A NEW METHODOLOGY FOR ESTIMATING RAINFALL AGGRESSIVENESS RISK BASED ON DAILY RAINFALL RECORDS FOR MULTI-DECENNIAL PERIODS

Leoncio García-Barrón[1], Julia Morales[2], Arturo Sousa[2*]

[1] *Departamento de Física Aplicada II, Universidad de Sevilla, E-41012 Sevilla, España*

[2] *Departamento de Biología Vegetal y Ecología, Universidad de Sevilla, E-41012 Sevilla, España*

ABSTRACT

The temporal irregularity of rainfall, characteristic of a Mediterranean climate, corresponds to the irregularity of the environmental effects on soil. We used aggressiveness as an indicator to quantify the potential environmental impact of rainfall. However, quantifying rainfall aggressiveness is conditioned by the lack of sub-hourly frequency records on which intensity models are based. On the other hand, volume models are characterized by a lack of precision in the treatment of heavy rainfall events because they are based on monthly series. Therefore, in this study, we propose a new methodology for estimating rainfall aggressiveness risk. A new synthesis parameter based on reformulation using daily data of the Modified Fournier and Oliver´s Precipitation Concentration indices is defined. The weighting of both indices for calculating the aggressiveness risk is established by multiple regression with respect to the local erosion *R* factor estimated in the last decades. We concluded that the proposed methodology overcomes the previously mentioned limitations of the traditional intensity

[*] Correspondence to: A. Sousa, Departamento de Biología Vegetal y Ecología, Universidad de Sevilla, E-41012 Sevilla, Spain. E-mail: asousa@us.es

and volume models and provides accurate information; therefore, it is appropriate for determining potential rainfall impact over long time periods. Specifically, we applied this methodology to the daily rainfall time series from the San Fernando Observatory (1870-2010) in southwest Europe. An interannual aggressiveness risk series was generated, which allowed analysis of its evolution and determination of the temporal variability. The results imply that environmental management can use data from long-term historical series as a reference for decision making.

KEY WORDS: Aggressiveness; Rainfall erosivity; Land use; Environmental risk; Southwest Europe

1. Introduction

One of the features of the rainfall regime in a Mediterranean climate is the inter- and intra-annual irregularity (García-Barrón *et al*., 2013). Inter-decadal climate studies help to explain the causes of terrain alteration over time (Diodato *et al.,* 2008). Rainfall erosivity causes a loss of fertile soil, damage to agriculture and infrastructure and water pollution and is influenced by changes in rainfall patterns (Martín-Fernández & Martínez-Nuñez, 2011; Sánchez-Moreno *et al*., 2014) and by predictable effects of climate change (Diodato *et al*., 2011). In this study, we consider aggressiveness risk as a potential estimate of the physical effects of rainfall on soil dynamics *sensu* Fournier (1960). Our view is that aggressiveness risk is an appropriate environmental indicator and directly related to erosion and associated with the incidence of torrents, floods, landslides, displacement, etc. (Gregori *et al*., 2006). Therefore, knowledge of this variable over long periods is particularly useful for the management of water resources, soil conservation, agricultural planning and the development of environmental policy. Moreover, annual estimates of aggressiveness risk enable the comparison of orders of magnitude among different observation sites at different times. This environmental indicator is based on daily rainfall records and does not include other aspects related to erosion such as slope length, soil types, wind activity, land use, etc.

For the direct calculation of soil erosion, the universal soil loss equation (USLE) has been frequently used (Wischmeier & Smith, 1978). Specifically, the rainfall erosivity, or *R* factor, depends on the energy of every rainfall episode (Panagos *et al.*, 2015). The *R* factor is an accepted instrument for local erosion measurement, successively updated and empirically endorsed by means of field measurements (Renard *et al.*, 1997). Models such as the USLE and RUSLE were originally developed for detailed scale application in the farming sector, so their application on a regional scale presents some limitations (Terranova *et al.,* 2009). Although USLE is one of the most widely used erosivity models worldwide, it has some limitations because the estimations of soil erosion do not fit the empirical measures of sedimentation, and the *R* erosivity factor does not explicitly incorporate direct runoff of water, which affects the accuracy of the model (Kinnell, 2010). Additionally, the spatial distribution tends to overestimate the *R* factor at regional or river basin levels (Hernando & Romana, 2016), and its is not recommended in areas different from those in which it was developed without an analysis of the validity of the equations.

