Article

Multiple temporal scales assessment in the hydrological response of small Mediterranean catchments

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Abstract: Mediterranean catchments are characterized by significant spatial and temporal hydrological variability caused by the interaction of natural as well human-induced abiotic and biotic factors. This study investigates the (non-)linearity rainfall-runoff relationship at multiple temporal scales in representative small Mediterranean catchments (i.e., < 10 km^2) to achieve a better understanding of the hydrological response. Rainfall-runoff relationship was evaluated in 44 catchments at annual and event –203 events in 12 of these 44 catchments– scales. A linear rainfall-runoff relation was observed at annual scale with higher scatter in pervious than impervious catchments. Larger scattering was observed at event scale, although pervious lithology and agricultural land use promoted significant rainfall-runoff linear relations in winter and spring. These relationships were particularly analysed during five hydrological years in Es Fangar catchment (3.35 km^2; Mallorca, Spain) as a temporal downscaling to assess intra-annual variability in which antecedent wetness conditions played a significant role in runoff generation.

Keywords: rainall-runoff; multiple temporal scales; non-linearity; small catchments, Mediterranean.

1. Introduction

The complexity of Mediterranean fluvial systems is caused by the multiple temporal and spatial heterogeneity in the relationships between the natural and human-induced abiotic and biotic variables [1,2]. Accordingly, Mediterranean rivers are characterized by a high diversity in hydrological regimes [3,4] promoting significant temporal and spatial differences in the hydrological response [5–7]. Seasonality of Mediterranean climate plays a key role in the runoff generation processes, increasing the non-linearity of the rainfall-runoff relationship at event scale [7–10]. In winter and early spring, saturation processes are dominant due to water reserves trigger the runoff generation [7,11]. During late spring, summer and early autumn, those same authors observed how runoff was generated under Hortonian conditions due to high rainfall intensities. Different runoff mechanisms can co-exist within a catchment [12], although flood events under antecedent saturation wetness conditions enable larger hydrological response [11,13–15].

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Spatial variability of runoff generation is also elucidated in the catchment hydrological response as a combination of rainfall distribution [16] and runoff-contribution areas [17]. Under this context, river connectivity is conceptualized as a continuum from fully connected to disconnected over diverse temporal and spatial scales in the different compartments of a catchment [18]. Main factors governing connectivity are associated to changes in topography [19], soil properties [20], soil type [21] and in vegetation cover [22]. In addition, river connectivity occurs along a three spatial dimension (i.e., longitudinal, lateral and vertical) which can change markedly over time, especially in ephemeral rivers [23]. Consequently, flow pathways activation depends on rainfall amount and intensity as well as soil moisture antecedent conditions [24–26]. In terms of catchment structure, topography and topology are key factors to interpret catchment hydrology [27].

Lithology effects on runoff response in Mediterranean fluvial systems are conditioned by the presence of karst features, as the proportion of carbonate rocks is significantly higher than other landscapes [28]. Then, its characteristics related to hydrology as high infiltration rates, deep percolation and spring sources must be taken into account [29–31]. In limestone areas, Hortonian and saturation runoff can both be generated and infiltrated downslope [32,33], whilst in badland areas the runoff generation is characterized by a low soil infiltration capacity [34]. In areas with high clay subsoil content [35] and over granite bedrock [36], runoff is generated as a combination of a lack of deep percolation and the presence of a subsoil layer with low permeability.

Land uses and their changes also alter the hydrological response, depicting a runoff reduction when agriculture uses are changed by forests [37]. Afforestation processes due to land abandonment can promote a 40% of reduction in the annual water yield in Mediterranean river systems [38], whilst forest logging may increase up to 16% the annual runoff coefficient [39]. However, afforested catchments generate largest flows and peak discharges at event scale if compared with forest catchments [40]. Most of these catchments are affected by soil and water conservation structures historically built to reduce overland flow and prevent erosion [41]. The abandonment and degradation of these structures may promote and increase runoff and sediment yield [42], with runoff coefficients between 20% and 40% in abandoned terraces [43].

To reduce the spatio-temporal scale variability, small experimental and representative catchments are useful to observe the hydrological response under different or specific land use, lithology and human effects characteristics [44]. The aim of this paper is to investigate the rainfall-runoff relationship at different temporal scales in representative small Mediterranean catchments (i.e., < 10 km^2), evaluating the role of lithology and land uses. At annual scale, the runoff response was assessed at 44 catchments under pervious or impervious lithology. At event scale, the rainfall-runoff response of 203 events was investigated to examine the effects of seasonality, lithology and land uses. In addition, the inter- and intra-annual variability of the rainfall-runoff and the temporal downscaling (i.e., annual to event scale) was studied in Es Fangar Creek catchment (3.35 km^2; Mallorca, Spain) during five hydrological years.

2. Materials and Methods

2.1. Study areas

2.1.1. Small Mediterranean catchments

A total of 44 small catchments (i.e., < 10 km^2) from 22 published studies on the Mediterranean region (Figure 1a) were selected to analyse the hydrological response of the small Mediterranean catchments. The geographical distribution of the catchments is grouped as: (1) Western coast of USA, (2) Western Mediterranean Region (from Spain to Tunisia) and (3) Eastern Mediterranean Region (Israel). Catchments area ranges from 0.05 to 9.61 km^2, being the median value 1.02 km^2 and the standard deviation 2.6 km^2. The annual rainfall ranges from 367 to 1794 mm y^{-1} with a median value of 866 mm y^{-1} ± 346 mm y^{-1}. The main lithology at 13 and 31 catchments is pervious and impervious, respectively. Within these 44 catchments, 12 of them also include information related to the main land

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use to assess their hydrological response at event scale. The main land uses are agricultural, agroforestry, forestry and shrub. Each land use is composed by 3 catchments.

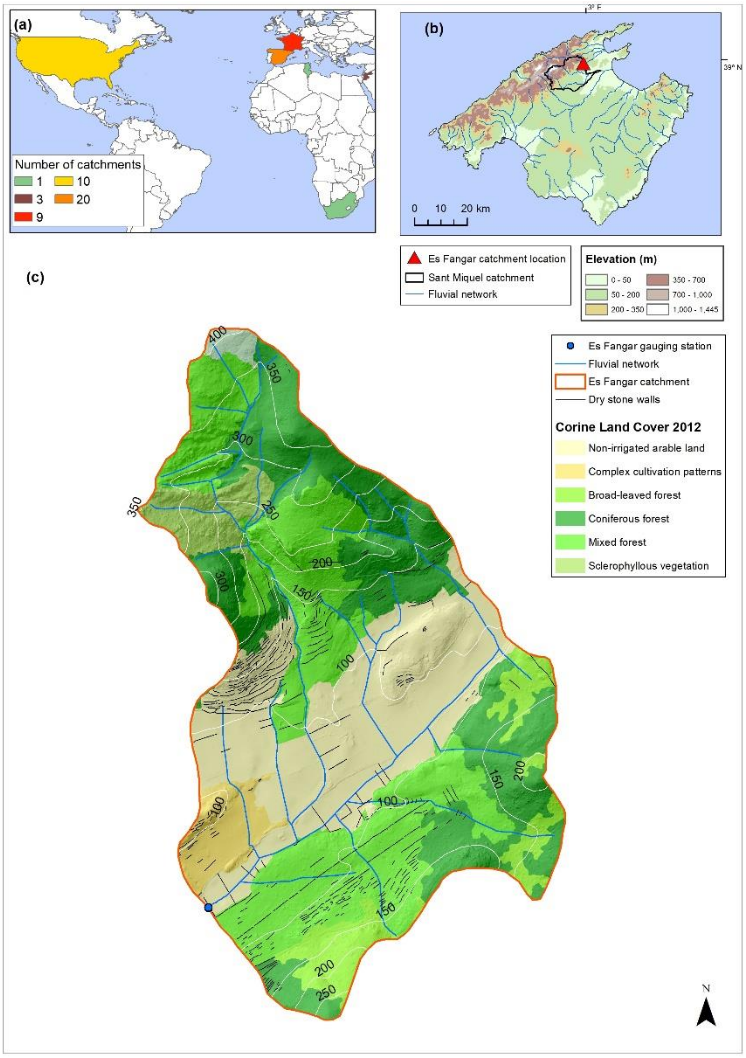

Figure 1. (**a**) Map of the small Mediterranean catchments selected to assess the rainfall-runoff relationship at annual and event scale. (**b**) Map of Mallorca island showing the location of the Sant Miquel catchment and Es Fangar Creek. (**c**) Map of Es Fangar Creek showing the different land-uses and the stream network and gauging station.

2.1.2. Es Fangar Creek

Es Fangar Creek catchment is a headwater tributary of the Sant Miquel River catchment (151 km^2) located in the north-east part of Mallorca Island (Figure 1b). The lithology is mainly composed of marl and marl-limestone formations from medium-upper Jurassic and Cretaceous eras in the valley bottoms. In the upper parts of the catchment, massive calcareous and dolomite materials from lower Jurassic eras and dolomite and marls formations from the Triassic eras (Rhaetian) are dominant. Es Fangar catchment has an area of 3.4 km^2, with altitudes ranging from 72 m.a.s.l. to 404 m.a.s.l. (Figure 1c). The mean slope of the catchment is 26% and the length of the main channel is 3.1 km (average slope of 22%). The drainage network is natural in the headwater parts. In the bottom valley, flow lamination is applied with transverse walls and also straightening and diverting the main stream with the banks fixed with dry-stone walls for flood control and erosion prevention. In addition, subsurface tile drains are also installed to facilitate drainage during wet period due to the agricultural activity. As a result, 16% of the surface catchment is occupied by soil and water conservation structures. Since 1950, important socio-economic changes have caused a gradual

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abandonment of farmland in marginal areas, leading to afforestation. Land uses in 1956 were rainfed herbaceous crops (54%), forest (31%) and scrubland (15%). Nowadays, main land uses (Figure 1c) are forest (63%), rainfed herbaceous crops (32%) and scrubland (5%). In addition, the 54% of terraced lands are currently covered by forests (Figure 1c). The climate of the area is classified on the Emberger scale [45] as Mediterranean temperate sub-humid. The mean annual rainfall (1965-2016, Biniatró AEMET station) is 927 mm y^{-1} with a variation coefficient of 23% and the mean annual temperature is 15.7ºC. Rainfall amount of 180 mm in 24 hours is estimated to have a recurrence period of 25 years.

