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Research papers

Spatial variability of the relationships of runoff and sediment yield with weather types throughout the Mediterranean basin

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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

Soil degradation by water is a serious environmental problem worldwide, with specific climatic factors being the major causes. We investigated the relationships between synoptic atmospheric patterns (i.e. weather types, WTs) and runoff, erosion and sediment yield throughout the Mediterranean basin by analyzing a large database of natural rainfall events at 68 research sites in 9 countries. Principal Component Analysis (PCA) was used to identify spatial relationships of the different WTs including three hydro-sedimentary variables: rainfall, runoff, and sediment yield (SY, used to refer to both soil erosion measured at plot scale and sediment yield registered at catchment scale). The results indicated 4 spatial classes of rainfall and runoff: (a) northern sites dependent on North (N) and North West (NW) flows; (b) eastern sites dependent on E and NE flows; (c) southern sites dependent on S and SE flows; and, finally, (d) western sites dependent on W and SW flows. Conversely, three spatial classes are identified for SY characterized by: (a) N and NE flows in northern sites (b) E flows in eastern sites, and (c) W and SW flows in western sites. Most of the rainfall, runoff and SY occurred during a small number of daily events, and just a few WTs accounted for large percentages of the total. Our results confirm that characterization by WT improves understanding of the general conditions under which runoff and SY occur, and provides useful information for understanding the spatial variability of runoff, and SY throughout the Mediterranean basin. The approach used here could be useful to aid of the design of regional water management and soil conservation measures.

1. Introduction

General climatic conditions, particularly precipitation, are one of the most important factors that trigger soil degradation. The seminal paper of Langbein and Schumm (1958) identified a complex non-linear relationship of specific sediment yield with annual precipitation, based on the link between moisture conditions and plant cover. Thus, a rapid rise in sediment yield occurs with increasing rainfall in regions that have an annual rainfall of 100–500 mm and little protection by vegetation. In contrast, if the mean annual precipitation is greater, the presence of a dense plant cover decreases sediment yield. Further examination of this relationship by Walling and Kleo (1979) showed that the Mediterranean climatic zone, together with monsoonal and semi-arid areas, is especially vulnerable to soil degradation and water erosion. They proposed several explanations. First, the mean annual precipitation in Mediterranean regions is relatively low, and this leads to dispersed or low-density plant cover. Second, the Mediterranean climate has high spatial and temporal variability, with extremely intense rainstorms that can increase soil erosion and sediment availability. Third, human activities further compromise the vulnerability of these landscapes (Grove and Rackham, 2003; García-Ruiz et al., 2013). Therefore, identifying the environmental factors that control the spatial and temporal patterns of rainfall, runoff, erosion and sediment yield in Mediterranean regions is important for designing effective regional water and soil conservation measures.

There has been extensive research on soil erosion throughout the Mediterranean basin in the past 3 decades (Kosmas et al., 1997; García-Ruiz et al., 2013). This research has examined study sites with different physiographic features, soil types, land uses and cover management practices on different spatial scales (Gallart et al., 2013; Nadal-Romero et al., 2013). Most studies conclude that seasonal rainfall regimes (climate conditions) control runoff, soil erosion and sediment transport (García-Ruiz et al., 2013), and that a small number of annual events are usually responsible for soil erosion (González-Hidalgo et al., 2007).

Likewise, the majority of the sediment load in Mediterranean rivers is also carried in a small fraction of the time, clearly influenced by the availability of sediment (i.e. López-Tarazón et al., 2010). However, there has been no synthetic analysis of how climate conditions influence runoff, soil erosion and sediment yield across the Mediterranean basin.

Previous studies in the Mediterranean basin have examined the spatial and temporal distribution of precipitation defining the weather conditions under which they occur, also named weather types (WTs) (Ramos et al., 2015). This integrative approach is a well-established methodology, using daily synoptic conditions according to the surface pressure field and identifies the main direction of surface wind. Thus, each WT compiles daily information on the various origins and characteristics of air masses responsible for generating rainfall and runoff leading to erosion and sediment yield.

There have been several climate studies analyzing the relationships of WTs to different climate phenomena, such as teleconnection indices (Navarro-Serrano and López-Moreno, 2017), spatial distribution of precipitation (Fernández-González et al., 2011; Hidalgo-Muñoz et al., 2011; Cortesi et al., 2014; Fernández-Raga et al., 2016), and temperature (Peña-Angulo et al., 2016). Other studies have examined the link between WTs and natural hazards, such as landslides, floods and hydrological droughts (Messeri et al., 2015; Teale et al., 2017), and the distribution and occurrence of forest fires (Trigo et al., 2016; Ruffault et al., 2016, 2017; Rodrigues et al., 2019). Other research has examined the relationships of WTs with atmospheric contaminants, human health and pathologies (Santurtún et al., 2014; Royé et al., 2016; Liao et al., 2017), and air quality (Collaud-Coen et al., 2011). Therefore, the WT has been proved a useful tool in understanding the relationship between climate and many connected processes. However, information on the relationships of different WTs with runoff, soil erosion, and sediment yield is scarce.

Wilby et al. (1997) found that historical changes in the frequency of winter cyclonic WTs could account for a significant proportion of the variation in sediment yield in rivers of the United Kingdom. In addition, Foster and Lees (1999) found that long-term trends in sediment yield of large catchments in the United Kingdom were linked to changes in the occurrence of specific WTs. In northwest Spain, Fernández-Raga et al. (2010) concluded that WTs with a western component produced most of the precipitation with high kinetic energy. Recently, Tylkowski (2017) and Montreuil et al. (2016, 2017) analyzed coastal erosion in the Polish Baltic and Belgian coasts, respectively, concluding that only a few atmospheric conditions are responsible for heavy storm surge and large percentages of coastal erosion. All of these studies indicate that research into WTs holds great promise for finding the relationship between geomorphological processes and specific atmospheric patterns.

The main objective of this research was to analyze the relationships between rainfall, runoff, soil erosion, and sediment yield (SY, hereafter used to refer both to soil erosion measured at plot scale and sediment yield registered at catchment scale) with WTs throughout the Mediterranean basin. We compiled the most complete database for the area containing information on rainfall, runoff, and SY at high temporal resolution (event scale) from experimental plots and catchments. This study aims to progress beyond previous analyses by Nadal-Romero et al. (2014, 2015), and to pioneer the use of collective efforts aimed at understanding hydrological and erosion dynamics in the Mediterranean region (Merheb et al., 2016; Taguas et al., 2017).

