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Relationship of Weather Types on the Seasonal and Spatial Variability of Rainfall, Runoff, and Sediment Yield in the Western Mediterranean Basin

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Abstract: Rainfall is the key factor to understand soil erosion processes, mechanisms, and rates. Most research was conducted to determine rainfall characteristics and their relationship with soil erosion (erosivity) but there is little information about how atmospheric patterns control soil losses, and this is important to enable sustainable environmental planning and risk prevention. We investigated the temporal and spatial variability of the relationships of rainfall, runoff, and sediment yield with atmospheric patterns (weather types, WTs) in the western Mediterranean basin. For this purpose, we analyzed a large database of rainfall events collected between 1985 and 2015 in 46 experimental plots and catchments with the aim to: (i) evaluate seasonal differences in the contribution of rainfall, runoff, and sediment yield produced by the WTs; and (ii) to analyze the seasonal efficiency of the different WTs (relation frequency and magnitude) related to rainfall, runoff, and sediment yield. The results indicate two different temporal patterns: the first weather type exhibits (during the cold period: autumn and winter) westerly flows that produce the highest rainfall, runoff, and sediment yield values throughout the territory; the second weather type exhibits easterly flows that predominate during the warm period (spring and summer) and it is located on the Mediterranean coast of the Iberian Peninsula. However, the cyclonic situations present high frequency throughout the whole year with a large influence extended around the western Mediterranean basin. Contrary, the anticyclonic situations, despite of its high frequency, do not contribute significantly to the total rainfall, runoff, and sediment (showing the lowest efficiency) because of atmospheric stability that currently characterize this atmospheric pattern. Our approach helps to better understand the relationship of WTs on the seasonal and spatial variability of rainfall, runoff and sediment yield with a regional scale based on the large dataset and number of soil erosion experimental stations.

Keywords: weather types; rainfall; runoff; erosion; sediment yield; seasonal analyses; Mediterranean basin

1. Introduction

It is well-known that there is a close relationship between atmospheric circulation and climatic variables (i.e., precipitation, snow accumulation, temperature) [1–3]. In addition, precipitation variability is a recognized characteristic of Mediterranean environments [4] and the relationship between rainfall and atmospheric circulation, and its spatial and temporal variability have been widely studied [5,6]. Also, recent research has achieved promising results in the relationship among atmospheric pattern, runoff, and sediment yield [7–9].

The studies of rainfall variability and its causes are of particular interest for hydrology and soil erosion research, because rainfall patterns directly affect runoff and soil erosion and its temporal distribution [10]. There are several studies that analyzed the relationships between rainfall and flood generation, runoff, erosion processes, and sediment yield [11–13], but few studies focused on their relationship with the atmospheric circulation patterns, being one of the leading controlling causes. Caspary [14] analyzed the relationships between the occurrence of floods in southwest Germany and westerly circulation patterns. Another example is the study by Quinn and Wilby [15] that analyzed the relationships between weather types and variations in multi-decadal floods in England, Scotland, and Wales since the 1870s. Recently, Mountreuil et al. [16] and Tylkowski [17] examined the storm surge events associated with erosion and its relationships with weather types.

In the Mediterranean region, different studies have analyzed WTs and environmental variables. Kostopoulou and Jones [18] investigated the relationships between atmospheric circulation patterns and surface climatic elements (temperature and precipitation) in the eastern Mediterranean basin. Fernandez-Raga et al. [19] studied the relation between the kinetic energy and other rainfall characteristic with the WTs in forest plantation in northern central Portugal. Furthermore, Grimalt et al. [20] determined a temporal analysis of the weather types for the western Mediterranean basin over the 1948–2009 period. On the other hand, Royé et al. [21] focused on the spatial and temporal patterns to cloud-to-ground lightning related to the circulation weather types over the northwest Iberian Peninsula. More specific research analyzing the synoptic situations associated with flood episodes were presented by Llasat et al. [22] in Catalonia (Spain) between 1840–1870. Also, Rodrigo-Comino et al. [23] focused on the identification of which WTs were associated to rainfall events were able to generate specific surface flows and soil loss rates in Málaga (Spain).

However, despite the fact that the marked seasonal variability of rainfall regime in Mediterranean areas clearly determines the hydrological and erosion response, few studies have been carried out to define these temporal patterns and the relationships between atmospheric conditions and the hydrological response. Gilabert and Llasat [24] analyzed the circulation weather types associated with extreme floods in Catalonia (North-eastern Spain) and established their temporal patterns. The previous study shows that most synoptic situations were pure cyclonic structures, in both extraordinary and catastrophic events in Catalonia.

Lastly, there are scarce contributions about the efficiency of the WTs related to rainfall events, hydrological responses, and sediment transport particularly at seasonal scale. For the Iberian Peninsula, Nadal-Romero et al. [7] calculated the efficiency of the WTs in sediment transport by means of magnitude-frequency analyses, i.e., 'work done' in physical concept (see the classical contribution of Wolman and Miller [25], Thornes and Brunsden [26], Wolman and Gerson [27], and Thorn [28]), and found that the most efficient WTs in sediment production were westerly flows, although spatial differences were identified.

Following the previous paragraphs, the main objective of this study was to analyze the seasonal variability of the relationships between rainfall, runoff, and sediment yield (SY, used to refer to erosion depths at a plot scale and sediment yield at a catchment scale) with weather types (WTs) in the western Mediterranean basin, specifically Portugal, Spain, and south France areas. The specific objectives were: (i) to detect the seasonal contribution of the different WTs in the magnitude of rainfall, runoff, and SY in the study sites; and (ii) to analyze the seasonal efficiency of the different WTs to result in rainfall event, hydrological responses and sediment production based on the relation frequency and magnitude of

rainfall, runoff and SY, respectively. We hypothesized that: (i) there is a temporal (i.e., seasonal) and spatial pattern in the relationships between rainfall, runoff and SY with WTs in western Mediterranean basin; and (ii) these relationships vary seasonally and differ among rainfall, runoff, and SY, as well as the seasonal efficiency in terms of rainfall, runoff generation, and sediment fluxes of the different WTs. More specifically, we expect that some WTs, despite their high frequency, will contribute little to the generation of rainfall, runoff, and SY (i.e., they are not very effective), while other (low-frequency) WTs will show a very effective contribution to rainfall runoff and SY. We also expect that the efficiency of the WTs will be affected by season. To a certain extent, this study provides seasonal analyses of previous Mediterranean analyses regarding the relationships of hydrological and sediment response to different WTs in the Mediterranean region by Nadal-Romero et al. [7] and Peña-Angulo et al. [8].

