)
$\text{Log SDR} = 4.5 - 0.23 \text{Log} A - 0.51 \text{colog} \left(\frac{R}{L}\right) - 2.79 \text{log} R_b$	A =catchment area (km ²) R =difference in catchment elevation (m) L =length of catchment (m) R_b =Horton bifurcation ratio	5.7–190	Roehl (1962)
$\text{SDR} = 0.627 D^{0.043}$	D =steepness of the main canal (%)	0.5–18	Williams and Berndt (1972)
$\text{Log SDR} = 1.793 - 0.142 \text{Log} A$	A =area of the catchment (km ²)	1–262	Renfro (1975)
$\text{SDR} = 0.42 A^{-0.125}$	A =area of the catchment (mi ²) ^b	1–500	Vanoni (1975)
$\text{SDR} = 1.37 \times 10^{-11} A^{-0.00998} \left(\frac{R}{L}\right)^{0.363} \text{CN}^{5.44}$	A =area of the catchment (km ²) R =difference in catchment elevation (m) L =length of the catchment (km) R_b =Horton bifurcation ratio CN =Número-Curvas do NRCS	200	Williams (1977)
$\text{SDR} = 0.51 A^{-0.11}$	A =area of the catchment (mi ²) ^b	0.5–150	USDA-NRCS (1979)
$\text{SDR} = 0.418 A^{-0.135} - 0.127$	A =area of the catchment (mi ²) ^b	0.01–1000	USDA-NRCS (1983)
$\text{SDR}_i = \text{SDR}_i A_i S_i$	Y_i =sediment yield (t year ⁻¹) A_i =soil loss in plot i (t ha ⁻¹ year ⁻¹) S_i =soil loss in plot i	500	Fernandez (2001)
$\text{SDR} = 2 \left(\frac{\text{tr}}{\text{tc}}\right) \left\{ 1 - \left(\frac{\text{tr}}{\text{tc}}\right) + \left(\frac{\text{tr}}{\text{tc}}\right) \text{Exp} \left[\left(\frac{\text{tr}}{\text{tc}}\right) \right] \right\}$	tr =duration of excess rainfall tc =time of concentration in the catchment	50	Lu et al. (2006)