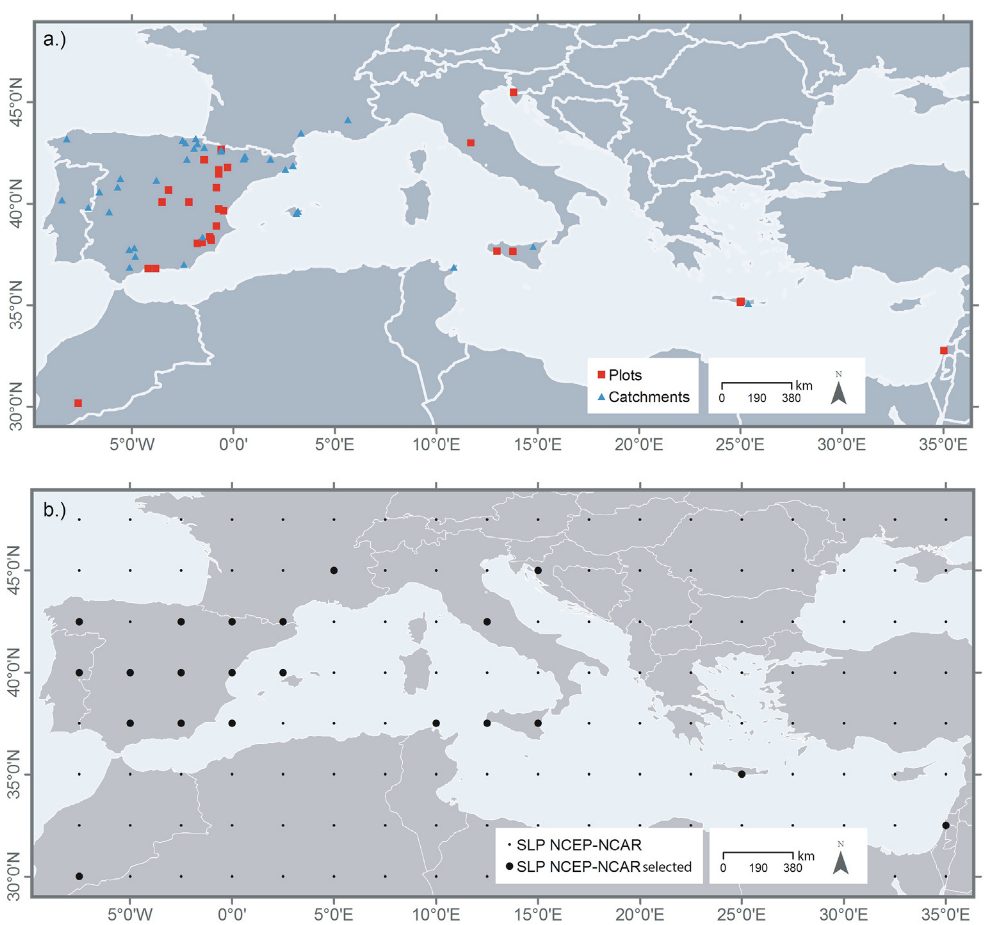

Fig. 1. a) Locations of study sites (plots and catchments) within the Mediterranean basin; b) Grid points from the National Center for Atmospheric Research (NCAR) data set (SLP NCEP-NCAR).

Table 1
Location, period of data collection, length of the dataset (in years) and other characteristics of the study sites included in the database.

Country	Name	Location		Scale	Study period		Length of the dataset (years)	Number of rainfall recorded events	Land cover	Reference
		Lat.	Long.		Start period	End period				
Greece	Agia Varvara	35.1433	24.9894	Plots	2008	2011	4	111	Pastures	Kairis et al. (2015)
Spain	Aisa	42.6744	−0.6119	Plots	1995	2010	16	637	Cereal, shrubland, crop abandonment, meadows	Nadal-Romero et al. (2013)
Spain	Aixola	43.1529	−2.5014	Catch.	2003	2008	6	222	Mostly reforested with *Pinus radiata*	Zabaleta et al. (2007)
Spain	Albaladejito	40.0762	−2.1957	Plots	1994	1997	4	28	Cereal and pastures	Bienes et al. (2001, 2005)
Spain	Añarbe	43.2255	−1.8498	Catch.	2003	2005	4	18	Reforested and mature *P. nigra* in the lower part and autochthonous (*Quercus robur and Fagus sylvatica*) in the upper part	Zabaleta et al. (2007)
Spain	Araguás	42.5958	−0.6208	Catch.	2005	2015	11	360	Badlands, reforested (*P. nigra* and *P. sylvestris*), meadows	Nadal-Romero and Regüés (2010)
Spain	Aranjuez	40.0798	−3.5250	Plots	1994	1997	4	38	Cereal and pastures	Bienes et al. (2001, 2005)
Spain	Abanilla	38.1994	−1.0917	Plots	1988	1992	5	40	Open shrubland	Díaz et al. (1997)
Spain	Ardal	38.0741	−1.5383	Plots	1989	2000	12	146	Cereal, shrubland and abandoned land	Romero-Díaz et al. (1999)
Spain	Arnas	42.6430	−0.5847	Catch.	1999	2009	11	96	Abandoned sloping fields with shrubs and forest	Lana-Renault et al. (2011)
Greece	Avgeniki	35.1911	25.0222	Plots	2008	2010	3	92	Olives orchards	Kairis et al. (2013)
Spain	Bardenas Norte	42.1677	−1.4547	Plots	1993	2004	12	118	Badlands	Desir and Marín (2007)
Spain	Bardenas Sur	42.1550	−1.4191	Plots	1993	2004	12	89	Badlands	Desir and Marín (2007)
Spain	Barrendiola	43.0026	−2.3509	Catch.	2003	2004	2	25	Autochthonous vegetation (*F. sylvatica, Q. robur* or *Q. petraea*) and reforested (*P. radiata. P. nigra* or *Larix decidua*)	Zabaleta et al. (2007)
Spain	Burete	38.0500	−1.7667	Plots	2006	2011	6	142	Forest	Martínez-Mena et al. (2008)
Spain	Can Revull	39.5500	3.1011	Catch.	2004	2007	4	19	Rainfed herbaceous crops, rainfed tree crops and forests	Estrany et al. (2009a)
Italy	Cannata	37.8833	14.7666	Catch.	1996	2006	11	169	Rangeland and cereal	Licciardello et al. (2019)
Spain	Carrasquero	42.3112	0.5327	Catch.	2007	2009	3	24	Forest, grassland, shrubland, agricultural lands	López-Tarazón et al. (2012)
Spain	Ceguera	42.2386	0.5109	Catch.	2007	2009	3	30	Forest, grassland, shrubland	Brosinsky et al. (2014)
Portugal	Casal das Hortas	40.1886	−8.4619	Catch.	2011	2013	4	9	Permanent crops, rangeland, pastures, forest (74%), urban (16%)	Ferreira et al. (2016)
Spain	Corbeira	43.2181	−8.2285	Catch.	2005	2014	10	651	Forest, pasture, cultivated land, impervious area	Rodríguez-Blanco et al. (2013)
Spain	El Cautivo	37.0027	−2.4404	Catch.	1992	2014	23	134	Low-intensity hunting and cereals farming associated to hunting; hiking	Cantón et al. (2001)
Portugal	Idanha	39.8467	−7.1667	Catch.	2010	2015	6	27	Oak and cork trees (young forest), wheat, maize, sorghum, meadow	Canatario-Duarte (2011)
Tunisia	Kamech	36.8773	10.8753	Catch.	2005	2012	8	167	Cropland (mainly cereal crops occasionally rotated with leguminous crops); Mediterranean shrubland, dwellings, gully and grazing	Inoubli et al. (2016)
Spain	La Conchuela	37.8178	−4.8958	Catch.	2006	2011	6	185	Conventional tillage	Gómez et al. (2014)
Spain	La Concordia	39.7500	−0.7167	Plots	1995	2012	18	203	Forest	Gimeno-García et al. (2007)
Spain	La Parrilla	37.7333	−5.1500	Catch.	2010	2013	4	74	Irrigated annual crops	Cid et al. (2016)
Spain	La Puebla	41.6645	−0.7239	Plots	1991	2003	13	187	Badlands	Desir et al. (1995)
Spain	La Tejeria	42.7363	−1.9492	Catch.	2000	2014	15	177	Winter cereals (wheat and barley)	Casalí et al. (2008)
Spain	Lanaja	41.7797	−0.2889	Plots	1991	2004	14	163	Badlands	Sirvent et al. (1997)
Spain	Lascuarre	42.2066	0.4977	Catch.	2007	2009	3	32	Forest, shrubland, agricultural lands	López-Tarazón et al. (2012)
Spain	Latxaga	42.7854	−1.4364	Catch.	2003	2014	12	189	Winter cereals (wheat and barley)	Casalí et al. (2008)
France	Laval	44.1406	5.6392	Catch.	1985	2014	30	465	Badlands	Cambon et al. (2015)
Spain	Malaga	36.8001	−3.8492	Plots	2011	2013	3	23	Shrubland	Martínez-Murillo et al. (2016)
Spain	Marchamalo	40.6822	−3.2147	Plots	1994	1997	4	48	Cereal and pastures	Bienes et al. (2001, 2005)
Italy	Masse	42.9928	11.7089	Plots	2008	2015	8	78	Bare and seeding bed	Todisco et al. (2012)
Spain	Mediana	41.4534	−0.7158	Plots	1991	2004	14	137	Badlands	Desir et al. (1995)
Greece	Mesara	35.0833	25.3800	Catch.	2012	2015	4	250	Olives, vines, citrus fruit and vegetables	Varouchakis (2016)
Spain	Morille	40.8315	−5.7053	Catch.	2002	2010	9	88	Open forest	Hernández-Santana and Martínez-Fernández (2008)
France	Moulin	44.1406	5.6392	Catch.	1988	2003	16	149	Badlands	Cambon et al. (2015)

(*continued on next page*)

Table 1 (*continued*)