2. Experiments

2.1. Data

A database of rainfall events with hydrological and SY information was compiled from a network of experimental plots and catchments (<50 km^2) in the Mediterranean basin. From the database compiled by Peña-Angulo et al. [8], only those study sites with at least 3 years of data were included in this study (Table 1). In that sense, this investigation is focused on 8245 rainfall events obtained from 46 sites (29 catchments and 17 plots) from Portugal, Spain, and France during 1985–2015 period (Table 1). This dataset has involved the collaboration of many researchers, which have allowed us to compile the most extensive collection of real rainfall, surface hydrology and SY in Mediterranean basin at plot and catchment scales (for more details see Peña-Angulo et al. [8]).

The WTs classification relies on the daily sea level pressure dataset from NCEP/NCAR 40-year Reanalysis Project [29]. We used the WTs classification proposed by Jenkinson and Collinson [30], based on the original work of Lamb [31], following the approach suggested by Jones et al. [32], and Trigo and DaCamara [33] for the Iberian Peninsula. Furthermore, the 26 WTs of the original classification defines directional: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW); two WTs dominates by the strength of vorticity: anticyclonic (A) and cyclonic (C); and hybrid types (eight for each C or A). However, we decided to follow the methodology explained by Cortesi et al. [5] and Nadal et al. [6], aggregated in 10 classes. WTs were aggregated into 10 types, the original (A and C), and the combination of pure directional types with hybrid types accordingly to wind direction (NE, E, SE, S, SW, W, NW, and N).

Table 1. Location of study sites (catchments and plots), data collection period (start and end), number of records, and reference of the study sites included in the database

ID	Name	Lat.	Long.	Scale	Start	End	Records	Reference
1	Aisa	42.6744	−0.6119	Plots	1995	2010	637	Nadal-Romero et al. [34]
2	Aixola	43.1529	−2.5014	Catch.	2003	2008	222	Zabaleta et al. [35]
3	Albaladejito	40.0762	−2.1957	Plots	1994	1997	28	Bienes et al. [36,37]
4	Araguás	42.5958	−0.6208	Catch.	2005	2015	360	Nadal-Romero and Regüés [38]
5	Aranjuez	40.0798	−3.5250	Plots	1994	1997	38	Bienes et al. [36,37]
6	Abanilla	38.1994	−1.0917	Plots	1988	1992	40	Díaz et al. [39]
7	Ardal	38.0741	−1.5383	Plots	1989	2000	146	Romero-Díaz et al. [40]
8	Arnas	42.6430	−0.5847	Catch.	1999	2009	96	Lana-Renault et al. [41]
9	Bardenas Norte	42.1677	−1.4547	Plots	1993	2004	118	Desir and Marín [42]
10	Bardenas Sur	42.1550	−1.4191	Plots	1993	2004	89	Desir and Marín [42]
11	Burete	38.0500	−1.7667	Plots	2006	2011	142	Martínez-Mena et al. [43]
12	Can Revull	39.5500	3.1011	Catch.	2004	2007	19	Estrany et al. [44]
13	Corbeira	43.2181	−8.2285	Catch.	2005	2014	651	Rodríguez-Blanco et al. [45]

Table 1. *Cont.*

ID	Name	Lat.	Long.	Scale	Start	End	Records	Reference
14	El Cautivo	37.0027	−2.4404	Catch.	1992	2014	134	Cantón et al. [46]
15	Idanha	39.8467	−7.1667	Catch.	2010	2015	27	Canatario-Duarte [47]
16	La Conchuela	37.8178	−4.8958	Catch.	2006	2011	185	Gómez et al. [48]
17	La Concordia	39.7500	−0.7167	Plots	1995	2012	203	Gimeno-García et al. [49]
18	La Parrilla	37.7333	−5.1500	Catch.	2010	2013	74	Cid et al. [50]
19	La Puebla	41.6645	−0.7239	Plots	1991	2003	187	Desir et al. [51]
20	La Tejeria	42.7363	−1.9492	Catch.	2000	2014	177	Casali et al. [52]
21	Lanaja	41.7797	−0.2889	Plots	1991	2004	163	Sirvent et al. [53]
22	Latxaga	42.7854	−1.4364	Catch.	2003	2014	189	Casali et al. [52]
23	Laval	44.1406	5.6392	Catch.	1985	2014	465	Cambon et al. [54]
24	Marchamalo	40.6822	−3.2147	Plots	1994	1997	48	Bienes et al. [36,37]
25	Mediana	41.4534	−0.7158	Plots	1991	2004	137	Desir et al. [51]
26	Morille	40.8315	−5.7053	Catch.	2002	2010	88	Hernández-Santana and Martínez [55]
27	Moulin	44.1406	5.6392	Catch.	1988	2003	149	Cambon et al. [54]
28	Munilla	42.1912	−2.2908	Catch.	2012	2015	17	Lana-Renault et al. [56]
29	Oskotz	42.9584	−1.7792	Catch.	2003	2014	416	Casali et al. [57]
30	Porta Coeli	39.6590	−0.4890	Plots	1988	2012	240	Andreu et al. [58]
31	Puente Genil	37.4128	−4.8383	Catch.	2005	2011	93	Taguas et al. [59]
32	Rinconada	40.6003	−6.0367	Catch.	2000	2010	331	Hernández-Santana and Martínez [55]
33	Roujan	43.4917	3.3213	Catch.	1992	2015	410	Molénat et al. [60]
34	Santomera	38.2700	−1.1167	Plots	1989	2002	283	Martínez-Mena et al. [61]
35	Sa Vall	39.6386	3.1766	Catch.	2004	2006	77	Estrany et al. [62]
36	Setenil	36.8736	−5.1269	Catch.	2005	2011	121	Taguas et al. [63]
37	Venta Olivo	38.3544	−1.5194	Catch.	1997	2011	108	Castillo et al. [64]
38	Venta Olivo plot	38.3833	−1.1667	Plots	2001	2008	161	Boix-Fayos et al. [65]
39	Vernega Bosc	41.8772	2.9325	Catch.	1993	2011	44	Outeiro et al. [66]
40	Vernega Campas	41.8738	2.9213	Catch.	1993	2011	44	Outeiro et al. [66]
41	Villamor	41.2457	−5.5839	Catch.	2002	2010	87	Martínez Fernádez et al. [67]
42	Navalón	38.9166	−0.8333	Plots	2004	2014	470	Cerdà et al. [68]
43	Ca L'Isard	42.1934	1.8232	Catch.	2005	2012	55	Latron et al. [69]
44	Can Vila	42.1981	1.8234	Catch.	2005	2012	93	Latron et al. [70]
45	Parapuños	39.6105	−6.1333	Catch.	2001	2015	161	Schnabel and Gómez Gutiérrez [71]
46	Montnegre	41.7000	2.5666	Catch.	1998	2002	77	Bernal and Sabater [72]

