Water erosion and connectivity analysis during a year with high precipitations in a watershed of Argentina

María Guadalupe Ares, Fabricio Bongiorno, Mauro Holzman, Celio Chagas, Marcelo Varni and Ilda Entraigas

ABSTRACT

Soil erosion is a global concern because of its consequences for the environment and the economy of countries. In the Argentine Pampas Region, soil erosion process is a priority issue, although there is little information about sediment concentration (SC) in agricultural catchments. The study aimed at assessing the factors that have a major influence on SC and discussing the dynamics of hydrological and sedimentological connectivity during 2012, a year with precipitation over the mean and significant erosive events. The study was conducted in a watershed of Buenos Aires province, Argentina. A linear regression model, that considered autocorrelation, was obtained. Maximum rainfall intensity in 30 minutes and peak flow were related to SC. An analysis of satellite images was carried out to discuss the hydrological connectivity, and a connectivity index was calculated to assess changes in sedimentological connectivity. The analyses suggested increments in hydrological and sedimentological connectivity, associated with the drainage area expansion and with water erosion rills. Hydrological connectivity is needed for sedimentological connectivity. However, increments in sedimentological connectivity may have been conditioned by the input of energy to detach and to transport particles. This may have been evidenced when flows exceeded a threshold runoff coefficient.

Key words | hydrological connectivity, rill erosion, runoff, sediment concentration, sedimentological connectivity

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INTRODUCTION

Soil erosion is a serious challenge for the world, because it affects food production, the quality of the environment, human health and the economy of countries (Capra 2013). Global climate change is expected to lead to the increment of precipitation and runoff and, consequently, water erosion rates, in some regions of the world (Nearing *et al.* 2004). In this context, it is important to assess the dynamics and factors involved in this degradation process during years with high precipitations, to gather useful information to predict soil erosion behaviour in global changing scenarios.

Regression models may be used as a first step towards understanding factors controlling suspended sediment yield in watersheds (Haregeweyn *et al.* 2008; de Vente *et al.* 2011), and may be performed with an explanatory purpose, or to predict the sediment yield. These models are known as empirical models (de Vente & Poesen 2005), and are the alternative to more complex process-based soil erosion models, which require a large amount of data, often unavailable (de Vente *et al.* 2011).

During humid periods, the interactions between rainfall, runoff and antecedent moisture may generate watershed responses that evidence threshold behaviours, revealing significant changes in natural ecosystems. Threshold behaviours can be defined as rapid and significant changes in the dynamics of processes (infiltration, runoff, particle detachment and erosion), which implies that the response

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associated with those processes becomes faster or slower (Zehe & Sivapalan 2009). Threshold values may show sensitivity of agroecosystems during less frequent events, which provide useful information for land use and management planning (Cerdan *et al.* 2002).

The significant changes mentioned may be related to the development of spatial linkages, and the expression of those changes may determine the dynamics of connection and disconnection between landscape components (Cammeraat 2004). Western *et al.* (2001) refer to connectivity in the context of the variability in spatial distribution of features hydrologically relevant (soil moisture, hydraulic conductivity in aquifer formations), whose continuity in their spatial organization outlines flow paths. Then, by the term connectivity they denote 'the extent to which connected features, such as arbitrary shaped bands or pathways having similar values, are present in a hydrologically relevant spatial pattern'. Knudby & Carrera (2005) also refer to the term in the framework of spatial patterns, as they explain it as 'spatially connected features which concentrate flow and reduce travel times'. At watershed scale, Tetzlaff *et al.* (2007) define connectivity as the flow of matter and energy, such as water, nutrients, sediments, heat, between different landscape units. Croke *et al.* (2013) mention that connectivity is often employed as a powerful concept in hydrology and geomorphology to describe water and sediment movement through different landscape compartments and the watershed. Therefore, connectivity may lead to increments in runoff (Appels *et al.* 2011) and sediment yield when flow is effective enough to remove blockages within the watershed (Fryirs 2013; Zimmermann *et al.* 2014). Soil erosion may have an important role in coupling slopes to channel network, by formation of rills and gullies that act as flowpaths increasing hydrological and sedimentological connectivity (Bracken & Croke 2007; Rodríguez-Blanco *et al.* 2010).

Connection may change over time, defining temporal scales over which connectivity–disconnectivity prevail (Lexartza-Artza & Wainwright 2009). Regarding sedimentological connectivity, Croke *et al.* (2013) point out the need to study its temporal dynamics, as there is limited understanding of the changes needed to activate–deactivate connectivity. As well, Wainwright *et al.* (2011) mention the need to analyse this temporality to understand changes in systems response. Then, it is important to assess which circumstances define these temporal changes, in which interactions between seasonal variations in land use (Steegen *et al.* 2000) and natural events, like rainfall (Lexartza-Artza & Wainwright 2009), may be involved.

The objective of this work is to assess the factors that have a major influence on sediment concentration (SC) and to discuss the hydrological and sedimentological connectivity, and their temporal dynamics during a year with precipitation over the mean and significant erosive events in an arable watershed of Argentina. For this purpose a statistical regression analysis was carried out considering correlations between the events recorded in a watershed of 560 ha located in the Pampas Region. An analysis of satellite images obtained during that year was done to discuss the hydrological connectivity, and a connectivity index was calculated to assess changes in sedimentological connectivity in the studied watershed.

As stated earlier, very little is known about factors and mechanisms involved in the activation–deactivation of hydrological and sedimentological connectivity. This paper attempts to make an original contribution in this regard. Moreover, this work centres the analysis on the new approach to the study of hydro-sedimentological connectivity recently proposed by Bracken *et al.* (2015). This approach considers aspects related to the frequency and magnitude of the events, the mechanisms involved in sediment detachment and the temporal sequencing of the events, to reach comprehensive knowledge of connectivity–disconnectivity at small watershed scale, in this case. Such an analysis is the first for this region of Argentina and it may provide novel information for soil and water conservation.

