Received: 15 January 2020 | Accepted: 11 April 2020
DOI: 10.1002/hyp.13782

RESEARCH ARTICLE

WILEY

Runoff response of a small agricultural basin in the argentine Pampas considering connectivity aspects

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Funding information
Agencia Nacional de Promoción Científica y Técnica - Argentina, Grant/Award Number: PICT 2015 N°2012; Universidad de Buenos Aires, Grant/Award Number: UBACYT 20020170100533BA

Abstract

Our manuscript analyses the surface runoff variability, and its controlling factors in a small basin with gentle slopes, at the headwaters of a flat catchment, to improve the knowledge of the hydrology of plain areas under agriculture. We study runoff, rainfall and antecedent conditions in the argentine Pampas region. We use correlations, regressions and quantitative and qualitative descriptive information of the system: erosion signs, ground cover by crops, groundwater depth data and temporal changes in the drainage network, to discuss and understand the complexity of the runoff process by frameworks to study (dis)connectivity. The analysis of 56 events evidenced a nonlinear rainfall–runoff relationship. In contrast with other works, we identified clear upper limit events, under which hydrological responses emerge, as a result of combinations of antecedent wetness, rainfall erosivity, ground cover and preferential drainage paths. We separated the nonlinear rainfall–runoff response in three linear relationships according to differences in antecedent wetness conditions. We found differences in runoff responses under wet and dry antecedent conditions, but complex responses under medium antecedent conditions. The analyses of the inputs, the structural and the functional elements of the (dis)connectivity frameworks, were key in the understanding of the temporal changes of runoff, and its complex responses. Temporal coincidences of connectivity components and their feedbacks appear to be strongly associated with the runoff dynamics. High-magnitude hydrological responses occur with complete coincidences, while partial coincidences between the components reduce connectivity and low magnitude and/or heterogeneous responses prevail. Thus, these analyses suggest that runoff is controlled by (dis)connectivity in this basin with gentle slopes. Our work contributes to the understanding of the process of surface runoff in the context of humid flatlands under agricultural land use, by the identification of the complex combinations of factors which regulate/control the (dis)connectivity that helps to interpret the nonlinearities of runoff.

KEYWORDS
agricultural basin, antecedent wetness conditions, erosion signs, gentle hills and slopes, hydrological (dis)connectivity, pampas region, rainfall, runoff response

1 | INTRODUCTION

According to Ambroise (2004), "Any hydrological process depends on some factors or combination of factors, which control its activation, intensity and deactivation." Those factors include climate, geology, geomorphology, soils, vegetation and land use, which interact and determine the rainfall–runoff response of catchments (Mirus & Loague, 2013). These interactions are complex (Minella et al., 2018) and variable over time, and result in the nonlinear rainfall–runoff responses frequently observed in basins (Latron & Gallart, 2008; Lehmann, Hinz, McGrath, Tromp-van Meerveld, & McDonnell, 2007; Nadal-Romero, Peña-Angulo, & Regüés, 2018). Some of the factors previously mentioned are combined in spatial patterns: geology, geomorphology, soils, vegetation and land use, and constitute the structure or the anatomy of catchments (Turnbull et al., 2018). These patterns interact with the rainfall, an element of climate, and, as a consequence, the water transfer emerges as runoff or connected flow (Turnbull, Wainwright, & Brazier, 2008).

Tetzlaff et al. (2007) state that connectivity involves the flows of matter and energy, such as water, nutrients, sediments, heat, between the components of the landscape: the hillslopes and the drainage network at catchment scale. The concept of hydrological connectivity has been proposed to analyse systems with complex and nonlinear responses (Lexartza-Artza & Wainwright, 2009; Wohl, 2017). In this sense, Wohl et al. (2019) highlight the importance of connectivity in the understanding of the spatial and temporal variability of fluxes. So, a spatial and temporal dynamics of hydrological connectivity may be identified, characterized by increments in runoff by connectivity (Phillips, Spence, & Pomeroy, 2011) or reduction of hydrological fluxes by disconnectivity (Wohl et al., 2019). In this context, integrated analyses of the conditions of the structural elements in relation with antecedent conditions, rainfall inputs and their feedbacks are key to the interpretation of variability in the hydrological response and (dis)connectivity in basins (Wainwright et al., 2011). These analyses are within the frameworks proposed by Lexartza-Artza and Wainwright (2009), Bracken et al. (2013) and Keesstra et al. (2018) for the study of complex hydrological systems of the connectivity approach. These frameworks coincide in the need to consider the interactions between the drivers of connectivity, or the inputs, the structure of the system and its state at a given time, and the fluxes associated with processes or the functional elements of connectivity. They also highlight the need to describe the relevant components of each system to implement the frameworks, based on field knowledge. These include precipitation, antecedent conditions, human activities and land use decisions, changes in pathways, erosion signs and temporal runoff discharge. No unified consensus about how to measure connectivity has been achieved (Rinderer, Ali, & Larsen, 2018). However, qualitative and quantitative monitoring strategies are suggested for these analyses, including the identification of structural, functional components of the connectivity and the descriptions of feedbacks within the systems (Lexartza-Artza & Wainwright, 2009). For example, Wainwright et al. (2011) studied the connectivity in an agricultural basin, and they included, among others, physical characteristics of catchments, land use data or presence of pathways as descriptors of the structure. Interactions between rainfall and runoff, soil moisture, the presence of ephemeral channels, signs of water erosion and sedimentation are examples of the descriptors of functional connectivity components. Changes in the structure of the system as a consequence of the management practices or seasonal processes, or differences in preferential pathways by erosion or soil redistribution are considered as feedbacks to take into account. In addition, rainfall and runoff are the most frequent variables monitored at catchments, and their measurements have been included in connectivity analyses combined with statistical methods to identify runoff responses and connectivity (Ali, Roy, Turmel, & Courchesne, 2010), or with tracers and isotopes (McGuire & McDonnell, 2010). Ali et al. (2010) state that the analysis of hydrographs and variables derived from them such as peak discharge or runoff coefficients (RCs), in conjunction with surrogates of antecedent wetness conditions, may help to understand catchment responses associated with connectivity.

Several plain regions of the world are arable lands, dedicated to livestock and cropping activities: the Great Plains in United States of America (Ferguson & Maxwell, 2012), the Indo-Gangetic plains in South Asia (Lal, 2011), the North China plain (Aeschbach-Hertig & Gleeson, 2012) or the South American Pampas region (Kuppel, Houspanossian, Nosseto, & Jobbágy, 2015). These areas are of key importance for the satisfaction of the world´s food demand, which is increasing as a consequence of the growing population (Alexandratos & Bruinsma, 2012). So, the need to increase the food production emerges as a challenge for agricultural production systems. The expansion of the area under agriculture, and livestock production intensification have been experienced in the Pampas region in the last decades, with accelerated replacement of natural grasslands by pastures, cereals, oilseed crops or forest plantations (Modernel et al., 2016; Reichert et al., 2017). Agricultural intensification induces changes in runoff and increases runoff hazards (Wheater & Evans, 2009), and these issues have been reported in the Pampas, associated with the water erosion degradation process (Lavado & Taboada, 2009; Sasal, Boizard, Andriulo, Wilson, & Léonard, 2017; Wingeyer et al., 2015).

The argentine Pampas region occupies an area of 400,000 km^2, and in its lands of high fertility and productivity, the 90% of the country's grain production takes place (Magrin, Travasso, & Rodríguez, 2005), and 48% of the cattle stock is raised (Canosa, Feldkamp, Urruti, Morris, & Moscoso, 2013). According to Mateucci (2012), the 13% of this region is occupied by gently hilly areas, at the headwaters of plains. The hydrology of these plain areas has a particular dynamics, associated with the low regional slopes that give the low morphological energy-content to these areas, where the vertical movement of water dominates over the horizontal movement (Kruse & Zimmermann, 2002). Consequently, according to Varni, Usunoff, Weinzettel, and Rivas (1999), the main mechanisms by which most of the water discharges are infiltration and evapotranspiration. So, the accelerated runoff generated in the upper lands by agricultural intensification flows to the plains, increases the natural flooding and sediment accumulation risks and could affect the water quality downstream. Headwater streams play key hydrological and ecological functions as they maintain natural discharge regime, regulate sediment and nutrient exports (Lowe & Likens, 2005). Thus, it is important to improve the knowledge of the hydrological response, its complexity and the factors associated with its variability at the headwaters of these areas, in the regional context of flatlands. Analyses of the hydrology in these regional contexts are not frequent and are still needed (Aragón, Jobbágy, & Viglizzo, 2011; Ares et al., 2018; Dalponte et al., 2007).

