

Impact of no-tillage agricultural systems on sediment yield in two large catchments in Southern Brazil

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Abstract

Purpose The impact of agriculture on water resources has long been a problem associated with the formation of runoff, the siltation of lakes and reservoirs, and overall depletion of water quality. In Brazil, these problems are mainly related to soil degradation by water erosion. However, studies of catchment-scale erosion are still rare particularly in grain-producing regions which have adopted conservative tillage systems for soil protection. In order to contribute to a better understanding of the impact of conservation agriculture on water resources, this study determined the runoff coefficient and sediment yield for two agricultural catchments.

Materials and methods Hydrological and sedimentological monitoring was conducted in two catchments: the Conceicao catchment is characterized by grain production in weathered soils and a gently sloping landscape, while the Guapore catchment is characterized by heterogeneous soils and topography. Both catchments have problems associated with water erosion.

Results and discussion The magnitudes of annual runoff coefficients and sediment yield were high, even if compared to similar agricultural regions, including a catchment with widespread adoption of no-tillage. The sediment yield was $140 \text{ t km}^{-2} \text{ year}^{-1}$, and the runoff coefficient was 14 % for the Conceicao catchment, while the sediment yield was $270 \text{ t km}^{-2} \text{ year}^{-1}$, and the runoff coefficient was 31 % for

the Guapore catchment. The results indicate that problems such as gullies, soil compaction, runoff, floods, siltation, and water quality depletion associated with the misuse of agricultural areas in terms of soil conservation and water use are still evident and important even in regions with widespread adoption of no-tillage systems.

Conclusions The magnitudes of both runoff and sediment yield clearly indicate the need to adopt complementary practices of soil conservation measures, such as mechanical runoff control.

Keywords Erosion · Monitoring · No-tillage · Sediment yield

1 Introduction

The loss of soil, nutrients, pesticides, and water in agricultural areas is the result of one of the main agents of degradation of agricultural soils, water erosion. In Brazil, it is estimated that the economic impact of erosion is in the order of US\$ 4 billion per year generated by the annual loss of about $847 \times 10^6 \text{ t}$ of soil (Hemani et al. 2002; Merten et al. 2010). Soil erosion is an important factor of degradation of agricultural land worldwide, and in Brazil it is considered as the main factor. According to Lal (1997), erosion causes the decline of soil quality and its ability to perform multiple functions. Other than the more visible problems associated with local erosion, damaging consequences of water resources are also generated by the presence of sediments and agrochemicals (e.g. Graaf 1996; Defersha and Melesse 2012).

Brazil has been a pioneer in the development and use of soil conservation techniques especially the no-tillage system (NTS). Even though about 90 % of areas cultivated with soybeans, corn, and winter cereals in southern Brazil are managed under NTS, its ability to mitigate conservation and environmental problems related to soil degradation and

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diffuse pollution is less than expected. The main NTS deficiencies regarding soil conservation are: abandonment of mechanical practices for runoff management; incipient crop rotation; low biomass production by improper management of crop-livestock integration; excessive and uncontrolled traffic of equipment; and excessive use of agrochemicals (Silva et al. 2011). Consequently, economic and environmental losses due to reduced infiltration rates, high rates of soil, water and pesticide loss, as well as pollution of water bodies have been observed in important grain-production regions.

However, in Brazil, the results of erosion at the catchment scale are still scarce particularly in grain crop regions which tend to adopt a conservationist NTS approach for soil protection. There is no quantitative information on the impact of conservation agriculture on water resources, which would be essential to assess the current condition of conservation systems, calibrate mathematical models, and propose conservation measures to reduce erosion processes that are not being effectively controlled.

The study of catchment-scale erosion depends fundamentally on the monitoring of water discharge and suspended sediment concentration (SSC) at the catchment outlet. This is done to quantify the overall loss of water and sediment which is exported by the sum of all erosion processes. In this case, it is considered that sediment production directly reflects the complex dynamics of land use according to the economic and environmental interests of society. Sediment yield is considered as a variable integrating numerous processes and can be used as an indicator of good or bad soil management in the region.

Runoff is another important issue related to the dynamics of the hydrological cycle in agricultural activities. Even if soil erosion problems can be reduced by protecting the bare soil with mulch, runoff remains an issue of great concern. Low soil infiltration capacity causes runoff which consequently leads to lower water availability to plants during periods of drought and also transports fertilizers and pesticides into the drainage network. In Brazil, few studies have documented the effectiveness of catchment-scale conservation agriculture on hydrological processes and erosion, which leads to an increasing demand for information that is able to support and guide the implementation of measures to control runoff and thus reduce erosion and water loss and improve water quality.

Monitoring of flow and SSC not only enables researchers to quantify the magnitude of erosion and sediment yield, but also enables the calibration and validation of mathematical models—such as Limburg Soil Erosion Model (LISEM; De Roo et al. 1996), Soil and Water Assessment Tool (SWAT; Arnold et al. 1998), and Water Erosion Prediction Project (WEPP; USDA 1995)—that describe the process from farm to catchment scale and can be used to better comprehend the erosion process and thus plan more effective soil conservation measures based on real case scenarios.

Considering the need to generate information and thus contribute to the improvement of conservation agriculture in Brazil, the objective of this study was to determine sediment yields and runoff coefficients in order to contribute to a better understanding of the impact of conservation agriculture on water resources in catchments where soil conservation practices are either partially or incorrectly used. The monitored catchments have particular characteristics and are distinct from each other in terms of land usage, soil, and topography, and both represent the two major physiographic conditions and anthropogenic processes that control erosion in southern Brazil, namely: (i) the plateau regions and (ii) the slopes between the plateau and the great valleys.

