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Influence of weather types on the hydrosedimentary response in three small catchments on the Island of Mallorca, Spain

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A R T I C L E I N F O

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A B S T R A C T

The influence of the sea and topography are vital factors in the atmospheric processes affecting any island, as they introduce peculiarities in the hydrosedimentary response of fluvial systems. In view of that, the relationship between the surface atmospheric conditions (weather types, WTs), rainfall, runoff and erosion dynamics in three small catchments located in Mallorca were analysed. The catchments are representative in terms of geomorphology and land use but also due to their location within the major rainfall areas previously identified in the island by (Sumner et al., 1993). Data of rainfall, runoff and sediment variables, coupled with calculated WTs were used for the 2013–2017 period. WTs frequency and distribution during this period were compared to the last climatic period reference (1981–2010) to test the climate validity of the study period. The results illustrated how hydrosedimentary response was mostly caused by eco-geographical patterns but also by differences in the response of each catchment to WTs, related to the intrinsic geographical position in the island and different exposures to humid winds. Anticyclonic WT was the most frequent, despite it being only involved in one flood event at the eastern catchment. Conversely, eastern and northeastern WTs generated more than 85% of the total runoff and sediment, representing only 39% of flood events. The understanding of the specific role of WTs on the island's hydrology was improved, considering that freshwater resources are scarce and eco-sociologically crucial.

1. Introduction

The seasonality of precipitation and temperature are considered the main driving factors in the hydrological response of Mediterranean fluvial systems, while it should also be borne in mind that the inter-annual variability of climate can produce fluctuating flow conditions (Bonada and Resh, 2013). In parallel, soil erosion represents a serious worldwide environmental problem affecting agricultural production and terrestrial ecosystems (García-Ruiz et al., 2017; Jie et al., 2002). In this way, the resilience of agricultural soils could be increased if tillage practices were reduced, allowing hillslope soil loss and sediment discharge to significantly decrease by > 75% (Luetzenburg et al., 2020). Spatial analyses have indicated that the distribution of Mediterranean climate areas will be altered by changing global climate dynamics (Deitch et al., 2017) where a projected decrease of precipitation for this century above a certain threshold may also produce a decrease in soil erosion. However, changing precipitation patterns with a higher frequency of great magnitude events can significantly trigger erosion processes (Calsamiglia et al., 2018a; Raclot et al., 2018; Ribas et al., 2020).

The Mediterranean climate is characterized by dry and hot summers, with maximum equinoctial precipitation in spring and autumn. In some Mediterranean regions, such as the Balearic Islands (Spain), the seasonal rainfall distribution is slightly different, showing the autumn maximum,

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but with winter instead of spring being the second rainiest season (Sumner et al., 2001). In addition, rainfalls in this area present an irregular pattern and, especially in summer and autumn, torrential rains occur, due –among other factors– to the high temperatures reached by the Mediterranean Sea (Fumière et al., 2020; Martín Vide and Olcina Cantos, 2001; Serrano-Notivoli et al., 2018). Over the island of Mallorca –the largest on the Balearic Archipelago– the distribution of significant rainfalls is associated with recognized dominant surface circulation types (Sumner et al., 1995a). In addition, elevation and orientation on the island scale were used as descriptive variables, as they provide a strong structure for major rainfall areas in Mallorca (Sumner et al., 1993) producing a high diversity of climates (Guijarro, 1986).

The spatio-temporal variability of rainfall in Mediterranean areas due to the general surface atmospheric conditions, defined by weather types (WTs), have been analysed (Cortesi et al., 2014; Fernández-González et al., 2012; Fernandez-Raga et al., 2017; Hidalgo-Muñoz et al., 2011; Ramos et al., 2015), highlighting that most of the rainfall is produced by just a few WTs, with Western (W), Southwestern (SW) and Cyclonic (C) being the most influential. Accordingly, westerly flow is the most important, followed by the cyclonic. However, in the Mediterranean fringe, easterly flows are more accountable for this than westerly flows. Considering that in the Mediterranean basin rainfall is one of the main factors that affect soil erosion (García-Ruiz et al., 2013; Smetanová et al., 2018), other studies on hydrosedimentary response have also depicted the role of land use and land cover changes (Estrany et al., 2009; García-Ruiz et al., 2008; Kosmas et al., 1997; Lana-Renault et al., 2018; Nadal-Romero et al., 2012), the antecedent moisture conditions (Ceballos and Schnabel, 1998; Fortesa et al., 2020a; Nadal-Romero et al., 2018; Rodrigo-Comino et al., 2017) or the characteristics of rainfall events (i.e. Llorens et al., 2018; Zuecco et al., 2018).

Furthermore, some attention has been also paid to the effects of atmospheric conditions and the relationships between these conditions and runoff and erosion rates (Gilabert and Llasat, 2018; Nadal-Romero et al., 2014; Nord et al., 2017; Pereira et al., 2018; Rodrigo-Comino et al., 2019). The spatial variability assessment of the relationships existing between runoff, sediment yield and WTs in the Iberian Peninsula (Nadal-Romero et al., 2015) and throughout the Mediterranean basin (Peña-Angulo et al, 2019, 2020), suggested four main spatial classes of WT's relationships with rainfall, runoff and sediment yield. However, no research has been carried out, as a downscaling exercise, on the effects of atmospheric conditions and their relationship with runoff and erosion rates on islands, taking into account the contrasted and particular rainfall patterns in these regions, such as Mallorca. It is worthy to be noted that climate of small islands (<5000 km^2) is mostly influenced by their location, area, altitude, orientation and proximity to continental or larger island land masses (Falkland, 1991). As a result, the influence of the sea and topography are vital factors in the atmospheric processes affecting any island, as they introduce peculiarities in the hydrosedimentary response of fluvial systems. In this context, the usefulness of small representative catchments has been recognized worldwide (Latron and Lana-Renault, 2018). These "field laboratories" provide highly detailed quality measurements, and the datasets obtained are rich resources when to comes to evaluating hydrosedimentary responses. The MEDhyCON Research Group controls three small representative catchments in Mallorca Island strategically located: Can Revull, hereinafter Eastern catchment –E-Cat; Sa Murtera, Western catchment –W-Cat; and Es Fangar, Northern catchment –N-Cat (see http://medhycon.uib.cat/study-areas.html); studies about the hydrosedimentary response of these catchments have been published during the last decade (Calsamiglia et al., 2018a; Estrany et al., 2009, 2010, 2019; Fortesa et al., 2020a; García-Comendador et al., 2017).

This study aimed to progress beyond previous hydrological and geomorphological analysis carried out in the three catchments, and to pioneer analysis of the relationships between WTs and hydrosedimentary response in a Mediterranean island. The main objective was to unravel the eco-geographical (location, land uses, topography, lithology and soil types) and climate influences on the three catchments considering that two of the catchments show a similar climate but a different eco-geographical background (E-Cat and W-Cat), and two of them, differences in climate but a similar eco-geography (W-Cat and N-Cat). A through climate and hydrosedimentary analysis, focusing on the rainfall-runoff-erosion response of the catchments by WTs, should clarify the role of WTs as regards this response within these catchments. Therefore, it was decided to (1) compare the hydrosedimentary dynamics between the catchments by using rainfall, runoff and sediment transport variables in each catchment during 2013–2017 as the study period; and (2) evaluate the relationship between hydrosedimentary responses with WTs in each catchment. Previously, the frequency of WTs during the referenced climatic period (1981–2010, 30 years) and the study period (2013–2017) was assessed. Considering the climate change impacts on the availability of natural resources in the Mediterranean Region (García-Ruiz et al., 2011) and specially the decrease of precipitation in Mallorca during the last 30 years (López Mayol et al., 2017), a detailed analysis of hydrosedimentary dynamics and precipitation patterns has become especially relevant.