The objective of this work is to study and understand the surface runoff variability, and its controlling factors in a small basin with gentle slopes, at the headwaters of a flat catchment, to improve the knowledge of the hydrology of plain areas under agriculture. The study area is located in the argentine Pampas region and the analysis takes elements and concepts of the (dis)connectivity frameworks previously described which help to explain the runoff response of our system. Quantitative and qualitative data are used for this study. In this case, we consider runoff and rainfall data monitored at the outlet of a catchment, at event scale. We analyse and describe the relationships between runoff variables: surface runoff and RCs, and a set of hydro-meteorological variables, by their correlations and by regressions. We introduce elements of the (dis)connectivity frameworks to discuss and understand the relationships found and the variability in runoff. In our case, we consider the erosivity of rainfall related to runoff, the antecedent conditions, the erosive processes, the seasonality of the events, in terms of cover by crops. Temporal changes in these factors and in the drainage network, and their feedbacks throughout the study period, are also studied to interpret the variability in runoff, as a part of a qualitative analysis. The conceptual approach of (dis)connectivity has not been previously analysed in our region and is still not frequently considered in watersheds with gentle slopes (Bracken et al., 2013), and in South America, where studies using this approach are in their early stages. We propose the use of simple data analysis methods such as correlations and regressions combined with the study of quantitative and qualitative descriptive information of the system to discuss and understand the complexity of the runoff process with the (dis)connectivity framework. The combinations of these methods can be used in other study cases where connectivity studies are missing, or more complex techniques such as tracing have still not been implemented, such as in our basin.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was carried out in a small basin of 560 ha, which has been monitored since 2011. It is located in the catchment of the Videla stream that flows into the Del Azul stream in the argentine Pampas region (Figure 1). The geographical coordinates of the basin outlet are 37°08′47.61″S 59°55′25.17″W. The climate is temperate humid with average annual temperature of 14.4°C. The annual rainfall is 914 mm and 71% occurs between October and April. Geomorphologically, the catchment is located in the area of rocky outcrops of the Del Azul stream basin, which includes areas of catchment divides and fluvial valleys (Zárate & Mehl, 2010). The area of rocky outcrops, the basin headwaters, occupies 10% of the Del Azul stream basin (Figure 1a), while 90% of the basin corresponds to a plain sector, with slopes decreasing progressively from 2 to 0.2%, considering the regional context (Sala, Kruse, & Aguglino, 1987). Thus, the gently hilly area has a local importance in a neighbouring flat landscape which causes a hydrological behaviour typical of subhumid plains, with shallow groundwater levels related to the precipitation–evapotranspiration balance. These phreatic levels bring water to the streams (baseflow) (Varni, Comas, Weinzettel, & Dietrich, 2013).

The average slope of the small basin is 3%, with a range between 1 and 10%. According to the digital elevation model, three sectors are identified: the upper, the middle and the lower sectors of the basin (Figure 1b). The upper sector has the lowest mean slope, 2.3%, and there, the headwaters of the drainage network is located in an area of wetland. In the middle and lower sectors, the slopes are somewhat higher: 3.7 and 3.6%, respectively. The relief is undulating with isolated hills of granite rocks up to 285 m above the sea level. Soils of valleys are derived from loess deposited with a thickness ranging between 1 and 2 m above a very hard carbonate crust (Instituto Nacional de Tecnología Agropecuaria [INTA], 1990) and a hydrogeologic basement at an average depth between 5 and 10 m. According to the available maps (INTA, 1992), the prevailing soil class is Typic Argiudoll, with good drainage, covering 67.9% of the basin. Lithic Hapludolls and Lithic Argiudolls cover 27.6% of the basin area, and are located in hilly areas. Finally, 4.5% of the surface corresponds to poorly drained bottomlands, located near the watercourse. Predominant deep and well drained soils in the small basin do not register subsurface horizons with platy structure, indicative of subsurface flow. This flow may be restricted to areas occupied by Lithic Hapludolls and Lithic Argiudolls. In addition, parts of the surface of the rocky outcrops are covered by dense natural pastures, and bare rocks are usually weathered, with cracks that induce water infiltration and percolation. These areas are important sources of water recharge to the aquifer (Sala et al., 1987). So, the vertical movement of water to the aquifer prevail.

In general, the soils of the basin have high aggregate stability and abundant macropores due to their loam topsoil texture and high average organic matter content (6.6%), which determine their high productive capacity. Soils are used for agriculture, and rotations include, mainly, wheat, barley, soybean, corn or sunflower under no tillage system.

2.2 | Rainfall data

The rainfall was measured by an automatic weather station located 5 km away from the outlet of the basin (Cerro del Águila station, Figure 1a). It is the closest station to the basin that has detailed data for the analysed period. It has a rain-gauge constructed according to

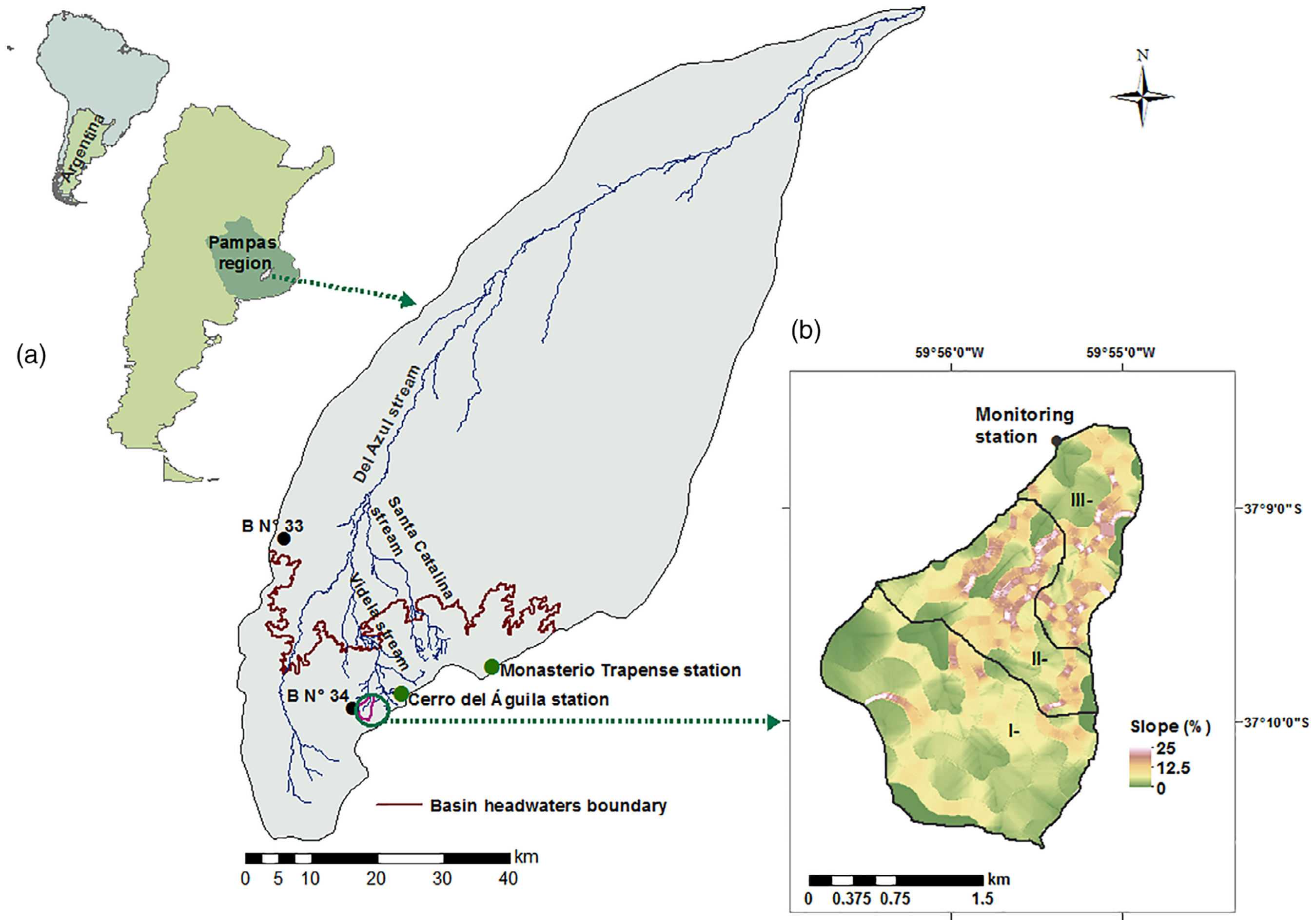

FIGURE 1 (a) Location of the small watershed under study in the basin of the Del Azul stream, rain-gauge stations (Cerro del Águila and Monasterio Trapense), and groundwater monitoring stations (B N° 33 and B N° 34). (b) Detail of the small watershed with location of the upper, middle and lower sectors (I, II and III, respectively) and the flow monitoring station

the standards of the World Meteorological Organization, which records the rain every 10 min with an accuracy of 0.20 mm through a tipping-bucket recording rain gauge.

The calculated rainfall variables were total rainfall depth (P, mm) and the product EI30 (MJ mm/[ha hr]), between total rainfall kinetic energy (E, MJ/ha), and its maximum intensity in 30 min (I30, mm/hr). Rainfall energy was obtained from the sum of the individual energies of 10 min intervals according to the mathematical relationship set by Wischmeier and Smith (1978), by Equation (1):

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

where e = kinetic energy of the interval (MJ/[ha mm]) and i = rainfall intensity (mm/hr). The rainfall erosivity index, EI30, describes the erosive power of rainfall to detach and transport soil particles in the rainsplash erosion process (van Dijk, Bruijnzeel, & Rosewell, 2002). Once they are detached, these particles may contribute to the formation of surface seals because they infill surface pore spaces (Morgan, 2005). These seals reduce water infiltration into the soil. Thus, the EI30 was included in this analysis to consider the consequences of the erosive power of rains in runoff.

2.3 | Runoff data

Water level was measured every 30 min using a digital water level recorder with pressure sensor located at the outlet of the basin (Figure 1b). Records were turned into flow through the stage-discharge rating curve of the section obtained by stream discharge measurements conducted with current metres. This curve was obtained using an electromagnetic current metre, which measures flow velocity and water depth. Data were processed to calculate the rating curve of the section. Because of the difficulty to access to the control section in some periods, calculations by the Manning equation were also done, considering the cross-sectional area of the flow, the Manning's roughness factor and the water surface slope (Dingman, 2015). The results of the rating curve were contrasted with the results obtained by the Manning equation for the monitoring section.

Total runoff separation in direct and base flow was performed by applying a digital filter (Rodríguez, Vionnet, Parkin, & Younger, 2000) based on one of the methods reviewed by Chapman (1999) and Nathan and McMahon (1990). 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).