2 Materials and methods

The study was conducted in southern Brazil in the state of Rio Grande do Sul. The choice of catchments was guided by the need to characterize the magnitude of erosive and hydrological processes in distinct and representative land use, soil and landscape conditions, as well as the fact that both catchments adopt a considerable proportion of soil conservation practices. Two large catchments were chosen (Fig. 1, Table 1) so that results would reflect broader regional conditions and processes rather than local conditions and specific processes. The first catchment, the Conceicao catchment, is located on the plateau and is characterized by deep clay soils, the landscape is gently sloping with moderate surface drainage, and >80 % of the area is under soybean cultivation in NTS, whereas, the second catchment, the Guapore catchment, is located on the plateau slopes and is characterized by steep slopes and high environmental fragility with high heterogeneity of land use and soil types.

2.1 Catchment characteristics

The Conceicao catchment is located in the northwest region of Rio Grande do Sul state, with a drainage area of 800 km², and the monitored section is located at coordinates 28°27'22"S and 53°58'24" W. According to Köppen, the climate is Cfa type, subtropical humid without dry season, with an average annual rainfall between 1,750 and 2,000 mm and an average temperature of 18.6 °C. The source material is basalt, with a formation of deep and highly weathered soils (Oxisols, Ultisols, and Alfisols), with Oxisols being the dominant soil class in the catchment. The soils are rich in iron oxides and kaolinite. The landscape is characterized by gentle slopes (6–9 %) on top and hillside slopes and higher steepness (10–14 %) near the drainage channels. The slopes are long and have distinctive forms. Farming based on the production of soybeans (*Glycine max*) in summer and wheat (*Triticum* spp.), oats (*Avena strigosa*), and ryegrass (*Lolium multiflorum*) in

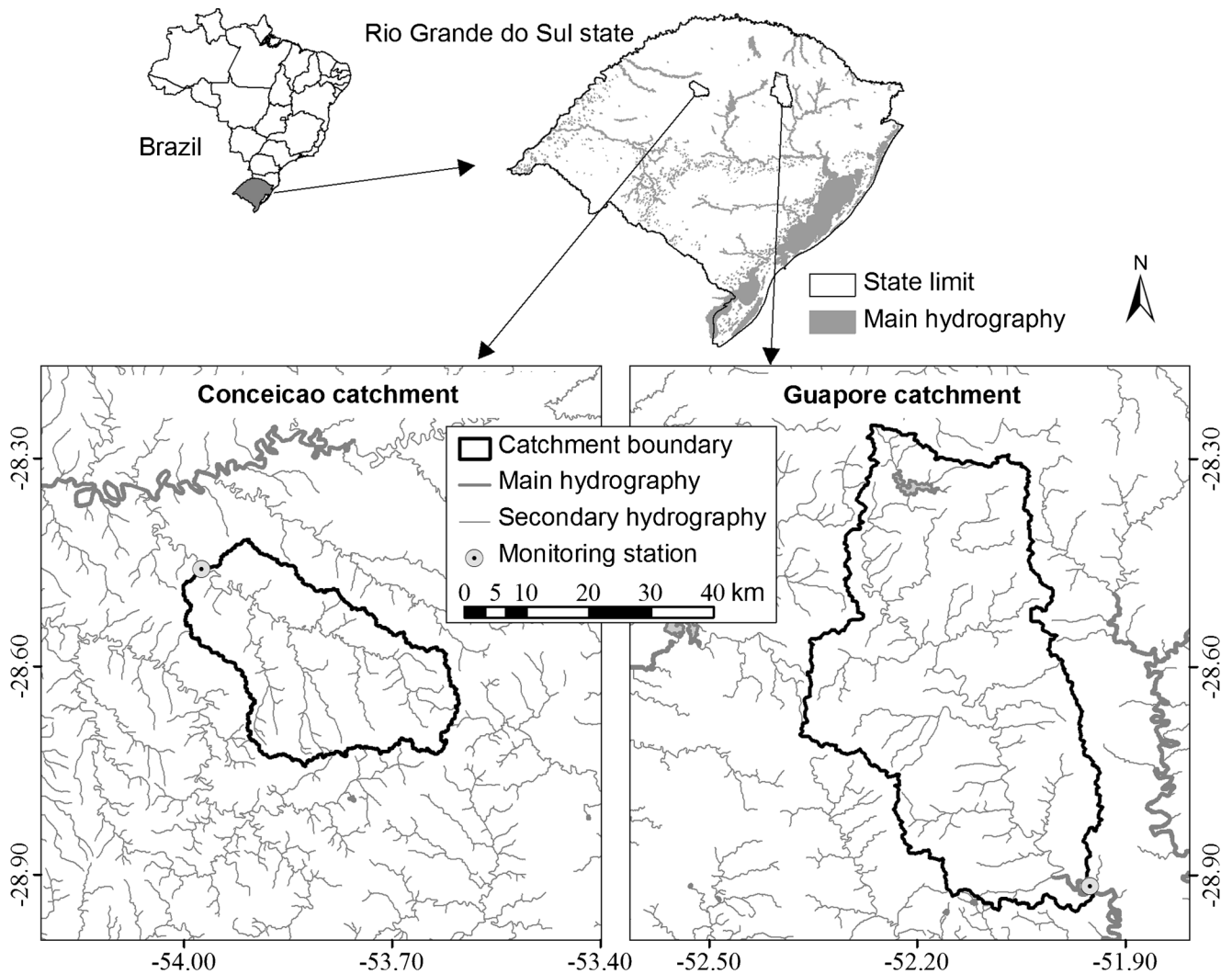


Fig. 1 Location of the two monitored watersheds, Rio Grande do Sul state, Brazil

winter are the main land uses, the two latter crops used for the formation of straw for mulching in the summer and also for the production of pasture for dairy cattle. Soil management for grain production is based on NTS in >80 % of the crop-field area, however, with no use of additional measures such as terraces, strip cropping, vegetated ridges, or planting in level to control runoff. The other uses represent <15 % of the area and are composed of surrounding forests, wetlands, and urban areas.

