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ORIGINAL PAPER

Factors determining the soil available water during the last two decades (1997–2019) in southern Spain

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Abstract

Assessing soil hydrological conditions can provide essential information for understanding the environmental processes that affect ecosystem services and, particularly in the context of ongoing climate change. This is key in areas affected by water scarcity such as the Mediterranean belt. Therefore, the main goals of this research are (i) to assess the main rainfall dynamics and trends of some representative hotspots along with southern Spain and (ii) to determine the impact on the soil available water content (AWC) over the last two decades. An analysis of daily precipitation and soil hydrological conditions was combined with soil sampling (543) and laboratory analyses to evaluate the properties related to the soil infiltration and retention capacity. The results show that the organic factors control soil properties and their hydrodynamics in southern Spain. Furthermore, a general declining trend in soil water availability is observed over the last two decades. This is more extreme in arid and semi-arid areas, where there have been several years in the last decade with more than 200 days without the available water content. Moreover, in these areas, heavy rainfall during specific moments of the year is the key factor that manifests a greater incidence in areas with steeper slopes, which in turn, also conditions the biological factors and the hydrodynamics of the soil. In short, in the context of climate change, the analysis of soil hydrological dynamics could be used to identify biodiversity thresholds in the Mediterranean area and even to detect phenological changes in specific plant species.

Keywords Regional studies · Climate change · Mediterranean belt · Soil dry periods

Introduction

The Mediterranean climate is characterized by dry summers; therefore, the native vegetation must adapt to increasingly frequent and recurring conditions of water stress (Klausmeyer and Shaw 2009; Nardini et al. 2014). Some authors claimed that this situation will impact pasture (Dlamini et al. 2016; Abdalla et al. 2018), crop productivity (Rodrigo-Comino et al. 2021), and plant mortality (Peñuelas et al. 2001; Bréda et al. 2006), and, as a consequence, it will enhance the fuel for forest fires (Vidal et al. 1994; Alcasena-Urdíroz et al. 2019; Martínez-Torres et al. 2019; Fernandez-Anez et al. 2021). Thus, an increase in the intensity or frequency of droughts can limit productivity and the ecological and economic values of this fragile ecosystem (Guillot et al. 2019; Lobo Do Vale et al. 2019). Some authors confirm that timely and accurate monitoring of soil moisture and vegetation is necessary to inform early warning services, assess droughts, and develop efficient management plans that reduce economic and environmental vulnerabilities (Guo et al. 2019; He et al. 2017).

The soil water balance has been traditionally used to estimate various soil hydrological parameters (Wang and Dickinson 2012) and can be fundamental to understand the soil–plant–atmosphere relationships (Gabarrón-Galeote et al. 2013) that underpin diverse hydrological issues. The spatiotemporal evolution of soil water conditions directly determines various natural

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conditions including the state and composition of vegetation cover, vulnerability to erosion processes, and the stability of soil aggregates (Eskandari Damaneh et al. 2021). This is also fundamental to assess other phenomena including climate change and desertification, which are necessary to develop efficient water resource management plans (Jodar-Abellan et al. 2019a, 2019b).

Recent reports have estimated that the predicted climate change would imply a modification in not only the total amount of rainfall, but also the spatiotemporal distribution patterns (IPCC 2014, 2019). Future climate change projections indicate a trend of decreasing total rainfall and an increase in its intensity and concentration periods (Dore 2005; Pendergrass and Hartmann 2014). Spatial ecosystem responses are variable depending on the specific characteristics of each region, which are conditioned by local factors, and the ability of species to adapt to new climatic conditions (Rahmati et al. 2019). Especially, in the Mediterranean belt, including southern Spain, this issue is becoming more intense (Sillero-Medina et al. 2019a, 2019b). Understanding changes in the soil water balance and, therefore, water availability for plants is of great relevance for fragile ecosystems including the Mediterranean one (e.g., Grayson et al. 1997; Llorens et al. 2003; Fernández and Trillo 2005; Katz et al. 2005; Negri et al. 2005; Medrano et al. 2007; De Luis et al. 2011; Lemus-Canovas and Lopez-Bustins 2016; Olcina-Cantos 2017). In this area, water is the major limiting factor determining the plant production and structure of communities (Ferreras Chasco 2000; Terradas 2001).

The water available for plants can be defined as the amount of water retained into the soil, resulting from the difference between the field capacity (FC) and the permanent wilting point (PWP) (Kirkham 2005). This varies according to soil characteristics such as soil texture and structure (Behnam et al. 2020). Both soil texture and structure affect soil matrix potential linked to the water suction capacity by plants (Givi et al. 2004; Martínez-Fernández 1996). This is directly modified by the potential evapotranspiration (Campos et al. 2013). In arid and semiarid environments, large differences in soil AWC occur because of fluctuating water balances and ongoing changes between water revenues and demand (Dong et al. 2019; Gomes Marques et al. 2019). The open vegetation pattern in the Mediterranean results in only part of the excess water being stored in the root zone and depending on its depth; plants can use it during deficit periods, while the rest drains to deeper layers (Joffre and Rambal 1993). Campos et al. (2016) reported that areas registering diverse soil moisture conditions differed according to their degradation states and inclination. These differences favor a greater plant cover in climatic environments ranging from subhumid to dry. As aridity increases, the pattern of moisture in the soil profile becomes more uniform. This results in less significant changes in vegetation, which uses to be better adapted to lower water availability (Ruiz Sinoga et al. 2011).

Under Mediterranean conditions, when soil moisture is high and soil moisture content is sufficient to support plant physiological processes (Laio et al. 2001), soil transpiration rate depends on the vegetation pattern itself and climatic conditions (Campos et al. 2016). However, below this moisture point, plants start to reduce transpiration to avoid internal water loss (Gabarrón-Galeote et al. 2013). Below that point, soil water availability becomes a key factor determining the current evapotranspiration, which continues at a reduced rate until soil moisture reaches the PWP. These points depend on the type of vegetation and soil characteristics and are generally determined in terms of the soil matrix potential for volumetric water content (Gabarrón-Galeote et al. 2013; Laio et al. 2001; Larcher 1995).

The FC refers to the amount of water retained into the soil when excess water has drained away, and downward flow has ceased being usable by vegetation (Ruiz Sinoga et al. 2011). Consequently, the PWP can be defined as the moisture content of the soil in the root zone at which a withered plant cannot recover turgidity, even if it is in a saturated atmosphere for 12 h (Ruiz Sinoga et al. 2011; Campos et al. 2016). The relationship existing in a given soil between the moisture content at PWP and the one it possesses in FC is known as AWC (Martínez-Fernández 1996). However, there is currently no information about the number of consecutive days those Mediterranean soils are subject to a soil moisture content below the PWP (soil driest period), especially in southern Spain. In this study, rainfall data, field measurements using soil moisture probes (TDR), and laboratory simulations of soil wetting/drying to relate the number of days without precipitation to the hydrological state of the soil were estimated. We hypothesize that our results should aid the development of land management plans and predictions of the negative impacts of climate change on Mediterranean ecosystems. Understanding the soil AWC, as well as its dynamic in recent years, will represent a step forward in analyzing the possible impacts of these impacts on the phenology of the vegetation.