Events over 800 m^3 and/or related to erosive rainfalls, over 12.7 mm (Wischmeier & Smith, 1978), were included in this study as they were considered of a relevant magnitude according to the basin area and the climatic characteristics of the region. In cases of runoff events with multiple peaks, only the events related to the first peak were incorporated to the analyses, to avoid the complexity of the hydrological response associated with closely successive rainfall events. This was the case of four events only, which peaks were clearly separated and were associated with individual rainfall events. These rainfall events were identified and separated because they had a period of 6 hr or more with less than 1.3 mm between the successive events. This criterion is based on that proposed by Wischmeier and Smith (1978) to separate rainstorms events. It is important to mention that the rest of the events which registered a single peak consisted of single storms identified under the same criterion to relate adequately the corresponding EI30 value to each event.

Direct runoff was characterized by the surface runoff sheet (R, mm), peak flow (Qp, m^3/s), RC (%), calculated by the ratio of surface runoff sheet and total precipitation event. Data between 2011 and 2015 were analysed.

Flood intensity (IF, m^3/min), which describes the discharge speed to reach the peak flow during a flood event (Oeurng, Sauvage, & Sánchez-Pérez, 2010), was calculated by Equation (2):

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

where Qb is baseflow at the beginning of the event (m^3/s) and Tp is time to peak (hr).

The antecedent condition was evaluated through the baseflow at the beginning of the event. Each event was related to the corresponding ground cover by crops periods, which were identified considering the area occupied by crop residues, winter crops and summer crops. The period dominated by crop residues was considered as the low ground cover period and the medium to high ground cover period started when crops covered the soil in a proportion over 50%. We calculated the date of the beginning of this period considering the date of sowing of the crops, registered in field campaigns and the length of growth stages of each crop defined by Allen, Pereira, Raes, and Smith (2006), as the 50% of cover by crops coincides with the middle of the development stage. We corroborated these estimations with data of crops cover obtained by field measurements using the line intercept method (USDA & US DOI, 1999), carried out regularly in the study area. In our study, the low ground cover period was coincident with the last part of the autumn and the winter, and extended to spring during years with rainfalls over the mean. The medium to high ground cover period started in spring during years with precipitations below the mean, and included summer and the first part of the autumn.

2.4 | Groundwater levels

Groundwater depths presented in Section 4 correspond to the borehole N° 33, located 27 km away from the outlet of the basin (Figure 1a). High correlations among groundwater levels in wells located in the Del Azul basin have been reported by Varni, Barranquero, and Zeme (2019). The authors state that the aquifer behaves as "a plane that ascends or descends according to the recharge/discharge ratio." Low regional slopes have been associated with this regional homogeneous behaviour, which induce the predominance of vertical groundwater movements in the upper part of the aquifer (Varni et al., 2019). The linear regression between daily data of borehole N° 34, located 2.8 km away from the outlet of the basin (Figure 1a), and daily data of borehole N° 33, is significant ($p < .05$, $n = 23$), with a coefficient of determination of 0.53. Noncontinuous data of borehole N° 34 are available. Therefore, data of borehole N° 33 were considered, because a complete data series is available for the studied period in this work.

2.5 | Drainage network identification

The temporal changes in the drainage network were included in Section 4 to consider and exemplify changes in the structure of the system occurred during the studied years, as a consequence of wet periods. Drainage network data corresponds to that extracted from Spot's 4 and 5 satellite images by Ares et al. (2016) based on minimum reflectances in near infrared and short-wave infrared bands of the study area. These images have a spatial resolution of 10 m, and, in this case, we present data of 01 February 2012 and 21 December 2012 (Figure 8). In addition, the analysis of three Landsat 8-OLI scenes is incorporated in this work, corresponding to 25 July 2013, 13 August 2014 and 16 August 2015. The panchromatic band was considered, taking into account the spatial resolution of 15 m. A visual interpretation of the scenes was done, based on minimum reflectances of humid surfaces, the knowledge of the study area from observations in the field and on the results obtained from the mentioned Spot images. These scenes corresponded to the low ground cover period, thus low reflectances are associated with high surface soil moisture (Holzman, Rivas, Carmona, & Niclòs, 2017).

2.6 | Data analysis

Quantitative and qualitative data analyses carried out at event scale were used for this study. Quantitative analyses included descriptive statistics, correlation and regression analyses. The descriptive statistics calculated were the median, maximum and minimum values of the variables included in this study. The Spearman correlations between R and P, EI30, Qp, Qb, RC and IF and those between RC and P, EI30, Qp, Qb, RC and IF were analysed.

The scatterplots between runoff variables (RC and R) and rainfall, the EI30 index, antecedent conditions, peak flow and flood intensity, combined, were analysed. Two scatterplots showed the most relevant and significant patterns to interpret the variability in the runoff response of the basin: RC versus Qb and R versus P.

Data grouping by different methods have been appropriate techniques to understand the complexity of the runoff response in watersheds and to identify runoff responses types (Ali et al., 2010; Zhang, Li, Wang, & Xiao, 2016). Events were grouped according to the arrangement shown in the scatterplots, by the median RCs and by the median base flow, to interpret the variability in the hydrological response of the basin. By using the medians, we separate data under the ranges of our own maximum and minimum observed conditions. Our criteria for the selection of the grouping variables is based on the statement of Ali et al. (2010), who mention that RCs may be considered as indicator of the (dis)connectivity in catchments. In addition, antecedent wetness conditions modify runoff responses in our region (Ares, Chagas, & Varni, 2012), and they have been also recognized key to the understanding of connectivity (Ali & Roy, 2009).

The simplest model was selected to describe and explain the relationships found, following the parsimony principle (Montgomery, Peck, & Vining, 2002). So, simple linear regressions models were performed to discuss the relations between runoff variables and independent variables for the groups of data that were defined. The linear regressions significance between the variables was tested and the models were assessed by the adjusted coefficient of determination (R^2). The models were tested for normality of the error terms using Shapiro–Wilk's test with a confidence interval level of 95%. Independence of errors and homogeneity of variance of the errors' terms of the models were analysed with the plot of studentized residuals versus the fitted values (Myers, 1990).

A quali-quantitative analysis was implemented to discuss our results, and it is based on a descriptive context-specific for the connectivity framework, proposed by Lexartza-Artza and Wainwright (2009). It suggests the description of the key structural and functional components of the (dis)connectivity of a system based on field knowledge. We also considered the aspect of the connectivity framework proposed by Keesstra et al. (2018), which consists on the analysis of the state in which a system is at a particular moment, regarding the structure and the processes in relation with the inputs at the system. According to our previous knowledge of the system, we included the analysis of water erosion signs, groundwater depth data, ground cover by crops periods and temporal changes of the drainage network, as relevant factors to explain the (dis)connectivity. The temporal distribution of the last three elements mentioned, and of that corresponding to rainfall, runoff, and RC was analysed, as an indicator of the system state. Interactions between these factors, rainfall erosivity and erosion processes were also examined. We related the temporal distribution of the events with the temporal distribution of the other elements studied. We discussed factors' coincidences and feedbacks, to understand the runoff response variability between the groups, in terms of the (dis)connectivity approach.

3 | RESULTS

3.1 | Data description

A total of 56 rainfall–runoff events were analysed. Annual rainfall during the studied period was 807 mm in 2011, 1,351 mm in 2012, 668 mm in 2013, 1,171 mm in 2014 and 743 mm in 2015. Three runoff events corresponded to 2011, 17 to 2012, 9 to 2013, and 16 and 11 to 2014 and 2015, respectively. Thirty-two events were during the low ground cover period, and 24 during the medium to high ground cover period. Table 1 shows the minimum, maximum and median values of the variables associated with the events considered in this work.

During 17 events, rainfall exceeded 50 mm and only 3 events were generated by rainfalls over 100 mm. The mean annual EI30, the R factor, for the available data in the weather station near the outlet of the basin, which correspond to the periods 2006–2007 and 2011–2015, is 4,083 MJ mm (ha/hr). Four events exceeded the value of 1,000 MJ mm (ha/hr) in the spring–summer (21/09–20/03) of 2011, 2014 and 2015, and in the autumn–winter (21/03–20/09) of 2012.

According to runoff variables, the 75% of the events were associated with Qb greater than 0.043 m^3/s. During 15 events runoff values were over 0.9 mm, and only in 5 events runoff was greater than 3 mm. Twenty-five percent of the events showed peak discharges over 0.19 m^3/s, and in six events, peaks exceeded 0.5 m^3/s. Runoff coefficients showed a similar trend, with only four events over 5%. The median value of this variable is of special interest, because it is very near from the value that was identified as the minimum RC, 1.65%, during the period May 2012–December 2012, characterized by hydrological and sedimentological connectivity. This is based on an analysis carried out for the events registered during 2012, with rainfalls over the mean. Figure 2 shows the dynamics of RC and of the concentration of suspended solids during that year. The events studied in that case corresponded to those in which both, suspended sediments and runoff, were registered. From the event of 17 May 2012, RC values evidenced an increment and Ares, Varni, and Chagas (2014) identified this event as the first of a series of rill erosion events, corresponding to 23/08; 05/12; 19/12 and 28 December 2012. The period of these events was also associated with groundwater levels

TABLE 1 Minimum, maximum and median values of the variables analysed, corresponding to the 56 rainfall–runoff events studied

Variable	Minimum	Maximum	Median
P[a] (mm)	13.2	136.4	36.6
EI30[b] (MJ mm/[ha hr])	6.9	3,030.3	111.9
R[c] (mm)	0.14	6.65	0.50
Qp[d] (m^3/s)	0.06	0.83	0.12
Qb[e] (m^3/s)	0.022	0.077	0.054
RC[f] (%)	0.4	10.7	1.6
IF[g] (m^3/min)	0.003	0.302	0.007

[a]Rainfall.
[b]Rainfall erosivity index.
[c]Runoff.
[d]Peak flow.
[e]Base flow.
[f]Runoff coefficient.
[g]Flood intensity.