^a Area from which the equations were derived

^b Country Mile

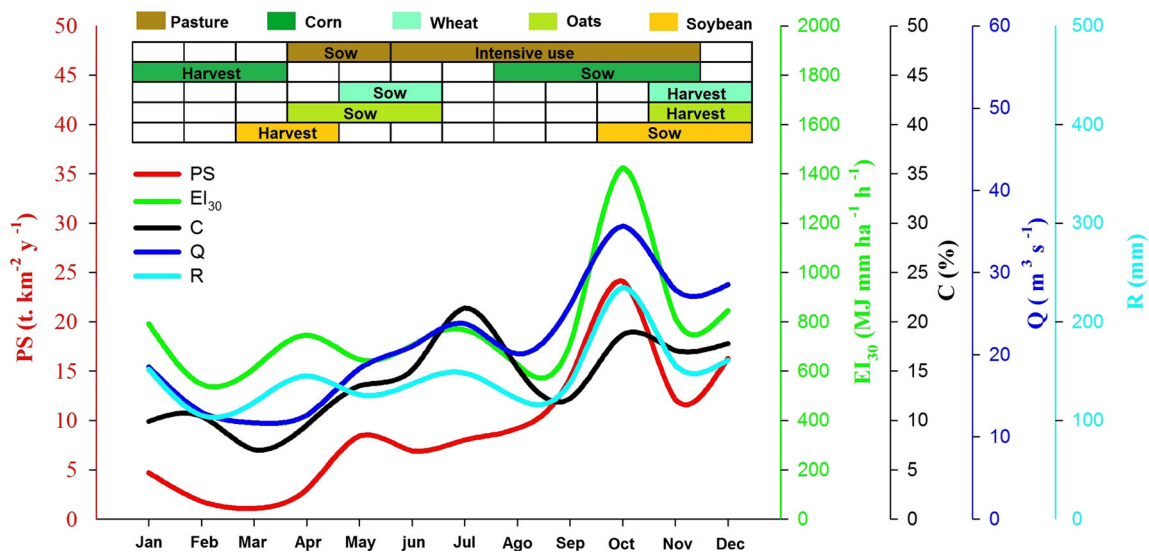


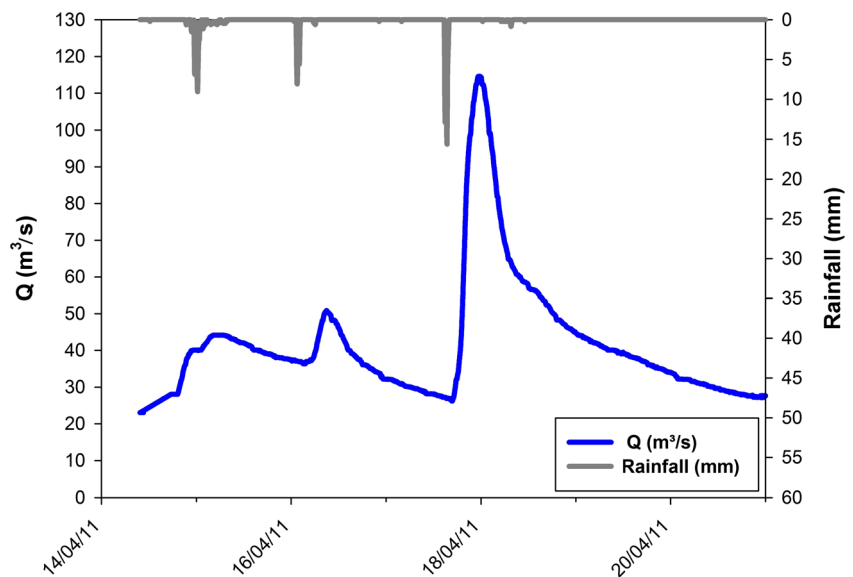
Fig. 4 Average monthly rainfall (*R*), rainfall erosivity (EI_{30}) daily streamflow (*Q*), runoff coefficient (*C*), and sediment yield (*SY*) for the Conceição River catchment

The maximum SSC values occurred primarily between the months of April and October. These months are associated with more erosive rainfall (Fig. 4) and the period of sparse soil cover that occurs following soybean harvest, during early establishment of winter crops, and then early establishment of summer crops.

The misconception (by farmers and some sectors of agricultural research) that the no-till system alone is able to reduce runoff encouraged farmers to eliminate the use of terraces, as well as other complementary conservation practices such as contour farming (Cogo et al. 2003; Denardin et al. 2008). Additionally, the lack of commitment to basic no-till system principles—based on residual biomass production through crop sequence, including cover crops and corn—has contributed to the overall failure of the no-tillage system as used in the catchment to efficiently control runoff.

Sediment yield measured in 2011 (wet year) and 2012 (dry year) was 102 and 61 t km⁻² year⁻¹, respectively, reflecting the differences of precipitation and runoff between 2011 and 2012. Considering the average sediment yield during the monitoring period, we believe that the erosion in the catchment reached values similar to those found in other catchments with high sediment yield, for example, some catchments located in the state of Paraná, Brazil, where the soil and erosivity are similar to those of the Conceição catchment (Lima et al. 2004; Lopes et al. 2004). The SSC and turbidity values observed during base flow stage varied between 80 and 120 mg l⁻¹ and between 50 and 80 NTU, respectively. High turbidity values are mainly associated with a high percentage of dispersed clay. During storm events, turbidity values are >330 NTU and frequently cause the water supply for local communities to be interrupted. According to Brasil (2005),

Fig. 5 Hydrograph showing rainfall and the rapid rising and falling limb of the Conceição River over a short period of time. This figure and the previous one are numbered differently in this list and on the figures



the acceptable value for water supply and drinking water (after water treatment) is below 100 NTU. However, 3.5 % of the values found during this monitoring period exceeded this value. Values this high not only hinder water supply but also put aquatic life at risk. According to Newcombe and Jensen (1996), non-salmonoid freshwater fish may experience lethal effects after a 6-day exposure to SSC of $>55 \text{ mg l}^{-1}$.