2.2. Hydrological response of small Mediterranean catchments

Bivariate statistical regressions were used to establish correlations at annual and event scale between rainfall and runoff in order to assess the hydrological response of small Mediterranean catchments (i.e., < 10 km^2; Figure 1c). At the annual scale, data from the 44 representative catchments (Table Appendix A 1a; hereinafter A1a) were collected to observe the influence of lithology on this response; i.e., catchments were classified by pervious or impervious. At the event scale, 203 events from 12 representative catchments were classified according to (a) seasonal occurrence (autumn, winter, spring or summer), (b) pervious or impervious lithology and (c) main land use (agricultural, agroforestry, forest or shrub) (Table A1b). Most of these studies (77%) are located in the Mediterranean Sea basin and half are catchments < 1 km^2.

2.3. Monitoring and data acquisition in Es Fangar

Rainfall data since 2012 was obtained from B696 Biniatró AEMET station (1 km away from the catchment. In October 2014, a rainfall gauge station (Míner Gran) was installed less than 2.5 km away from the catchment). Míner Gran rainfall gauge is located 1 m above the ground and connected to a HOBO Pendant® G Data Logger - UA-004-64 that recorded precipitation at 0.2 mm resolution. A linear regression was established (n=978; R^2: 0.88) for daily rainfall (2014-2017) between Biniatró and Míner Gran stations to reconstruct rainfall data series from 2012 to 2014 for Míner Gran station. Due to the lack of temperature data available in the study area, data of neighbour AEMET weather stations (i.e., less than 8 km away from the catchment) were used to estimate the catchment's temperature by using the block kriging technique. With this information, the monthly ET_o was estimated using Hargreaves and Samani [46] equation.

The gauging station of the Es Fangar catchment was built in July 2012. The cross section of the station has a rectangular broad-crested for low water stages to better measure low discharge. The water level is continuously (1 min time step) measured using a pressure sensor (Campbell CS451 connected to a CR200X datalogger) and average readings are kept every 15 minutes. Between 2012 and 2017 discharge was measured during baseflow conditions and flood events (measured range between 0.004 and 2.166 $m^3\ s^{-1}$) using an OTT MF Pro electromagnetic water flow meter. These discharge measurements (n=17) were subsequently used to calibrate the stage-discharge relationship.

2.4. Rainfall-runoff relationship assessment

This study is based on data from 5 hydrological years (2012-13 to 2016-17). For each runoff event (i.e. when the water stage exceeds the low-flows channel; i.e., 0.036 $m^3\ s^{-1}$), a simple hydrograph separation between quickflow and baseflow components was performed through a visual technique based on the logarithmic falling limb of the hydrograph [47]. This hydrograph separation method was used only to characterize the response of the catchment to a rainfall with no aim to derive any interpretation in terms of runoff processes. Over a 5-year period, hydrograph separation was conducted on 49 events. Based on hydrograph separations, baseflow and quickflow contributions for each hydrological year (October to September) were calculated.

For each rainfall-runoff event, several variables were derived from the hyetograph and hydrograph (Table 1). These variable aimed to characterize pre-event conditions (antecedent

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precipitation in 24h, AP1d; baseflow at the start of the event, Q_0) as well as event characteristics (rainfall depth, P_{tot}; mean and maximum rainfall intensity, $IP_{mean}30$ and $IP_{max}30$; runoff depth and runoff coefficient, R and R_c; and peak-flow discharge, Q_{max}). Relationships between those variables were assessed through Pearson correlation matrix. A more detailed analysis of rainfall-runoff relationships in Es Fangar catchment was carried out in a second step to investigate the variability of the hydrological response of similar size rainfall events. For this, 7 rainfall events with similar rainfall depth (from 41.8 to 49.8 mm) but with different antecedent conditions or rainfall dynamics were selected.

Table 1. Pre-event and event conditions variables to explain the rainfall-runoff relationship.

a) Pre-event conditions		b) Event conditions	
Q_0	Baseflow at the start of the flood ($m^3\ s^{-1}$)	P_{tot}	Rainfall depth (mm)
AP1d	Antecedent precipitation 1 day before (mm)	$IP_{mean}30$	Average rainfall intensity ($mm\ h^{-1}$)
		$IP_{max}30$	Maximum 30' rainfall intensity ($mm\ h^{-1}$)
		Q_{max}	Maximum peak discharge ($m^3\ s^{-1}$)
		R	Runoff (mm)
		R_c	Runoff coefficient

3. Results

3.1. Hydrological response of small Mediterranean catchments

3.1.1. Annual scale: lithology influence

Annual rainfall and runoff ranged from 376 to 1794 mm yr^{-1} and from 3.7 to 1200 mm respectively for these representative catchments under Mediterranean conditions. The relationship between annual rainfall and runoff (Figure. 2) showed a positive linear significant correlation (R^2= 0.67; $p < 0.01$). However, some scattering was also apparent in the relationship. Then, the relation in Figure 2 is improved if catchments with pervious lithology were not included (R^2= 0.77; $p < 0.01$). The lowest annual runoff values (< 10 mm) corresponded to catchments with annual rainfall lower than 500 mm yr^{-1} and pervious lithology (Figure 2), located in the East Mediterranean Sea (Lower Jordan River). Besides, catchment with pervious lithology close to annual rainfall of 1500 mm yr^{-1} showed large differences in their runoff amount.

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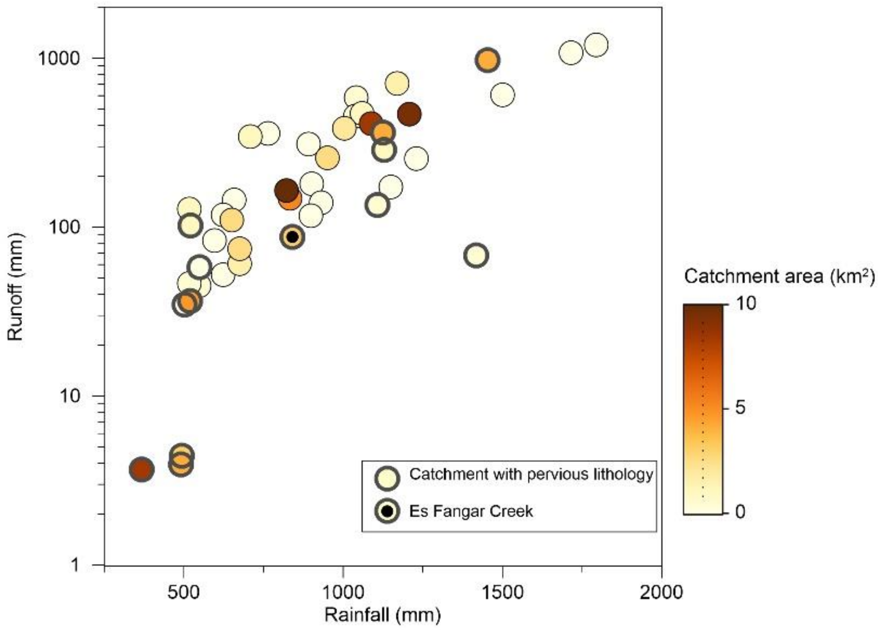

Figure 2. Rainfall – runoff for 44 small Mediterranean catchments at annual scale. Catchments with pervious lithology are marked with a grey halo. Es Fangar Creek value is illustrated with a black dot.

3.1.2. Event scale: seasonality, lithology and land uses influences

To investigate the variability of the hydrological response at event scale the rainfall-runoff relationship of 203 events from small Mediterranean catchments were analysed (Table A1b). Out layers were marked with an ellipsoid (Figure 3) and were excluded from the correlations.

The seasonal distribution of the events was winter (34%), autumn (32%), spring (22%) and summer (12%), most of them occurred from November to February (47%). Similar seasonal median rainfall was observed, ranging from 26.2 mm (winter) to 29.0 mm (autumn). The highest seasonal median of event runoff corresponds to winter (4.2 mm). Then, events occurred during the transition periods had a similar median runoff (autumn = 2.3 mm; spring = 2.2 mm) and the seasonal median for the summer events was the lowest (0.6 mm). However, the highest rainfall-runoff relationship was obtained in spring (R^2 = 0.63), followed by winter, autumn and summer (Figure 3a).

Small differences between the median of runoff events in catchments with pervious lithology (2.2 mm) and catchments without pervious lithology (3.1 mm) was found. Nevertheless, significantly differences in rainfall-runoff relationships can be observed as events in catchment with pervious lithology showed a highest correlation and a lowest scattering (Figure 3b). Rainfall events higher than 55 mm generated a runoff higher than 4 mm, except in events of late spring (Figure 3a) in catchments with pervious lithology (Figure 3b). In this case, the transmission losses due to pervious lithology has more influence on the hydrological response than the seasonal role of the water catchment reserves.

Event rainfall-runoff relationship were carried out under different land use (Figure 3c). The median event runoff in agricultural (5.0 mm) catchments was higher than forest (3.9 mm), agroforest (1.5 mm) and shrub (1.5 mm) land use. However, the highest correlations were obtained in catchments under agricultural (R^2 =0.61) and agroforest (R^2 =0.58) land uses.

