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Positive rainfall erosivity trends compared with the reduction in soil erosion in a Mediterranean area (1996–2020)

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ABSTRACT

This work describes a procedure that uses the regression line slope to calculate the time trend of any variable in a raster image with ArcGIS Pro Geographic Information System (GIS) tools. The procedure is applied to estimated mean soil erosion and mean annual rainfall erosivity in the Andalusian territory (Spain) using data from the regional environmental agency.

During the analyzed period (1996–2020), soil erosion values (RUSLE) show a region affected by low and medium estimated erosion values (91.74 % of the territory between 0 and 50 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$) and a large part by low to very low rainfall erosivity rates (70.43 % of the territory between 132 and 1000 $MJ{\cdot}mm{\cdot}ha^{-1}{\cdot}h^{-1}{\cdot}yr^{-1}$). The highest values for both parameters are limited to the mountain areas of the Baetic and Sierra Morena ranges.

Estimated mean erosion presents a general downward trend, with 92.64 % of the territory with slopes between 0 and −344 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$ per year. Nevertheless, mountainous enclaves stand out for a positive trend in this parameter during the analyzed period, with regression line slope values of up to + 5 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$ (7 % of the region, 6131.79 ha). The observed rainfall erosivity time trend shows that a combination of high rainfall erosivity rates and a strong upward trend is only found in the western extreme of the Baetic mountain ranges.

Analysis of mean distribution by subwatershed has been verified to allow the competent environmental agencies to read the results more easily to address the erosion problem. The combination of mean estimated erosion values and the upward erosion trend in the Guadalete, Guadalhorce, and Verde subwatersheds helps guide actions in these areas.

1. Introduction

Water soil erosion is a natural process that intensified human activity has caused to become one of the gravest environmental problems in the world (Montanarella et al., 2016; Borrelli et al., 2017, 2020). Erosion issues are linked to topsoil layer removal (Zheng et al., 2008; Li et al., 2009), which is where the organic matter and nutrients that sustain the soil's productivity congregate, and to river course changes that cause eutrophication problems, increased turbidity (Ouyang et al., 2010; Yao et al., 2016), an increase in the sediment load that clogs up dams and reservoirs (Rickson, 2014; Arnhold et al., 2014), and even affect coral reefs (Fisher et al., 2019). Soil erosion causes a change in ecosystem goods and services, *inter alia*, including biodiversity, soil biota, plant composition, run-off control, water retention capability, carbon sequestration, and ecosystem productivity (Van Oost et al., 2000; Cerdan et al., 2010; García-Ruiz et al., 2013; Fenta et al., 2020; Cunha et al., 2022).

Attention has been drawn to the interest that large-scale erosion mapping has for national and even international organizations and their environmental and agricultural policies (Alewell et al., 2019).

It is also very relevant to study the effect of climate change triggering a significant increase in erosion in the coming decades (Martínez-Casasnovas et al., 2016; Borrelli et al., 2017, 2020; Eekhout & Vente, 2022; Andualem et al., 2023). One of the goals of these studies appears to be to highlight large-area erosion analysis and its evolution over time. The comprehensive review by Borrelli et al. (2021) of scientific publications that analyze soil erosion modeling in the GASEMIT database determined that only 5 % of studies made qualitative erosion estimates with time trend evaluations, spatial patterns, and trigger factors. So, temporal erosion assessment has only received limited attention in the scientific literature.

The few studies that have analyzed the time trend of soil erosion values can be classified by the number of years analyzed as most compare the results for two dates separated by an extended time interval. These include studies of the Modjo watershed (Ethiopia) for 1973 and 2007 (Gessesse et al., 2015), the Sudetes Mountains (Poland) for 1885 and

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2013 (Latocha et al., 2016), and Calabria Regio (Italy) for 1955 and 2016 (Conforti & Buttafuoco, 2017; Conforti and Buttafuoco, 2017). On other occasions, the chosen dates have been closer in time, e.g., the Borrelli et al. (2013) global analysis for 2001 and 2012. In other cases, the authors compare the estimated erosion results for three or five different dates separated by similar intervals, e.g., Yinjiang County (China) for 2000, 2005, and 2013 (Zeng et al., 2017), the Dong River upstream basin for 1999, 2004, 2009, 2014, and 2017 (Yuansheng et al., 2020), and the Beijing-Tianjin-Hebei region (China) for 2000, 2005, 2010, and 2015 (Guo et al., 2021). Lastly, examples exist of comparisons between historical, current, and future estimates, for example, the Southern Rockies Ecoregion (US) for a historical period, 1970–2006, and two future estimates for 2010–2040 and 2041–2070 (Litschert et al., 2014), the Lacang-Mekong River Basin (China) for 2015 and predictions for 2030 and 2040 (Chuenchum et al., 2020), and India for 2018 and predictions for 2040, 2060, 2080, and 2100 (Pal et al., 2021).

Even more scarce are the studies that compare a significant number of years. The most noteworthy of these are the Sancha River Basin (China) study from 1980 to 2015 (Jiangbo & Huan, 2019) and, more recently, agrosystems in the Andalusian region of Spain for 1956 and from 1990 to 2018 (Milazzo et al., 2022). Analyses such as these, based on continuous time series, are more relevant for identifying the determinants of soil variability than time series based on discontinuous time series (Irvem et al., 2007; Ouyang et al., 2010; Jiangbo & Huan, 2019).

Regarding the methods used to analyze the recognizable evolution of these estimates, differences in the percentage of surface area affected by the erosion ranges (Zeng et al., 2017; Milazzo et al., 2022) are also habitually considered. In other cases, they focus on the increase or decrease in erosion, subtracting the values of the most recent date from those of the oldest date and calculating the percentage of surface area affected by the ranges of increase or decrease (Borrelli et al., 2013; Latocha et al., 2016; Conforti & Buttafuoco, 2017).

In addition, evolutionary analyses of this type also evaluate the increase or decrease in erosion to establish which of the parameters used to calculate the models is most relevant for the end result. Examples of this are the studies that consider land use changes and rain erosivity as the main engines of spatiotemporal soil erosion variability (Barral Muñoz et al., 2020; Huang et al., 2021). These studies compare the surface areas obtained to the erosion in each of the ranges of said parameters, either for the slope or the lithology (Zeng et al., 2017; Guo et al., 2021). More complex methods designed to achieve the same goal must be highlighted, including, for example, the geographic detector method, which permits quantitative attribution analysis (Jiangbo & Huan, 2019). However, this method cannot be used for continuous territorial variables and can only be applied to discrete polygon information.

In many of these studies, results are generally presented in data tables or graphs (Gessesse et al., 2015) and, in some cases, in the form of regional distribution (Latocha et al., 2016; Zeng et al., 2017; Conforti & Buttafuoco, 2017; Huang et al., 2021).

Apart from studies that use model calculations to analyze the time dynamic of erosion, it is also important to consider the methods and objectives of other works on the temporal variability of some of the variable parameters in the USLE calculation, such as rainfall erosivity (R-Factor) and land use (C-Factor).

In the case of rainfall erosivity, weather station information is objective time-continuous data that can be used to analyze long, homogeneous time series. For example, rainfall erosivity evolution in farmland areas in Japan has been addressed through models such as RCM20, which gives the R-Factor and the seasonal mean for the recent past and two future periods (Shiono et al., 2013). These authors measured the parameter's evolution based on the percentage differences between the resulting raster images for the analyzed periods.

Using spreadsheets for long time series of rainfall erosivity data from hydrological or weather stations (specific locations) enables regular principal component and regression analysis. One example of this type of methodology was applied to the observed rainfall erosivity (R-Factor) trend analyzed for the Italian Piedmont region (Acquaotta et al., 2019), and to detect the relationship between runoff and factors that can influence variability in the middle Yellow River basin (China) (Changxing et al., 2012). The obtained analysis results were synthesized in Tables, graphs, or, in the case of Changxing et al. (2012), extrapolated to show their distribution in the study area.

Analysis of spatiotemporal land use and cover evolution has mainly been based on the calculation of the NDVI index. This is habitually used to estimate vegetation quantity, quality, and development, with soil erosion calculated using maps for successive dates. Some studies have applied change vector analysis (CVA) and principal component analysis to NDVI to detect changes in ecosystem dynamics in China (Yun-Hao et al., 2001) and land use in Duy Tiene (Vietnam) (Tong et al., 2020). Land use evolution in southern Spain and its effect on erosion value estimates have also been addressed using cartography published by national and international organizations (Barral Muñoz et al., 2020; Milazzo et al., 2022).

