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Spatial variations of runoff thresholds associated with changes in land use over the period 1990-2018 in the Mediterranean side of Andalusia

Variaciones espaciales del umbral de escorrentía asociadas a cambios de usos de suelo durante el período 1990-2018 en el área de la vertiente mediterránea andaluza

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Abstract

The runoff threshold is the amount of precipitation that exceeds the infiltration capacity of the soil and from which water begins to flow over the land surface. Its spatial variation will determine the appearance of a series of processes and risks such as soil erosion, sediment transport, water pollution or flooding, all of which are of great interest in the field of land planning and management. This article provides an update of the runoff threshold in the territorial scope of the Demarcación Hidrográfica de las Cuencas Mediterráneas Andaluzas and evaluates the spatial changes occurred between 1990 and 2018 because of land use dynamics. For this purpose, the methodology described in Regulation 5.2-IC related to surface drainage, of the Instrucción de Carreteras (Ministerio de Obras Públicas y Urbanismo [MOPU], 1990; Ministerio de Fomento, 2016, 2019) was used. The results obtained show very contrasting runoff threshold values, with maximums in the western sector and minimums in the eastern sector. On the other hand, the dynamics of land use changes have led to a significant increase in impermeable surfaces and sclerophyllous vegetation, which has generated a clear reduction in runoff threshold values in different areas, mainly in the eastern region. Specifically, the former forest areas, currently occupied by sclerophyllous vegetation, stand out, with a reduction of 17 mm over an area of approximately 229.1 km^2. The conversion of agricultural lands into urban areas is also noteworthy, with a decrease in their retention capacity by up to 14 mm of precipitation, covering a total area of 97.1 km^2.

Keywords: runoff threshold; land uses; andalusian Mediterranean basin; water management; soil moisture; infiltration capacity.

Resumen

El umbral de escorrentía es el valor de precipitación que excede la capacidad de infiltración del suelo y a partir del cual el agua comienza a fluir sobre la superficie del terreno. Su variación espacial va vinculado a la aparición de una serie de procesos y riesgos ambientales como la erosión del suelo, el transporte de sedimentos y contaminantes hacia cuerpos de agua o inundaciones, todos ellos de gran interés en el ámbito de la planificación y la gestión del territorio. Por tanto, vinculado directamente con los conceptos de peligrosidad y riesgo relativos al agua. En este estudio proporcionamos una actualización del umbral de escorrentía en el ámbito territorial de la Demarcación Hidrográfica de las

Cuencas Mediterráneas Andaluzas basado en los cambios espaciales producidos entre 1990 y 2018 como consecuencia de la dinámica de usos del suelo. Para ello, se ha utilizado la metodología descrita en la Norma 5.2-IC del Ministerio de Fomento de 2019 relativa al drenaje superficial. Los resultados obtenidos muestran una variabilidad espacial y temporal de los valores, con máximos coincidentes en el sector occidental y mínimos en el oriental. Y, además, como la dinámica de cambios de usos del suelo ha supuesto un incremento significativo de las superficies impermeables y de vegetación esclerófila rala, lo que ha generado una clara reducción de los valores del umbral de escorrentía en diferentes áreas, especialmente de la mitad oriental, con las consecuentes implicaciones en los riesgos del agua. Concretamente, destacan las antiguas áreas de bosque, actualmente ocupadas por vegetación esclerófila, con una reducción de 17 mm y con una extensión de unos 229,1 km^2. También es notable la conversión de tierras agrícolas en áreas urbanas, con una disminución en su capacidad de retención de hasta 14 mm de precipitación, cambio que afecta a 97,1 km^2.

Palabras clave: umbral de escorrentía; usos del suelo; Mediterráneo; gestión hídrica; humedad del suelo; capacidad de infiltración.

1. Introduction

Within the framework of hydrological planning, researching the modelling of runoff processes is considered as a fundamental task, as it provides highly interesting information in terms of environmental risk assessment, water management, agriculture or the conservation of ecosystems, among others (Zhang et al., 2018; Xie et al., 2021). These processes are particularly relevant in the Mediterranean region, where water risks are conceived as one of the principal problems faced by society today (Intergovernmental Panel on Climate Change [IPCC], 2021; Olcina Cantos, 2017). Specifically, an increase in the recurrence of the number of torrential events, together with an increase in rain erosivity, water erosion, the intensity and frequency of droughts and water stress or the xeric period of the soil have been identified (Sillero-Medina et al., 2019, 2020, 2021). Similarly, it has been found that the water erosion processes of the land constitute one of the principal environmental problems, particularly in recent years, coinciding with the promotion of new international policies for reducing erosion levels and the conservation of the soil. In this respect, we can refer to initiatives of the European Commission within the framework of the 2030 Biodiversity Strategy and the EU soil protection strategy, such as the "4 per 1000" (Minasny et al., 2017) or the "From Farm to Fork" strategy of 2020 (Montanarella & Panagos, 2021; Panagos et al., 2022), both forming part of the EU's Green Deal. In short, this phenomenon has arisen due to the fact that more than 25% of the European Union's land is currently at risk of desertification. This situation is particularly critical in the Mediterranean region (European Court of Auditors [ECA], 2018). Here, the specific characteristics of the natural system, such as the physiography, the rainfall pattern, the vegetation cover, the soil properties or the use of the land foster the activation of these processes (Martínez-Murillo & Ruiz-Sinoga, 2006; Nadal-Romero et al., 2019; Bravo-Peña et al, 2020). Therefore, these variables represent a key factor for estimating what is known as the runoff threshold (P_o). This parameter determines the total quantity of water that can be absorbed by the soil before surface runoff occurs and is fundamental in the hydrological study of a basin (Camarasa-Belmonte et al., 2006; Campón et al., 2015). The modifications in the most dynamic variables, such as the use of the land, generate major alterations in the hydrological functioning of the basins (Hundecha & Bárdossy, 2004; Viramontes-Olivas et al., 2012; Cerdá et al., 2021), which converts them into a fundamental object of study in any territorial water plan.

Over the last few decades, the Mediterranean area has become a space of opportunity. It has a clear pull factor, in which an extraordinary urban development has coincided with a rapid modification of different agricultural and forestry land uses (Cerdá et al., 2007; Pascual & López, 2016). These modifications in land uses constitute one of the principal human alterations that directly influences the hydrological dynamics. Therefore, determining the functioning of the ecosystems in their entirety is a decisive factor when designing an adequate territorial plan (Asmar et al., 2021). It is essential to identify the dynamics of the changes in land uses in recent years and understand how they came about. It is also important to learn about the response of the eco-geomorphological system to these changes (Calvo-Cases et al., 2021; Daneshi et al., 2021). In parallel, there has also been a major process of abandonment of agricultural areas, which, according to the paradigm of the current climate dynamics, is generating direct repercussions on the eco-geomorphological system. In arid and semi-arid conditions, an increase in the land erosion processes can be observed in response to a greater generation of surface runoff (López García et al., 2007; Camarasa-Belmonte et al., 2018). Such areas have become particularly fragile and sensitive to these processes (Puigdefábregas, 2005; Sillero-Medina et al., 2019).

In short, the recent dynamics in the Mediterranean region have given rise to studies focused on determining runoff thresholds (P_0), in which several facets related to this process are addressed. The study by Lucas-Borja et al. (2019) examines the influence of different factors in these processes. The hydrological responses in highly vulnerable experimental areas have been evaluated (Ruiz-Sinoga & Martínez-Murillo, 2012) and the study by Meléndez-Pastor et al. (2013) proposes different methodologies for estimating these environmental phenomena.