Figure 4 depicts the intra-annual erosion pattern variability of the study area. Notably, the period from September to November contributes ~45 % of the sediment losses. The surface runoff coefficient had a mean value of 14 %, and variations ranged from 21 p; % in July to 19 % in October. Castro et al. (1999) determined the runoff coefficient for the 20-km² Potiribu catchment situated near the Conceição catchment. The authors

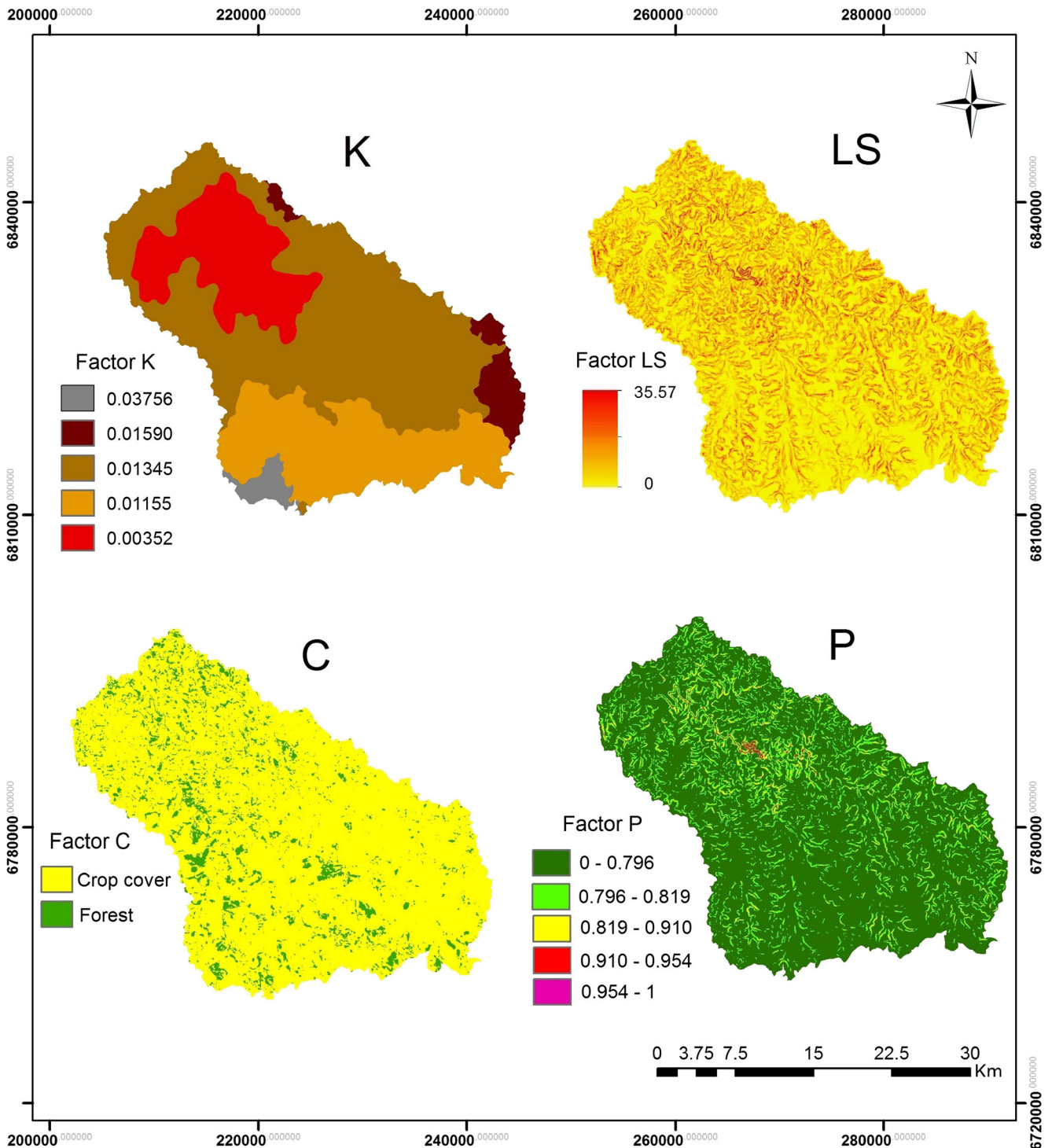


Fig. 6 Spatial variability of *K*, *LS*, *C*, and *P* factors that make up the soil loss estimation model for the Conceição River catchment

monitored 74 rainfall events over two distinct periods of soil tillage: conventional tillage with terraces (1992–1994) and no-tillage (1994–1995). According to Castro et al. (1999), for conventional tillage with terraces, the average surface runoff coefficient was 6 %, while for no-tillage, the average surface runoff coefficient was 8 %. These results contrast with those obtained by this study. Water loss under the no-till system currently monitored in the Conceição catchment is significantly higher than the water loss values for the no-till system in the mid-1990s and for the conventional systems with terracing measured by Castro et al. (1999) in the early 1990s. Considering that the Potiribu and Conceição catchments are similar, it would be reasonable to assume that water loss has intensified in the last decade due to the deterioration of the no-tillage system.

