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SUSPENDED SEDIMENT CONCENTRATION CONTROLLING FACTORS: AN ANALYSIS FOR THE ARGENTINE PAMPAS REGION

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Abstract In the Argentine Pampas region, there is little information about sediment concentration in agricultural catchments. The aims of this work are: (1) to analyse fluctuations in sediment concentration and discharge, as a first attempt to characterize hysteresis patterns; and (2) to study sediment concentration controlling factors and to assess the importance of these factors using principal components analysis and a multiple regression model. Twenty-five events registered during 4 years in a 560 ha gauged basin of Argentina were studied. Analysis of data suggested a positive clockwise pattern. The multiple regression model was performed with three factors obtained by principal component analysis: runoff, precipitation and antecedent conditions factors. The model explained 83% of the variability of sediment concentration. Runoff factor contributed to modelled sediment concentration with the highest magnitude, followed by precipitation and antecedent condition factors. Although the watershed is under conservation tillage, rill erosion seems to be the main source of sediment concentration.

Key words water erosion; discharge; precipitation; principal component analysis; regression analysis

1 INTRODUCTION

Water erosion is the result of the interactions among different environmental factors, including topography, soil properties, climatic characteristics, runoff and land use and management (Shi *et al*. 2013). Sediment yield is strongly dependent on runoff: doubling the velocity of runoff increases its scouring capacity and transportability to the fifth and sixth powers, respectively (Shaxson *et al*. 1977). Rainfall intensity and antecedent soil water content affect runoff generation and sediment production (Römkens *et al*. 2001, Seeger *et al*. 2004). Wei *et al*. (2007) report variations in soil losses for different land uses under rainfall of different duration, intensity and frequency.

Several studies analyse the relationships between factors acting in runoff events and sediment yield in rivers (Zabaleta *et al*. 2007, Estrany *et al*. 2009, Onderka *et al*. 2012). Regression models may be used as a first step towards understanding these relationships controlling suspended sediment yield, and as prediction tools (Verstraeten and Poesen 2001, Mingguo *et al*. 2008, López-Tarazón *et al*. 2010, de Vente *et al*. 2011), but some of the variables to use in regression studies are often correlated (Ares *et al*. 2014b). In this sense, principal component analysis (PCA) enables to analyse the relationships among variables (Giménez *et al*. 2012) and regressions may be performed with the factor scores of the components, considering they are statistically independent (Gellis 2013).

As well as the analysis of the relationships between variables involved in sediment production, the relationship between discharge and sediment concentration during individual events may be studied. Frequently, this relationship is not homogeneous during the events, producing hysteretic loops (Williams 1989, Nadal-Romero *et al*. 2008, Eder *et al*. 2010, Ziegler *et al*. 2014). It has been suggested that the hysteresis effect may indicate location of sediment sources and mechanics of sediment delivery (Duvert *et al*. 2010, Oeurng *et al*. 2010).

The Argentine Pampas region is a plain of more than 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*. 2013).

During the last 3 decades this region has experienced a continuous increase in the land area dedicated to agriculture (Manuel-Navarrete *et al*. 2009), facilitated by the adoption of no tillage system, and the introduction of genetically modified crops and agrochemicals. However, in many areas of this region, particularly in the highly fertile lands of the Videla stream watershed, no tillage system was introduced unsustainably. This includes over-grazing of stubble, associated with the decrease in the area dedicated to cattle breeding, and poor planning of rotations, in which soybean has high participation. In addition, no tillage seeder is used in combination with previous tillage operations (Sfeir *et al*. 2006). Thus, vegetation cover has been reduced in this area and, consequently, the protective effect that it has on soil surface has also decreased. At the same time, the rainfall increase recorded in recent decades, related to the above conditions, has contributed to increasing runoff and soil susceptibility to water erosion in the area. This is evidenced by recurring overflow events of streams in the region (in the years 1980, 1985, 1992, 2001, 2002, 2012 and 2014) and by the erosion symptoms that are often observed in the fields, which determine that this degradation process is a priority issue in the area (Irurtia *et al*. 1996). Attempts have been made to model the rainfall–runoff process (Dalponte *et al*. 2007) and the hydrological response has been already studied in this region (Ares *et al*. 2012). However, in this area, as in the rest of Argentina, there is little information about sediment concentration and transport in agricultural small catchments, even knowing that water erosion affects severely land quality and productivity (Lal 2001). Ares *et al*. (2014b) have recently analysed the dynamics of sediment concentration associated with water erosion. They found that the most frequent type of erosion may be interrill process.

The present manuscript reports results of field studies on suspended sediment concentrations carried out at the Argentine Pampas region. A first approximation to characterization of relationships between sediment production and its controlling factors was possible to carry out with available data, at watershed scale. Thus, the aims of this work are: 1- to analyse fluctuations in sediment concentration and discharge, as a first attempt to characterize possible hysteresis patterns; 2- to study sediment concentration controlling factors and to assess the importance of these factors, using a multiple regression model performed with variables obtained by principal components analysis. The approach to the analysis of sediment concentration controlling factors by regression models performed with the variables obtained by principal components may be considered, in a certain degree, as a new contribution for the study of water erosion in different regions. This study is based on field measurements in a small basin of the Videla stream, located in the centre of Buenos Aires Province, in the Pampas region, Argentina.