Country	Name	Location		Scale	Study period		Length of the dataset (years)	Number of rainfall recorded events	Land cover	Reference
		Lat.	Long.		Start period	End period				
Spain	Munilla	42.1912	−2.2908	Catch.	2012	2015	4	17	Abandoned terraces with herbaceous vegetation and sparse shrubland	Lana-Renault et al. (2018)
Spain	Oskotz	42.9584	−1.7792	Catch.	2003	2014	10	416	61% Forest and 39% pasture	Casalí et al. (2010)
Spain	Porta Coeli	39.6590	−0.4890	Plots	1988	2012	25	240	Forest land	Andreu et al. (2001)
Spain	Puente Genil	37.4128	−4.8383	Catch.	2005	2011	7	93	Olive orchard	Taguas et al. (2013)
Spain	Rinconada	40.6020	−6.6153	Catch.	2000	2010	11	331	Dense forest	Hernández-Santana and Martínez-Fernández (2008)
France	Roujan	43.4917	3.3213	Catch.	1992	2015	24	410	Vineyards and cereals crops, orchards, mediterranean shrubland	Raclot et al. (2009)
Spain	Santomera	38.2700	−1.1167	Plots	1989	2002	14	283	Forest	Martínez-Mena et al. (2002)
Spain	Sa Vall	39.6386	3.1766	Catch.	2004	2006	3	77	Rainfed tree crops, rainfed herbaceous crops, forests, irrigated crops	Estrany et al. (2009b)
Spain	La Barranca de los Pinos	41.1582	−3.8086	Catch.	2010	2010	1	13	Badlands, forest and pastures	Lucía et al. (2011)
Spain	Setenil	36.8736	−5.1269	Catch.	2005	2011	7	121	Olive orchard	Taguas et al. (2015)
Italy	Sicilia Agata	37.6547	12.9853	Plots	2014	2014	1	11	Bare soil	Novara et al. (2016)
Italy	Sparacia	37.6366	13.7658	Plots	2002	2015	14	210	Bare soil	Bagarello et al. (2013)
Slovenia	Slovenian Istria	45.4982	13.7983	Plots	2005	2006	2	52	Badlands, bare soil (in an olive grove), meadow, forest	Zorn (2009)
Spain	Venta Olivo	38.3544	−1.5194	Catch.	1997	2011	15	108	Shrubland	Castillo et al. (2003)
Spain	Venta Olivo plot	38.3833	−1.1667	Plots	2001	2008	8	161	Shrubland	Boix-Fayos et al. (2007)
Spain	Vernega Bosc	41.8772	2.9325	Catch.	1993	2011	19	44	Forest	Outeiro et al. (2010)
Spain	Vernega Campas	41.8738	2.9213	Catch.	1993	2011	19	44	Agricultural practices	Outeiro et al. (2010)
Spain	Villacarli	42.3489	0.5540	Catch.	2006	2008	3	20	Forest, grassland, shrubland, badlands	López-Tarazón et al. (2012)
Spain	Villamor	41.2457	−5.5839	Catch.	2002	2010	9	87	Cereal	Martínez Fernández et al. (2012)
Morocco	Rheraya	31.2000	−7.9300	Plots	2003	2009	7	15	Rangeland (stones cover and vegetation cover)	Simonneaux et al. (2015)
Spain	Navalón	38.9166	−0.8333	Plots	2004	2014	11	470	Cultivated area	Cerdà et al. (2017)
Spain	Almáchar	36.8000	−4.2167	Plots	2014	2015	2	13	Conventional sloping vineyards	Rodrigo-Comino et al. (2017)
Spain	Ca L'Isard	42.1934	1.8232	Catch.	2005	2012	8	55	Forest, meadows, sparse vegetation, rocky outcrop, badlands	Latron et al. (2009)
Spain	Can Vila	42.1981	1.8234	Catch.	2005	2012	8	93	Forest, meadows, sparse vegetation, rocky outcrop, badlands	Latron et al. (2010)
Spain	Utrillas	40.796231	−0.839938	Plots	2005	2006	2	24	Reclaimed mining slopes	Moreno-de las Heras et al. 2010
Spain	Parapuños	39.6105	−6.1333	Catch.	2001	2015	15	161	Dehesa	Schnabel and Gómez Gutiérrez (2013)
Spain	Montnegre	41.7000	2.5666	Catch.	1998	2002	4	77	Forest	Bernal and Sabater (2012)
Israel	Israel	32.75631	35.019918	Plots	2006	2007	2	24	Natural recovery of post fire Mediterranean maquis	Wittenberg et al. (2014)

2. Materials and methods

2.1. Database creation

2.1.1. Rainfall, runoff and sediment yield

A database of rainfall events with hydrological and SY information was compiled from a network of experimental plots and catchments ($< 50\,km^2$) throughout the Mediterranean basin. This information was collected by research groups from several universities and research institutes, with most financial support provided by the European Commission, with further aid from national and regional governments. The data set included information from 68 sites, 28 experimental plots and 40 catchments, referenced to 182 case studies, and from 9 countries: Morocco, Portugal, Spain, France, Italy, Tunisia, Slovenia, Greece and Israel (Fig. 1a and Fig. 7 in Supplementary Material). The number of study sites varied greatly among countries, and most of the data came from Spain. In total, 22,458 rainfall events between 1985 and 2015 were entered in the database. Fifty-seven of the study sites (84%) had data on SY.

The datasets for each site differed in the duration of the record (1 to 29 years), the size of the study area (a few m^2 to $50\,km^2$), and land use and land cover (Table 1). 62% of the datasets included records for more than 5 years, and 41% for 10 years or more. Only 10% of the datasets covered less than 3 years. Likewise, 67% contained over 50 events, and 50% more than 100 events. Therefore, an inter-comparison of different time periods, from 1988 to 2015 (Table 1), was performed to gain a broad assessment of Mediterranean environmental characteristics. This is similar to the procedures of previous research that examined these global characteristics (García-Ruiz et al., 2015; Panagos et al., 2017).

2.1.2. Weather types

The classification of daily WTs over the Mediterranean region relies on the daily sea level pressure dataset from NCEP/NCAR 40-year Reanalysis Project (Kalnay et al., 1996) for the period 1985–2015. We used the WT classification proposed by Jenkinson and Collison (1977), based on the original work of Lamb (1972), and an approach suggested by Jones et al. (1993) and Trigo and DaCamara (2000). Briefly, for each grid cell and daily record, a WT is calculated by a set of indices that take into account the direction and vorticity of the geostrophic flow of the nearest 22 NCAR pressure points. The result (i.e. the WT for day n) is then assigned to the study site according to location (Fig. 1b).

In the present research, 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).

2.2. Database analysis

The analysis of WTs was performed across the Mediterranean basin according to the NCEP Re-analysis grid resolution, and final WT classification was assigned to the different local study sites, depending on their location (see Fig. 1b). The rainfall, runoff, and SY were related to the daily WTs estimated in each site. In that respect, WT evaluation is spatially independent, but based on sea level pressure data from NCEP Re-analysis (i.e. the same day can be classified as northerly or southerly WTs in different study sites). Each of the 22,458 daily events was associated with a WT type for individual sites. For each site, the percentage of total rainfall, runoff and SY produced under each WT was estimated. A Principal Component Analysis (PCA) was used to summarize and classify these data (Everitt and Horton, 2011). The 8 directional WTs were considered as variables, and the percentages of rainfall, runoff, and SY associated with each WT at each site were considered observations (Cyclonic (C) and Anticyclonic (A) WTs were discarded from the PCA analysis which was based only on directional WTs). Each PC was selected according to the percentage of the total variance explained, and interpreted from its correlation with the different WTs. The results of the PCA established spatial patterns of rainfall, runoff and SY and their relationships with WTs in the Mediterranean basin (based on the loadings from the PCA). All statistical analyses were carried out using R software (R, version 3.2.3) (R Development Team Core 2013). The results were divided into four subsections describing the relationship of WTs with rainfall, runoff and SY. In each sub-section, the spatial distribution of the association of WTs with hydro-sedimentary variables was determined, with grouping into classes defined by the PCA results. For each distribution class, three representative study sites were selected to show the total distribution of WTs (including A and C). Detailed results for the 68 sites examined in this study are provided as Supplementary Material (Figs. 9–19). At the end of the results section, we present 6 examples showing the relationships of daily WTs with rainfall, runoff, and SY at specific sites (synoptic situations).