2.2. Method

The analyses of the temporal variability of the three study variables (rainfall, runoff, and SY) due to the WTs, was done seasonally considering classical monthly aggregation (winter: December, January, and February; spring: March, April, May; summer: June, July, August; and autumn: September, October, November). Each of the 8245 daily events was associated with WTs for individual sites. For each site and daily events, the percentage of rainfall, runoff and SY produced was estimated over the whole period, and we obtained the total percentage in each season for each study site (see Annex Table 1 for more details). First, we checked seasonal differences in the percentage of rainfall, runoff and SY using boxplot and we applied Wilcoxon signed-rank test [73] between seasons for each study variable. After, we analyzed the spatial distribution of rainfall, runoff and SY in each season with maps and we obtained around 25% of the sites in each study variable. The value 25% represents a uniform distribution over the four seasons. Secondly, to identify temporal patterns of the relationships between rainfall, runoff, and SY with WTs, we calculated in each site the seasonal percentage of rainfall, runoff and SY produced by each WTs. The statistical distribution of the percentage of rainfall, runoff, and SY was represented in the boxplots. Then, the analysis of the spatial variability was carried out by

mapping the percentage of rainfall, runoff and SY below and above 2.5% for the different WTs per each season and study site. The 2.5% value represents the uniform distribution of 10 WTs and four seasons.

We applied three specific analyses to detect the most efficient WTs in terms of generating the largest contribution (% of magnitude) of rainfall, runoff and SY in each season. First, we checked whether the frequency of rainfall events during the study period at each site responds to the frequency of the WTs with the aim to verify if the contribution of the WTs to rainfall were due to the frequency of the WTs or due to another cause (i.e., direction of the wind). This analysis was done by comparing the frequency of the WTs in the reference climate period (1981–2010, 30 years) with the frequency of the rainfall events in the study period (1985–2015, 30 years). Secondly, we obtained the frequency of the WTs in each season with the major contribution, more than 5% of magnitude of rainfall, runoff, and SY. Finally, we calculated an efficiency index in each study sites, following the methodology used in Nadal-Romero et al. [7]. The index is defined as the product of the contribution to rainfall, runoff, and sediment yield (% of magnitude) and frequency of rainfall events, hydrological responses and sediment production in the study period. High values for the index represent high efficiency of WTs, and low values mean WTs less efficiency. We obtained the mean of the efficient index in each season, WTs, and study variable. All analyses and figures were carried out using R software (R, version 3.2.3) [74].

3. Results

3.1. Temporal Relationships between Rainfall, Runoff, and Sediment Yield with Weather Types

The seasonal percentage of rainfall, runoff and SY is shown in the boxplots presented in Figure 1. Rainfall peaks in winter and autumn and shows the smallest contribution in summer. Rainfall shows significant differences between seasons, except between winter and autumn and for winter and spring. Runoff occurred mostly during winter and autumn, which, on average, accounted for more than 50% of the total runoff. Yet, the seasonal percentage of runoff was highly variable across sites, especially in winter and autumn, as indicated by the long whiskers of the box plots that could range from 0 to 80%. Runoff shows significant differences between seasons, except between winter and autumn. SY variability is very large for all the seasons and no significant differences were observed between the seasons, only occur between summer and autumn. The median SY percentage values of the seasons reach the highest contribution in autumn, followed by spring, winter, and summer.

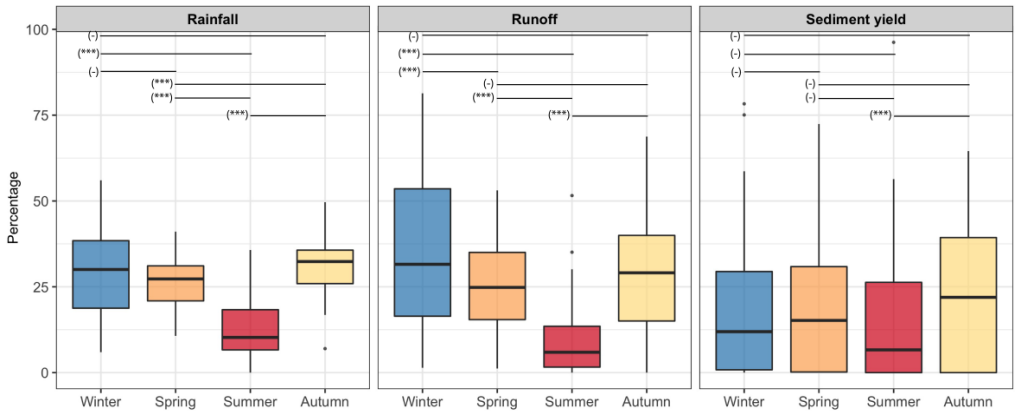


Figure 1. Seasonal distribution of the percentage of rainfall, runoff, and sediment yield. The ends of the box are the upper and lower quartiles, so the box spans the interquartile range, the median is marked by a vertical line inside the box, and the whiskers are the two lines outside the box that extend to the highest and lowest observations. The significant value at $p < 0.05$ (***) and not significance (-) of Wilcoxon signed-rank test are paired remarked between winter and spring, winter and summer, winter and autumn, spring and summer, spring and autumn, and summer and autumn.