2 MATERIALS AND METHODS

2.1 Study Area

The study was conducted in a small watershed of 560 ha. It is located in the watershed of the Videla stream that flows into the Del Azul stream, located in the centre of Buenos Aires province, Argentina (Fig.1). The climate is temperate humid with average annual temperature of 14.4ºC. The annual rainfall is 914 mm and 71% occurs between October and April. The relief of the small watershed is undulating with isolated hills of granite rocks up to 285 meters above the sea level, and piedmont areas. Soils of piedmonts are derived from loess deposited with a thickness ranging between 1 and 2 m above a very hard carbonate crust (INTA 1990). The average slope of the watershed is 3%, with a range between 1% and 10%. 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 soils with less drainage capacity, located near the watercourse. In general, the soils of the watershed have stable and porous structures, and are used for agriculture. Rotations include wheat, barley, soybean, corn or sunflower under no tillage system perpendicular to the main slope as management practice for water erosion control.

Figure 1

2.2 Data measurement

Data were obtained between January 2011 and August 2014. Water level was measured every 30 minutes using a digital water level recorder with pressure sensor located at the outlet of the watershed (Fig. 1b). 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 digital filter removes the high frequency component of the hydrograph, i.e. direct runoff, and determines the low frequency component, that is, the base flow.

An automatic water sampler, located at the outlet of the watershed, was used to collect samples during flood events (Fig. 1b). The device has two suctions pumps and two sensors that trigger 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. Each pump has its own sample bottle of 3.8 litres, and control for setting the size of individual samples. The first pump was set to take full-bottle discrete sample for 7 minutes since the watercourse reached 0.3 m from the riverbed. The second pump 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. In 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 sediment concentration. The determination was performed in duplicate. Previous analyses not reported in this manuscript showed that the highest sediment concentrations were registered between the beginning of the event and near its peak discharge. The two sampling modes were selected to analyse fluctuations in sediment concentration and discharge, as a first attempt to characterize relations between concentration and water discharge in individual runoff events. Discrete sampling occurred during the rising limb of events of high magnitude, or near the peak flow of the events of small magnitude. 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. The time of concentration of the watershed is 2.6 hours, according to Kirpich´s equation cited by Chow *et al*. (1994).

The rainfall was measured by an automatic weather station located 5 km away from the outlet of the watershed (Fig. 1a). It is the closest station to the watershed that has detailed data for the analysed period. It has a rain-gauge 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 rain gauge.

Data uncertainty results from sampling, measurement and interpretation errors in the observed data (Renard *et al*. 2010). Reported errors of rainfall records are between 1-5% of the total rainfall (Winter 1981), while Carter and Anderson (1963) reported standard deviation of flow measurements between 4 and 7% using current flow meters. These values were taken as guidance to consider uncertainty measurements in this work.

2.3 Data analysis

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

Variables related to precipitation of the recorded events were calculated: the total water depth (P, mm), the total rainfall kinetic energy (E, MJ ha^{-1}), the maximum intensity in 10 and 30 minutes (I_{10} and I_{30}, respectively, 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 and Smith (1978) (Equation 1):

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

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

The antecedent condition was evaluated trough the accumulated precipitation of 5 and 10 days prior to the analysed events (P5 and P10, mm).

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, and time to peak (Tp, h). The duration of the runoff event (Dur, h) was calculated as the time between the beginning and the end of the hydrograph of the event. Flood intensity (IF, m^3 min^{-1}), that describes the discharge speed to reach the peak flow during a flood event (Oeurng *et al*. 2010), was calculated by Equation 2:

$$IF = \frac{(Qp - Qb)}{Tp} \qquad (2)$$

where Qp is peak flow (m^3 min^{-1}), Qb is beginning base flow (m^3 min^{-1}), before the flood and Tp is time to peak (min).

Soil loss ratio is ‘the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow’ (Wischmeier and Smith 1978). Records of land use and rotations of the plots in the watershed were obtained for each rainfall–runoff event studied. Considering sowing dates, crop stages and fallow periods, soil loss ratios were calculated with the information of tables published in Handbook 537 (Wischmeier and Smith 1978). According to each parcel area and its soil loss ratio obtained, a weighted soil loss ratio was calculated for each event.

The concentration of suspended solids was calculated for the discrete sampling (DS, g L^{-1}) and composite sampling (CS, g L^{-1}). Average differences between duplicate measurements of DS and CS sediment concentration were 4.8% and 6%, respectively. Concentration values were not included in the PCA because they were used as the dependent variables in the regression analysis.

Ares *et al*. (2014b) described the correlations among the variables associated with precipitation, runoff and antecedent precipitation for the study area. Principal component analysis was performed to reduce multicollinearity of predictor variables (Jolliffe 2002, Afifi *et al*. 2012, Dormann *et al*. 2013). The new variables obtained from this statistical technique, the principal components (PC), are statistically independent and may be used in regression analysis to handle multicollinearity (Abdul-Wahab *et al*. 2005). In addition, these new variables with more statistical weight, explain more variance than the original variables. Therefore, the original variables are replaced by orthogonal “supervariables”, which summarize the environmental data that may cause the variation in sediment concentration.

The assessment of the data suitability for principal component analysis was done using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (Kaiser,

1974) and the Bartlett's test of sphericity (Bartlett, 1950). The KMO index indicates the proportion of variance which may be generated by underlying factors. In this case, the value of the KMO index was 0.6, suggesting data adequacy for principal component analysis (Williams *et al*. 2010). The Bartlett's test of sphericity checks for the hypothesis that the correlation matrix is an identity matrix, which would indicate that the variables are uncorrelated. This test was not significant ($p<0.05$), suggesting significant relations among variables, and suitability for PCA analysis (Williams *et al*. 2010).

Using principal component analysis, the new variables with their corresponding values (the factor scores), were obtained for each flood event. The initial solution was then rotated using the Varimax method (Richman 1986). The R software was used for this statistical analysis (R Development Core Team 2011).