3. Results

The PCA analysis showed the location of the 8 directional WTs in the factor space for rainfall, runoff and SY (Fig. 2). For rainfall and runoff data, all study cases clearly separate these WTs, but groups of WTs were not as strongly defined for the SY data. Fig. 8 of the Supplementary Material shows the distribution of the different study sites in the factor space.

3.1. Rainfall classes

PC1 accounted for 40% of the total variance, and had significant

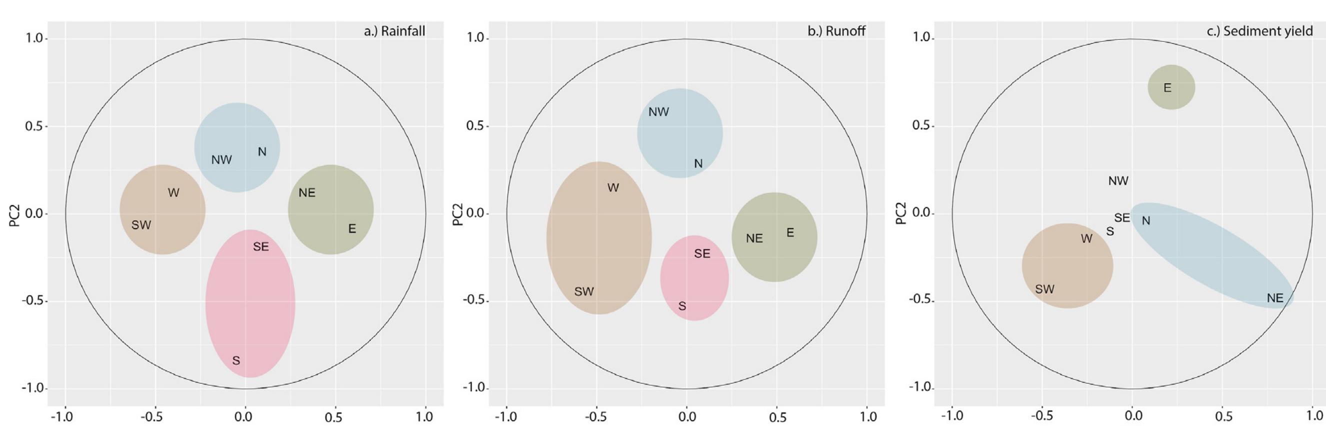

Fig. 2. PCA components for rainfall, runoff and sediment yield.

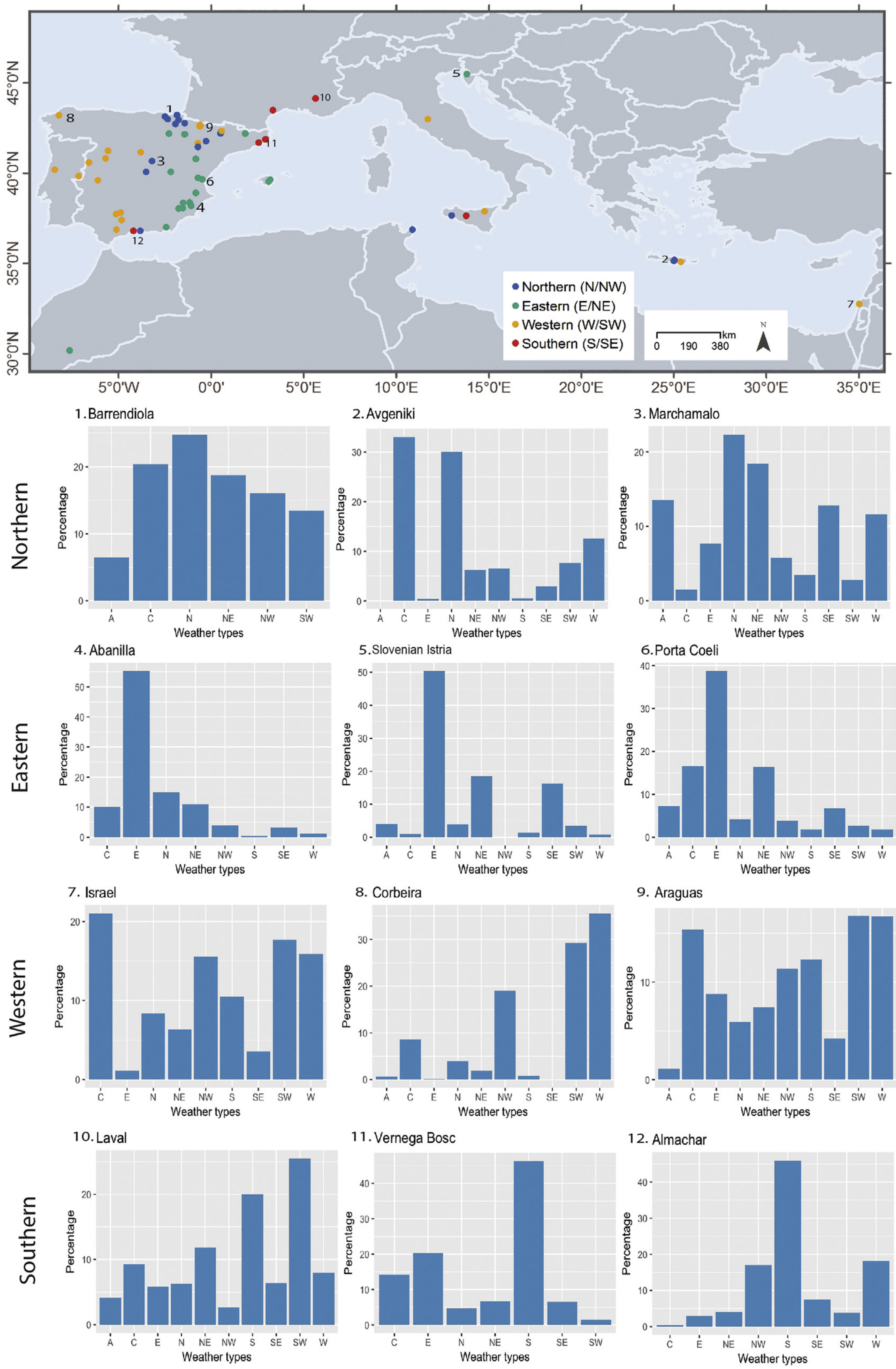

Fig. 3. Spatial distribution of the relationship of rainfall with WTs in the Mediterranean basin, indicating the presence of 4 classes: northern (class 1), eastern (class 2), western (class 3), and southern (class 4). The total frequency of rainfall events associated with different WTs is shown for 3 representative locations in each class. Northern sites: Barrendiola, Augeniki, Marchamalo; Eastern sites: Abanilla, Slovenia, Porta Coeli; Western sites: Israel, Corbeira, Araguás; Southern sites: Laval, Vernega Bosc, Almachar. Please note, that different scales are included.

positive correlations with E and NE WTs, and significant negative correlations with W and SW WTs. PC2 accounted for 19% of the total variance, and showed significant positive correlations with the N and NW WTs, and significant negative ones with the S and SE WTs. The contribution of the directional WTs to total rainfall differed notably among sites (Table 3 in the Supplementary Material). Thus, we grouped the study sites into 4 classes based on their distribution in the PCA plane (Fig. 3).

The first class encompassed sites with predominantly NW and N WTs (n = 17). In most of these sites, these 2 WTs accounted for more than 25% of total rainfall (mean: 31.2%, Table 2), and for more than 45% of rainfall for Añarbe and Latxaga (Spain) (Table 3 in the Supplementary Material and Fig. 3). This class included sites in the Basque Country and Navarre regions of northern Spain, as well as those in the Ebro Valley and Pre-Pyrenees (Spain), northeastern Tunisia, Sicily (Italy), and Crete (Greece).

The second class contained sites with predominantly E and NE WTs (n = 21), which accounted for 44% of total rainfall (Table 2). In some of the sites of this class, these WTs produced more than 55% of the total rainfall (*e.g.* Abanilla in Spain and Slovenian Istria) (Table 3 and Fig. 3). The sites were located along the Spanish Mediterranean coast, Morocco, and Slovenia (Fig. 3).