Gubiani et al. (2013) and Suzuki et al. (2013), working in areas similar to the Conceição catchment, observed severe soil compaction problems caused by hydric, physical, and mechanical stress generated by the lack of soil moisture, the action of plant roots, and traffic of agricultural machinery.

Another important hydrologic aspect observed during the monitoring period was how quickly the runoff was reduced to base flow following the end of the rainfall (Fig. 5). The high values of the runoff coefficient suggest that a significant portion of the rainfall volume, instead of infiltrating the soil and replenishing base flow and groundwater, is being converted into runoff, causing rill erosion and transferring pollutants to the river.

Rates of rill erosion caused by runoff and interrill erosion caused mainly by the impact of raindrops are represented by the RUSLE model (Renard et al. 2011). However, there is evidence of gully erosion in the thalwegs of the catchment, indicating that the model has a limitation when representing this important erosion process. Bank erosion is also not covered by the model and is a source of uncertainty in estimating erosion (underestimation). Thus, further studies are being carried out to quantify surface and subsurface erosion.

3.2 Modeling of gross erosion

The results of the factors that constitute the gross erosion estimation model are shown in Fig. 6. From this set of spatially distributed information, the factors were multiplied to

obtain predicted values of annual soil loss for the Conceição catchment. Due to the fact that the *C* factor was estimated for three different scenarios (Table 4), the calculation of gross erosion generated three different results (Fig. 7).

The spatial distribution pattern of gross erosion clearly demonstrates the influence of downhill farming. Gross erosion rates were higher along longer slopes where the value of cumulative area is greatest, which consequently generates a high *LS* factor value. This condition suggests the need to control surface runoff by using a combination of soil conservation practices, such as increasing the amount of soil residue to improve infiltration and surface roughness, and use of contour farming and terraces to reduce surface runoff.

The soil erodibility class is another important factor associated with erosion control in the Conceição catchment. Lower gross erosion rates (due to lower erodibility) are identified in the catchment (Fig. 7) where there is a predominance of soil with low erodibility, such as nitisols (Table 1). This lower erodibility is due to soils with higher clay, iron oxide, and aluminum content, combined with lower sand content and the absence of a textural B horizon. This combination makes the soil less sensitive to erosion. On the other hand, in the southwest region of the catchment, there is a predominance of acrisols, lixisol soils with the highest soil erodibility, which coincides with elevated values of the *LS* factor and the highest gross erosion values in the catchment (Fig. 7). In the eastern part of the catchment, higher rates of gross erosion are also present; in that case, the determining factor is associated with inadequate land use and soil management (i.e., insufficient surface soil residue due to soybean monoculture).

Table 5 shows the categories of erosion areas and their corresponding gross erosion for the three simulated scenarios. Average simulated gross erosion values for scenarios I, II, and III (Table 4) were 2, 4.4, and 13 t ha⁻¹ year⁻¹, respectively. Cogo et al. (2003), in an area close to the Conceição catchment, compared no-till, reduced tillage, and conventional tillage soil losses for a crop sequence of oats/soybean (contour farming). Using natural rainfall–runoff erosion plots (24 m long × 4 m wide), soil losses of 1, 4, and 13 t ha⁻¹ year⁻¹ were found for no-till, reduced tillage, and conventional tillage, respectively. Merten et al. (1995) reported a value of

Table 4 Description of the different scenarios used for modeling the Conceição River catchment

	Scenario I	Scenario II ^a	Scenario III
Crops	Soybean/turnip/oats/corn	Soybean/oats/wheat/soybean	Soybean/fallow/soybean
Crop rotation	Frequent use of crop rotation	Partial use of crop rotation	Lack of crop rotation
Cover crops	100 %	70–80 %	50–70 %
Amount of phytomass	Large amount of dry matter >5 t ha year ⁻¹	Medium amount of dry matter 3–5 t ha ⁻¹ year ⁻¹	Low amount of dry matter <3 t ha ⁻¹ year ⁻¹
Erosion control	High erosion control	Medium erosion control	Low erosion control