The Guapore catchment is situated in the northeastern region of Rio Grande do Sul state and has a drainage area of 2,000 km², and the monitored section is located at coordinates 28°54'41"S and 51°57'10"W. It covers part of the physiographic regions of the middle plateau (upper third of the basin) and the lower northeastern slope (intermediate and lower thirds of the basin). Climate is classified as Cfa according to the Köppen climate classification. Average annual rainfall varies between 1,400 and 2,000 mm, and the average annual temperature is 17.4 °C. Geology is characterized by volcanic

lava flows, and topography is undulating to hilly. Due to variations in landscape, several classes of soils (i.e., Entisol, Luvisol, Cambisol, Oxisol, Ultisol, Chernisol) and rocky patches can be found in the catchment. The land use is highly heterogeneous. In the upper third of the catchment where the terrain is characterized by gentle hills, there is a clear predominance of soybean (*G. max*) cultivated under NTS. In the other two-thirds of the catchment (middle and lower parts), land use and soil management are very heterogeneous. The main land uses are tobacco (*Nicotiana tabacum*) and maize (*Zea mays*) crops, areas that have been reforested with *Eucalyptus* (*Eucalyptus* spp.), as well as pastures for dairy cattle and pig production. In these areas it is possible to identify different types of soil management, mainly, conventional and minimum tillage. In areas of greater steepness, especially riversides, there are large portions of native forest area as well as small towns and urban areas.

The contribution of unpaved roads is relevant to the production of sediments in both catchments. Severe erosive processes

Table 1 Main differences between the monitored catchments

Characteristic	Conceicao catchment	Guapore catchment
Soil	Deep, highly weathered soils (Oxisols, Ultisols, and Oxisols)	Shallow to deep (Entisols, Luvisol, Cambisol, Oxisol, Ultisol, Chernosol)
Source material	Basalt	Basalt
Landscape	Gentle slopes (6–9 %) on top and hillside slopes and higher steepness (10–14 %) near the drainage channels	Steep slopes in the middle and lower parts of the catchment and gentle slopes at the top of the catchment.
Climate ^a	Cfa subtropical without dry season	Cfa subtropical without dry season
Average daily temperatures	Hottest month: 24.84 °C Coldest month: 13.94 °C	Hottest month: 22.97 °C Coldest month: 13.10 °C
Drainage area	800 km ²	2,000 km ²
Annual rainfall	1,750 and 2,000 mm	1,400 and 2,000 mm
Vegetation ^b	Grassy-woody steppe with occasional presence of gallery forests	Grassy-woody steppe with presence of gallery forests as well as deciduous stationary forests
Main crops	Soybean (<i>G. max</i>) in summer and wheat (<i>Triticum</i> spp.), oats (<i>A. strigosa</i>) and ryegrass (<i>L. multiflorum</i>) in winter	Soybean (<i>G. max</i>) and tobacco (<i>N. tabacum</i>) in summer, maize (<i>Z. mays</i>) crops in spring, and oats (<i>A. strigosa</i>) and ryegrass (<i>L. multiflorum</i>) in winter, and reforestation (<i>Eucalyptus</i> spp.)
Soil management	No-tillage system (aprox. 80 %)	No-tillage, minimum tillage, and conventional plow farming
Property size ^c	Medium to high	Small to medium

^a According to the Köppen climate classification

^b Brena et al. (2003). Inventário florestal contínuo do Rio Grande do Sul

^c IBGE (2006), Small <10 ha, medium 10–100 ha, high >100 ha

along the roads can be observed in both the Conceicao and the Guapore catchments; however, so far, their contribution to the total sediment yields in this region has only been estimated for small catchments. Using the sediment source fingerprinting approach, Minella et al. (2008) and Tiecher et al. (2012) estimated the contribution of unpaved roads in the production of sediments in two small catchments. Minella et al. (2008) estimated that the contribution of unpaved roads in a headwater catchment, which is part of the Guapore catchment, was 20–30 % of the total sediment yield. On the other hand, Tiecher et al. (2012) estimated that the contribution of unpaved roads was at 60 % for a small field (0.8 m²) under soybean cultivation in the Rio Grande do Sul plateau region. This clearly indicates that unpaved roads have a relevant contribution to the total sediment yield; however, the magnitude of the values obtained for the smaller catchments cannot necessarily be extrapolated to catchments the size and proportion of the ones in this study.

2.2 Hydrological and sedimentological monitoring

The monitoring strategy was based on the intensification of already active monitoring sections operated by the National Water Agency (ANA). The ANA has for a number of years collected daily flow and SSC data through four annual sample-collecting campaigns comprising a significant database. In March 2011, automatic water level and turbidity equipment were installed in the monitoring sections with sub-hourly-interval data acquisition. Moreover, campaigns to monitor SSC were carried out on a fixed schedule (monthly), and events

were tracked (once a month), which was essential for the calibration of the turbidity meter so as to enable SSC to be estimated continuously. The sediment samples were taken to the Sedimentology Laboratory at Federal University of Santa Maria, Brazil, to determine SSC by the evaporation and filtration method (Shreve and Downs 2005).

The monitoring of flow rate (Q) was performed with water level measurements using a limnigraph in a recording stage gauge, and pressure quota values were transformed into flow using the appropriate discharge rating curve for the chosen sections. In addition to the data from the limnigraph, a local daily observer recorded readings from the gauge installed in the section; limnigraph data were later checked against these observer readings. Rainfall (R) data were obtained from the network of ANA climatic stations, which covers the spatial variability of rainfall in the region at daily intervals. Automatic Q and SSC data were acquired in 10 min intervals from April 2011 to December 2012 comprising 20 months with significant differences in the magnitude of Q and SSS. Using this database, sediment production for the monitored period was estimated by multiplying SSC and Q values for each time interval and then integrated for the entire period.