The third class included those sites in which rainfall was dominated by W and SW WTs (n = 22), accounting for 43% of total rainfall (Table 2). In some cases, such as Idanha (Portugal), these WTs produced up to 70% of the total rainfall (Table 3). Most of the sites in this class were on the western side of the Mediterranean basin (Atlantic sites), Andalusia and the Central Pyrenees (Spain), the Italian Peninsula and Sicily (Italy), Crete (Greece) and Israel (Fig. 3).

The fourth class was a specific area in which most rainfall was associated with S and SE WTs (n = 8; Fig. 3). The S and SE WTs accounted for more than 40% of the total rainfall (Table 2), with greater influence from southerly flows. Most of the southern sites were around the Gulf of Lion (Spain and France) (Fig. 3).

3.2. *Runoff classes*

PC1 accounted for 32% of the total variance, and had significant positive correlations with the E and NE WTs, and significant negative correlations with the W and SW WTs. PC2 comprised 19% of the total variance, and showed significant positive correlations with the N and NW WTs, and significant negative ones with the S and SE WTs. The contribution of runoff differed among sites and WTs (Table 3 in the Supplementary Material). We grouped the study sites into 4 classes based on their distribution in the PCA plane (Fig. 4). Notably, the sites included in each runoff class were not necessarily coincident with those in each rainfall class, but spatial distributions were similar.

The NW and N WTs accounted for almost 40% of total runoff (n = 16) (Table 2), and up to 55% in some cases (*e.g.* Latxaga and Barrendiola in Spain; Fig. 4 and Table 3). Locally, and only at 3 sites, the C WT had a strong influence (*e.g.* almost 40% in Avgeniki, Greece; Fig. 4). The spatial distribution of sites in this class was similar to that of the first rainfall class: northern Spain (Basque Country and Navarre), some sites in the central Iberian Peninsula (IP), Málaga, Tunisia, Sicily (Italy) and Crete (Greece) (Fig. 4).

The E and NE WTs accounted for about 45% of total runoff in the second class (n = 21), and up to 70% in some cases (*e.g.* Montnegre, Albaladejito and Abanilla in Spain; Table 3 and Fig. 4). The spatial distribution of the sites in this class was similar to that of the second rainfall class: the Mediterranean coast of the IP, Morocco and Slovenia (Figs. 3 and 4).

The W and SW WTs accounted for 52% of total runoff in the third class (n = 18, Table 2), and more than 75% in Rinconada, Villamor and Coimbra (Table 3 in the Supplementary Material). These 2 WTs produced more than 40% of total runoff in most sites, with the exception of Mesara (Greece) and Carrasquero (Spain), where the C WT caused a large amount of runoff (Supplementary Fig. 16). The sites in this class were in the western Mediterranean (Atlantic sites), and in Andalusia, the Pyrenees, Sicily, Crete and Israel, similar to the pattern for the third rainfall class (Fig. 4).

The S and SE WTs accounted for 33% of total runoff (Table 2) in the fourth class (n = 12), and up to 50% in Roujan (France), Venergà, and Almachar (Spain) (Table 3 and Fig. 4). However, the contribution of the predominant WTs varied greatly among sites (coefficient of variation: 68%). The spatial distribution of sites in this class was similar to that of the fourth rainfall class: southern and northern sites of the IP and central Italy (Fig. 4).

3.3. *Erosion and sediment yield classes (SY)*

PC1 accounted for 33% of the total variance and had significant positive correlations with the N and NE WTs, and significant negative ones with the W and SW WTs. PC2 was responsible for 21% of the total variance, and had a significant positive correlation with the E WT. Notably, the SY classes had higher variability than those for rainfall and runoff (Fig. 5 and Table 2). We grouped the study sites into 3 classes based on their distribution on the PCA plane (Fig. 2c).

The N and NE WTs accounted for 48.6% of the total SY in the first class (n = 17, Table 2). In addition, the NE WT comprised more than 90% of the total SY at the Moroccan site (Rheraya), and both WTs amounted to approximately 40% of the total SY in all cases (Table 2). The sites in this class were in Morocco, the eastern IP (including Mallorca), Sicily (Italy) and Crete (Greece) (Fig. 5).

The E WT accounted for 25% of the total SY in the second class (n = 16), but this rose to 50% in El Cautivo, Abanilla, Ardal, Santomera and Venta del Olivo (all on the south-east Spanish Mediterranean coast) (Fig. 5). In addition, the C WT had a strong influence in 3 cases (Malaga, Burete, and Porta Coeli in Spain, Fig. 5). These sites were in the eastern IP (Fig. 5), Slovenia, Tunisia and Italy.

The W and SW WTs accounted for 40% of SY in the third class (n = 24), and 60–80% in the most western Mediterranean sites (Portugal and Galicia [Spain], Table 3 and Fig. 5). These 2 WTs caused approximately 40% of the total SY in Israel.

3.4. *Synoptic patterns*

Fig. 6 shows six representative examples of daily atmospheric patterns throughout the Mediterranean basin, obtained from NCEP Reanalysis, and the corresponding WTs of selected sites where an event was registered on a chosen day.

Fig. 6a presents an event on September 11, 1996, a date when E flows affected all sites where rainfall, runoff or SY were recorded

Table 2
Relative contributions of the different WTs to total rainfall, runoff, and SY at the different study sites (plots and experimental catchments) within each spatial class, based on PCA analysis.

PCA classes	Environmental variables (%)	mean	standard deviation	Coefficient of variation	Max
Northern (NW, N)	*rainfall*	31.2	11.5	37	51.1
	runoff	38.6	15.6	41	64.7
	SY	48.6	16.1	33	92.3
Eastern (E, NE)	*rainfall*	43.8	14.7	34	69.0
	runoff	45	21.2	47	72.7
	SY	25.1	21.5	86	60.7
Southern (SE, S)	*rainfall*	42.7	12.1	28	58.0
	runoff	32.9	22.2	68	82.0
	SY	–	–	–	–
Western (SW, W)	*rainfall*	43.3	15.2	35	71.9
	runoff	52.2	15.4	30	80
	SY	40.3	19.8	49	83.1