Materials and methods

Study area

The study area is located in a representative hotspot along with southern Spain (Fig. 1). This area is situated along the Littoral Betic Range, where over just 308 km of differences in pluviometry gradient occurs from 1400 mm per year in the Sierra de Grazalema (Cadiz) to 150 mm per year in Cabo de Gata (Almeria). This gradient reflects a climatic variability that oscillates between a humid Mediterranean climate in the western part and aridity in the eastern one. Therefore, some authors hypothesized that this gradient would have direct

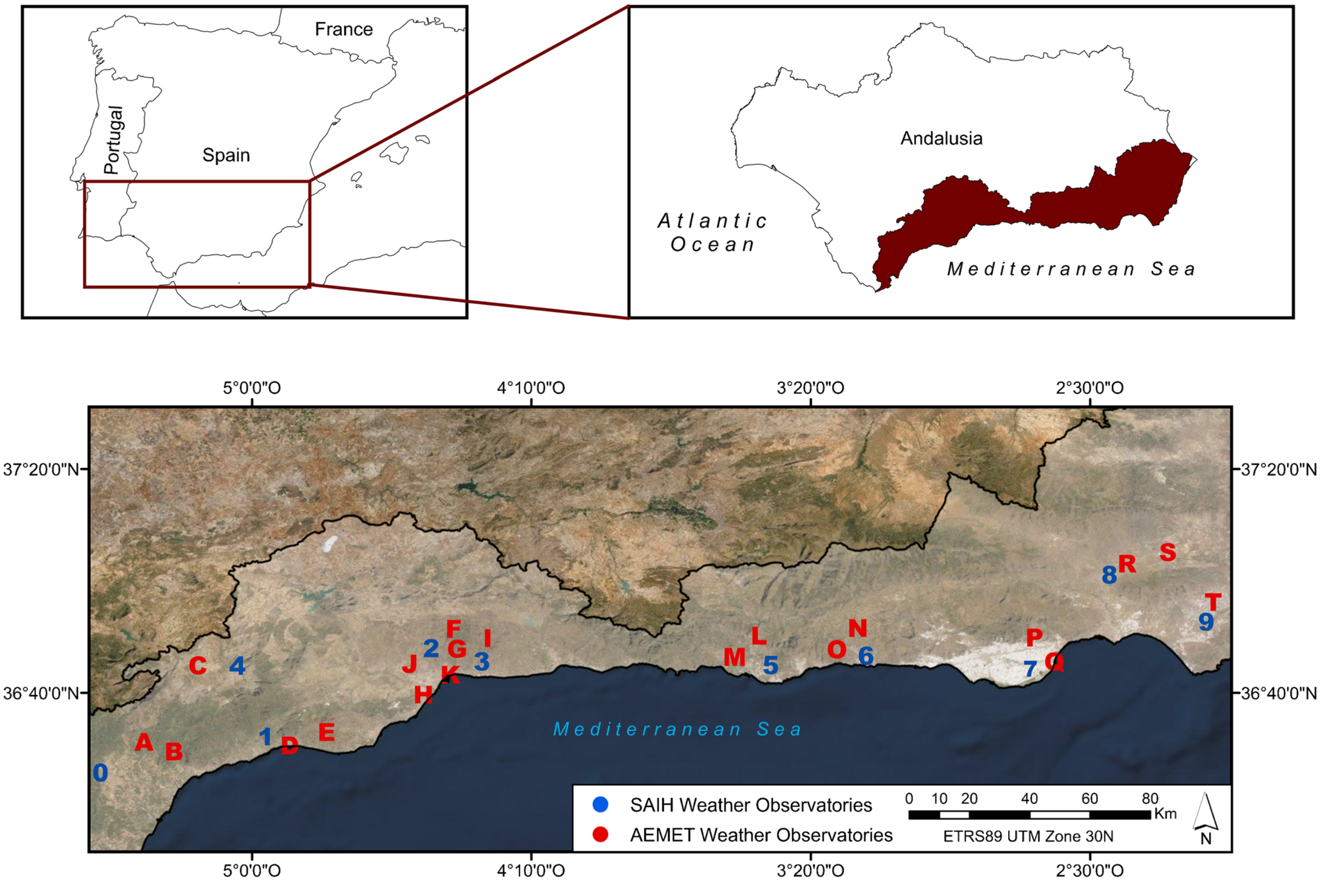

Fig. 1 Study area

impacts on the landscape, ecosystems, and geomorphological processes (Ruiz-Sinoga and Romero Diaz 2010).

Rainfall monitoring data and assessment

Data from ten climate observatories of the Spanish State Meteorological Agency (AEMET) located along some points in southern Spain were used. Our analysis was divided into four different areas from the West to East, due to their different climatic conditions: (i) the western area (W), with a humid Mediterranean climate (> 700 mm/year); (ii) Málaga (M) and Costa Granadina (G), with dry conditions (400–700 mm/year); and (iii) the eastern area (E) with semi-arid and arid characteristics (< 400 mm/year).

The daily precipitation database was obtained from AEMET (Table 1; Fig. 1) and allowed us to analyze the following parameters: rainfall on rainy days, the daily maximum rainfall, the number of consecutive days without rain, dry periods, and the maximum number of consecutive days without precipitation (duration of the dry period).

Hourly rainfall data obtained from the Automatic Hydrological Information System (SAIH) network for the Andalusian Mediterranean Basins (Table 2; Fig. 1) for the period (1997–2019) were used to assess climate variations associated with the soil moisture conditions (1997–2019). Hourly events able to reach rainfall amounts higher than the infiltration rates were selected to determine how much rain was not infiltrated. Finally, evapotranspiration data (Table 3) from the Institute for Agricultural and Fisheries Research and Training (IFAPA) for the same period (1997–2019) was also analyzed.

The databases were integrated chronologically for the four zones along the pluviometry gradient. This involved a database of daily precipitation covering at least 50 years, a 22-year hourly precipitation database, and a database of soil moisture at a depth of 50 cm for the last 22 years. For the 25 representative sites, the soil moisture corresponding to the two basic hydrological states (PWP and FC) was also included.

Soil hydrological conditions and laboratory analysis

A total of 543 soil samples were collected in spring 2008 and 2009 analyzed for 25 representative sites. Thus, 112 samples belonging to the Mediterranean humid area, 99 to the subhumid part, 118 to the dry territories, 102 to the semi-arid points, and 112 to the arid climate locations were collected. All of them belong to areas with metamorphic lithology (phyllites, schist), similar hillslope inclinations (between 10

Table 1 Selected AEMET weather observatories used in the study. Abbreviations: W, western area; M, Málaga; G, Granada coast; E, eastern area

AEMET code	*Station name*	*Coordinates XY ETRS89 UTM Zone 30N*	*Altitude (m)*	*Area*
1-43	Gaucín	292081-4044073	630	W
1-44	Genalguacil	300017-4040747	534	W
2-72	Ronda	307023-4069091	743	W
3-55	Marbella	330975-4042108	16	W
3-56	Marbella2	330887-4042799	59	W
4-64	Pantano Agujero	372123-4070772	117	M
4-49	Boticario	376124-4073244	576	M
5-48	Aeropuerto Malaga	366937-4058334	24	M
5-50	Contadoras	376458-4076289	760	M
5-51	Málaga Ejido	373351-4065628	40	M
5-52	Málaga Oficina	374207-4064799	10	M
6-226	Motril	453724-4070052	29	G
6-227	Motril. Club náutico	452887-4064467	4	G
7-96	Albuñol	481947-4071845	200	G
7-97	Albuñol a Órgiva	481558-4074080	685	G
8-259	Roquetas Pueblo	534364-4068719	9	E
8-260	Roquetas Faro	535100-4068001	3	E
9-265	Tabernas	554239-4100777	408	E
9-266	Tabernas a Sorbas	565062-4104645	561	E
10-231	Níjar	577232-4088198	140	E

and 16%), and vegetation cover degree and typology. After sampling (disturbed and non-ones cores), we analyzed the percentage of vegetation cover, the number of species in the surroundings of the sample (100 m^2), bulk density (BD), soil texture, organic matter (OM), organic carbon (OC), structural stability (AS), permeability, as well as FC and PWP (Table 4). Moreover, both humidification and drying tests under laboratory conditions and using in situ tests through TDR (time domain reflectometry) humidity sensors during the periods 2002–2006 (Hydrosur Project), 2006–2010 (Hydrosur2 Project), 2010–2014 (REME Project), and 2016–2019 (GLOMEDLAND Project) were used following the protocols described by Ruiz-Sinoga and Romero Diaz (2010).