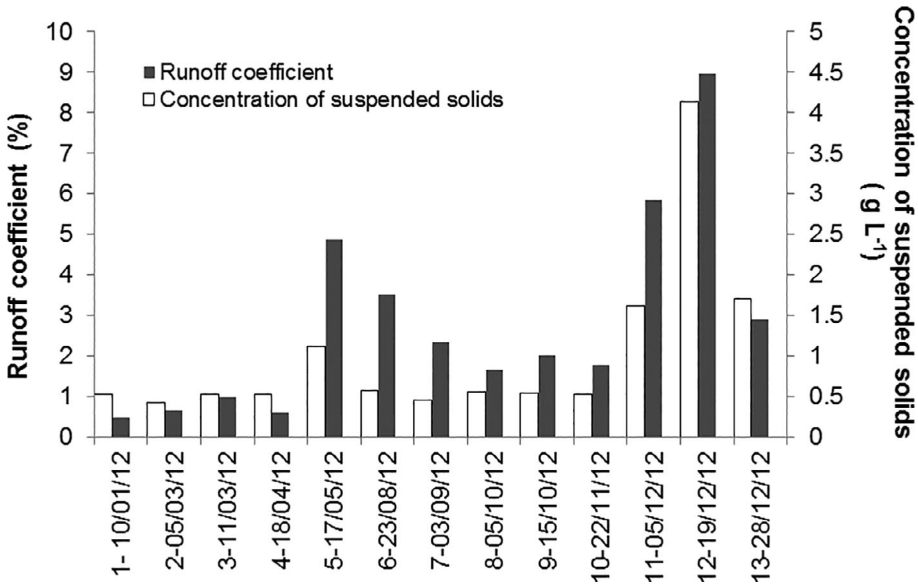

FIGURE 2 Runoff coefficients and concentrations of suspended solids for 13 events registered during the year 2012 in the small basin under study

near the surface, and, in relation with this, the drainage network was expanded. Thus, those results suggested that the rills and the expanded drainage network, together, favoured the hydrological connectivity. The events with RC over the median may be considered as those with hydrological connectivity and the factors associated with the runoff response for these cases, during the period 2011–2015, which have not been studied yet, will be analysed.

3.2 | Relationships between variables. Groups of data description

Runoff and P, EI30, Qp, Qb, RC and IF showed positive and significant correlations ($p < .05$), and only the correlations between RC and Qp, Qb and IF were significant and positive ($p < .05$). These results show that surface runoff is related to rainfall, and the antecedent wetness conditions. The erosive power of rains suggests that the erosion process may be another factor involved in the catchment runoff response.

The relationship between R and P (Figure 3) evidences the nonlinearity associated with the hydrological response mentioned by several authors (Bronstert & Bárdossy, 2003; Palleiro, Rodríguez-Blanco, Taboada-Castro, & Taboada-Castro, 2014; Zabaleta & Antigüedad, 2013), and the scattering of data may be related to different aspects which will be discussed in the next section. Rainfalls between 13 and 65 mm may generate, mostly, runoff values between 0.14 and 1.1 mm, while extreme runoff responses are very variable, associated with rainfalls between 39 and 136 mm and runoff between 2.5 and 6.7 mm. Figure 4 shows that in most of the events the RC were between 0.4 and 3.5%, related to a wide range of Qb values, between 0.022 and 0.077 m^3/s. Besides, the set of data corresponding to Events 1 (15 January 2011), 6 (5 March 2012), 9 (17 May 2012), 19 (19 December 2012), 30 (22 January 2014), 34 (11 June 2014) and 40 (5 September 2014) share the same positive trend that the remaining data, but clearly separated forming, in addition, an enveloping line. This line suggests a limit in the hydrological response in terms of RC and antecedent conditions. The same points were identified in the scatterplot R versus P, and they, except for Event 6, appear as the distant points which indicate maximum hydrological responses (Figure 3).

Analyses considering separately the sets of data with RC over the median (RC > 1.6%) and RC below the median (RC < 1.6%) were carried out, to study further the diversity of hydrological responses and to understand the possible hydrological (dis)connections in the basin. The group of data with RC over the median contains most of the cases identified in the envelope line previously mentioned. These cases were considered as a subgroup, named RC > 1.6%-envelope (G1), to analyse separately which factors control their maximum responses. The rest of the data formed the group RC > 1.6%, and all the events with RC below the median were included in the group RC < 1.6%. In addition, to study the effect of antecedent conditions in groups RC > 1.6% and RC < 1.6%, data were separated into two subgroups according to the median value of Qb, 0.064 m^3/s and 0.045 m^3/s, respectively. Four groups were formed by events corresponding to Qb values over the median and below the median. Each group was named as: RC > 1.6% – Qb > 0.064 (G2); RC > 1.6% – Qb < 0.064 (G3); RC < 1.6% – Qb > 0.045 (G4) and RC < 1.6% – Qb < 0.045 (G5). Median, maximum and minimum values of the variables, in each of the five groups are shown in Table 2.

The analysis of the medians shows that G1 and G5 had the highest rainfall medians, and G4, G3 and G2 had the lowest median rainfalls, in descendent order. The events in the envelope line were the most erosive, followed by the events in G5, G4, G2 and G3. The highest median runoff values corresponded to G1, G2 and G3, and the median runoff of G5 was 13% higher than that of G4, but with lower minimum and maximum values. Peak flow, RC and IF median values showed the same trend, and, in descendent order, G1 showed the highest median values followed by G2, G3, G4 and G5. According

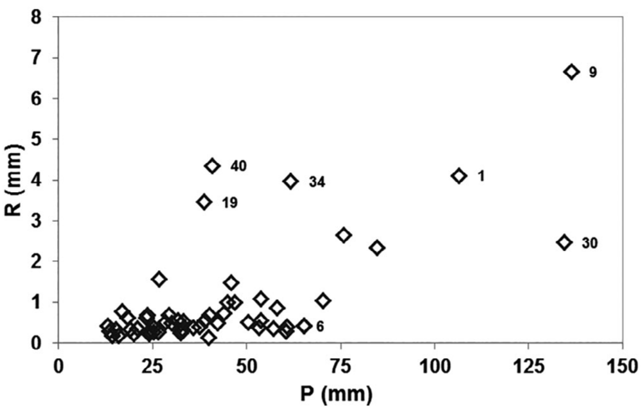

FIGURE 3 Relationship between runoff (R, mm) and rainfall (P, mm) for the 56 events studied in the small basin. The numbers identify the events which suggest a limit in the hydrological response in the basin

to the data grouping, the highest median Qb corresponded to events in G2 and G3, and the medium to low medians to G4 and G5, the same as G1.

All the variables in G1 had the highest interquartile range values, which suggest the wide range of conditions under which the events occurred, and, as a consequence the differences in the responses associated. The highest inputs of rainfall and EI30 were necessary to generate the maximum median RC of G1, and at the same time, the minimum median RC of G5. The differences in catchment conditions, such as antecedent wetness conditions, or vegetation cover may be interacting in each case to generate the contrasting runoff responses. Regarding G5, 11 of its 14 cases corresponded to the medium to high ground cover period; in contrast, half of the events in G1 were associated with the same ground cover period. Groups 2 and 3 had the minimum median rainfall and EI30 values, and medium to high runoff, which indicates the high susceptibility of the system to rainfall under these cases. According to Qb values registered in these groups, not only high antecedent conditions may have been associated with this susceptibility, as they ranged between the value of the first quartile (0.043 m^3/s) and the maximum Qb (0.077 m^3/s). Most of the events in these groups occurred during the low ground cover period (nine of the 11 events of them). The cases in G4 generated medium to low runoff, in relation to rainfalls of medium erosivities, under conditions of low and medium to high ground cover, because eight events were associated with the first period mentioned, and six with the second. The descriptions in the last paragraphs show the wide range of conditions or factors that may interact in each group to generate the runoff response.

3.3 | Regression analyses

Figure 5a,b show the relationships between runoff and rainfall for the groups G2, G3, G4 and G5, and, in general, the comparison between groups suggests that initial base flow modifies the rainfall–runoff response. Linear models were adjusted for the groups (Table 3). The comparison between the models adjusted for G2 and G3 shows that their slopes are the same, but the value of the intercept is different,