Another important variable to quantify the impact of agriculture on the hydrological cycle is the runoff coefficient (C) defined as the proportion of rainfall that has been converted into runoff during a runoff–rainfall event. This component of the hydrological cycle is responsible for an important fraction of water erosion, transport of pollutants, and the occurrence of floods. To determine C , the volume of runoff is estimated from

the graphical analyses of the hydrographs based on the base-flow separation approach (Chow 1964).

In addition to the analysis of sediment yield and C in the monitored period (April 2011 to December 2012), daily sediment yield for the last 10 years was also estimated. This was possible by constructing a discharge rating curve considering pairs of measured SSC and Q data. From this correlation, daily values of Q were used to estimate daily sediment discharge (QSS) and, from this, estimate sediment yield. Moreover, monthly erosion was estimated from the historical rainfall data (Eq (1)) (Cassol et al. 2007) to identify the possible weather patterns that may have affected the magnitude of the erosion process:

$$EI_{30} = 109.65 * Rc^{0.76} \quad (1)$$

where EI_{30} is the erosivity index ($MJ \text{ mm ha}^{-1} \text{ h}^{-1}$) and Rc is the rainfall coefficient in millimeters ($Rc = p^2/P$, where p is the average monthly rainfall (mm), and P is average total annual rainfall (mm)).

For the purpose of this study, it was assumed that soil use and management for the last 10 years were not sufficiently altered so that the relationship between Q and SSC did not change. Based on this premise, the discharge rating curve was considered valid for estimating SSC from historical data, even though the data have been obtained from only the past 2 years, which introduced some degree of uncertainty to the results. An important positive aspect is that there was extensive amplitude of SSC during the monitoring period, with many points at the top part of the curve, reducing uncertainty in estimating sediment discharges in large rainfall events. Equations (2) and (3) characterize the discharge rating curves established for the Conceicao and Guapore catchments, respectively.

$$QSS = 2.1126 * Q - 0.8614 \quad R^2 = 0.84 \quad (2)$$

$$QSS = 2.1125 * Q - 1.5564 \quad R^2 = 0.96 \quad (3)$$

Erosion and sediment yield were determined from the daily flow and rainfall data for the past 10 years. Thus, an average value was obtained with reduced interference from years with either long droughts or the effects of extreme rainfall events.

3 Results

3.1 Current values of sediment yield and runoff coefficient

Table 2 presents the results of rainfall monitoring as well as estimates of erosion, runoff coefficient, and sediment yield for

the period April 2011 to December 2012 for both catchments. The results show large intra-annual variability governed primarily by the volume of rain. The years 2011 and 2012 were characterized by extreme situations, both by rainfall events of great magnitude that generated high values of Q and SSC and also by long periods of drought. From the standpoint of establishing discharge rating curves, this condition was favorable because it allowed a good coverage of possible water and sediment discharges.

The Conceicao catchment from April to August of 2011 and also July of 2012 presented high sediment yield and Q values. This was due to the occurrence of a long wet period in 2011 and an extreme event in July 2012 (Fig. 2). In the Guapore catchment, similarly, for the period from April to August 2011 showed high levels of sediment yield and Q and in 2012 (July, September, and October) contributed to higher discharges (Fig. 3).

It can be clearly noticed in both catchments that variability is partly controlled by the volume of rainfall and erosion. However, important features of extreme rainfall events are not evident at the monthly scale. For example, a 3-day event that occurred in July 2011 in both catchments with rainfall ~ 120 mm generated more than 90 % of the sediment yield for that month. Another example is an event in the Guapore catchment in September 2012 which was responsible for 80 % of the total sediment yield for that month. This clearly demonstrated that even though these are large catchments, the impact of major events represents a large part of the processes of sediment generation and transport.

Comparing the magnitude of the sediment yield in 2011 between the Conceicao and Guapore catchments, the values were in the order of 242 and 390 $t \text{ km}^{-2} \text{ year}^{-1}$, respectively. In 2012, the values were significantly lower, in the order of 41 and 158 $t \text{ km}^{-2} \text{ year}^{-1}$, respectively. Regarding C , values calculated for 2011 were 8.47 % and 12.75 % in the Conceicao and Guapore catchments, respectively, and for 2012, the results were 2.67 % and 5.13 %, respectively. It should be noted that the magnitude of the erosion processes follow the same trend as the runoff values as expected. This demonstrates the strong control of extreme events over erosion and the consequent need for additional structures and/or approaches to prevent runoff.

The difference in rainfall between the catchments was 220 mm higher in the Conceicao catchment in 2011 and 200 mm higher in the Guapore catchment in 2012. The difference in erosion in 2011 was 500 $MJ \text{ mm ha}^{-1} \text{ h}^{-1}$ (9 %) less in the Conceicao catchment, and in 2012, the figures were nearly identical. The results involving the magnitude of sediment yield and runoff on the amounts of accumulated rainfall and erosion indicate, obviously, the importance of rainfall but they also indicate the importance of isolated and extreme rainfall events that control the largest proportion of water and soil losses in the year. However, the

Table 2 Monthly hydrosedimentologic summary for the Conceicao and Guapore catchments in 2011 and 2012