Statistical analysis

Based on environmental, pedological, and climatic data, a principal component analysis (PCA) was carried out to determine those factors that allow to explain the soil hydrological dynamics along with southern Spain. Thus, these data have been normalized into five different categories depending on the variable, either from the lowest to the highest values or from the oldest to the newest ones. This analysis was performed using SPSS version 25 (IBM Corp 2017, USA; corporate license of the University of Malaga). The variables used were annual rainfall (mm), vegetation biodiversity (number of species) (VB), available water (days) (AW), rainy days,

Table 2 Selected weather observatories in the SAIH network. Abbreviations: W, western area; M, Málaga; G, Grenadine coast; E, eastern area

SAIH Hydrosur Network Code	*Station name*	*Coordinates XY ETRS89 UTM Zone 30N*	*Altitude (m)*	*Area*
9	Hozgarganta	280189-4034238	37	W
16	Concepción	324643-4045234	110	W
20	Limonero	372436-4069267	136	M
22	Málaga	374218-4064810	24	M
27	Ronda	306584-4069318	770	W
60	Motril	453614-4067322	69	G
72	Albuñol	484959-4070128	414	G
78	Punta Sabinar	526616-4060200	9	E
93	Rambla de Tabernas	549623-4097053	264	E
97	Níjar	575436-4081658	231	E

Table 3 Selected weather observatories in the IFAPA network https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/estaciones. Abbreviations: W, western area; M, Málaga; G, Grenadine coast; E, eastern area

Station name	*Coordinates XY ETRS89 UTM Zone 30N*	*Altitude (m)*	*Area*
Jimena	286263-4032470	50	W
Estepona	301937-4035540	185	W
Churriana	365680-4059740	17	M
Campanillas	360629-4065960	63	M
Pizarra	346918-4070360	71	M
Cártama	350119-4064780	78	M
Almuchécar	439384-4067570	29	G
Cádiar	483613-4086360	928	G
Adra	500683-4066780	2	E
Almería	553282-4076780	5	E
Tabernas	561998-4105230	502	E
Níjar	577785-4089250	158	E

OM (%), OC (%), rainfall summation of 50 days before the dry season (mm), rainfall summation of 10 days after the dry season (mm), vegetation cover, AS, BD, sand (%), silt (%), clay (%), hydraulic conductivity, heavy rainfall (HR) (%), available water continuous period (days), evapotranspiration, slope (%), field capacity period (days) (FC), wilting point period (days) (WP), xeric period (XP) (days), and driest year (days). In addition, factor analysis was performed using the covariance (raw data) and the correlation matrix (standardized data). Using a correlation matrix, factors with eigenvalues >1 were retained and subjected to varimax rotation to maximize the correlations among factors (Shukla et al. 2006). Finally, Bartlett's test and the KMO (Kaiser-Meyer-Olkin) test were applied.

Results and discussion

Rainfall patterns

Analysis of the AEMET database (1959–2019) showed changes in the daily rainfall distribution over time in southern Spain (Figs. 2 and 3). This included a progressive reduction in the number of rainy days, which is consistent with other reports for other arid and semiarid regions of the world (Dore 2005; Pendergrass and Hartmann 2014). Similarly, the average number of consecutive days without rain also decreased (from almost 6 to 5.3 days). Therefore, the number of rainy days hardly changed, even the maximum number of days without rain increased; however, the duration of the XP did increase. Thus, the length of the dry season increased, which is also consistent with other recent studies in Australia and China among others (Guo et al. 2019; He et al. 2017; Rahmati et al. 2019).

The reduction in rainy days was assessed in the context of changes in the rainfall pattern. The historical AEMET database showed this progressive change, evident as a reduction in the average rainfall for each rainy day (from 12 to 8.8 mm) (Fig. 4). Thus, there was a considerable increase in the maximum daily rainfall amount (from 88 to 110 mm), probably because of more intense precipitation, as reported for all of Spain by Martin Vide (2004).

Hydrological dynamics of the soil surface

Figure 5 shows that during summer, soils were conditioned by the effects of summer droughts and registered the minimum humidity values. Consequently, this coincides with a stressful period for plants, as also reported by Jordano et al. (2002).

Table 4 General characteristics of the study areas. Abbreviations: SD, soil depth (cm); BD, bulk density (g/cm^3); OM, organic matter (%); OC, organic carbon (%); AS, structural stability (%); Ksat, permeability (cm/h); VB, vegetation biodiversity (number of species); VC, vegetation cover (%); SM Max, soil moisture maximum value (%); SM Min, soil moisture minimum value (%); SM, soil moisture (%); WP, wilting point (%); FC, field capacity (%)

	SD	*BD*	*Porosity*	*Very fine sand*	*Sand*	*Silt*	*Clay*	*OM*	*OC*	*AS*	*Ksat*	*VB*	*VC*	*SM Max*	*SM Min*	*SM*	*WP*	*FC*
Western area	69.00	1.20	48.8	12.36	38.18	34.87	23.36	7.74	28.10	74.53	17.57	8.50	81.64	35.27	2.45	19.86	12.00	32.00
Málaga	56.00	1.30	46.6	17.34	31.64	35.05	24.65	3.97	13.83	72.55	10.22	7.22	57.22	24.80	1.86	12.63	7.10	18.20
Grenadine Coast	38.00	1.38	44.3	25.23	57.82	28.53	12.94	2.03	7.71	62.27	6.84	4.20	44.60	17.65	1.42	8.66	3.60	18.00
Eastern area	23.00	1.44	43.7	13.77	54.18	30.73	15.09	1.61	6.42	59.23	5.08	2.00	40.00	8.50	1.18	5.05	2.50	18.10

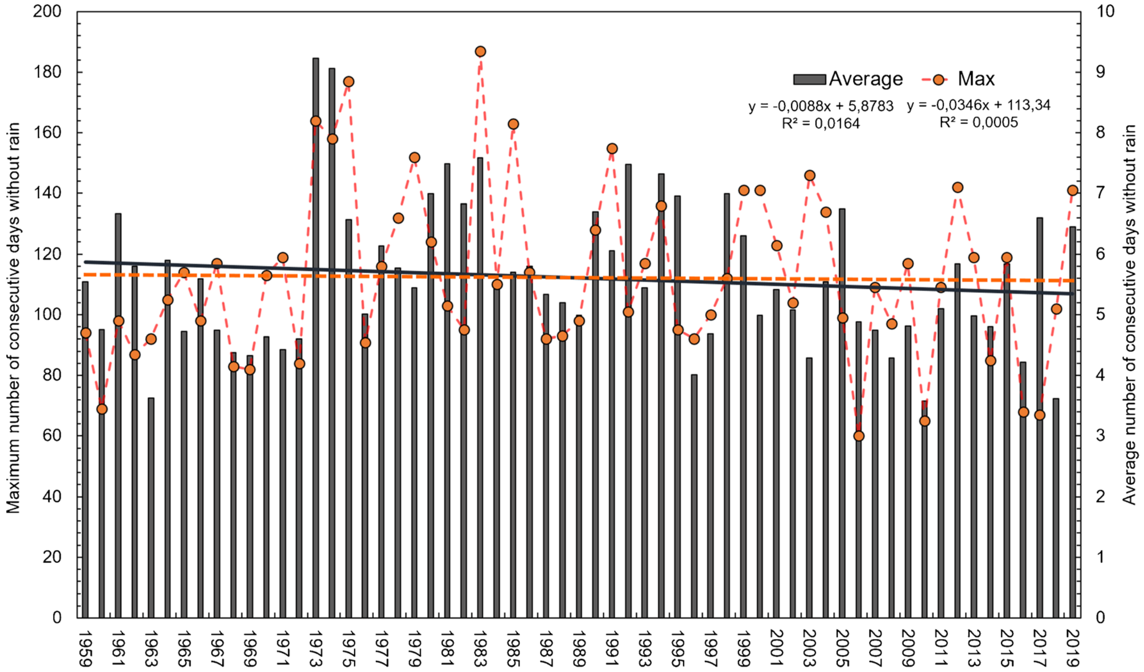

Fig. 2 Analysis of the AEMET database (1959–2019)

This situation, which occurred almost every year, indicates that the soil water available for vegetation was low (Martínez-Fernández et al. 2001; Cortesi et al. 2012). In contrast, during spring and autumn, optimum soil moisture values were reached for the use of plants, sometimes exceeding the content that determines the FC.