Argentine Pampas Region is a plain of over 50 million hectares, with lands of high fertility and productivity (Hall *et al.* 1992). There, 90% of the country's grain production takes place (Magrin *et al.* 2005), and 48% of the cattle stock is raised (Canosa *et al.* 2013), because it is the most productive rain-fed and the strongest economic region of Argentina (Holzman *et al.* 2014). Soil erosion process is a priority problem in this region (SAGyP-CFA 1995). However, in this area as in the rest of Argentina, there is little information about sediment yield and transport in agricultural small catchments, even knowing that water erosion impacts severely on land quality and productivity (Lal 2001) as well as on water quality. Ares *et al.* (2014) have recently analysed the water erosion types in the study area of this work, and Ares *et al.* (2016) characterized the possible suspended sediment-discharge hysteresis patterns. This paper considers the approach of connectivity for the analysis of the erosion process using the first data registered at small watershed scale in the country. This work focuses on the study of data corresponding to a humid year to understand the hydrological and erosive response under these conditions, which can provide useful knowledge for decision-makers to design sustainable land use and management planning strategies in the area.

METHODS

Study area

The study was carried out in a small watershed of 560 ha monitored since 2011. It is located in the watershed of the Videla stream that flows into the Del Azul stream, in the centre of Buenos Aires province, Argentina (Figure 1(a)). The geographical coordinates of the watershed outlet are 37 °08′47.61″S 59 °55′25.17″W. The climate is temperate humid with an average annual temperature of 14.4 °C. The annual rainfall is 914 mm and 71% occurs between October and April. Geomorphologically, the watershed is located in the area of rocky outcrops of the Del Azul stream basin, which includes areas of watershed divides and fluvial valleys (Zárate & Mehl 2010). The average slope of the watershed is 3%, with a range between 1 and 10%. The relief is undulating with isolated hills of granite rocks up to 285 meters above sea level. The soils of valleys are derived from loess deposited with a thickness ranging between 1 and 2 metres above a very hard carbonate crust (INTA 1990). According to the available maps (INTA 1992), the prevailing soil class is Typic Argiudoll, with good drainage, covering 67.9% of the watershed. Lithic Hapludolls and Lithic Argiudolls cover 27.6% of the watershed area, and are located in hilly areas. Finally, 4.5% of the surface corresponds to poorly drained

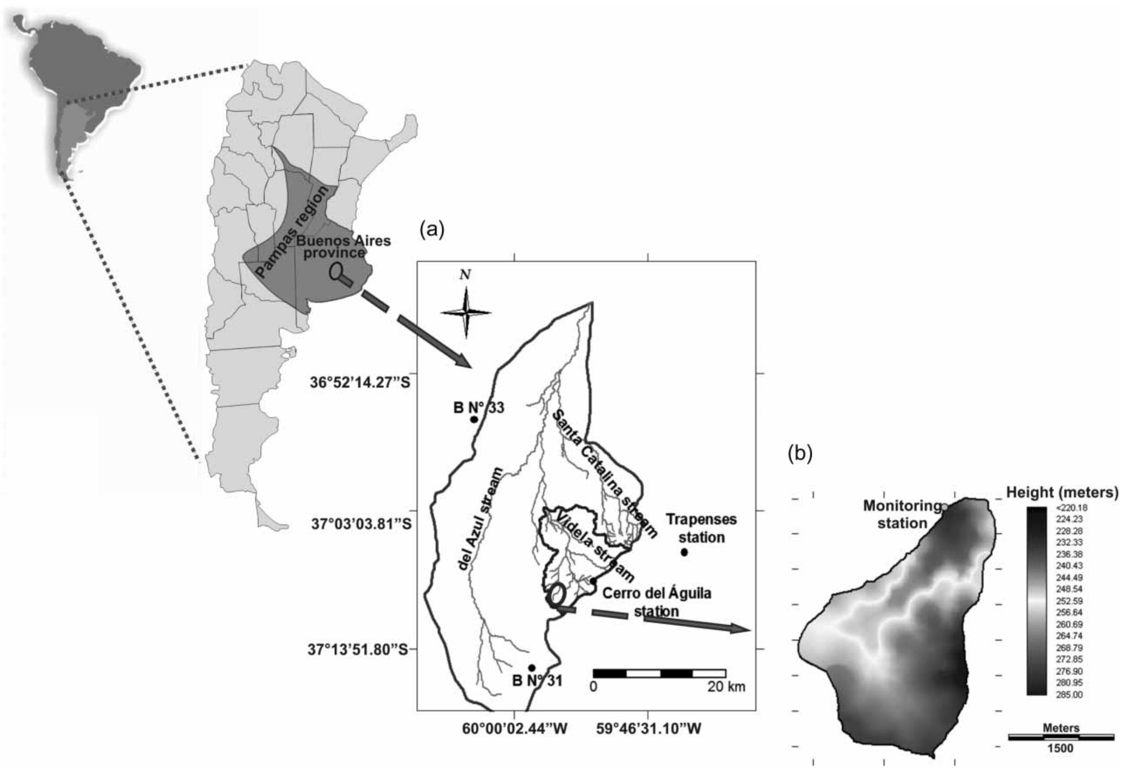

Figure 1 | (a) Location of the small watershed under study in the basin of the Videla stream, recording raingauges (Cerro del Águila and Trapenses) and groundwater monitoring stations (B No. 31 and B No. 33). (b) Detail of the small watershed with location of the flow monitoring and runoff water sampling station.

bottomlands, located near the watercourse. In general, the soils of the watershed have high aggregate stability and abundant macropores due to their loam topsoil texture and high average organic matter content (6.6%). Soils are under agriculture, and rotations include wheat, barley, soybean, corn or sunflower under a no tillage system and are sown across the main slope as management practice for water erosion control.

