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SEDIMENTS, SEC 3 • HILLSLOPE AND RIVER BASIN SEDIMENT DYNAMICS • RESEARCH ARTICLE

Impact of broad-based terraces on water and sediment losses in no-till (paired zero-order) catchments in southern Brazil

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Abstract

Purpose Soil degradation is a widespread problem and currently one of the biggest challenges in modern-day agriculture. The partial adoption of conservation agriculture, such as no-till management, does not provide adequate erosion control, and the hydrology dynamics on hillslopes under no-till management remain poorly quantified. This study examines the hydrology of agricultural hillslopes under no-till management, with and without terraces in southern Brazil.

Materials and methods Water and soil losses were measured in two paired, zero-order catchments (2.4 ha) under no-till cultivation, with and without broad-based retention terraces. Rainfall, surface runoff, and suspended sediment concentrations were monitored during major rainfall events. Analysis of hydrographs and sedigraphs was used to derive the peak flow, runoff duration, and sediment yield values and the hysteresis between surface runoff and the suspended sediment concentration during different seasons.

Results and discussion The results show higher soil and water losses in the catchment without terraces. Terracing reduced peak flow rates by 79%, sediment yield from 0.44 to 0.16 t ha^{-1}, and the total surface runoff from 3943 (126 mm) to 855 m^3 (36 mm) during 31 events over 16 months. The no-till system without terraces was unable to adequately control surface runoff and soil erosion. Surface runoff and sediment yield were higher under no-till without terraces than under no-till with terraces.

Conclusions The difference in terms of surface runoff volume and sediment yield indicates an important difference in the hydrology and soil erosion in the catchment without terraces, which is represented by high-surface-runoff coefficient values observed during the rainfall-runoff events. The short lag time and steep rising limb of the hydrographs indicate high-surface-runoff responsivity to rainfall in no-till without terraces.

Keywords Conservation tillage · Erosion · Hydrograph · Peak flow · Runoff · Sedigraph

1 Introduction

Conservation agriculture, promoted worldwide, has aimed to improve the overall balance of agricultural crop production by enabling the more efficient use of natural resources (Pimentel 2006; Evrard et al. 2008; Kuhn et al. 2016). Brazil is considered a pioneer in soil conservation practices and no-till soil management systems in tropical and sub-tropical conditions (Landers 2005). This is the result of high-soil losses observed in agricultural areas managed under conventional tillage systems in the 1970s and 1980s. The no-till system (NTS) has stood out as a conservation technique that maximizes the agricultural and environmental functions of the soil, e.g., Thierfelder and Wall (2009), Lal et al. (2012), and Williams et al. (2014).

Despite widespread use in 32 million hectares across Brazil (FEBRAPDP 2012), which represents 58% of the area under grain production, these regions still suffer land and water degradation (Bertol et al. 2007a). In South America, especially Brazil, the positive effects of NTS have caused farmers, who initially

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believed that NTS alone would control water and soil loss, to rely heavily on no-till farming and encouraged them to either partially or completely withdraw their retention terraces from their lands (Pruski 2009; Pruski et al. 1996; Caviglione et al. 2010). Additionally, withdrawing the terraces is justified, since it favors operational activities with large agricultural machinery and implements (Levien et al. 2011). Along these lines, the current no-till system is not being conducted according to the principles recommended in its development (Reicosky 2015), and this is highlighted by poor crop residue on the soil surface, lack of crop rotation, and absence of surface runoff control practices (Denardin et al. 2008; Derpsch et al. 2014; Lal 2015).

In NTS, disturbances in the physical properties of the soil may occur, such as soil compaction (Suzuki et al. 2008; Gubiani et al. 2015) and reduction of soil roughness, which reduces infiltration rates and, consequently, increases surface runoff. This has a significant impact on hydrology and triggers soil and water degradation (Poesen et al. 2006; Montgomery 2007; Beyene et al. 2010; Wang et al. 2011; Maetens et al. 2012; Van den Putte et al. 2012). The negative effects of reduced infiltration and increased surface runoff have led to soil degradation in the no-till system. These consequences are due to partial and inadequate adoption of conservationist principles, including crop rotation, high-biomass input, contour farming to maintain soil productivity, and environmental functions, such as surface runoff control (Hobbs et al. 2008; Verhulst et al. 2010; TerAvest et al. 2015).

Over the last 15 years, the NTS applied in southern Brazil evolved into a soybean monoculture model based on the absence of plowing, low-biomass input, and removal of mechanical surface runoff control measures, such as broad-based terraces, water ways, and buffer strips (Denardin et al. 2008; Derpsch et al. 2014). In addition to the problems related to soil degradation, soil erosion, and surface runoff, it also supplies considerable amounts of sediment and agrochemicals to rivers (Bortoluzzi et al. 2007; Tiecher et al. 2015, 2016). This causes the siltation of reservoirs and waterways, which consequently increases the risk of flooding and depletion of water quality due to the transport of contaminants, including nutrients and pesticides (Bilotta and Brazier 2008). Despite NTS being more efficient in controlling soil erosion, studies in southern Brazil have shown that NTS is not as efficient in controlling surface runoff as it is in reducing soil loss (Merten et al. 2015). Intense and/or long-term rainfall can generate significant surface runoff volumes in NTS, especially when soil structure degradation is evidenced by the reduction of meso and macropores. Significant surface runoff volumes in NTS (chiefly when associated with relief characterized by hillslopes with high slopes and/or long lengths) can potentially remove crop residues and provoke rill erosion, as observed by Cogo et al. (2003) in southern Brazil.

Although the impact of NTS on water and soil erosion dynamics has been investigated at the plot scale (Eltz et al. 1984; Cogo et al. 2003; Bertol et al. 2007b; Lanzanova et al. 2013), few studies have quantified the impact of this practice at the hillslope or zero-order catchment scale (Boix-Fayos et al. 2006; De Vente et al. 2013). Therefore, monitoring water and sediment discharge at this scale is important for furthering our understanding of the impact of farming practices on hydrology and soil erosion, which will reduce land degradation and decrease sediment transfer to rivers (Renschler and Harbor 2002; Silva and De Maria 2011; Levien et al. 2011).

To achieve the proposed objectives, two paired zero-order no-till catchments were monitored: one with surface runoff control structures (retention broad-base terraces) and another one without terraces. Rainfall, surface runoff, and suspended sediment concentrations were monitored during major rainfall events over a period of 16 months. Data were analyzed by comparing total surface runoff volume and sediment yield at each event, as well as by comparing the characteristics of the hydrographs and sedigraphs from each catchment.