2. Materials and methods

2.1. Study area

Mallorca has an area of 3640 km^2, being the largest island of the Balearic Archipelago. It is characterised by a basin-and-range topographical configuration. The range areas correspond to uplifted blocks of the Alpine fold belt, mainly composed of Jurassic and Cretaceous carbonates, dolomites and marls (Jenkyns et al., 1990). The basins respond to half-grabens filled by Neogene-Quaternary sedimentary deposits (Silva et al., 2005). The pedology is mainly characterized by weathered relict soils and by fossil soils and soil complexes in coastal alluvial fans (Wagner et al., 2015). Poorly developed soils are common, in accordance with the formation factors, since the current climatic conditions do not allow the genesis of more developed soils (De la Cruz et al., 2001). This geomorphological configuration, characterized by important relief units densely affected by karstification, leads to different exposures to rain bearing maritime winds (Romero and Ramis, 2002). Guijarro (1986) defined the climatic diversity of the Balearic Islands for the period 1961–1980 by applying a multiparametric interpolation, including altitude, topographic complexity, sea distance, terrain gradient, and urban areas. On the island of Mallorca, the Tramuntana Range showed an average annual precipitation >1000 mm, with peaks exceeding 1400 mm; in the central and eastern parts 500–700 mm, and the meridional coast only just reached 300 mm per year. The distinctive topography and size of the island of Mallorca means that rainfall is produced which tends to be variable in time and space. The particularly dense rain-gauge network available on the island of Mallorca (≈100 rain-gauges) facilitated the regionalisation of daily rainfall in Mallorca, which is delimited by the three major coastal basins and both upland regions (see Fig. 1). Sumner et al. (Sumner et al, 1993, 1995b) summarized the main atmospheric mechanisms that generate rainfall over Mallorca, such as (a) local interaction between near-surface airflow and topography at all spatial scales and for all rainfall types, (b) the enhancement provided by sea-breeze effects particularly outside the cooler winter season, (c) conditional instability over the Tramuntana Range when the polar front commonly reaches Mediterranean latitudes during winter, and (d) high rainfall intensity produced by convection during the warmer part of the year, especially in autumn, that is highly variable over small areas and for short durations.

This study was performed using data from three small representative catchments located on the island of Mallorca together with differences in their eco-geographical and climate characteristics (Fig. 1 and Table 1). N-Cat-Es Fangar (Fig. 1c; 3.40 km^2) varies in altitude from 404 m a.s.l. at the highest point to 72 m a.s.l. at the outlet, with a mean slope of 26%. The climate is Mediterranean temperate sub-humid with an average

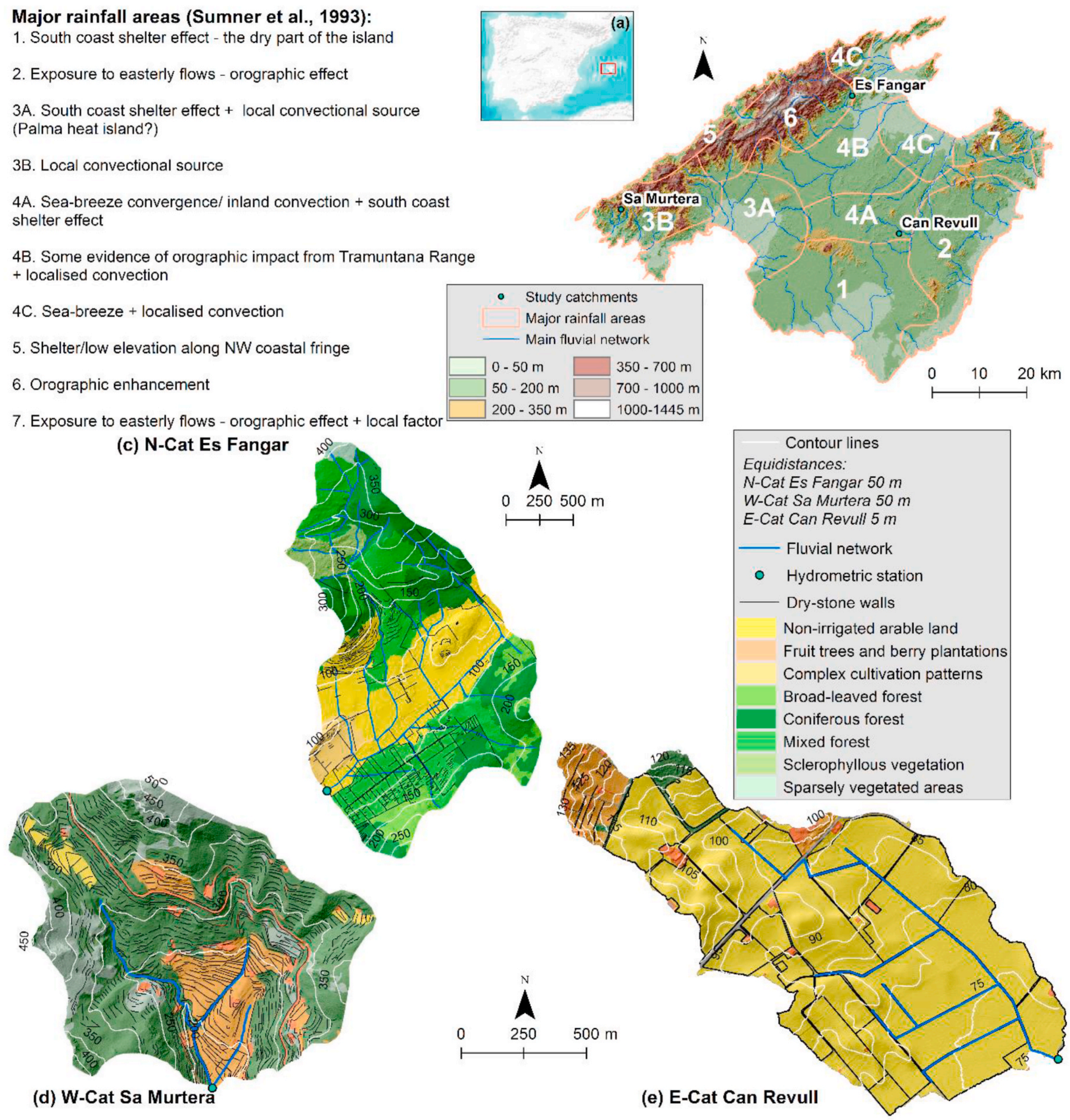

Fig. 1. (a) Location of the island of Mallorca in the Western Mediterranean. (b) A map of the island of Mallorca showing the relief, main fluvial network, major rainfall areas previously identified by Sumner et al. (1993), and the location of the three selected small catchments used in this study. Other maps show land uses and soil conservation structures, topography, stream network and hydrometric stations in (c) N-Cat Es Fangar, (d) E-Cat Can Revull, and (e) W-Cat Sa Murtera catchments.

annual rainfall of 926 mm, being in the 4C and 6 major rainfall areas. It is characterised by the presence of different land use classes including forests, scrublands and agricultural fields (for more information see Fortesa et al., (2020a)).

In W-Cat-Sa Murtera (Fig. 1d; 1.10 km^2) the altitude ranges from 490 m a.s.l. at the highest point to 191 m a.s.l. at the outlet with a mean slope of 40%. The climate is Mediterranean temperate sub-humid with an average annual rainfall of 532 mm, this being in the major rainfall area 3B. Forest predominates in the catchment (66%) together with shrublands and rainfed tree crops (see Table 1), and was also affected by two large wildfires in 1994 and 2013.