Data measurement

The water level was measured every 30 minutes using a digital water level recorder with pressure sensor located at the outlet of the watershed (Figure 1(b)). Records were turned into flow through the stage–discharge rating curve of the section obtained by stream discharge measurements conducted with current meters. Total runoff separation in direct and base flow was performed by applying a digital filter (Rodríguez *et al.* 2000) based on one of the methods reviewed by Chapman (1999). The filter removes the high frequency component of the hydrograph, i.e., direct runoff, and determines the low frequency component, i.e., the base flow. The obtained direct flow data were then considered for the present analysis.

An automatic water sampler, located at the outlet of the watershed, was used to collect samples during flood events (Figure 1(b)). The device has a suction pump and a sensor that triggers sampling when making contact with floodwater. Sampling started when the level of the watercourse reached 0.3 m from the bottom of the riverbed. This sampling level provided water samples from events of significant magnitude for this watershed, so the analysis included the runoff events that equalled or exceeded 0.3 m. The pump has its own sample bottle of 3.8 l, and control for setting the size of individual samples. It was set to collect a composite sample consisting of smaller samples taken every 5 minutes. This collection lasted for 1.5 hours, from the initial water level of 0.3 m. Other analyses not reported in this paper showed that the highest SCs were registered between the beginning of the event and near its peak discharge. Composite sampling occurred during the rising limb of events of high magnitude, or between peak flow and the initial part of the falling limb of small magnitude events.

In the laboratory, each sample was shaken, a 250 cm^3 aliquot was taken and oven dried at 60 °C to constant weight, according to ASTM D3977-97 (2007), to measure SC. The determination was performed in duplicate.

The rainfall was measured by an automatic weather station located 5 km away from the outlet of the watershed (Figure 1(a)). It is the closest station to the watershed that has detailed data for the analysed period. It has a raingauge constructed according to the standards of the World Meteorological Organization, which records the rain every 10 minutes with an accuracy of 0.20 mm through a tipping-bucket recording raingauge.

Data analysis

The rainfall–runoff events were characterized by variables associated with precipitation, runoff, antecedent precipitation as surrogate of antecedent conditions, and soil loss ratio from the Universal Soil Loss Equation (Wischmeier & Smith 1978) to consider the effect of soil cover and management on the erosion process.

Variables associated with precipitation of the events were calculated: total water depth (P, mm), precipitation duration ($PDur$, h), total rainfall kinetic energy (E, MJ ha^{-1}), maximum intensity in 30 minutes (I_{30}, mm h^{-1}), and the product EI_{30} (MJ mm $(ha\ h)^{-1}$). Rainfall energy was obtained from the sum of the individual energies of 10 minute intervals according to the mathematical relationship set by Wischmeier & Smith (1978), by Equation (1):

$$e = 0.119 + 0.0873\log_{10}(i) \quad (1)$$

where e is kinetic energy of the interval (MJ $(ha\ mm)^{-1}$) and i is rainfall intensity (mm h^{-1}).

Direct runoff was characterized by the surface runoff sheet (R, mm), peak flow (Qp, $m^3\ s^{-1}$), mean surface flow (Qms, $m^3\ s^{-1}$), runoff coefficient (RC, %), calculated by the ratio of surface runoff sheet and total precipitation event. The accumulated precipitation of 5 days previous to the analysed events ($P5d$, mm) was calculated to evaluate the antecedent condition.

The soil loss ratio was defined by Wischmeier & Smith (1978) as 'the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow'. Records of land use and rotations of the plots in the watershed were obtained for each rainfall–runoff event studied. Sowing dates, crop stages and fallow periods were considered to calculate the soil loss ratios using the information in tables published in Handbook 537 (Wischmeier & Smith 1978). According to each parcel area and its soil loss ratio obtained, a weighted soil loss ratio was calculated for each event for the whole watershed.

The concentration of suspended solids was calculated for the composite sampling (SC, g L^{-1}).

Data were obtained for the 2011–2013 period. Data corresponding to the dryer years (2011 and 2013) were used to make comparisons with those corresponding to 2012, the year with precipitations over the mean in the study area, to identify the differences between the variables monitored during those contrasting years. Data of the year 2012 were used for the statistical and the connectivity analysis.

Statistical analysis

A multiple regression analysis was developed with an explanatory purpose, to identify the variables related to SC, with data corresponding particularly to 2012.

The condition number test was performed to check for multicollinearity. The condition number (φ) was calculated as:

$$\varphi = \sqrt{\frac{\lambda_{max}}{\lambda_{min}}} \tag{2}$$

where λ_{max} and λ_{min} are the maximum and the minimum eigenvalues of the matrix X'X, that is the matrix of the centred and scaled regression variables. The value of φ was $>>>$ 1,000, which evidenced strong multicollinearity (Myers 1990).

Pearson's correlations were analysed to identify the significant relationships between the variables. To handle multicollinearity, four independent variables were selected: P, I_{30}, $P5d$ and Qp, that represent the rainfall and runoff erosive forces and the antecedent conditions during the events.