As such, the spatiotemporal evolution for prolonged periods and the trend presented by soil erosion or the variables involved in its estimation have clearly not been sufficiently addressed. In this sense, the objectives of the present work are to: (i) analyze the spatiotemporal evolution of estimated soil erosion and rainfall erosivity in the Andalusian territory (Spain) for 25 successive years of data (from 1996 to 2020); (ii) apply a regression analysis to both parameters for the entire Andalusian region to determine their spatiotemporal trends; (iii) identify differentiated behaviors of estimated soil erosion or rainfall trends based on climatic subunits and hydrographic subwatersheds, and (iv) offer environmental agencies a methodology that helps orient their soil erosion actions.

2. Materials and methods

2.1. Study area

The Andalusian region is situated in the southern part of the Iberian Peninsula ($36^\circ - 38.5^\circ$ N; $1^\circ - 8^\circ$ W) and constitutes Europe's transition from the Atlantic coast to the Mediterranean Sea. This region is extensive (87597 km^2) with medium heights along the Guadalquivir River valley. The highest peaks can be found in the Penibaetic systems (Fig. 1).

The Andalusian Autonomous Community's position at the western end of the Mediterranean Sea means that it is affected by unstable, humid winds that give rise to winter rainfall (Pita López, 2003). According to the Koppen-Geiger classification, Andalusia has a mild climate (Csa), i.e., hot, dry summers (Kottek et al., 2006). A more detailed classification distinguishes between coastal climates, inland climates, medium mountain climates, high mountain climates, and southeastern climates and describes the variability caused by the mountain alignments and how they interfere with the circulation of humid air masses traversing the Autonomous Community from W to E (Gómez-Zotano et al., 2015) (Fig. 2).

There are two main land use divisions in the Andalusian territory: forest, scrub, and pastureland coverage (54.16 %) and agricultural use (40.49 %) (Romero Romero et al., 2016). Most of the natural vegetation is Mediterranean woodland, mainly perennial trees such as oak, pine, and fir, and dense riverside woods and Mediterranean scrub, whereas agriculture is traditionally based on wheat, olive, and grape farming (Bermejo et al., 2011; Romero Romero et al., 2016). Land use evolution during the analyzed period shows an initial period with a low number of land cover changes (1990–2006) and especially, a decline in non-irrigated arable crops and irrigated crops (olive trees, citrics, mainly crops under plastic) (Bermejo et al., 2011; Milazzo et al., 2022). The second period sees significant increases in the relative proportion of permanent grassland (+43 %) and permanent crops (+20 %), with olive trees predominating (2007–2011). Following this, there is another period of practically no change (2012–2018) (Milazzo et al., 2022). Vigorous intensively irrigated agriculture, with crops under plastic and in

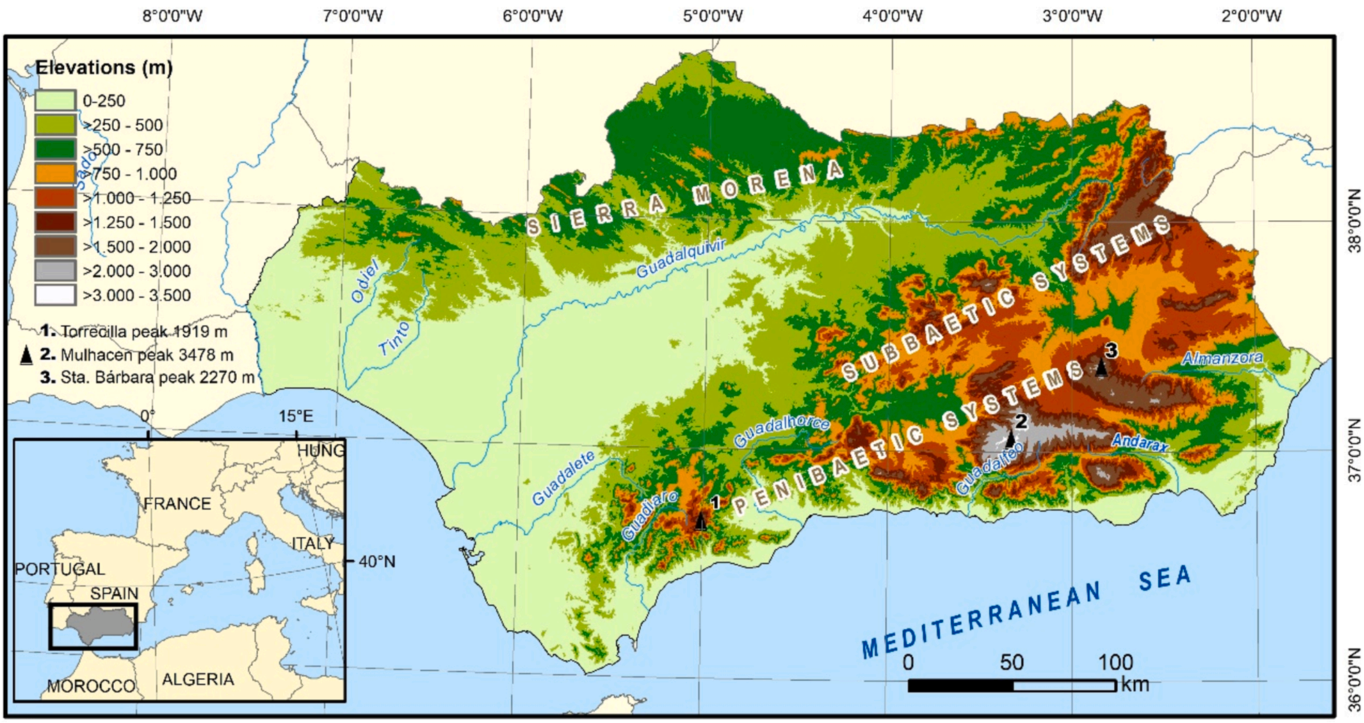

Fig. 1. Relief map of Andalusia. .
Source: Prepared by authors from the Spanish National Geographic Institute

greenhouses and fruit tree farming, represented 17.8 % of total agricultural uses in the first decade of the 21st century (Bermejo et al., 2011). However, this proportion has increased progressively, as it has throughout the Spanish Mediterranean (Hernández, 2019).

2.2. Data sources

The State and Autonomous authorities' concern for soil erosion is demonstrated by their development of a National Inventory of Soil Erosion that provides cartography and provincial-scale analysis (https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/inventario_nacional_erosion.aspx), and a National Action Plan to Combat Desertification that helps identify factors that contribute to desertification, actions to combat same, and actions to mitigate the effect of drought (https://www.miteco.gob.es/es/biodiversidad/temas/desertificacion-restauracion/lucha-contra-la-desertificacion/lch_pand.aspx).

Given this concern, the Junta de Andalucía's (regional government) Department of the Environment applied the RUSLE model to monitor annual soil erosion evolution and its incidence rate in the territory from 1996 to 2020. Its estimates and the calculated R-Factor values are freely available to researchers and citizens via the REDIAM geoportal ([Dataset], Junta de Andalucía, 2020).

Since its formulation, the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) and its subsequent revisions (Revised Universal Soil Loss Equation RUSLE, Renard, 1997) have been some of the most popular methods for estimating potential soil erosion. USLE/RUSLE estimates possible sediment remobilization according to a fixed and variable parameter set. Table 1 shows the RUSLE model and the various factors included in the calculation. The formulation involves factors such as annual soil loss (A); erosivity (R); erodibility (K); slope length (L) and steepness angle (S); vegetation cover (C), and efficacy of erosion control achieved through soil conservation measures (P). The administration constructs raster images of estimated soil erosion for the entire Andalusian territory and makes them available to the research community and private users through the REDIAM Geoportal. The quality and temporal continuity of the maps make this a very interesting and useful series and are indicative of the enormous amount of work that the Andalusian Environmental Agency has invested. Specifically, these are 1:200.000 scale (75 m grid cell resolution) images of mean monthly and annual mean values expressed in $t{\cdot}ha^{-1}{\cdot}yr^{-1}$.

The RUSLE model rainfall erosivity (R-Factor) results are given as raster images with quantitative information on the gross mean annual results in $MJ{\cdot}mm{\cdot}ha^{-1}{\cdot}h^{-1}{\cdot}yr^{-1}$. The Junta de Andalucía classifies the results with eight intervals (Table 2).

Rainfall erosivity is calculated as the product of rainfall kinetic energy and maximum intensity during 30 consecutive minutes. The autonomous administration followed the methodology detailed in Junta de Andalucía, 2014 to prepare these maps. Rainfall data are taken from the State Meteorology Agency's Automatic Weather Station Network and the Secondary Station Network and are based on storm data divided into 10-minute intervals. To extrapolate results based on regular calculations for each of the automatic stations, the administration used the IDW (Inverse Distance Weighted) method for the spatialization of rain erosivity results producing a raster format map of the R-Factor with monthly and annual mean values.