MacCallum *et al*. (1999) suggested communalities should be all greater than 0.6, or the mean level of communality to be at least 0.7. Then, variables with communality values less than 0.6 were discarded for the PCA, and the mean level of communality was 0.85.

The regression analysis for predicting the runoff event sediment concentration was performed using the standardized factor scores as independent variables. The proposed model is a quadratic equation:

$$\text{Conc} = A\text{PC1}^2 + B\text{PC1} + C\text{PC2}^2 + D\text{PC2} + E\text{PC3}^2 + F\text{PC3} + \text{G}\ldots \quad (3)$$

where Conc is the sediment concentration (g L^{-1}).

The model was solved through the Levenberg-Marquardt algorithm (Pujol 2007), that is a method used to solve non-linear least squares problems, using the R software (R Development Core Team 2011).

The performance of the model was evaluated by two criteria: the coefficient of determination (R^2) and the efficiency E, proposed by Nash and Sutcliffe (1970), which is defined as:

$$E = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(Oi - \overline{O})^2} \quad (4)$$

where O_i and P_i are the observed and predicted data, and $\overline{O}$ is the average of observed data.

3 RESULTS AND DISCUSSION

During the study period, 25 flood events were analysed. The inter-annual variability of rainfall was high: 807 mm year^{-1} in 2011, 1351 mm year^{-1} in 2012, 668 mm year^{-1} in 2013 and 1171 mm year^{-1} in 2014. Mean annual precipitation corresponding to the period 1994–2014 for the Monasterio Trapense pluviometer is 915.5 mm year^{-1}. This station is approximately 20 km from Cerro del Águila station, and is the nearest with complete and reliable rainfall records for the area (Varni and Custodio 2013). The analysis of precipitation indicates that two of the studied years had rains over the mean, while the other two years had rains below the mean. Then, the studied period is representative of the climatic variability of the region.

Table 1 summarizes the main characteristics of the events studied. Seven events occurred in summer (December–March), seven in autumn (March–June), five in winter (June–September) and six in spring (September–December). Three of the events were registered in 2011, 12 in 2012, five in 2013, and four between January and August 2014. The rainfall that caused the events ranged between 17.8 and 136.4 mm, and 40% of the events presented rainfall exceeding 50 mm.

The rainfall–runoff events analysed included a wide range of discharge characteristics. The peak discharge ranged from 0.14 to 4.6 $m^3 s^{-1}$, and nine of the events had discharges exceeding 1 $m^3 s^{-1}$. Discrete and composite sediment concentration also showed high variability. Considering discrete sampling, six of the events reached concentrations that exceeded the mean value. With regard to composite sampling, five of the events exceeded the mean concentration. Ares *et al.* (2014b) analysed the variability in rainfall–runoff response and the related sediment concentration for the study area. This variability was associated with different factors controlling runoff and sediment dynamics such as intensity of rainfall, the time since the last rainfall and evapotranspiration during that period that, together with soil properties, determine soil moisture. In turn, the surface characteristics in terms of their physical state or the type and amount of vegetation affect the infiltration capacity of the soil through the effect on porosity and micro relief. Variability and complexity in sediment production was related to detachment, transport, and sedimentation that occur differentially at watershed scale during the recorded events. Authors like González-Hidalgo *et al*. (2007) and Estrany *et al*. (2009) point out that high percentage of suspended material is transported in a small number of events, which is in agreement with results obtained in this study area.

Table 1

3.1 Sediment-discharge relationship

To characterize possible hysteresis patterns, discrete and composite sampling data and peak discharge of each recorded event were analysed. The date and hour of peak discharge and sampling was also considered (Table 2).

The comparison between discrete and composite sampling shows that suspended sediment concentration decreased during the 1.5 hours of sampling. The comparison between the date and hour of peak flow and sampling modes shows higher concentrations before peak for 20 cases. These cases had a higher magnitude, and sampling occurred during the rising limb of water discharge. Although there is no available data about peak concentration, the differences between discrete and composite sampling show that suspended sediment concentration would peak before discharge, suggesting that a positive or clockwise hysteresis pattern would occur in the first part of the event.

With regard to events of smaller magnitude, sampling occurred between peak discharge and the initial part of the falling limb of water discharge. Again, there is no available data about peak concentration, but it is possible to establish that, in these events, concentration decreases at the same time water discharge decreases. According to Nu-Fang *et al*. (2011), these cases would be associated with a positive hysteresis pattern.

Other analyses, carried out at different scales, showed similar patterns regarding to sediment-discharge relationships. First, at the Videla stream watershed scale (116.3 km^2) recent analyses showed a clockwise hysteresis pattern (J. González-Castelain personal communication, 12 December 2014) during significant events that caused surface runoff at that scale. Second, at a micro-plot scale of 0.0625 m^2, in the small watershed of 560 ha, Ares *et al*. (2014a) conducted experiments with a rainfall simulator. Runoff and sediment concentration under average rainfall intensity of 120 mm h^{-1} were measured. Results showed that highest sediment concentrations were registered prior to peak runoff.