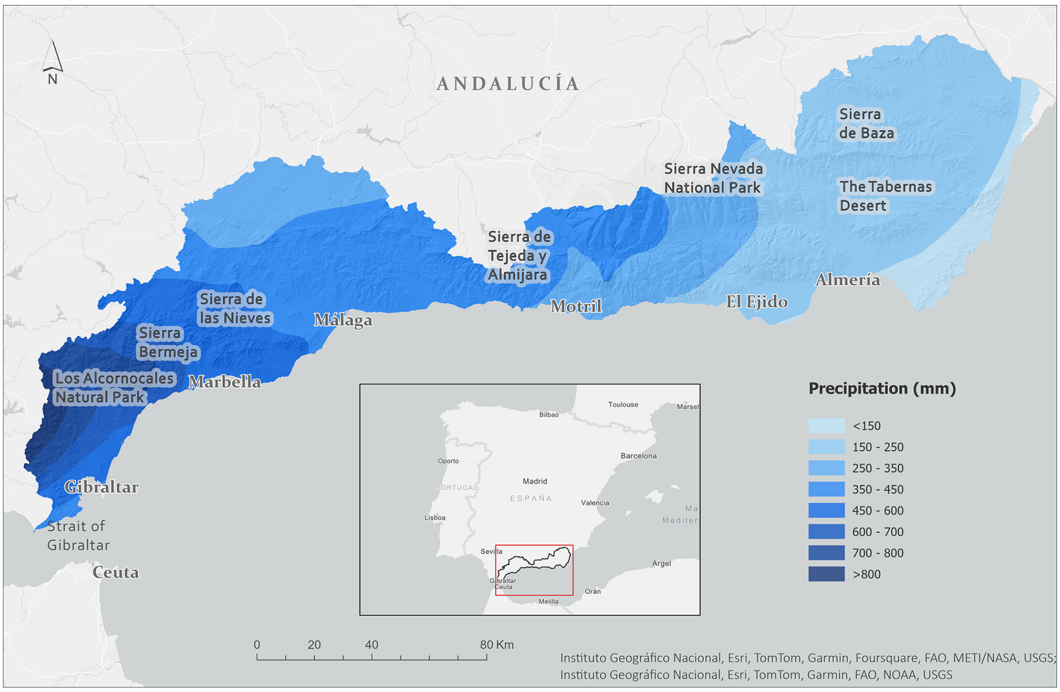
According to these considerations, the principal objective of this study is to provide an update of the P_0 threshold for the territorial area of the Andalusian Mediterranean river basins (Demarcación Hidrográfica de las Cuencas Mediterráneas Andaluzas) (hereafter, CMA) for different states of soil humidity. The importance of this study resides in the need for updated and precise tools for managing the water resources in Mediterranean areas, where the availability of water is limited and the demand is high. With this objective, the changes in the P_0 threshold occurring due to the variations in land uses in the coastal area of the CMAs over the last few decades have been determined. Specifically, the average P_0 of 1990 and 2018 has been calculated, together with the different levels of humidity in the most recent year. The study also evaluates the surface and uses of the land that has undergone the most alterations in this threshold, both positive and negative, together with their possible incidence on water hazards and risks related to surface runoff and, therefore, the territorial fragility and/or vulnerability. With this objective, the study seeks to provide useful information for water managers and to contribute to a sustainable management of the water resources in the region.

2. Methodology

2.1. Area of study

The area included in the CMAs is made up of a series of river basins, streams and watercourses that originate in the Baetic mountains and flow into the Mediterranean sea (Figure 1). This area of 20,000 km^2 is particularly interesting because a longitudinal pluviometric gradient occurs in a little over 300 km with implications for the landscape dynamics, as analysed in different studies (Ruiz-Sinoga et al., 2015). Contrasting with the rainfall characteristics of the humid Mediterranean climate, with values of over 1,400 mm/year in the western area, on the eastern side, there is a rainfall of 150 mm/year, characteristic of an arid Mediterranean climate, with a whole series of intermediate situations throughout the territory, with direct effects on the landscapes.

Figure 1. Map of the distribution of average mean precipitation in the CMAs (period 1997-2022)



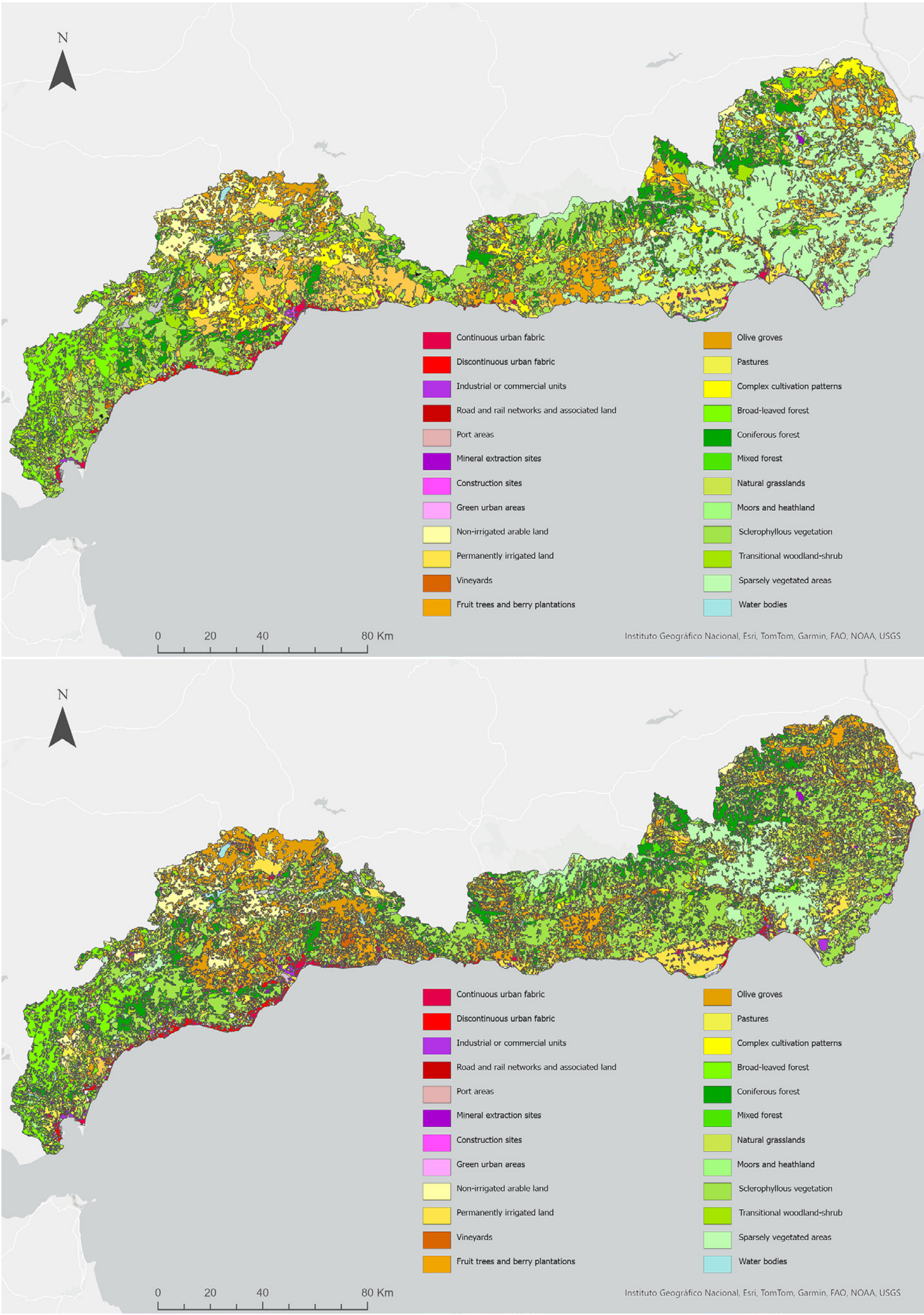
Source: Red SAIH Hidrosur. Own elaboration

This territory has been modelled by a drainage network that was formed as it sought a connection with the sea level, sculpting a relief very close to the coastline with a short hydrographic network consisting in steep slopes and with rivers that descend sharply between their sources and mouth into the Mediterranean sea. This also gives rise to high solar thermal coefficients due to the exposure of the hillsides and the latitude. Similarly, the land uses are characterised by their special space-time dynamics. It is a traditionally agricultural area, particularly on the valley floors. However, in recent years and due to the expansion of the coastal urbanisation process, there has been a displacement and transformation of the uses of the land caused by the expansion of artificial and sealed areas, the increase in intensive irrigated agriculture and abandoned crops. In summary, a series of specific characteristics prevail that have made the eco-geomorphological system a territory that is highly sensitivity and/or vulnerability to extreme rainfall events that are becoming increasingly intense and frequent and to floods between long spells of drought within a clear context of climate change.