Month/year	Conceicao catchment				Guapore catchment			
	R mm	EI ₃₀ MJ mm ha ⁻¹ h ⁻¹	C %	SY t km ⁻² year ⁻¹	R mm	EI ₃₀ MJ mm ha ⁻¹ h ⁻¹	C %	SY t km ⁻² year ⁻¹
April/11	274	1,321	12.4	41.39	131	699	19.6	14.58
May/11	121	441	9.30	32.25	47	181	17.00	3.69
June/11	182	913	13.65	11.62	204	1,284	5.70	11.7
July/11	239	1,269	20.19	27.04	306	2,351	21.40	156.97
August/11	229	1,155	16.98	37.57	253	1,730	32.80	65.89
September/11	42	129	0.40	2.02	83	250	3.80	3.95
October/11	207	1,034	1.19	5.10	120	572	1.70	2.03
November/11	111	284	2.19	3.89	17	38	0.00	0.97
December/11	17	54	0.00	0.48	34	66	0.00	0.37
January/12	111	1,112	0.00	2.48	127	610	0.00	0.02
February/12	45	294	0.00	0.74	162	1,169	0.00	0.14
March/12	17	200	0.00	0.49	151	798	0.00	0.20
April/12	58	237	0.00	0.34	76	282	0.00	0.19
May/12	19	431	0.00	0.85	39	124	0.00	0.29
June/12	57	225	0.00	0.37	153	660	2.20	0.93
July/12	190	1,417	7.55	15.53	232	1,531	15.90	23.65
August/12	72	322	0.00	1.48	72	267	0.00	2.27
September/12	228	1,867	8.33	2.41	187	1,105	18.90	55.64
October/12	302	2,868	7.51	6.34	149	787	16.80	26.48
November/12	90	458	0.00	1.76	45	128	0.00	1.05
December/12	274	2,363	6.00	8.30	267	1,900	13.00	47.81
2011	1,422	6,600	8.47	242.04	1,195	7,171	12.75	390.22
2012	1,463	9,485	2.67	41.09	1,660	9,361	5.13	158.67

R rainfall, EI₃₀ erosivity index, C runoff coefficient, SY sediment yield

large contribution (specifically the sediment yield) from the Guapore catchment is also evident, which despite the greater area, contributes to a higher amount of sediment per unit of area than the Conceicao catchment. This is related to the fact that the Guapore catchment has steeper landscape, shallower soils, higher proportion of conventional soil management, and crops with lower soil protection (less mulch), such as tobacco.

In determining the water and sediment discharges for the study period, the analysis of a particular event stands out in the Guapore catchment (see Fig. 3). From 20th to 22nd July 2011, there was a maximum flow of 120 m³ s⁻¹, whereas events with a maximum flow in the order of 20 m³ s⁻¹ are more usual. The maximum sediment discharge obtained in this period was 247 t day⁻¹. This solid discharge was responsible for 84 %

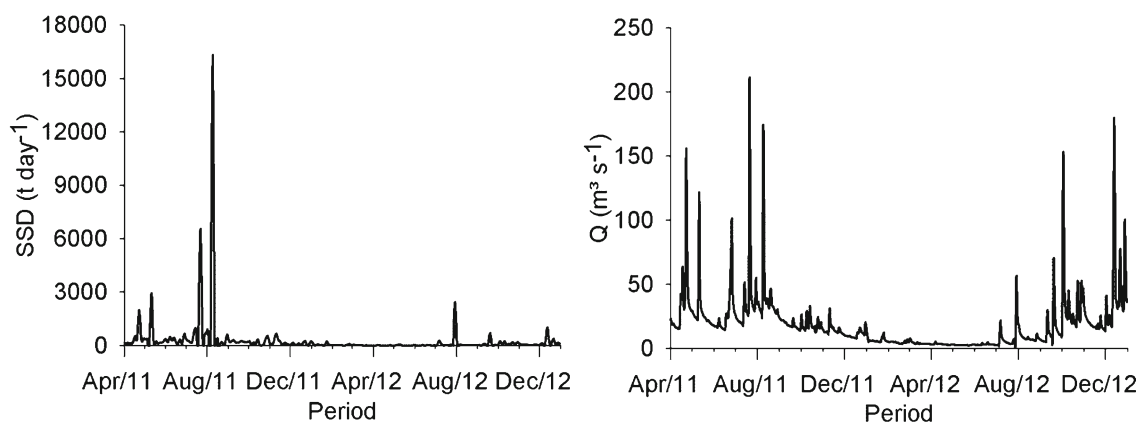


Fig. 2 Suspended sediment (SSD) and water (Q) discharge for the Conceicao catchment from April 2011 to December 2012

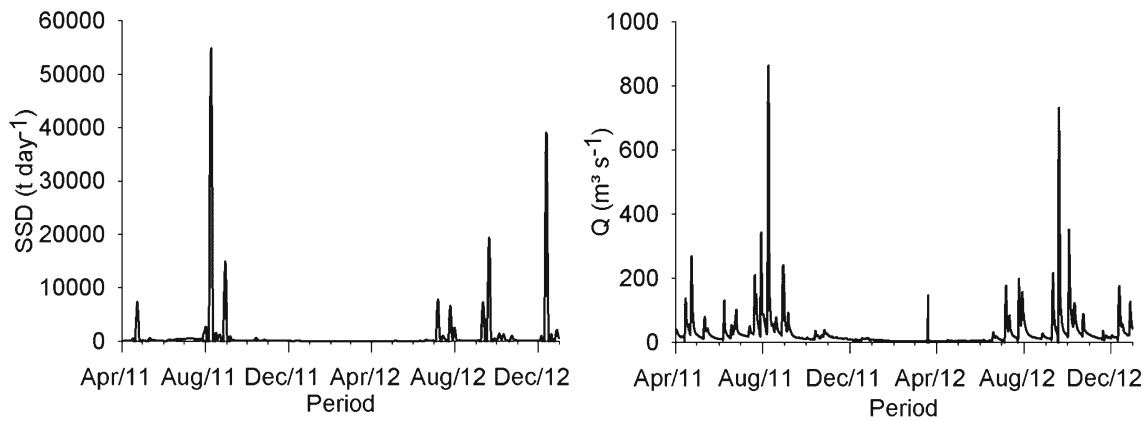


Fig. 3 Suspended sediment (SSD) and water (Q) discharge for the Guapore catchment from April 2011 to December 2012

of the sediment discharge in July and around 40 % of the total annual sediment yield. In the Conceicao catchment, a similar situation occurred, especially for events that occurred during the months of July and August, which contributed about 40 % of the total sediment yield for 2011.