Considering SC as the dependent variable, all possible regression models were performed with the selected independent variables. Fifteen regression models were obtained, which were assessed by the adjusted coefficient of determination (R^2 adj). The best model was selected, which included the variables I_{30} and Qp (R^2 adj $= 0.69$). It was tested for normality of the error terms using Shapiro Wilk's test, which indicated normality ($P > 0.05$). Independence of observations was analysed with a plot of residuals versus time. The sudden changes in the signs of residuals indicated autocorrelation. Considering the latter, a longitudinal data analysis was carried out (Diggle *et al.* 2002). Linear models were fitted using generalized least squares, and correlations between observations were modelled by the linear, exponential and Gaussian functions (Pinheiro & Bates 2000). Models were assessed by the Akaike's information criterion (AIC), and the model with the lowest AIC was selected. The performance of the model selected was evaluated by the efficiency E, proposed by Nash & Sutcliffe (1970), which is defined as:

$$E = 1 - \frac{\sum_{i=1}^{n} (Oi - Pi)^2}{\sum_{i=1}^{n} (Oi - \bar{O})^2} \tag{3}$$

where Oi and Pi are the observed and predicted data, and $\bar{O}$ is the average of observed data.

The analyses described were performed using Infostat statistical software (Di Rienzo *et al.* 2014) and R software (R Development Core Team 2011).

Analysis of connectivity

Hydrological connectivity: drainage network dynamics

The dynamics of the drainage network was analysed to assess hydrological connectivity during 2012. According to the definitions of Western *et al.* (2001) and James & Roulet (2007), who state that connectivity refers to hydrologically significant spatial arrangements of properties or state variables that facilitate flow and transport in a watershed, variations in the area of the drainage network may be useful to evaluate changes in connectivity at a watershed scale.

Changes in the drainage area are associated with variations in moisture of riparian zones and of temporal flow paths which may saturate from below, by the rise of the water table (Dunne 1978) or by the infiltration of rainwater in the soil.

Spot's 4 and 5 satellite images were used for this purpose, with spatial resolution of 10 m that is appropriate for studies at semi-detailed scales. According to the revisit period and the availability of cloud-free scenes, three images corresponding to 2012 were selected. The studied dates were 01/02/2012, 13/09/2012 and 21/12/2012, which coincided with different wetness conditions in association with the rainfall events registered during the previous days to the scenes' capture. Then, the image of February was representative of dry conditions, and the images of September and December were representative of humid conditions.

Bands 3 and 4 corresponding to near-infrared (NIR) and short-wave infrared (SWIR), respectively, were used for the spatial delimitation of the drainage network. The scenes of high surface wetness condition (September and December 2012) were considered to define the maximum surface of drainage network during the study period. The use of NIR and SWIR bands is based on the fact that they are located in the region of strong absorption by free water and vegetation liquid water (Gao 1996). The combination of both bands are useful to detect not only free water surfaces but also vegetation water content, which is highly correlated with surface and sub-surface soil moisture availability (Fensholt & Sandholt 2003; Khanna *et al.* 2007; Holzman *et al.* 2014).

Regions of interest were delimited by digitizing on the three analysed images taking into account the spectral response of wet areas. Then, the regions of interest were integrated to define the drainage network. In addition, high pass filtering was used to extract the minimum area of drainage network in the image of February, when dry conditions prevailed. This filter removes the low frequency components of an image, and preserves the high frequency (local variations). It accentuates edges between different areas (Jensen 1996), so it was useful to demarcate the boundaries of the drainage network in this case. Finally, the delimited areas corresponding to the drainage network of the three scenes analysed were calculated to assess the dynamics in the hydrological connectivity during 2012.

Sedimentological connectivity

This connectivity was assessed according to the approach suggested by Jain & Tandon (2010). The authors define connectivity considering two basic aspects: physical contact between landscape units or compartments and amount of sediment transfer, and they propose an index as a measure of connectivity:

$$C_{pc} = A{*}\mathrm{i_m} \quad (4)$$

where C_{pc} is connectivity index, A is area of physically connected dimensions and i_m is rate of material transfer.

The index was calculated to compare differences in sedimentological connectivity during three dates of 2012, using data corresponding to the drainage area, and, in this case, the concentration of suspended solids, which was the variable registered at the outlet of the catchment. The index was expressed in units of kg m^{-1}. The dates of the events selected for the analysis were those chronologically near to the day of estimate of the drainage network area. Then, the variables required to calculate the index corresponded to different dates. To establish whether conditions were comparable between the dates, the depth to groundwater of the dates associated for the index calculation was examined. It was considered that differences in this variable may guide about relevant changes in moisture of riparian zones and temporal flow paths. According to Dunne (1978), the moisture dynamics of these zones is related to variations of groundwater depth. There, the water table is located at a relatively shallow depth, and saturation may occur by the rise of the water table to the surface when rainfall occurs over the watershed. Then, percentage differences of depth to groundwater between the values corresponding to the date of estimate of the drainage area and the date of the selected event to measure connectivity were calculated.

Groundwater depths were registered in borehole No. 31, located 13 km away from the outlet of the watershed (Figure 1(a)). Depth to groundwater of boreholes located in the same aquifer show high correlations. As an example, Figure 2 shows the correlation between depth to groundwater of boreholes No. 31 and No. 33, located in the upper basin of the Del Azul stream. Therefore, the variations in groundwater depths corresponding to the considered boreholes may be related to the study area.

Table 1 shows the percentage differences of depth to groundwater between the dates of analysis of the drainage network area and the erosion events selected to calculate the connectivity index. Depth to groundwater percentage differences were between 9.8 and 2.4%. As well, percentage differences of depth to groundwater corresponding to the

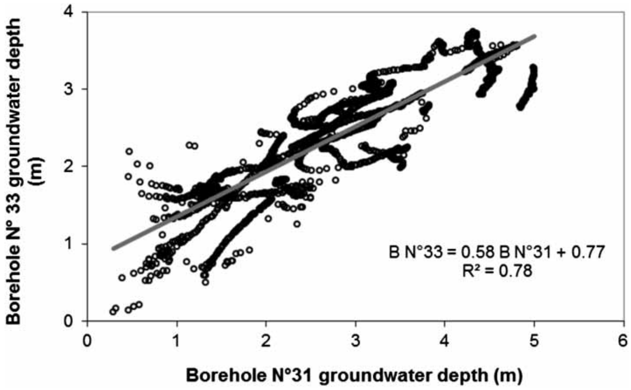

Figure 2 | Relationship between groundwater depth of boreholes No. 33 and No. 31, located in the upper basin of the Del Azul stream. Daily data corresponding to the 01/04/2007–22/03/2014 period.

dates of analysis of the drainage network were calculated, which were between 68 and 139%. According to the results, it was considered that conditions between the selected dates to obtain the index value were comparable. Therefore, the connectivity index was calculated for the dates: 05/03/2012, 03/09/2012 and 19/12/2012.