2.2. Data sources

The data referring to land uses have been obtained from the CORINE Land Cover project for 1990 and 2018 and have been downloaded from the Instituto Geográfico Nacional (Ministerio de Transportes, Movilidad y Agenda Urbana, s. f.). The Digital Elevation Model (DEM) has also been taken from the same source with a resolution of 25 m/pixel/pixel (Figure 2).

Figure 2. Land use maps, CORINE Land Cover project 1990 (top) and 2018 (bottom)



Source: Centro Nacional de Información Geográfica. Own elaboration

2.3. Calculation of the runoff threshold

In order to determine the P_o, the criteria and procedures implemented by Road Regulation 5.2-IC regarding surface drainage have been followed (Ministerio de Fomento, 2019). Meanwhile, in order to calculate net rainfall, the *Soil Conservation Service* (SCS) (1956) (*Natural Resources Conservation Service* --NRCS-) has been used. The whole process is summarised in Figure 3.

The thresholdP_o(mm) is defined as the minimum amount of rain that should fall on the basin for it to initiate a runoff process. Mathematically, it is developed with two variables, P_o^i(mm), representing the value of the initial runoff and β (adimensional), which is the correction coefficient associated with the humidity of the soil through which the rational method with which it is developed is calibrated:

$$P_o = P_o^i \cdot \beta$$

The first value that is required refers to the initial runoff value, which has been estimated through the classifications provided by the Ministerio de Fomento (2019) based on the information derived from: (i) land uses; (ii) cultivation practices; (iii) slope percentage; (iv) hydrological soil group.

Initially the cultivation practices are categorised into three different types (R, N; R/N). Within this context, "N" denotes the crop in accordance with the level curves. This means that the crop is grown following the contour lines of the terrain, seeking to minimise the soil erosion and conserve the humidity as runoff is prevented. On the other hand, "R" denotes that the crop is grown in line with the maximum gradient. This indicates that the crop follows the direction of the steepest slope of the terrain. This approach is usually used on hillsides with steep slopes in order to use gravity in irrigation and water drainage. Due to the large spatial area covered in this study and given that each of these approaches can have advantages and disadvantages depending on the characteristics of the terrain, the farming practices have been generalised as type "N" in areas with gradients of over 3%. This is done under the understanding that the majority of cultivation techniques are aimed at making the most efficient use of water.

In this way, taking as a reference the land use assigned to the terrain, we can obtain the runoff threshold in accordance with the other previously mentioned factors.

Table 1. P_o values assigned to land uses, cultivation practices, slopes and hydrological soil groups

Land use	[1]	Slope (%)	Soil group			
			A	B	C	D
Rainfed land (cereals)	R	≥ 3	29	17	10	8
	N	≥ 3	32	19	12	10
	R/N	< 3	34	21	14	12
Rainfed land (vegetables)	R	≥ 3	23	13	8	6
	N	-	25	16	11	8
	R/N	< 3	29	19	14	11
Abandoned land	-	≥ 3	16	10	7	5
	-	< 3	20	14	11	8
Permanently irrigated land, irrigated arable crops	R	≥ 3	37	20	12	9
	N	≥ 3	42	23	14	11
	R/N	< 3	47	25	16	13

Source: Ministerio de Fomento (2016)

Subsequently, using the DEM, the slope of the terrain was calculated in the area of study. Once the sections corresponding to the area of study were downloaded, a conditional evaluation of the maximum gradient of 3% was carried out. This generated two types of terrain that correspond to the runoff threshold tabulation.

The last factor to be implemented is that of the hydrological soil groups. These are categorised in accordance with a series of characteristics that can be found in Regulation 5.2-IC (Ministerio de Fomento, 2019) and summarised in Table 2. Two categories are included for the area selected, with Group C being the most widespread, with 75% of the total CMA area, followed by Group B.

This procedure for obtaining geographical data has been carried out using the software ArcGIS Pro-2022 (Corporate Licence of the Universidad Complutense de Madrid). In this way, once the information relating to the four previous factors had been obtained, using the Python dictionaries in ArcGIS Pro, a total of four initial thresholds were generated for all of the Andalusian Mediterranean basins. However, this initial runoff threshold has been obtained with an intermediate degree of soil humidity (prior to precipitation). Therefore, following the instructions for calculating net rainfall using the SCS method, a correction coefficient drawn from the numerical tables of Ferrer (1993) was applied, in accordance with the recommendations for hydro-meteorological calculations of floods of the Centre of Hydrographical Studies (Campón et al, 2015).

Therefore:

- On previous dry days: $P_o = P_o^i \cdot 2.31$
- On previous wet days: $P_o = (P_o^i)^2 \cdot 0.0072 + P_o^i \cdot 0.167$
- In the case of previous days with an intermediate humidity the correction factor is not applied.

Table 2. Properties of the hydrological soil groups in order to determine the P_o threshold

Group	Infiltration	Power	Texture	Drainage
A	Fast	Large	Sand	Perfect
			Loamy sand	
B	Moderate	Medium to large	Silt loam	Good to moderate
			Loam	
			Loam-silt-sand	
			Silt loam	
C	Slow	Medium to small	Loam-clay	Imperfect
			Sand-clay-loam	
			Sandy clay	
D	Very slow	Claypan	Clay	Poor or very poor

Source: Ministerio de Fomento (2016). Own elaboration

The criterion used for considering the soil as dry, intermediate or wet can be found in Table 3 (Singh, 1992, p. 477), understanding that the prior conditions refer to the five previous days:

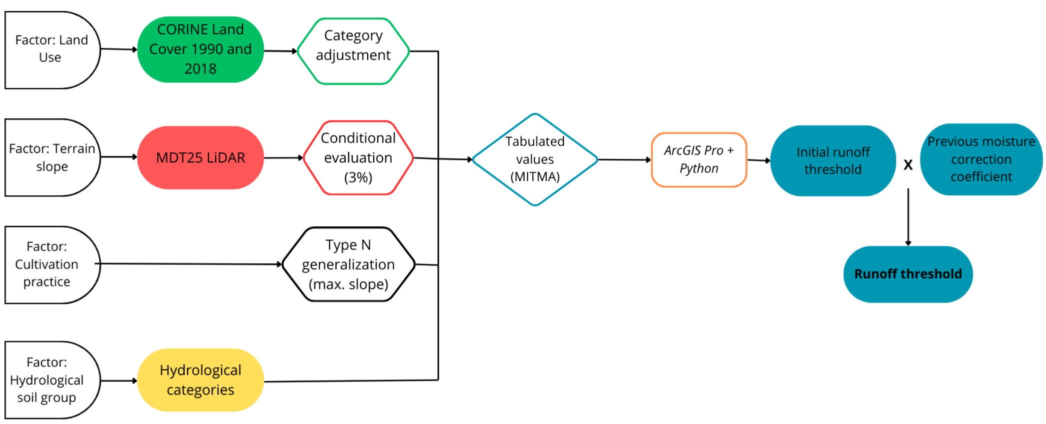
Table 3. Prior humidity conditions to determine the value of P_o

Plants in latent period	Plants in growth period	Previous humidity
< 13 mm	< 35 mm	Dry (1)
13 – 32 mm	35 – 52 mm	Normal (II)
> 32 mm	> 52 mm	Humid (III)

Source: Singh (1992). Own elaboration

The afore-mentioned method refers to the use of correction when procedures are applied to the data of real precipitations. However, if we wish to use statistically calculated rainfall, the Spanish Regulation 5.2-IC provides a specific correction based on the region and return period considered (Ministerio de Fomento, 2019). It is important to take into account that this correction is not appropriate for land without vegetation such as continuous urban land, and in these cases, it is recommended that it is not applied or that the lowest available threshold is used (type I).