For periods of drought, the impact of La Niña was also monitored; this created, for southern Brazil, reduced rainfall volume, which lasted for 10 months. According to the State Foundation for Agricultural Research (FEPAGRO), the areas surrounding the Conceicao catchment were one of the regions with the lowest accumulated rainfall from November 2011 to May 2012, a reduction of up to 2.8 times the amount of rainfall expected for that period, and was reflected by the low the sediment yield.

Regarding the rates of average runoff, there were low mean values for both catchments, which is justified by the drought period. Analyzing the months with the historical average rainfall, it can be seen that C for the Conceicao and Guapore catchments was 11 % and 15 %, respectively. However, depending on the climate variability observed in these 2 years of monitoring, the mean values of C should be considered through the analyses of the 1-year series presented below.

3.2 Sediment yield and runoff coefficient for the last decade

To extend the data series of SSC and make the estimate of annual sediment yield less susceptible to climatic variations, a discharge rating curve was established for SSC and Q samples collected during monitored events in 2011 and 2012. The Q values in this case refer to the daily readings made by the observer, and then, consequently, daily SSC values were calculated (Fig. 4). The use of daily data instead of data with sub-hourly intervals tends to underestimate C and the sediment yield due to less time discretization of rainfall–runoff events, especially in obtaining the maximum amount of flow and SSC. However, since the catchments are relatively large, the flood wave is slower than in smaller catchments, and the daily value is a good estimate of flow. Based on measured

SSC and Q data, both calibration curves exhibit a good performance. Pairs of data necessary to elaborate the discharge rating curves were obtained by the collection of samples during significant events. It should be noted that the applicability of this curve is due to the high values obtained from SSC and Q data.

The summary of daily flow and rainfall data and the estimated values of sediment yield, erosivity index, and C are presented as monthly averages for the interval from 2000 to 2010 in Table 3. The mean annual specific sediment yield is approximately $140 \text{ t km}^{-2} \text{ year}^{-1}$ for both catchments. During the considered period, the average annual rainfalls for the Conceicao and Guapore catchments were 1,718 mm and 1,550 mm, respectively. Due to the fact that rainfall in the Guapore catchment was higher (10 %) and because it has a drainage area two and half times greater, the magnitude of the erosion process in this catchment is considered to have been more intense. Similarly to sediment yield values, C values are also relatively high for both catchments, especially for the Guapore catchment.

The intra-annual variability for the 2000–2010 period displays an erosion pattern common to the southern region of Brazil. From September to November, erosive rainfall events tend to occur more often, consequently generating the largest soil losses and sediment yield. In addition, the planting of summer crops starts in August. Therefore, especially in areas under conventional soil management with plowing and harrowing, the more erosive rainfall events coincide with low vegetation cover. Note that in both catchments, sediment yield in October was significantly higher, followed by September (see Table 2).

The 10-year average (2000–2010) sediment yield for the Conceicao catchment ($\sim 140 \text{ t km}^{-2} \text{ year}^{-1}$) approached the average obtained in the 2 years of current monitoring (2011 and 2012) ($141 \text{ t km}^{-2} \text{ year}^{-1}$). In the case of the Guapore catchment, the 10-year average was $\sim 140 \text{ t km}^{-2} \text{ year}^{-1}$, and the average for the last 2 years (2011 and 2012) was $274 \text{ t km}^{-2} \text{ year}^{-2}$. Unlike sediment yield, C was 14 % for

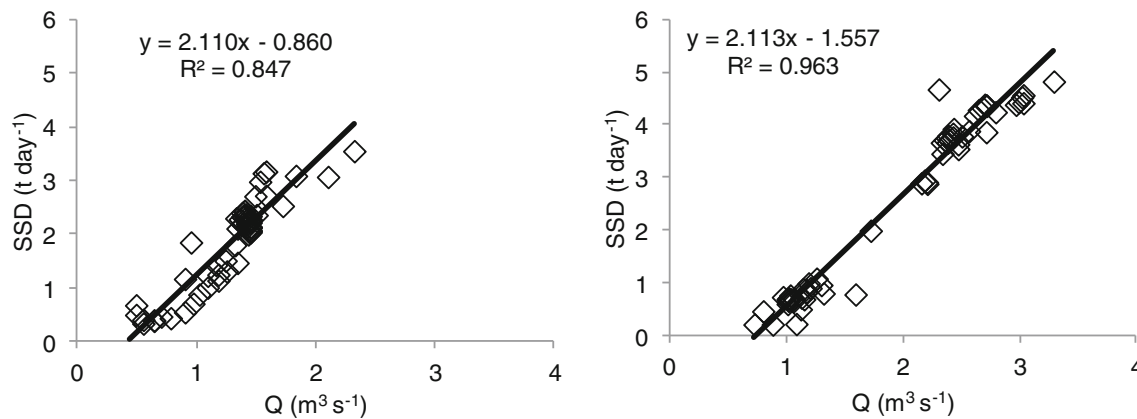


Fig. 4 Suspended sediment (SSD)—water (Q) discharge rating curves for Conceicao (*left*) and Guapore (*right*) catchments

the Conceicao catchment and 31 % for the Guapore catchment. The difference in the magnitude of this variable may be correlated with the higher slopes and shallower soils that characterize the Guapore catchment.

In Table 4, sediment yields for different catchments worldwide are presented for comparative purposes. It can be noted that the magnitude of sediment yield in both the Conceicao and the Guapore catchments is relatively high when compared to catchments of similar drainage basin area.