E-Cat-Can Revull (Fig. 1e; 1.40 km^2) is located toward the east of the island. The highest point lies at 144 m a.s.l. and the outlet at 70 m a.s.l. with a mean slope of 5%. According to Emberger climate classification (Guijarro, 1986), the climate is sub-humid Mediterranean with an average annual rainfall of 517 mm, as it is in the major rainfall area 4A. Agricultural land use predominates (more information is available in Calsamiglia (2020)).

For more information about the catchments, monitoring and field data acquisition check Estrany et al. (2010), Fortesa et al. (2020a) and García-Comendador et al. (2017). E-Cat and W-Cat show very similar average annual rainfall but contrasting eco-geographical conditions (e.g. differences in land-use and topography). N-Cat and W-Cat evidence contrasting average annual rainfall (926 mm and 532 mm respectively) but very similar eco-geographical conditions, with a similar distribution of land-uses and high values of mean slope. Finally, E-Cat and N-Cat show contrasting eco-geographical and climate conditions.

2.2. Database

A compiled database was created with information recorded during 83 flood events during the hydrological years 2013–2017. A hydrologic

Table 1
Topographical, Climatic and Land use characteristics of N-Cat Es Fangar, E-Cat Can Revull, and W-Cat Sa Murtera catchments.

Topographical	N-Cat Es Fangar	E-Cat Can Revull	W-Cat Sa Murtera
Area (km^2)	3.4	1.0	1.2
Slope (%)	26	5	40
Elevation range (m.a.s.l.)	72–404	70–142	191–490
Mean elevation (m)	162	90	303
River length (km)	3.1	2.4	1.4
Lithology/Soils	N-Cat Es Fangar	E-Cat Can Revull	W-Cat Sa Murtera
Lithology	Massive calcareous and dolomite materials from lower Jurassic and dolomite and marls formations from the Triassic (Rhaetian) in the upper parts. Jurassic and Cretaceous marl-limestones in the valley bottoms	Quaternary alluvial silty-clay-loams supported by an impervious lower-middle Miocene (Burdigalian) layer	Raethian dolomites and Lias limestones in the upper parts Keuper clays and loams in the valley bottoms
Soils	Entisols at the catchment headwaters and Alfisols in the downstream areas		
Climate	N-Cat Es Fangar	E-Cat Can Revull	W-Cat Sa Murtera
Type	Mediterranean temperate sub-humid		
Major rainfall area (Sumner et al., 1993)	4C and 6	4A	3B
Mean annual rainfall (mm)	926	517	532
Variation coefficient of rainfall (%)	23	23	23
Mean temperature (°C)	15.7	16.5	16.5
Rainfall return period of 25 years in 24 h (mm)	180	100	85
Land uses (%)	N-Cat Es Fangar	E-Cat Can Revull	W-Cat Sa Murtera
Rainfed herbaceous crops	32	91	2
Rainfed tree crops		6	14
Forest	63	3	66
Scrubland	5		14
Urban			4

event was defined when a sudden increase in discharge was 1.5 times higher than the initial discharge (García-Ruiz et al., 2005). A hydrograph separation between quickflow and baseflow components was performed through a visual technique based on the breakpoints detected on the logarithmic falling limb of the hydrograph (Maidment, 1993).

In order to characterise the pre-event conditions and event characteristics, for each flood event 12 variables were derived from the rainfall, hydrosedimentary response in the three catchments (Table 2): Total precipitation (Ptot), duration of the rainfall event (Tevent), Rainfall depth accumulated during 1 day before the event (AP1d), rainfall erosivity (RE), maximum 30 min rainfall intensity (IPmax30), total flow (TF), storm flow (SF), mean discharge (Qaverage), maximum peak discharge (Qmax), total suspended sediment load (SSL), maximum suspended sediment concentration (SCCmax), and mean suspended sediment concentration (SSCaverage).

Table 2
Weather types and hydrosedimentary variables with their derived abbreviations.

Classes	Types	Variables (Unit)	Abbreviation
Weather types	Pure	Anticyclonic	A
		Cyclonic	C
	Directional	North	N
		South	S
		East	E
		West	W
		Southwest	SW
		Northwest	NW
		Southeast	SE
		Northeast	NE
Hydrological and erosion	Rainfall	Total precipitation (mm)	Ptot
		Duration of the defined event (h)	Tevent
		Rainfall depth accumulated during 1 day before the event (mm)	AP1d
		Rainfall erosivity (MJ mm h^{-1} h^{-1})	RE
	Runoff	Maximum 30 min rainfall intensity recorded during the event (mm h^{-1})	IPmax30
		Total flow at the end of the event (mm)	TF
		Accumulated stormflow at the end of the event (mm)	SF
		Mean discharge recorded during the event (m^3 s^{-1})	Qaverage
		Maximum peak discharge recorded during the event (m^3 s^{-1})	Qmax
	Sediment yield	Total suspended sediment load (t)	SSL
		Maximum suspended sediment concentration (mg l^{-1})	SSCmax
		Mean suspended sediment concentration (mg l^{-1})	SSCaverage

The weather types (WTs) were also obtained using the Sea Level Pressures for the node latitude 40° and longitude 2.5° of the NCEP/NCAR 40-year Reanalysis Project (Kalnay et al., 1996), for the study period 2013–2017, and the climatology period (1981–2010). WTs were obtained using the objective classification proposed by Jenkinson and Collinson (1977) and modified by Trigo and DaCamara (2000). The 26 WTs of the original classification were aggregated into 10 types, by combining the original, pure directional, and hybrid types: Anticyclonic (A) and Cyclonic (C), and 8 directional types, North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W) and Northwest (NW). The hybrid types were regrouped with the directional types.

2.3. Statistical analysis

First, the climate representativeness of the study period was assessed through a WTs frequency analysis of both the referenced climatological period (1981–2010) and the study period (2013–2017). The frequency of the WTs which occurred during the flood events were also compared against the climatic frequency of the WTs. Second, the hydrological and erosion variables were also statistically evaluated in a comparative assessment between catchments. Two analyses were used to determine the statistical significance of differences between catchments. The significance was evaluated at p-level 0.05. Firstly, the Mann-Witney test (Mann and Whitney, 1947) was applied between pairs of catchments. Secondly, differences between the three catchments were statistically analysed by running a Kruskal-Wallis test (Kruskal and Wallis, 1952) encompassing each hydrological and erosion variable with each WT.

To evaluate the hydrosedimentary impact of WTs at each catchment, data of the different hydrological and erosion variables were grouped by WTs. Accordingly, Ptot, SSL, TF, and SF were presented in relative values (%) per WT; for Tevent, RE, AP1d, Qaverage and SSCaverage, by using median values produced in each WT; and IPmax30, Qmax, and SCCmax were displayed according to their maximum values as they occurred in each WT. All statistical analyses were carried out using R software (R Development Core Team, 2018).

3. Results

3.1. Weather types frequency during the climatological and study periods and flood events frequency

The most frequent WTs during the referenced climatological period (1981–2010) and the study period (2013–2017) were A, N, C, NE and NW. Both frequency distributions were statistically similar (Fig. 2). The most frequent WTs in which flood events occurred in the three catchments were N, NE, C and E, generating more than 75% of the events in all the catchments: 77.4% in E-Cat, 83.8% in N-Cat and 100% in W-Cat. The highest range of WTs generating flood events was detected in E-Cat, as events were also observed during A, NW, S, SE and SW. In N-Cat, events were also observed during S and SE. It is worth noting that under W WTs no flood event was generated.