Figure 3. Flow diagram of the methodology used to calculate the runoff threshold



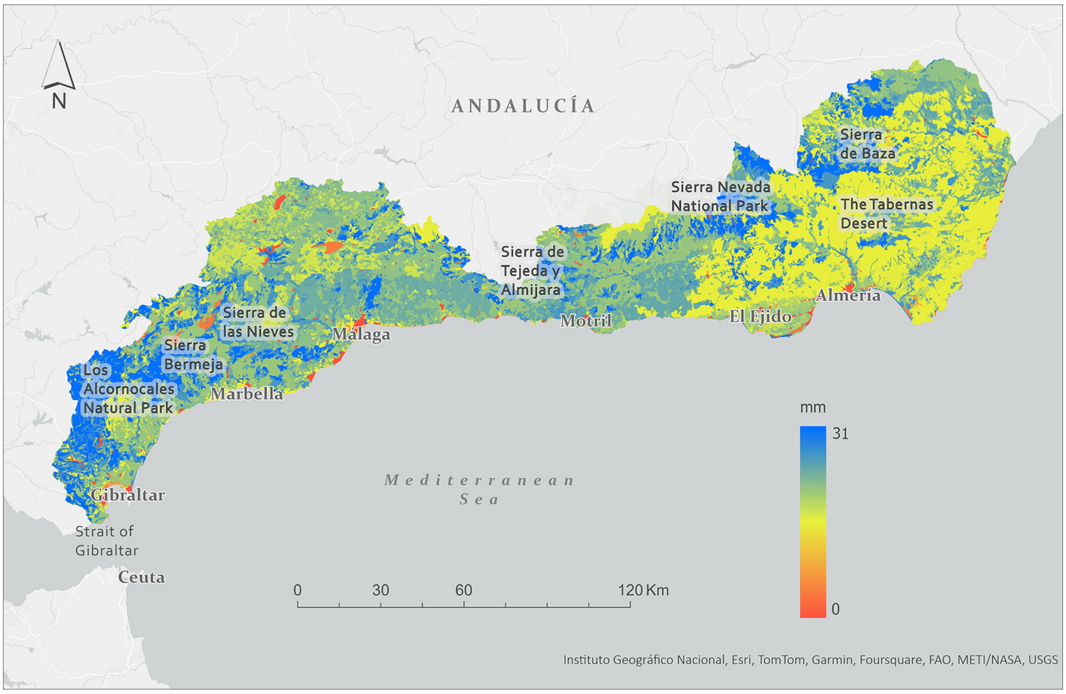
Own elaboration

3. Results

3.1. Average runoff threshold in 1990

The calculation of the average runoff threshold for 1990 obtained using an intermediate land humidity shows the highest values, close to 30-31 mm, in the western Andalusian sector (Los Alcornocales Natural Park, Sierra Bermeja or Sierra de las Nieves National Park), some unique mountains (Montes de Málaga, Sierra de Mijas) and in the Sierra Nevada (Figure 4), which corresponding to broad-leaved forests in the most westerly area of the CMA and coniferous forests in the rest. The small unique mountains are classified as broad-leaved, coniferous or mixed forests. On the contrary, the lowest values, except the water bodies with a zero threshold, are dominant in the eastern sector, where there are sparsely vegetated areas (The Tabernas Desert) and rainfed croplands and natural pastures to the north-west of Málaga (South and West of Antequera). The intermediate runoff values (15-17 mm) are found principally in the centre and far north-east of the area, where there are large areas of sclerophyllous vegetation, agricultural land with large natural vegetation spaces and some complex cultivation patterns.

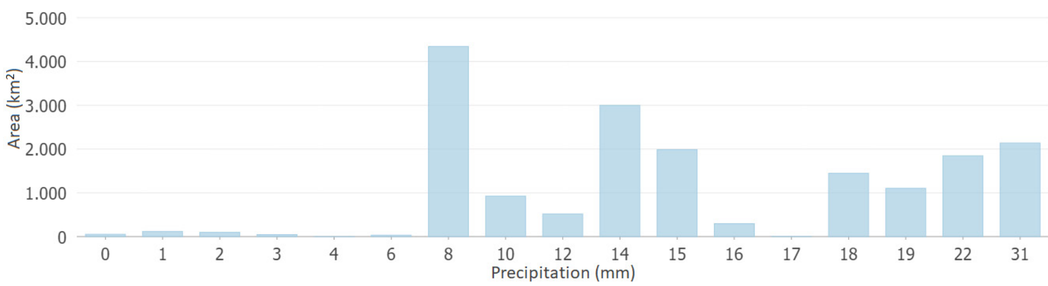
Figure 4. Runoff threshold of the year 1990 with an average prior soil humidity.



Own elaboration

The distribution of the runoff threshold of 1990 in the frequency histogram (Figure 5) shows a range between 31 and 0 mm of precipitation, with a mean value of 15.67 mm and a median of 14 mm. It should be noted that the most frequent runoff threshold is found in the lowest values (8 to 9 mm). This last threshold represents a combination of uses, including areas of discontinuous urban fabric, sparsely vegetated areas, natural pasture and areas under construction. In short, the infiltration capacity of the soils was greater where its level of protection went in the same direction. Finally, a moderate standard deviation of 7.33 can be observed, with a coefficient of variation of 46.74%, which is moderately high in comparison with the mean.

Figure 5. Frequency histogram of the runoff threshold of the year 1990 with intermediate prior soil humidity