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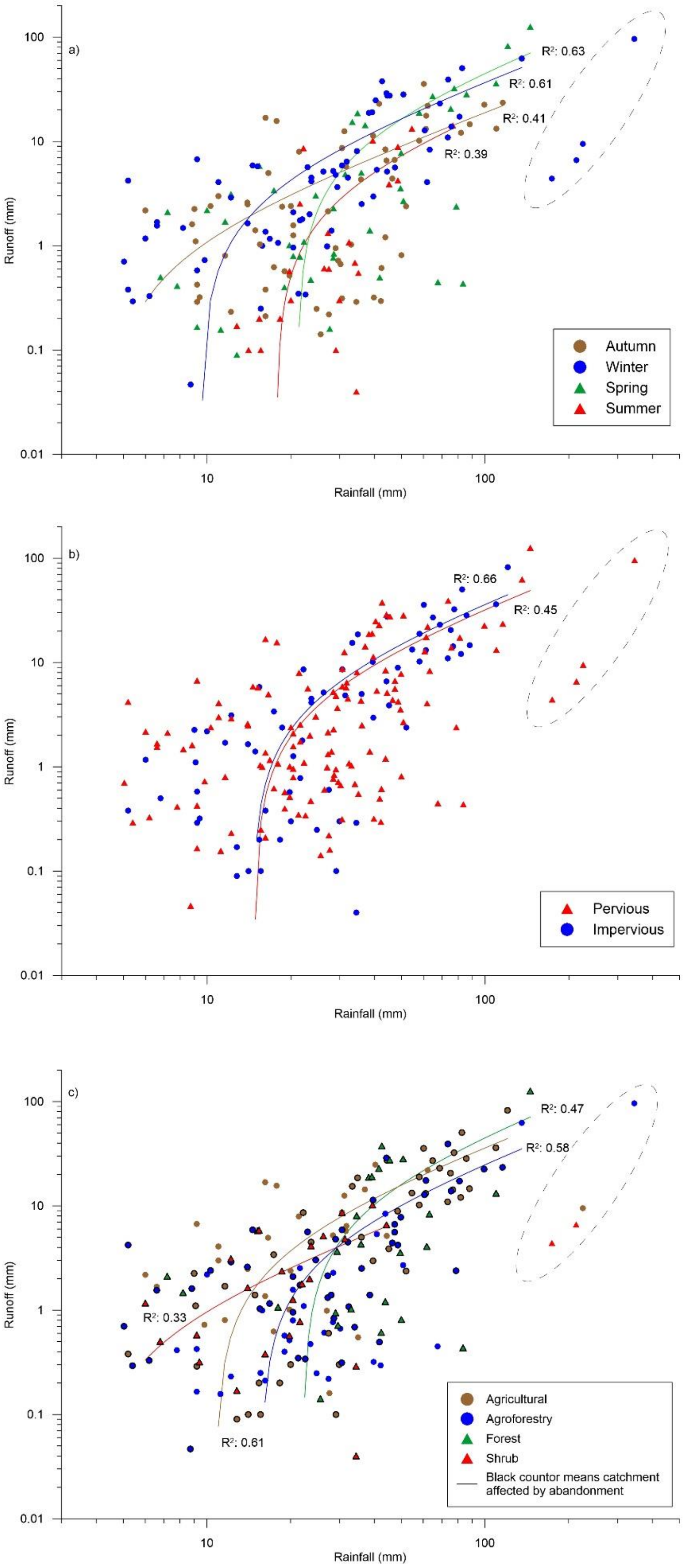

Figure 3. Rainfall – runoff at event scale classified by (**a**) season, (**b**) lithology and (**c**) land use at 12 small Mediterranean catchments. Out layers are marked with an ellipsoid.

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3.2. Hydrological response of small Mediterranean catchments

3.2.1. Annual scale

The mean annual rainfall (840.8 mm yr^{-1} ± 213 mm y^{-1}) calculated over the five hydrological years was broadly representative (-9%) of the long term annual rainfall (927 mm y^{-1} ± 215 mm y^{-1}: 1965-2016) and showed a high range of variation (from 553 mm y^{-1} to 1090 mm y^{-1}), characteristic of Mediterranean conditions. Figure 4 shows the annual variability of rainfall, baseflow and quickflow contributions as well as the annual runoff coefficient and the number of days with observed flow at the outlet of the catchment. Linear positive relationship were observed between annual rainfall, runoff, runoff coefficient, baseflow and quickflow ($R^2 \geq 0.84$, data not shown). The annual runoff coefficient ranged from 2.9% to 14.2% (mean value = 10.4%) and quickflow contribution from 9.9% to 45% (mean value = 33%). During the study period, flow was observed 42.8% of the time at the outlet of the catchment. From year to year, the cumulated number with observed flow ranged from 37.8% (138 days) to 65.2% (238 days) (Figure 4). An inverse relation between annual runoff volume and the number of days with observed flow was established. On the one hand, hydrological years with larger runoff volume (2013-14, 2014-15 and 2016-17) showed less days with observed flow and a lower (<60%) baseflow contribution. In these years, 50% to 62% of the annual runoff was reached in 5 or less days (Table A2). In addition, days with more runoff were always during autumn and winter. On the other hand, hydrological years with lower runoff (2012-13 and 2015-16) showed 208 and 238 days with observed flow. Baseflow contributions represented 70% and 90% respectively and 50% of the annual runoff was reached in 10 and 17 days also respectively. The contribution of the 5 days with more runoff did not exceed 28 and 37%, and these days with more runoff were distributed along the four seasons.

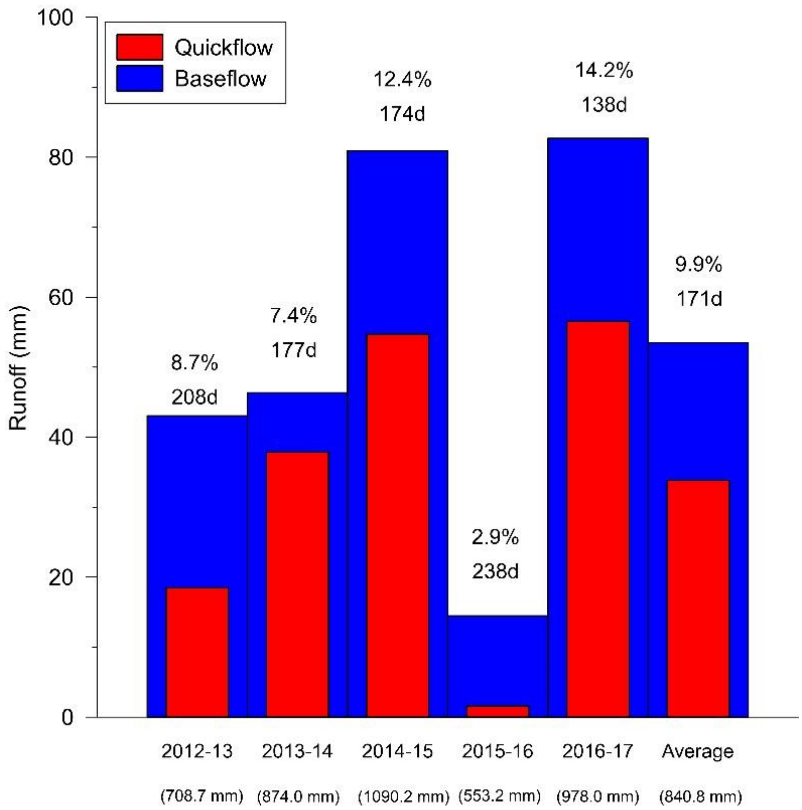

Figure 4. Baseflow and quickflow contributions (mm) in the total flow for each hydrological year (October to September) at Es Fangar Creek. The annual runoff coefficient is depicted in % as well as the total number of days (d) with recorded flow at the gauging station.

3.2.2. Seasonal scale

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Figure 5 shows the monthly mean values of rainfall, reference evapotranspiration and minimum, median and maximum runoff values. Mean monthly rainfall values were broadly comparable to those observed for long-term period, except for October when rainfall during the study period was much lower (56% lower than long-term rainfall).

Seasonal dynamics of rainfall and evapotranspiration controlled the runoff response observed in the catchment. Characteristics wet (winter) and dry (summer) periods alternated along the year, separated by transition periods (last autumn and early spring). Autumn was the rainiest season with low evapotranspiration and flow observed at the outlet for 52.7% of the time on average. Autumn mean runoff coefficient was 9.1% and ranged from 4.1% to 11.4%. During November and December, a continuous baseflow was generated in response to large rainfall amount after the pre-filling of the initial water storage in October. From October to December, the mean runoff coefficient increased from 1.3% to 13.1%. Finally, minimum, median, average and maximum monthly runoff amounts in December were higher than in November even with lower rainfall amounts (Figure 5). Although differences between the different years were observed, autumn was the season with less inter-variability in terms of runoff response.

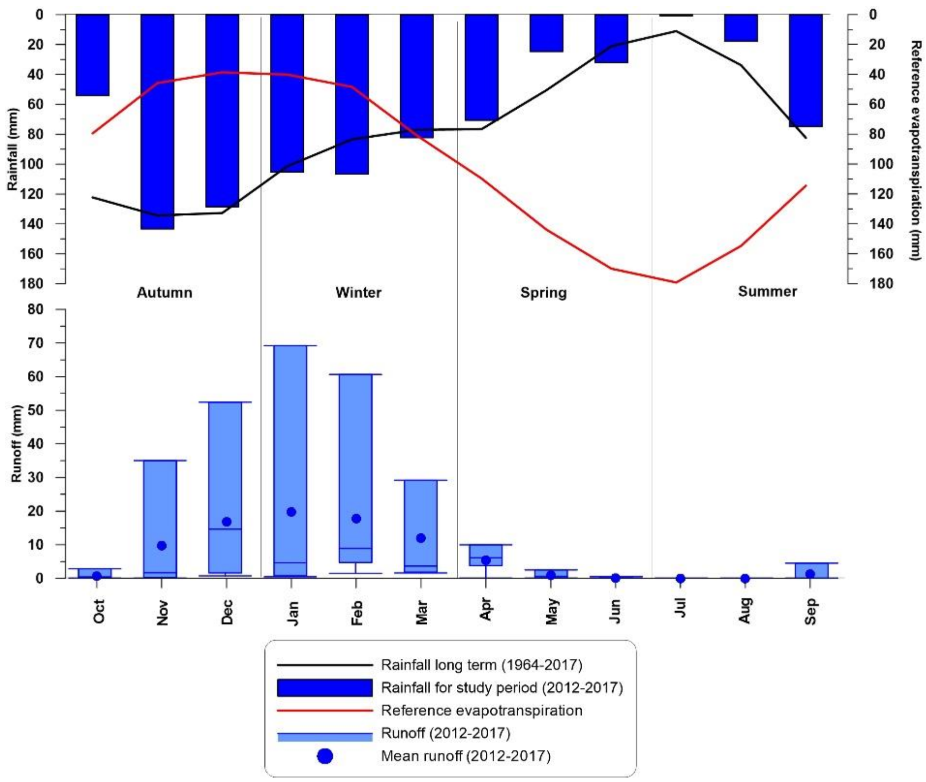

Figure 5. Monthly time series of rainfall, runoff, reference evapotranspiration during the study period (2012-2017) at Es Fangar Creek. Box plots show minimum, median and maximum monthly runoff. Blue dots show mean monthly runoff. Long term (1964-2017) monthly rainfall distribution is also shown.