RESULTS AND DISCUSSION

During the humid year of 2012, 13 flood events were registered, whereas only eight events during the dry years of 2011 and 2013 were registered. The inter-annual variability of rainfall was high: 807 mm precipitated during 2011, 1,351 mm during 2012 and 668 mm during 2013. Mean annual precipitation corresponding to the 1993–2013 period of Monasterio Trapense pluviometer station is 905.2 mm. This station is 20 km away from the Cerro del Águila station (Figure 1(a)), and is the nearest with complete and reliable rainfall records for the area (Varni & Custodio 2013).

Table 1 | Percentage difference of depth to groundwater between the values corresponding to the date of estimate of the drainage area and the date of the event selected for the connectivity index calculation

Date		
Drainage area	Event	Percentage difference of depth to groundwater (%)
01/02/2012	05/03/2012	6.7
13/09/2012	03/09/2012	2.4
21/12/2012	19/12/2012	9.8

Table 2 summarizes the main characteristics of the events studied. The mean values of the variables related to rainfall events that promoted runoff (*P*, EI_{30}, *E*) had higher means in 2011 and 2013 than during 2012. However, *P5d*, *R* and associated variables (*Qp*, *Qms* and RC) and SC showed higher mean values in 2012 than during 2011 and 2013. This analysis suggests that during the dryer years, rainfalls of higher magnitude and erosivity were needed to generate hydrological and sedimentological response in the watershed.

With regard to the regression models performed, the model considering correlations fitted with a linear function did not converge. The model selected was fitted with a Gaussian function:

$$SC = 0.03 * I_{30} + 0.39 * Qp - 0.36 \quad (5)$$

with an AIC value of 38.5. The model efficiency calculated was 0.73, which shows good agreement between measured and calculated sediment by the regression model.

Table 2 | Mean, maximum and minimum values of the variables studied during 2011–2013 in the watershed of the Videla stream

	No. of events	Parameter	P	PDur	EI_{30}	E	I_{30}	P5d	R	Qp	Qms	RC	SLR	SC
		Mean	47.6	15.3	276.0	9.7	24.9	20.4	9.3	1.4	0.3	17.9	0.1	1.0
2012	13	Maximum	136.4	42.0	1,030.3	28.3	57.2	77.8	42.6	4.6	1.2	56.9	0.2	4.1
		Minimum	17.8	3.0	41.6	3.9	8.4	0.0	0.4	0.1	0.0	1.9	0.1	0.4
		Mean	52.2	14.8	320.1	10.6	24.7	5.3	5.3	0.9	0.2	7.7	0.1	0.5
2011–2013	8	Maximum	106.6	31.0	1,144.5	22.7	50.4	18.6	26.0	3.2	0.9	24.4	0.3	0.9
		Minimum	32.6	4.5	43.1	6.3	6.8	0.2	0.4	0.2	0.0	1.0	0.1	0.4

P, precipitation that promoted runoff (mm); *PDur*, precipitation duration (h); EI_{30}, erosivity index (MJ mm (ha h)$^{-1}$); *E*, total rainfall kinetic energy (MJ ha^{-1}); I_{30}, maximum intensity in 30 minutes (mm h^{-1}); *P5d*, accumulated precipitation of 5 days previous to the events (mm); *R*, surface runoff sheet (mm); *Qp*, peak flow (m^3 s^{-1}); *Qms*, mean surface flow (m^3 s^{-1}); RC, runoff coefficient (%); SLR, soil loss ratio; SC, composite sampling concentration of suspended solids (g L^{-1}).

According to the model obtained, the concentration of suspended solids is associated with variables of precipitation (I_{30}) and runoff (*Qp*). The variable I_{30} is related to detachment and transport in sheet erosion (Gumiere *et al.* 2009). Peak discharge controls particle detachment, by the scouring of superficial flow, while its energy is the driving force for the transport of particles. Peak discharge has a key role in rill erosion (Duvert *et al.* 2012). Thus, the model includes the variables that are the active forces in the detachment and transport of the soil particles in both types of erosion. Ares *et al.* (2014) studied the erosion types in events registered in the small watershed using cluster analysis and a statistical test to evidence differences between the groups obtained. In addition, erosion symptoms were observed in the field, where rills were located predominantly in the steepest lands of the middle and the lower part of the watershed, which have a higher mean slope (3.65%) than the upper part (2.26%). According to the results of that work, sheet erosion was the main process in eight events during 2012 (10/01; 05/03; 11/03; 18/04; 03/09; 05/10; 15/10; 22/11), whereas rill erosion was dominant in only five events in 2012 (17/05; 23/08; 05/12; 19/12; 28/12). As well, rill erosion events may have conditioned the hydrological response in the watershed. The analysis of the RC of the 13 events during 2012 showed the highest values of this variable from event 5, registered in May 2012: the first rill erosion event (Figure 3). After this case, rill erosion was more frequent than in the former period (January–May 2012): of a total of eight events studied between August and December 2012, four corresponded to this erosion type. Rills act as preferential flow paths, and water flows with high energy and little potential for infiltration (Bracken & Croke 2007). This may have also been evidenced in the peak discharge registered during those five events, which ranged between 1.7 and 4.6 $m^3 s^{-1}$. Considering sheet erosion events, the peak discharge showed values in the range 0.1–0.2 $m^3 s^{-1}$ during the four events previous to May and values between 0.6 and 0.9 $m^3 s^{-1}$ for the cases registered after May 2012. The differences in runoff of sheet erosion events mentioned show the importance of the preferential flow paths which remained during 2012, on the hydrological response.