Own elaboration

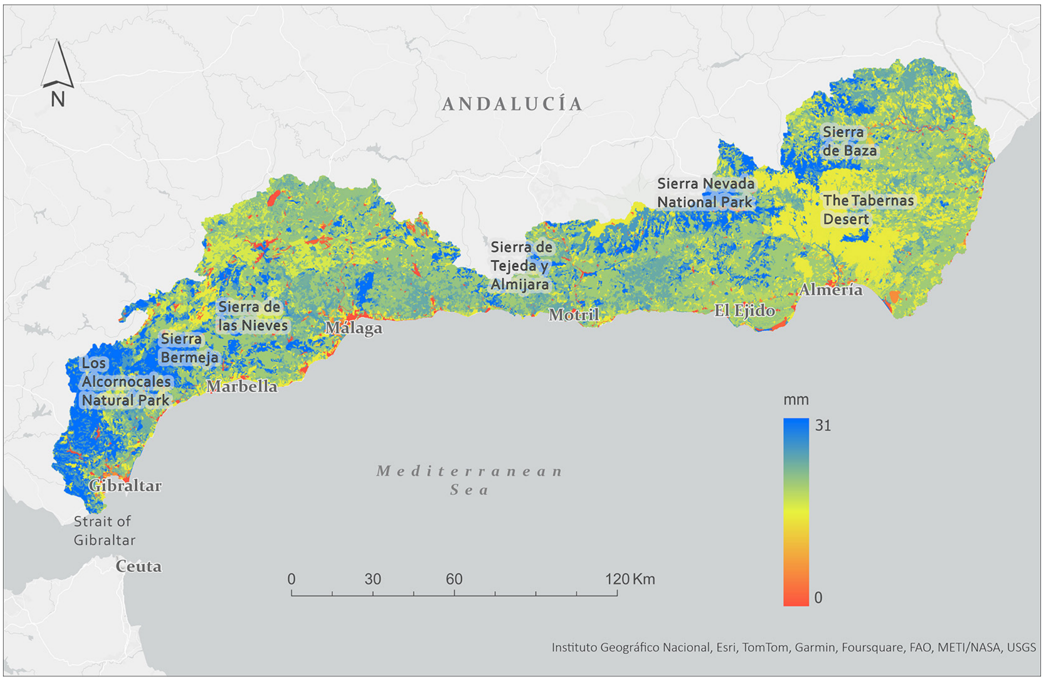
3.2. Runoff threshold in 2018

The mean runoff threshold in 2018 (Figure 6) exhibits changes with respect to the three preceding decades, with a notable reduction in the surface area with lower thresholds (in yellow), which are dominant in the eastern sector and in most of the province of Almería, marked in green tones, denoting a somewhat higher threshold. The land use is characterised by sparse sclerophyllous vegetation and a low spatial coverage with an area of more than 210 km^2.

The mean value of this threshold is determined in the interval of 14-15 mm and covers 28% of the area of the CMAs. This terrain is principally characterised by sparse sclerophyllous vegetation, olive groves and rainfed complex cultivation patterns and has a gradient of over 3%. It mostly belongs to hydrological group C, with a generally slow infiltration. The second most frequent interval is the 8-9 mm interval, with an occupancy percentage of 15.12% and is mainly composed of sparsely vegetated terrain and natural pastures, with a more significant influence in the eastern sector of the CMAs.

The interval with the highest water retention capacity before the runoff begins (30-31 mm) is still dominant in the western sector and in the land at a higher altitude (Sierra Nevada and Sierra de Baza Natural Parks). It covers 13.93% of the surface area and is formed, as in decades past, by forestry uses, including coniferous, broad-leaved and mixed forests, represented in blue tones (Figure 6). These have a greater influence in the most westerly sector, highlighting the differences in precipitation and temperature existing longitudinally along the whole of the Mediterranean side of Andalusia.

Figure 6. Runoff threshold of the year 2018 with an average prior soil humidity

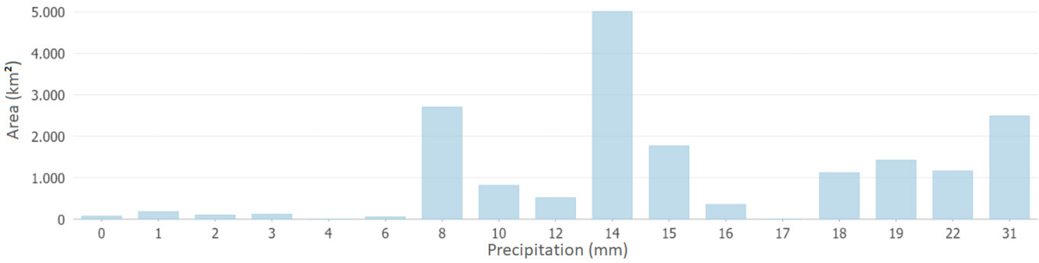


Own elaboration

Finally, the lowest values observed (< 8 mm), in orange tones in Figure 6, affect three different categories of land cover: natural and artificial water bodies, rock forms and mining areas and the land that has been strongly modified by human activity (continuous and discontinuous urban fabric, port areas, sporting spaces, airports, railway infrastructure and areas under construction). These latter sectors with a high percentage of impermeable land have high levels of runoff. In Figure 6 we can observe that this sealed land has a distribution that is on the whole parallel with the coastline or follows natural watercourses, in line with the pattern of the urban and tourism development of the Mediterranean coasts. The area occupied by this latter group affects 673.5 km^2 and the impact is particularly strong in the western sector of the CMAs (the coast of the province of Málaga).

The frequency distribution of the mean runoff threshold in 2018 has the same precipitation range (0 and 31 mm), with an arithmetic mean of 16.17 mm, which constitutes a slight increase with respect to 1990. The standard deviation remains practically unchanged (7.31 mm), which indicates a moderate dispersion around the mean. Furthermore, the coefficient of variation of 45.2% shows a relative variability of the distribution in relation to the mean (Figure 7).

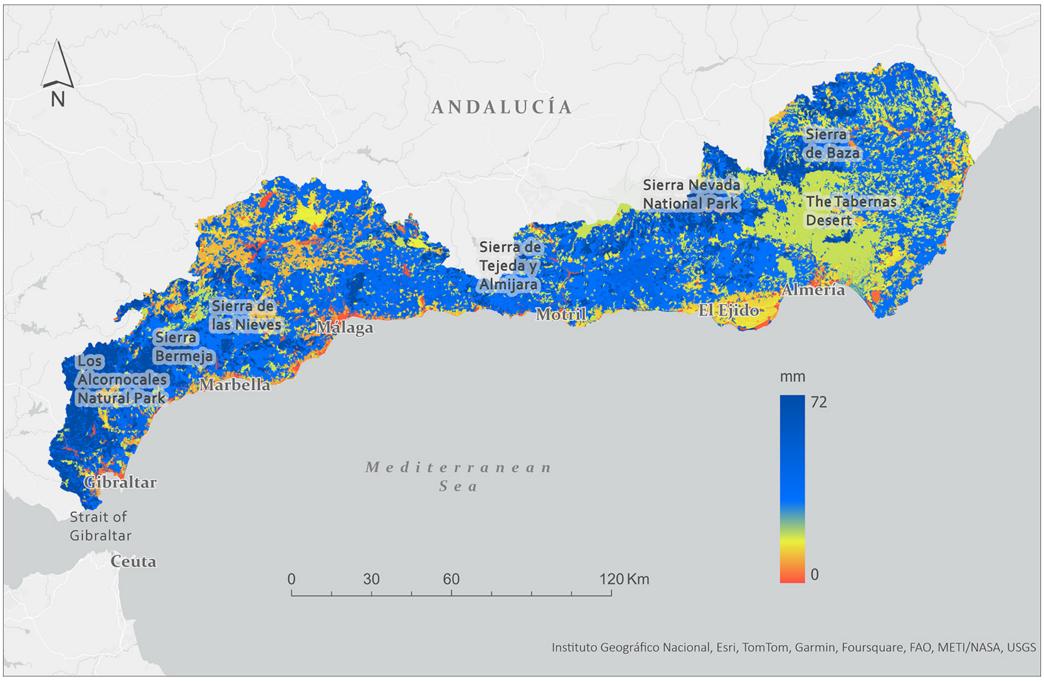
Figure 7. Frequency histogram of the runoff threshold of the year 2018 with an average prior soil humidity



Own elaboration

On the other hand, when applying the correction factor of prior humidity β (low or "dry" land humidity) to 2018, we can appreciate that the distribution of the threshold remains almost constant, although there is a greater variability in certain terrains. Therefore, the water retention capacity of dry land (type I or with rainfall lower than 13 mm in the previous 5 days) increases to a value of 72 mm, with the maximum thresholds of the forest soils remaining unchanged (Figure 8).