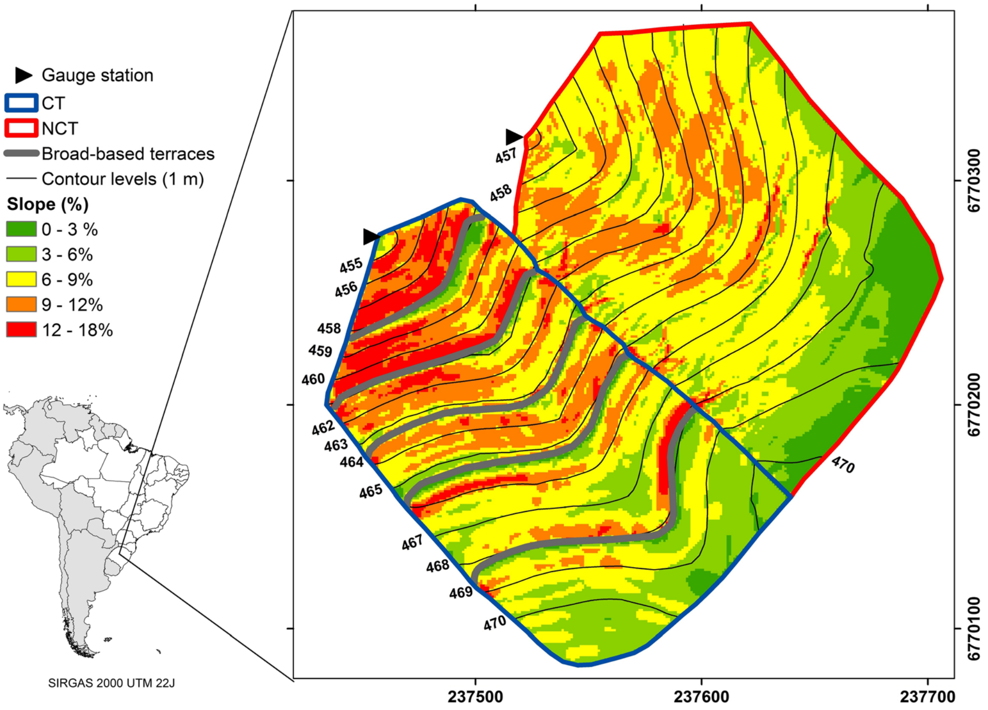
2 Materials and methods

2.1 Study area

The study was carried out in the Meridional Plateau, which is located in southern Brazil (29°13′39”S, 53°40′38”W) (Fig. 1). This plateau was formed by a succession of volcanic rock layers and is characterized by a gently rolling landscape, with slopes ranging from 5 to 13%. The study site soil is classified as deep, strongly weathered Nitisols (FAO 1998) with a high-clay content (> 50%). According to Köppen's classification, the climate is Cfa, which is described as a humid, subtropical climate with hot humid summers and mild to cold winters. The average annual rainfall of 1677 mm is evenly distributed throughout the year, and the average annual rainfall erosivity reaches approximately 10,037 MJ mm ha^{-1} h^{-1} (Fig. 2), based on historical rainfall data.

Water and sediment fluxes were monitored in two paired convergent-convex zero-order catchments, characterized by the presence of ephemeral channels in their thalwegs. The catchments were chosen based on topographical, hydrological, and soil similarities. The numerical elevation model was obtained, and topographical indices were calculated (slope, accumulated flow, length slope, and plan and profile curvature) based on this model for comparison between the catchments and delimitation of the area of contribution, with the highest similarity possible. In both catchments, the upper and side boundaries present convexity, and in the middle, there is a thalweg where the catchment surface runoff converges into the gauge section. Despite thorough verification of the relief between catchments to ensure similarity between them, some differences naturally exist. Table 1 shows the main characteristics of each catchment concerning the relief. In addition to the features of the relief, a soil survey was also carried out in both

Fig. 1 Location and topographic map of the two catchments in Southern Brazil



catchments. This analysis was based on the morphological, chemical, and physical attributes of six profiles of each catchment, and no significant differences were found between them.

Both catchments followed the natural boundaries (Fig. 3) of the landscape units, and the ridges of compacted soil were built into the boundaries to be as small as possible. These ridges were dug out along the edges of the catchment in order to delimit the area and prevent water from entering or exiting the catchment. The ridges were reinforced on the lower part of the plot next to the gauge section. Soil was compacted and vegetated to prevent erosion within the ridges. Notably, this study did not detect erosion or deposition along the ridges during rainfall events.

The catchments were named No Terrace Catchment (NTC) and Terrace Catchment (TC). The southwest catchment (Fig. 1 and Table 1) was chosen for construction of the retention terraces due to its slightly steeper and longer hillslope. In this catchment, five broad-base retention terraces were built (Huffman et al. 2015; USDA-NRCS 2011), which are closed at the ends to prevent water from leaving the terrace. Terraces reduce the slope length, decreasing the runoff volume and velocity, thereby reducing soil and nutrient losses, as well as increasing infiltration and water availability to plants. The terrace distances were calculated, considering the need to control the inter-rill and rill erosion using slope, soil type, land use, and soil management information. It was built with a

Fig. 2 Long-term average precipitation and erosivity over the last 40 years

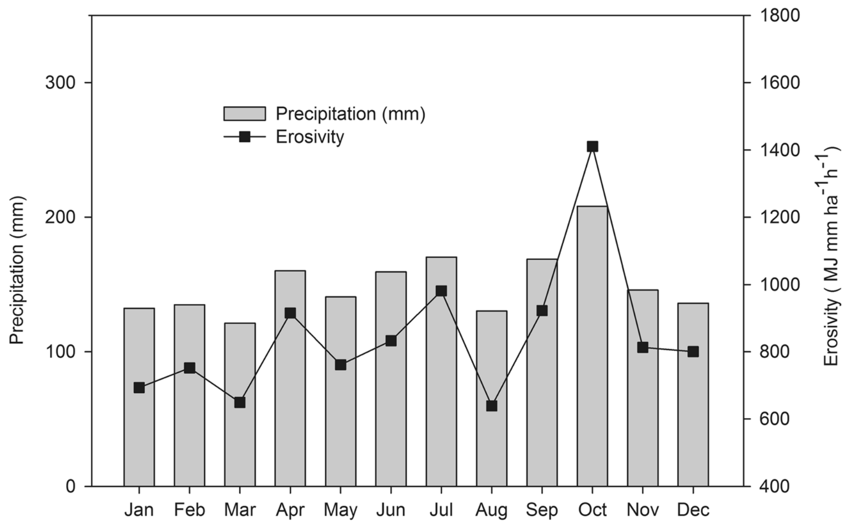


Table 1 Physiographic characteristics of the paired catchments

Catchments	Slope (%)	Slope curvature	Length of slope (m)	Contribution area (ha)
NTC	6.8	0.20	194	2.43
TC	7.1	0.50	216	2.35

vertical spacing of 2.7 m, and horizontal spacing was set, ranging between 30 and 40 m. The last terrace is located 36 m (horizontal spacing) from the gauge section, thus creating an area of 1689 m^2 without surface runoff control and where a small quantity of water and sediment may be generated. The terrace size was calculated, considering the need to store excess precipitation volume, using the following information: contribution area between the terraces, slope of 0.10 m m^{-1}, infiltration rate of 30 mm h^{-1}, and rainfall of 110 mm. Precipitation was estimated using a return period of 10 years and 24 h duration time (Sampaio 2011). The basic infiltration rate measured is controlled by the soil densification that occurs in the no-till system, driven by heavy agricultural vehicles and the high amount of clay (> 50%). Silva et al. (2009) and Girardello et al. (2011) found similar values for the same region. From the precipitation and infiltration data, it was then possible to estimate the volume of excess precipitation that should be contained by the terraces. Based on this volume, a 6-m-wide strip of soil was mobilized to build a broad-based terrace with a ridge of approximately 0.50-m high and a retaining channel of 0.2-m deep. This generated a 2-m^2 cross-sectional triangular area, based on the ridge and retaining channel sizes.

The terraces were built in mid-June 2014, using a 3-disc plow and a back-blade pulled by a tractor to establish the cross-section. The time spent for construction of all terrace was approximately 5 h (120 m h^{-1}). The shape of the terraces enables the crops to be sown in the ridges and in the retention channels. The ridges are lightly compressed during the construction and *Avena strigosa L.* (black oat) subsequently sowed in order to minimize the effects of erosive agents (raindrop and surface runoff). The area mobilized in the ridges and retention channels was limed and fertilized, allowing the plants to grow with the same coverage and productivity as the rest of the field. The benefits were obtained immediately after its establishment. The negative effects generated by the mobilization of the soil during its construction were soon overcome after the crop was established.

The adopted soil management was the no-till system. For this management, the soil was left unploughed and soybean (*Glycine max*) sowing occurred directly after the desiccation of winter crop, black oat. These crops and soil management were chosen to represent the cereal production system currently