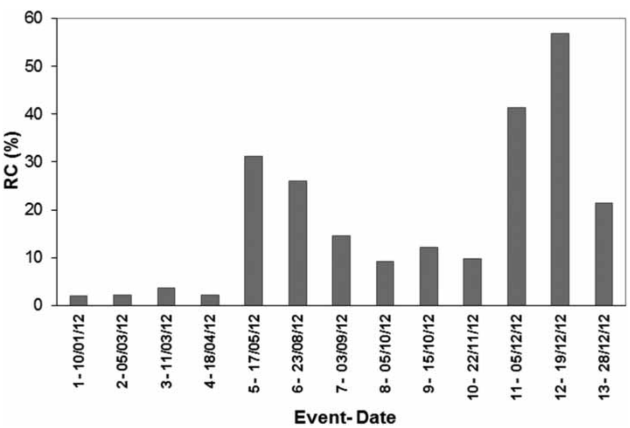

Figure 3 | Runoff coefficient (RC) corresponding to the 13 events registered during the analysed year.

The analysis of the drainage network dynamics showed changes in the contributing drainage area during 2012 (Figure 4). The drainage area obtained from the three images was 18.9 ha in February, 35.6 ha in September and 42.5 ha in December. Considering that changes in hydrologically relevant variables and in their spatial continuity may show variations in patterns from which transfer may be derived (Bracken *et al.* 2013), the comparison of the results may suggest a higher hydrological connectivity in the watershed in the cases of September and December 2012 than in February 2012. According to Bracken *et al.* (2013), groundwater depths were examined to complement this analysis. The dynamics of this variable during 2012 showed high values between August and December 2012 (Figure 5). The persistence of water table depths near the surface (at an average depth of 0.94 m, with maximum and minimum values of 2.07 m and 0.14 m, respectively) in association with the rainfalls registered, suggest the possibility of an active drainage network in that period.

Therefore, the wet area expansion, in addition to the presence of channelized pathways corresponding to rills linked to the water course, may have facilitated connectivity in runoff. Zimmermann *et al.* (2014) report that connectivity development by expansion of the drainage network increased runoff coefficients in a forested catchment of Panama. Borselli *et al.* (2008) point out that few events are responsible for the generation of flowpaths that increase the connectivity between hillslopes and channels, which may have been evidenced by the RC and *Qp* observed from May 2012. As well, this connectivity may have also contributed to correlations between observations.

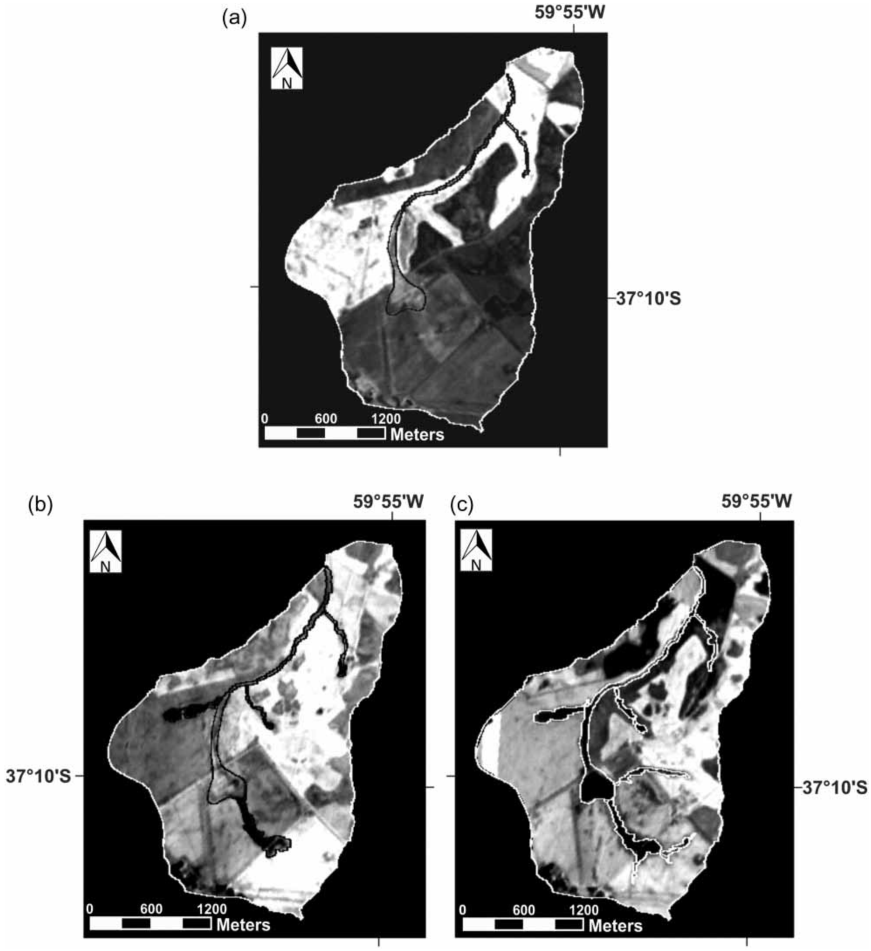

Figure 4 | Drainage area obtained from near infrared (NIR) and shortwave infrared (SWIR) bands of Spot 4 and 5 satellite images for (a) February 2012 (01/02/2012, outlined in black), (b) September 2012 (13/09/2012, outlined in black) and (c) December 2012 (21/12/2012, outlined in white).