The cases discussed before suggested positive or clockwise hysteresis patterns at different scales in the study area. This pattern has been reported as a normal condition for most fluvial systems (Hudson 2003) and as the most frequent pattern in different studies (Williams 1989, Seeger *et al*. 2004, Giménez *et al*. 2012). Several causes have been attributed for this type of hysteresis. In this first characterization for the study area, some of them may be explained. Exhaustion of sediment sources that occurs during a runoff event can lead to reduced sediment concentrations (Fan *et al*. 2013). Causes of less sediment availability include decreased detachment that may occur in the end of rainfall. In addition, a possible decrease in sediment availability may occur when soil moisture increases, during a runoff event. Vermang *et al*. (2009) reported higher aggregate detachability for dry soil aggregates, while lesser aggregate breakdown for prewetted soil aggregates. Analysis of aggregate stability for the study area showed lesser values of mean weight diameter for dry (1.79 mm) than for prewetted aggregates (3.10 mm) (F. B. Kraemer personal communication, Sept 2013). This result suggests that dry soils have lower resistance to slaking forces acting during wetting process, and that more particles would be detached and, in turn, be available to be eroded at the beginning of an event.

Another cause for sediment exhaustion may be the dilution effect from increases in surface runoff and groundwater flow (Walling and Webb 1982) that may have been possible in the larger registered events. In some of these, runoff separation into superficial and base flow showed the increment in groundwater flow during the composite sampling period.

According to the analysis in this section, composite sediment concentration was selected to perform the regression analysis, because it contains average information of a longer period of the events, between 2 and 11% of them, not only of the most erosive initial part of them.

Table 2

3.2 Principal component analysis of factors supposed to affect sediment concentration

The PCA carried out achieved a good explanation of the variance of the original variables, initially supposed unitary. The minimum values are given for P10 and SLR.

Table 3 shows the explained variance (communalities) of variables with values greater than 0.6, which were the variables finally included in the PCA. These variables are less than initially considered, because some were discarded through a process of variable screening discarding and-or adding variables.

Table 3

Three principal components were selected, that explain 85.2% of the total variance. In order to interpret each component, Table 4 shows the factor pattern, which is the product of the eigenvector and the square root of the eigenvalue. Also, it is equal to the correlation coefficients between the derived component variables (principal components) and the original variables. The PC1 shows high correlation coefficients with RC, Qp, Qsup and IF, ordered by coefficient values. These variables are all related to the runoff of the events. Thus, this component is referred to as 'runoff factor (RF)'.

The second PC is highly correlated with EI_{30}, P and I_{10}. These variables are related to precipitation, its intensity and its erosivity. This component is called 'precipitation factor (PF)'.

The PC3 is correlated with the 10 days antecedent rainfall (P10), and with soil loss ratio (SLR). This component shows the combined effect of wetness and the protective effect of vegetation cover, which are interpreted as previous conditions to the event. Thus, the third is defined as the 'antecedent conditions factor (ACF)'.

Table 4

Figure 2 shows the relationship between the original variables and the components axis. The 10-days previous precipitation and SLR are located near the origin, and this is because they have low correlation with the first two components, but they are highly correlated with the component 3, which is an axis perpendicular to the figure plane.

As new variables, the principal components have a value for each event analysed, that are called factorial scores. These values are standardized; this is, with zero mean and unit standard deviation. Table 5 shows the runoff event dates and the factor scores values for each.

Figure 2

Table 5

3.3 Regression analysis

To study factors controlling suspended sediment concentration, a regression analysis was performed. The standardized factor scores were used as independent variables (Table 5) and the composite sediment concentration of suspended solids as dependent variable, because it contains average information of a longer period of the events, as it was explained in section 3.1.

The adjusted equation was

$$\mathrm{Conc} = 0.257\mathrm{RF}^2 + 0.196\mathrm{RF} + 0.067\mathrm{PF}^2 - 0.22\mathrm{PF} - 0.004\mathrm{ACF}^2 + 0.186\mathrm{ACF} + 0.459 \qquad (5)$$

with $R^2 = 0.83$. The standard errors of the parameters estimates are shown in Table 6. The model explains more than 80% of the variance of suspended sediment concentration. Figure 3 shows the relationship between the observed composite samples and the model predicted sediment production. The model efficiency calculated was 0.83, which shows good agreement between measured and calculated sediment by the regression model. Preliminary tests were made with linear models but adjustment levels obtained were lower than that corresponding to the quadratic equation.

Table 6

Figure 3

Runoff factor contributed to modelled composite sediment concentration with the highest magnitude (78.4%), followed by precipitation factor (20.4%), and then the antecedent condition factor (1.2%). Other authors point out the importance of runoff in the control of suspended sediment supply, because it is the factor explaining most of the variation in regression models (Restrepo *et al*. 2006, Rodríguez-Blanco *et al*. 2010, Polyakov *et al*. 2010). In a similar analysis considering correlations between principal components and suspended sediment concentrations, Giménez *et al*. (2012) discuss moderate correlations between sediment concentration and the factor correlated with rainfall erosive power. They indicate that these correlations show the importance of splash erosion in sediment production. Also, those authors report low correlations between sediment concentrations and antecedent conditions, described by antecedent precipitation, while other authors did not find correlations between these variables in regression models (Rodríguez-Blanco *et al*. 2010, Nu-Fang *et al*. 2011).

Regarding the contribution of the factors to the modelled sediment concentration in the individual events (Fig. 4), RF showed the highest contribution in 8 events (group one), PF had the highest value in 10 events (group two), while the ACF, in 7 of the events (group three).

Figure 4

Considering these groups of events, the mean values of the original variables involved in the factors with higher contribution to the modelled sediment concentration, were analysed. This is proposed as a way to corroborate the relevance of such factors in the grouped events.