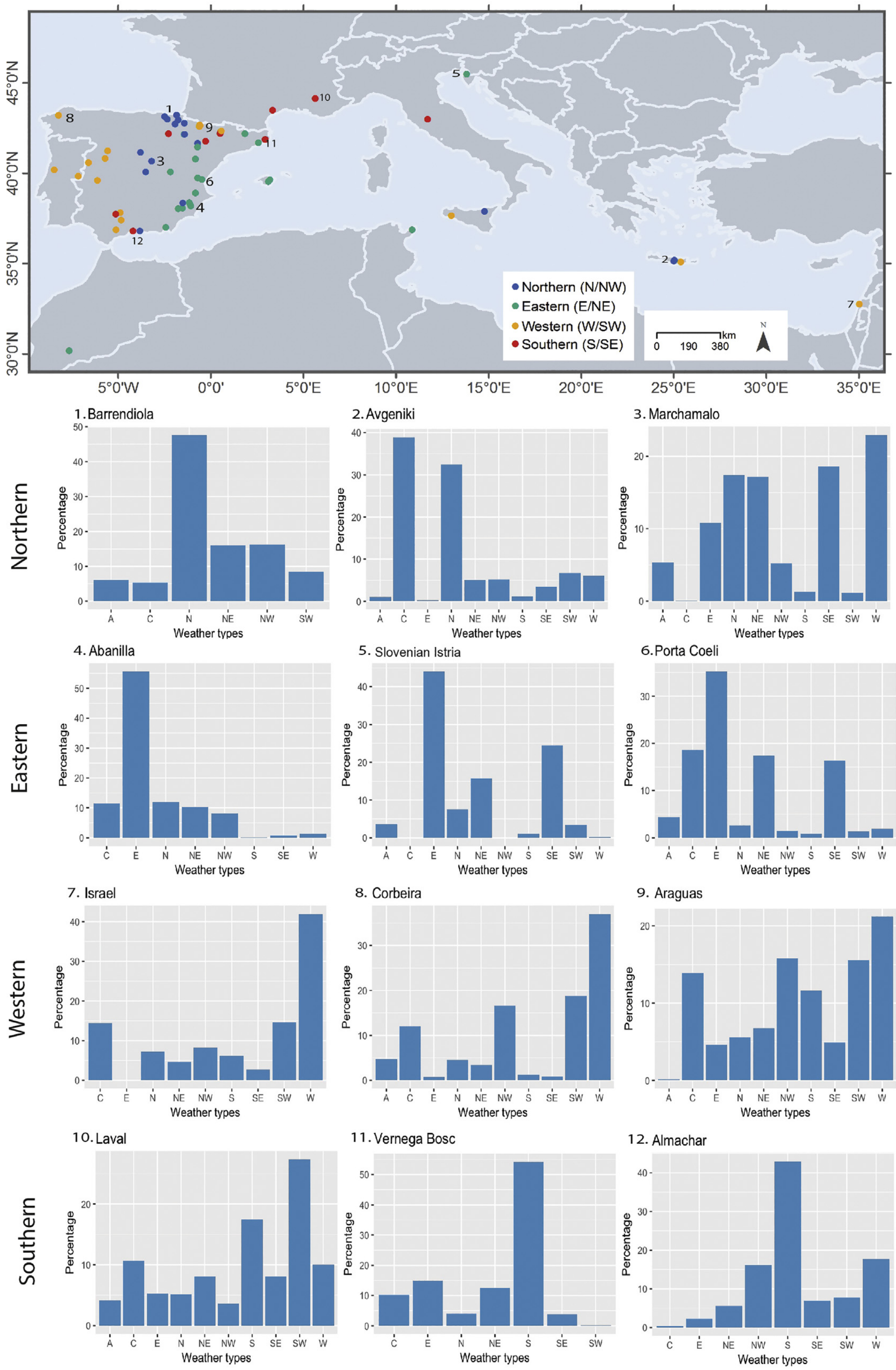

Fig. 4. Spatial distribution of the relationship of runoff with WTs in the Mediterranean basin, indicating the presence of 4 classes: northern (class 1), eastern (class 2), western (class 3), and southern (class 4). The total frequency of runoff events associated with different WTs is shown for 3 representative locations in each class. Northern sites: Barrendiola, Augeniki, Marchamalo; Eastern sites: Abanilla, Slovenia, Porta Coeli; Western sites: Israel, Corbeira, Araguás; Southern sites: Laval, Vernega Bosc, Almachar. Please note, that different scales are included.

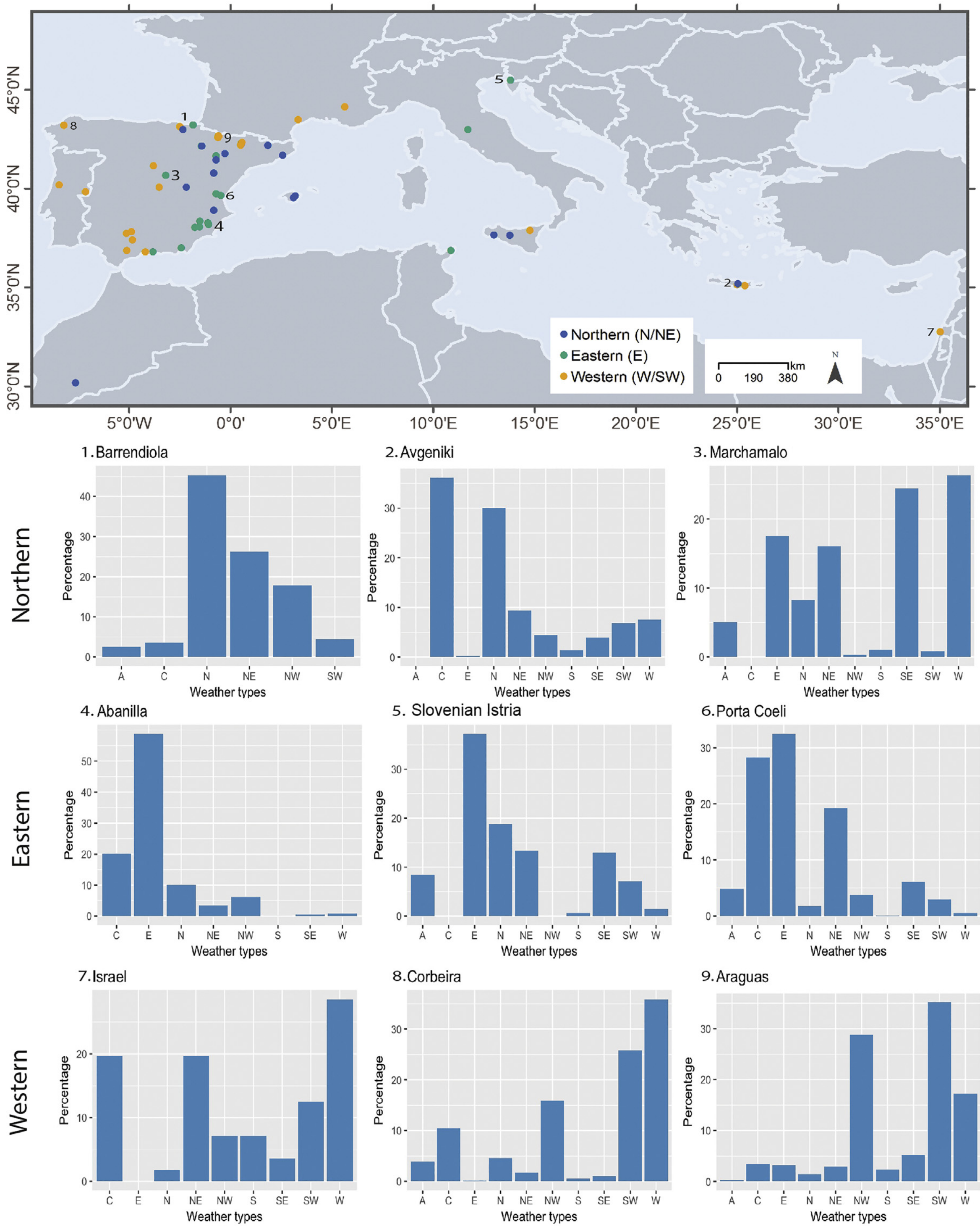

Fig. 5. Spatial distribution of the relationship of sediment yield with WTs in the Mediterranean basin, indicating the presence of 3 classes: northern (class 1), eastern (class 2), and western (class 3). The total frequency of events producing sediment yield associated with different WTs is shown for 3 representative locations in each class. Northern sites: Barrendiola, Augeniki, Marchamalo; Eastern sites: Abanilla, Slovenia, Porta Coeli; Western sites: Israel, Corbeira, Araguás.

(Albaladejito, La Concordia, El Cautivo and Porta Coeli in Spain), or NE (Santomera). The isobaric configuration shows a low-pressure system located between the IP and North Africa, and the resulting predominant wind directions were east–west and northeast-southwest, accordingly.

The second synoptic chart (Fig. 6b) presents an event on February 19, 2003 and shows a low-pressure system in the northwest of the IP. The 1010 mb isobar includes the Western Mediterranean, causing W and S flows in the Gulf of Lion (Roujan and Vernegà).

The third synoptic chart (Fig. 6c) shows a low pressure system located in the centre of the IP on March 29, 2004, that generated synchronic responses in the Mediterranean basin. E-NE flows were recorded on the Spanish Mediterranean side (La Concordia, Porta Coeli, Navalón, and Sa Vall), with SE flows in the Ebro basin (Bárdenas, La Puebla, Lanaja, and Mediana). On the other hand, the data for Morocco indicated that the response was due to N/NW flows.