Other variables that can be very relevant in the RUSLE calculation are the C-Factor and P-Factor, although the public administration does not publish these calculations independently. C-Factor has been calculated with a specific value assigned to each identified land use in the successive use and vegetation cover maps. A large proportion of the values can be observed in a study that addressed their evolution in two hydrographic basins (Barral Muñoz et al., 2020). In other respects, the scant application in this region of the conservation practices stated by Wischmeier and Smith (1978) (e.g., contoured and strip cropping are not common and there are few examples of crop terraces and forestry repopulation) has led the administration to disregard P-Factor values.

2.3. Regression line slope calculation

The linear regression statistical technique calculation was applied pixel-by-pixel to the entire Andalusian territory to identify the spatial

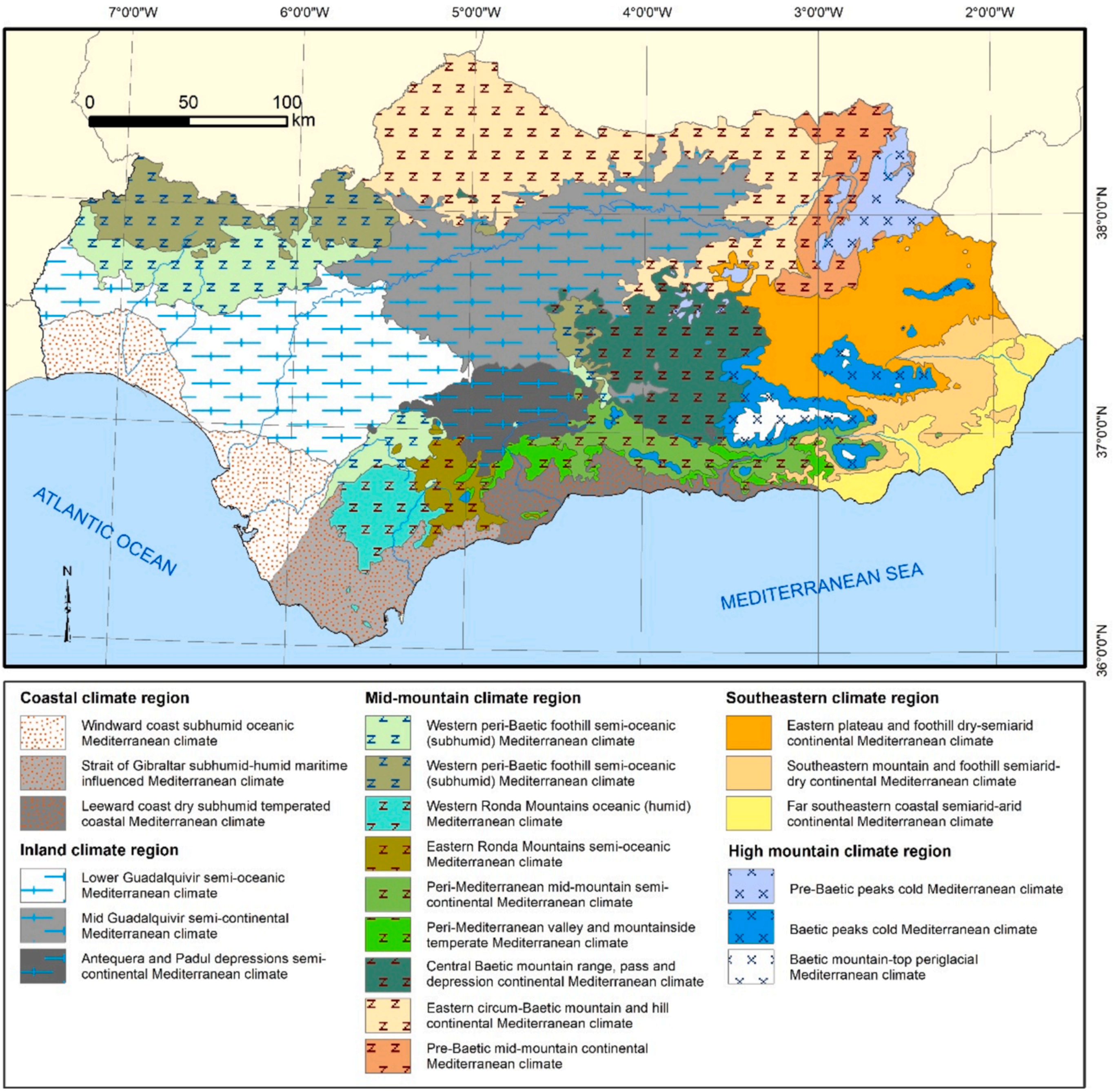

Fig. 2. Classification of Andalusian climates by district (Gómez-Zotano et al., 2015).

Table 1
RUSLE model specifications used by the Andalusian Department of the Environment

$\boldsymbol{A} = \boldsymbol{R}\cdot\boldsymbol{K}\cdot\boldsymbol{L}\cdot\boldsymbol{S}\cdot\boldsymbol{C}\cdot\boldsymbol{PA}$	Annual soil loss in Tm/ha/year
R	Rainfall erosivity
K	Soil erodibility measured in the field
L	Estimated length of slope in experimental plots
C	Soil protected by ground cover based on land use maps (MUCVA-SIOSE)
S	Slope steepness angle in experimental plots
P	Erosion control effectiveness due to soil conservation measures based on land use maps (MUCVA-SIOSE).

Source: Junta de Andalucía, 2014a.

distribution of the positive or negative trend of the estimated annual mean soil erosion values and the annual mean rainfall erosivity values for the 25 years.

The following formula was used:

$$P = [N\cdot\Sigma xy\text{-}\Sigma x\cdot\Sigma y]/[N\cdot\Sigma x^2\text{-}\Sigma x^2].$$

in which $\boldsymbol{P}$ = linear regression statistical technique; $\boldsymbol{N}$ = number of values, elements, or, in this case, number of years to be analyzed; $\boldsymbol{x}$ = yearly values, with the first analyzed year assigned a value of 0 with

Table 2
Rainfall erosivity intervals (Junta de Andalucía, 2014a).

Defined levels	MJ·mm·ha^{-1}·h^{-1}·yr^{-1}
1. Extremely low	10–250
2. Very low	>250–500
3. Low	>500–750
4. Moderately low	>750–1000
5. Moderate	>1000–1500
6. Moderately high	>1500–2000
7. High	>2000–3000
8. Very high	>3000–5000
9. Extremely high	>5000

subsequent yearly increments of 1. These represent the values of the analyzed variable, in this case, erosion or erosivity. In this formula, both N and x are constants that depend on the number of analyzed years.

A Geographic Information System was needed to calculate ***P*** of the values of each of the pixels (***y***). The ArcGIS Pro *Model Builder* tool was used for calculations with raster images (Fig. 3).

Although this method obtained information for the entire territory, 16 points were selected from the regression line slope to show the estimated erosion value, annual rainfall erosivity variability, and the trend graphically. Random locations were chosen between the values of maximum trend increase (>5–112 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}; points 3, 10, and 12), moderate increase (>0–5 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}; points 6, 11, and 16), moderate decrease (>-30–0 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}; points 5, 8, 9, 13, and 15) and steep decrease (<-30–112 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}; points 9, 11, 12, 13, and 16) (see Fig. 5A below).

2.4. Calculation of mean values of discrete units

Mean R-Factor and estimated soil erosion means were calculated for the Andalusian Autonomous Community's climatic units and hydrographic subwatersheds.

The Gómez-Zotano et al. (2015) district-scale classification of climates in Andalusia (Fig. 2) was chosen. Vector cartography prepared from the Junta de Andalucía Department of the Environment's (REDIAM) Topographic Map 1:100.000 (Fig. 4) was used for subwatersheds.

ArcGIS Pro *Zonal Statistics as Table* by *Spatial Analyst Tools* was used to obtain the mean values of the climates and hydrographic subwatersheds. The calculation used was the mean value of the pixel set that coincided spatially with each of the considered polygons.