Figure 2 shows the spatial distribution of the seasonal percentages of rainfall, runoff, and SY, below and above 25% of annual value. Sites with >25% rainfall in winter, spring and autumn show a fairly homogeneous spatial distribution, while on the contrary in summer, high rainfall contribution values are only reached in the northeastern inland region. Runoff follows a similar pattern in sites with >25% contribution in winter, spring and autumn, while in summer high values are only reached in the eastern area. Last, SY distribution shows less spatial coherence and high seasonal spatial variability: winter and spring show a fairly homogeneous spatial distribution, while for summer and autumn sites with >25% are mostly located in the eastern area.

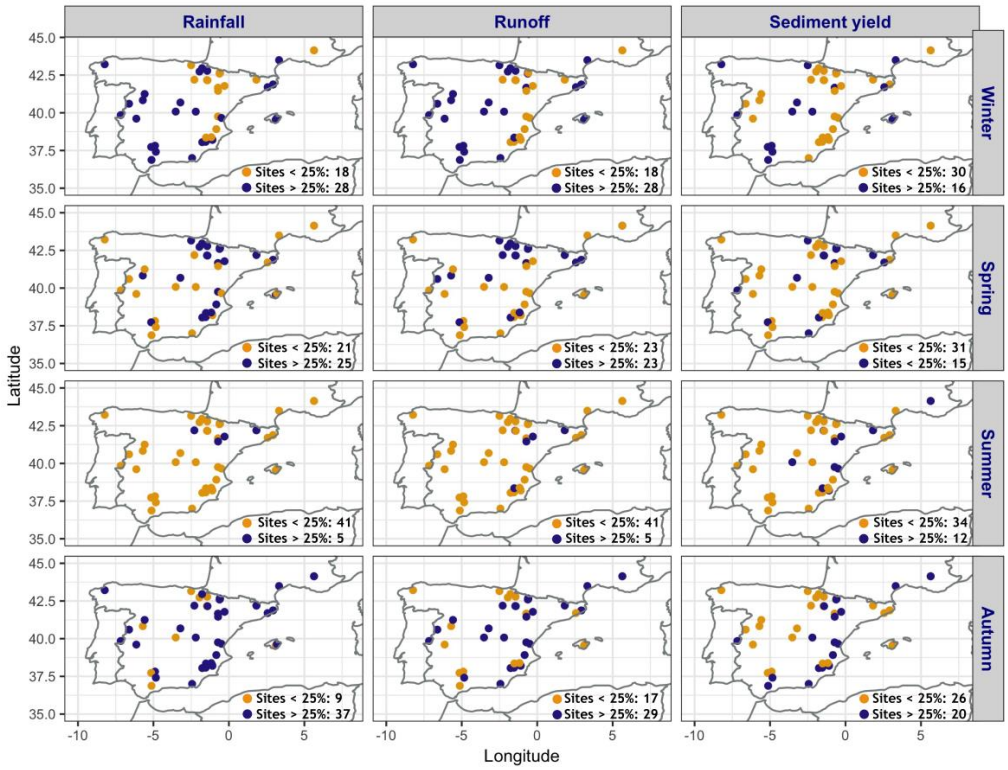


Figure 2. Spatial distribution of the percentage of rainfall, runoff, and sediment yield for each season in the study sites, and the number of sites with values higher or lower than 25%.

The seasonal percentage contribution of rainfall, runoff and SY by different WTs are shown in Figure 3. The WTs with more generalized high percentage contribution are C (cyclonic) and W (west) types. The C type contributes to the three variables in all the seasons, reaching the lowest contributions in summer SY. The westerly types (W, NW, and SW) present a high contribution in rainfall and runoff for winter, spring, and autumn, and to a lesser extent in summer SY. The easterly types (E, NE, and SE) have a high contribution in summer rainfall and runoff, and also, in relative terms, in summer SY. North WT shows a high contribution for rainfall in spring and autumn, and for runoff and SY in spring. South WT contribution is mainly concentrated in spring in rainfall, runoff, and SY.

The seasonal percentage of rainfall, runoff, and SY produced under WTs shows a high spatial variability (Figure S1: rainfall, Figure S2: runoff, Figure S3: SY). Figure 4 is an example and shows the spatial distribution of rainfall, runoff, and SY below and above 2.5% under W and E types. In winter, and also in spring and autumn, westerly WTs produce preferably the highest rainfall and runoff values in the central-western areas, being no so clear for the SY response. Contrarily, easterly WTs predominate in summer, especially in the northeast and eastern part of the Iberian Peninsula. In general, the seasonal percentage of SY distribution accordingly to WTs is more heterogeneous than the observed in rainfall and runoff, suggesting a more complex relationship between SY and WTs than rainfall or runoff.

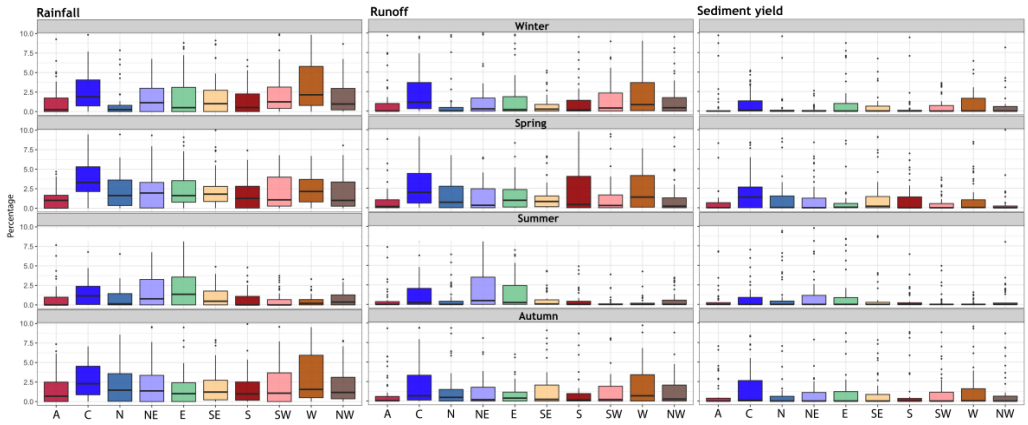


Figure 3. Seasonal distribution of the percentage of rainfall, runoff and sediment yield for the different WTs by each season. The ends of the box are the upper and lower quartiles, so the box spans the interquartile range, the median is marked by a vertical line inside the box, and the whiskers are the two lines outside the box that extend to the highest and lowest observations.