4 Discussion

Considering sediment yield results for the Conceicao catchment, a high magnitude of sediment yield ($140 \text{ t km}^{-2} \text{ year}^{-1}$) was obtained in both the high frequency monitoring period as well as

in the period where the series was extended with the use of a discharge rating curve. This is relevant because natural soil and landscape characteristics indicate low susceptibility to erosion (Campagnoli 2005; Lima et al. 2005) due to weathered soils and gentle-slope landscape, consequently, high sediment yield results suggest that soil use and management worsens the problem beyond what natural conditions are able to minimize. The natural characteristics of the catchment which contribute to low erosion potential are: (a) soils are deep, loamy, and rich in iron oxides, which provide unfavorable characteristics for the detachment by raindrop impact and runoff; (b) average topography is characterized by gentle slopes, this way shear-flow energy controlled by steepness is small; and (c) the NTS is used for planting crops.

Results from the Conceicao catchment show that despite the significant contribution of the NTS, further efforts are still necessary to further reduce soil erosion. Some local aspects

Table 3 Average rainfall (millimeter) and the sediment yield (t km^{-2}) for 10 years and for the monitored year of 2011 in the Conceicao and Guapore catchments

Months	Conceicao catchment				Guapore catchment			
	R mm	EI_{30} MJ mm ha ⁻¹ h ⁻¹	C %	SY t km ⁻² year ⁻¹	R mm	EI_{30} MJ mm ha ⁻¹ h ⁻¹	C %	SY t km ⁻² year ⁻¹
January	163	801	9.90	7.5	142	840	20.03	1.2
February	91	486	10.43	2.1	97	556	17.78	1.7
March	123	568	7.02	1.5	105	585	18.00	0.5
April	138	773	9.54	2.7	124	687	17.31	2.1
May	141	648	13.52	10.9	102	617	29.96	8.4
June	131	713	15.19	10.5	140	789	50.63	12.5
July	129	720	21.41	9.2	129	943	50.43	22.8
August	114	585	15.30	9.6	99	550	36.17	7.5
September	124	613	12.27	18.6	173	748	33.35	28.9
October	228	1,446	18.72	31.4	193	1,200	43.50	37.2
November	166	851	17.18	17.7	126	692	31.58	9.3
December	171	773	17.87	18.0	125	603	28.55	7.7
Sum	1,718	8,977	14.03	139.7	1,555	8,810	31.44	139.8

R rainfall, EI_{30} erosivity index, C runoff coefficient, SY sediment yield

Table 4 Sediment yield in catchments worldwide

Country/catchment	Area km ²	Main use	SY	Reference
Brazil/Arvorezinha	1.2	Agriculture/forest	138	Barros (2012)
China/Zidianhe	257	Extractivism/agriculture	468	Zhang et al. (2012)
Ghana/Butre	422	Agriculture/extractivism	35	Akrasi (2011)
Ukraine/Dnestr	850	Agriculture/forest	190	Walling and Webb (1996)
England/Edem-WB	1,370	Pasture/agriculture	14	Bathurst et al. (2005)
Germany/Lech at Fussen	6,600	Agriculture/forest	200	Walling and Webb (1996)
Colombia/San Juan	14,000	Forest/agriculture	1,150	Restrepo and Kjerfve (2000)
Siberia/Kolyma	99,400	Not widely exploited	30	Walling and Webb (1996)
Argentina/Negro	100,000	Fruticulture/livestock	140	Milliman and Syvitski (1992)
Brazil/Uruguai	163,547	Agriculture	22	Lima et al. (2005)
Siberia/Upper Ob ² -Kolpashevo	486,000	Agriculture	24	Bobrovitskaya et al. (1996)
Brazil/Parana	802,150	Agriculture	10	Lima et al. (2005)
Brazil/Madeira	954,285	Extractivism	254	Lima et al. (2005)
China/Upper Yangtze	1,000,000	Agriculture	520	Dingzhong and Ying (1996)
USA/Livingston	3,650,000	Agriculture/industrial	467	Phillips et al.(2004)
Brazil/Amazon	4,680,000	Extractivism	121	Lima et al. (2005)

SY sediment yield (t km⁻² year⁻¹)

related to the agricultural production system may explain the high sediment yield values despite its low erosion potential. The first aspect is the contribution of sediment from the roads; erosion channels can easily be seen by the roads and are significantly lower when compared to the original road level. The second aspect, also visible, are the channels that drain excess water from crops in the converging landscape (talwegs) without any kind of vegetation cover or structure that could reduce water speed, thus, deep erosion channels and, in many cases, gullies are formed. As a result of this process, large sediment deposits can be observed on floodplains and in rivers where farmers build drains which directly connect crops to the drainage network. The third aspect is related to crop management; the no-till crop rotation system aims to maximize biomass production which should go back into the soil as organic matter. Currently, crop rotation has been neglected due to the high economic value of soybean production along with the possibility of feeding dairy or beef cattle with the biomass destined for soil coverage and mulch formation. Also, the planting of crops is not performed on level areas but in straight lines guided by the largest length of the field. This significantly contributes to the increase of runoff speed and consequently causes more erosion. The fourth aspect is related to degraded soil structure and increased compaction due to the traffic of the heavy machinery used in inadequate moisture conditions. These conditions results in the reduction of infiltration and increased runoff and erosion. Finally, there is the absence of additional soil conservation practices that could increase infiltration and reduce runoff speed, which are exemplified by practices such as crop leveling, strip cropping, vegetated ridges, wide base terraces, and channel sinks. Depending on how these management operations, planting, harvesting, and

phytosanitary treatments are carried out, local farmers interpret these practices as a hindrance to daily activities and an additional cost due to longer time spent moving between plots parallel to the contours of the terrain. Note that cultivation towards the ridges and without the presence of runoff containment structures is a “facilitator” for the occurrence of erosion.