Events in group one showed the highest mean values of RC (26.3%), Qp (2.6 $m^3\ s^{-1}$), Qms (0.74 $m^3\ s^{-1}$) and IF (0.44 $m^3\ min^{-1}$). In a previous analysis conducted in the study area, Ares *et al*. (2014b) related most of these events to rill erosion, the less frequent, but the most erosive process. In this type of erosion runoff and its energy is the main force acting in the detachment of soil particles (Morgan 2005). This suggests that the model recognizes the role of runoff in these highly erosive events. These are the most important to predict and model, because of their high contribution to soil loss (Mingguo *et al*. 2008).

Events in group two showed intermediate to low mean values of P (42.7 mm), EI_{30} (365.5 MJ mm (ha h)$^{-1}$) and I_{10} (32.2 mm h^{-1}). In the same work reported previously, Ares *et al*. (2014b) related most of these events to sheet erosion, with low sediment concentration, associated with less erosive rains. Additionally, mean SLR values of these events were the highest of the 3 considered groups (0.15), indicating poor vegetation cover. This situation may have been favourable to soil detachment by rainfall impact as the main driver of this type of erosion (Blanco and Lal 2008). This analysis may corroborate the major role of precipitation in these cases.

Finally, the events in group three showed the highest mean values of the variable P10 (48.5 mm), but the lowest mean value of SLR (0.08), indicating, in general, good soil cover. This is possible, as these events corresponded mainly to the summer, end of summer or the beginning of autumn, when soil cover is good because of the presence of summer crops. Therefore, this may indicate the possibility that antecedent precipitation may have played a more important role in these events, combined with rainfall force, as these cases showed the highest mean value of I_{10} (57.6 mm h^{-1}).

Despite the importance of soil cover as a factor to control water erosion reported by several studies (Bartley *et al*. 2006, Durán Zuazo and Rodríguez Pleguezuelo 2008, Nadal-Romero *et al*. 2013), this work shows the greater impact of runoff and precipitation in suspended sediment concentration for these events. However, rainfall simulation experiments conducted in the study area showed the importance of vegetation cover for runoff and sediment yield control (Ares *et al*. 2014a, Sfeir *et al*. 2005). These results indicate that changes in the scale of analysis, from microplot to watershed may highlight the relevance of climatic and hydrologic factors on sediment production under natural rainfall events. Meanwhile, it is interesting to point out the need to study relationships between seasonal rainfall patterns and soil cover and their influence on runoff and sediment production dynamics. This would help in the design and adjustment of conservationist managements for this region, as well as in the interpretation of results of monitoring programs carried out at agricultural watershed scales.

Finally, the results discussed are the first for a small watershed in Argentina. Because the proposed model should be validated, it is important to mention the need of continuing with a monitoring program in the study area, that includes continuous data of sediment concentration during the runoff events.

4 CONCLUSIONS

This manuscript reports results of field studies on suspended sediment concentrations carried out at the Argentine Pampas region. A first attempt to characterize possible hysteresis patterns suggested a positive clockwise pattern in the study area. Some possible causes were attributed to this type of hysteresis: a decrease in sediment availability with increasing soil moisture or dilution effect from increases in surface runoff and groundwater flow.

To study sediment concentration controlling factors, principal component analysis and a multiple regression model were applied. The approach to the analysis of sediment concentration controlling factors by regression models performed with the factor scores of principal components may be considered, in a certain degree, as a new contribution for the study of water erosion in different regions. Three principal components were obtained, correlated with runoff related variables, precipitation variables, and antecedent conditions variables. Then, 3 factors (runoff, precipitation and antecedent conditions factors) were identified to perform the multiple regression model, with composite sediment concentration as the independent variable. The model explained 83% of the variability of suspended sediment concentration. Runoff factor contributed to modelled composite sediment concentration with the highest magnitude (78.4%), followed by precipitation factor (20.4%), and then the antecedent condition factor (1.2%).

Considering individual events, RF showed the highest contribution in 8 events (group one), PF had the highest value in 10 events (group two), while the ACF, in seven of the events (group three). Complementary analyses considering previous results and the mean values of the original variables involved in the 3 factors obtained, showed that the model recognized the relevance of such factors in the grouped events.

It is important to point out the need of continuing with a monitoring program in the study area, to get data to validate the proposed model.

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Table 1 Range, mean, standard deviation (SD) and coefficient of variation (CV) for the 17 variables studied during the 25 events recorded. P.: precipitation; E: the total rainfall kinetic energy; I_{10}. and I_{30}.:the maximum intensity in 10 and 30 minutes, respectively; R.: surface runoff sheet; Qp.: peak flow; Qms.: mean surface flow; RC.: runoff coefficient; Tp.: time to peak flow; Dur.: duration of the runoff event; IF.: flood intensity; SLR.: soil loss ratio; P5. and P10.: the accumulated precipitation of 5 and 10 days previous to the events; DS. discrete sampling concentration of suspended solids; CS. composite sampling concentration of suspended solids.

Variable	Range	Mean	SD	CV
P (mm)	17.80-136.40	51.55	32.32	159.49
E (MJ ha^{-1})	3.92-36.42	10.83	7.88	137.43
I_{10} (mm h^{-1})	6.00-152.40	45.79	31.55	145.13
I_{30} (mm h^{-1})	6.80-83.20	26.76	17.68	151.35
EI_{30} (MJ mm (ha h) $^{-1}$)	41.59-3 030.27	389.41	620.10	62.79
R (mm)	40.24-0.40	7.86	10.17	77.3
Qp (m^3 s^{-1})	0.14-4.60	1.32	1.38	95.73
Qms (m^3 s^{-1})	0.02-1.50	0.35	0.43	82.55
RC (%)	0.97-53.8	13.69	13.79	99.26
Tp (h)	2.50-15.00	8.50	3.53	240.79
Dur (h)	8.00-75.00	37.06	16.83	220.22
IF (m^3 min^{-1})	0.01-1.76	0.20	0.36	55.55
SLR (-)	0.07-0.26	0.13	0.06	216.6
P5d (mm)	0.00-77.80	13.01	21.64	60.12
P10d (mm)	0.20-115.80	29.34	34.15	85.91
DS (g L^{-1})	0.38-8.54	1.6	2.16	74.07
CS (g L^{-1})	0.36-4.14	0.77	0.78	98.71

Table 2 Values of suspended sediment concentration for discrete (DS) and composite (CS) sampling. Date and hour of the two sampling modes and of peak discharge during the 25 events studied. The asterisk in the events number indicate cases with higher concentrations before peak discharge.