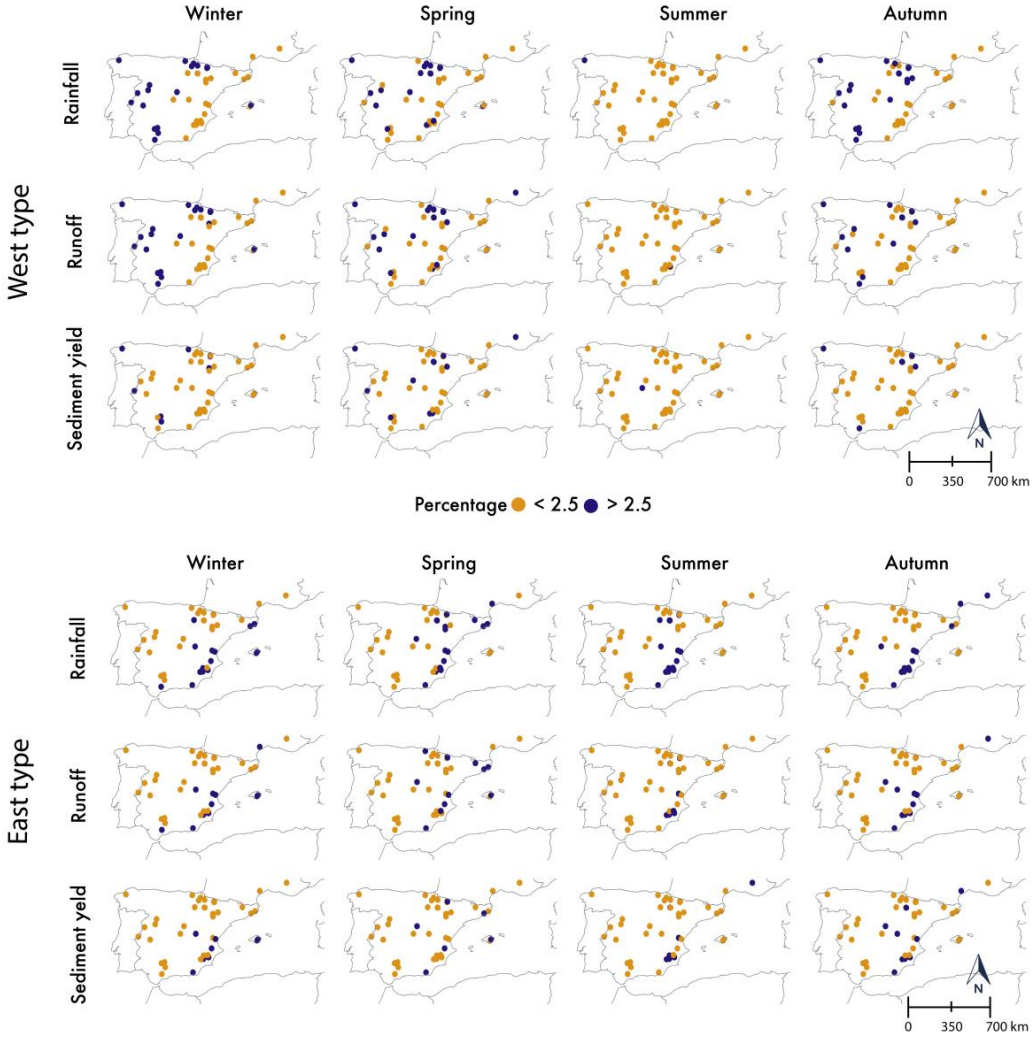


Figure 4. Spatial distribution of the percentage of rainfall, runoff and sediment yield in the west (W) and east (E) weather types for each season. The 2.5% value represents the uniform distribution of 10 WTs and 4 seasons.

3.2. Seasonal Efficiency of Weather Types to Produce Rainfall, Runoff, and Sediment Yield

The analysis of the WT efficiency in rainfall, runoff, and SY shows great differences among them. Figure 5 shows the seasonal frequency distribution of each WTs during the reference climate period (1981–2010) and the rainfall events studied (1985–2015). The most frequent WTs during the climate reference period are A, N, NE, E, SE, and eventually C (summer), W, SW, and NW (winter). Differently, the WTs that show a high rainfall event frequency are C (spring), SW, W, and NW (winter), with noticeable contributions of NE and E through the year. The anticyclonic (A) WT is the dominant atmospheric pattern in the western Mediterranean area, although it does not correspond with a high frequency of rainfall events. This is a logic result, because A WT is usually associated with atmospheric stability, not only in summer season but also in winter. Contrarily, the low frequency of cyclonic (C) WT during the reference period is coupled with a high frequency of rainfall events, especially in spring and autumn, which is in line with its characteristic instability, sometimes associated to polar front depressions and to a lesser extent to low-pressure systems developed in the inland areas as a consequence of intense heating during warm season (i.e., thermal lows).