3.2. Hydrosedimentary response

The total number of events during the period was 37, 34, and 12 in N-Cat E-Cat, and W-Cat, respectively. Six flood events commonly occurred in the three catchments, representing 16% of the total flood events in N-Cat, 6% in E-Cat, and 25% in W-Cat. NE (3 events) was the most frequent WT, followed by N (2) and E (1). Likewise, between pairs of catchments, N-Cat and E-Cat commonly produced 9 flood events, (24% of N-Cat events and 26% in E-Cat), in which NE (3 events) was the most frequent WT, followed by N (2), C (2), E (1), and S (1). Between N-Cat and W-Cat, there were commonly 3 flood events, representing 8% in N-Cat and 25% in W-Cat, with one event for N, C, and E WTs'. Finally, between E-Cat and W-Cat there was 1 common flood event, representing 3% in E-Cat and 8% in W-Cat, which was C WT. The highest number of events was recorded in autumn in E-Cat (48.4%), and winter in N-Cat (48.6%) and W-Cat (50%). In summer, only 2 events were recorded in E-Cat and 1 in N-Cat. This pattern is strongly correlated with the intra-annual rainfall distribution within the island, showing the maximum rainfall in autumn followed by winter.

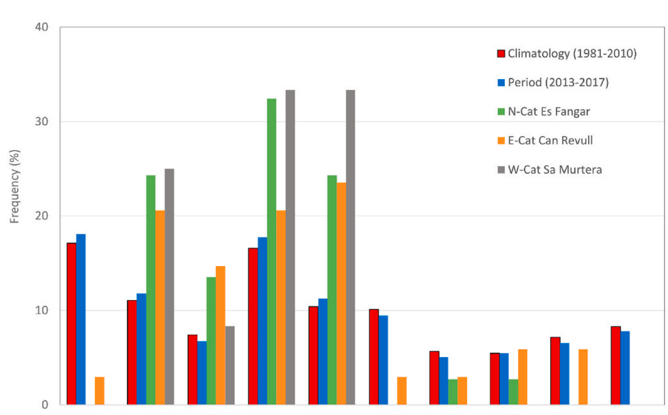

Fig. 2. Frequency (%) for each WT (A, C, E, N, NE, NW, S, SE, SW and W) during the climatological period (1981–2010) and during the study period (2013–2017) for the node latitude 40° and longitude 2.5° of the NCEP/NCAR 40-year Reanalysis Project (Kalnay et al., 1996). Frequency (%) for each WT during flood events recorded in the three study catchments during the 2013–2017 study period.

Fig. 3 shows the rainfall, hydrosedimentary response in the three representative catchments. Despite showing similar rainfall conditions, W-Cat evidenced statistically significant higher values of Ptot than E-Cat. In the same sense, non-statistical differences between N-Cat and W-Cat were observed, despite N-Cat having a higher average annual rainfall. Related to IPmax30, the highest values were recorded in W-Cat, and the only significant differences were detected between E-Cat and N-Cat. It should be remarked that heavy rainfall >40 mm h^{-1} was recorded in E-Cat and N-Cat. The AP1d elucidated similar values in the three catchments.

TF and SF illustrated a similar pattern to Ptot, with the highest values in N-Cat and W-Cat and the lowest values in E-Cat. The differences were only statistically significant for TF and between E-Cat and the two other catchments. In Qaverage and Qmax, N-Cat showed the highest values. The highest Tevent were recorded in W-Cat and N-Cat, while the lowest values in E-Cat, probably related to the lowest Ptot, and TF values in this last catchment.

The lowest values in SSCaverage and SSCmax were recorded in N-Cat, with the highest values being in E-Cat and W-Cat, respectively. Nevertheless, the higher Qaverage values in N-Cat rebalanced the lower SSC with SSL values showing a very similar distribution between the three catchments. To recapitulate, the Mann-Witney test revealed significant differences between the catchments in Tevent, Ptot, IPmax30, TF, Qaverage, Qmax, SSCaverage and SSCmax.

3.3. Weather types, rainfall, runoff and erosion

Fig. 4 shows some statistics distribution for rainfall, runoff and erosion variables according to each WT contribution in each catchment. Fig. 4a–d shows the percentages of Ptot, TF, SF and SSL, Fig. 4e–i the median values of Tevent, RE, AP1d, Qaverage and SSCaverage, and Fig. 4j-l shows the maximum IPmax30, Qmax and SSCmax values.

In the three catchments, Ptot was mainly generated by only four WTs (C, E, NE and N), being these four WTs mostly involved in the runoff generation. Although small differences were observed between the catchments in Ptot from each WT contribution, the catchments response in terms of TF, SF and SSL was quite different depending on the contribution of each WTs. An extreme case occurred in the W-Cat, where only NE WT produced 77% of TF, 80% of SF and 88% of SSL. In E-Cat, the major contribution was produced by two WTs: E, generating 48%, 53% and 57% for TF, SF and SSL respectively; and NE with 46%, 37%, and 40% for these same variables. On the other hand, these same 4 WTs (C, E, NE and N) contributed with high values in N-Cat, with the NE which generated 35%, 33% and 35% for TF, SF and SSL being predominant, although C showed similar values (31%, 33% and 30% for TF, SF and SSL).

AP1d showed the highest median values during NE WT in all catchments (Fig. 4e). The highest median RE was recorded in E-Cat under A WT, for a unique specific event. This value should be compared with median RE values from the other catchments and WTs. However, if this value is discarded, a high contribution of the 4 WTs (C, E, NE and N) generating runoff is detected, but the relatively high values for S and SE WTs in N-Cat should be noted. The highest median values of Qaverage (≈1 m^3s^{-1}) were recorded in E-Cat, specifically during E WTs, whereas for the rest of the catchments and WTs the median values were much lower. Only in N-Cat, NE WT promoted a median Qaverage ≈0.25 m^3s^{-1}. For SSCaverage, the highest median value was also recorded during E WT in E-Cat, with relevant values also in NE and S WTs. In W-Cat, the highest median value was recorded during C WT, although this peak median value was not related with Qaverage. The median values of Tevent were higher during S and N WTs in N-Cat and during N and NE in W-Cat. The maximum values of Qmax were the highest during NE in N-Cat and W-Cat, and during E and NE in E-Cat (Fig. 4k). The highest SSCmax was recorded during E WT in E-Cat, and C WT in the other two catchments. It should also be stressed that W WT was not involved in runoff generation within all the catchments; whereas the A WT only