^a The most common scenario in the Conceição catchment

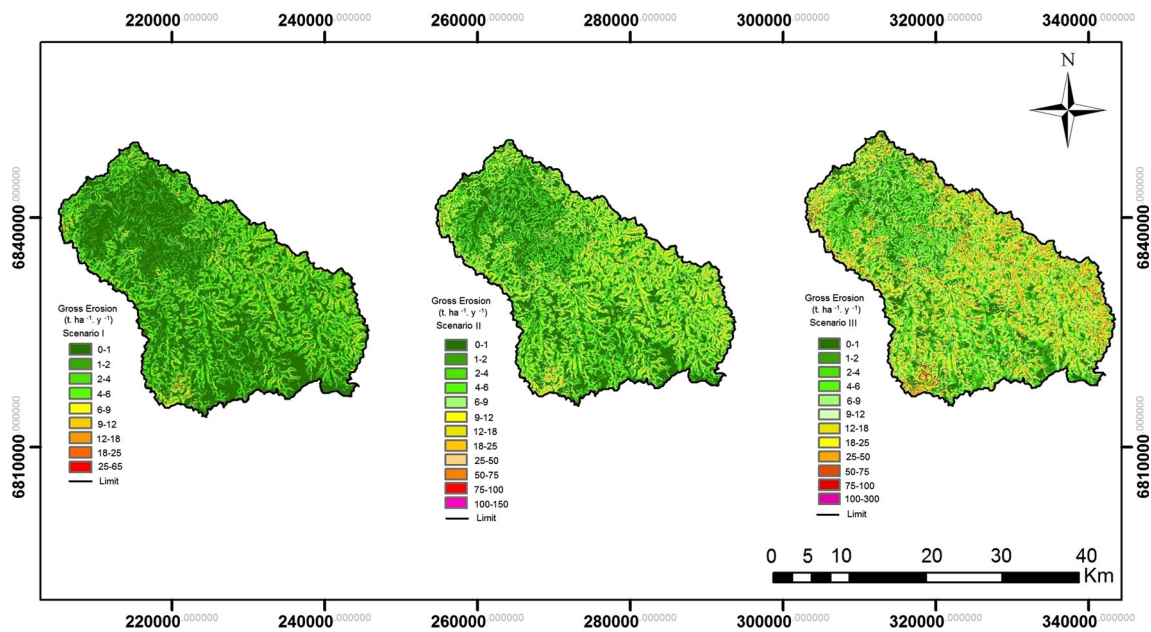


Fig. 7 Spatial representation of the gross erosion in the Conceição River catchment according to different land use and soil management scenarios. Scenario I (left), scenario 2 (center), and scenario III (right) (see text for details on each scenario)

1.8 t ha⁻¹ year⁻¹ for a crop sequence of wheat/soybeans using no-till (downhill) when assessing soil loss in a catchment in Paraná state, Brazil, with soils and topography similar to those in the Conceição catchment.

According to Table 5, a large percentage of the catchment, regardless of the scenario, has soil loss values higher than the 1-t ha⁻¹ year⁻¹ found by Cogo et al. (2003) in an area in the same region with the same soil characteristics where contour farming, no-till, and winter cover crop are used. This suggests the need to improve the soil conservation practices in the entire Conceição catchment area. Despite good soil management practices simulated in scenario 1 (no-till and crop

sequence of soybean/oats/corn), these conservation practices are not enough to reduce soil erosion to below the 1–2-t ha⁻¹ year⁻¹ limit, especially in places with a long slope length (Figs. 6 and 7). This result suggests the need to include runoff control as an essential soil conservation practice.

In scenario I (Figs. 7 and 8), 13 % of the gross erosion is concentrated in classes <1 t ha⁻¹ year⁻¹. It can also be observed that there is a decrease of 4 and 0.8 % in scenarios II and III, respectively, for the same classes. The highest gross erosion values in scenarios I and II are between classes 4 and 9 t ha⁻¹ year⁻¹ which corresponds to 34 and 29 %, respectively, of the total erosion for these scenarios. For scenario III, gross