N° of event	Date event	DS (g L^{-1})	CS (g L^{-1})	Date and hour of sampling				Date and hour of peak flow	
				Beginning (DS and CS sampling		End (CS sampling)			
1*	16 January 2011	1.94	0.85	16/01/2011	04:30 h	16/01/2011	06:00 h	16/01/2011	11:30 h
2*	30 April 2011	1.86	0.48	30/04/2011	14:00 h	30/04/2011	15:30 h	30/04/2011	19:30 h
3	19 July 2011	0.52	0.38	19/07/2011	04:00 h	19/07/2011	05:30 h	19/07/2011	04:00 h
4	10 January 2012	1	0.52	10/01/2012	13:00 h	10/01/2012	14:30 h	10/01/2012	13:30 h
5	5 March 2012	1.02	0.42	05/03/2012	16:30 h	05/03/2012	18:00 h	05/03/2012	17:00 h
6	12 March 2012	0.56	0.52	12/03/2012	06:00 h	12/03/2012	07:30 h	12/03/2012	06:00 h
7*	19 April 2012	0.74	0.52	19/04/2012	06:00 h	19/04/2012	07:30 h	19/04/2012	06:00 h
8*	17 May 2012	8.54	1.12	17/05/2012	11:30 h	17/05/2012	13:00 h	17/05/2012	16:30 h
9*	23 August 2012	0.62	0.57	23/08/2012	02:00 h	23/08/2012	03:30 h	23/08/2012	12:00 h
10*	4 September 2012	0.5	0.46	04/09/2012	01:00 h	04/09/2012	02:30 h	04/09/2012	07:00 h
11*	5 October 2012	0.64	0.56	05/10/2012	18:30 h	05/10/2012	20:00 h	06/10/2012	00:00 h
12*	16 October 2012	0.58	0.54	16/10/2012	02:30 h	16/10/2012	04:00 h	16/10/2012	10:30 h
13*	22 November 2012	0.6	0.52	22/11/2012	04:30 h	22/11/2012	06:00 h	22/11/2012	11:30 h
14*	5 December 2012	3.74	1.62	05/12/2012	08:30 h	05/12/2012	10:00 h	05/12/2012	14:30 h
15*	19 December 2012	6.76	4.14	19/12/2012	13:30 h	19/12/2012	15:00 h	19/12/2012	16:00 h
16*	28 December 2012	5.28	1.70	28/12/2012	01:30 h	28/12/2012	03:00 h	28/12/2012	05:00 h
17*	30 January 2013	0.52	0.46	30/01/2013	01:30 h	30/01/2013	03:00 h	30/01/2013	08:00 h
18*	25 March 2013	0.76	0.70	25/03/2013	00:30 h	25/03/2013	02:00 h	25/03/2013	04:00 h
19*	1 April 2013	0.38	0.36	01/04/2013	20:30 h	01/04/2013	22:00 h	02/04/2013	02:00 h
20*	28 May 2013	0.64	0.52	28/05/2013	10:00 h	28/05/2013	11:30 h	28/05/2013	13:00 h
21*	10 November 2013	0.52	0.46	10/11/2013	09:30 h	10/11/2013	11:00 h	10/11/2013	13:00 h
22*	22 January 2014	0.52	0.47	22/01/2014	22:30 h	23/01/2014	00:00 h	23/01/2014	02:30 h
23*	12 June 2014	0.46	0.45	12/06/2014	07:30 h	12/06/2014	09:00 h	12/06/2014	15:30 h
24*	5 July 2014	0.5	0.46	05/07/2014	07:00 h	05/07/2014	08:30 h	05/07/2014	14:00 h
25*	22 August 2014	0.72	0.54	22/08/2014	06:00 h	22/08/2014	07:30 h	22/08/2014	10:00 h

Table 3 Communalities of the analyzed variables. Qp.: peak flow; RC.: runoff coefficient; EI30.: product of the total rainfall kinetic energy (E) and the maximum intensity in 30 minutes (I_{30}); Qms.: mean surface flow; I_{10}.: maximum intensity in 10 minutes; P.: precipitation; IF.: flood intensity; SLR.: soil loss ratio; P10.: the accumulated precipitation of the 10 days previous to the events.

Variable	Communality
Qp	0.98
RC	0.97
EI_{30}	0.95
Qms	0.94
I_{10}	0.85
P	0.80
IF	0.79
SLR	0.75
P10	0.64

Table 4 Regression coefficient between original variables and principal components (PC) (runoff factor, RF; precipitation factor, PF and antecedent conditions factor, ACF). Qp.: peak flow; RC.: runoff coefficient; EI_{30}.: product of the total rainfall kinetic energy (E) and the maximum intensity in 30 minutes (I_{30}); Qms.: mean surface flow; I_{10}.: maximum intensity in 10 minutes; P.: precipitation; IF.: flood intensity; SLR.: soil loss ratio; P10.: the accumulated precipitation of the 10 days previous to the events.