The fourth chart (Fig. 6d), recorded on October 16, 2009, shows the synoptic configuration related to central and eastern sites of the Mediterranean region, in which a low pressure system between southern

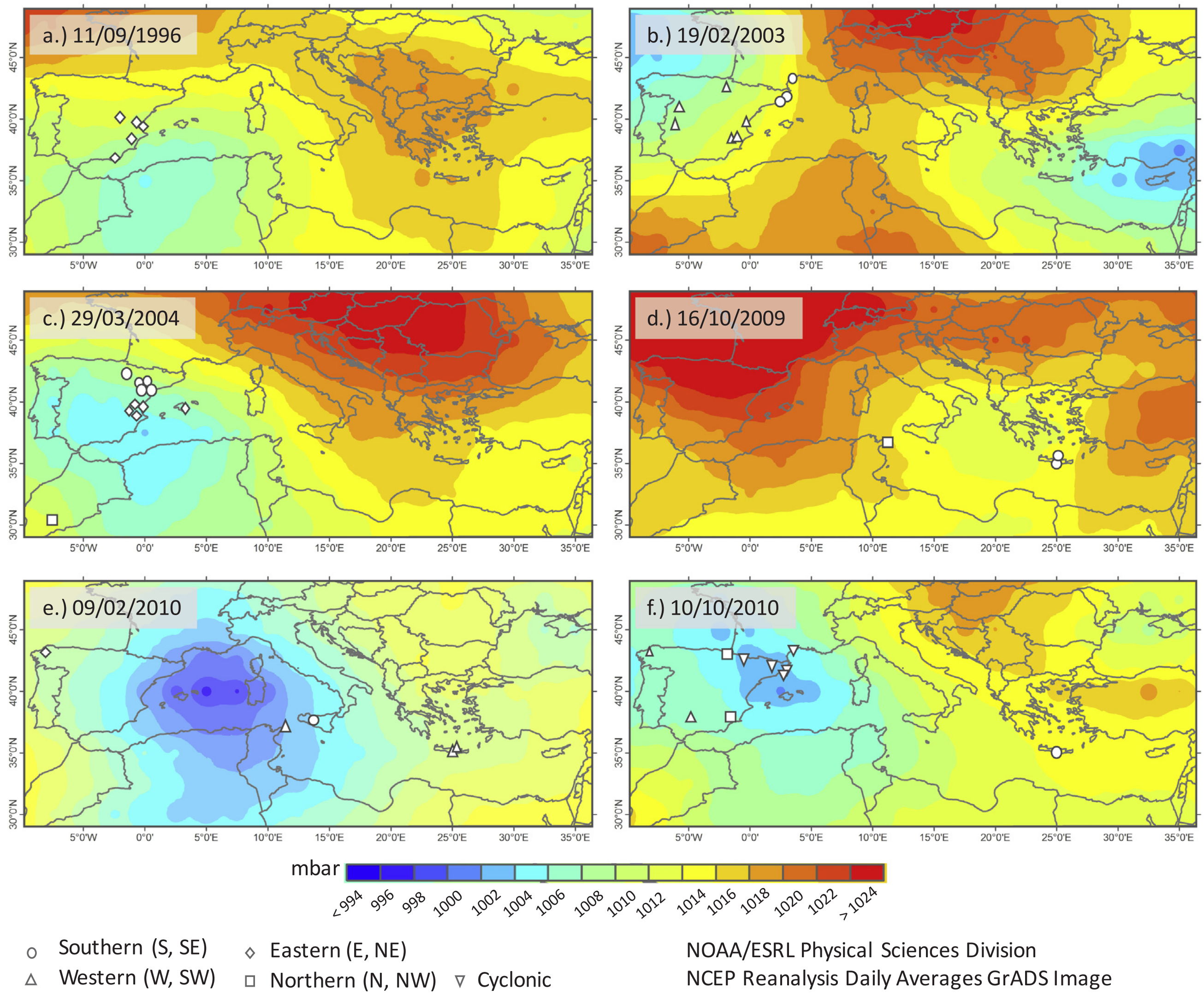

Fig. 6. Synoptic maps showing sites where an event occurred and WT information for the day and site. a) September 11, 1996, b) February 19, 2003, c) March 29, 2004, d) October 16, 2009, e) February 9, 2010, and d) October 10, 2010.

Italy and Greece produced mostly S WTs in Greece and N/NW flows in Tunisia.

The fifth chart (Fig. 6e), recorded on February 9, 2010, shows a new configuration related to the Western Mediterranean basin, in which a deep low pressure system around the Balearic Sea gave rise to W and S flows in Tunisia and Sicily.

The last chart (Fig. 6f), recorded on October 10, 2010, shows high variability. There was a low-pressure system in the IP and the eastern Mediterranean basin, but not affecting North Africa. Different WT patterns were recorded in many different sites. C patterns were observed in the Pyrenees and the Gulf of Lion, such as Araguás, Vernegà, Ca L'Isard, Can Vila (Spain) and Roujan (France); N WTs were recorded in Oskotz (Navarre, Spain) and Burete (Murcia, Spain); and W WTs were observed in the western sites of the IP (Corbeira in Galicia and Conchuela in Andalucía). There was also an event in the Eastern Mediterranean (Agia Varvara, Greece), although the synoptic situation did not allow the classification used to determine the S/SE flows in detail.

Synoptic charts are affected by the synchrony of the recorded data, and must therefore, be interpreted with caution. However, the charts shown here indicated that the disturbances associated with low-pressure systems were generally responsible for most responses in the Mediterranean basin.

4. Discussion

During the last three decades, many studies of experimental plots and catchments throughout the Mediterranean basin have quantified the factors that are most responsible for runoff, soil erosion and SY (Kosmas et al., 1997). There is now a huge amount of information on how of these parameters relate to climatic factors, plant cover, land use and land management practices (García-Ruiz et al., 2008; Taguas and Gómez, 2015; Rogger et al., 2017); also on the temporal and spatial variations of these processes (Boix-Fayos et al., 2005, 2006, 2007; Vanmaercke et al., 2012, 2015; García-Ruiz et al., 2015; Merheb et al., 2016). In this study, we tried to go beyond these previous studies by compiling the largest data set available for the Mediterranean basin to analyze the relationships between daily rainfall, runoff, and SY with WTs. This was possible only due to the efforts of numerous research groups from several universities and research institutes in 9 Mediterranean countries, with the Iberian Peninsula being the most widely-represented region (Fig. 1 and Fig. 7 Supplementary Material). Most of the sites are located in Spain while fewer are in France, Italy and other countries (Morocco, Tunisia, Slovenia, Greece and Israel).

The scarcity of information in central and far east of the Mediterranean basin did not enable us to conduct a global detailed analysis, and in that respect, the larger representation of Spanish study sites could be understood as a limitation of the data set. A similar situation occurred to García-Ruiz et al. (2013) who carried out a review on erosion in Mediterranean landscapes based on more than 650 published studies, from which more than 60% came from Spanish sites. Nevertheless, we consider that the over-representation of sites in Spain is counterbalanced by the fact that each one has been analyzed individually and the results not extrapolated to those areas with no or little data. Notwithstanding this limitation, the present study provides interesting results, showing clear relationships between WTs and rainfall, runoff, and SY, as well as clear spatial patterns throughout the Mediterranean basin (each case can be individually analyzed in Figs. 9–19). Despite the inherent limitations associated with the available dataset, we believe that the spatial patterns emerging from this analysis are of interest, even more so because they allow for a discussion on the influence of WTs on the studied variables. Additional data, especially SY information from the less well-represented regions in the dataset, would be essential to confirm the extent and influence of WTs on the identified rainfall, runoff, and SY classes.

Recent spatial studies have highlighted the importance of analyzing the relationships of environmental variables with atmospheric circulation patterns (Ramos et al., 2015). However, there are no previous global analyses of the effects of atmospheric conditions in the Mediterranean basin on rainfall, runoff and SY. Our analysis allowed representative study sites around the Mediterranean basin to be identified according to synoptic weather patterns. Our results show the presence of 4 homogeneous classes for rainfall and runoff, and 3 classes for SY. In general, the spatial patterns of the rainfall and runoff classes were similar, with only minor variations. The first class (N WTs) covered mainly the Basque and Navarre sites, some study areas within the Iberian Peninsula, and others in Italy (Sicily) and Greece (Crete). The second class (E WTs) mostly corresponded to eastern Spanish Mediterranean sites. The third class (S WTs) contained the fewest sites, mostly in the Gulf of Lion (Spain and France) and displayed high variability in the relationships. The fourth class (W WTs) corresponded to western Mediterranean sites in Portugal and Spain, the Central Pyrenees and Israel. However, there were only 3 classes for SY: sites dominated by N and NE WTs, those with E flows, and ones with W and SW flows. On the other hand, there was greater variability for SY than rainfall and runoff, probably due to its more diverse and complex causative factors.