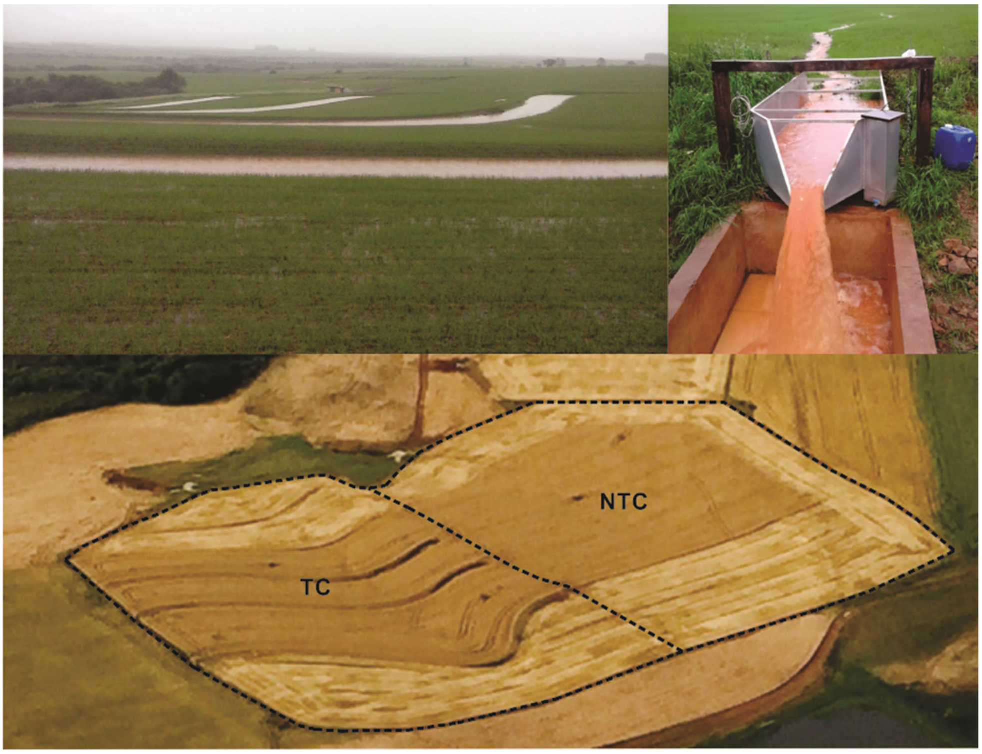


Fig. 3 Paired catchments monitored with a view of the contour bench terraces and the monitoring section

adopted in southern Brazil. After the soybean harvesting, the crop fields are kept under fallow until the wheat (*Triticum aestivum*) or black oats are cultivated in winter/spring. Subsequently, the soybeans, and sometimes corn, are cultivated during the summer. These crops are sown using drill seeders adapted for no-till farming. The period between soybean harvesting and the establishment of the winter cover provides minimal soil protection due to the low amount of residue from the soybeans, as well as their rapid decomposition (Fig. 3). Fertilization, pesticide treatment, and other crop management techniques followed the appropriate technical recommendations for the crops (Lângaro and Carvalho 2014; de Oliveira & da Rosa 2014). Table 2 shows the crop stage characteristics during each event monitored. Before the monitoring period, since 90s, the experimental area was cultivated with the same soil management and land use without terraces.

2.2 Monitoring

Monitoring was performed between July 2014 and October 2015. Rainfall gauges were used in order to quantify precipitation at daily and 2-min intervals. In the first case, pluviometers were installed at a local weather station near the catchments. In the second case, a tipping-bucket rain gauge was used to measure the depth in short durations to estimate the intensity at high frequencies. With these data, it was then possible to obtain precipitation variables, such as erosivity, with high-temporal discretization for each rainfall-surface runoff event. This was then calculated by using the relationship between kinetic energy and rain intensity (Eq. (1)) (NOAA 2016; Ramon et al. 2017), obtained through the direct monitoring of these two variables using the disdrometer.

$$E_{time} = 14.551 \times I^{1.139} \tag{1}$$

where E_{time} is the energy per unit area and time (J m^{-2} h^{-1}) and I is in millimeter per hour.

Additionally, daily precipitation data over 41 years, obtained from the National Water Agency (ANA), were used to estimate the monthly average of the total depth and erosivity (MJ mm ha^{-1} h^{-1}) by using Eq. (2), as proposed by Cassol et al. (2007) for the region.

$$\mathrm{EI}_{30} = 109.65 \times \mathrm{PC}^{0.76} \tag{2}$$

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

Surface runoff was measured in a 0.61-m-wide, stainless-steel H Flume installed in the outlet of each catchment (Fig. 3). H flumes are small flumes for measuring water flow using a known relationship between depth and water flow. This flume has a V-shaped throat whose design enables a wider range of flow depths. Upstream to the H flume, a 3-m-long galvanized metal channel was built in order to regulate water flow. The flume dimensions were calculated based on the estimation of peak flow using the Rational Method (Smith and Lee 1984), while taking into account a maximum surface runoff coefficient of 0.70, a rainfall duration of 1 h and a 10-year return period. The maximum peak flow calculated was 0.34 m^3 s^{-1}. A pressure sensor installed in a stilling well attached to the H flume was used to measure surface runoff depth and, based on a rating curve, the water flow was estimated at 2-min intervals.

The suspended sediment concentration (SSC) was determined based on manual sampling during events. Ten to 40 samples were collected during the hydrograph rising and falling limb at intervals ranging from 1 to 15 min depending on the magnitude and velocity of the event. Samples were then analyzed using the evaporation method (Shreve and Downs 2005).

Additionally, an in situ turbidity meter (model SL 2000-TS SOLAR®) was installed in order to increase temporal discretization of SSC measurements over time. The turbidity sensor was installed with the surface runoff sensor level and recorded measurements at 2-min intervals. The conversion of turbidity data into SSC was performed according to the methodology described by Merten et al. (2014). The concomitant SSC and turbidity data obtained during each rain event were used to establish a mathematical relationship, specific for each event, between both variables. Therefore, the turbidity data measured at a high frequency were transformed into SSC.

The antecedent moisture condition was evaluated using the daily rainfall data considering the antecedent precipitation that occurred during the last 5 days. To establish a relation between the quantities of rain and antecedent soil moisture, the classification of "Curve Number" (USDA-NRCS 2009) was used, where soil with moisture under the field capacity was represented with rainfall below 36 mm, soil at field capacity between 36 and 53 mm, and saturated soil with precipitation values above 53 mm.

For each rain-surface runoff event, a set of response variables was obtained in the two compared catchments (NTC and TC). This was done in order to establish any differences between them and consider the response to the precipitation event based on the water flow and suspended sediment concentration. The main variables measured in each event were (i) rainfall (P, mm/h), (ii) water flow (Q, l s^{-1}), (iii) surface runoff volume (R_{tot}, m^3), (iv) peak flow (Q_{peak}, l s^{-1}), (v) surface runoff coefficient (C, dimensionless, calculated by dividing the total runoff volume by total precipitation, both in millimeter), (vi) suspended sediment concentration (SSC, mg l^{-1}), and (vii) sediment yield (SY, kg) (Eq. (3).

$$\mathrm{SY} = k\sum(Q_{\mathrm{i}}.SSC_{\mathrm{i}}) \tag{3}$$

where SY is the total sediment yield in each event (kg), Q_{i} is the instantaneous water flow (l s^{-1}), SSC$_{\mathrm{i}}$ is the instantaneous

Table 2 Rainfall and crop stage characteristics for each event monitored

Event	P mm	I mm h^{-1}	I_{30} mm h^{-1}	Crop and stage
17/07/2014	23	2.4	9.2	Black oats, germination
23/07/2014	65	3.5	21.2	Black oats, vegetative
02/09/2014	65	11.8	27.8	Black oats, vegetative
10/09/2014	31	4.3	19.9	Black oats, vegetative
14/09/2014	41	18.1	31.6	Black oats, vegetative
30/09/2014	45	2.5	8.2	Black oats, vegetative
17/10/2014	26	1.8	30.4	Black oats, flowering
18/10/2014	14	1.7	9.3	Black oats, flowering
19/10/2014	19	2.2	11.2	Black oats, flowering
30/10/2014	69	5.6	27.7	Black oats, grain filling
03–04/11/14	51	7.5	39.9	Black oats, physiological maturity
01/01/2015	25	8.1	27.6	Soybeans, vegetative stage
27/01/2015	24	6.8	38.8	Soybeans, flowering
29/03/2015	31	17.4	23.9	Soybeans, after harvest
27/05/2015	62.0	6.4	10.6	Fallow
17/06/2015	32.0	2.7	7.3	Fallow
22/06/2016	35.0	2.1	16.6	Wheat, seeding
23/06/2015	17.0	3.0	14.9	Wheat, seeding
24/06/2015	53.0	4.8	7.9	Wheat, seeding
30/06/2015	39.6	3.8	10.8	Wheat, germination
07/07/2015	31.1	3.7	7.3	Wheat, vegetative
08/07/2015	25.0	2.0	8.3	Wheat, vegetative
13/07/2015	25.0	6.5	23.7	Wheat, vegetative
14/07/2015	22.0	2.1	18.5	Wheat, vegetative
20/07/2015	65.0	5.0	18.3	Wheat, vegetative
26/08/2015	41.0	3.5	19.7	Wheat, vegetative
19/09/2015	71.0	4.1	29.0	Wheat, flowering
21/09/2015	15.0	4.2	31.3	Wheat, flowering
22/09/2015	34.0	8.4	21.5	Wheat, flowering
08/10/2015	160.0	7.8	57.6	Wheat, grain filling
15/10/2015	47.0	4.5	33.6	Wheat, grain filling

P *(mm)* total rainfall, I *(mm h^{-1})* average rainfall intensity, I_{30} *(mm h^{-1})* maximum rainfall intensity in 30 min

suspended sediment concentration in (mg l^{-1}), and K a unit conversion factor.