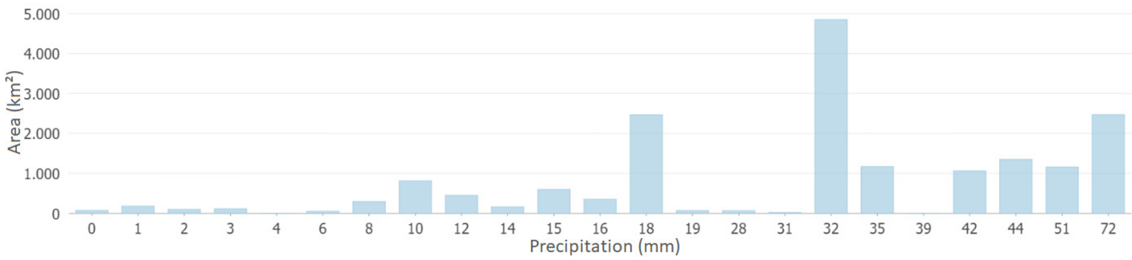
Figure 8. Runoff threshold of the year 2018 with a low prior soil humidity



Own elaboration

The histogram referring to 2018 in conditions of a low prior humidity (Figure 9) shows an arithmetic mean of 34.61 mm, which is more than double that of the precipitation necessary to initiate the runoff when the soil has an intermediate humidity. The standard deviation is also higher, as it increases to 19.2 mm, indicating a higher dispersion around the mean with respect to the threshold obtained with an intermediate humidity. Finally, the coefficient of variation increases to 56.11%.

Figure 9. Frequency histogram of the runoff threshold of the year 2018 with a low prior soil humidity



Own elaboration

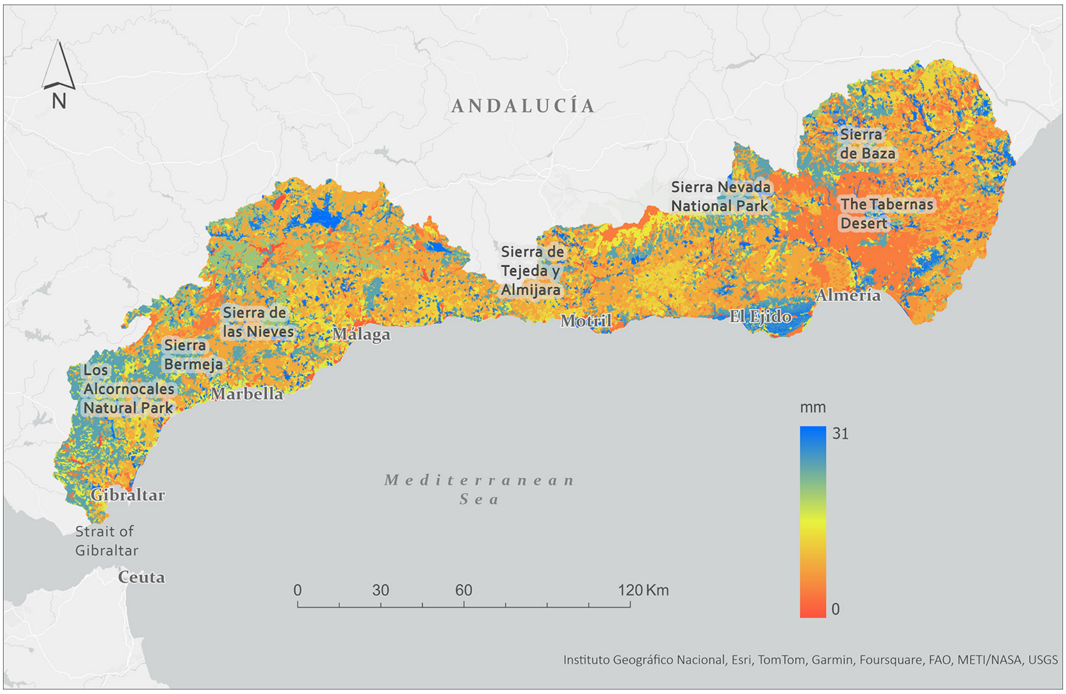
In the current scenario, due to the scarce rainfall, the most frequent runoff threshold is at 32-33, of rainfall, which represents an increase in the water capture of up to 18 mm on land with sclerophyllous vegetation.

It is important to point out that the forest soils have a higher threshold (up to 72 mm), which more than doubles the P_o in a situation of intermediate humidity. Furthermore, the moors, scrubland, meadows and fruit crops, which cover approximately 20% of the total area of the CMAs, have a P_o of between 40-50 mm.

On the other hand, the sparsely vegetated areas, which also occupy a considerable part of the terrain (4.5% of the area), experience a lower increase in their threshold, from 8 to 18 millimetres. This increase is lower in the case of sclerophyllous vegetation (18 mm) and considerably lower than in forest soils (41 mm).

Finally, the P_o in 2018 with a high prior soil humidity (type III) logically reduces considerably with respect to the value under normal humidity conditions (Figure 10). In the areas with latent vegetation, the runoff threshold range decreases to 21 mm. The forest terrain loses a water retention capacity of up to 19 mm and the sclerophyllous vegetation up to 10 mm, while sparsely vegetated areas only reduce their capacity by 6 mm.

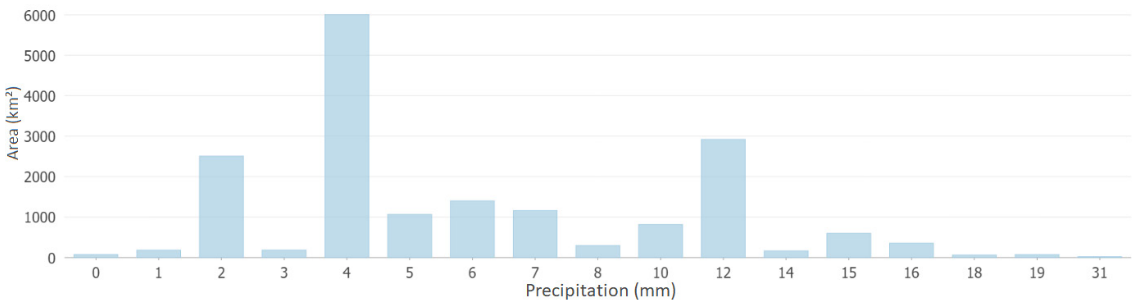
Figure 10. Runoff threshold of the year 2018 with a high prior soil humidity



Own elaboration

The frequency distribution for 2018 in high prior soil humidity conditions shows that the arithmetic mean reduces considerably to 6.55 mm of rainfall, the median decreases to 4 mm and the standard deviation to 4.2 (Figure 11). Finally, the coefficient of variation increases to the maximum value of the three distributions (64.42%). These latter two statistics indicate that, although the absolute variability of the P_o in conditions of low prior humidity is lower, the relative variability is higher than those detected in standard humidity conditions in 1990 and 2018.

Figure 11. Frequency histogram of the runoff threshold of the year 2018 with a high prior soil humidity