Similar spatial patterns were obtained in different studies analyzing several environmental variables. For example, Gámiz-Fortis et al. (2011) analyzed the spatial and temporal streamflow variability of the Ebro River Basin (Spain) and its association with large-scale patterns of atmospheric circulation. These authors identified 3 spatial patterns: the Basque-Cantabrian region, the southern-Mediterranean area, and the Pyrenees. Ramos et al. (2014) studied the relationships between WTs and daily rainfall in the IP, and identified four areas: the northern Cantabrian coastland, the Central-southwest, the Mediterranean coastland, and the Ebro Basin. Nevertheless, rainfall events are not only linked to synoptic scale atmospheric circulations, as has been demonstrated by various authors in climatological studies (Cortesi et al., 2014; Peña-Angulo et al., 2016). Local factors, such as convective processes, orography and distance to the sea, could play a major role in the frequency of rainfall and runoff events and in the extent of spatial patterns. For example, the geographical layout of the main mountain chains (i.e. Pyrenees, Alps) could be one of the most important factors promoting the spatial patterns, and could help to establish sharply delimited areas according to specific effects from WTs.

PCA groups were found to characterize spatial patterns at Mediterranean scale, although individual WTs displayed some variations between sites. Consequently, an interesting finding of our study is that a high percentage of rainfall, runoff and SY events occurred for a small number of WTs, representing atmospheric conditions that are often rare. For example, in Idanha (Portugal) 60.6% of SY occurred during an SW WT, and in Rheraya (Morocco) 91.3% of SY occurred during an NE flow. These results are similar to those of Pattison and Lane (2012), who indicated that only 5 WTs accounted for 80% of the recorded extreme events in the River Eden (United Kingdom). These results also agree with those of Ramos et al. (2014), who concluded that a high percentage of monthly rainfall (about 70%) occurred during only 7 WTs. Additionally, studies elsewhere in the world confirmed that a small number of extreme events generate most rainfall, runoff and SY (López-Bermúdez, 1990; Martínez-Mena et al., 2001; González-Hidalgo et al., 2007). Related to these results, changes in the frequency of these WTs are bound to have a significant impact on the hydrological and erosion response and the export of sediment. These results may provide an insight into the development of water planning and soil conservation measures. Over time, the Mediterranean basin has become drier and the rainfall patterns more erratic. The insights from the present study might help to evaluate the relationships of atmospheric conditions with rainfall, runoff and SY around the Mediterranean basin in a context of global change.

Furthermore, this study shows that the predominance of one WT for rainfall does not mean that this WT also predominates for runoff or SY (Table 3 in the Supplementary Material). Indeed, the patterns obtained suggest that rainfall, runoff and SY had different responses to different WTs, probably as a consequence of the non-linear relationships among these variables, especially for SY events. These results agree with those of previous studies in Mediterranean areas (López-Tarazón et al., 2010; Rodríguez-Caballero et al., 2014; Hueso-González et al., 2015), and illustrate the complexity of water and sediment dynamics. This non-linearity could be at least partially explained by the availability of detached material that can be readily eroded, and the existence of different sediment sources, which in turn depend on various processes (*e.g.* previous weathering processes and rainfall conditions) influencing sediment availability and SY.

The analyzed dataset comprises a wide range of physiographical and geomorphological conditions (topography, soils, plant cover) and length of data records (see Table 1). The latter can lead to biased results, because the minimum record length is an issue that has not yet been resolved in geomorphology studies. Most authors claim that short temporal series present compressed variance (Kirkby, 1987). Wischmeier and Smith (1978) stated that “care must be taken to ensure that the duration is sufficient to account for cyclical effects and random fluctuations in uncontrolled variables whose effects are averaged in the USLE factor values”. The time frame varies from author to author and usually is expressed in years (Lane and Kidwell, 2003; Ollesch and Vacca, 2002). However, González-Hidalgo et al. (2012) suggested including a minimum number of 100 events instead of years to avoid the effects of maximum erosion events. In the present study, the records vary between 9 and more than 800 events spanning from 1 to 22 years. Furthermore, the reliability of the dataset is guaranteed because more than 67% of the study sites recorded more than 50 events, and 50% of sites included over 100 events. In this respect, the range of the dataset ensures the reliability of results and, regardless of the spatial distribution of the study sites, the global conclusions are not affected by the effect of maximum events. However, a few WTs are responsible for a high percentage of runoff and SY, varying at spatial level.

Characterization of the relationships of rainfall, runoff, and SY with WTs is crucial for understanding hydrological and SY dynamics in the Mediterranean basin. In fact, improving our understanding of hydrology and soil erosion dynamics is a strategic research step, essential for the development of protection and management policies, with adaptations to the distinct environments within the Mediterranean basin. However, we acknowledge that many other environmental factors related to runoff and soil erosion dynamics are outside the scope of the present study, such as land use/land cover, topography, weathering dynamics, antecedent conditions such as soil moisture, and the distribution of rainfall and rainfall intensity within storms. We consider that further research is needed to better understand the relationships of rainfall, runoff, and SY with WTs. This is particularly important, because a small increase in the frequency of certain WTs may lead to more frequent events with high runoff volumes and greater SY. Therefore, future research should focus on: *(i)* analyzing the temporal and seasonal variability of the relationships of WTs with different hydro-sedimentary variables, *(ii)* evaluating extreme events and their relationships with different WTs (Hidalgo-Muñoz et al., 2011), and *(iii)* studying the effect of changes in the frequencies of different WTs.

5. Conclusions

This study investigated the relationships of three hydro-sedimentary variables — rainfall, runoff and SY — with different WTs, and their spatial variability in the Mediterranean basin. Compilation and analysis of this very large dataset required the cooperation of a sizable group of scientists from 9 Mediterranean countries, whose common aim was to advance knowledge of rainfall, runoff, and SY dynamics throughout the Mediterranean basin. Thus, the prime innovation of the present work concerns the compilation of this Mediterranean database, which has taken information from 68 study sites (plots or catchments) and 22,458 events. The results demonstrate that WTs influence to a different extent rainfall, runoff, and SY, and that the relationships of these hydro-sedimentary variables with WTs have distinct spatial patterns throughout the Mediterranean basin. Moreover, our study indicated that the synoptic WT classification can be effectively used to study hydrological and SY responses in Mediterranean areas, and that this is a valuable new tool for studies of hydrological responses, soil erosion, and sediment delivery.

In addition to these, there are several specific insights from this study:

(i) A small number of WTs are responsible for most rainfall, runoff, and SY in Mediterranean environments.
(ii) For each site, different WTs are associated with the greatest rainfall, runoff, and SY, indicating a non-linear relationship between these hydro-sedimentary variables.
(iii) There were 4 spatial classes of sites that had similar rainfall and runoff relationships with WTs: *(a)* northern sites (including the Basque country and Navarre in Spain, inland of the Iberian Peninsula, and some sites in Sicily and Crete), which depend on N and NW flows; *(b)* eastern sites (including the eastern Iberian Peninsula, Morocco, and Slovenia), which depended on E and NE flows; *(c)* southern sites (located around the Gulf of Lion but with high variability) which depended on S and SE flows; and *(d)* western sites (from the western Mediterranean to Israel), which depended on W and SW flows.
(iv) There were 3 spatial classes that had higher variability in SY than observed for rainfall and runoff: *(a)* northern sites, characterized by N and NE flows, *(b)* eastern sites, characterized by E flows, and *(c)* western sites, characterized by W and SW flows.

This study confirms that Mediterranean dynamics are highly variable due to geographical and atmospheric factors: atmospheric patterns provide meaningful information toward understanding the spatial variations in the Mediterranean, identifying regions with different behavior, most of which are influenced by the relief. Finally, the analysis of the spatial variability of the relationships of runoff and sediment yield with weather types and the database generated would be useful tools presenting practical applicability for designing regional water and soil conservation measures (*e.g.* combined with meteorological forecasting).

Author contributions

DPA, ENR and JCGH together conceived and designed the study. All the authors contributed with experimental data to the compilation of the hydrological dataset. DPA, ENR and JCGH analyzed the data and led the writing of the paper, with significant contributions from all the other authors.

Declaration of interests

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.

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Appendix A. Supplementary data

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