Variable	Principal component		
	PC1 (RF)	PC2 (PF)	PC3 (ACF)
Qp	0.91	0.39	0.05
RC	0.98	0.00	0.10
EI_{30}	0.14	0.96	0.05
Qms	0.88	0.40	0.00
I_{10}	0.16	0.81	0.40
P	0.20	0.87	-0.07
IF	0.88	0.04	0.10
SLR	0.08	-0.26	-0.82
P10	0.22	-0.08	0.76

Table 5 Runoff event dates and factor scores values corresponding to principal components (runoff factor, RF; precipitation factor, PF and antecedent conditions factor, ACF) for the events studied.

Date	RF	PF	ACF
15 January 2011	0.68	1.21	0.53
1 May 2011	-0.65	0.16	-1.16
19 July 2011	-0.47	-0.56	-1.96
10 January 2012	-1.05	0.67	0.29
5 March 2012	-0.91	0.20	0.48
11 March 2012	-0.83	-0.20	1.90
18 April 2012	-0.83	-0.49	0.27
17 May 2012	1.17	1.49	-0.44
23 August 2012	0.69	-0.35	0.95
3 September 2012	-0.19	-0.69	-0.65
5 October 2012	-0.38	-0.63	-0.32
15 October 2012	-0.17	-0.45	-0.51
22 November 2012	-0.40	-0.59	-0.32
5 December 2012	1.28	-0.98	0.53
19 December 2012	3.12	-0.45	0.27
28 December 2012	0.52	-0.62	2.18
29 January 2013	-0.76	-0.12	0.67
24 March 2013	-0.35	0.45	0.20
1 April 2013	-0.41	-0.32	1.04
28 May 2013	-0.52	-0.15	0.26
9 November 2013	-0.61	-0.59	-0.35
22 January 2014	-0.25	3.86	-0.04
11 June 2014	1.95	0.15	-1.43
5 July 2014	-0.47	-0.44	-1.82
22 August 2014	-0.18	-0.55	-0.56

Table 6 Standard errors of the parameters estimates of the quadratic model performed.

Parameter	Standard Error
A	0.06
B	0.13
C	0.05
D	0.15
E	0.06
F	0.08
G	0.13

Fig. 1 a) Location of the small watershed under study in the basin of the Videla stream and pluviometric record station (Cerro del Águila). b) Detail of the small watershed with location of the flow monitoring and runoff water sampling station.

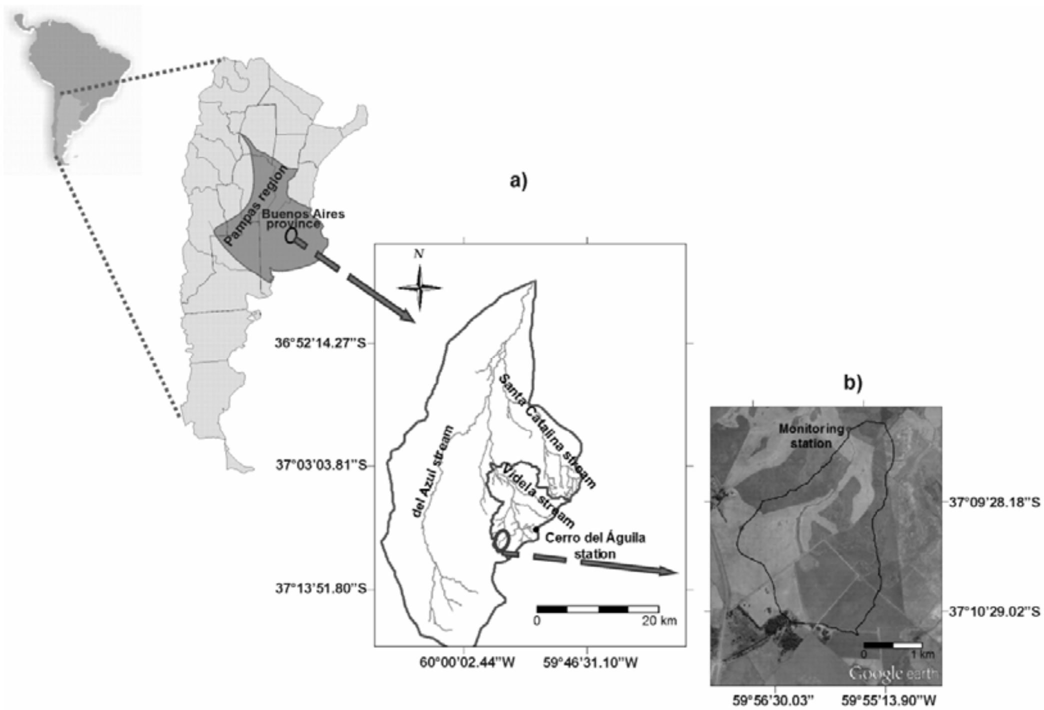

Fig. 2 Relationship between the original variables and principal components 1 (PC1) and 2 (PC2). The variables with the highest correlations with PC 1, 2 and 3 are outlined in I, II and III, respectively. Qp.: peak flow; Qms.: mean surface flow; RC.: runoff coefficient; IF.: flood intensity; EI_{30}.: product of the total rainfall kinetic energy (E) and the maximum intensity in 30 minutes (I_{30}); I10.: maximum intensity in 10 minutes; P.: precipitation; SLR.: soil loss ratio; P10.: the accumulated precipitation of the 10 days previous to the events.