3. Results

3.1. Estimated soil erosion and rainfall erosivity values in Andalusia (1996–2020)

The first result that can be highlighted is that the majority of the

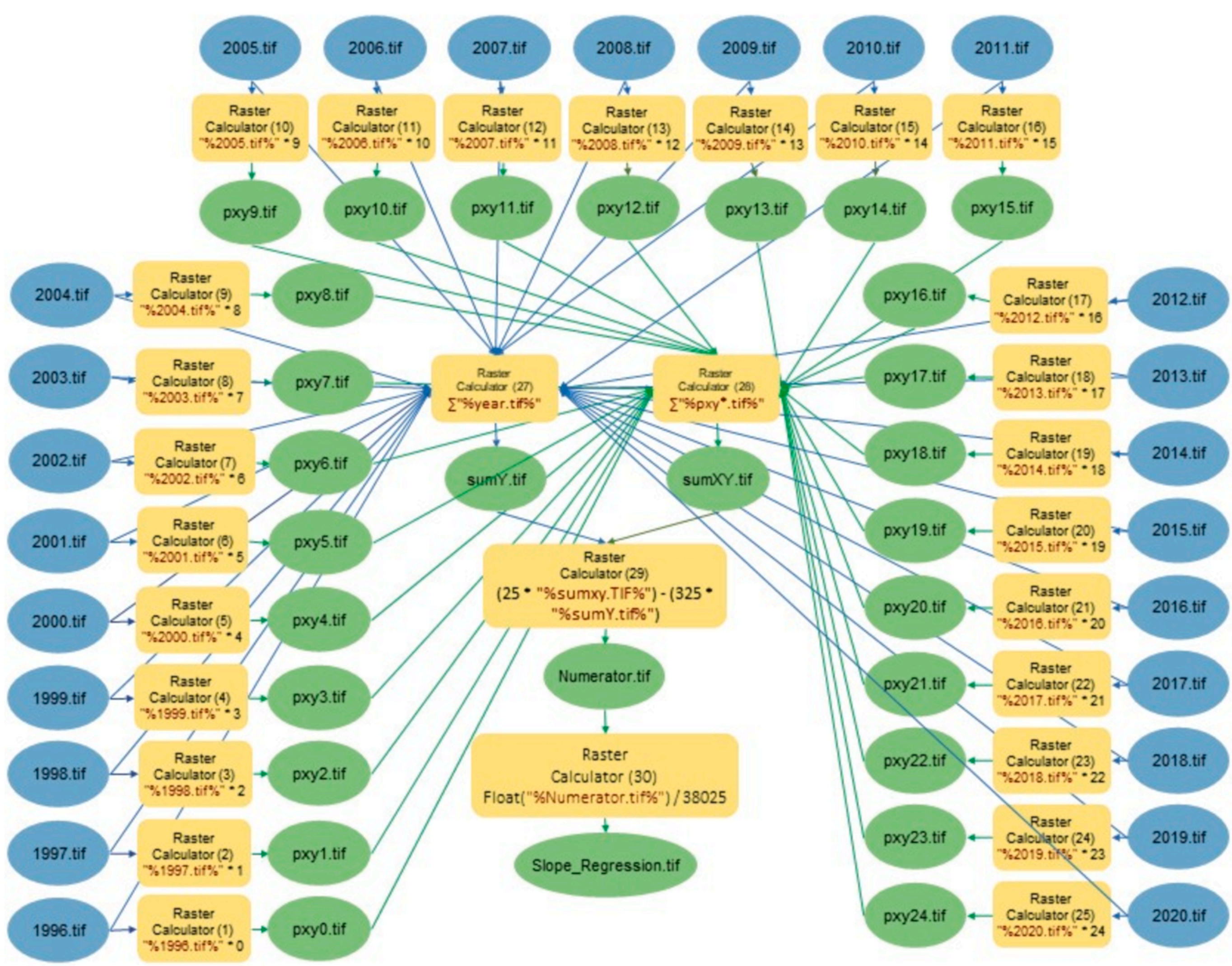

Fig. 3. Model builder diagram to calculate the regression line slope for a variable of 25 successive years with ArcGIS Pro.

Fig. 4. Map of subwatersheds in Andalusia. G. is the Guadalquivir River Source: REDIAM Geoportal.

Andalusian region presents low and medium estimated erosion values for the analyzed 25 years (0–12 and > 12–50 t·ha^{-1}·yr^{-1}) (Fig. 5A). These values can also be stated to have shown a tendency to remain stable or decrease. Eleven percent of the Andalusian surface area stands out for a reduction in estimated erosion of between −1180 and −1 t·ha^{-1}·yr^{-1} per year (Fig. 5B). These results can be explained by agricultural intensification in areas with less pronounced slopes, which results in less erosion, at the same time as the abandonment of less productive agriculture in mountainous areas, which contributes to scrub and woodland vegetation recovery and, consequently, improves soil retention. This natural revegetation process can explain why the areas in the region with the steepest slopes (Baetic Systems and Sierra Morena Mountains) and high or very high estimated erosion values 8.26 % surface > 50 t·ha^{-1}·yr^{-1}), (−1183 to −5 t·ha^{-1}·yr^{-1} per year), coincide with the most marked downward trends in the entire Autonomous Community. Examples of this are locations 1, 5, and 16 in the Sierra Morena and 4 and 7 in the Baetic Systems (Fig. 6). However, the area distribution of the highest estimated erosion trend increases coincides with the areas of the highest mean values, although these are very localized sectors that represent only 1.65 % of the territory that would be affected by estimated annual erosion increments of > 1–344 t·ha^{-1}·yr^{-1}. For example, this is the case of location 10 (Fig. 6).

Mean rainfall erosivity distribution (R-Factor) in the entire Andalusian territory shows that most of the surface area is affected by moderately low to very low values (132–1000 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}, 70.43 %). Despite being slightly lower than the values established for Andalusia by other studies (>1000 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) (Diodato and Bosco, 2014), these values are similar to the mean levels for Spain as a whole (928.5 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) and for the Mediterranean area of the EU (1050.6 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) (Panagos et al., 2015b; Panagos et al., 2015a). The area that presents high to extremely high results (3.38 % surface with > 2000–4693 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) is small and located in the Grazalema and De Nieves mountains and their extension toward the southern coast and the Aracena mountains in the far west of the Sierra Morena mountains (Fig. 5C). Despite being small, these mountainous areas in the far south of Andalusia are extremely important as they present both high rainfall and high erosivity density (ED – rainfall erosivity per mm of precipitation) (Panagos et al., 2015b; Panagos et al., 2015a). The highest rainfall erosivity results are above the established mean for the Mediterranean climate zone, where values below 2000 MJ·mm·ha^{-1}·h^{-1}·yr^{-1} are detected (Panagos et al., 2017).

The rainfall erosivity trend over the 25 analyzed years is slightly decreasing (>-30–0 MJ·mm·ha^{-1}·h^{-1}·yr^{-1} in 89.77 %) (Fig. 5D, Fig. 7) and similar to that described in the Italian Piedmont (Acquaotta et al., 2019). However, numerous isolated enclaves show a significant rise (>1–112 MJ·mm·ha^{-1}·h^{-1}·yr^{-1} in 8.12 % of the territory). One example of this upward trend is the far southeast of the Autonomous Community (locations 11 and 12), where the dry-semiarid Mediterranean climate experiences little, but highly concentrated torrential rainfall (Gómez-Zotano et al., 2015).

3.2. Rainfall erosivity values by climate distribution

Forecasts of the effect that climate change will have, or is already having, on Mediterranean climates, with a net reduction in rainfall, greater interannual variability, and an increased frequency of extreme events (Giorni and Lionello, 2008; Lionello and Scarascia, 2018), make it especially important to know the mean values and observed rainfall erosivity trend over 25 years, not only for Andalusia generally, but also individually for each of the region's district-level climatic subunits (Fig. 8).