Own elaboration

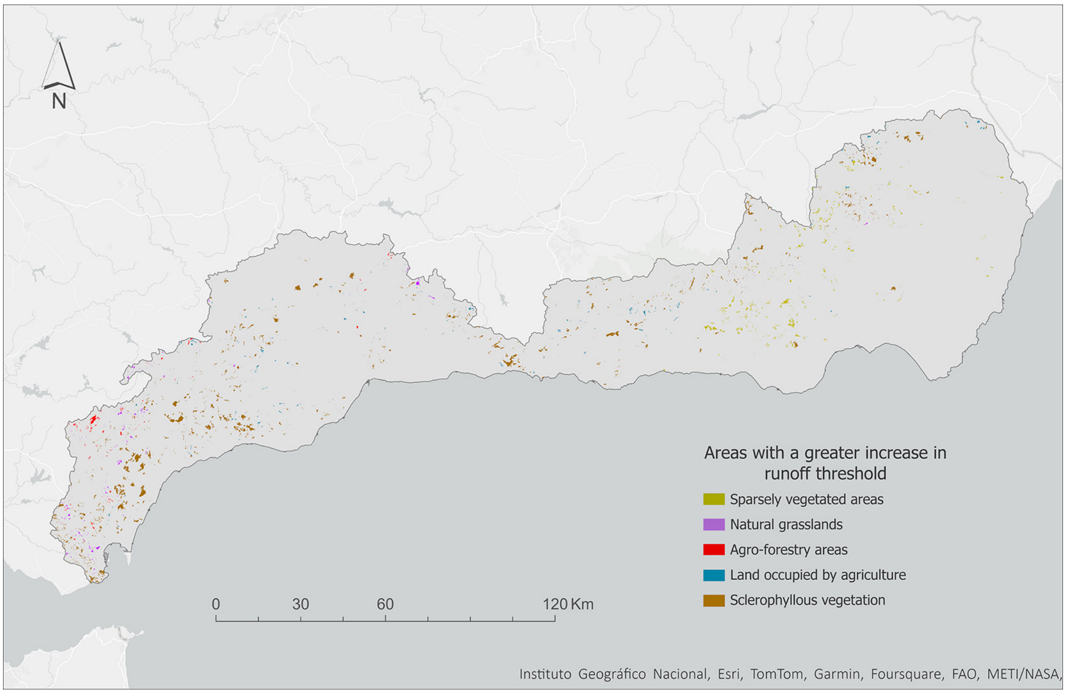
The most frequent runoff threshold is 4-5 mm of rainfall, characteristic of the sparse sclerophyllous vegetation, thin soil cover. On these terrains, we can observe a reduction in the water capture in a soil with an intermediate prior humidity of 10 mm of precipitation.

The complex cultivation patterns have the P_o with the highest capacity in high prior humidity conditions, except for certain specific dune and sandy areas that record a level of 31 mm. Depending on the gradient of the terrain, in these areas we can observe a threshold of 15-19 mm. Moreover, it is important to note that the retention capacity of the natural forest terrains is reduced to 12-13 millilitres of precipitation.

3.3. Modifications in the runoff threshold between 1990 and 2018

The mean runoff thresholds in 1990 and 2018, in intermediate soil humidity conditions, reveal that 44.6% of the area has not experienced significant changes (Figures 4 and 6). On the contrary, the areas that have experienced the greatest increase in their thresholds are the forest terrains (Figure 12). It is important to note that the eastern sector of the CMAs is currently experiencing an increase in the runoff threshold of up to 6 millimetres with respect to 1990, mainly due to the modification of the spaces with sclerophyllous vegetation (10% of the total area) causing a modification in the hydrological pattern (Figure 12). Furthermore, another important runoff threshold increase is concentrated in the western sector, reaching up to 5 mm more than in 1990. These are areas of natural sclerophyllous vegetation that have been transformed into agricultural land, but conserve large areas of natural vegetation and pastures. In the central sector we can observe a transition from complex cultivation patterns to fruit crops. Finally, it should be noted that in the eastern sector, the sparsely vegetated areas have been transformed into permanently irrigated land. Together, these transitions represent approximately 4.76% of the total area.

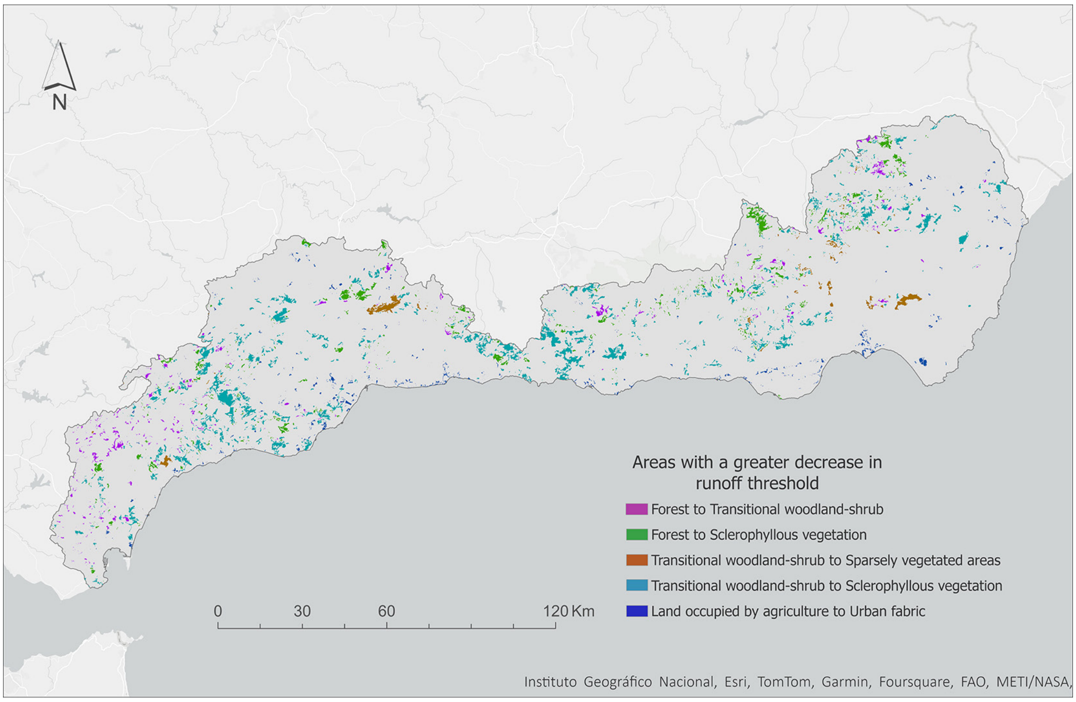
Figure 12. Areas in which the runoff threshold increased between 1990 and 2018



Own elaboration

Moreover, the areas where the P_o (Figure 13) diminished account for 13% of the area with a broad interval of 2 to 8 mm in the threshold. This means that, currently, a less intense precipitation can potentially generate runoff as it exceeds the defined threshold. These areas correspond mainly to agricultural land that conserves large spaces of natural vegetation, located principally in the central and western sectors of the river basin and are made up of olive groves, vineyards, complex cultivation patterns, agro-forestry systems and sclerophyllous vegetation. It should be highlighted that approximately 3% of the area exhibits considerable losses in the runoff threshold, in an interval of 13 to 18 mm. They are distributed throughout the Mediterranean side of Andalusia analysed and correspond to transitions from broad-leaved, mixed or conifer forests to sclerophyllous vegetation and transitions from woodland scrub to sparsely vegetated areas and discontinuous urban fabric.

Figure 13. Areas in which the runoff threshold decreased between 1990 and 2018



Own elaboration

4. Discussion

When studying hydrological processes and, in particular, when calculating the runoff threshold, it is essential to understand the role of soil humidity as a key factor of the water cycle and soil loss. The soil humidity prior to precipitation determines the part of the rainfall that is prone to infiltrating into the soil and the amount that, as a result, can form part of the surface runoff process (Aubert et al., 2003). This study explores different modellings of the runoff threshold according to different soil humidity conditions and comparing different dates (1990 and 2018) between which considerable changes in the coverage and uses of the land have been found.

The maximum runoff thresholds occur at any date and humidity condition in the forest areas with a good soil cover, although the values change considerably between the two years. For 1990, the forest sectors (Sierra Bermeja or Sierra de las Nieves) recorded the maximum runoff threshold at 30-31 mm. These spaces provide a unique biological and ecosystemic service. They constitute a fundamental element in the regulation of the runoff processes, favouring infiltration, reducing the speed of the water film and, therefore, reducing the erosion dynamics (DeFries et al., 2010). Meanwhile, Martínez-Murillo and Senciales-González (2003) highlight the role of the protection entities in the conservation and regeneration of the territory in response to a dynamic of uses that has sometimes lacked adequate territorial planning. Therefore, the protected natural areas intensify their fundamental role in controlling the runoff and reducing the water-associated risks. Gallegos (2018) indicated the importance of Sierra Bermeja in Málaga for controlling the floods of the coastal area. Therefore, all of these areas record the highest values in the runoff threshold, where the volume of rainfall should be higher to activate these types of hydrological processes.