During winter, flow was observed at the outlet during 90.6% of the time although the mean rainfall amount (294 mm) was lower than in autumn (326 mm). This more frequent presence of flow was favoured by the low evapotranspiration demand maintaining active the hydrological pathways. Figure 5 shows that in winter, a runoff amount similar to that of autumn can be generated from a lower rainfall amount. Winter mean runoff coefficient was 16.9%, ranging from 1.5% to 27%. Along winter, mean monthly runoff coefficient decreased from 18.9% to 14.6% between January and March as the consequence of decreasing rainfall amount and increasing evapotranspirative demand.

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In spring, flow was observed 41.3% of the time. Monthly rainfall decreased along the season and was much lower (127.4 mm) than in autumn and winter. Despite monthly evapotranspiration losses increased and were higher than rainfall, accumulated water reserves during autumn and winter months sustained the flow contribution. Spring mean runoff coefficient was 5.1%, ranging from 0.4% to 8.4% during the study period. Average monthly runoff decreased along the season from April (7.7%) to June (0.3%).

Finally, in summer flow was observed only 0.9% of the time. Stream was most often dry in this season due to the high negative balance between rainfall and evapotranspiration. Runoff was only ephemeral in response to episodic rainfall events more frequent in September, when 80% of rainfall occurred on average (Figure 5). Summer runoff coefficient was 1.4%.

3.2.3. (Non-)linearity assessment at event scale

During the study period, the number of flood events per hydrological year was between 2 (2015-16) and 14 (2014-15). The seasonal distribution of flood events was heterogeneous, with 13 events in autumn, 25 in winter, 7 in spring and 4 in summer. Events characteristics are detailed in Table A3 but main characteristics are summarized as follows. In order to investigate the variability and the non-linearity of the hydrological response at event scale, seven rainfall-runoff events with similar rainfall depth ranging (from 41.8 to 49.8 mm) were analysed comparatively. These events, ranked (Figure 6) according to their runoff coefficient had different antecedent conditions and rainfall dynamics.

The event on 21th January 2017 (Figure 6a) occurred during wet conditions following a runoff event on the day before. AP1d was 35.4 mm and Q_0 was high (0.229 $m^3 s^{-1}$). Rainfall characteristics (duration and intensity) were similar to those observed for other events of the same magnitude (Figure 6b, 6e and 6g), but in this case the hydrological response was an order of magnitude higher in terms of runoff (28.9 mm), runoff coefficient (65%) and Q_{max} (3.942 $m^3 s^{-1}$) due wet antecedent conditions (Table A4). This event had a similar duration than events that occurred under higher rainfall intensities (11/11/12, 29/09/14). However, wet antecedent conditions were much more favourable than rainfall intensity to reach a high Q_{max} and especially a higher runoff contribution (i.e. runoff coefficient). The importance of the antecedent conditions in runoff generation at the event scale is comparable to the one observed at the season scale when winter rainfall depths were lower than autumn but the winter runoff responses were larger.

The event on 4th April 2012 (Figure 6b) happened during the beginning of the transition period (early spring) from wet to drier conditions. Antecedent conditions were favourable to runoff generation due to the presence of baseflow maintained by water reserves accumulated during autumn and winter months. Runoff coefficient was 16%. The event on 11th November 2012 (Figure 6c) had the highest $IP_{max}30$ (i.e., 77.5 mm h^{-1}) of the study period and occurred in the transition period from dry to wet conditions (middle autumn). There was no baseflow before the event. Under these conditions of rainfall intensity the runoff coefficient reached 14%. Even if the event on 4th April 2012 had a similar runoff coefficient (16%) than the event that occurred on 11th November 2012, both events showed different hydrographs because of different rainfall characteristics (in terms of duration and intensity). Whereas the event on 4th April 2012 had a duration of 44.7 h, duration of event on 11th November 2012 was only 18 h. In addition, differences between these two events were also relevant in terms of Q_{max} that reached 1.006 $m^3 s^{-1}$ for the April event and 1.747 $m^3 s^{-1}$ for the event on 11th November 2012.

The event on 8th February 2017 (Figure 6d) occurred during the wet season. AP1d and a Q_0 were respectively 0 mm and 0.012 $m^3 s^{-1}$. At the contrary, event on 19th December 2016 (Figure 6e) occurred at the end of the transition period with an AP1d and a Q_0 of 2 mm and 0.012 $m^3 s^{-1}$ respectively. Both events had similar values of $IP_{max}30$, AP1d and Q_0 (Table A4). Nevertheless, runoff and runoff coefficient were slightly larger for the event on 8th February 2017 likely because of the large rainfall amount accumulated between the two events (more than 400 mm of rainfall between 19th December 2016 and 8th February 2017).

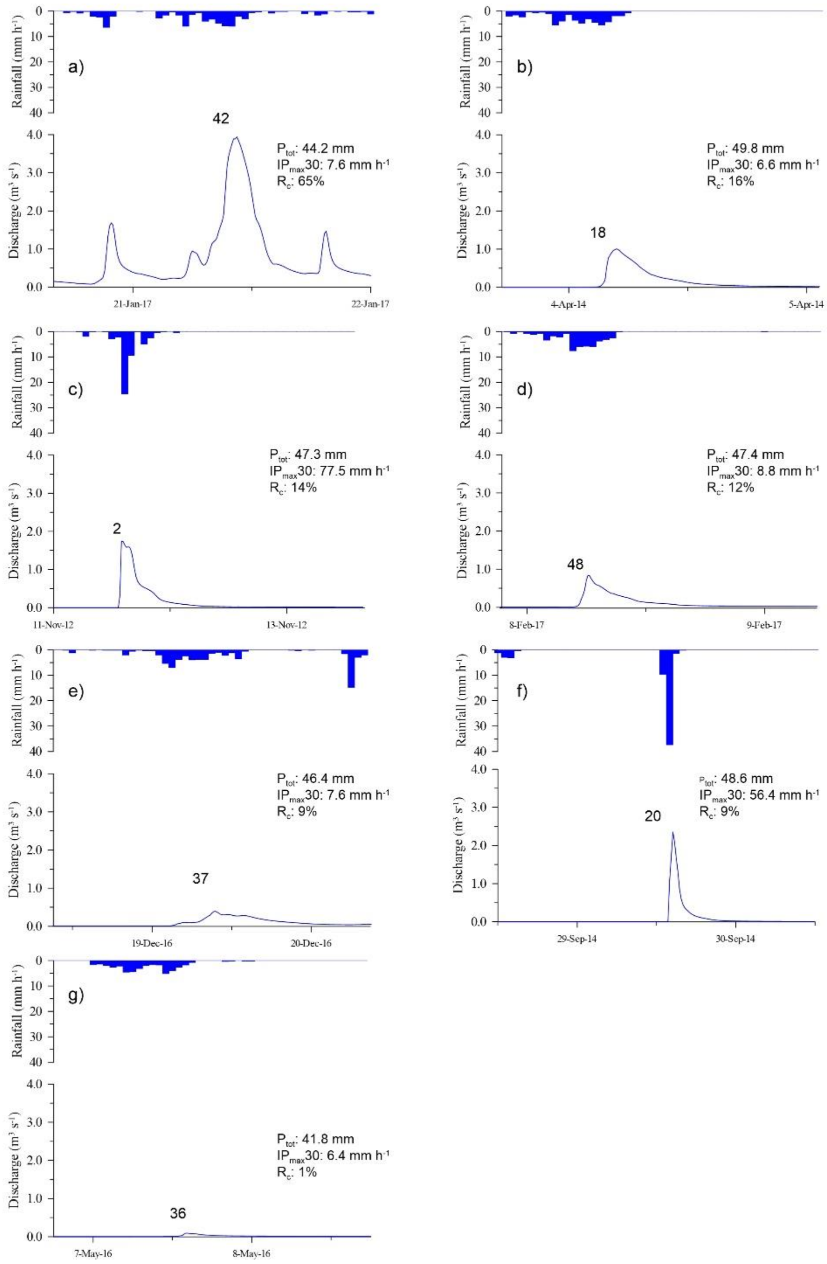

Figure 6. Selected events for non-linearity analysis at Es Fangar Creek. Events with a total precipitation between 40-50 mm.

The event on 7th May 2016 (Figure 6g) was similar to event on 19th December 2016 (Figure 6e) in terms of rainfall depth, duration and intensities. Even if the patterns of both rainfall events were similar, runoff response started earlier (i.e. shorter response time) for the event on 19th December 2016 than for the one on 7th May 2016. This difference in response time is related to the fact that this event occurred during the wetting up period with increasing catchment water reserves. As a result, even if the runoff response was relatively small (4.4 mm), runoff coefficient (9%) and Q_{max} (0.394 m^3 s^{-1}) were significantly larger than for the event on 7th May 2016 (Table A4) with similar rainfall characteristics, but occurring during the transition period under dry conditions, with an AP1d and Q_0 of 1.6 mm and 0.006 m^3 s^{-1} respectively. In these conditions, a long rainfall event of low intensity under dry antecedent conditions generated the lowest runoff response in terms runoff, runoff coefficient and Q_{max} (Table A4). This runoff response was also the most delayed as shown on Figure 6g, where it can be observed that the runoff response only started at the end of the rainfall event after 95% of the rainfall (39.8 mm) had fallen on the catchment.

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The event on 29th September 2014 (Figure 6f) occurred during the dry season (i.e., late summer, early autumn) but with an antecedent precipitation AP1d of 11.8 mm. The rainfall event was the shortest of the selected events of Figure 6 (3.2 h) and had the second highest $IP_{max}30$ (56.4 mm h^{-1}) of all events of the study period. Only because of this particular rainfall pattern (very high intensity), a runoff response was observed at the outlet. Similar summer rainfall but with lower intensities in dry conditions produced a lower response ($R_c \leq 3\%$). For this event, even if the runoff response was relatively small (4.2 mm) and the runoff coefficient remained below 10%, Q_{max} was relatively high (2.356 $m^3 s^{-1}$) in response to rainfall intensity.

4. Discussion on hydrological responses at small Mediterranean and Es Fangar catchments

4.1. Annual and seasonal scales

4.1.1. Small Mediterranean catchments: lithology influences

Similarly to our results (Figure. 2), Merheb et al. [48] obtained a significant rainfall-runoff correlation (R^2= 0.69) using 160 Mediterranean catchments (0.35 to 21,700 km^2). Those authors highlighted that the scattering observed was due to karstic catchments or snowmelt contributions. In our results, catchments with annual rainfall ranging from 500 to 900 mm yr^{-1} showed annual runoff between 20 and 350 mm. In this group of catchments, the role played by lithology on the annual runoff response was important, as the highest annual runoff values (> 350 mm) were observed for catchments with badlands areas [34] and in catchments with high subsoil clay content that promote lateral flow and a perennial regime [35]. Swarowsky et al. [49] also reported an annual runoff 60 mm lower than in an adjacent catchment investigated by Lewis et al. [35] and related this difference to greater deep seepage.