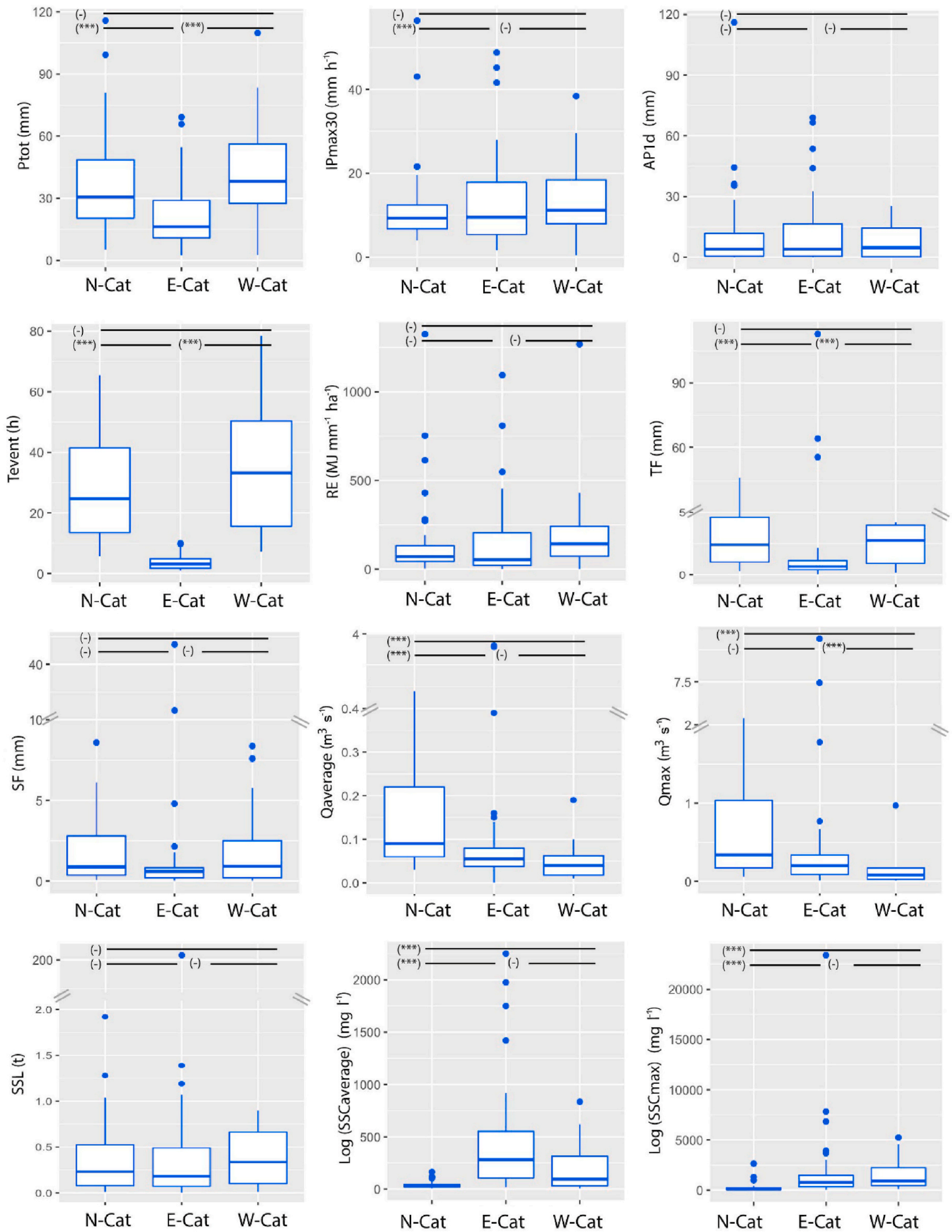

Fig. 3. Boxplots of the variables collected in N-Cat Es Fangar, E-Cat Can Revull and W-Cat Sa Murtera (from left to right and from top to bottom): rainfall (Ptot, Ipmax30, APd1, Tevent, RE), runoff (TF, SF Qaverage, Qmax) and sediment transport (SSL, SSCaverage, SSCmax). Each boxplot uses a box shape to show the range of variation with the first and third quantile, inside the box the median is shown, outside the box the minimum and maximum values are shown, with a whisker, and outliers are shown with points. The significant values at $p < 0.05$ (***) and not significance (–) of Mann-Witney test are paired, highlighted between E-Cat Can Revull and W-Cat Sa Murtera, E-Cat Can Revull and N-Cat Es Fangar, as well as N-Cat Es Fangar and W-Cat Sa Murtera.

produced an intense rainfall event which generated a large and intense flood event in E-Cat.

Two representative synoptic charts (Fig. 5) with the hydro-sedimentary response in each catchment are useful examples to illustrate how a NE (specific C-NE) WT in December 20, 2016 generated a flood event in all the catchments (Fig. 5a-d). The second one, Fig. 5e and f, depicts an A WT situation in May 27, 2014, but only generated a flood event in E-Cat. In the first synoptic situation, a low-pressure system

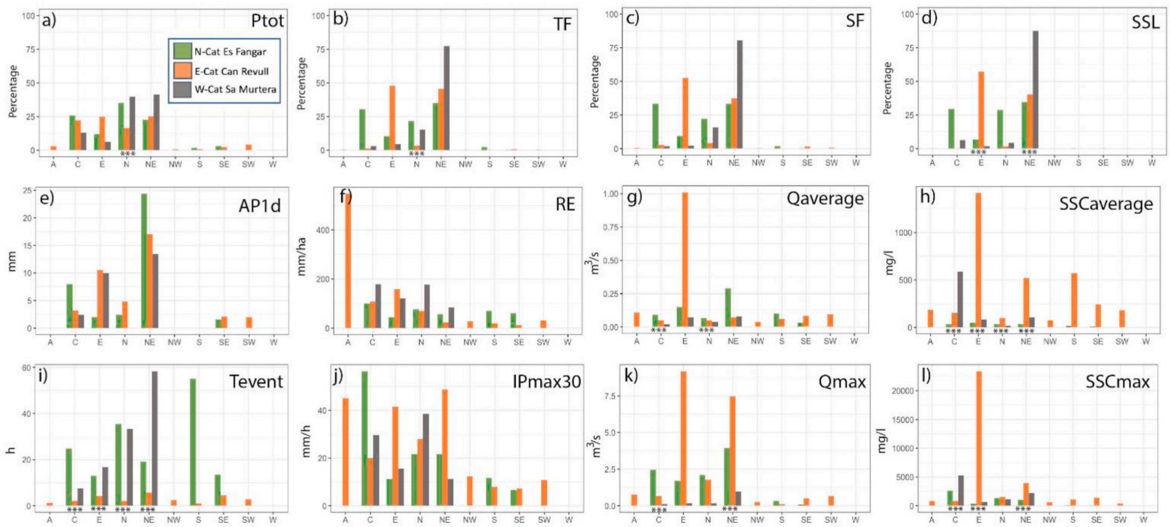

Fig. 4. (a–d) Percentage of Ptot, SSL, TF and SF values; (e–i) Median values of Tevent, RE, Ap1d, Qaverage and SSCaverage; and (j–l) Maximum values of IPMax30, Qmax and SSCmax in each WT (A, C, E, N, NE, NW, S, SE, SW and W) are shown for three study locations (N-Cat Es Fangar, E-Cat Can Revull, and W-Cat Sa Murtera). The significant value at $p < 0.05$ (***) of the Kruskal-Wallis test is highlighted between N-Cat, E-Cat, and W-Cat.