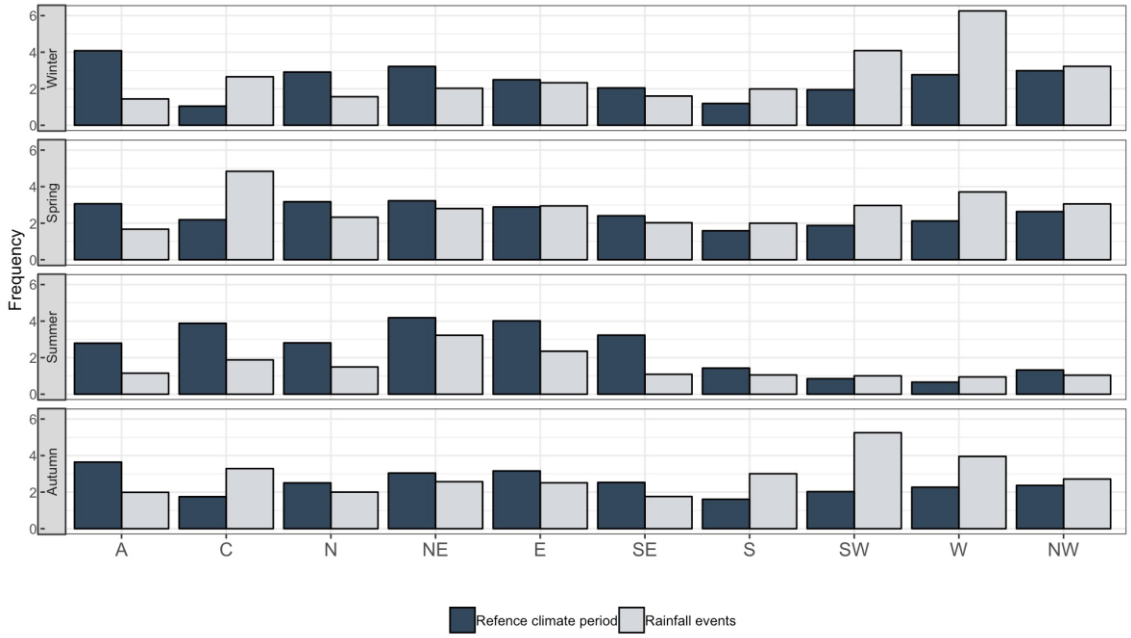


Figure 5. Frequency of the reference climate period (1981–2010) and in the study events (1985–2015) in the WTs in each season.

On the other hand, westerly flows (W, SW, and NW) show a moderate frequency in the reference climate period, but they appear to be very frequent in rainfall events, except in summer. The south WT shows a low frequency in the reference climate period and rainfall events during the year, except during autumn. For the easterly flows (E and NE) the frequency in the reference climate period and rainfall events is very similar. Lastly, the SE and N types show a high frequency in the reference climate period but a low frequency in rainfall events throughout the year.

These results are in agreement with the information shown in Figure 6, which represents the frequency of the WTs with major contributions (more than 5%) of rainfall, runoff, and SY in each season. The westerly flows (W and SW) show a high contribution, producing the maximum values in rainfall and runoff in winter and autumn. In addition, the S and SE types show maximum contributions in autumn. The C WT produces the highest contribution in spring and autumn, while the E and NE WTs produce the maximum values in summer. It should be highlighted that the low values related to SY contribution especially in winter, and the high contribution of C, SW, and E WTs in autumn.

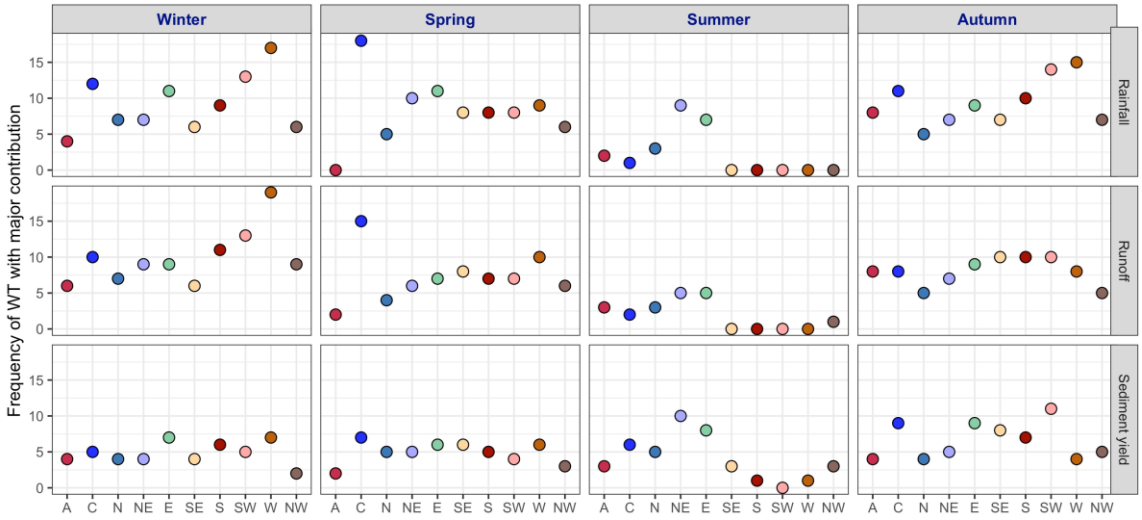


Figure 6. Frequency of the weather types with the major contribution (more than 5%) of the percentage of rainfall, runoff, and sediment yield in each season.

The efficiency to produce rainfall, runoff and sediment discharge of each WTs varies substantially in each season (Figure 7). The westerly WTs (W and SW) are very efficient (low frequency and high contribution) in autumn and winter, and the NW type is also very efficient related to rainfall and runoff values in winter. The C type is very efficient related to rainfall and runoff in spring. On the other hand, the NE and E WTs are efficient in summer, and the E and S types in autumn. The A, N, and SE types show low efficient values in all variables and seasons.