Our results confirm that there were extreme weather situations conditioning ASWC. It is appreciated that there was a large number of drought periods and, by contrast, sporadic and random occurrences of heavy rainfall events (Martínez-Fernández et al. 2001; Cortesi et al. 2014; Martin-Vide and Lopez-Bustins 2006). In short, there was marked seasonal variability in the soil moisture conditions (Gallart et al. 2002), as was evident in the data from most of the weather stations analyzed (Fig. 5). At the Hozgarganta station, in particular, the FC state was exceeded on a large number of days. The same was evident at the Malaga City weather station, where this state was reached at lower humidity values (%), which, considering the recent publication by Senciales-González et al. (2020), could even generate heat islands at the urban scale.

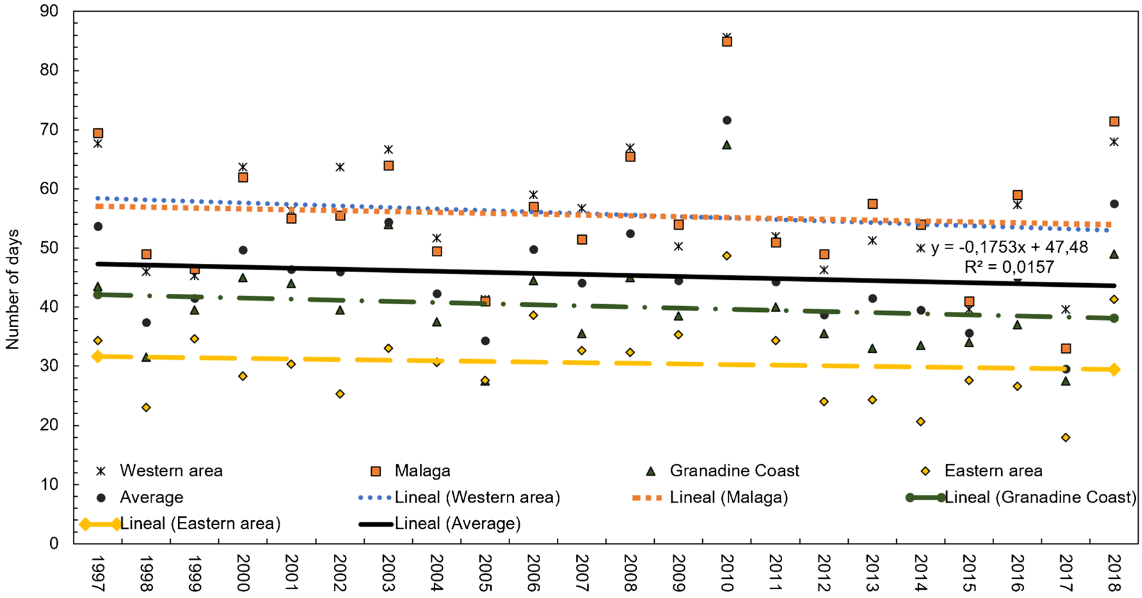

Fig. 3 Number of days of rainfall distribution

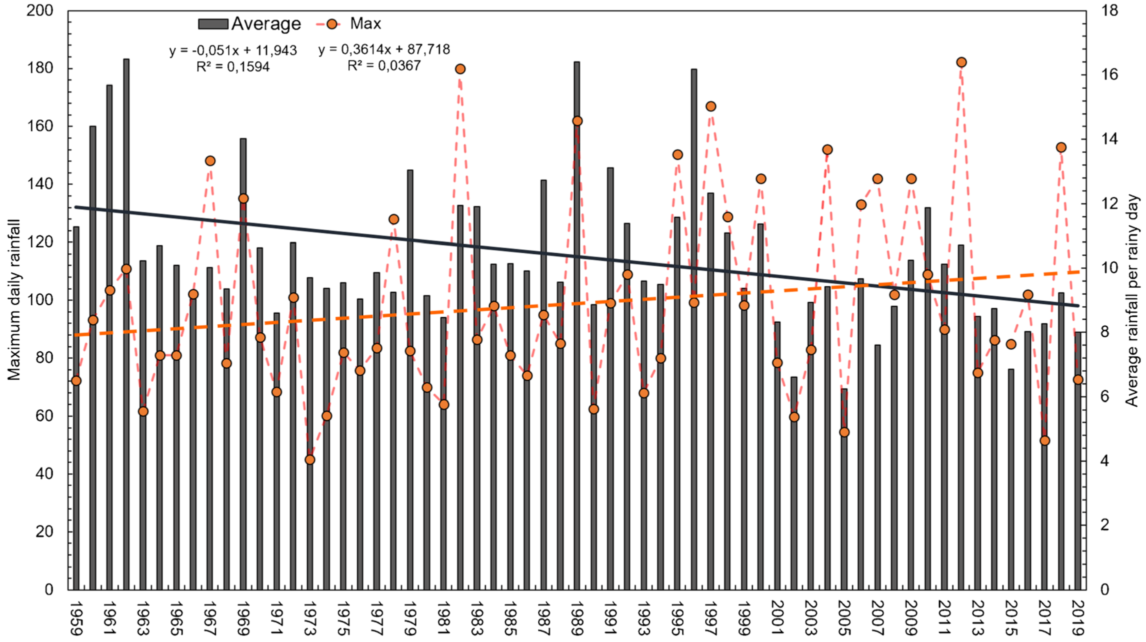

Fig. 4 The historical AEMET database

Along the pluviometry gradient considered in this study, the periods during which the soil was below the PWP occurred much more frequently and for a longer duration in the more arid eastern sector (E) of the Mediterranean basin. Thus, sampling sites including Albuñol (Granada province) or Tabernas (Almería province) reached an optimum state of soil moisture (useful reserve) on few occasions and very irregularly, resulting in frequent occurrences of water stress throughout the year.

Figure 5 also shows in each selected zone the medium values of the interannual pluviometry variability. The hydrological state of the soil showed an elevated spatiotemporal variability, which depended on several factors. In terms of the potential AWC, in the westernmost zone (W), the wettest soils registered values of 12% for the PWP and 32% for the FC, while in the easternmost (E) area, those parameters had values of 3% and 18%, respectively. However, as the aridity conditions increased, the number of days on which the soil was above the FC declined, because of several consecutive days of precipitation. The number of consecutive days on which the ground was below the PWP also increased.

Based on this interannual perspective and the variability patterns, the number of days without rain increased at all climate observatories, except those in the western (W) zone (Fig. 6). In general terms, the number of days on which the soil hydrological state was below the PWP increased for most of the observatories (in W and M increased in more than 10 days), except in the oriental ones, where was slightly reduced (Fig. 7). The stations were grouped considering the number of days without rain and soil moisture.

These general approaches did not consider that at some observatories the magnitude of the soil driest periods could be interpreted as extreme. The largest increase in the number of days in the soil driest period corresponded to the eastern (E) observatories, where in several years in the last decade, this period has extended well beyond 200 days; for example, in 2016, there were 338 days at Níjar station during which the soil was below the PWP, and in 2019, it was up to 256 days. They have practically been found all year round in what could be known as the "driest period" (Table 5).

Thus, as other scholars have previously demonstrated (e.g., Grayson et al. 1997; Llorens et al. 2003; Fernández and Trillo 2005; Katz et al. 2005; Negri et al. 2005; Medrano et al. 2007; De Luis et al. 2011; Lemus-Canovas and Lopez-Bustins 2016; Olcina-Cantos 2017), the Mediterranean is a fragile ecosystem in which water is the most important limiting factor for plant production (Ferreras Chasco 2000; Terradas 2001) and a major determinant of the configuration of plant communities (Sillero-Medina at al. 2019). If this trend continues in the number of days without rain and on which the soil is in water deficit, the repercussions for the ecosystem will be severe, especially regarding the water availability for plants (Dunkerley 2002; Martínez-Fernández et al. 2001).