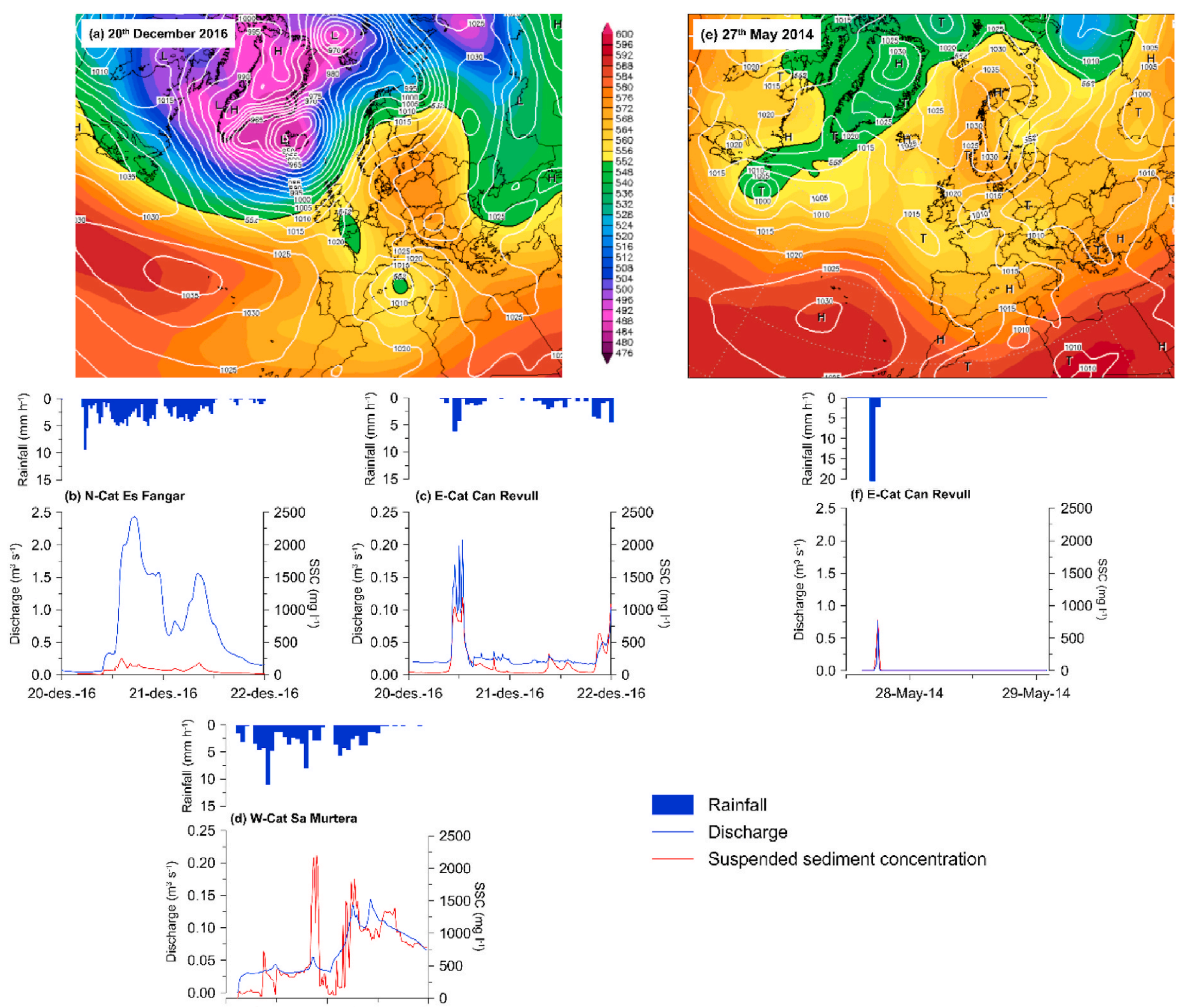

Fig. 5. Geopotential height (shaded) at 500 hPa level (gpdm) and mean seal level pressure (contours) from CFS reanalysis 0.5° for a.) December 20, 2016 and b.) May 27, 2014. Source: www.wetterzentrale.de, Rainfall, discharge and suspended sediment concentrations generated at the three study catchments related with a December 20, 2016 synoptic chart are illustrated in (b), (c) and (d); whilst in (e) the same variables for the May 27, 2014 synoptic chart, which only produced hydrosedimentary response in E-Cat Can Revull.

was located close to Sardinia (Italy), and NE flow influenced the Balearic Islands, affecting the three catchments with a multi-peak hydrosedimentary response. In N-Cat and W-Cat, a clockwise hysteretic pattern was described during this flood event, because the maximum SSC was recorded before the peak Q. In the second synoptic situation, the atmospheric circulation was under an A WT, but guided by a trough at mid-levels. It favoured a local convection triggered by sea breeze convergence, only affecting E-Cat (see Figs. 3 and 4). A flood event was generated by high rainfall intensities with a flashy hydrosedimentary response in which peak Q and SSC were recorded at the same time.

4. Discussion

The analysis of observation data carried out in this paper proved to be efficient when assessing the role of climate in the spatial variability of hydrosedimentary response of three small representative catchments (N-Cat Es Fangar, E-Cat Can Revull and W-Cat Sa Murtera) located in contrasting major rainfall areas of the island of Mallorca (*sensu stricto* Sumner et al., 1993). Moreover, the interaction of natural and anthropogenic factors are involved in the spatial and temporal complexity of hydrosedimentary response in drainage catchments.

4.1. Weather types and flood event frequencies in three small catchments located in contrasting rainfall areas on a Mediterranean island

Under the distinctive climatic conditions explained in section 2, N-Cat accumulated higher average annual rainfall amounts than the two other catchments (926 mm *vs* ≈ 500 mm) because N-Cat is located in the central part of the Tramuntana Range (the 6 major rainfall area; Sumner et al., 1995b) where orographic enhancement promotes the highest rainfall amounts within the Island. This is also the origin of the Ptot differences at event scale, these differences only being significant between N-Cat and E-Cat because this last catchment is located in the structurally gentle alpine relief of the Central Ranges, without orographic enhancement. Statistical analysis evidenced that N-Cat and W-Cat recorded similar Ptot values as both are located in rainfall areas (6 and 3B respectively) where orographic enhancement influences rainfall distribution. Considering the similar eco-geographical background at both N-Cat and W-Cat, W-Cat only recorded 12 flood events during the study period probably indicating that similar synoptic situations –which were involved in runoff generation in N-Cat– were not able to accumulate enough rainfall depth for generating runoff because W-Cat is located on the south-western slope of the Tramuntana Range, with a lower level of exposure to northerly flows.

The most frequent WTs generating flood events in the 2013–2017 study period were N, NE, C and E, which caused more than 75% of the events recorded in the three catchments. The C WT frequency is caused by the cyclogenetic character of the Western Mediterranean basin (Jansá, 1997). Cyclogenesis also influences the frequency of N, NE and E as the presence of a low-pressure system around the Western Mediterranean is usually one of the main factors influencing the low-level flux, as well as the exact location of the high-pressure system. Furthermore, these WTs are those maximizing the low-level circulation over the Mediterranean Sea prior to reach the island of Mallorca, hence facilitating the presence of high values of air humidity, one of the requirements for heavy rainfall events (Raveh-Rubin and Wernli, 2015). In detail, these four most frequent WTs were associated with 84% of flood events in N-Cat, 77% in E-Cat, and 100% in W-Cat. The widest range of WTs generating flood events was detected in E-Cat, with flood events also observed during A, NW, S, SE and SW. This pattern was produced by the location of E-Cat in the 4A major rainfall area of Mallorca (Sumner et al., 1995b), strongly conditioned by local convection or sea-breeze convergence and the location of this catchment in the centre of the Island. Accordingly, when the mid and upper level conditions of the troposphere are suitable, the low-level convergence taking place in this area easily triggers the convection. This situation can even happen during A WT, as the sea-breeze convergence can provide the low-level forcing. In N-Cat, events were also observed during S and SE. Eventually, S and SE WTs –being infrequent in the area– can be forced by a warm/cold front approaching the Western Mediterranean basin from the Atlantic, possibly favouring pre-frontal showers. The location of N-Cat in the southern slope of the Tramuntana Range increases the possibility of these WTs to cause rainfall events due to the uplift effect of the mountains. It is worth noting that under W WTs no flood event was generated, despite being the fourth most frequent WT in the Western Mediterranean (Grimalt et al., 2013). This meteorological situation is not able to produce rain in the Balearic Islands because the westerly flow is of air which is a warm and dry after having crossed the Iberian Peninsula.