This set of variables was analyzed in order to evaluate the differences between both treatments. Therefore, descriptive statistics were used, including dispersion measurements and central tendency. In addition to this, Student's t test for paired samples was used in order to assess the differences between the variables considering all events. In this case, the mean of the variables of both catchments is compared considering that each event in a catchment can be paired with the observations in the other catchment (Williams et al. 2014).

The strategy of analysis and data interpretation objective was to quantify the differences between treatments over time while seeking to isolate the impact of climate, soil, and land use factors. Therefore, the source of variation was the presence of the terraces. However, the source of uncertainty in the results may be due to small variations in relief or in the soils. In addition to the estimates of total losses of water and soil, the study explores the behavior of Q and SY during events. In this analysis, the hydrographs from the paired catchments were compared considering the rate of the rising limb (high or low), synchronism between P and Q peaks, duration of P and Q events and hysteresis between Q and CSS, as presented by Williams (1989) and Lawler et al. (2006).

3 Results and discussion

The 31-monitored events occurred in the period from the beginning of the winter cover crops (black oats) in July 2014 to the end of the next winter crop (wheat) in October 2015 through the summer crops (soybeans). During this period, rainfall-surface runoff events of different magnitudes occurred under different soil cover conditions (Table 2). The total precipitation during the monitored period (16 months) was 2497 and 1233 mm during the events (Table 3). The set of observed events was classified into three groups according to the *Q*-event duration (hours): (a) seven minor surface runoff events lasting from 1 to 4 h, (b) 12 intermediate surface runoff events from 4 to 10 h, and (c) 12 longer surface runoff events from 10 to 17 h.

Although the monitoring period was rather short (16 months), the 31-monitored events covered a wide range of rainfall characteristics (volume, intensity, and duration), land use, and soil conditions. Precipitation occurred mainly during September and October 2014 and June and July 2015, when 18 (of a total of 31) rainfall-surface runoff events were measured. During these periods, the soils of the catchments were fully protected by the black oats in 2014 and the wheat in 2015, since they provide good coverage during these stages of development.

The observed temporal patterns in the hydrological response were assessed in each catchment for each individual event, since they reveal unique combinations of rainfall, antecedent soil moisture, and soil cover conditions.

3.1 Water and soil losses

Measured water and sediment losses (Table 3) indicate that the NTC presented a different hydrology and erosion pattern than the TC. Water and sediment losses were higher in the NTC than in the TC, especially during events of higher rainfall and poor ground cover. Regarding the 31-monitored events, the sum of the R_{total} in the NTC was 3943 m^3, compared with 855 m^3 observed in the TC (Table 3). Given that there is no evidence that catchment soil is different when considering a slight difference in topography, one may assume that the difference in losses was directly impacted by the retention terraces, even though other factors may have also influenced the observed variability.

The results of a descriptive statistical analysis of the 31-monitored events can be seen in Table 4 and Fig. 4. Even considering the high amplitude between the events, there is a clear difference between the variables (R_{tot}, Q_{peak}, *C*, and SY) for both catchments. Considering the measurements of central tendency, it is clear that NTC values are higher than TC values, which indicates increased losses of water and sediment. Similarly, the measurements of dispersion also indicated the positive effect of the presence of the terraces. The highest values of kurtosis and amplitude between the maximum and minimum of each variable indicate that the TC has a greater capacity to reduce flow and, consequently, SY. Standard deviation and standard error measurements also indicate the lower amplitude of the variables, as well as a greater NTC susceptibility to extreme precipitation events.

The water losses previously mentioned, especially sediment yield, were influenced by the occurrence of an event of greater magnitude that occurred on 23/07/2014. This event accounted for 7% of the total water loss and 57% of the total NTC sediment loss in the monitored period. Despite the low frequency, these events are very important for establishing the magnitude of soil loss and sediment yield. Although most events occurred in September and October, this extreme event occurred in July, when the soil cover was low. Notably, the soil losses in this event were affected specifically by (a) poor soil coverage composed of black oat in the early stage of development (5 cm), (b) the soil mobilized by the sowing seeder a month before, (c) the high-antecedent soil moisture, and (d) the main peak of precipitation (higher intensity) that occurred at the end of the event.

The magnitude of surface runoff in the NTC was 2 to 90 times greater than the TC. Such a difference is strongly affected by factors including rainfall, poor soil residue coverage, and high-antecedent moisture. Regarding SY and Q_{peak}, there was a reduction of 65 and 78%, respectively (Table 3). The difference in sediment yield values was less evident than the difference in runoff values, since the SY difference is less important in small and intermediate events (most of the events). In the NTC, the total soil loss was approximately 1.08 *t* (Table 3) for the 16-month monitoring period, which means 0.31 t ha^{-1} y^{-1}. However, this soil loss rate cannot be considered as a long-term annual average because of the short monitoring period. Merten et al. (2015) monitored large plots at a similar scale and soil characteristics and found soil losses of approximately 1.70 t ha^{-1} in the conventional system and 0.05 t ha^{-1} in the no-till without terracing.

It is generally agreed upon that adequate management of the no-till system is extremely important for controlling soil erosion in Brazilian agriculture. The positive effect of greater residue on the soil surface generated by the no-till carried out in southern Brazil is incontestable, even without the terraces. However, the same claim cannot be made about water loss. Surface-runoff coefficient (*C*) values of the NTC indicate lower soil infiltration capacity in the no-till soil management. The control of surface runoff solely by this conservationist tillage was inefficient, as also noted by Barcelos et al. (1999). Despite the reduced erosion rate observed in the scale of this study, the high volume of surface runoff generated can lead to downstream erosion processes, such as rill and gully erosion and bank erosion in rivers. Trimble (1983) demonstrated that the introduction of soil conservation practices decreased the concentration of sediment in the flow, thus increasing its transport capacity and causing greater erosion into the river system.

Regarding the events that occurred on 23/07/2014 and 08/10/2015 in the NTC, the higher volume of surface runoff with *C* of 19 and 44%, respectively, indicates an environment with restricted infiltration capacity, rainwater detention, and storage. For this region and under good soil management, it is

Table 3 Summary of hydrological variables measured during the monitoring period in the non-terraced catchment (NTC) and the terraced catchment (TC)