Into this group, with annual rainfall ranging from 500 to 900 mm yr^{-1}, catchments located in Mallorca yielded annual runoff between 36 and 130 mm. From those catchments, the highest runoff value was observed by Estrany et al. [14] in an agricultural small catchment with a lowland area prone to receive subsurface contributions. García-Comendador et al. [50] found spatial differences in annual runoff between headwater (102 mm) and catchment outlet (36 mm) due transmission losses in the main channel. Those same authors also reported temporal differences as they found runoff coefficients ranging from 1 to 22% from one year to the other in the Sa Font de la Vila catchment. Within the study period, Es Fangar catchment showed a relatively low mean annual runoff value (87 mm) according to its mean annual rainfall value (black dot on Figure 2). This result is most likely related to the presence of massive karstic dolomites formation and breccia's lithology in the headwaters of the catchment (44% of the catchment area).

Also scattering can be observed in the relationship for catchments with annual rainfall larger than 1000 mm yr^{-1}. For this group of catchments, annual runoff ranged from 135 to 1200 mm, except for the Santa Magdalena catchment, totally on limestone lithology that yielded an annual runoff value of 70 mm [44]. Large annual runoff values usually corresponded to watertight catchments as reported by Didon-Lescot et al. [36] who estimated runoff values higher than 1000 mm yr^{-1} for two small Mediterranean catchments on granite bedrock. However, high annual runoff values were also unusually reported by Calsamiglia et al. [51] in a karstic environment at Mallorca island, as a result from incoming spring sources in the middle part of the catchment. Then, accordingly to the conceptual model of Borg Galea et al. [2], the climate is the main driver of the rainfall-runoff relationship but catchment geology is the main conditioning factor.

The different dynamics of rainfall and reference evapotranspiration along the year, wet (winter), dry (summer) and transition periods (last autumn and early spring) can be observed [52]. Then, different seasonal rainfall-runoff relationship are reported in relation to the influence of rainfall and evapotranspiration characteristic of the previous season [53]. Accordingly, several studies identified winter as the season with highest runoff coefficient, from 17% to 56%, due to rainfall accumulated during autumn and low evapotranspiration demand [9,14,53], also in according to the data depicted during the five hydrological years in Es Fangar Creek. Besides, those authors coincide that in summer

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the hydrological response was limited or null as being the driest season (runoff coefficient < 10%). Serrano-Muela [53] observed runoff coefficients <5% in a range of rainfall amounts 15-200 mm during summer. The driest environments of those studies obtained a summer runoff coefficient lower than 2%. Runoff coefficient in autumn and spring were similar, ranging 9-25% and 5-28% respectively. However, a variability along those seasons can be observed, especially in last autumn and early spring, as transition periods. Besides, Lana-Renault [9] found that the wetting-up period was steeper than the drying-down period, which was more progressive. Autumn was the season after the driest period and it was when the evapotranspiration reached the maximum values. The beginning and the end of this season can be quite different in runoff coefficients. Then, catchments have a null or limited response until a succession of rainfall events that allow fill water reserves and generate favourable conditions for runoff generation [53]. The findings of those studies in spring conclude that the accumulated rainfall during autumn and winter maintain high water reserves allowing high runoff coefficients, even spring was not the rainiest season.

4.1.2. Es Fangar

The hydrological response of Es Fangar can be compared with similar catchments in terms of catchment size and climate considering the relevance of the long-term monitoring in small catchments (i.e., < 10 km^2) as outdoor laboratories [54]. These authors highlighted their multiple role for long-term observatories to understand extreme events (floods and drought), sites for method and model validation, testing novel measurement technologies and places for training young researchers. Then, small catchments are an essential tool in the study, planning and management of the natural environment, especially in the context of increasing water resources demand, land uses changes and climate change projections [55,56]. Moreover, the Mediterranean climate is characterized by a high inter- and intra-annual spatiotemporal variability in precipitation combined with a characteristic summer drought. These seasonal characteristics, among other factors, generate strong seasonal variations in streamflow regimes, which can be classified from ephemeral to perennial [4]. According to this classification, Es Fangar is an example of this variability as could be classified as intermittent flashy (49% of zero days), with an annual variability from intermittent (35% zero days flow) to harsh intermittent (62% zero days flow).

4.2. Event scale

4.2.1. Seasonality, lithology and land uses influences on small Mediterranean catchments hydrological response

Seasonally, the highest correlation observed in spring could be related to the accumulated water reserves during autumn and winter seasons, being favourable for runoff generation [11]. According to the results, others studies in Mediterranean catchments found an event seasonality in the hydrological response [7,9,57]. In those studies, autumn rainfall events had a limited or non-runoff response, especially at the begging of the season. In addition, in winter and spring runoff coefficients were always up to 3%, being the maximum in spring (70%).

The role of transmission losses due to lithology has been investigated [32,58]. Cantón et al. [33] studied the runoff generation across different scales and lithology, which observed the lowest runoff coefficient under limestone lithology. Accordingly, events under pervious lithology (Figure 3b) showed a higher scattering than events under pervious lithology, as most of the events classified as pervious had limestone lithology. In addition, rainfall events higher than 55 mm generated a runoff higher than 4 mm except in catchments with pervious lithology. Similarly, Ries et al. [59] identified a different runoff response in rainfall events higher than 50 mm based on the physiographic catchment and rainfall characteristics. Events occurred in catchments, even had different land uses, with less bedrock permeability and less soil water storage but with higher values of rainfall intensity generate a greater runoff response than catchments with more bedrock permeability and soil water storage

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under low rainfall intensities. Contrarily, other types of lithology (i.e., badland areas) are characterized by a low infiltration capacity [60]. Latron and Gallart [61] observed that frequently badlands are the only active area to runoff response. According to this findings, Nadal-Romero et al. [62] observed event stormflow coefficient until 20% in a Mediterranean catchment with badland areas, even the headwater catchment was forested (30% of the catchment area).

Events under agricultural land use had the highest median runoff and correlation as arable land and its spatial distribution within a catchment have been demonstrated to be a driver for runoff generation [63]. Unexpectedly, forest catchments had the second highest median runoff when the water yield and rainfall-runoff relationship decrease in forest catchments [64]. However, this median value cannot be understood without taken in account the presence of spring sources in one of the forest catchments. Median runoff of forest catchments is similar to afforested catchments values as both land uses trigger a reduction in the runoff generation. This reduction were quantified in a loss of water yield ca. 10-40% [38, 64–67]. Nevertheless, larger flows and peak discharges were observed in afforested catchments than forest ones. Shrub median runoff was the lowest value and the rainfall-runoff had the highest non-linearity as only two studies at event scale with available data were found in the literature.

4.2.2. Rainfall-runoff relationship at Es Fangar catchment

To identify factors that can explain the variability of the runoff coefficient we explore the relationships between observed runoff coefficients and runoff and rainfall depth, rainfall, maximum intensity and baseflow at the beginning of the event, as Latron et al. [7] did in a mountain Mediterranean catchment in North Eastern Spain.

From those relationships only one correlation (between runoff and runoff coefficient) was significant in Es Fangar catchment (Figure A1a), explaining 73% of variance. As in Latron et al. [7] this relationship was the one with the highest correlation. However, contrarily to Latron et al. [7], the relation between rainfall and runoff coefficient was highly non lineal for Es Fangar catchment. This relationship presented a huge scattering especially for rainfall depths between 20 and 60 mm (Figure A1b), that yield runoff coefficients ranging from 1% to 65%. Even for rainfall events of 50 mm or more a huge variability of runoff coefficient persisted for Es Fangar catchment. For large rainfall events, runoff coefficients were indeed generally high (above 20%), but some low responses (with runoff coefficient of 1 to 3 %) were also sometimes observed corresponding to large rainfall events occurring after or during dry conditions. In line with results from Latron et al. [7], runoff coefficient was not related at all with rainfall intensity (Figure A1c). Finally the relationship between base-flow at the beginning of the event and runoff coefficient was not straightforward in Es Fangar catchment (Figure A1d). A threshold was identified leading to larger runoff coefficient (higher than 10%) for events with Q_0 above 0.04 m^3 s^{-1} km^2 (always occurring between November and April). The relationship between base-flow at the beginning of the event and runoff coefficient in Latron et al. [7] was stronger, because of the presence of baseflow during most of the year. In general terms, in Es Fangar catchment, the frequent absence of baseflow between May and October worsen most of the relationships presented in Figure A1 in comparison to a catchment with almost permanent baseflow as in Latron et al. [7]. Then, baseflow – runoff coefficient correlation increased as wetter was the environment, from R^2= 0.19 in Es Fangar to R^2= 0.70 in a humid catchment [68].

In order to help identifying the main factors of the hydrological response in Es Fangar catchment, multiple relationship were carried out to investigate the influence of rainfall, Q_0 and $IP_{max}30$ on runoff and Q_{max} (Figure 7). The observed hydrological response in terms of runoff and Q_{max} was highly non-linear, as observed in other Mediterranean catchments [7,10]. Figure 7a shows how runoff response could not be explained by the antecedent discharge as the highest runoff values presented a large scattering along the Y axis. This confirmed that large runoff amounts resulted independently from large rainfall events occurring in dry or wet conditions (i.e. with low or high Q_0 values). Rainfall amount was indeed a key factor for runoff response, as shown by the significant positive correlation ($p<0.01$) between both variables (Table 2). In addition, Ceballos and Schnabel [8]

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found that rainfall amount was a key factor for runoff generation only in those events where the valley bottoms were saturated. Largest runoff events always happened during last autumn or winter (see event marked in Figure 7a). These largest events had runoff contributions larger than 17 mm (Figure A2 and Table A5) and were characterized by P_{tot}, R, R_c, Q_{max} and AP1d values much higher than median values (Table A3). Contrarily large rainfall events that occurred in spring resulted in small runoff contribution because of dry antecedent conditions (i.e low Q_0 values). Others authors also found relationships between seasonality and runoff generation. Lana-Renault [9] found, in a mountainous catchment, that the highest event rainfall-runoff relationship were in winter and spring due to a higher water reserves than autumn and summer. In Es Fangar, a group of events during autumn and winter characterized by Q_0 >0.080 m^3 s^{-1} always generated a runoff coefficient up to 14% (Figure A1d). The P_{tot} of these events ranged from 5.2 to 61.4 mm but the AP1d was up to 20 mm, except in one event (AP1d: 3.4 mm) that was characterised for the highest $IP_{max}30$ (i.e., 77.5 mm h^{-1}) of the study period. Those events characteristics suggest that P_{tot} is the main but not the only factor that control an effective hydrological response as antecedent conditions (i.e., soil moisture degree of the catchment) has been demonstrated to play an important role in runoff generation [69]. Similarly, Lana-Renault [9] identified a cluster of events characterized with a highest Q_0 that generated a larger runoff response. However, contrarily to this study, those authors did not observed a seasonal pattern.