4.2. The role of physical factors in the hydrosedimentary response in the three contrasting small Mediterranean catchments

In Mediterranean environments, the relationships between rainfall, runoff and sediment transport are primarily controlled by the physical catchment characteristics (i.e. geology and lithology, soils, slope and topography, land use/land cover), although antecedent conditions and rainfall intensity and its spatial distribution determine the hydrosedimentary response (Fortesa et al., 2020a; García-Ruiz et al., 2015; Huza et al., 2014; Kosmas et al., 1997; Uber et al., 2018). These physical factors and processes driving the hydrosedimentary response in the three contrasting catchments during 2013–2017 study period have enabled the assessment of dynamic patterns at event scale considering that SSC magnitude is clearly associated to the sediment generated by erosion processes produced in its drainage basin. The amount of runoff is also a key factor because the mean SSC is a result of the annual load divided by the annual runoff volume (Walling, 1996). Accordingly, runoff during events (TF, Qaverage and Qmax) were higher in N-Cat than those measured in E-Cat and W-Cat due to the higher amounts of rainfall in N-Cat. Overall, runoff for the three catchments was low and probably caused by the combination of soil conservation practices and calcareous lithology as has been previously demonstrated (cf. Estrany et al., 2010; Fortesa et al., 2020a; García-Comendador et al., 2017). This process is analogous to similar Mediterranean catchments, in which notable transmission losses are mainly caused by lithological variations in permeability (Calvo-Cases et al., 2003; Tzoraki and Nikolaidis, 2007). As Mallorca is mainly composed of carbonate deposits, all the catchments required high antecedent wetness conditions, as depicted by the similar AP1d values in the three catchments.

Rainfall was not the only factor controlling sediment transport in these three catchment systems; i.e., it worked in combination with the production, erosion and availability of sediment which were basically dependent upon land uses and land cover. Consequently, higher SSC were observed in E-Cat and W-Cat compared to N-Cat. In the case of E-Cat, SSCmax values were recorded in middle of the winter when rainfall intensities were high and headwater slopes ploughed and thus bare (Estrany et al., 2009). Despite W-Cat and N-Cat are mid-mountainous catchments with very similar land uses, the severe perturbation in W-Cat –caused by a large wildfire which occurred in July 2013 (García-Comendador et al., 2017)– triggered higher values of SSCaverage and SSCmax than N-Cat. The lowest SSCaverage and SSCmax values were hence recorded in N-Cat –not affected by any perturbation in the last two decades– because typical geomorphic features of karstic rivers and the systematic use of traditional soil conservation practises promoted highly limited sediment delivery processes (Calsamiglia et al., 2018b; Estrany et al., 2009; Fortesa et al., 2020a). In all the three catchments, SSL were significantly lower than those estimated for other Mediterranean climate catchments (see a comparison developed in García-Comendador et al., 2017). Parent material played a significant role in the hydrosedimentary response due to calcareous soils with high rates of infiltration and percolation and very low sediment availability meant that significant source areas were only accessed or eroded during the most extreme events (Estrany et al., 2012; García-Comendador et al., 2020).

4.3. Hydrosedimentary response and weather types in three contrasting small catchments on a Mediterranean island

The influence of weather types on the hydrosedimentary response as discussed here, demonstrated that complex interactions among physical catchment features were the main drivers in controlling the hydrosedimentary response of these three contrasting catchments. The comparison of the frequency distribution of WTs during the study period (2013–2017) against the reference climatic period (1981–2010) confirmed the climatic representativeness of the study period. The most frequent WTs in the catchments during 2013–2017 period were the A, N, C, NE and NW, and the most frequent WTs generating flood events in the three catchments were N, NE, C and E. The A was the most frequent WT during 2013–2017 period, although no flood event was generated in N-Cat and W-Cat. This observation is in agreement with other climate studies developed in the Western Mediterranean confirming that A WT is the most frequent (i.e. Fernández-González et al., 2012; Grimalt et al., 2013), although it is mostly related with low rainfall amounts. E-Cat was the only catchment where A WT generated runoff, but just from one flood event. Nevertheless, it recorded the highest RE and maximum rainfall intensity –typical of convective rainfalls that can be produced in the 4A major rainfall area Sumner et al. (1995b); see Fig. 1)– strongly conditioned by local convection or sea-breeze convergence. Gilabert and Llasat (2018) indicated that extraordinary events are attributed to A patterns in North-western Mediterranean. Although only representing 6% of the total studied events, these authors suggested diurnal summer convection as the generation mechanism of localized floods (also observed in Llasat and Puigcerver, 1997) under hortonian conditions (Estrany et al., 2010). Jansà et al. (2001) showed that the highest rainfall events in the Balearic Islands were related to Mediterranean cyclogenesis (C WT) and eastern flows (NE and E WTs).

The relationships between WTs and the hydrosedimentary response in the three contrasting catchments elucidated how only four WTs (NE, N, C and E) determined this response in all the catchments. The eastern class (E and NE WTs) is strongly related to runoff generation which, in the western Mediterranean, tends to generate intense rainfall events (Peña-Angulo et al., 2019). Additionally, Llop-Garau and Alomar-Garau (2012) –who analysed the rainfall events >200 mm in 24 h in Mallorca for the period 1939-2011– identified the pure C in the Balearic Islands as the most frequent WT related to heavy rainfall, and also identified a relevant contribution of easterly flows, mainly NE and E. This is consistent with other studies that indicated that a small number of WTs are responsible for most rainfall, runoff, and erosion in Mediterranean environments (i.e. Nadal-Romero et al., 2015). In accordance to these authors, the hydrosedimentary response of the studied catchments demonstrated how E and NE WTs produced 91% of sediment (SSL) and 69% of runoff (TF), representing only 39% of the events.

In the N-Cat, located in the 6 rainfall major area (see Fig. 1), topography is the main driving and enhancing mechanism of rainfall generation, but convergence also triggers storms during the warmest part of the year (Sumner et al., 1995b). The orientation of the reliefs SW-NE and also the location of N-Cat in the northernmost part of Mallorca also govern these rainfall patterns, clearly promoting that the northern flow and convergence strongly influenced its hydrosedimentary response. N and NE WTs generated 57% of flood events, 63% of SSL and 57% of TF. C WT also played an important role in sediment transport, especially during the warmest period of the year when the highest average values of RE (i.e., 225 Mj mm h^{-1} h^{-1}) and the maximum average values of SSCmax (509 mg l^{-1}) were recorded when the soil was practically dry but there was more sediment availability on bare agricultural slopes, causing the generation of 24% of SSL and representing 33% of SF. However, the maximum average values of Qmax were recorded under NE WT, mostly produced in winter when wet conditions allowed high runoff responses (Fortesa et al., 2020b).

In the E-Cat, E and NE WTs produced almost the entire SSL at recorded event scale (58% and 41% respectively) representing also only 38% of flood events. E WT also generated the maximum average values of Qmax (4.29 m^3 s^{-1}) and SSCmax (8543 mg l^{-1}) promoted by high average values of RE (i.e., 319 Mj mm h^{-1} h^{-1}). Estrany et al. (2009) reported in E-Cat that most of the sediment was transported during short-time periods (50% of the total load occurred in only 0.13% of the time), being considered extremely ephemeral compared to other Mediterranean counterparts. In this current study, a combined effect has been elucidated from the low E WTs' frequency triggering the highest erosive capacity in a lowland area closest to the eastern coast of the island with easy access to the easterly winds in the 4A major rainfall area of Mallorca.