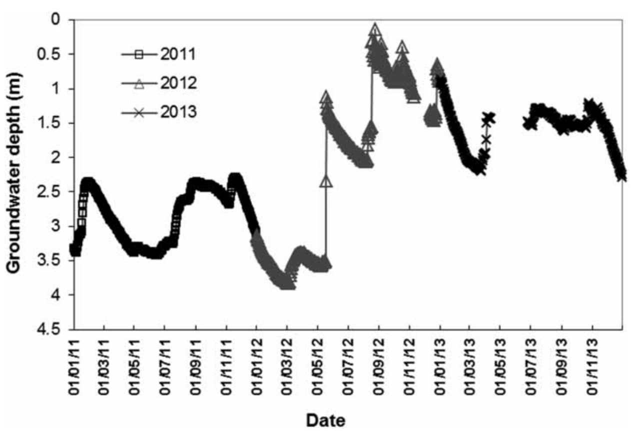

Figure 5 | Groundwater depth registered in borehole No. 31 between 2011 and 2013.

Other key aspects when discussing connectivity are the moment and frequency of disturbances (Wainwright *et al.* 2011). It is important to analyse the moment of occurrence of the events with regard to the temporal variation of land use, and thus, the presence of different vegetation cover that provides surface roughness and decreases overland flow velocity. Bracken & Croke (2007) and Lesschen *et al.* (2009) point out the role of vegetation cover in catchment hydrological connectivity, and Lexartza-Artza & Wainwright (2009) mention that temporal changes in land use have to be considered for a better understanding of connectivity in watersheds. In this case, at the beginning of the rainy period from event 5 in May and until November, the watershed was predominantly under fallow. Approximately 50% of the area was covered with soybean stubble, which provides limited surface roughness (Alberts & Neibling 1994). Corn, wheat or barley residues occupied the rest of the watershed area. Less than 20% of the area was sown with barley in early July. Summer crops were sown between October and November, so, at the moment of the rainfall events, they were still in the early stages of growth. Then, over the period when relevant erosive events occurred more frequently, as stated above, vegetation may have had little effect as a barrier to prevent connectivity. Observations in the field showed that on plots under fallow or recently sown, rills remained or were formed during these events. Moreover, the lack of conservation practices, such as terraces and diversions, may have favoured the connection of the drainage network. These analyses may suggest the persistence of hydrological connectivity during the period considered.

Hydrological connectivity is necessary to the occurrence of sedimentological connectivity, as sediment needs a transporting agent to reach the watershed outlet (Croke *et al.* 2013). An analogous analysis of the SC of the 13 events during 2012 was carried out to assess the dynamics of SC. This variable did not show continuous high values from event 5, as RC values did (Figure 6).

Regarding sedimentological connectivity, the values of the connectivity index were 7.9, 16.4 and 175.9 for the events registered on 05/03/2012, 03/09/2012 and 19/12/2012, respectively. The values show the increments in sedimentological connectivity of three contrasting situations. The first value corresponds to an event previous to May 2012, when sheet erosion prevailed. The second value of the index is also associated with a case of sheet erosion, but following the event of 23/08/2012, which was classified as a rill erosion event. The third index reported corresponds to the event of highest SC registered during 2012, which belonged to the rill erosion events group.

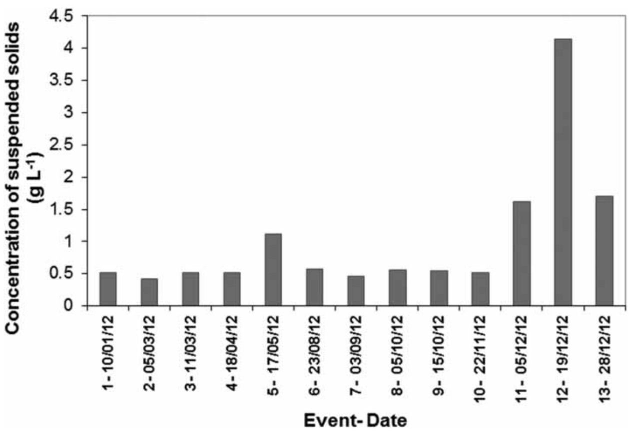

Figure 6 | Concentration of suspended solids corresponding to the 13 events registered during the analysed year.

Other aspects may be indicated to analyse the dynamics of sedimentological connectivity. Croke *et al.* (2013) mention that connectivity is activated when thresholds of stability are exceeded. Fryirs (2013) point out that threshold conditions of flows may be quantified by studying relationships which evidence relevant sediment movement in the assessment of connectivity–disconnectivity. Considering the runoff variables the possible threshold value was analysed for the study area. The relationship between SC and RC showed increments in SC from RC over 20% (Figure 7), which may be considered as the critical value to trigger sedimentological connectivity during 2012. Data corresponding to 2011 and 2013 were also included in the figure. Although there are only eight events registered, they show a trend comparable to that of 2012 data (Ares *et al.* 2014). In addition, the values of the connectivity index were included in Figure 7. Even though there are only three values, they show a positive trend in relation with RC. This might be indicative of the relevance of runoff to generate changes in sedimentological connectivity.