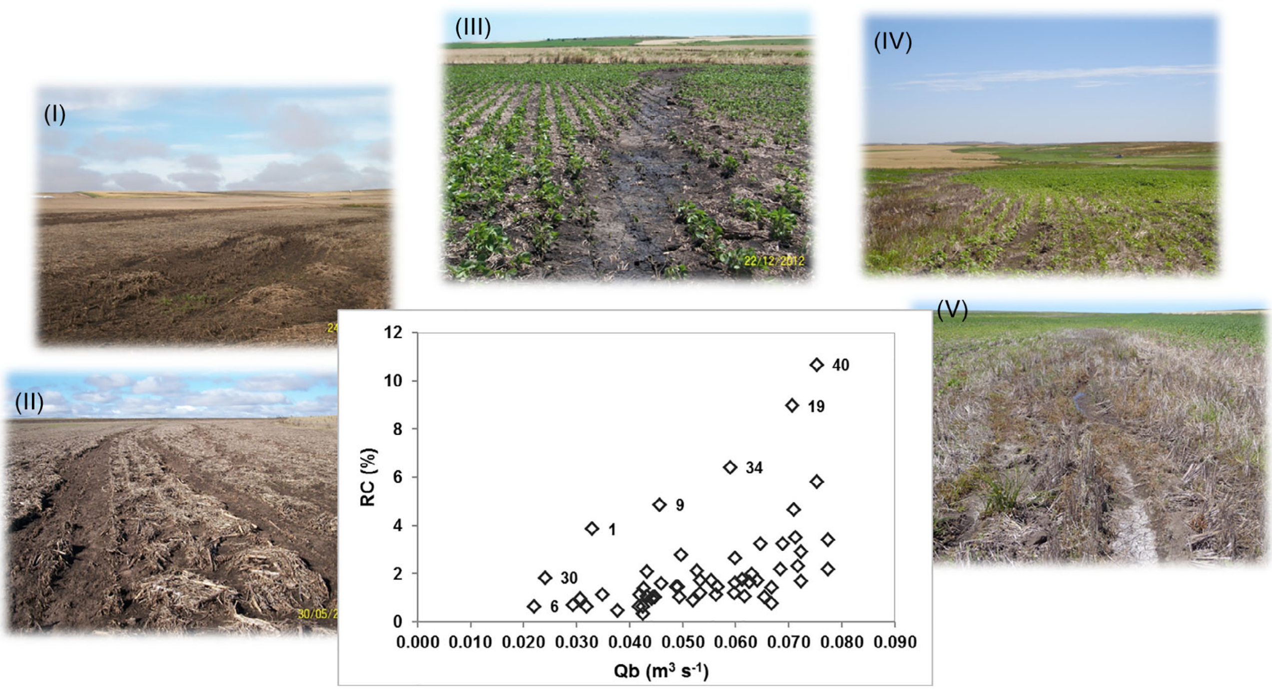

FIGURE 4 Relationship between runoff coefficient (RC, %) and base flow (Qb, m^3/s) for the 56 events studied in the small basin. The numbers identify the events which suggest a limit in the hydrological response in the basin. (I, II) Photographs of the rills formed after Event 1; (III) photograph of one of the rills formed after Event 19; (IV, V) photographs of the expanded saturated area after Event 40

TABLE 2 Minimum, maximum and median values the variables analysed corresponding to the five groups of events defined (G1–G5), according to the values of runoff coefficient and base flow

Group	n	P[a] (mm)			EI30[b] (MJ mm/[ha hr])			R[c] (mm)			Qp[d] (m^3/s)			Qb[e] (m^3/s)			RC[f] (%)			IF[g] (m^3/min)		
		Min[h]	Max[i]	Med[j]	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med
RC > 1.6% – envelope (G1)	6	38.6	136	84.2	305.0	3,030.0	793.5	2.47	6.65	4.04	0.52	0.83	0.70	0.024	0.075	0.052	1.8	10.7	5.7	0.042	0.302	0.074
RC > 1.6% – Qb > 0.064 (G2)	11	13.2	75.8	26.8	6.9	400.6	99.0	0.33	2.66	0.69	0.11	0.45	0.19	0.065	0.077	0.072	1.7	5.8	3.2	0.004	0.062	0.015
RC > 1.6% – Qb < 0.064 (G3)	11	13.6	84.8	30.0	21.0	294.0	55.0	0.29	2.35	0.55	0.10	0.49	0.14	0.043	0.064	0.060	1.6	2.8	1.8	0.004	0.024	0.008
RC < 1.6% – Qb > 0.045 (G4)	14	14.4	70.4	32.5	34.4	1,030.0	111.5	0.17	1.03	0.34	0.09	0.22	0.11	0.045	0.067	0.055	0.8	1.6	1.2	0.003	0.03	0.006
RC < 1.6% – Qb < 0.045 (G5)	14	20	65.4	46.3	28.0	537.1	184.5	0.14	0.55	0.39	0.06	0.14	0.08	0.022	0.044	0.042	0.4	1.4	0.9	0.003	0.01	0.004

[a]Rainfall.
[b]Rainfall erosivity index.
[c]Runoff.
[d]Peak flow.
[e]Base flow.
[f]Runoff coefficient.
[g]Flood intensity.
[h]Minimum.
[i]Maximum.
[j]Median.

which indicates, again, that the cases in G2 generated higher runoff than the cases in G3. In contrast, the model corresponding to G4 had a lower slope than those previously mentioned, which denotes different rainfall–runoff relationship between these groups. The cases in G5 did not evidence a significant linear relationship, but the scatterplot suggests that higher base flows in G4 induced higher runoff responses than the cases in G5. The linear regression model between RC and Qb for the data in G1 was also performed to describe the envelope line. The results show a linear significant relationship between the variables (Table 3).

The analysis of the Qb values corresponding to the groups may highlight the complexity in the runoff response that the rainfall–runoff relationships show. By those Qb values, we may propose that humid antecedent conditions were dominant during the events in G2, medium antecedent conditions prevailed in the groups G3 and G4, and dry antecedent conditions in G5. In this sense, the Kruskal–Wallis test was performed to compare the medians of the Qb, and the Qb values of G2 and G5 were significantly different (p > .05), while the values of G3 and G4 did not differ significantly (p < .05). These results support our classification of the antecedent conditions. In addition, the cases in G1 were associated with a wide range of Qb values, as they indicate the maximum possible hydrological responses within the range of antecedent conditions registered during the studied period. According to Alencoão and Pacheco (2006) and La Torre Torres, Amatya, Sun, and Callahan (2011), who studied the rainfall–runoff relationships of humid catchments considering wet and dry periods, the slope of the regression lines is higher for wet conditions than under dry antecedent conditions. In our case this is evident in the comparison of the models adjusted for G2 and G5. Besides, our results also show that under medium antecedent conditions runoff responses may be similar to wet conditions, as the case of G3, or completely different, showing medium runoff responses, as the case of G4. So, our question is: which combinations of factors operate under these situations to generate the differences in surface runoff, which changes the capacity of the system to respond to rainfall, or generate the limit runoff responses, as the observed in G1? The results suggest that antecedent wetness conditions, ground cover by crops, rainfall and its erosivity are different for the groups of events. Thus, runoff may emerge from complex interactions among several factors. We discuss these aspects in the next section, by the (dis)connectivity approach.

4 | DISCUSSION

4.1 | Characterization of the studied years. Seasonal variations of rains, erosivity and ground cover

The total rainfall of the studied years showed variability. The mean annual rainfall, for the period 1985–2015, at Monasterio Trapense pluviometer is 930 mm/year. This station is located at approximately 20 km from the Cerro del Águila station (Figure 1a),

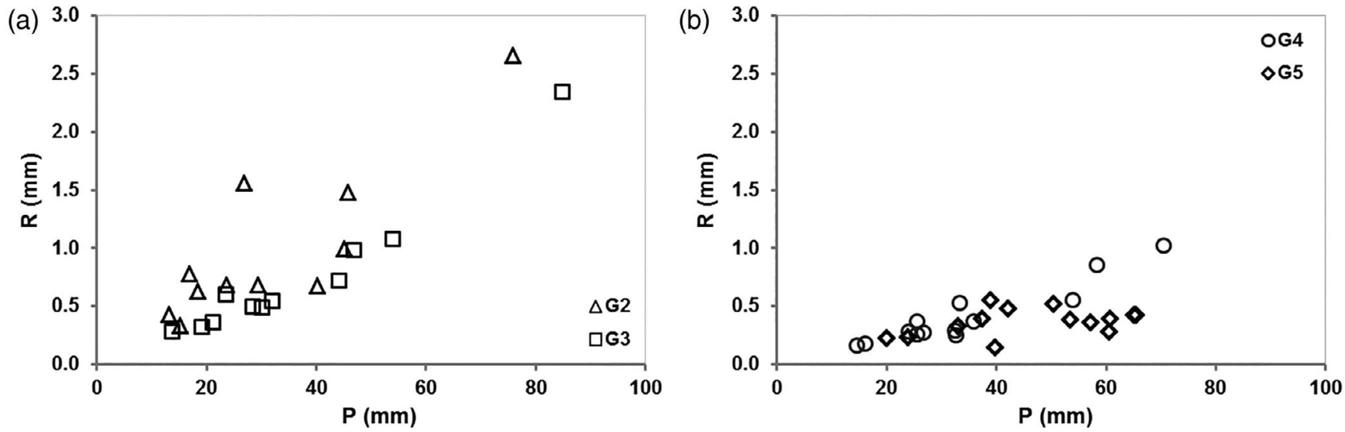

FIGURE 5 Relationship between runoff (R, mm) and rainfall (P, mm) for the events studied in the small basin. (a) Events corresponding to the defined groups with runoff coefficients (RC) over the median, excluding Cases 1, 9, 19, 30, 34 and 40 – envelope line – (RC > 1.6%, *n* = 22): Group 2 (G2, *n* = 11) with base flow over the median (0.064 m^3/s) and Group 3 (G3, *n* = 11) with base flow below the median. (b) Events corresponding to the defined groups with RC below the median (RC < 1.6%, *n* = 28): Group 4 (G2, *n* = 14) with base flow over the median (0.045 m^3/s) and Group 5 (G5, *n* = 14) with base flow below the median

TABLE 3 Linear regression models adjusted for the five groups of data defined (G1–G5), variables included in the models, models coefficients, performance and assumptions including the adjusted regression coefficients

Linear regression models							Model's assumptions	
Group	Variable		Regression coefficients		Linear regression significance	R^2	Residuals' normality	Independence and variance homogeneity of residuals
	Dependent	Independent	Slope of regression line	Intercept	*p*-value		*p*-value	
RC > 1.6% – envelope (G1)	RC[a]	Qb[b]	157.37	−1.94	<.05	0.95	>.05	Satisfied
RC > 1.6% – Qb > 0.064 (G2)	R[c]	P[d]	0.03	0.02	<.05	0.69	>.05	Satisfied
RC > 1.6% – Qb < 0.064 (G3)	R	P	0.03	−0.25	<.05	0.92	>.05	Satisfied
RC < 1.6% – Qb > 0.045 (G4)	R	P	0.01	−0.08	<.05	0.87	>.05	Satisfied
RC < 1.6% – Qb < 0.045 (G5)	R	P	0.003	0.23	>.05	0.07	>.05	Not satisfied

Note: Each linear model was tested for normality, independence and variance homogeneity of residuals.
[a]Runoff coefficient.
[b]Base flow.
[c]Runoff.
[d]Rainfall.

and is the nearest with complete and reliable rainfall records for the area (Varni & Custodio, 2013). During 2012 and 2014 annual rainfall exceeded 45% and 26% the average value, respectively, while during 2011, 2013 and 2015 annual rainfall was 13%, 28% and 20% less than the 30-year mean, respectively. These data show that the analysed period considers the climatic variations of our region.