Date	*P* (mm)		EI30		R_{tot}	R_{tot}	Q_{peak}	RC	SSC	SY
	Event[1]	Previous[2]	MJ mm ha^{-1} h^{-1}		m^3	mm	l s^{-1}	%	g l^{-1}	kg
17/07/2014	23	0	33.4	NTC	1.7	0.1	1.1	0.3	1.8	1.11
				TC	No available data					
23/07/2014	65	23	245.2	NTC	300	12.3	117	19.00	0.6	623.00
				TC	78	3.3	34.3	9.1	1.5	295.00
02/09/2014	65	10	386.2	NTC	17	0.7	3.4	1.07	0.2	5.7
				TC	0.9	0.0	0.6	0.06	1.3	1.1
10/09/2014	31	60	126.3	NTC	1.5	0.1	1	0.2	0.1	0.4
				TC	0.8	0.0	1.1	0.1	0.5	0.7
14/09/2014	41	37	305.6	NTC	101	4.1	39.4	10.00	0.1	9.1
				TC	3.3	0.1	3	0.4	0.8	3.8
30/09/2014	45	74	65.4	NTC	107	4.4	14.7	9.8	0.03	3.5
				TC	6	0.3	1.2	0.6	0.4	0.9
17/10/2014	26	13	162.4	NTC	1.1	0.0	0.3	0.2	0.08	0.1
				TC	0.4	0.0	0.1	0.1	0.04	0.00
18/10/2014	14	34	23.3	NTC	2.1	0.1	0.2	0.6	0.05	0.1
				TC	0.5	0.0	0.1	0.1	0.09	0.00
19/10/2014	19	47	37.8	NTC	62.2	2.6	8.2	13.00	0.05	3.9
				TC	2.1	0.1	0.7	0.4	0.4	1.7
30/10/2014	69	0	392.7	NTC	3.2	0.1	0.6	0.3	0.04	0.00
				TC	0.4	0.0	0	0.02	0.08	0.00
03/11/2014	51	59	491.2	NTC	144	5.9	110	11.00	0.1	5.7
				TC	14	0.6	18.4	1.1	0.6	12.3
01/01/2015	25	0	251.3	NTC	98	4.0	36	16.00	0.5	8.3
				TC	6.6	0.3	11.5	0.9	0.3	3.4
27/01/2015	24	15	214.5	NTC	8	0.3	4	1.3	2.2	2.7
				TC	0.5	0.0	0.8	0.1	1.2	0.3
29/03/2015	31	21	119.4	NTC	0.4	0.0	0.2	0.06	0.4	0.1
				TC	0.1	0.0	0.1	0.02	0.07	0
27/05/2015	62	34	862.5	NTC	220.74	1.0	35.8	15.2	0.1	8.2
				TC	7.8	0.3	3.4	0.5	0.04	0.3
17/06/2015	32	2	75.8	NTC	106.5	0.5	19.7	14.2	0.1	3.5
				TC	2.1	0.1	1.2	0.3	0.03	0.1
22/06/2016	35	34	511.05	NTC	8.6	0.4	1.4	1.4	0.04	0.3
				TC	0.9	0.04	0.5	0.9	0.03	0.03
23/06/2015	17	35	178.3	NTC	39.0	1.7	6.5	21.6	0.7	27.8
				TC	1.4	0.06	0.5	0.4	0.05	0.01
24/06/2015	53	52	143.8	NTC	321.4	14	18.2	55.8	0.5	149.4
				TC	3.6	0.2	5.4	0.3	0.7	2.6
30/06/2015	40	0	162.7	NTC	24.4	1	8.4	5.7	0.2	5.4
				TC	1.5	0.06	1.0	0.2	0.7	0.1
07/07/2015	31	8	328.2	NTC	3.6	0.2	0.8	1.1	0.3	1.1
				TC	1.2	0.05	1.2	0.2	1.0	1.1
08/07/2015	25	39	65.5	NTC	33.2	1.4	4.6	5.9	0.1	4.1
				TC	0.9	0.04	0.2	0.1	0.2	0.2
13/07/2015	25	31	446.0	NTC	5.2	0.2	2.9	0.9	0.4	2.2
				TC	2.6	0.00	3.8	0.4	0.8	2.1

Table 3 (continued)

Date	P (mm)		EI30		R_{tot}	R_{tot}	Q_{peak}	RC	SSC	SY
	Event[1]	Previous[2]	MJ mm ha^{-1} h^{-1}		m^3	mm	l s^{-1}	%	g l^{-1}	kg
14/07/2015	22	28	257.9	NTC	43.5	1.9	13.2	8.4	0.4	19.0
				TC	3.9	0.2	3.4	0.7	0.8	3.3
20/07/2015	65	0	915.4	NTC	226.5	9.7	34.0	14.9	0.5	107.1
				TC	18.6	0.8	5.4	1.2	0.8	15.4
26/08/2015	41	0	890.2	NTC	7.4	0.3	3.0	0.8	0.1	0.8
				TC	0.6	0.02	1.3	0.06	0.2	0.10
19/09/2015	71	18	1219.1	NTC	9.2	0.4	1.3	0.6	0.04	0.3
				TC	0.0	0.0	0	0.00	0.0	0.00
21/09/2015	15	89	104.3	NTC	9.4	0.4	4.2	2.7	0.04	0.4
				TC	1.0	0.04	1.7	0.3	0.2	0.2
22/09/2015	34	104	529.8	NTC	162.1	6.9	44.0	20.3	0.04	7.2
				TC	8.6	0.4	5.3	1.1	0.2	1.4
08/10/2015	160	36	4481.1	NTC	1722.6	70.8	353.6	44.2	0.4	79.4
				TC	686.2	29.2	82.5	18.3	0.3	33.5
15/10/2015	47	15	739.5	NTC	152.6	0.7	71.8	1.4	0.02	0.01
				TC	0.7	0.03	14.2	0.1	0.2	3.1
Total	1233			NTC	3943.1	158.0				1079.9
				TC	855.2	36.2				382.7
Significance level (α) *t* test					*		*	*	*	**

P precipitation, [1] precipitation during the event, [2] antecedent precipitation that occurred during the last 5 days, EI_{30} erosividade (MJ mm ha^{-1} h^{-1}), R_{tot} total runoff volume, Q_{peak} peak water discharge, *RC* runoff coefficient, *SY* sediment yield. * Values significantly $p \leq 0.05$ and ** values $p \geq 0.05$

expected that the runoff coefficient does not exceed 10%, considering the gentle relief, deep soils, and good soil cover (Castro et al. 1999; Merten et al. 2015). This larger amount of surface runoff and peak flow values (Table 3) may be associated with high-erosion potential for the downstream parts of the landscape. Further studies at intermediate scales (1–10 km^2) are required to describe the erosion processes located in thalwegs (channels and gullies) and rivers (fluvial erosion) due to increasing transport capacity of the concentrated flow. The results in Table 3 may help explain flooding and high turbidity observed in rivers that drain agricultural catchments (or cultivated slopes) where a partial no-till system is applied, such as that observed by Didoné et al. (2014) and Tiecher et al. (2015) in an 800 km^2 no-till catchment located in the same region as the present study.

The surface-runoff coefficient at the NTC assumes relatively high values for an agricultural condition where conservation tillage is adopted. The variation in *C* can easily reach values above 15%, even for low- and medium-magnitude events of precipitation, and the observed maximum was 56%. In the NTC, 45% of the monitored events presented *C* values above 9%. On the other hand, only two events resulted

Table 4 Hydrological variables monitored during the 14 rain events in zero-order paired catchment

Statistics	NTC R_{tot} (m^3)	TC	NTC Q_{peak} (l s^{-1})	TC	NTC *C* (%)	TC	NTC SY (kg)	TC
Mean	131.4	28.5	31.9	6.8	9.9	1.3	36.1	12.7
Median	36.1	1.5	7.3	1.2	5.8	0.3	3.7	0.8
Standard deviation	314.3	125.0	67.9	16.0	13.0	3.6	116.1	53.7
Standard error	57.4	22.8	12.4	2.9	1.8	0.7	21.2	9.8
Kurtosis	23.4	27.3	18.1	18.2	8.8	18.3	23.4	27.2
Skewness	4.5	5.1	3.8	3.9	2.3	4.0	4.6	5.1
Minimum	0.4	0.0	0.2	0.0	0.06	0.0	0.1	0.0
Maximum	1722.2	686.2	353.6	82.5	55.8	18.3	623.0	295.0
Range	1721.8	686.2	353.4	82.5	55.7	18.3	623.0	295.0

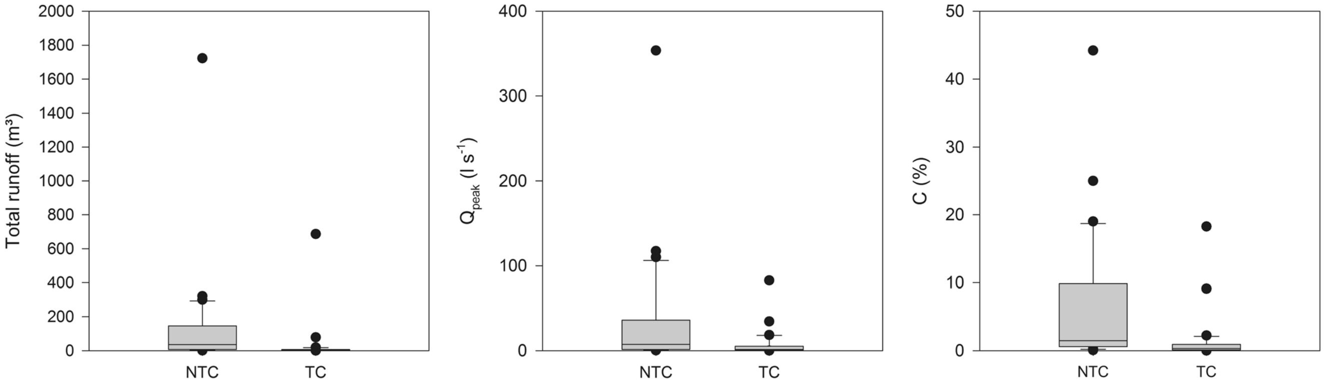


Fig. 4 Box plot of hydrologic variables in NTC and TC

in a high-surface-runoff coefficient in the TC when the runoff on terraces overflowed. The remaining events in the TC presented surface runoff coefficients below 1.5%. Surface runoff and soil loss measurements under similar conditions (scale, soil, and soil management) are scarce. Nevertheless, Castro et al. (1999) monitored surface-runoff coefficients in Ferralsols with a high-clay content (> 70%) in conventional tillage and no-till without terraces in southern Brazil and found mean values of 5.8 and 7.7%, respectively. Merten et al. (2015) performed a monitoring study to evaluate surface runoff and soil loss in large field plots with the no-till system, while comparing it with conventional tillage. The average surface-runoff coefficient obtained during the 6 years of monitoring was 1% for the no-till system, which is lower than those obtained in this work.