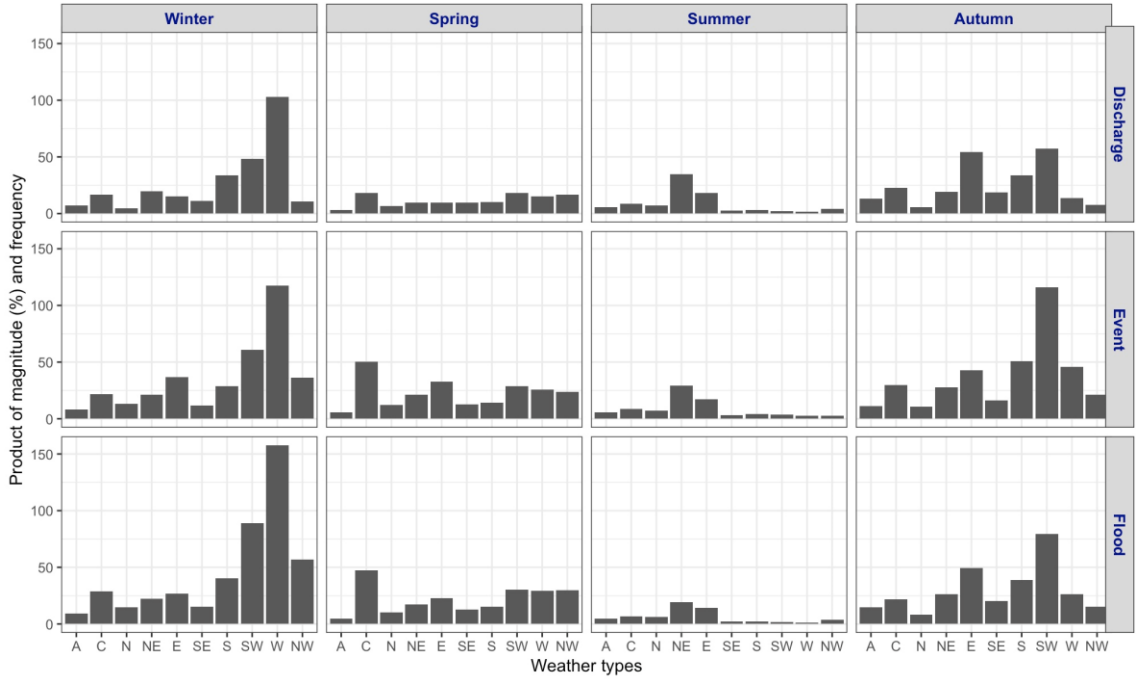


Figure 7. Efficiency index calculated by the product of magnitude (%) and frequency of the seasonal rainfall, runoff, and sediment yield for the different weather types.

4. Discussion

4.1. Seasonal Differences in the Contribution of Rainfall, Runoff, and Sediment Yield Produced by the Weather Types

The western Mediterranean basin is located in the transition between tropical and mid latitudes in which atmospheric dynamic interacts with a complex topography to produce a high spatio-temporal variability of rainfall, and where climate models recurrently show a very low capability to forecast and predict rainfall [75]. In this region, general results from previous studies have suggested the potential of using atmospheric patterns (i.e., weather types) to analyze spatial variability of rainfall [5], runoff, and SY [7,8,23], that could help us to understand the spatial variability on the response of natural systems [76].

We show that the spatial variability of rainfall strongly determines the spatial variability of the runoff and SY responses across the western Mediterranean basin. This influence holds through the year, though spatial patterns change across seasons. Our results are in line with previous studies showing that seasonal patterns of rainfall and runoff are highly variable depending on the study sites [77–79]. For example, Smetanova et al. [80] performed an analysis of the seasonal distribution of the sediment for different environments in the Mediterranean. The highest SY response occurs in spring and summer for catchments with oceanic climates, while catchments with semi-arid or dry climates experience minimum values in summer. Tuset et al. [81] identified in the northeast of the Iberian Peninsula (Ribera Salada catchment) that low runoff and sediment values are recorded in winter. Meanwhile the majority of runoff and sediment is produced in spring, while little runoff and high amount of sediment is produced in summer and autumn. Lana-Renault et al. [82] showed a strong seasonality in the hydrological response in the Arnás catchment (Central Pyrenees), with high responses during winter and spring, and low responses during summer and early autumn. At slope scale, the influence of rainfall intensity and distribution was also a key factor in soil erosion studies. Topographical measurements carried out in vineyards by Martínez-Casasnovas et al. [83], measurements carried out in the field with USLE research plots in arid [84], and wet climates [85] as well as by means of small research plots [86], show how relevant rainfall intensity and volume is to determine soil erosion rates.

This spatio-temporal variability in runoff and sediment patterns is well captured in the maps presented in this study. In addition, our results show that this variability can be associated, at least to some extent, with the occurrence of different weather types. These finding stresses that the seasonality of atmospheric conditions plays an important role on determining runoff and SY patterns, and thus, a better understanding of atmospheric circulation can help us to understand hydrology and sediment export in Mediterranean regions.

The high seasonal variability of rainfall, with high values in winter and autumn, and very low values in summer, is also reflected spatially. That means that the rainfall, runoff, and SY show a homogeneous spatial contribution in winter, and a high heterogeneity in summer, and the WTs help to explain their spatial and seasonal distribution. The westerly flows (SW and W) are frequent in winter and autumn, and also have a high contribution to rainfall, runoff, and SY throughout the territory. The westerly flows are usually loaded with moisture from the Atlantic Ocean (wet air masses and frontal systems governed by the North Atlantic Oscillation), which increases rainfall, and therefore runoff and SY from west to east across the Iberian Peninsula. Furthermore, these flows do not find a topographic barrier, and then they can affect extended inland areas except for the eastern Mediterranean coastland and south of France. On the other hand, the frequency of these westerly flows in summer is reduced as a consequence of the northerly migration of pressure systems [5]. During summer, the easterly flows (NE and E) predominate, in such a way that the greatest contribution of rainfall, runoff, and SY comes from these WTs, which have a limited spatial influence to inland by the effect of topographic barriers parallel to the coast. These easterly flows that come from the Mediterranean Sea have different origins: (i) sometimes are related to the presence of a thermal low over northwestern Africa; (ii) but most commonly are related with a low pressure system which has become completely

displaced (cut-off) from westerly current and moves independently, particularly at the end of summer, spring, and autumn; and (iii) finally, these WTs sometimes originate by orographic depressions (as Ligura and Gulf of Lion low). In all the cases, these easterly flows find a mountain barrier parallel to the coast of the Iberian Peninsula from northeast to the southeast (the Catalan Coastland Range, the Iberian System, Subbetic Systems) that limit their influence exclusively to the Mediterranean coastland [5].

Some specific cases should be highlighted such as C (cyclonic) weather type, which is characterized by a homogeneous influence at the spatial level and through the year in the analyzed events, with two relative peaks in spring and autumn. Contrarily, the A (anticyclonic) type has very little spatial and seasonal influence. These observations are in agreement with the results obtained by Morán-Tejeda et al. [87] that analyzed the hydro-meteorological response of major floods in Spanish mountain rivers, and concluded that the floods were more frequent under cyclonic (26%), as well as under advection of westerly flows (26% of total floods) and easterly flows (22% of total floods).