Table 5 Description of gross erosion classes (GE) for the different scenarios

Class of erosion (t ha ⁻¹ year ⁻¹)	Scenario I		Scenario II		Scenario III	
	Area ^a (%)	GE ^b (t year ⁻¹) (% erosion)	Area (%)	GE (t year ⁻¹) (% erosion)	Area (%)	GE (t year ⁻¹) (% erosion)
0–1	50	20,279 (13 %)	34	13,502 (4 %)	21	8468 (0.8 %)
1–2	18	21,790 (14 %)	14	16,626 (5 %)	7	8486 (1 %)
2–4	17	42,105 (27 %)	18	42,635 (12 %)	11	26,721 (3 %)
4–9	13	54,112 (34 %)	20	103,099 (29 %)	19	96,406 (9 %)
9–12	2	10,885 (7 %)	6	49,542 (14 %)	8	64,454 (6 %)
12–18	0.5	6842 (4 %)	5	66,079 (19 %)	11	127,864 (12 %)
18–50	0.1	2278 (1 %)	3	62,494 (17 %)	20	501,473 (48 %)
>50	0.01	20 (0.01 %)	0.06	2508 (0.8 %)	3	201,725 (20 %)
Total	100	178,032	100	356,485	100	1,035,797

Scenario I=soybean/turnip/oats/corn; scenario II=soybean/oats/wheat/soybean; and scenario III=soybean/fallow/soybean

^a Area (%) total catchment

^b GE is gross erosion (t year⁻¹) and % total erosion for each class

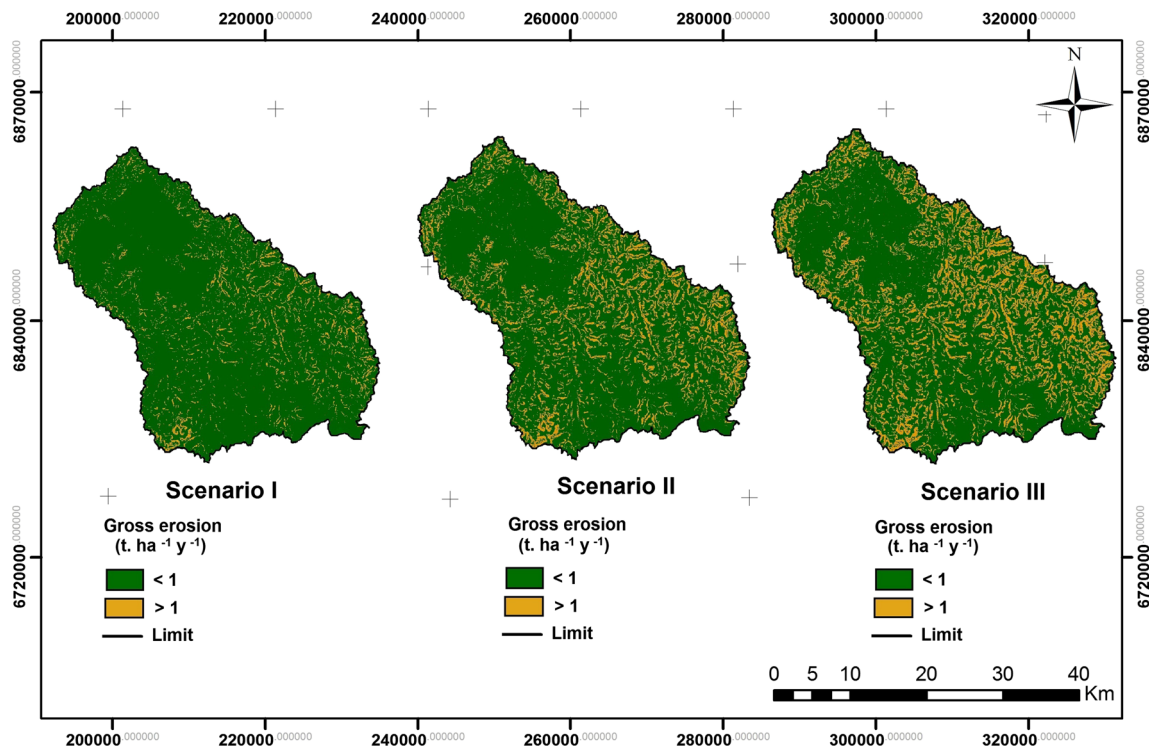


Fig. 8 Visual evolution of gross erosion for the different scenarios in intervals of less than and greater than $1 \text{ t ha}^{-1} \text{ year}^{-1}$

erosion is concentrated between classes 18 and $50 \text{ t ha}^{-1} \text{ year}^{-1}$ which corresponds to 48 % of the total erosion for this scenario. Visually, the evolution of gross erosion can be observed (Fig. 8) for different scenarios I, II, and III (Table 4), where the increase in erosion is noticeable among the different agricultural uses.