Mean rainfall erosivity values are only high (>2000–3000 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) in the oceanic (wet) Mediterranean climate of the western Ronda mountains. This climatic unit presents the

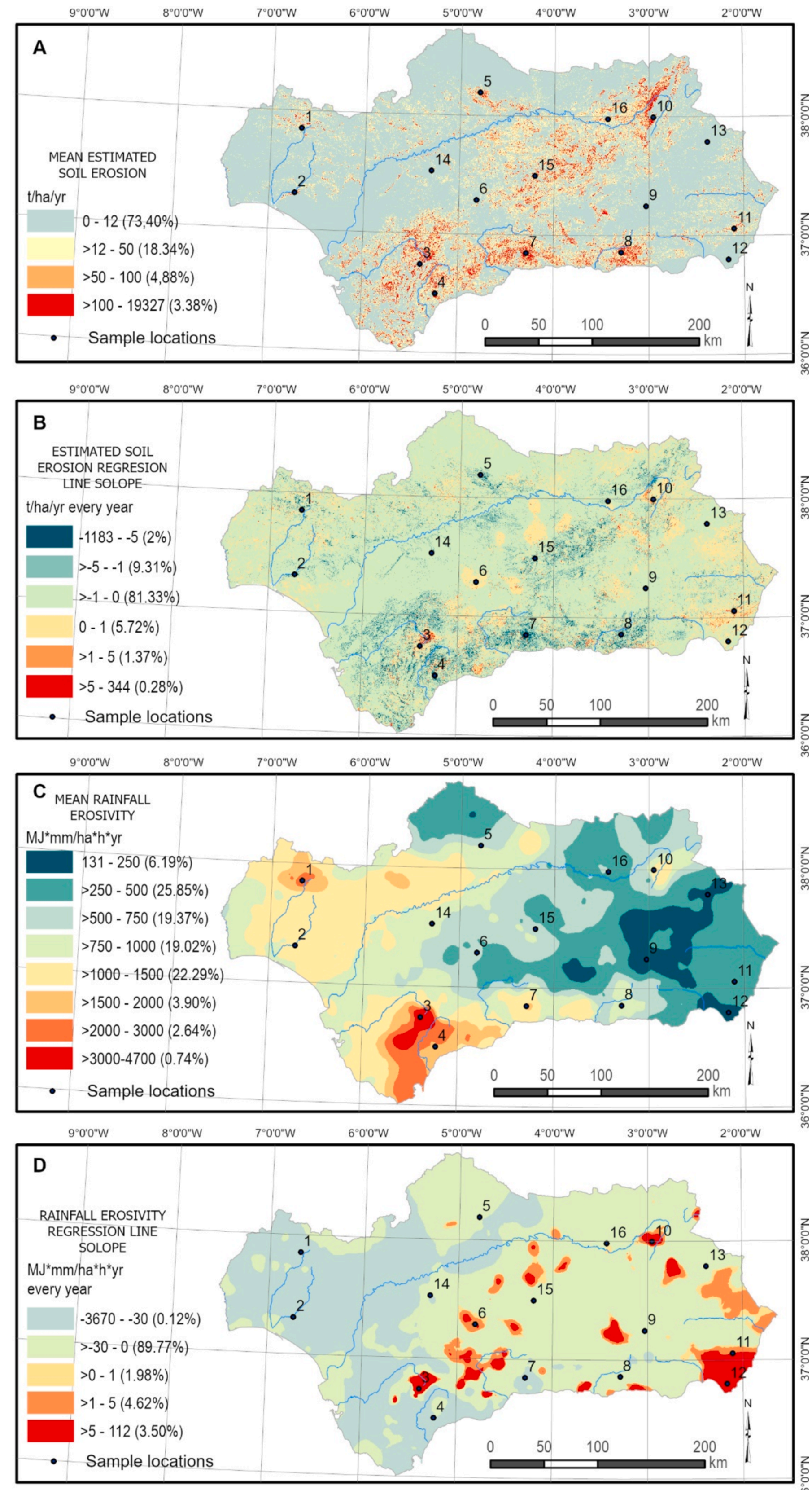

Fig. 5. A. Mean estimated soil erosion; B. Estimated soil erosion regression line slope; C. Mean rainfall erosivity (R-Factor); D. Rainfall erosivity regression line slope (R-Factor).

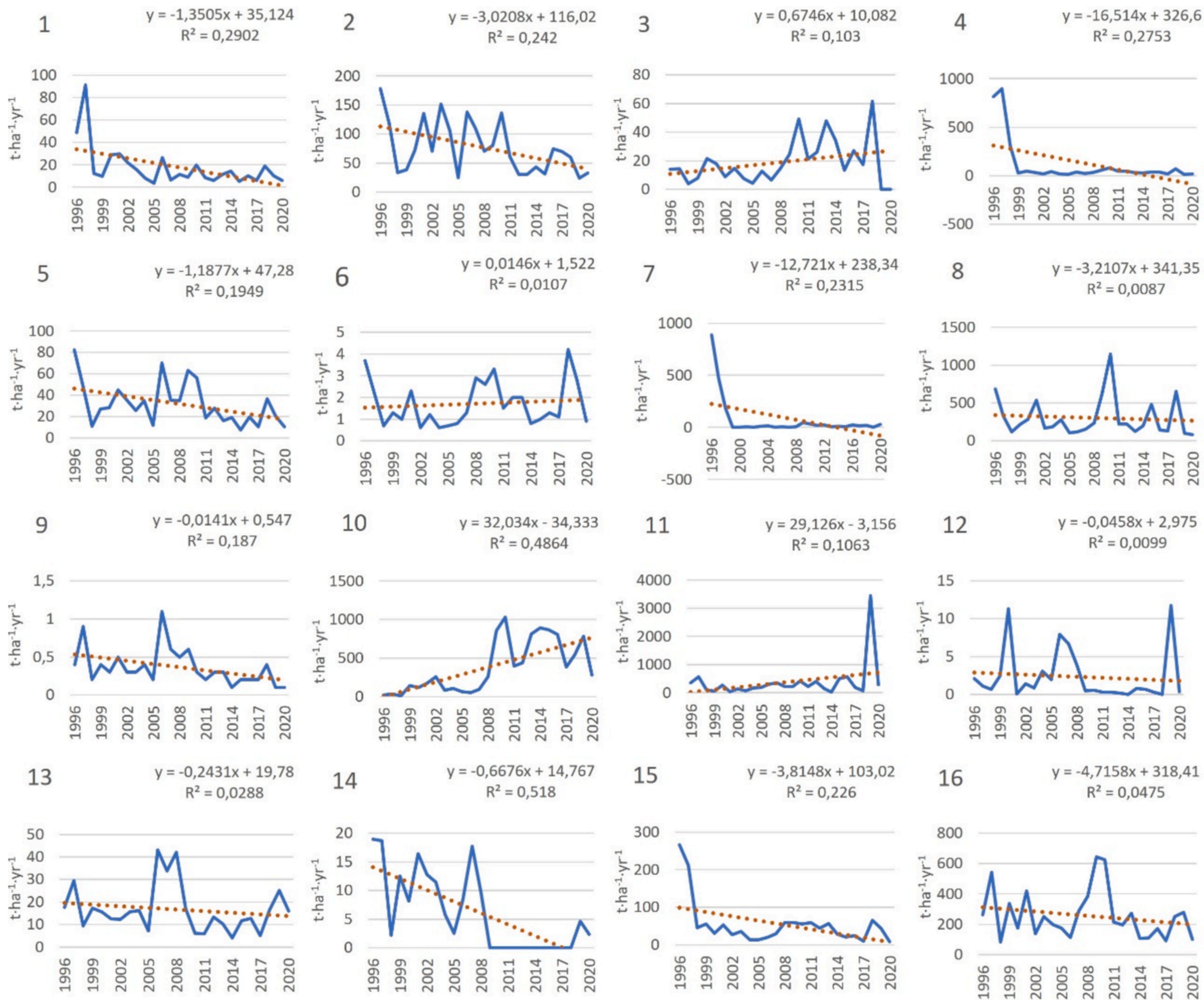

Fig. 6. Examples of annual mean erosion behavior and its trend line during the 25 analyzed years.

pluviometric maximums in Andalusia, i.e., mean values approaching 2000 mm·yr^{-1}. Moderately high rainfall erosivity values (>1500–2000 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) are distributed through the subhumid–humid Mediterranean maritime-influenced climate of the Straits of Gibraltar and in the semi-oceanic Mediterranean climate of the eastern Ronda mountains. These climates are clearly influenced by oceanic air masses from the W and also east winds, with mean rainfall of between 700–1500 mm·yr^{-1} recorded in the coastward area and 600–1200 mm·yr^{-1} in the mountainward area (Gómez-Zotano et al., 2015).

The linear regression statistical technique by climatic unit only detects positive values in the semiarid–arid Mediterranean climate of the coast in the far southeast (>1–5 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) and in sporadic sectors in other subunits. Significantly, the ongoing increase in intense rainfall events represented by rainfall erosivity has occurred in a climate where rainfall is characteristically torrential and mean values are below 350 mm·yr^{-1}.

3.3. Estimated soil erosion and rainfall erosivity values by hydrographic subwatershed

Considering the mean values and estimated soil erosion trend by subwatershed is a very effective method to guide environmental agencies in taking actions to correct soil loss trends and to complement morphometric parameter analysis methods (Vulevic et al., 2015; Ameri et al., 2018). In this case, over 10 subwatersheds have been highlighted where the mean erosion values for the analyzed 25-year period exceed 50t·ha^{-1}·yr^{-1}. To these must be added the Guadalete and Vélez subwatersheds, which present mean annual values above 100t·ha^{-1}·yr^{-1} (Fig. 9A). All these basins are aligned with the Penibaetic and Subbaetic mountains, as are the maximum soil erosion values.