Moreover, Jain & Tandon (2010) and Bracken *et al.* (2015) point out that high-magnitude events increase sedimentological connectivity, as a result of the input of

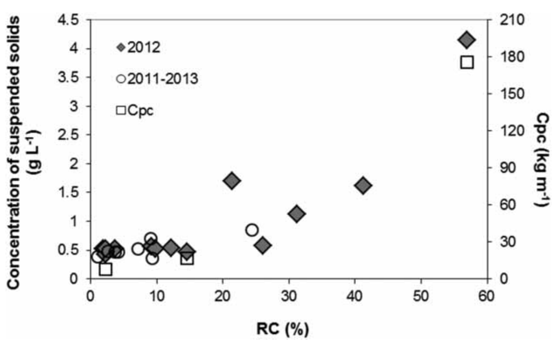

Figure 7 | Relationship between concentration of suspended solids and runoff coefficient (RC) for the events registered between 2011 and 2013. Sediment connectivity index (*Cpc*) calculated for the events of 05/03/2012, 03/09/2012 and 19/12/2012.

energy that increases sediment detachment and transport. Then, connectivity may be related to these episodic events that pulse sediment to the system. Considering Figure 7, the events with RC greater than 20% were the five previously classified as rill erosion events. Concentrated flow is characterized by high energy to detach and transport particles (Bracken & Croke 2007). Therefore, during those events, flow delivered by the channel network previously analysed and by rills formed during event 5 and eroded during subsequent events, may have been responsible for the high SCs registered.

Some final aspects regarding connectivity should be pointed out. The increment in hydrological connectivity from May 2012 may be related to rill formation during different rainfall events in addition to the presence of an active drainage network. The persistence of these active flowpaths may have caused the higher RC and *Qp* values than those registered between January and April 2012, even during sheet erosion events. In contrast, the increment in sedimentological connectivity may be associated with the occurrence of events of energy enough to detach and transport soil particles. In this case, rill erosion events were responsible for the input of that energy, evidenced by RC over 20%. The exceedance of this threshold value determined the increment of sedimentological connectivity, a significant aspect that may distinguish this type of connectivity from hydrological connectivity between May and December 2012.

This analysis has been carried out at small watershed scale, and the findings of this work may be generalized for other catchments under conditions comparable with those of this study area: size, slopes, soil types, land use, rainfall–runoff characteristics. An analysis for a larger region may be carried out considering the approach proposed by El Haj Tahir *et al.* (2010), for example, who upscaled soil erosion areas using geographical information systems and remote sensing data with different spatial resolution to study the consequences of an exceptionally wet year. However, a new interpretation of the processes involved in hydrological and sedimentological (dis)connectivity would be necessary, based on field observations or models' results at large watershed scale. This is associated with the scale dependence of hydro sedimentological processes noted by several authors (de Vente & Poesen 2005; Lesschen *et al.* 2009; García-Ruiz *et al.* 2010; Yang *et al.* 2012). Runoff decreases as plot or watershed area increases, in relation to the possibility of reinfiltration and detention in reservoirs and depressions (Esteves & Lapetite 2003; Cerdan *et al.* 2004; Feng & Li 2008). De Vente & Poesen (2005) discuss the reduction in sediment yield with the increment in basin area. The authors point out different erosion processes that become active at different spatial scales, which affect sediment yield. Thus, high variability in local conditions causes the variability in soil loss measurements at plot scale, where the splash erosion process may be analysed (García-Ruiz *et al.* 2010). At small watersheds (0.03–10 km^2), de Vente & Poesen (2005) mention that rill and gully erosion play an important role in suspended sediment yield and connectivity at the basin outlet. Whereas, in large catchments (>10 km^2) sediment deposition becomes dominant over its transport, which reduces sediment yield at the outlets (Medeiros *et al.* 2014). In addition, it is important to highlight that spatial patterns of vegetation and land use, soil types, microtopography and topography and rainfall erosivity may affect runoff and sediment yield at the scales specified (Lane *et al.* 1997; de Vente *et al.* 2007; Huang *et al.* 2013), and, thus, are key factors to take into account in upscaling. Therefore, these processes and factors mentioned interact at different spatial scales, and affect water and sediment movement between landscape compartments, that is, the (dis)connectivity. The approach recently proposed by Bracken *et al.* (2015) may be useful in this interpretation for larger regions, as these authors discuss that spatial scale is intimately related to this framework proposed for the analysis of connectivity.

According to the previous discussion, the conclusions of this work are valid at small watershed scale. It is considered that this is an important scale of study, because it is appropriate to implement agricultural management practices for soil and water conservation (Collins & Owens 2006) and to test their efficiency for the control of runoff excess and water erosion, two degradation processes that affect lands worldwide.

SUMMARY AND CONCLUSIONS

The events recorded during 2012, a year with precipitations over the mean, were studied in a watershed where rainfall, runoff and SC were monitored between 2011 and 2013, in the Argentine Pampas Region.

To identify variables that were related to SC, a regression analysis that considered the correlations between the observations was performed. Maximum rainfall intensity in 30 minutes and peak flow explained SC variation for the year studied.

Some differences between hydrological and sedimentological connectivity during the studied year were considered. Hydrological connectivity was more active from the rill erosion event registered in May 2012, in association with the increment of the drainage network area and the presence of rills. This was favoured by little vegetation cover, consisting predominantly of soybean residues or crops in the early stages of growth, which may have reduced its effect as a barrier to prevent connectivity. On the other hand, although hydrological connectivity is essential for sedimentological connectivity, the latter may have been dependent on the occurrence of flows over a threshold, with energy enough to detach and transport particles from hillslopes to channels. The exceedance of that threshold value led to increased sedimentological connectivity, an important aspect that may differentiate sedimentological from hydrological connectivity during the studied period.

These are the first results analysed considering the connectivity approach for a small watershed in Argentina. It is necessary to continue monitoring the variables in the study area, to get data under humid conditions comparable to 2012, to validate the model obtained, and to corroborate the manifestation of threshold behaviours. However, the results obtained are indicative of the dynamics and conditions that may activate connectivity in agricultural watersheds. In addition, this information can be useful to evaluate soil erosion in global changing scenarios.

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