The amount of suspended sediment in this catchment is a situation of great concern both from the standpoint of the farmer and society in general. Other than the loss of fertility, soil disruption, loss of usable area due to gullies and channel erosion, and reduced water storage in soil, there is also the potential for the transfer of nutrients and pesticides into water bodies. The soils of Conceicao catchment are mainly clay and with a large proportion of micro-aggregates which gives soil particles a high capacity to adsorb chemicals, such as phosphorus and pesticides used on crops. This is an off-site effect of erosion that results in a great cost to society since it increases the cost of water treatment, the risk of eutrophication, the contamination of water resources, and also exposes the population to potentially hazardous substances.

The monitoring results indicate two important temporal situations. The first is related to the intra-annual temporal variability that was evidenced by the sediment yield results for the 2000–2010 period. The magnitude of sediment yield as a reflection of erosion and runoff assumes very high values in a specific period of the year from September to November with a peak in October. In this case, the planning of agronomic practices should consider this temporal aspect in order to help mitigate erosion. Soil management must prioritize soil conditions to provide maximum coverage for the period most likely to incur high rainfall erosion.

The second important condition is related to the probability of extreme events occurring with greater frequency. This was clearly evidenced by the results from the 2011–2012 period when events occurred with return periods of 20 years. The impact of extreme events with return periods of 10 years or less are responsible for high soil losses with damaging and irreversible consequences both from the standpoint of the farmer and society. Quantification of water and sediment discharges in these situations justifies the need to implement mechanical runoff control measures. Farmers' cropping plans should always take into consideration the geomorphological characteristics of the landscape and the hydrological processes conditioned by it. This action could guide the excess rainfall that will inevitably occur regardless of these additional measures being able to maximize the potential of water infiltration into the soil.

Regarding the Guapore catchment, the average sediment yield in the period monitored with high frequency was $274 \text{ t km}^{-2} \text{ year}^{-1}$, whereas that in the period when the series was extended with the use of a discharge rating curve was $140 \text{ t km}^{-2} \text{ year}^{-1}$. This difference can be explained by a sequence of extreme events that occurred in July and August 2011 and July, September, October, and December 2012, which contributed significantly to the increase of sediment yield and C above the historical average. The average erosivity index for the 2011–2012 period was $10,000 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$ and for the 2000–2010 period was $8,800 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$, which may partly reflect the variability found in the sediment production.

The Guapore catchment has natural characteristics that favor erosion processes and the transfer of sediment from the source to the river network, mainly in the middle-third and bottom sections, where the terrain is hilly and soils are shallow. In the upper-third of the catchment, the natural features, land use, and occupation are similar to the Conceicao catchment; i.e., deep weathered soils and a gentle landscape under no-tillage crops for grain production with the same characteristics as described above. However, in the rest of the catchment, there is a wide variety of land uses, usually without any soil conservation measure, with visible degradation by erosion and sediment transfer to the drainage network. The land uses in this section of the catchment are tobacco, corn and soybean crops, pasture, reforestation with eucalyptus, and native forests.

The key causes of soil degradation by water erosion are intensive cultivation and plowing of the soil on steep hillside slopes. In addition, soil preparation for planting of summer crops occurs in the months of greatest soil erosion (September–November) increasing soil detachment and transport toward the drainage network. Similarly, the contribution of unpaved roads in this catchment is relevant as well as the formation of channels and gullies at the property limits and thalwegs. In terms of the processes of fluvial erosion in the

drainage network (margins and bottom), there are no studies that have quantified its importance for sediment yield. Visual analysis indicate that this process is significantly less than in other regions with sandy soils due to the cohesion effect of clay margins and the rocky basalt bottom.

The main problem observed in the Guapore catchment, in the middle and lower thirds, is the exploitation of agricultural lands. In general, farmers cultivate their lands with inadequate crops and procedures that do not take into account the natural fragility of the land causing the depletion of soils, low economic returns, and rural poverty. There is a need to better plan land use and occupation in the region by promoting awareness among farmers, developing economic alternatives for small properties, and considering the potential fragility of soils. Note that due to the high steepness of slopes and shallow soils, it is fundamental to include mechanical runoff control measures, which should be adapted according to the characteristics of each site, as well as the investment capacity of farmers or public administrators.

5 Conclusions

Two years of continuous and intensive monitoring of runoff–rainfall events enabled the estimation of the magnitude of sediment yield and runoff coefficient in two catchments characteristic of the soils, topography, and agricultural production systems found in southern Brazil. Sediment yield was $140 \text{ t km}^{-2} \text{ year}^{-1}$, and the runoff coefficient was 14 % for the catchment under no-tillage in the plateau region of the state, the Conceicao catchment, while sediment yield was $270 \text{ t km}^{-2} \text{ year}^{-1}$, and the runoff coefficient was 31 % for the Guapore catchment which has a wide variety of soil uses and management and is in the plateau slope region.

With the use of a discharge rating curve, average annual sediment yield and runoff coefficient were estimated for both catchments for a longer period which is more representative of weather patterns in the region. The results showed that for both catchments, sediment yield and runoff coefficient values, are too high for local conditions, thereby providing a warning regarding current erosion processes. Moreover, there is clearly intra-annual variability in rainfall erosion, with maximum values occurring from September to November, with direct consequence to runoff values and sediment yield estimates. This has a direct influence on the planning of crop management and soil cover.

The soil management systems used by farmers in both catchments are inefficient to reduce (mitigate) runoff and erosion in areas with crops. Due to the responses to high magnitude events, we can infer that the absence of mechanical runoff control measures, along with inadequate land use and soil management, is the main causes for the observed magnitude of the hydrological and sedimentological processes.

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