Figure 6 shows the monthly mean rainfall for the periods 1985–2015 and 2011–2015. The 30-year mean data indicate that rainfall concentrates in spring–summer and in the beginning of autumn. The comparison between the periods evidences increments of precipitation between 2011 and 2015 during April, May, July and August. These months correspond to those of less evapotranspiration (Ares, 2010) and low vegetation cover, because they coincide with the fallow period. These circumstances increase the risk of runoff responses of important magnitude during autumn–winter. Similar conditions were reported by Smith (2008) in a basin of Australia.

Most of the annual erosivity was registered between October and March, with a remarkable importance of the rainfall erosivity in December and January (Figure 6). During these 2 months of high EI30 the basin is covered by winter crops residues (barley or wheat) or by summer crops in different growth stages (soybeans, corn or sunflower), which may be associated with variable ground cover percentage (Ares, 2010), depending on the area occupied by winter and summer crops, and on the sowing date of these crops. The variability in ground cover and its spatial patterns contribute to the differences in rainfall–runoff responses (Durán Zuazo & Rodríguez Pleguezuelo, 2008; Liu et al., 2018), as it will be discussed in this section.

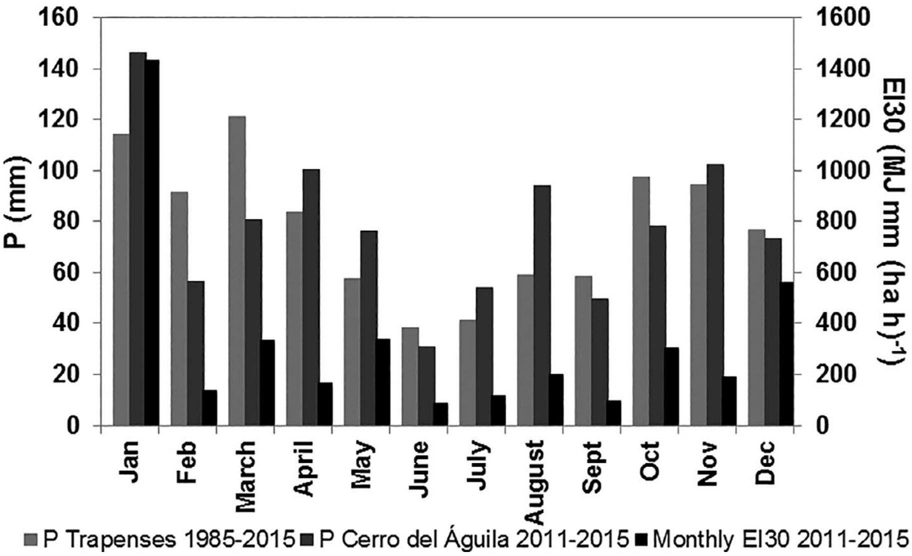

FIGURE 6 Mean monthly rainfall data (P, mm) corresponding to Monasterio Trapense station (period 1985–2015) and to Cerro del Águila station (period 2011–2015). Mean monthly erosivity data (EI30, MJ mm/[ha hr]) corresponding to Cerro del Águila station (period 2011–2015)

4.2 | Analysis of the events, the groups of data and the regression models adjusted

Few events showed the highest values of rainfall, erosivity, runoff and related variables. These results coincide with those of Ares (2010) who studied rainfall and runoff at the outlet of the Videla stream basin between 2001 and 2007. The author reported that the most frequent events corresponded to rainfalls and runoff lower than 50 mm and 2.5 mm, respectively. Also, Gómez, Vanwalleghem, De Hoces, and Taguas (2014) found a skewed frequency distribution of rainfall, erosivity, runoff depth and sediment yield in a Mediterranean catchment, in relation to the low magnitude of most of the events.

Most of the events were coincident with medium to humid conditions, which suggests the relevance of wetness conditions in the hydrological response of this basin. The correlations performed including all the cases together indicate this aspect and the importance of precipitation in runoff, in general. Other authors reported significant correlations between RC and Qb (Nadal-Romero et al., 2018; Tarasova, Basso, Zink, & Merz, 2018; Tuset, Vericat, & Batalla, 2016; Zabaleta & Antigüedad, 2013) and between R and P (Palleiro et al., 2014; Penna, Tromp-Van Meerveld, Gobbi, Borga, and Dalla Fontana, 2011; Rodríguez-Blanco, Taboada-Castro, & Taboada-Castro, 2010). Rodríguez-Blanco, Taboada-Castro, and Taboada-Castro (2012) also point out the scatter in the relationship RC-Qb in a humid catchment, with similar RCs associated with a wide range of Qb values. Janzen and McDonnell (2015) state that rainfall–runoff data scatter is related to the variations in antecedent moisture and rainfall intensity between events. However, the hydrological response is complex and more than one factor may explain its variability, those factors include the inputs, the processes and the structure of the system, based on field knowledge (Lexartza-Artza & Wainwright, 2009). An integrated analysis including these factors is carried out to understand the variability in the runoff response for the studied cases. The analyses for each of the groups defined help to understand the variability in the runoff response.

Considering G1, the regression model adjusted between RC and Qb describes the linear envelope line. The surface runoff of these events is very variable, and related to a wide range of rainfalls and rainfall erosivities. Figure 7a,b present the scatterplots between RC and Qb associated with the corresponding value of EI30 and IF for each event, to explain further the hydrological functioning of the basin during these upper limit events. All the cases were included in these figures, to show comparatively the values of the variables in G1 in contrast with the rest of the events.

The hydrological response, under the driest condition, was generated by the most erosive rainfall: Event 30. Its EI30 represented 45% of the annual erosivity – the R factor – and this rainfall was registered during January, in summer, under the medium to high ground cover period. Vegetation cover contributes to reduce runoff and its velocity, increases the time to peak flow and dissipates the energy of rainfall, which prevents soil for sealing and crusting (Blanco & Lal, 2008; Mohammad & Adam, 2010; Ramos et al., 2016; Wei et al., 2014). These crusts and seals reduce water infiltration (Bracken & Croke, 2007). An event similar to number 30 was recently registered in the basin. It was characterized by a comparable RC, EI30, Qb and Qp, and these data were included in the scatterplots of Figure 7a,b. In addition, field observations after this event are available and are incorporated to this discussion to illustrate some characteristics of these cases. Although this event corresponded to 10 April 2019, the beginning of autumn, the basin was still covered by soybeans. Figure 7I,II also show the soil surface under areas without cover by crop, with the presence of interrill erosion and shallow and ephemeral rills. Figure 7III,IV evidence the detention of water in small depressions which are part of the surface roughness in the basin. These areas diminish the volume of surface water to runoff.

Rainfall erosivity decreased for the rest of the events in G1, in comparable conditions of vegetation cover of Event 30 (Case 1), or under lower vegetation cover than this event: Cases 9, 34 and 40 corresponded to the low ground cover period, with plots mainly under fallow; Case 19 coincided with the beginning of summer crops' active