In the W-Cat, also governed by the orographic rainfall enhancement, N and NE WTs predominated in the hydrosedimentary response, representing 66% of flood events, the 92% of SSL and TF. If compared with E-Cat, E WT was residual with only a flood event because the easterly flow is warmed and dried up air in this westernmost part of the Island. Its location in the 3B rainfall area characterized by steep slopes in a highly diverse topography with a wide variety of geomorphic forms (Gelabert et al., 1992) promote localised convergence and/or convection outside the warmer part of the year (Sumner et al., 1995b). Accordingly, C WT was the third WT –in terms of runoff generation– with three flood events representing 6% of SSL and TF. In a similar fashion, Lana et al. (2007) explained how C WTs can be linked to heavy rainfall events in Balearic Islands.

Other studies demonstrated the high spatial variability observed in Mediterranean environments. Goodess and Palutiko (1998) showed that the E and NE WTs generated 25% of total annual rainfall (only in 10% of the days) in the east of the Iberian Peninsula. Nadal-Romero et al. (2014) in the Central Pyrenees, concluded that the most efficient WTs account for more than 70% of the total sediment yield (in less than 30% of the total events). Similarly, Peña-Angulo et al. (2019) identified an eastern class (E and NE WTs) including the eastern Iberian Peninsula, Morocco and Slovenia sites. However, spatial differences have been observed and previous studies carried out for the whole Iberian Peninsula recognized NW, W and C as the wettest WTs due to Atlantic influence (Cortesi et al., 2014; Trigo and DaCamara, 2000). Likewise, C and N WTs are associated with high values of rainfall and low temperatures (Martín Vide and Olcina Cantos, 2001).

5. Conclusions

The findings outlined above provide a valuable insight into the combined assessment of atmospheric circulation patterns and related rainfall as driven factors of the hydrosedimentary response in three different major rainfall areas of a western Mediterranean island with a distinctive eco-geographical background. Understanding of their specific role on the island hydrology was improved when it is taken into consideration that freshwater resources distribution is mostly determined by climatology; i.e., given that it affects the key input and output components of the water balance.

In this research, a detailed study of the relationships between weather types and hydrosedimentary responses have been developed in three small contrasting catchments located in different major rainfall areas of Mallorca during 2013–2017, when the weather types frequency was statistically similar to that during the climatological period (1981–2010). Results elucidated how similar rainfall amounts at event scale were recorded in the two mountainous catchments where orographic enhancement influenced the rainfall patterns but their different locations within the mountains also conditioned the occurrence of flood events because the northern catchment recorded 50% more precipitation than the western one. The eastern and northeastern weather types generated more than 85% of the total runoff and sediment in the three catchments, but eastern weather type was residual in the

Western catchment. These easterly weather types in the Western Mediterranean Region have a strong tendency to generate heavy rainfall, particularly on the island of Mallorca due to its distinctive topography with a SW-NE orientation of the reliefs. The highest runoff at event scale was recorded in the northern catchment due to the higher amounts of rainfall, although this catchment recorded the lowest suspended sediment concentrations due to typical geomorphic features of karstic rivers and systematic use of soil conservation practices that limited sediment delivery processes. These ecogeographical features also promoted that runoff for the three catchments were low within Mediterranean standards.

This assessment has also helped confirm that there exist differences in the hydrosedimentary response in these three catchments, some of them based on different atmospheric conditions (related to geographical conditions). Due to the particular climatic conditions of the Mediterranean and the particular topography of the study area, with high mountains surrounding the Mediterranean Sea, heavy rainfalls can produce natural hazards and socio-economic consequences. Consequently, the study of the relationships between atmospheric conditions and hydrosedimentary response would be a useful tool together with meteorological forecasting for designing water and soil conservation measures and for mitigating the effects of natural hazards. This being the case, land use and climate change may play an important role in modifying the cycles of water and sediment fluxes in this type of highly contrasted and vulnerable environment that will, ultimately, alter the downstream transfer of water and sediments. It is thus necessary that future studies be focused on (i) analysis of the relationships between WTs and runoff generation mechanism (saturation and hortonian processes) together with previous soil moisture conditions in the catchments, and (ii) an understanding of the behaviour of the atmospheric conditions at different pressure levels.

CRediT author statement

Dhais Peña-Angulo, Conceptualization, Formal analysis, Writing - original draft, Joan Estrany, Conceptualization, Investigation, Resources, Writing - original draft, Supervision, Project administration, Funding acquisition, Julián García-Comendador, Methodology, Visualization, Josep Fortesa, Methodology, Visualization, Miquel Tomàs-Burguera, Conceptualization, Formal analysis, Supervision, Jaume Company, Validation, Data curation, Visualization, Bartomeu Alorda, Validation, Data curation, Funding acquisition, Estela Nadal-Romero, Conceptualization, Validation, Investigation, Resources, Writing - original draft, Project administration, Funding acquisition

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Topographical	N-Cat Es Fangar	E-Cat Can Revull	W-Cat Sa Murtera
Area (km^2)	3.4	1.0	1.2
Slope (%)	26	5	40
Elevation range (m.a.s.l.)	72–404	70–142	191–490
Mean elevation (m)	162	90	303
River length (km)	3.1	2.4	1.4
Lithology/Soils	N-Cat Es Fangar	E-Cat Can Revull	W-Cat Sa Murtera
Lithology	Massive calcareous and dolomite materials from lower Jurassic and dolomite and marls formations from the Triassic (Rhaetian) in the upper parts. Jurassic and Cretaceous marl-limestones in the valley bottoms	Quaternary alluvial silty-clay-loams supported by an impervious lower-middle Miocene (Burdigalian) layer	Raethian dolomites and Lias limestones in the upper parts Keuper clays and loams in the valley bottoms
Soils	Entisols at the catchment headwaters and Alfisols in the downstream areas		
Climate	N-Cat Es Fangar	E-Cat Can Revull	W-Cat Sa Murtera
Type	Mediterranean temperate sub-humid		
Major rainfall area (Sumner et al., 1993)	4C and 6	4A	3B
Mean annual rainfall (mm)	926	517	532
Variation coefficient of rainfall (%)	23	23	23
Mean temperature (°C)	15.7	16.5	16.5
Rainfall return period of 25 years in 24 h (mm)	180	100	85
Land uses (%)	N-Cat Es Fangar	E-Cat Can Revull	W-Cat Sa Murtera
Rainfed herbaceous crops	32	91	2
Rainfed tree crops		6	14
Forest	63	3	66
Scrubland	5		14
Urban			4

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Classes	Types	Variables (Unit)	Abbreviation
Weather types	Pure	Anticyclonic	A
		Cyclonic	C
	Directional	North	N
		South	S
		East	E
		West	W
		Southwest	SW
		Northwest	NW
		Southeast	SE
		Northeast	NE
Hydrological and erosion	Rainfall	Total precipitation (mm)	Ptot
		Duration of the defined event (h)	Tevent
		Rainfall depth accumulated during 1 day before the event (mm)	AP1d
		Rainfall erosivity (MJ mm h^{-1} h^{-1})	RE
	Runoff	Maximum 30 min rainfall intensity recorded during the event (mm h^{-1})	IPmax30
		Total flow at the end of the event (mm)	TF
		Accumulated stormflow at the end of the event (mm)	SF
		Mean discharge recorded during the event (m^3 s^{-1})	Qaverage
		Maximum peak discharge recorded during the event (m^3 s^{-1})	Qmax
	Sediment yield	Total suspended sediment load (t)	SSL
			SSCmax

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(*continued*)

Classes	Types	Variables (Unit)	Abbreviation
		Maximum suspended sediment concentration (mg l^{-1})	
		Mean suspended sediment concentration (mg l^{-1})	SSCaverage

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