It is also noteworthy that all the monitored rainfall events have a return period of less than 2 years, indicating that surface runoff was significant, even in rainfall conditions close to normal. This suggests that the system is highly susceptible to surface-runoff formation. Additionally, the large amounts of surface runoff observed in this work may increase sediment transport capacity. In addition to proving the efficiency of the terraces in controlling surface runoff, the results demonstrate quantitatively significant water loss at the NTC. The agricultural system, represented by the NTC, is characterized by a conservationist tillage (no-till); however, it cannot be effectively considered as an example of conservationist agriculture, as defined by TerAvest et al. (2015) and Reicosky (2015), due to the restriction in infiltration rates, low input of biomass, and the absence of surface-runoff control.

Regarding the erosive process, the results for SY (Table 3) indicate that terracing reduces soil erosion. However, the differences are considered statistically non-significant ($p = 0.06$), considering the cutoff point of 5%. The mean values of the SSC in the two catchments were relatively similar, but the maximum values measured in the TC were higher. In the NTC, the mean value was 0.31 g l^{-1} with a maximum observed value of 2 g l^{-1}. In the TC, the mean value was 0.45 g l^{-1}, and a maximum value of 8 g l^{-1} was observed. The maximum SSC values are higher in the TC in 64% of the events, which is possibly due to the crest of the last terrace, which is close to the monitoring section (approximately 30 m). Despite the higher SSC values observed in the TC for most of events, the sediment yield (SY) in all events was lower, driven by the lower amount of the runoff total volume (R_{tot}) (Table 3).

According to Pimentel (1995; 2006), elevated surface runoff and its associated processes (erosion, nutrient loss, water body contamination, and siltation) may lead to economic losses that affect farmers and society. The adoption of soil conservation practices, such as terracing, has positive effects on agricultural production, since increasing crop yields may be encouraged by increasing the availability of water and nutrients. Terraces are widely used in agriculture for water management and runoff control. Numerous studies have demonstrated its importance in conservation agriculture, such as in Spain (Lasanta et al. 2001; Lessechn et al. 2008; Bellin et al. 2009), China (van Dijk et al. 2002, 2005), India (Huang et. 2003), Italy (Tarolli et al. 2014), and South America (Griebeler et al. 2000; Posthumus and de Graaff 2005). Moreover, not using flow control mechanisms contributes to the degradation of agricultural land, as shown by Diaz et al. (2007) and Bellin et al. (2009). In southern Brazil, terracing in grain production under no-till is done using retention and broad-base type terraces. They are built at ground level for water retention and infiltration or with a gradient in order to lead the excess water to a natural drainage network or artificial-vegetated channels. The estimated cost of their construction is approximately 34 USD per kilometer of terrace (Griebeler et al. 2000). In most of the cases, the construction is carried out with a 3-disc plow pulled by a tractor. The time spent for construction is approximately 120 m h^{-1} or 2.5 h ha^{-1}, depending on the terrace size, relief, and soil. Terraces are constructed and planned to be permanent, but they require regular maintenance to maintain their cross-sectional area that defines the water storage capacity. Such maintenance involves raising the ridge and deepening the furrowing and should be performed whenever there is significant loss of the cross-sectional area, which is initially calculated to receive the excess flow.

Although no-till is able to reduce erosion to low levels (Williams et al. 2014; Kurothe et al. 2014), it is clearly noted that water losses are high. The processes associated with surface runoff, such as the mobilization of nutrients and pesticides, indicate the need to properly manage water, especially on steep hillslopes, long-length slopes, and/or slopes with a convergent profile curvature. Therefore, mechanical practices are suggested in order to control the runoff and reduce the soil degradation by erosion (Merten et al. 2015; Ali et al. 2016). According to Tiecher et al. (2017), the current cropping system adopted by farmers is inefficient at reducing runoff and soil losses that exceed a rate of $2\ t\ \mathrm{ha}^{-1}\ \mathrm{yr.}^{-1}$. Although soil losses found in this study were relatively lower ($< 0.5\ t\ \mathrm{ha}^{-1}$), we must emphasize that high loss of water and associated nutrients (Van Esbroeck et al. 2017) and pesticides (Dores et al. 2008) harm farmers and the environment.

Even if the use of terraces is resumed, the methodology for defining the spacing may need to be overhauled. The methodology used thus far has been built on the estimation of soil loss as a function of critical slope lengths. Currently, however, the dynamics of the degradation process are based on the surface-runoff formation controlled by other factors, such as infiltration reduction by compaction and reduced roughness. This indicates that when determining the spacing between terraces, the hydrological dynamics of the slopes should be taken into account, and new protocols for determining the distance between terraces in the no-till system should be proposed whilst considering surface runoff. It is also important to emphasize that soil compaction may be strongly affected by soil texture, as described by Mentges et al. (2016) and Lima et al. (2015) for Brazilian soils under the no-till system.

3.2 Classification of hydrological and sediment responses

Analysis of Q and SSC enabled a better understanding of hydrological and sediment responses during events. During the monitoring period, two different types of events regarding rainfall-surface-runoff responses were observed: multiple (Fig. 5) and single (Fig. 6) peaks. These two different types of monitored events address important aspects of the mechanisms responsible for transferring water and sediment out of the catchment.

In Fig. 5, two events are shown (30/09/2014 and 19/10/2014), with multiple peak flows driven by a long rainfall event and with a significant volume of surface runoff. This rainfall pattern is a characteristic of the spring season, which represents a period of high erosivity in southern Brazil. In multi-peak and long-term rainfall events, the highest peak intensity may sometimes occur at the end of the event, in which the soil is wetter (30/09/2014) and very susceptible to rill erosion.

Based on the hydrograph and sedigraph of two events shown in Fig. 5, it is possible to observe the differences of peak flow and discharge between the catchments and the fast response after the rainfall. In the NTC, the sediment supply decreases rapidly, since the highest SSC corresponds to the first Q peak, suggesting a detachment-limiting condition, such as in Williams (1989). In both events in the two catchments, the SSC peak is before the Q peak, creating a clockwise hysteresis type (Fig. 7), which may represent sediment exhaustion during this event, since the SSC peak precedes the Q peak.

Figure 6 shows events with a single Q peak resulting from the following: (i) a summer storm (01/01/2015) with a short duration but high intensity and (ii) a winter storm (23/07/2014) with high intensity after many hours of low-intensity rain. The January event can be considered as representative of summer thermal-convective storms, while the July event is representative of frontal storms that occur during the winter, with a higher antecedent soil-water content. The characteristics of the rainfall event contributed to the high magnitude of the water flows observed on 23/07/2014 (Fig. 5). The event was long, with low intensity at the beginning of the event, followed by great intensity at the end. This condition favored an increase in soil moisture, reducing the rate of infiltration at the moment of higher rainfall intensity and resulting in a high amount of surface runoff and fast-rise limb of the hydrograph (Figs 5 and 6).