Rainfall pattern impacts on soil hydrological conditions

In the context of climate change, rainfall in the Mediterranean area is expected to become more concentrated, and extreme rainfall will increase (IPCC 2014). Under these conditions, the

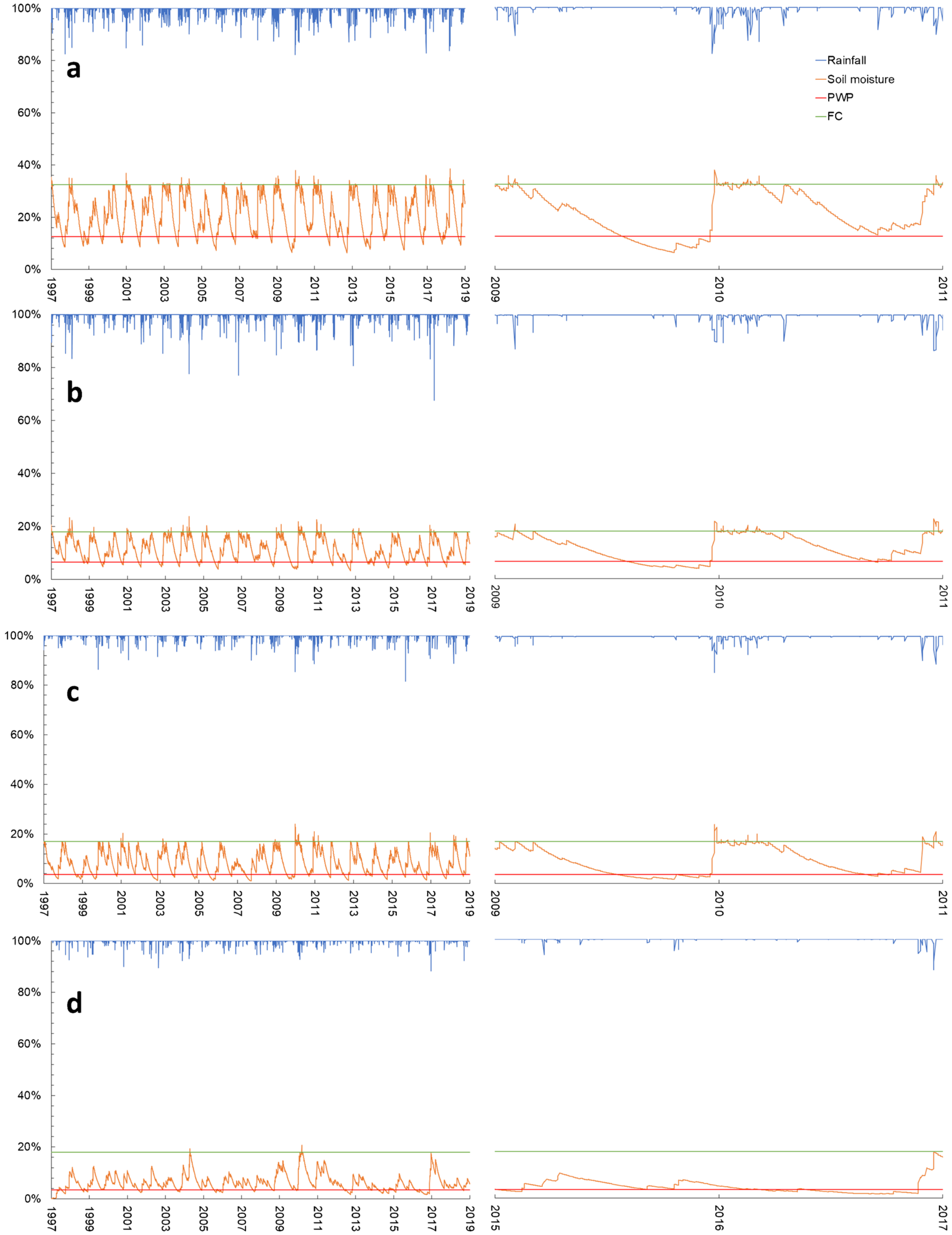

Fig. 5 Marked seasonal variability in the soil moisture conditions

infiltration rate of a given soil may be exceeded with greater frequency (Fig. 8), and when precipitation exceeds the infiltration rate of the soil, runoff is generated (Cerdà et al. 2021a; Imeson and Lavee 1998). The poor development of soils, resulting from intense erosion processes, and the proximity of the topsoil to the parent material, also exacerbates rapid soil saturation and consequently surface runoff in the case of continuing precipitation (Cerdàet al. 2021b; Panagos et al. 2014). Thus, changes in rainfall patterns can directly affect the hydrodynamics of surface formations and the retention of water by soil, as manifested through its moisture content.

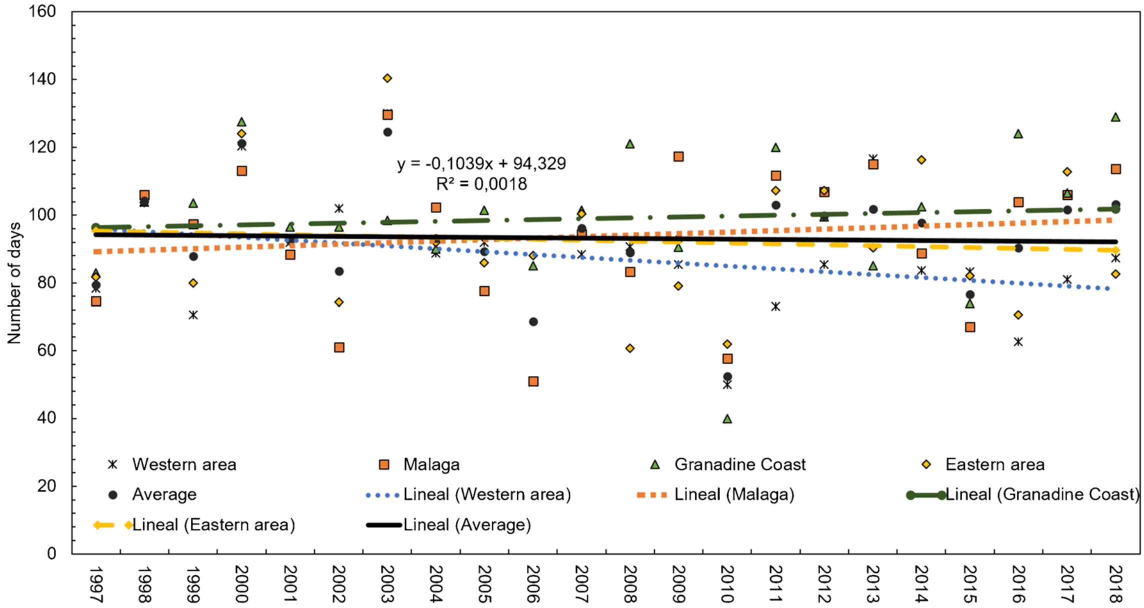

Fig. 6 The number of days without rain increased at all climate observatories

For the study period, it has been defined a rainfall pattern, with a direct incidence from soil hydrology. At those observatories corresponding to a humid–subhumid Mediterranean climate, a slight decrease in rainfall was recorded, net precipitation increased, or precipitation exceeded the soil infiltration rate. Thus, more than 40% of rainfall generated runoff, indicating much of the rainfall infiltrated into the soil; this is especially significant, considering the absolute values (Martin-Vide 2004; Cortesi et al. 2012; Ruiz-Sinoga et al. 2010a). At those observatories corresponding to a dry Mediterranean climate, a slight reduction in rainfall and an increase in excess rainfall was also observed, but the levels were lower than in the humid–subhumid zone, and approximately 50% of the precipitation infiltrated into the soil.