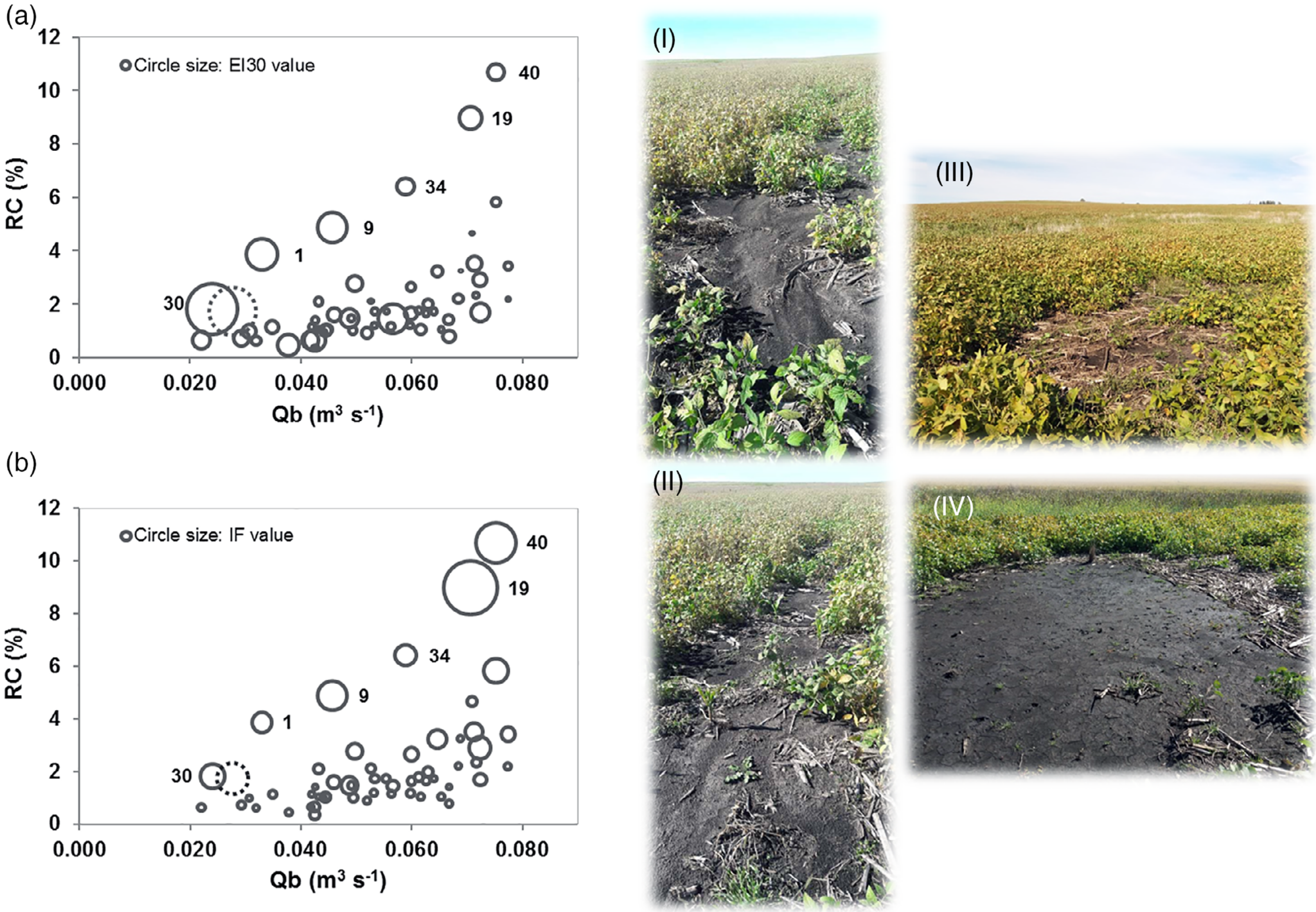

FIGURE 7 Relationship between runoff coefficient (RC, %), the associated base flow (Qb, m^3/s) and (indicated by circle size): (a) rainfall erosivity values (EI30, MJ mm/[ha hr]), (b) flood intensity values (IF, m^3/min), for the 56 events registered in the small basin. The dotted circle corresponds to the event registered on 10 April 2019. (I–IV) Photographs of the soil surface under areas with no cover by soybeans, after the event registered on 10 April 2019: sheet erosion and rill erosion signs (I and II); signs of water detention in small depressions (III and IV)

growth. The correlation performed between RC and EI30 for G1 was significant (p < .05) but with a negative sign. This suggests that very high EI30 is necessary to induce the hydrological response under combinations of dry antecedent conditions and high ground cover by vegetation.

Antecedent conditions were variable: dry, and medium to wet. Rills of important magnitude were observed in the field after Events 9 and 19 (Figure 4I–III), during the period of hydrological connectivity previously mentioned. The vegetation cover combined with the characteristics of these cases, and the antecedent conditions may have been associated with the expansion of saturated areas (Figure 4IV,V) and with the formation of rills (Ares et al., 2014), which act as preferential flow paths. Similar combinations of conditions may have determined the hydrological response of Events 34 and 40: observations in the field showed the signs of wet area expansion. The IF values suggest the rapid hydrological response in our cases, which may be also associated with the increment in wetness conditions along the envelope line (Figure 7b).

No clear upper limit events such as the ones found in our case have been reported in other agricultural basins. Rodríguez-Blanco et al. (2012) and Penna et al. (2011) show the relationships RC-Qb, for humid forested catchments, but they do not discuss the presence of a clear envelope line. It is interesting to note the combinations of conditions which may generate these particular hydrological responses in our case, which evidence their complexity.

Groups 2 and 3 showed linear relationships between R and P, the distinction between Qb values in the rainfall–runoff relationships helped to understand the scatter in data. Just like events in G1, the cases within these groups mainly corresponded to the wet periods of 2012 and 2014, the years with high annual rainfalls. Authors like Lehmann et al. (2007), Penna et al. (2011) and von Freyberg, Radny, Gall, and Schirmer (2014) made an equivalent separation of data and found comparable results in other catchments: rainfalls of equal magnitude generate higher runoff under wet conditions than under dry antecedent conditions. In our case this is evidenced by the intercept of the regression lines. Rodríguez-Blanco et al. (2012) state that only baseflow cannot explain rainfall–runoff response, and that rainfall and antecedent wetness together may be associated with RCs. In an agricultural catchment, Estrany, Garcia, and Batalla (2010) found that quickflow runoff was related to antecedent conditions and rainfall.

Medium antecedent conditions of G3 and G4 showed contrasting runoff responses. On the contrary to G3, most of the cases in G4 were registered during 2013 and 2015. The events in G5 corresponded to these years too, and also included cases of 2011 and the first months of 2012 and 2014. According to our previous analyses, the cases in G3 and G4 denote the limit between (dis)connectivities within the system. The results of this work indicate that not only rainfall and previous wetness may be involved in the generation of these responses. The identification of factors combinations and their feedbacks by the connectivity framework may help in the interpretation of these responses.

4.3 | The (dis)connectivity approach to understand the complexity of the runoff response

The previous analyses show how antecedent wetness conditions, vegetation cover, preferential drainage pathways, formed by rills and interril erosion areas and/or humid (talwegs) areas, and rainfall erosivity may interact and determine the hydrological response in the groups defined. These cases may be analysed considering the hydrological (dis)connectivity approach. In this sense, those interacting factors may be identified as the elements of structural and functional connectivity, or as the external forces which contribute to connectivity, such as rainfall and its erosivity (Heckmann et al., 2018). Vegetation cover is part of the structural elements of connectivity (Bracken et al., 2013). Antecedent wetness, in our case, is an emergent condition from the rainfall–runoff process, and it may be associated with the functional connectivity. The drainage network is part of the structure of the catchment, but it undergoes changes related to humid periods or rills or ephemeral gullies generated by water erosion, which expand it. According to Khosh Bin Ghomash, Caviedes-Voullieme, and Hinz (2019), the hydrological dynamics drives erosion (i.e., rill formation) and erosion signs constitute changes in topography, which increase the drainage area in the basin. Thus, feedbacks between processes and structure are established: the drainage network develops over time, it turns dynamic, and, therefore, functional (Turnbull et al., 2018). The series of extreme and episodic events during 2012 introduced long-lasting changes in the drainage network. Figure 8I–V show these changes, associated with the expansion–contraction of the network. This expansion was maximum during December 2012; however, it remained in the main watercourse during the studied period. So, according to Turnbull et al. (2018), the events, related to processes, left their imprint or memory, on the structure of the basin.

Connectivity changes over time, as a result of the interactions between inputs, structural and functional elements (Lexartza-Artza & Wainwright, 2009), and, as a result, has a temporal dynamics (Wainwright et al., 2011). Figure 8a,b show the temporal distribution of the RC of the events, associated with groundwater depth, base flow, surface flow, monthly rainfall, vegetation cover conditions – synthesized as medium to high and low ground cover periods – and the drainage network identification. Low ground cover periods coincided with part of the autumn and the winter under moderate precipitation amount conditions, which make possible small grains sowings. This was the case of the years 2011, 2013 and 2015. However, this period extended to spring when autumns and winters were humid (over 500 mm, Figure 8a), during 2012 and 2014, because high precipitations combined with low evapotranspiration induced soil water excesses which prevented winter crops sowings. As a consequence, farmers change their land use decisions and sow summer crops waiting for soil wetness reduction. Ground cover protection by crops remained scarce over a long period, which coincides with high precipitations and high antecedent wetness conditions that induce drainage network modifications with occasional rill formation by water erosion. The interactions between land use and drainage network on connectivity may be exemplified by an analysis of the potential flow and sediment connectivity that is being carried out, by the calculation of an updated version of the index of connectivity, IC, proposed by Borselli, Cassi, and Torri (2008). This index is based on two components of the hydrological connectivity: the land use and the topography of a basin. Other structural elements included in its calculation are the roads and trails, and the drainage network. In this case, we discuss preliminary results obtained for two of the dates reported in the previous analysis of the drainage network, corresponding to February 2012 and December 2012. These results suggest a higher connectivity potential for December 2012 in comparison with that obtained in February. This may be in association with differences in land cover and the area of the drainage network. In the case of February, the basin was occupied by soybeans and corn completely developed and by wheat and barley residues, with a drainage network weakly developed. In contrast, in December, the increment of the drainage network area, and also the presence of soybeans and corn, but in their initial growth stages induced the higher connectivity potential.

Thus, complex feedbacks between inputs, structure and functions of the system occur in the catchment (Wainwright et al., 2011), which generate hydrological (dis)connectivity with differences in RC, Qp and IF, evidenced in the medians of these variables for the groups. Figure 8a,b show, in general, the coincidence between shallow groundwater levels and high surface flow, base flow, RCs, induced by important rainfall amounts and low ground cover by crops. These conditions changed during dry periods, with deep groundwater levels, and low runoff values. Therefore, low levels of connectivity prevailed during 2011, 2013 and 2015 and the first months of 2012 and 2014 (associated with events in Groups 4 and 5). Considering 2013 and 2015, the memory of the system kept the changes, and landscape units remained connected by the drainage network. However, the inputs (rainfalls and their erosivities) were not enough to satisfy the storages and to activate the whole basin and waterways an in a connected manner, to generate RCs over the median. According to Spence (2010) "continual storage satisfaction" is not a permanent