Most of the Mediterranean basins show a tendency toward stability. It is even possible to find decreasing trends in some of the Subbaetic coastal basins (Fig. 9B). Only 11 basins show an upward estimated erosion value trend of as much as 1 t·ha^{-1}·yr^{-1} every year in their territories and only the Guadalete subwatershed shows higher increases than this (>1–3.7 t·ha^{-1}·yr^{-1} every yr).

Regarding mean rainfall erosivity by subwatershed, the highest values are all found in subwatersheds in the western half of the region, on both the Atlantic and the Mediterranean seaboards (Fig. 9C). Medium high to very high rainfall erosivity results (>2000 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) are found in the Guadalete River headwaters subwatersheds and the Guadiaro and Guadarranque-Palmones river subwatersheds. Moderately high values (>1500–2000 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) are also detected in the Odiel-Chanza river headwaters subwatersheds in the Sierra Morena mountains.

The linear regression statistical technique results for rainfall erosivity by subwatershed highlight 8 subwatersheds with a steep upward trend (>5–65 MJ·mm·ha^{-1}·h^{-1}·yr^{-1} every yr) and another 12 with

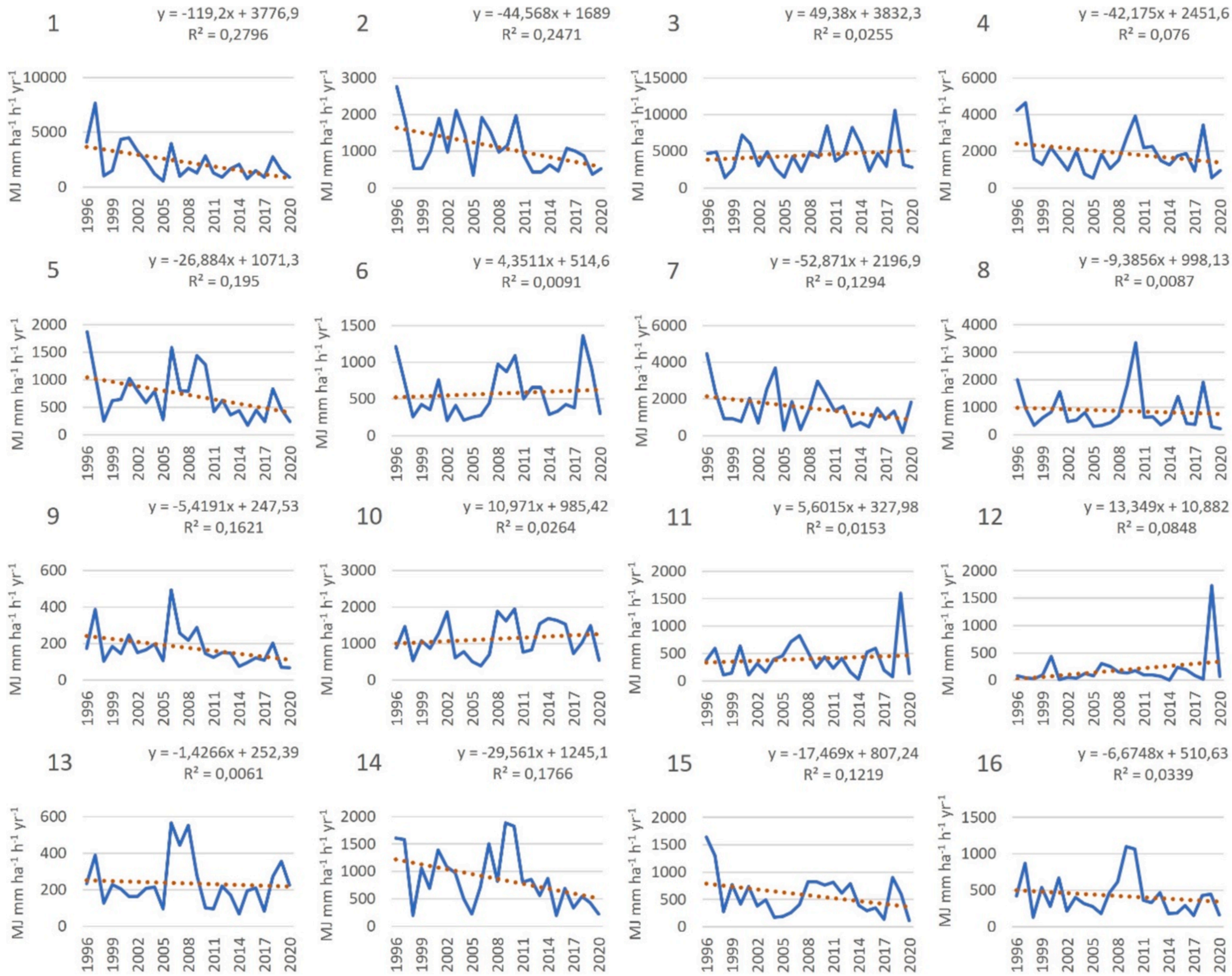

Fig. 7. Examples of annual mean rainfall erosivity behavior and corresponding trend lines for the 25 analyzed years.

lower mean increases (>1–5 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}every yr) (Fig. 9D). This upward trend in rainfall with a significant erosive capacity in hydrographic basins allows the administration to focus its preventive actions on the areas where they are most needed.

The subwatersheds with high mean estimated erosion values but medium and low rainfall erosivity values (Fig. 9A-C) are in territories where agricultural uses predominate (Guadalquivir Valley). Despite the studied 25-year trend evidencing more symmetrical results in both variables' increase trend in several hydrographic basins (Fig. 9B-D), it is the basins such as the Odiel and the Guadiamar and the intensively farmed marshlands (Zorrilla-Miras et al., 2014; Fernández-Nogueira & Corbelle-Rico, 2018) that explain positive soil erosion trends that do not correspond to rainfall erosivity behavior (Barral Muñoz et al., 2020).

4. Discussion

4.1. Procedure strengths and limitations

The data that underpin this work were taken from a notable project developed by the Andalusian Autonomous Community's environment department. Numerous prior research studies in a wide range of scientific fields have used the cartographic and statistical information produced by administrations and institutions and made available in open access databases (e.g., Meneses et al., 2017; Adhikari and Hansen, 2018; Gariano et al., 2018). The role of some institutions that actively participate in generating knowledge subsequently recognized by the scientific community needs to be highlighted. These include the UK Landscape Institute (LI, https://www.landscapeinstitute.org/), which is independent of the administration, and the European Soil Data Centre (ESDAC, https://esdac.jrc.ec.europa.eu/), a research center under the authority of the European Commission. Land use maps such as CORINE Land Cover (CLC, https://land.copernicus.eu/en/products/corine-land-cover), which is the responsibility of the European Environmental Agency and prepared by the National Reference Centre for Land Use in each of the member States, is one of the most outstanding examples of resources that administrations periodically offer society and, therefore, also scientists, who exploit them to their full potential (e.g., Freire et al., 2009; Poggi et al., 2019). In Spain, the National Geographic Institute (IGN, https://www.ign.es/web/ign/portal/inicio) is a significant information source for both basic recognition of the territory (orthophotos, lidar data, etc.) and for preparing periodic statistics and thematic cartography (land use maps, Seismic information, etc.). Lastly, since it was set up, the Junta de Andalucía's Environment Department has generated a large quantity of statistical and cartographic information and made it available to the public through the REDIAM geoportal (https://www.juntadeandalucia.es/medioambiente/portal/acceso-rediam). This information includes the Statistics on Soil Loss by Erosion in Andalusia project, as soil erosion is considered a relevant problem in the region and, consequently, for the environment department. According to information provided alongside