It is important to point out the degree of uncertainty in the estimation of gross erosion in the catchment. Since the RUSLE model involves only rill and interrill erosion, an underestimation of the total sediment eroded and mobilized to the drainage network is expected. The main erosion process occurring in the catchment is rill erosion; however, there is also evidence of gully erosion, road surface erosion, and river bank erosion. New studies are being carried out in this catchment to identify the sources of sediment. Thus, even if the underestimation of gross erosion is considered, the results clearly show that the erosion problems in the catchment are relevant and provide a good estimation of the ongoing erosion processes. The results also show that the tools used are able to identify the places of interest for soil recovery and conservation of soil.

3.3 Estimation of SDR and sediment yield

Considering that scenario II is the most likely condition of soil use and management in the Conceição catchment (gross erosion = $4.4 \text{ t ha}^{-1} \text{ year}^{-1}$) and considering that the average sediment yield (2011–2012) is $81 \text{ t km}^{-2} \text{ year}^{-1}$, the estimated SDR value is 0.18. In other words, 18 % of all soil material

mobilized as gross erosion is estimated to reach the catchment outlet. Working in an area close to the Conceição catchment, Minella et al. (2014) found a SDR value of 15 % in a highly erodible basalt terrain intensively cultivated with tobacco using techniques such as ^{137}Cs combined with sediment monitoring and fingerprinting.

The results in Table 6 were obtained by applying different methods to estimate SDR using the equations defined in Table 3. Among the methods tested, the method proposed by Vanoni (1975) approached the calculated value for the catchment and can be considered an appropriate method to estimate SDR for the Conceição River area. The SDR values in Table 6

Table 6 Values of sediment delivery ratio (SDR) and sediment yield estimated by different equations for scenarios I, II, and III

Equations	SDR (%)	Scenarios		
		I	II	III
		Sediment yield ($\text{t km}^{-2} \text{ year}^{-1}$)		
USDA	27	52.9	119.6	347.7
Vanoni	20	39.2	88.6	257.6
USSF	6	11.7	26.5	77.2
Renfro	14	27.4	62.0	180.3
Lu	11	21.5	48.7	141.6
Williams	35	68.6	155.0	450.8

Scenario I=soybean/turnip/oats/corn; scenario II=soybean/oats/wheat/soybean; and scenario III=soybean/fallow/soybean

indicate a broad range with a minimum value of 6 % and a maximum of 35 %. If these values were used to estimate the sediment yield in the catchment from the gross erosion estimated by RUSLE, it would produce values ranging from 27 to 155 t km⁻² year⁻¹ for the most likely scenario (scenario II). These differences in estimates will affect projects that depend on correct estimation of sediment yield, for example, the estimated life expectancy of reservoirs in areas where there are no hydrological data available to estimate sediment flux (i.e., Q and SSC).

4 Conclusions

According to the results obtained from this study, it can be inferred that the high runoff coefficient values and drastic falling limb in the hydrograph in the Conceição River catchment suggest low soil infiltration caused by inadequate soil management practices and soil compaction. It can also be inferred from our findings that when the no-till system is not accompanied by good soil management practices (e.g., increase in phytomass, contour farming, and terraces), a large area in the catchment presents higher soil loss values than those considered acceptable for the area. In addition, modeling of soil loss using different scenarios shows that the main erosion problems in the Conceição catchment are associated with areas of high potential of runoff formation and inadequate land management. Also, a sediment delivery ratio of 18 % indicates a high mobilization of sediments and pollutants from hillslopes making their way into the fluvial channel system. Although several equations were tested, the best SDR for the Basalt Plateau region in southern Brazil was estimated using the equations proposed by Vanoni (1975).

Monitoring and mathematical modeling can assist in the management of natural resources (soil and water) at the catchment scale by demonstrating the consequences of either the absence or the partial adoption of conservation practices. To reduce the risk of erosion, the Conceição River catchment requires the implementation of more effective soil conservation measures than those currently in place. However, the interannual variability of different soil and water conservation techniques is an issue that needs to be explored further before optimal soil and water conservation measures can be recommended for the area.

Acknowledgments The authors acknowledge the financial support granted by FAPERGS, CAPES, and CNPq, and the community of the Conceição River catchment who contributed to the development of this project. The authors also wish to thank Patricia Oliveira and Elena Metcalf for their help with this manuscript.

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