The analysis of the spatial and temporal distribution of rainfall, runoff, and SY contributions under each WT showed important differences in the magnitude of the explored relationships. Despite the high spatial variability observed, the present research found some clear spatial associations between some WTs and rainfall, runoff, and SY during several specific seasons. Our research revealed that rainfall or runoff events can take place under any type of weather type, with seasonal and spatial patterns, although C and advection from SW and W (in winter and spring) and E and SE (in summer and autumn) are the most dominant WTs in the western and eastern of the study area, respectively. SY showed a high spatial and temporal variability, suggesting that is a more complex and locally dependent processes than runoff, as it is dependent also on relief, connectivity, and land cover and land management practices [86,88].

4.2. Seasonal Efficiency of the Different Weather Types Related to Rainfall, Runoff, and Sediment Yield

A crucial characteristic to determine the role played by the WTs on the temporal and seasonal variability in the study period is firstly provided by WTs comparison of the frequency between the whole climate reference period (1981–2010) and the rainfall events observed during the study period (1985–2015). These comparisons show that despite of the high frequency of the anticyclonic WT their contribution to rainfall, runoff, and SY is low, and presents the lowest frequent in runoff and sediment production. The high frequency of A type has also been also observed in other Mediterranean areas [5,6,20,89]. These authors also indicate that the seasonal rainfall contribution of A type is quite small compared to its frequency. The predominance of the A type is strongly related to the migration of the Azores anticyclone towards the Iberian Peninsula [90]. However, in summer, under anticyclone situations, high values of runoff and sediment production can be recorded locally in high mountain areas due to the capacity of mountain ranges for triggering convective activity at the local scale because of high isolated radiation [87]. These local processes cannot be detected in this study due to the coarse spatial resolution of the applied reanalysis grid.

The frequency of easterly (NE, SE, E) flows during the climate reference period is higher than the frequency of rainfall events. In addition, important seasonal differences can also be also observed. For example, N and NE are the most frequent WTs in summer. Gilabert and Llasat [24] also observed this seasonal pattern analyzing WTs associated with extreme floods in the northeastern Mediterranean. These authors suggested that in summer there is an increase of the frequency of NE WTs, due to the relatively cool air that favors instability of the air mass and promotes precipitation.

WT frequency analyses in rainfall, runoff, and SY reveal again the classical question about the temporal distribution of the processes, the relationship between rainfall and runoff, and those with sediment yield. The westerly and cyclonic situations in winter and autumn are those that have a higher frequency in rainfall events [91] due to frontal systems that transport air masses with moisture from the ocean to the Iberian Peninsula, while easterly WT predominance in spring and summer suggest different mechanisms. Summer events are associated with short, intense, and localized rainfalls, often associates to thermal convective lows and high rainfall intensity. Morán-Tejeda et al. [87] suggested that large

rainfall amounts in the western Mediterranean basin are more intense and concentrated in events of a few hours, and have usually a convective origin due to the occurrence of cold depressions in the middle troposphere (cut-off-low) with advection of warm flows from the Mediterranean. Similar results were found in different areas of the Mediterranean basin by Ramos et al. (2014). Gilabert and Llasat [24] observed that floods were most common in autumn, followed by summer. Furthermore, in autumn, cyclonic situations were the most common, with more than 50% of the floods, while in summer accounted for approximately 40% of the floods.

The efficiency of each WTs in relation to rainfall, runoff, and SY varies substantially in each season. The westerly WTs are very efficient in autumn and winter, while easterly WTs are efficient in summer. There are a few studies that analyzed the efficient of the WTs related to the rainfall, runoff and SY. Nadal-Romero et al. [7,92] evaluated the efficiency of WTs on SY, and they found the most efficient WTs is westerly flow. We have found the westerly WTs are very efficient, but only in winter and autumn due to their high frequency, and the opposite in summer.

The results obtained in this study have encouraged further topics related to atmospheric patterns and the hydrological and sediment yield response. In that sense, future research should focus on: (i) evaluation the role play by extreme events and their relationships with different WTs; (ii) analyze the relationships between rainfall intensity and WTs; (iii) investigate different responses and WTs based on land use and land covers related to different runoff processes (infiltration excess overland flow and saturation excess overland flow).

5. Conclusions

This study presents spatial and temporal patterns in the relationships between WTs, rainfall, runoff, and sediment yield in the western Mediterranean basin. Overall, the main results of this study can be summarized as follows:

- The most frequent WTs is the anticyclonic, however it tends to produce a small number of rainfall events, and does not significantly contribute to the rainfall, runoff, and sediment yield (low efficiency).
- Westerly WTs (NW, W, and SW) predominate throughout the western Mediterranean basin and generate the highest rainfall, runoff, and sediment yield during the cold period (winter and autumn).
- Easterly WTs (NE, E, and SE) dominate rainfall, runoff, and sediment yield production during the warmer seasons (spring and summer).
- The spatial influence of the westerly WTs is particularly large, except in the eastern study area, during the cold period, and decreases in summer. Cyclonic WTs spread their influence over extensive areas of the western Mediterranean region. The easterly WTs predominate during the warm period and it is located on the Mediterranean coast of the study area. Other WTs provide a more localized contribution over relative narrow areas.
- Similar patterns for rainfall and runoff configurations were observed for sediment yield, although the last was influenced by a very marked spatial and temporal variability.
- This study indicates that the WTs analyses offer a high potential research for the design of water resources management and soil erosion measurements, because they play a key role on determining rainfall, runoff, and sediment yield response and its temporal and spatial patterns. Finally, the results suggest that the WTs approach could be a useful tool for soil erosion modelling research and climate model scenarios.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4433/11/6/609/s1, Table S1: Seasonal distribution of the percentage of rainfall, runoff, and sediment yield in each study site; Figure S1: Spatial distribution of the percentage of rainfall in the weather types for each season; Figure S2: Spatial distribution of the percentage of runoff in the weather types for each season; Figure S3 Spatial distribution of the percentage of sediment yield in the weather types for each season.

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Conflicts of Interest: The authors declare no conflict of interest.

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