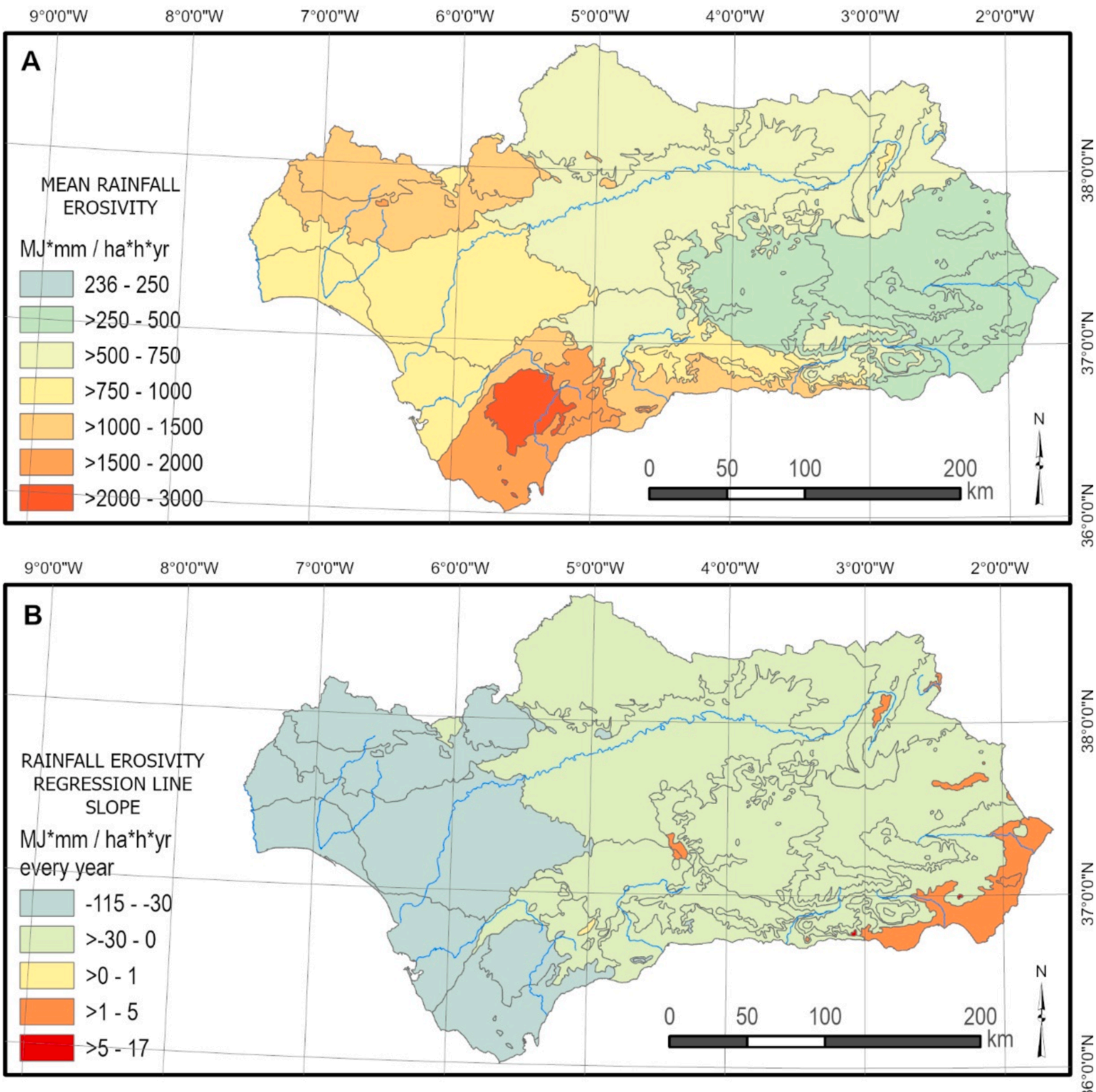

Fig. 8. A. Mean rainfall erosivity by climatic unit. B. Mean rainfall erosivity regression line slope by climatic unit.

the data (Junta de Andalucía, 2014a, b), RUSLE is calculated yearly for the entire Andalusian territory and offers mean monthly and annual data on soil erosion and rainfall erosivity. The explanation of the methodology states that once the data have been fed into the Statistical Management System (GESTA), the associated Services carry out an initial validation. The program also has automatic quality control filters. So, it is the institution itself that validates the data considered in this analysis. Nevertheless, as the institution itself acknowledges, it is important to consider that the data offered by these types of models are not exact but estimated or approximated, whereby the obtained values should be regarded as indicative or illustrative, only. This is in line with recent reviews that recommend that erosion modeling results should be considered more indicative of the best hypotheses than predictive models (Borrelli et al., 2021), and even more so given how complex it is to validate (R)USLE-type erosion models applied to extensive territories (Alewell et al., 2019).

Notwithstanding, it is worth highlighting that the main limitation of using these initial data is the impossibility of intervening in the design of the methodology used to construct the RUSLE equation. In addition, the administration itself warns that estimated soil erosion should be calculated at the regional scale and that the quality of its data goes down when analyzed at the local scale. The administration continued to neglect P-Factor values to maintain the methodological consistency of the series begun in 1996, despite methods subsequently being developed that can calculate it at the regional scale (Panagos et al., 2015b; Panagos et al., 2015a), as well as other studies that recognize soil conservation practices in the southern half of the Iberian Peninsula at a detailed scale (Fernández et al., 2018; Barrena-Gonzalez et al., 2020).

The continuity of the data, calculated without interruption since 1996, is noteworthy and indicative of the environmental agency's ongoing interest in the need to gather in-depth knowledge about the soil erosion issue since it was set up, given that in the last quarter of the 21st

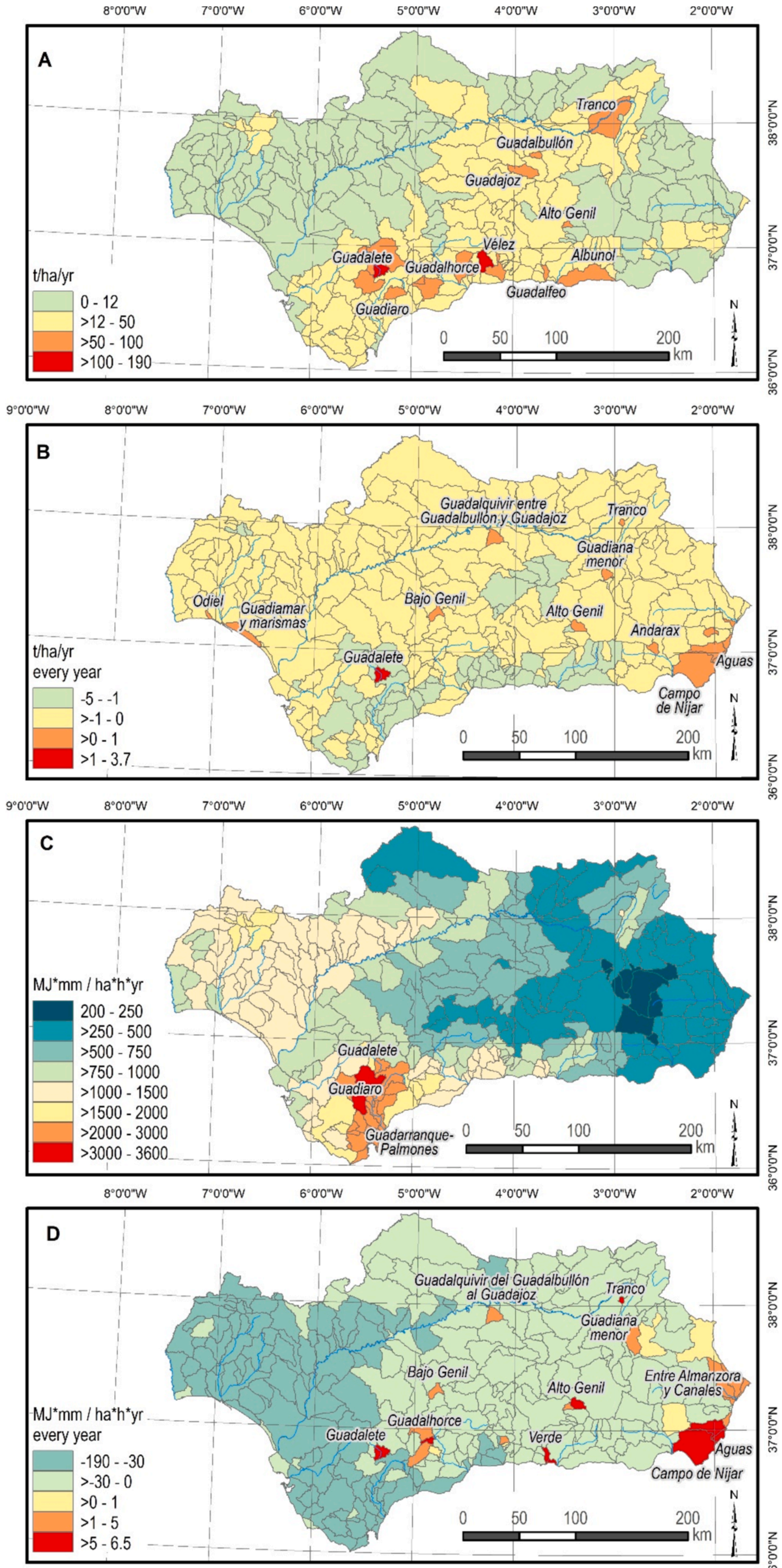

Fig. 9. Mean data by subwatershed. A. Mean estimated soil erosion. B. Estimated soil erosion regression line slope. C. Mean rainfall erosivity. D. Rainfall erosivity regression line slope.

century a significant increase was observed in the territory (Gómez-Zotano et al., 2015).