In most of events in the NTC, it is noted that an advance of the SSC peaks occurs in relation to the Q peaks (counter-clockwise direction; Table 5). This is an indication that the process of erosion that occurs at the site is limited by sediment supply. In the case of the TC, although the magnitude of the soil loss is relatively smaller, and the advance of the SSC peak is less evident, which is likely an outcome of the higher sediment supply resulting from the terrace crest of the last terrace, which mobilizes sediments towards the monitoring section. However, the SY in the TC is considerably reduced due to the lower volume of runoff, when compared to the NTC.

Even if the maximum SSC results were higher in the TC, the importance of the terraces in controlling Q was evident in all events. The differences found between the NTC and TC highlight the efficiency of the terraces in controlling surface runoff from severe storms, even in good soil cover conditions. In the same way, Tomer et al. (2005) observed a significant change in the hydrological pattern in catchments cultivated with different tillage (ridge-tilled × conventional tillage) and with and without terraces. The ridge-tilled catchment presented 47% less surface runoff and 36% more base flow than the conventionally tilled catchment. However, the authors found no differences between catchments, with and without terraces, in the surface runoff explained by the distance between the terraces, which was doubled that recommended by the extension agency.

Table 5 summarizes the characteristics that define the temporal pattern of the monitored hydrographs and sedigraphs.

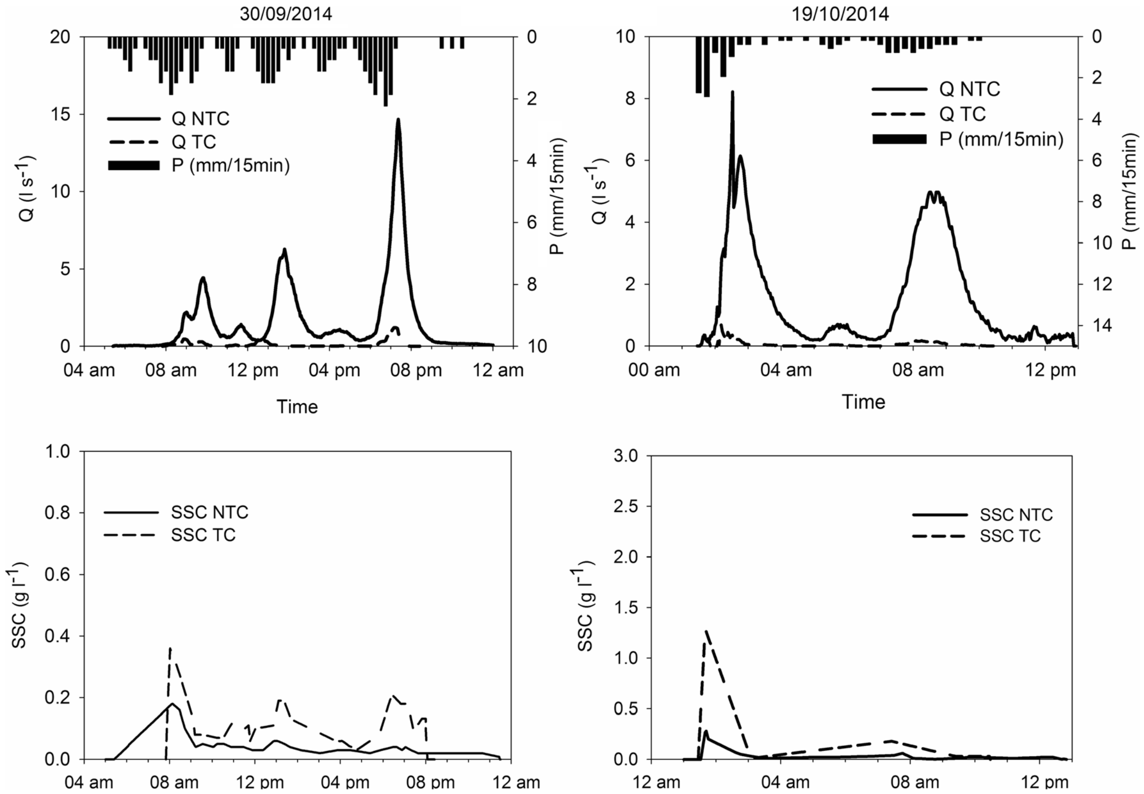


Fig. 5 Hydrograph and sedigraph with multiple peaks in NTC and TC from the 30/09/2014 and 19/10/2014 events

This analysis was based on *Q* and SSC peaks, the hydrograph rise slope, the hysteresis pattern between *Q* and SSC (Williams 1989) and a quantitative hysteresis index (Lawler et al. 2006). The hysteresis loops, which were evaluated by their shape and

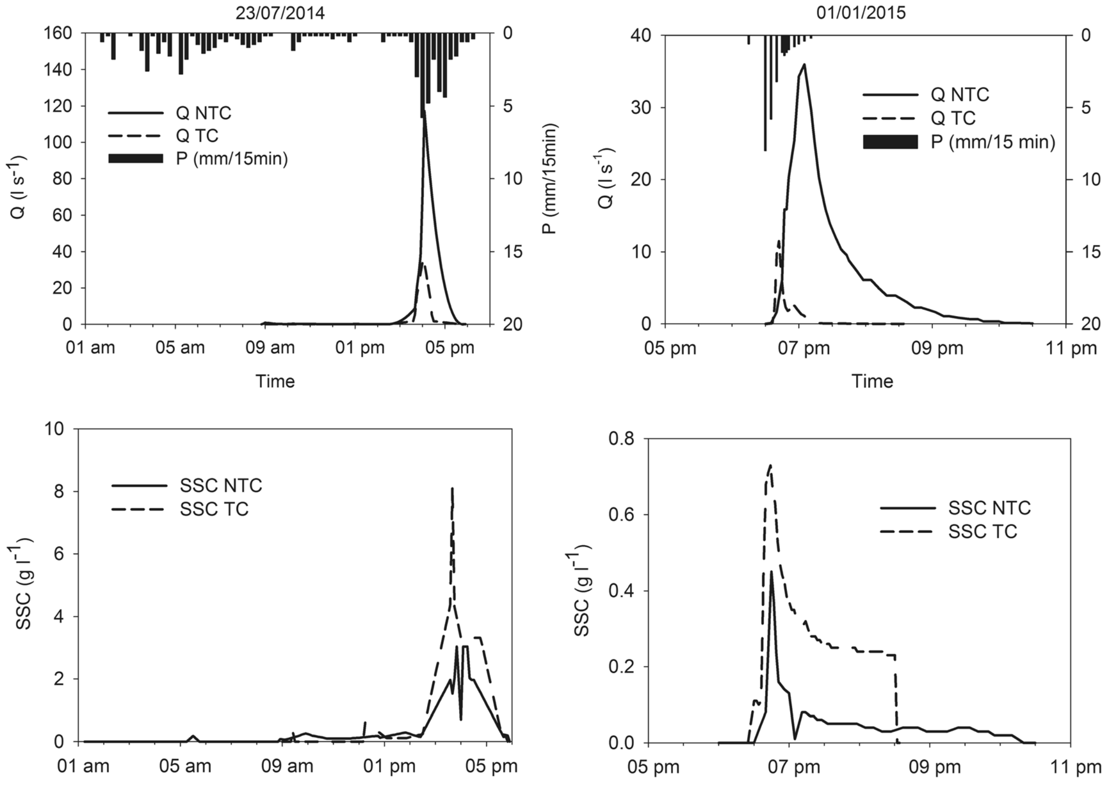


Fig. 6 Hydrograph and sedigraph with a single peak in NTC and TC from the 23/07/2014 and 01/01/2015 events