The areas with the minimum values correspond to the eastern sector (8-9 mm), with values similar to those estimated decades ago by Solé-Benet et al. (1996) for Almería. This is associated, first, with the rainfall patterns with climate conditions corresponding to arid and semi-arid conditions, where the soil protection by the vegetation coverage is very low and where there is clear evidence of soil degradation processes of the surface components (Sillero-Medina et al., 2020). Furthermore, the eco-geomorphological dynamics have led to a reduction in permeability, increasing the probability of crusting processes of the ground and decreasing the infiltration capacity of the soil (Pellegrini et al., 2018). This gives rise to a scenario marked by the presence of surface flow processes rather than infiltrating processes and the most evident manifestation of this can be found in the fact that up to 70% of fluvial networks in south-east Spain are wadis (Gómez et al., 2005).

For 2018, the most notable is the considerable growth in anthropogenic and sealed areas, affecting 673 km², which is a direct response to the major development of coastal areas in Andalusia (Requejo Liberal, 2002;

Ojeda Zújar & Villar Lama, 2007, Pascual-Aguilar, 2004) and has been clearly identified in the large current reduction of the runoff threshold.

The role of soil humidity prior to a precipitation event is also an important factor in calculating the P_0 (Aubert et al., 2003) for the year 2018, with the variations occurring when the prior soil humidity is low or high. It is still the forest environment where in conditions of low humidity, the runoff threshold is higher and where there is a higher growth with respect to an average level of humidity (P_0 = 72 mm), indicating a better water management by the soil. These areas where the soils have a greater content of organic material and a better structure also have a higher water retention capacity and an optimum infiltration (Sillero-Medina et al., 2020).

In short, this variability in the runoff thresholds associated with the previous soil humidity, defined at a spatial resolution of 25 m^2 as in the case of this study, is highly interesting for monitoring the hydrological state of the soil, constituting a fundamental strategy in hydrological planning processes. Furthermore, from the point of view of the management and prevention of environmental risk, it is equally important to understand the soil humidity prior to a precipitation event and its P_0, as it is a fundamental variable for warning about possible floods (Norbiato et al., 2008).

The results related to the modifications in the runoff threshold identified between 1990 and 2018 show major spatial differences for the area of study, with a clear contrast between the western and eastern sectors of the CMAs in line with the longitudinal rainfall gradient of this Mediterranean sector, but with a disparate incidence depending on the changes in the land coverage. This dynamic and temporal analysis emphasises the need to identify trends in the runoff processes, to serve as a base for designing action measures focused on hydrological management (Camarasa-Belmonte et al., 2018). Therefore, for this study, in the area with the most humid conditions (western sector), there is an increase in this threshold while, on the contrary, arid and semi-arid conditions denote a sharper decrease in the values corresponding to the runoff threshold. This fact is wholly associated with the dynamics of the eco-geomorphological system identified in Sillero-Medina et al. (2020), in which a favourable vegetation coverage trend is identified in the area with sub-humid climate conditions. On the other hand, in areas conditioned by Mediterranean characteristics more related to aridity, Ruiz-Sinoga and Martínez-Murillo (2012) identify erosion, sealing and soil degradation processes, with a considerable increase in the runoff as a result of the changes in the land uses from the second half of the twentieth century. During this period, a major landscape transformation has taken place in the Andalusian Mediterranean area, reflected in the results of Figures 10 and 11. On the one hand, from an agricultural perspective, the transformations of large areas of rainfed crop land into irrigated land have been identified (Cerdà et al., 2007) and there has been a continuous exodus from the countryside, with different responses of each territory depending on the climate conditions (López García et al., 2007; Romero-Díaz et al., 2017). We can observe how in the western region, the P_0 increased as a result of the revegetation of former agricultural and agro-forestry areas, in contrast with the most easterly area, where the degree of vegetation cover has decreased (Figure 11). Along the same lines, there has been an intense sealing processes of the ground due to the major urban expansion processes in different areas (Montanarella, 2007; Pascual & López, 2016), which are shown in yellow in Figure 13, particularly along the coastal strip. Malvárez (2012) and Molina et al. (2019) highlight the extraordinary urban development of the Andalusian Mediterranean coast as one of the fastest in Spain and Europe, specifically on the Costa del Sol (Málaga), where urban development is again more focused on the financial feasibility and profit in detriment to the environment and with no consideration to the quality of the soils (García & Pérez, 2016).

All of this is generating a new scenario of hydrological responses, which, according to the results of this study, reflects the predominance of lower runoff thresholds and, consequently, an increase in the soil erosion processes. In other words, an increase in the hazard and risk factors related to surface runoff processes (De Graaff et al., 2013; Camarasa-Belmonte et al., 2020).

In short, the calculation of the P_0 under the paradigm of the current Mediterranean territorial dynamics could be an efficient management tool. This is particularly relevant within a context of climate crisis, in which the rainfall pattern is displaying a greater concentration and intensity of precipitation events (IPCC, 2021). This same report states that the probability of extreme weather events, such as the serious urban floods, has increased significantly in the twenty-first century.

The current reality in the Mediterranean area has led to the elaboration of these types of studies. In sectors such as the eastern half of the CMA, with a reduction in the runoff threshold, the concentration in time of precipitation, its erosive nature and the scarce soil protection are giving rise to erosive events, with sudden runoffs and floods. This often alternates with long periods of drought, generating a scenario of uncertainty with respect to water management (Benhamrouche, 2014).

5. Conclusions

The space-time variability of the runoff threshold in the Cordilleras Béticas Litorales (or Demarcación Hidrográfica de las Cuencas Mediterráneas Andaluzas, according to its administrative name), has revealed clear differences related to the different land uses, associated with the longitudinal pluviometric gradient observed throughout the territory. First, it is directly related to the characteristics of the eco-geomorphological system in which the greater presence of vegetation cover with higher quality soils favours the infiltration processes and, therefore, reduces the occurrence of surface flows.

The land uses for which the highest values are recorded in any year correspond to forest areas, highlighting the role of the protected natural areas. In conditions of standard humidity, the soil has a water retention capacity prior to the beginning of a precipitation event that is close to 31 mm and reaches up to 72 mm if the ground is dry. On the contrary, the uses most sensitive to runoff processes are those associated with sparsely vegetated and sealed areas, particularly rainfed agricultural areas, where a runoff threshold of barely 8-9 mm is reached.

The dynamics of land uses identified in recent decades have given rise to a significant modification of the values corresponding to the runoff threshold. The western area has followed a trend towards an increase in the runoff threshold, in which an increase in vegetation cover has been detected, principally in abandoned farming areas. Currently, these forest sectors have a variable runoff threshold from dry soil prior conditions at around 28-72 mm of rainfall to humid soil prior conditions with a threshold of 25-31 mm. However, in the former forest areas that are currently occupied by sclerophyllous vegetation, the threshold has reduced to 17 mm, which affects 229.1 km^2. In the most arid and semi-arid sectors, the situation is different and the threshold rarely exceeds 5 mm. The fragility of these areas makes it more difficult to re-vegetate the abandoned areas, which are subject to erosion and degradation processes and where the runoff threshold is reducing.

Finally, from a water management and environmental risk assessment point of view, we must emphasise the role of the sealed areas, given that significant growth has been detected in these spaces in detriment to agricultural land, with losses in their threshold of 14 mm of rainfall in an area of 97.1 km^2. Their evaluation from a territorial planning perspective is essential so as to reduce risks based on the implementation of action measures.

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