Although it was introduced several decades ago, the RUSLE methodology used by the Andalusian Environmental Agency to calculate rainfall erosivity (Junta de Andalucía, 2014b) is a standardized method that continues to be used in the present day (Li et al., 2022; Huang et al., 2021). Panagos et al. (2017) referred to intervals of under 30 min to measure maximum intensity rainfall as high temporal resolution, although recent research highlights that the longer the time period considered, the more the results are underestimated. The same studies concluded that rainfall data with a fixed time interval of under 10 min was required for precise rainfall erosivity estimation (Picarreta et al., 2024). The analyzed data collected by the Junta de Andalucía's automatic weather stations, which the Junta de Andalucía itself analyzed, are for 10-minute intervals, so it cannot be stated that the data have been underestimated excessively.

Rainfall erosivity and soil erosion spatiotemporal trends have been analyzed using regional environmental agency data and have produced very relevant results for researchers and agency managers. One example of this is the formulation of the Soil Protection Strategy approved by the European Union in 2021, which lays down a period of up to 2050 to achieve healthy soil and urges member States to identify areas in their territories at risk of desertification or soil contamination and specify the procedures required to achieve their sustainability (COM/2021/699 final). Research in the framework of the EU Soil Observatory (European Commission) has published Europe-wide (Panagos et al., 2015b; Panagos et al., 2015a) and global-scale results (Panagos et al., 2017) with the primary goal of establishing action lines to combat this major environmental problem.

4.2. Analysis of spatiotemporal trends

The linear regression statistical technique is habitually used to analyze time series applied, for example, to climate data (Kato et al., 2020; Panagos et al., 2017; Nwagbara and Ibe, 2015; Katra et al., 2006). Therefore, its use for time variables with different spatial footprints should also be relevant for detecting differentiated trends in parameters in different areas of the same territory. However, some other statistical techniques such as the Contextual Mann-Kendall (CMK) test (Kendall, 1975; Mann, 1945) are known to have been applied to temporal data trend analysis. The main benefit of CMK is that when it is applied to raster images, it considers the trend for only one pixel and the eight neighboring pixels. The trend is considered more valid if the 9 pixels present similar trends as random noise is eliminated (Gutiérrez 2022). The discrete nature of the information on the parameters in the RUSLE model calculation leads us to consider the presence of atypical trends, as might be caused by a specific combination of factors that could be highly relevant for the analysis.

The trend toward a decrease in the mean estimated soil erosion values identified in most of the Andalusian territory during the 1996–2020 period and more marked in the large mountain alignments, has also been described in mountain areas in the north of Spain (Zabaleta et al., 2013) and other Mediterranean areas such as the Island of Crete in Greece (Nerantzaki et al., 2015). The abandonment of farming and its replacement with forestry and natural vegetation cover have been purported to be responsible for stable erosion in the south of Spain (Milazzo et al., 2022). The decrease in the soil erosion values in abandoned agricultural areas, where the vegetation cover has recovered to a certain degree, has even been detected in areas with very intense rainfall (Han et al., 2020). In these mountainous areas, the value of slope steepness is observed to be very relevant for the result in the RUSLE mean erosion calculation, where it greatly exceeds the value of C-Factor (Meliho et al., 2020; Milazzo et al., 2022) and the R-Factor (Barral Muñoz et al., 2020). However, it must be pointed out that these are the key factors in the trend analysis, as they are the only attributes that present temporal variability.

Subwatershed-scale analysis has highlighted 10 with mean estimated erosion results above 50 t·ha^{-1}·yr^{-1}, and a further two with values above 100 t·ha^{-1}·yr^{-1}. These are the subwatersheds that merit special attention from a regional administration seeking to mitigate any possible adverse effects. Spatiotemporal analysis of these parameters is considered to complement other analyses similarly applied to delimiting especially erodible subwatersheds (Vulevic et al., 2015; Ameri et al., 2018). A wide range of soil protection methods are available for use by the pertinent administrations and their application to different territories has been widely presented and compared (Al-Rahbi et al., 2020; Ricci et al., 2020; Du et al., 2022).

In regions with recurring wildfires such as the Mediterranean, it is especially relevant to recognize areas with a high growth trend in rainfall erosivity as the combination of these two events results in an enormous increase in soil erosion (Morán-Ordóñez et al., 2020). All this is exacerbated by the more frequent and more intense extreme rainfall events observed in the Mediterranean in the current context of climate change (Giorgi and Lionello, 2008; Jacob et al., 2014).

The relevance of intense rainfall events as the main trigger of erosion in this western Mediterranean region (González-Hidalgo et al., 2007) makes it more interesting to ascertain the rainfall erosivity trend during the analyzed period. In this regard, it is paradoxical that some areas exist where the very low mean erosivity data (131-250MJ·mm ha^{-1}h^{-1} yr^{-1}) are masking sporadic instances of the highest value (>3000MJ·mm ha^{-1}h^{-1} yr^{-1}). One example of this is the far southeastern part of the region with its semiarid–arid Mediterranean climate. Recent studies have associated both the increase in torrential rain events and the fall in mean precipitation in the SE of the peninsular as a result of Climate Change (González-Herrero and Bech, 2017; Camarasa-Belmonte et al., 2020).

5. Conclusions

The present work analyzes the spatiotemporal evolution of estimated soil erosion and annual mean rainfall erosivity in the Andalusian region of Spain during the 1996–2020 period. For this, the regression line slope time trend of both variables has been calculated with ArcGIS Pro GIS tools.

Analysis of R-Factor mean values and time trend and the RUSLE equation result for this 25-year period has shown major differences in findings but with an interpretation that is complementary.

Most of the region is affected by low and medium estimated erosion values (91.74 % of the territory between 0 and 50 t·ha^{-1}·yr^{-1}) and a large proportion by low to very low rainfall erosivity values (70.43 % of the territory between 132 and 1000 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}). The highest values for both parameters are limited to the mountain areas of the Baetic and Sierra Morena mountain chains. It can be highlighted that 3.38 % of the region is affected by high to extremely high rainfall erosivity values (>2000–4693 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}). Mean rainfall erosivity values (>2000–3000 MJ·mm·ha^{-1}·h^{-1}·yr^{-1}) by climatic subunit are only high in the oceanic (wet) Mediterranean climate of the western Ronda mountains, a climatic unit that also presents the pluviometric maximums for Andalusia with mean values approaching 2000 mm·yr^{-1}.

The general estimated erosion trend is clearly downward, with 92.64 % of the territory with slopes between 0 and −344 t·ha^{-1}·yr^{-1} every year. Notwithstanding, the mountain enclaves stand out as having a regression line slope above 0 and as high as + 5 t t·ha^{-1}·yr^{-1} during this 25-year period (7 % of the region, 6131.79 ha). The observed rainfall erosivity time trend only simultaneously presents mean high values and a rising trend in the far western part of the Baetic mountains. In the remainder of the Andalusian territory, significant increases in this variable are found where the mean values are medium or low. The most conspicuous case is the far southeast of the region, where extreme maximum rainfall erosivity and minimum mean estimated erosion values coincide.

When rainfall erosivity values are considered by climatic subunit, high mean results are only observed in the oceanic (wet) Mediterranean climate of the western Ronda mountains (>2000–3000 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$), where a progressively downward trend is also observed (−115 – 130 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$). However, apart from sporadic sectors in other subunits, positive trends are limited to the semiarid–arid Mediterranean climate of the coast in the far southeast (>1–5 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$).

Analysis of the mean distribution of both parameters by subwatershed is useful for environmental agencies needing to take corrective measures to combat the erosion problem to interpret the results. The coincidence of mean estimated erosion values and increase trends during the analyzed period is especially useful for guiding actions in the Guadalete, Guadalhorce, and Verde subwatersheds.

Also, in the previously mentioned semiarid–arid Mediterranean subunit climate of the far southeastern coast, the Campo de Níjar subwatershed and the Aguas subwatershed, especially, present low estimated erosion and low rainfall erosivity values despite exhibiting upward trends for both parameters over the analyzed 25 years. This behavior is an example of climate evolution toward more torrential rainfall in a climatic unit characterized, precisely, by very infrequent but very concentrated rainfall. The upward rainfall erosivity trend in over 10 % of the region's surface area is, in itself, an indication of a phase of more torrential rainfall, which was predicted to be one of the outcomes of Climate Change.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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