At the observatories in semiarid and arid areas, the pattern was different. With average annual records showing less than 300 mm rainfall in semiarid conditions and 150 mm in arid zones, the precipitation slightly increased. The variations of scarce water resources can also show even other different patterns depending on how soils are managed when the precipitation rate exceeds the soil infiltration rates. Rodrigo-Comino et al. (2019) demonstrated this in poorly managed abandoned plots

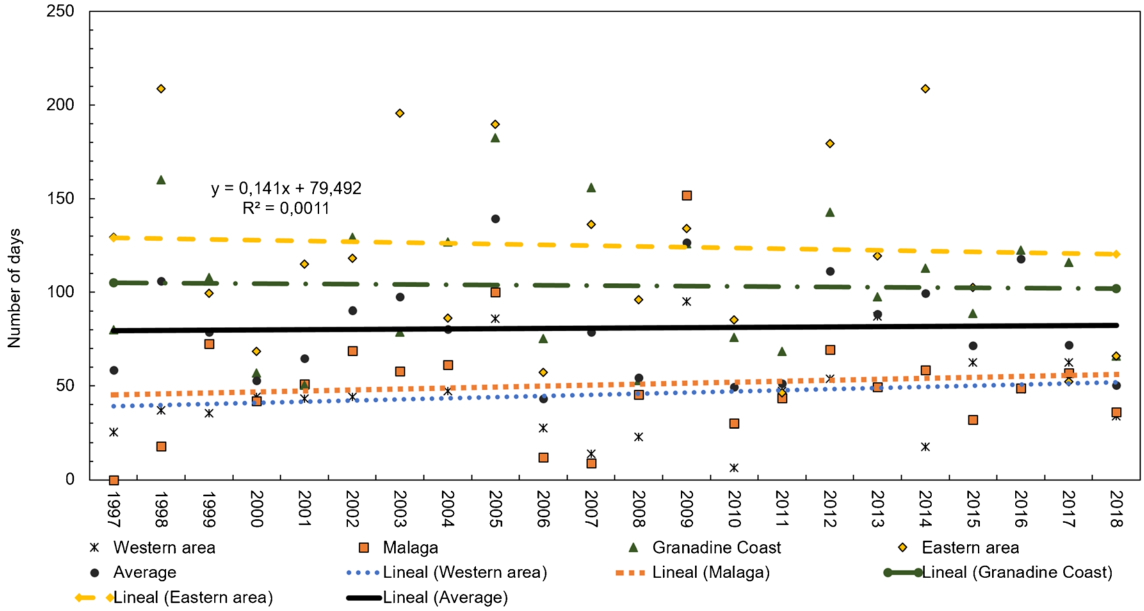

Fig. 7 The number of days on which the soil hydrological state was below the PWP increased for most of the observatories

Table 5 Duration of the soil driest period (1997–2019). The average of the stations is shown in bold letters

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Hozgarganta	61	70	30	41	47	36	51	42	83	49	9	29	141	0	42	87	134	18	77	39	38	54	129
Ronda	0	14	27	43	32	36	54	29	87	1	12	0	2	0	51	28	29	16	24	47	78	0	43
Concepción	15	27	49	49	51	61	69	71	88	33	21	40	142	19	49	47	99	19	87	59	72	48	70
Average	**25.3**	**37**	**35.3**	**44.3**	**43.3**	**44.3**	**58**	**47.3**	**86**	**27.7**	**14**	**23**	**95**	**6.33**	**47.3**	**54**	**87.3**	**17.67**	**62.7**	**48.3**	**62.7**	**34**	**80.7**
Limonero	0	23	84	54	53	86	72	78	134	21	18	54	168	52	57	54	73	51	40	60	72	50	111
Málaga	0	13	61	30	49	52	44	45	66	3	0	37	136	8	30	85	26	66	24	38	42	22	144
Average	**0**	**18**	**72.5**	**42**	**51**	**69**	**58**	**61.5**	**100**	**12**	**9**	**45.5**	**152**	**30**	**43.5**	**69.5**	**49.5**	**58.5**	**32**	**49**	**57**	**36**	**128**
Motril	96	187	136	90	100	150	115	167	238	129	198	103	155	132	99	199	175	159	143	162	174	111	278
Albuñol	64	133	80	24	1	109	43	87	127	22	114	3	97	20	38	87	20	67	35	83	58	21	144
Average	**80**	**160**	**108**	**57**	**50.5**	**130**	**79**	**127**	**183**	**75.5**	**156**	**53**	**126**	**76**	**68.5**	**143**	**97.5**	**113**	**89**	**123**	**116**	**66**	**211**
Sabinar	109	259	117	111	91	205	322	110	219	75	236	146	186	124	85	221	189	267	162	231	80	44	124
Tabernas	110	46	2	0	69	0	60	8	92	7	43	26	12	0	0	117	9	86	42	185	0	12	53
Níjar	169	321	179	95	185	150	205	141	258	90	130	116	204	132	54	200	160	273	104	338	77	142	256
Average	**129**	**208.7**	**99.3**	**68.7**	**115**	**118**	**196**	**86.3**	**190**	**57.3**	**136.3**	**96**	**134**	**85.3**	**46.3**	**179**	**119**	**208.7**	**103**	**251**	**52.3**	**66**	**144**

previously cultivated with vineyards in southern Spain. Therefore, the obtained results could also vary in several magnitudes considering human impacts.

Incidence of the rainfall gradient in determining factors of the soil hydrological dynamics

The results corresponding to the general hydrodynamics in the mentioned pluviometric gradient are consistent since they have been corroborated by principal component analysis (KMO test = 0.864; Bartlett's sphericity = 0.000) (Table 6).

For the considered pluviometry gradient, the results show the importance of the factors related to water and its consequences, mainly in the organic factors and in the properties of the soil, in the same line that has already been raised by other experts (Imeson and Lavee 1998; Cerdà 1998; Novara et al. 2014; Asgari et al. 2020). Thus, following the PCA results (Tables 7 and 8), five different components (C) are able to explain 85.9% of the total variance. Especially, it is significant that up to three components can explain 69.7%. C1 (29.5% of the variance) is related to the organic component, grouping the rainiest areas, not only with higher biodiversity and vegetation density, but also with a higher content of organic matter and organic carbon sequestration. These results agree with other recent studies that highlight the relevance of precipitation and increase in organic matter and, subsequently, in vegetation cover, although human activities (agriculture, urbanization, etc.) highly modify this trend (Lado et al. 2004; Ruiz-Sinoga and Romero Diaz 2010; Ruiz-Sinoga et al. 2010b; Ruiz Sinoga et al. 2011; Sillero-Medina et al. 2019b; Desjardins et al. 2020; Ayoubi et al. 2020).

C2 (27.3% of the variance) is directly related to the pedological properties. The most stable soils are those that register higher BD, sand, and silt percentages, showing a higher infiltration capacity (Shukla et al. 2006; Al-Shammary et al. 2020). C3 reaching a 12.8% of the whole variance is related to the torrentiality of the rain, grouping higher percentages of heavy rainfall, rainfall summation of 10 days after the dry season (mm) and evapotranspiration (Boegh et al. 2002; Bosch and Hewlett 1982; Domingo et al. 1999). However, torrential rainfall not only is important in the management of water resources by vegetation but also has a direct effect on landscape modelling (Angulo-Martínez et al. 2009; Negese et al. 2021). In addition, it is inversely related to the duration of the continuous period of AW and slope percentage. C4 (8.9% of the variance) grouped the years with a longer duration of XP; a higher number of days with soils below WP are the last in the series. Furthermore, this component is inversely related to the period in FC. Finally, clay explains 7.2% of the variance and appears as an isolated factor.