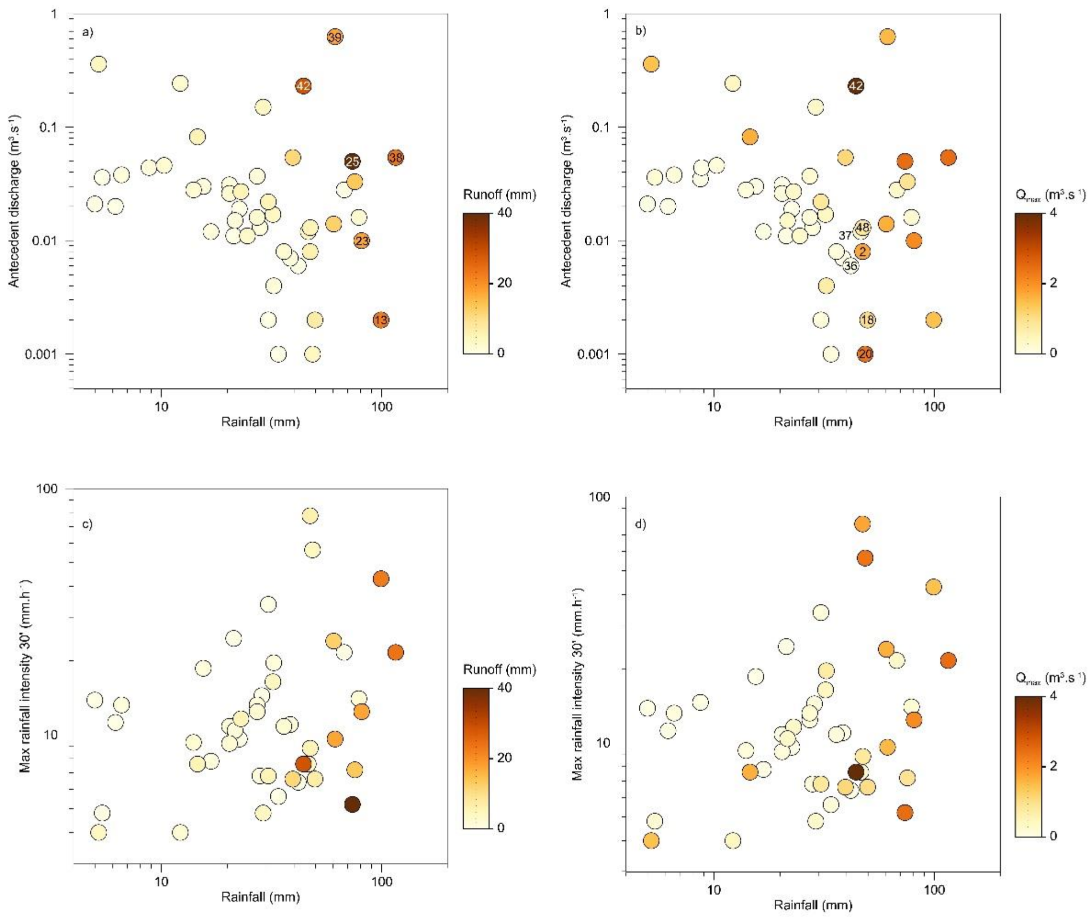

Figure 7. Multiples relationships within variables at event scale at Es Fangar Creek: (**a**) rainfall-antecedent discharge-runoff, (**b**) rainfall- antecedent discharge - Q_{max} relationship, (**c**) $IP_{max}30$-rainfall-runoff and (**d**) $IP_{max}30$-rainfall- Q_{max}. ID events correspond to the selected events for the non-linearity assessment.

Figure 7b shows that high Q_{max} values were observed in response to large rainfall amounts (above 50 mm) or for flood events with a Q_0 value higher than 0.080 m^3 s^{-1}. Both factors had a

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combined effect on the generation of high Q_{max} values as shown by the significant correlation observed between P_{tot} and Q_0 and Q_{max}. The role of wet conditions over Q_{max} also was observed in other Mediterranean catchments where antecedent precipitation correlated significantly with Q_{max} [14,16,70].

Table 2. Pearson correlation matrix between selected variables.

	Q0	Ptot	$IP_{mean}30$	$IP_{mean}30$	Q_{max}	R	Rc
Q_0	1.000	0.027	-0.003	0.082	**0.386**	0.276	**0.525**
P_{tot}		1.000	0.090	0.274	**0.554**	**0.676**	0.074
$IP_{mean}30$			1.000	**0.788**	0.153	-0.064	-0.206
$IP_{mean}30$				1.000	0.253	0.034	-0.173
Q_{max}					1.000	**0.824**	**0.674**
R						1.000	**0.622**
Rc							1.000
Correlation significant at 0.01 level							
Correlation significant at 0.05 level							

Runoff and Q_{max} were not significantly correlated with $IP_{max}30$ (Table 2). Figures 7c and 7d show that high values of runoff and Q_{max} could be observed for events with low $IP_{max}30$, if rainfall was large (i.e > 50mm) or if antecedent discharge was high. This absence of correlation between the catchment response (runoff and Q_{max}) indicates that runoff generation in the catchment is most likely the result of saturation excess processes [71], where P_{tot} and antecedent conditions play a key role. For events between June and September saturation excess processes were however probably less dominant and combined with infiltration excess processes in response to highest $IP_{max}30$ values ranging from 19 to 56.4 mm h^{-1}. As a result, events observed between June and September were shorter (5.7 to 14h duration compared to 8 to 65.5h for wet conditions events).

4.2.3. Non-linearity assessment at Es Fangar catchment

The events analysed in Figure 6 presented a huge variability in their hydrological response although the events had a similar rainfall depth ranging from 41.8 to 49.8 mm. Runoff coefficients ranged from 1 to 65% depending on catchment moisture conditions, rainfall intensities and seasonality characteristics. The highest hydrological response occurred under marked wet soil moisture conditions in winter period even if rainfall intensities were low (Figure 6a). Similar complexity in runoff responses has already been observed in other Mediterranean catchments [10,52]. Gallart et al. [72] also showed that different runoff generation behaviour could be observed during the year due to varying catchment wetness conditions and changing rainfall events characteristics. The results obtained by these authors are clearly illustrated by comparing events 2 and 20 with events 18 and 37 in Figure 6. Indeed, runoff events that occurred during a wet conditions with low rainfall intensities (18 and 37) showed similar runoff coefficients than events that occurred during dry conditions with high rainfall intensities (2 and 20). However, during dry conditions, runoff events resulting from low intensity rainfall yielded the lowest runoff responses (e.g. event 36). Our results are also in agreement with the observations made by Schnabel et al. [73], who observed higher runoff contributions for low rainfall intensities events occurring in periods with high soil water content than for events with high rainfall intensities. Besides, those authors pointed out that this condition was

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common during years with above average rainfall (i.e., during wet years) but was rarely observed during dry years.

5. Conclusions

The evaluation of multiple temporal scales in contrasted small Mediterranean catchments has improved the understanding of the role played by lithology and land uses on the hydrological response. The assessment of rainfall-runoff relationships at annual scale in small Mediterranean catchments showed a significant linearity in the hydrological response due to the importance of the annual rainfall amount. Nevertheless, lithology effects on runoff generation explained an increase of the scattering in the rainfall-runoff relationship because pervious and impervious materials triggered larger and lower runoff contribution respectively. Although the significant correlation between rainfall and runoff, Es Fangar Creek dataset illustrated a huge intra-annual variability of the rainfall-runoff relationship during the five hydrological years analysed as seasonal rainfall and evapotranspiration dynamics controlled the runoff response. These dynamics was clearly observed in the average seasonal runoff coefficients, decreasing from winter to summer.

At event scale, lineal and non-lineal relationships were observed in the rainfall-runoff relationships in small Mediterranean catchments suggesting that different factors conditioned the runoff response. Total rainfall was the most significant driver factor although the interaction between seasonality and the spatial diversity of lithology and land uses at catchment scale also played an important role over runoff generation. Thus, the highest correlations at seasonal scale were observed in those events occurred in winter and spring when the highest water reserves favoured the runoff response. Lithology caused higher dispersion in rainfall-runoff relationships at event scale in the set of small Mediterranean catchments because pervious materials required higher antecedent wetness conditions. Land uses promoted a decrease in runoff generation comparing agricultural with scrubland uses because agriculture promoted the highest correlation in the rainfall-runoff relationships due to lower vegetation cover. This temporal downscaling from annual to event scale elucidated how different runoff mechanisms can co-exist in small Mediterranean catchments considering the main temporal and spatial factors that governing the river catchment connectivity. Despite this, controls on runoff generation in Mediterranean catchments require further attention to assess the role of lithology, land uses and seasonality and their combined effects over the hydrological response for going beyond in the comprehension of highly sensitive areas to global change, such as the Mediterranean region, improving hydrological models particularly in ephemeral and intermittent rivers.

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Appendix A

Table A1. Mediterranean studies used into the rainfall – runoff relationship at (**a**) annual and (**b**) event scale.