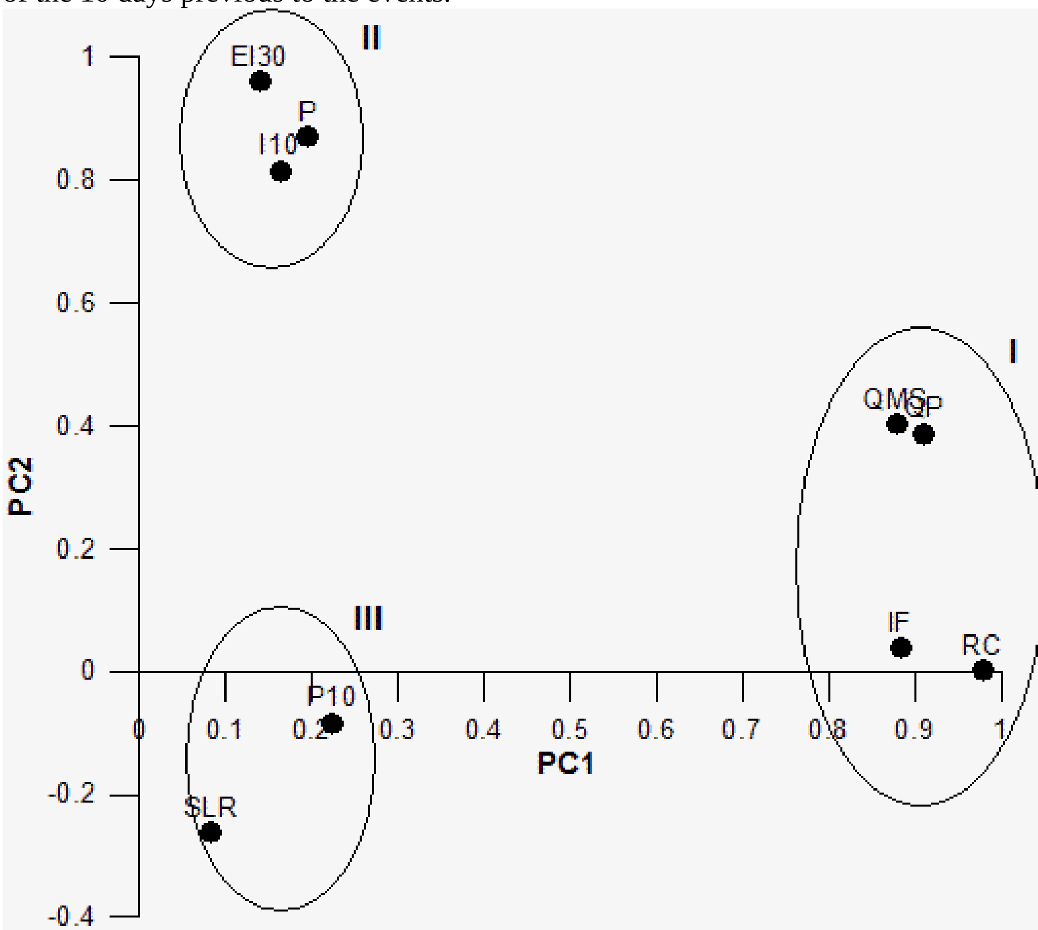

Fig. 3 Relationship between observed and predicted composite sediment concentration for the 25 studied runoff events.

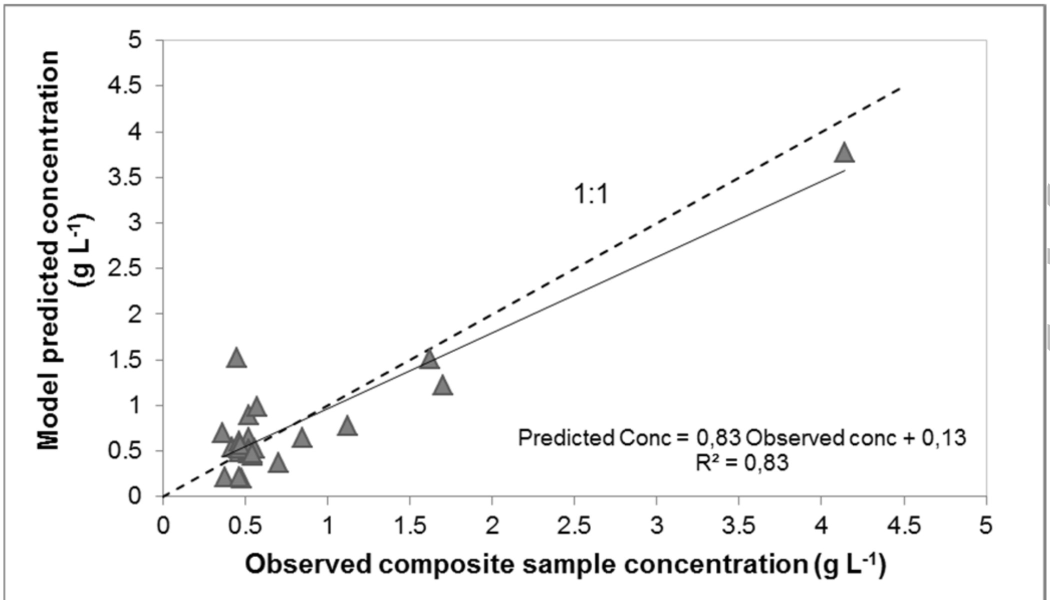

Fig. 4 Contribution of the runoff factor (RF), precipitation factor (PF) and antecedent conditions factor (ACF) to the modeled sediment concentration for the 25 studied events.