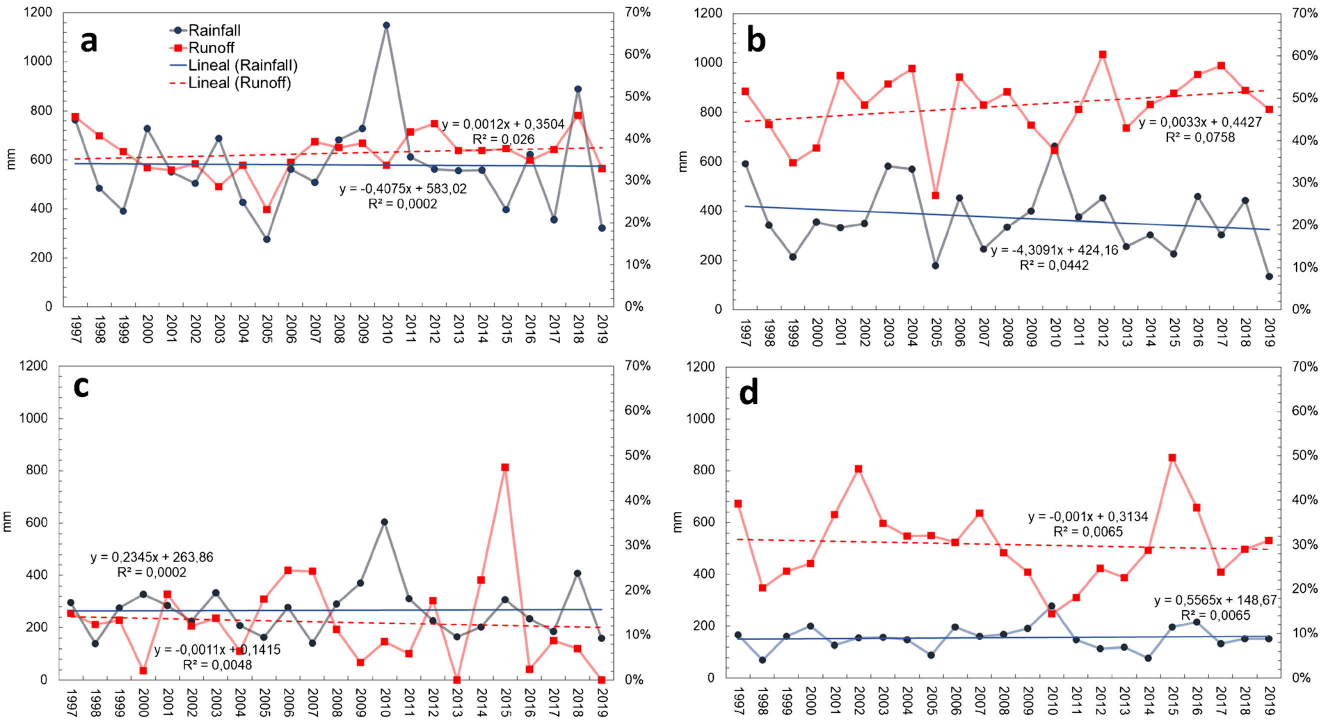

Fig. 8 The infiltration rate of a given soil

Humid areas (W) (> 700 mm/year)

In humid areas, the PCA has shown both a KMO and Bartlett's test with adequate values (Table 6), with six components that explain 75% of the variance, of which the first one explains 34% of it (Table 7). Thus, in these humid areas, the factors associated with water management explain most of the variance, grouping stable soils with high organic matter content (56.3% of the variance), in line with other studies (Laio et al. 2001; Shukla et al. 2006; Ruiz-Sinoga and Romero Diaz 2010; Pulido-Fernández et al. 2013; Novara et al. 2014). C1 (Table 9) is associated with hydrological variables (34.3% of the variance), with the AW. The areas with the highest rainfall are those with the longest AW period, even continuous (AWc), where maximum rainfall occurs in spring and where the highest values of VC, VB, and permeability are found. Thus, in these areas, the most recent years are the driest.

C2, with 12.4% of the variance, is related to the soil texture. The highest values of clay and silt contents correspond to the lowest values of FC. C3 explains 9.6% of the variance and it is related to the organic factor. The most structurally stable soils, i.e., with higher AS, correspond to higher OM and OC contents. C4 (7.1% of the variance) could be considered as a climate factor, since it links the torrential rainfall (HR) inversely to the duration of the XP and the percentage of sand, in relation to that identified by Sillero-Medina et al. (2019a, 2019b). C5, with 6.4% of the variance, is associated with topographical variables. The areas where the longest periods of WP are reached are those with the steepest slopes.

Dry areas (M and G) (400–700 mm/year)

In these areas, both the KMO and the Bartlett test have adequate values, which show a statistical significance (Table 6). Six components explain 85.5% of the variance, from which three explain 61.8% (Table 7). Thus, in these dry areas, biology, soil stability, and climate variables are the factors that explain this 61.8% of the variance. These areas act as a threshold between biotic and abiotic factors as controllers of soil

Table 6 Bartlett and the KMO (Kaiser-Meyer-Olkin) tests

		Total	*> 700 mm*	*700–400 mm*	*< 400 mm*
KMO and Bartlett's test		0.808	0.748	0.590	0.785
Bartlett's test of sphericity	*Aprox. chi-square*	4.154.953	1.405.681	665.801	781.251
	df	245	173	175	175
	Sig.	0.000	0.000	0.000	0.000

Table 7 Bartlett and the KMO (Kaiser-Meyer-Olkin) tests

Component	Total						Humid areas (W) (> 700 mm/year)						Dry areas (M and G) (700–400 mm/year)						Semiarid and arid areas (E) (< 400 mm/year)					
	Initial eigenvalues			Sum of the saturations to the square of the rotation			Initial eigenvalues			Sum of the saturations to the square of the rotation			Initial eigenvalues			Sum of the saturations to the square of the rotation			Initial eigenvalues			Sum of the saturations to the square of the rotation		
	Total	%Var.	%Acc.	Total	%Var.	%Acc.	Total	%Var.	%Acc.	Total	%Var.	%Acc.	Total	%Var.	%Acc.	Total	%Var.	%Acc.	Total	%Var.	% Acc.	Total	%Var.	%Acc.
1	5.411	29.523	29.523	5.863	29.523	29.523	6.869	34.303	34.303	5.858	32.715	32.715	4.682	28.517	28.517	3.886	20.804	20.804	5.746	29.946	29.946	4.982	28.417	28.417
2	5.011	27.339	56.862	4.951	27.339	56.862	2.491	12.439	46.742	2.741	14.790	47.504	2.758	17.662	46.179	3.685	16.826	37.630	2.972	16.968	46.914	2.974	17.930	46.348
3	2.356	12.852	69.714	2.431	12.852	69.714	1.916	9.569	56.311	1.949	9.815	57.320	2.449	15.708	61.887	1.931	12.490	50.120	1.936	10.943	57.857	1.791	9.995	56.343
4	1.641	8.954	78.668	1.356	8.954	78.668	1.418	7.081	63.392	1.820	8.431	65.751	1.731	9.280	71.167	1.827	9.846	59.966	1.927	8.698	66.556	1.697	8.700	65.043
5	1.331	7.264	85.932	1.249	7.264	85.932	1.277	6.375	69.768	1.715	7.326	73.077	1.916	7.798	78.965	1.740	8.442	68.408	1.712	6.619	73.174	1.588	8.678	73.720
6							1.238	6.185	75.952	1.160	6.109	79.186	1.603	6.580	85.545	1.508	7.358	75.765	1.474	5.127	78.302	1.285	6.808	80.529

Table 8 Component matrix obtained in the PCA analysis. Abbreviations: AR, annual rainfall; AS, structural stability (%); AW, available water (days); AWc, available water continuous period; Dap, bulk density; Dyear, drier year; ET, evapotranspiration; FC, field capacity period; HR, heavy rainfall (%); Ksat, permeability; OC, organic carbon (%);OM, organic matter (%); RD, rainy days; VB, vegetation biodiversity (number of species); VC, vegetation cover (%); WP, wilting point period; XP, xeric period (days); ∑pmm-50d, rainfall summation of 50 days before dry season (mm); ∑pmm+10d, rainfall summation of 10 days after dry season (mm)

	Components
AR	0.897
VB	0.875
AW	0.860
RD	0.840
OM (%)	0.769
OC (%)	0.729
$\sum_{\text{pmm -50d}}$	0.690
VC (%)	0.669
AS (%)	0.945
D_{ap} (g/cm^3)	0.929
Sand (%)	0.903
K_{sat} (cm/h)	0.878
Silt (%)	0.771
HR	0.899
$\sum_{\text{pmm+10d}}$	0.856
AWc	−0.841
ET	0.597
Slope (%)	−0.545
FC	−0.680
WP	0.678
XP	0.425
Dyear	0.412
Clay (%)	0.750