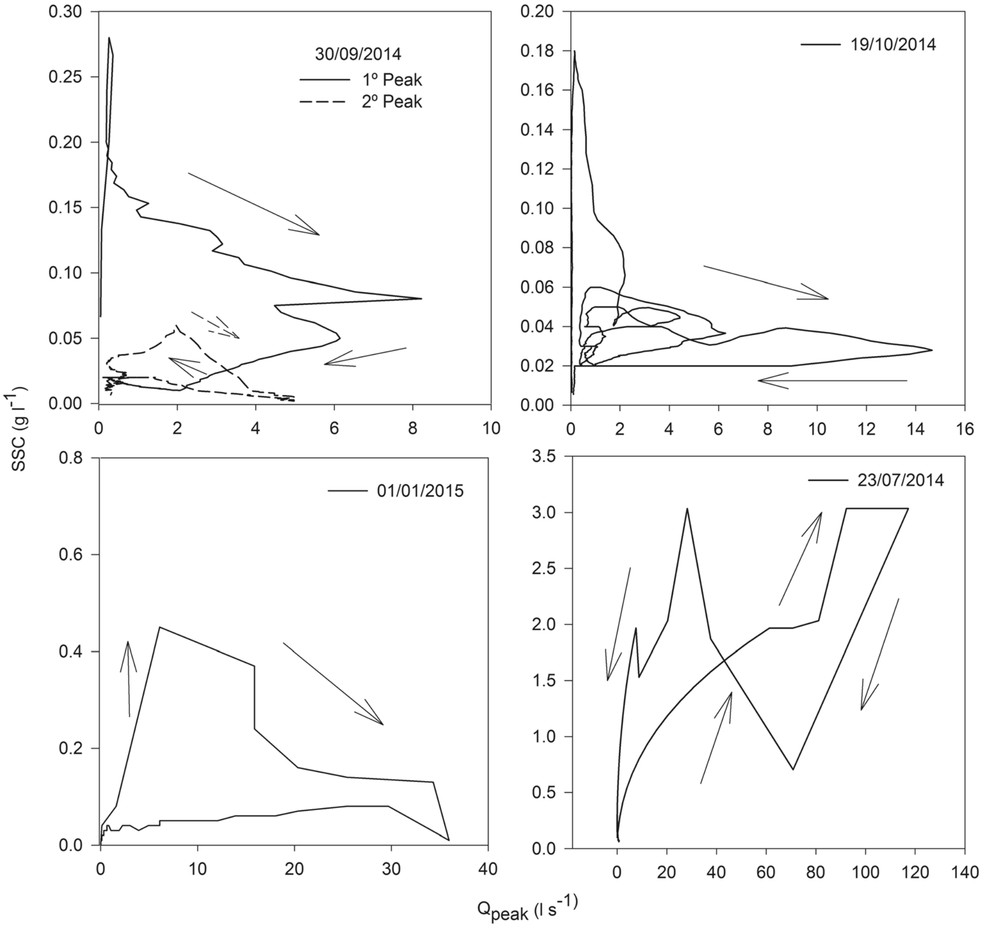


Fig. 7 Hysteresis loops characteristics (CSS-Q) from the 23/07/2014, 30/09/2014, 19/10/2014, and 01/01/2015 events in NTC

a quantitative index, may be indicators of sediment availability and transport (Steegen et al. 2000; Eder et al. 2010). In most events, the peak of the sedigraph tends to occur before the peak of the hydrograph, which shows a hysteretic loop when concentrations are plotted versus surface runoff. Similar results were observed by Novotny (1980), who perceived that the rise of the hydrograph has a higher sediment-carrying capacity than surface runoff at the end of the hydrograph.

Many studies have used water flow and suspended sediment concentration relationships by the hysteresis to make inferences about erosion processes in catchments, such as Bowes et al. (2005) and Duvert et al. (2010). According to King et al. (2008) and Huang et al. (2003), the use of monitoring data with paired catchments is a reliable tool for quantifying the effects of the changes in land use and management in hydrological dynamics, since from the first events, it is possible to verify the differences in the responses of water losses and associated processes.

To classify the pattern between these two variables for the NTC, Table 5 shows different event characteristics and their corresponding direction and hysteresis values for the events monitored. Hysteresis with positive values (counter-clockwise direction) is often explained as the consequence of removing sediments produced in the inter-storm period by the first flush of water (Eder et al. 2010) or sediment supply coming from the channel (Steegen et al. 2000). In the case of the present work, it may be related to sediment eroded in the thalweg in the NTC by concentrated flow or originating from the sediments available during the inter-event period.

The characteristics of the hydrograph for the NTC demonstrate a behavior highly responsive to rainfall, including hydrographs with short lag times and steep rising limbs. Moreover, despite a different Q_{peak} and R_{tot} magnitude, the rising and falling limb slopes of the hydrograph were similar among the catchments (Figs. 5 and 6). In most cases, the SSC revealed a slight advance of the sediment wave, with a clockwise hysteresis loop and distinct sediment supply exhaustion, as we can see the counter-clockwise direction between CSS and Q in Fig. 7. The graphs shown in Fig. 7 describe the relationship between the SSC and Q during the event. If the SSC-Q relationship has the same tendency between the rising and falling limb, the graph will have only one curve. If the CSS-Q relationship is different between the change from the rising and falling limb, the graph will form a loop which defines a hysteresis behavior between the variables.

Soil losses during events with good vegetation cover were lower when compared to events of the same magnitude that occurred the period after soybeans were harvested (poor

Table 5 Main characteristics of monitored hydrograph and sedigraph in the NTC

Event	Peak	*P* peaks replicate for *Q*	Rising limb rate	Hysteresis pattern*	Hysteresis index**
17/07/2014		Good	High	CCH	−5.32
23/07/2014		Good	High	CCH	−0.70
02/09/2014	1°	Good	High	CH	5.04
	2°	Good	High	CH	4.12
	3°	Bad	Low	CH	0.44
10/09/2014		Good	High	CH	1.00
14/09/2014		Bad	Low	CH	1.38
30/09/2014		Mean	Mean	CH	0.80
17/10/2014		Bad	Mean	CCH	−0.07
18/10/2014		Good	Mean	CH	1.21
19/10/2014	1°	Good	Mean	CH	1.98
	2°	Good	Mean	CH	3.50
30/10/2014		Bad	Mean	CH	0.95
03/11/2014		Good	High	CH	3.26
01/01/2015		Good	Mean	CH	2.35
27/01/2015		Good	Mean	CCH	−2.69
29/03/2015		Good	High	CH	0.98
08/10/2015	1°	Good	High	CH	0.99
	2°	Good	High	CH	0.06
	3°	Good	High	CH	0.62
	4°	Mean	Mean	CH	0.89

CH clockwise hysteresis, *CCH* counter-clockwise hysteresis direction

*(Williams 1989), **(Lawler et al. 2006)

coverage) and before complete coverage by winter crops (July). In some events, there was sediment exhaustion, which indicates that vegetation cover is able to buffer rainfall and runoff energy, consequently preventing soil disaggregation or detachment.

Many studies recommend vegetative measures such as soil cover (Myers and Watts 2015), crop rotation, and increasing biomass yield (Lal 2015) in order to reduce surface runoff. The surface runoff is controlled by the quantity and quality of biomass in two different mechanisms: (a) increasing the infiltration due to the macroporosity and organic matter performed by biology and (b) the amount of soil cover increases the roughness, decreasing the surface-runoff velocity and increasing the infiltration, retention, and detention. However, for rainfall events with high volume and intensities, the efficiency may be insufficient/partial, especially for fields with a high-length slope and steepness. The development of conservationist agriculture depends on a set of complementary techniques (Huang et al. 2003; Drescher et al. 2016), in which each practice acts to control the different processes that operate in time and space. Different managements (plant, soil, and water) will be able to circumvent the mechanisms of degradation and enhance soil functions in a manner that meets economic and environmental demands. The terrace alone is incapable of circumventing the problems of degradation. However, for complex relief conditions and large magnitude events, their presence seems to be essential for controlling surface runoff and its associated processes.

4 Conclusions

Based on the results obtained in this monitoring study (total values in Table 3), the retention broad-based terraces reduced R_{tot} by almost 78% (NTC-TC)/NTC) and Q_{peak} by almost 79%, thus indicating its effectiveness in controlling surface runoff. In the catchment without terracing, the high volume of surface runoff indicates a hydrological imbalance, represented by the high values of surface-runoff coefficients (more than 20%). This is a clear indication that conservation practices need to be considered in order to control runoff. The characteristics of the hydrograph for the NTC demonstrate a pattern highly responsive to rainfall, including hydrographs with short lag times and steep rising limbs. The magnitudes of the monitored flow rates indicate high-erosion potential, especially in the slope thalweg. Regarding the SY, terracing reduced sediment yield by almost 65%. Nevertheless, there is no significant difference (p value = 0.06) between the catchments.

Despite the short monitoring period, the results provide some evidence that terraces reduce sediment yield and peak runoff by interrupting slope length and encouraging infiltration in the no-till system, which has important implications for the design of effective water and sediment management strategies. However, additional work in terms of monitoring period, landscape types, and different scales is required to provide broader evidence for terracing design at the catchment scale.

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