Time scale	Catchment	Country	Area (km^2)	Precipitation (mm $year^{-1}$)	Main lithology	Reference
a) Annual scale	Watershed C	USA	0.05	657	Impervious	Cited in Latron[44]
	TM9	Spain	0.06	891	Impervious	Cited in Latron [44]
	Watershed B	USA	0.09	901.7	Impervious	Dahlgren et al. [74]
	Watershed G	USA	0.13	931.3	Impervious	Dahlgren et al. [74]
	Watershed B	USA	0.17	623	Impervious	Cited in Latron [44]
	Watershed A	USA	0.19	623	Impervious	Cited in Latron [44]
	Spruce	France	0.2	1794	Impervious	Didon-Lescot et al. [36]
	La Sapine	France	0.2	1715.6	Impervious	Didon-Lescot et al. [36]
	Watershed C	USA	0.23	898.8	Impervious	Dahlgren et al. [74]
	Mokobulaam	South Africa	0.26	1150	Impervious	Cited in Nadal-Romero [34]
	HREC	USA	0.33	549	Pervious	Swarowsky et al. [49]
	Fernow	USA	0.34	1500	Impervious	Cited in Nadal-Romero [34]
	Guadalperalón	Spain	0.35	502	Pervious	Ceballos and Schnabel [8]
	Pine Tree Branco	USA	0.36	1230	Impervious	Cited in Nadal-Romero [34]
	La Teula	Spain	0.39	595.5	Impervious	Cited in Latron [44]
	Araguás	Spain	0.45	764.6	Impervious	Nadal-Romero [34]
	Avic	Spain	0.52	548	Impervious	Cited in Latron [44]
	Sta Magdalena	Spain	0.53	1418	Pervious	Latron [44]
	Can Vila	Spain	0.56	1041	Impervious	Latron [44]
	Boussicaut	France	0.73	1038	Impervious	Cited in Latron [44]
	San Salvador	Spain	0.92	1108	Pervious	Serrano-Muela [53]
	Parapuños	Spain	1	516.2	Impervious	Schnabel et al [73]
	Schubert	USA	1.03	708	Impervious	Lewis et al. [35]
	Can Revull	Spain	1.03	517	Impervious	Estrany et al. [14]
	Sa Murtera	Spain	1.2	520.4	Pervious	García-Comendador et al. [50]
	Ca l'Isard	Spain	1.32	1128	Pervious	Latron [44]
	Vaubarnier	France	1.49	1059	Impervious	Cited in Latron [44]
	Desteou	France	1.53	1169	Impervious	Cited in Latron [44]

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Time scale	Catchment	Country	Area (km²)	Precipitation (mm year⁻¹)	Main lithology	Reference
	Bosc	Spain	1.6	675.1	Impervious	Pacheco et al. [75]
	TM0	Spain	2	1004	Impervious	Cited in Latron [44]
	Campàs	Spain	2.57	675.1	Impervious	Pacheco et al. [75]
	Kamech	Tunisia	2.63	650	Impervious	Slimane et al. [76]
	Arnás	Spain	2.84	951	Impervious	Lana-Renalut [9]
	Headwater 4	Jordan	3.2	493	Pervious	Riest et al. [77]
	Es Fangar	Spain	3.35	840.8	Pervious	This study
	Cal Rodó	Spain	4.17	1125	Pervious	Latron [44]
	Headwater 3	Jordan	4.2	491	Pervious	Riest et al. [77]
	Biniaraix	Spain	4.4	1453.2	Pervious	Calsamiglia et al. [51]
	Sa Font de la Vila	Spain	4.8	519.6	Pervious	García-Comendador et al. [50]
	Cogolins	France	5.47	833	Impervious	Cited in Latron [44]
	Headwater 2	Jordan	8.4	367	Pervious	Riest et al. [77]
	Maurets	France	8.48	1088	Impervious	Cited in Latron [44]
	Valescure	France	9.22	1208	Impervious	Cited in Latron [44]
	Maraval	France	9.61	822	Impervious	Cited in Latron [44]

Time scale	Catchment	Country	Area (km²)	Precipitation (mm year⁻¹)	Main lithology	Main land use	Reference
b) Event scale	Guadalperalón	Spain	0.35	22	Pervious	Agroforestry	Ceballos and Schnabel [8]
	Can Vila	Spain	0.56	39.6	Impervious	Agricultural	Latron and Gallart [7]; Roig-Planasdemunt et al. [78]; Cayuelta et al. [79]
	Parapuños	Spain	1	17.4	Impervious	Agroforestry	Schnabel et al. [73]
	Can Revull	Spain	1.03	19.9	Impervious	Agricultural	Estrany et al. [14]
	Sa Murtera	Spain	1.2	43.9	Pervious	Forest	García-Comendador et al. [50]
	Arnás	Spain	2.84	20.1	Impervious	Shrub	Lana-Renalut [9]
	Headwater 4	Jordan	3.2	225	Pervious	Agricultural	Riest et al. [77]
	Es Fangar	Spain	3.35	29	Pervious	Agroforestry	This study
	Headwater 3	Jordan	4.2	213	Pervious	Shrub	Riest et al. [77]
	Biniaraix	Spain	4.4	42.6	Pervious	Forest	Calsamiglia et al. [51]
	Sa Font de la Vila	Spain	4.8	36.9	Pervious	Forest	García-Comendador et al. [50]
	Headwater 2	Jordan	8.4	174	Pervious	Shrub	Riest et al. [77]

Table A2. Relative rainfall and runoff contribution of the highest 5 days and number of days to reach the 50% of runoff for each hydrological year.

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Year	Rainfall contribution of 5 days (%)	Runoff contribution of 5 days (%)	Number of days to reach 50% of runoff
2012-2013	32	37	10
2013-2014	35	53	5
2014-2015	23	50	5
2015-2016	35	28	17
2016-2017	41	28	3

Table A3. Flood event characteristics.

ID	Date	P_{tot} (mm)	$IP_{mean}30$ (mm h^{-1})	$IP_{max}30$ (mm h^{-1})	Q_{dur} (h)	Q_0 (m^3 s^{-1})	Q_{max} (m^3 s^{-1})	Runoff (mm)	Runoff coefficient (%)	AP1d (mm)	AP3d (mm)
1	27-10-12 20:15	30.6	10.1	33.8	8.0	0.002	0.144	0.3	1.0	0.0	0.0
2	11-11-12 22:20	47.3	11.3	77.5	18.0	0.008	1.747	6.7	14.1	3.4	3.4
3	28-11-12 8:00	15.5	6.2	18.6	17.5	0.030	0.094	1.0	6.7	9.7	9.7
4	24-1-13 9:00	21.3	5.7	24.6	12.7	0.011	0.036	0.3	1.6	0.0	15.3
5	24-1-13 22:30	5.0	6.7	13.8	15.7	0.021	0.083	0.7	13.9	21.3	36.6
6	28-1-13 3:30	16.8	4.5	7.8	44.5	0.012	0.064	1.2	6.9	1.7	32.5
7	28-2-13 8:00	32.1	3.9	16.4	21.2	0.017	0.427	4.5	14.0	4.6	11.0
8	1-3-13 21:00	8.7	5.0	14.6	8.0	0.035	0.077	0.0	0.5	32.2	40.6
9	13-3-13 14:15	60.6	8.7	24.0	12.8	0.014	1.610	12.8	21.1	0.0	0.0
10	14-3-13 20:30	6.6	8.8	13.2	17.6	0.038	0.156	1.6	23.5	60.8	60.8
11	5-4-13 22:30	38.5	4.1	11.0	48.5	0.007	0.059	1.4	3.6	0.0	0.0
12	28-4-13 21:00	24.6	ND	ND	46.5	0.011	0.347	3.0	12.3	22.1	23.0
13	19-11-13 2:15	99.3	5.3	43.0	64.7	0.002	1.414	22.5	22.7	7.0	75.5
14	22-11-13 9:30	8.8	ND	ND	24.7	0.044	0.093	1.6	18.2	1.3	1.3
15	27-11-13 18:45	14.0	3.1	9.3	39.5	0.028	0.115	2.6	18.6	9.2	15.3
16	29-11-13 10:30	10.3	ND	ND	25.5	0.046	0.155	2.4	23.3	3.6	28.8
17	30-11-13 18:45	39.5	2.3	6.6	46.3	0.054	1.105	11.3	28.7	10.3	40.2
18	4-4-14 3:15	49.8	2.6	6.6	44.7	0.002	1.006	7.8	15.6	3.8	8.0
19	25-4-14 6:45	28.6	6.4	14.4	15.5	0.000	0.180	0.8	2.9	5.0	13.4
20	29-9-14 13:45	48.6	16.2	56.4	14.0	0.001	2.356	4.2	8.7	11.8	13.9
21	4-12-14 22:45	27.2	4.5	12.4	44.3	0.016	0.197	2.1	7.9	9.4	69.2
22	28-12-14 10:45	36.0	5.1	10.8	39.3	0.008	0.183	2.5	7.0	2.2	2.2
23	20-1-15 13:00	81.0	2.7	12.4	50.0	0.010	2.094	17.3	21.4	9.0	9.0
24	3-2-15 9:45	22.6	1.4	9.6	7.5	0.019	0.058	0.3	1.5	0.4	21.6
25	4-2-15 11:15	73.6	1.3	5.2	65.5	0.050	2.453	39.2	53.2	22.6	35.8
26	21-2-15 22:15	30.6	1.6	6.8	24.8	0.022	0.883	5.9	19.3	0.0	0.0
27	24-2-15 0:45	20.4	2.7	10.8	18.2	0.031	0.077	1.0	4.7	0.0	30.6