Table 9 Component matrix obtained in the PCA analysis in humid areas. Abbreviations: AR, annual rainfall; AS, structural stability (%); AW, available water (days); AWc, available water continuous period; Dap, bulk density; Dyear, drier year; ET, evapotranspiration; FC, field capacity period; HR, heavy rainfall (%); Ksat, permeability; OC, organic carbon (%);OM, organic matter (%); RD, rainy days; VB, vegetation biodiversity (number of species); VC, vegetation cover (%); WP, wilting point period; XP, xeric period (days); ∑pmm-50d, rainfall summation of 50 days before dry season (mm); ∑pmm+10d, rainfall summation of 10 days after dry season (mm)

	Components
AW	0.970
AWc	−0.926
Dyear	0.961
∑ pmm-50d	0.956
VC (%)	0.937
VB	0.891
Ksat (cm/h)	0.790
∑ pmm+10d	0.599
FC	−0.897
Clay (%)	0.795
Silt (%)	0.539
OM (%)	0.858
OC (%)	0.709
AS (%)	0.565
HR	−0.778
XP	0.580
Sand (%)	0.531
Slope (%)	0.826
WP	0.604
D_{ap} (g/cm^3)	0.873

degradation processes, as demonstrated by other authors under similar conditions (Mohammed et al. 2020; Cerdà et al. 2021b).

C1 explains 28.5% of the variance and can be considered as a biological component. The higher AW content is related to a higher VC, VB, OM, and OC (Table 10). C2 (17.6% of the variance) is associated with soil stability. Thus, soils with a better AS are associated with a higher sand content (%), higher BD, and more days in FC. In addition, these variables are negatively related to torrential rainfall (HR).

C3 explains 15.7% of the variance and is entirely related to climatic variables. This component is linked to rainfall summation of 50 days before occurring dry seasons (mm) and inversely to 10 days of rain after a dry season (mm). So, C4 has a pedological character and explains 9.2% of the variance. The soils with higher clay or silt contents are those with lower permeability. C5 can also be connected to C3 and is relative to soil hydrology since as XP is extended, the number of days with AW is reduced. Furthermore, it explains 7.7% of the variance. Finally, C6 is related to physiography, with 6.5%. The areas with steeper slopes coincide with those that have a lower number of days with AW and the higher ones in WP.

Semiarid and arid areas (E) (< 400 mm/year)

KMO and Bartlett's test also showed significant results (Table 6). Six factors can explain 78.3% of the variance (Table 7). In this sense, in the arid environments, it is the torrential nature, the orography, and the biological factors that explain, in this order, 69.3% of the variance. In these environments, AW is linked to rainfall occurring in such a way that the soils can benefit, and not above the soil infiltration rates, as well as in areas where the slope prevents the generation of surface runoff processes, hence the importance of the physiographic factor and specific rainfall events during concentrated seasons (Li et al. 2020; Peña-Angulo et al. 2021). C1, with 29.9% of the variance, could correspond to torrential rainfall, since it relates the percentage of RH to the rainfall that occurs after the summer, in addition to the clay and silt content of the soils, and the number of days in WP and XP (Table 11).

C2, with 19.9% of the variance, is associated with topographical changes. The number of days in AW, the soils with higher AS and BD, and soft slopes are related. C3 and C4, with 19.5% of the variance in total, are related to the biological factor. Thus, increased precipitation before starting the dry season is associated with higher VC and VB, and these with higher levels of OM and OC. C5 (6.6% of the variance) is related to soil hydrology since it directly associates soils with a high percentage of sands with higher permeability and inversely with the number of days in FC. C6, with 5.1% of the variance, is associated with the current climatic dynamics, as it inversely relates the duration of the continuous period of soils with AW, with the most recent years. In other words, at present, the number of continuous days of soils with AW is increasingly lower (5.1% of the variance).

Table 10 Component matrix obtained in the PCA analysis in dry areas. Abbreviations: AR, annual rainfall; AS, structural stability (%); AW, available water (days); AWc, available water continuous period; Dap, bulk density; Dyear, drier year; ET, evapotranspiration; FC, field capacity period; HR, heavy rainfall (%); Ksat, permeability; OC, organic carbon (%);OM, organic matter (%); RD, rainy days; VB, vegetation biodiversity (number of species); VC, vegetation cover (%); WP, wilting point period; XP, xeric period (days); ∑pmm-50d, rainfall summation of 50 days before dry season (mm); ∑pmm+10d, rainfall summation of 10 days after dry season (mm).

	Components
AWc	0.979
VC (%)	0.892
VB	0.842
OM (%)	0.761
OC (%)	0.742
AS (%)	0.867
Sand (%)	0.763
FC	0.698
D_{ap} (g/cm^3)	0.665
HR	−0.614
∑ pmm+10d	−0.884
∑ pmm-50d	0.675
Clay (%)	0.819
Silt (%)	0.790
Ksat (cm/h)	−0.449
XP	0.875
AW	−0.571
Dyear	0.687
Slope (%)	0.856
WP	0.563

Table 11 Component matrix obtained in the PCA analysis in semiarid and arid areas. Abbreviations: AR, annual rainfall; AS, structural stability (%); AW, available water (days); AWc, available water continuous period; Dap, bulk density; Dyear, drier year; ET, evapotranspiration; FC, field capacity period; HR, heavy rainfall (%); Ksat, permeability; OC, organic carbon (%);OM, organic matter (%); RD, rainy days; VB, vegetation biodiversity (number of species); VC, vegetation cover (%); WP, wilting point period; XP, xeric period (days); ∑pmm-50d, rainfall summation of 50 days before dry season (mm); ∑pmm+10d, rainfall summation of 10 days after dry season (mm)

	Components
∑ pmm+10d	0.957
Clay (%)	0.949
WP	0.878
XP	0.841
Silt (%)	0.820
HR	0.690
D_{ap} (g/cm^3)	0.872
AW	0.878
AS (%)	0.795
Slope (%)	−0.577
∑ pmm-50d	0.694
VC (%)	0.686
VB	0.679
OM (%)	0.792
OC (%)	0.670
Sand (%)	0.734
Ksat (cm/h)	0.686
FC	−0.480
Dyear	−0.873
AWc	0.872

Conclusions and possible challenges

Following the objectives set out, there has been an increase in the length of dry periods as a result of a decrease in both the number of rainy days and the number of consecutive days without rain. While there was a reduction in average daily rainfall, there was an increase in maximum rainfall, indicating that the number of events involving extreme rainfall has increased. Therefore, there has been a significant change in the rainfall pattern, with more concentrated rainfall. Soils reflect the climatic seasonality through their hydrological state. Thus, in summer and early autumn, the humidity was low, with a general tendency to increase in the number of days in which the soil is water-deficient or has a humidity state below the WP. This is of particular significance when considering the main land uses in the Mediterranean drylands, since the driest period of the soil could be assumed to be a phenological summer and the hydrological state of the soil will be more often extreme. There is a need for a better understanding of the effect of rainfall dynamics on different land uses, which would modify the results obtained for bare soils, given that vegetation is one of the main consumers of water.

Finally, it can be seen that for the whole of the selected area it is the organic factors that control the properties of the soils and their hydrodynamics. However, while in humid areas, the dominant factor is soil hydrology, the availability of water, which provides consistent plant cover, regardless of its physiographic position. In arid and semi-arid areas, torrential rainfalls are keys, with a greater incidence in areas with steep slopes, to understand biological factors and soil hydrodynamics. This could be used to establish biodiversity thresholds in the context of climate change. Furthermore, a new challenge could be related to the determination of AWC dynamics from a phenological perspective, which could provide fundamental information for understanding the evolution or loss of plant species in each area and biodiversity. Ultimately, future research should aim at assessing landscape modifications as a result of specific AWC dynamics and identifying which species are most vulnerable.

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Data Availability Not applicable

Code availability Not applicable

Declarations

Conflict of interest The authors declare no competing interests.

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