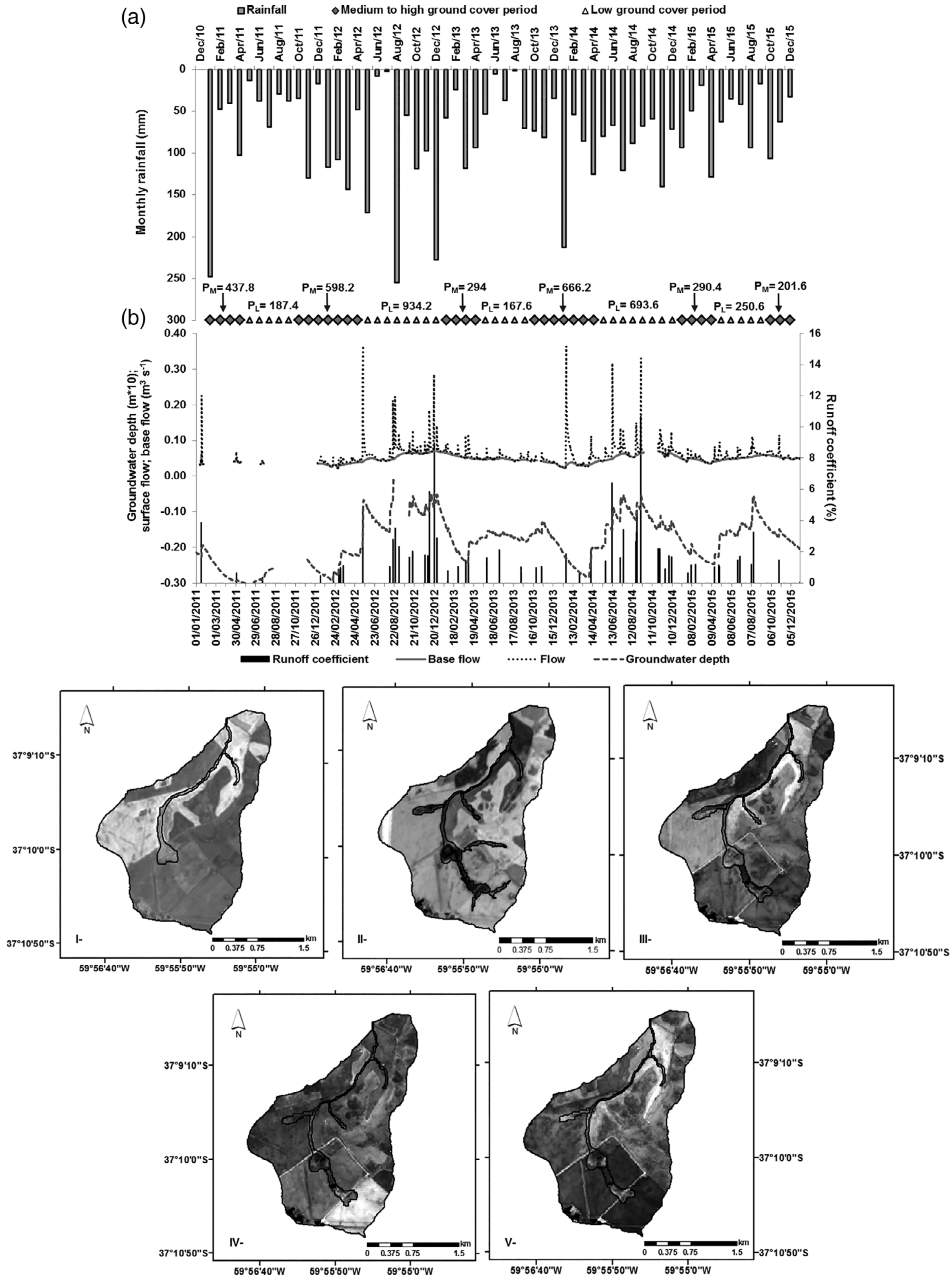

FIGURE 8 Temporal distribution of rainfall, ground cover by crops, runoff variables, groundwater depth and the drainage network state during the period 2011–2015 in the small basin under study. (a) Monthly rainfall, periods of ground cover by crops and the corresponding rainfall during these periods (PM and PL: rainfall during the medium to high ground cover period, and during the low ground cover period, respectively, in mm). (b) Daily groundwater depth (expressed in m * 10 units to fit to the values of flow data shown in the same plot), daily base flow and flow (m^3/s) and runoff coefficients (%) of the events studied. (I–V) Drainage network identified in the basin, outlined in black. Network identified from near infrared and shortwave infrared bands of Spots 4 and 5 satellite images for (I) February 2012 (01 February 2012), (II) December 2012 (21 December 2012) (adapted from Ares et al., 2016). Drainage network identified from panchromatic band of Landsat 8 OLI scenes, for (III) July 2013 (25 July 2013), (IV) August 2014 (13 August 2014) and (V) August 2015 (16 August 2015)

condition within catchments. The analysis of the groundwater levels in Figure 8b suggest the differences in water storage between the years analysed, with continuity between May 2012–January 2013 and June 2014–December 2014, with groundwater levels less than 1.5 m depth. In contrast, these levels remained deeper during the rest of the period. Temporal continuity in storage by groundwater levels near the surface in G2–G3 and some cases of G1, may have favoured the hydrological connections, in contrast with cases in G4–G5. These relations between groundwater depth and connectivity have been also noted by Saffarpour, Western, Adams, and McDonnell (2016), who studied an agricultural catchment in Australia. So, total or partial temporal coincidences in the connectivity components may explain the (dis)connectivity that operates under the cases in G3–G4. In addition, by this analysis we interpret that the response in G2 is also associated with complex interactions among connectivity components.

Considering events in G5, high and erosive rainfalls were necessary to generate the runoff response under the driest antecedent conditions. However, the relationship R versus P was not significant in this case, and evidenced variability. Infiltration and vertical water movements may have prevailed under these cases, with low lateral connectivity (James & Roulet, 2007), favoured by soil cover by crops in most of these events in this group, as they coincided with the medium to high ground cover period.

Local runoff signs within the hillslopes with weak connections to the channel are frequently observed in this study area during dry antecedent conditions, associated with patchiness in vegetation cover, the presence of surface seals, soil depth, which induce variability in infiltration capacity. In addition, the effect of surface roughness and small depressions within slopes is also visible after these events, which favours the expression of retention and detention. This delays the initiation of runoff and increases infiltration. In this sense, Penna et al. (2011) studied an alpine catchment and reported heterogeneity in runoff contributing areas under low antecedent rainfall conditions, while the entire catchment generated runoff under high antecedent rainfall conditions. In addition, Latron and Gallart (2008) observed local runoff contributing areas during dry antecedent conditions in a Mediterranean catchment. Therefore, spatially heterogeneous rainfall–runoff responses within the hillslopes may dominate in these cases, under disconnectivity. In contrast, this spatial variability in runoff contributing areas may be reduced under high lateral connectivity, inducing high RC, Qp and IF as in G1, G2 and G3.

Thus, our analyses suggest that runoff is controlled by (dis)connectivity in this basin with gentle slopes. Inputs, structural and functional components of the connectivity are differently combined over time, and, as a result, runoff response turns dynamic and evidences variability, according to the temporal coincidence of connectivity components. According to Keesstra et al. (2018), it is important to analyse the temporal changes the system experiments, in relation with the inputs, the structure, and the emergent processes, and their feedbacks. This helps to identify differences in the state of the system during the rainfall–runoff events, that is, connected or disconnected, and improve the understanding of the complexity of the runoff response.

5 | CONCLUSIONS

Our manuscript analyses the runoff response of a small basin at the headwaters of a plain catchment, by a study at event scale.

In contrast with other studies, we characterized clear upper limit events, under which hydrological responses emerge, as a result of combinations of antecedent wetness, rainfall erosivity, ground cover and preferential drainage paths. We separated the nonlinear rainfall–runoff response in three linear relationships, according to differences in antecedent wetness conditions, to characterize the variability of runoff. In this sense, we found differences in runoff responses under wet and dry antecedent conditions, but complex responses under medium antecedent conditions. We introduced elements of the (dis) connectivity frameworks to discuss and understand the relationships found and the variability in runoff by the conceptual approach of (dis) connectivity.

The analyses of the relationships between inputs, structural and functional elements of these frameworks, and their feedbacks, were useful to interpret the temporal changes in runoff, and to understand the complex responses identified. Those changes appear to be strongly related to the temporal coincidence of connectivity components, and their feedbacks. High and erosive rainfalls contribute to rill formation; humid periods induce drainage network expansion and groundwater recharge that, in coincidence with low ground cover by vegetation, activate hydrological connectivity. In contrast, partial coincidences between connectivity components reduce connectivity and low magnitude and/or heterogeneous runoff responses prevail.

Our work contributes to the understanding of the process of surface runoff in basins of gentle slopes under agriculture: we interpret the variability in runoff response by the identification of the complex combinations of factors which regulate/control the (dis)connectivity that helps to interpret the nonlinearities of runoff. We improve the knowledge of the hydrology of plains, and how, in these productive areas the seasonality of agricultural land use interacts with the natural process of rainfall, and the antecedent conditions, and contributes to the occurrence of processes that accelerate or reduce runoff. In this sense, our results are relevant from the land management point of view, to highlight the importance of the protective effect that living ground cover may have to reduce surface runoff losses from agricultural systems.

This is the first work to study surface runoff variability in our region, considering the (dis)connectivity approach by the analysis of the joint effects of rainfall, antecedent wetness conditions, water erosion signs, drainage network temporal changes, vegetation and groundwater depths on runoff. We underline the relevance of continuous monitoring programmes to get data to understand the hydrology of these areas, which are still not generalized in our region and its implementation is a challenge in developing countries (Montanari et al., 2013; Riveros-Iregui, Covino, & González-Pinzón, 2018). These data are essential for the application of models, which provide information for the design of integrated land management strategies, to preserve the productive capacity of the lands of plain regions.

ACKNOWLEDGEMENTS

This work was partially supported by the Agencia Nacional de Promoción Científica y Técnica under grant PICT 2015 N°2012, the Universidad de Buenos Aires under Grant UBACYT 20020170100533BA, and by the Consejo Nacional de Investigaciones Científicas y Técnicas. We thank Georgina Cazenave, Enrique Queupán and Joaquín Rodríguez Silveira for collaborating with data processing and field tasks.

DATA AVAILABILITY STATEMENT

Data available on request from the authors

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How to cite this article: Ares MG, Varni M, Chagas C. Runoff response of a small agricultural basin in the argentine Pampas considering connectivity aspects. *Hydrological Processes*. 2020; 34:3102–3119. https://doi.org/10.1002/hyp.13782