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ID	Date	P_{tot} (mm)	$IP_{mean}30$ (mm h^{-1})	$IP_{max}30$ (mm h^{-1})	Q_{dur} (h)	Q_0 (m^3 s^{-1})	Q_{max} (m^3 s^{-1})	Runoff (mm)	Runoff coefficient (%)	AP1d (mm)	AP3d (mm)
28	27-2-15 13:00	20.4	3.1	9.2	31.8	0.026	0.164	2.1	10.3	5.4	11.8
29	14-3-15 18:00	21.6	3.9	10.4	16.7	0.015	0.351	1.7	8.1	0.0	0.0
30	22-3-15 2:45	6.2	4.1	11.2	8.7	0.020	0.056	0.3	5.3	1.4	11.6
31	24-3-15 23:15	75.6	1.8	7.2	42.8	0.033	0.924	13.9	18.4	0.0	7.6
32	4-9-15 3:00	32.4	1.7	19.6	11.0	0.004	0.783	1.1	3.3	0.6	2.6
33	30-9-15 8:15	34.0	2.4	5.6	9.7	0.001	0.132	0.7	2.0	8.0	13.0
34	30-9-15 18:15	27.2	2.0	13.2	16.8	0.037	0.207	1.3	4.9	36.2	47.0
35	1-4-16 16:00	78.8	2.7	14.0	43.5	0.016	0.222	2.4	3.0	0.0	0.0
36	7-5-16 11:15	41.8	2.7	6.4	13.5	0.006	0.092	0.5	1.2	1.6	1.6
37	19-12-16 2:30	46.4	2.3	7.6	27.2	0.012	0.394	4.4	9.5	2.0	16.6
38	20-12-16 9:00	115.8	6.3	21.6	16.0	0.054	2.434	23.5	20.3	24.4	49.2
39	21-12-16 4:30	61.4	4.9	9.6	33.7	0.626	1.565	17.6	28.6	116.0	164.6
40	20-1-17 7:50	28.0	1.8	6.8	13.0	0.013	0.180	1.4	5.0	4.0	9.8
41	20-1-17 17:45	14.6	1.7	7.6	10.7	0.082	1.687	5.9	40.2	28.4	37.2
42	21-1-17 7:00	44.2	2.6	7.6	19.2	0.230	3.942	28.9	65.4	35.4	50.6
43	22-1-17 4:00	5.2	1.0	4.0	5.7	0.360	1.465	4.2	80.8	35.4	50.6
44	22-1-17 16:00	12.2	0.8	4.0	9.0	0.243	0.461	2.9	23.8	44.4	96.2
45	23-1-17 20:52	29.0	2.1	4.8	25.0	0.150	0.355	4.8	16.5	20.2	87.2
46	25-1-17 11:45	5.4	1.2	4.8	31.3	0.036	0.235	0.3	5.4	0.0	51.6
47	27-1-17 17:00	23.0	2.9	11.6	55.0	0.027	0.306	5.6	24.5	0.0	5.6
48	8-2-17 6:30	47.4	2.9	8.8	41.5	0.013	0.843	5.6	11.8	0.0	12.8
49	5-6-17 10:45	67.6	3.0	21.6	5.7	0.028	0.330	0.4	0.7	2.6	2.6
	Min	5.0	0.8	4.0	5.7	0.000	0.036	0.0	0.5	0.0	0.0
	Max	115.8	16.2	77.5	65.5	0.626	3.942	39.2	80.8	116.0	164.6
	Median	29.0	2.9	10.8	19.2	0.0	0.3	2.4	11.8	4.0	13.9
	SD	25.5	3.0	13.8	16.4	0.108	0.857	8.3	16.2	20.6	31.6

Table A4. Main characteristics of the selected events for non-linearity analysis.

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ID	Flood event	Ptot (mm)	$IP_{max}30$ (mm h^{-1})	Runoff (mm)	Runoff coef. (%)	Q_{max} (m^3 s^{-1})	Q_0 (m^3 s^{-1})	AP1d (mm)
42	21-01-2017 07:00	44.2	7.6	28.9	65	3.942	0.229	35.4
18	04-04-2014 03:15	49.8	6.6	7.8	16	1.006	0.002	3.8
2	11-11-2012 22:15	47.3	77.5	6.7	14	1.747	0.008	3.4
48	08-02-2017 06:30	47.4	8.8	5.6	12	0.843	0.012	0.0
37	19-12-2016 02:30	46.4	7.6	4.4	9	0.394	0.012	2.0
20	29-09-2014 13:45	48.6	56.4	4.2	9	2.356	0.015	11.8
36	07-05-2016 11:15	41.8	6.4	0.5	1	0.092	0.006	1.6

Table A5. Main characteristics of the highest runoff event contribution

ID	Flood event	Ptot (mm)	$IP_{max}30$ (mm h^{-1})	Runoff (mm)	Runoff coef. (%)	Q_{max} (m^3 s^{-1})	Q_0 (m^3 s^{-1})	AP1d (mm)
25	04-02-15 11:15	73.6	5.2	39.2	53	2.453	0.046	22.6
42	21-01-17 07:00	44.2	7.6	28.9	65	3.942	0.229	35.4
38	20-12-16 09:00	115.8	21.6	23.5	20	2.434	0.054	24.4
13	19-11-13 02:15	99.3	43.0	22.5	23	1.414	0.021	7.0
39	21-12-16 04:30	61.4	9.6	17.6	29	1.565	0.626	116.0
23	20-01-15 13:00	81.0	12.4	17.3	21	2.094	0.010	9.0

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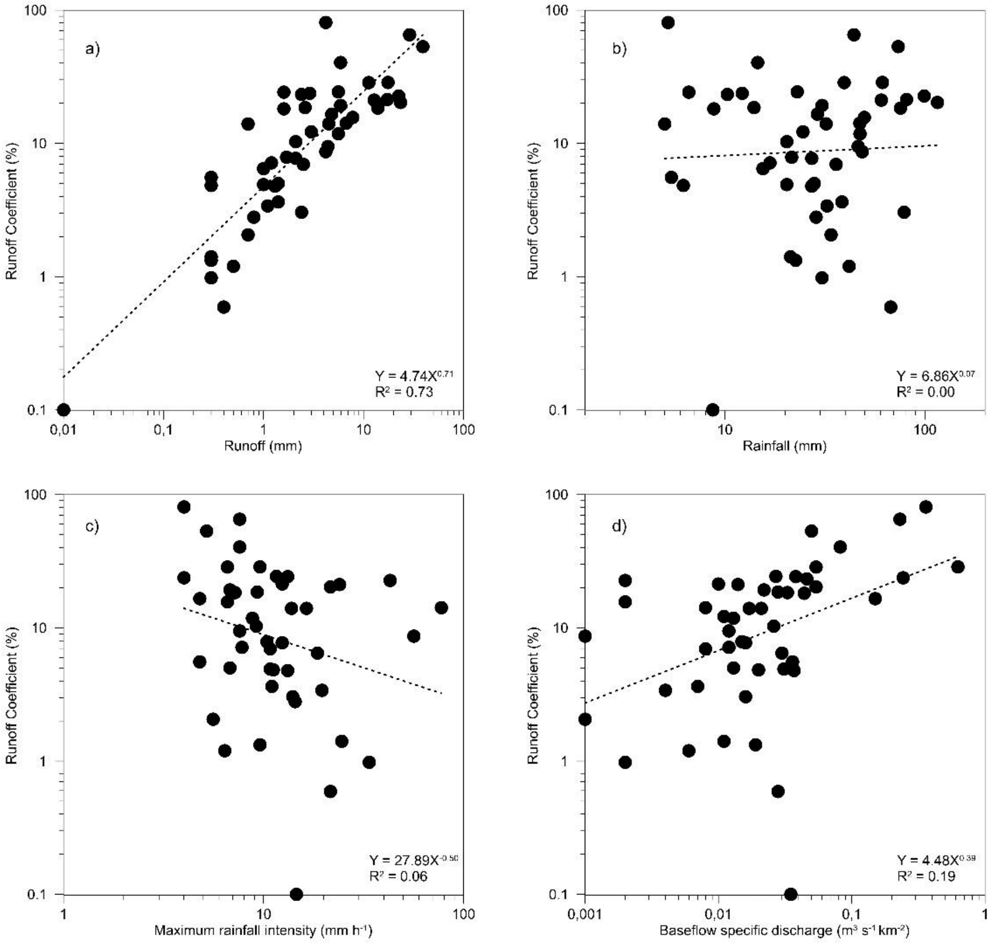

Figure A1. Relationship between (**a**) runoff and runoff coefficient, (**b**) rainfall and runoff coefficient, (**c**) maximum rainfall intensity and runoff coefficient and (**d**) base-flow specific discharge and runoff coefficient at Es Fangar Creek. Dotted lines show significant ($p < 0.001$) fits with a power function.

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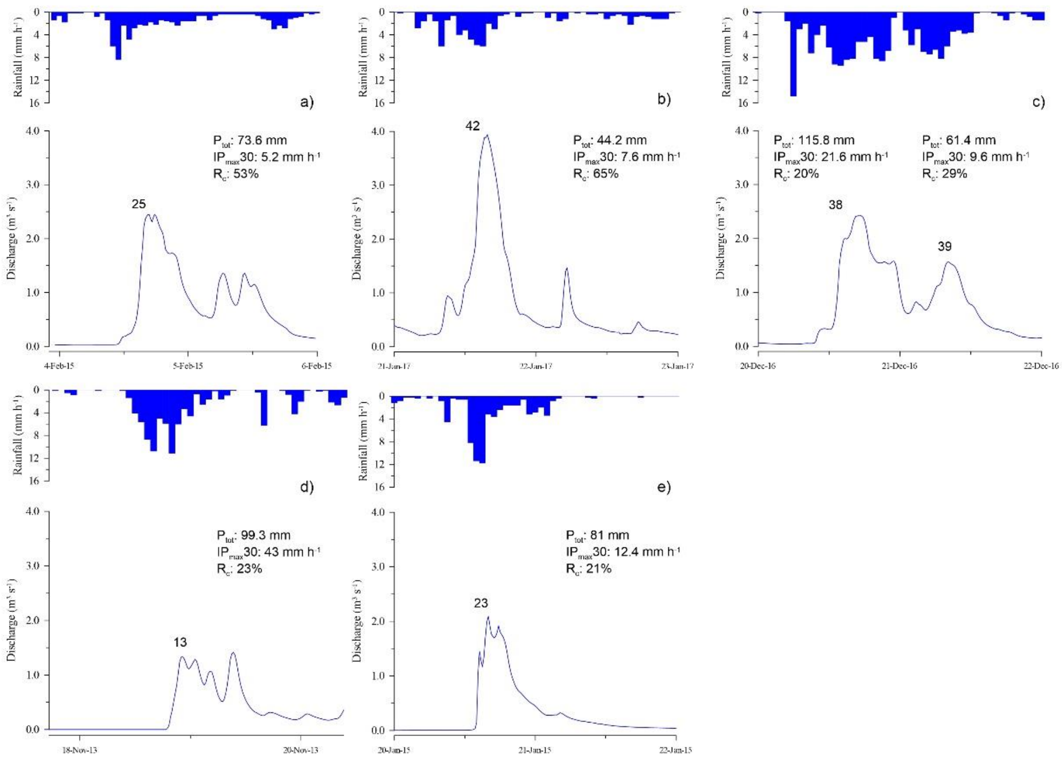

Figure A2. Highest runoff event contribution during the study period (2012-17) at Es Fangar Creek.

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