In the specific case of the study of rainfall aggressiveness effects, two complementary approaches are taken: intensity models are based on sub-hourly rainfall records, and volume models are based on monthly rainfall records. This model refers to the different partial accumulations of rainfall. That is, it does not take into account the number, the duration and the rainfall amount of each episode, so that it's based exclusively on the total monthly rainfall. Nevertheless for the direct calculation of the rainfall erosivity in large areas, it is desirable to make use of high frequency rainfall records collected by nearby weather stations during a period longer than twenty years (Angulo-Martinez *et al*., 2009). However, except for modern automatic weather stations, traditional observatories have no high-frequency series with sub-hourly records. On the other hand, volume models are based on monthly rainfall records that are extensively available in most countries. In this case, the regular use of the aggressiveness index in environmental studies (Fournier, 1960), subsequently modified by Arnoldus (1980) as the Modified Fournier Index (I_{FM}) and complemented with the Precipitation Concentration Index (I_{PC}) developed by Oliver (1980), is remarkable.

Both estimations for calculating the intensity of rainfall aggressiveness present limitations. The drawback of the intensity models is the lack of adequate time series records, and that of the volume models is the imprecision in the treatment of heavy rain episodes because they are based on finer timescale resolutions. The amount of precipitation is not the only relevant parameter; its temporal distribution is also relevant, as studies on Mediterranean river basins in the NE Iberian Peninsula (Sánchez-Canales *et al*., 2015) and in the SW Iberian Peninsula (Sousa *et al*., 2009) have made evident. Various studies have compared the results obtained using intensity models (the R factor of USLE) to those obtained using volume models. In the Iberian Peninsula, the Institute for the Conservation of Nature (ICONA, 1988) under the Spanish Ministry of Agriculture proposed an empirical relationship that locally associates the R factor with the I_{FM} index. Additionally, a high correlation between the R factor and the monthly and/or annual precipitation parameters, including the Fournier Index, has been obtained in various geographic areas, such as in the Mediterranean area (Diodato & Bellocchi, 2007; Taguas *et al*., 2013), East Asia (Lee &Heo, 2011; Yue *et al*., 2014) and the tropical zone (Sanchez-Moreno *et al*., 2014). In the USA, Renard & Freid (1994) proposed regression equations that calculate the R factor from I_{FM}. Additionally, Loureiro & Couthino (2001) estimated the R factor based on the monthly rainfall aggressiveness in southern Portugal, and Da Silva (2004) estimated the same in Brazil.

In this study, we propose to estimate the aggressiveness risk by means of a single annual parameter that improves the limitations of models based only on monthly records (volume models) and those based on sub-hourly records (intensity models). We used a method based on the daily scaled reformulation of the traditional indices of aggressiveness, I_{FM} and I_{PC}, that provides more accurate results. The method also allows numerous investigations because there are many weather stations that have large time series of daily data. This Estimated Annual Aggressiveness Risk (R_A) is calibrated locally by means of regression equations with respect to the erosivity *R* factor for a period of simultaneity. Backwards extrapolation of the resulting function generates the corresponding time series of the aggressiveness risk. Recently, García-Barrón *et al*. (2015) have synthesized in this parameter the aggressiveness risk using I_{FM} and I_{PC} to study trends in river basins of the Iberian Peninsula. In this article, we propose two main objectives:

a) To define and calculate a single annual parameter based on daily records that synthetically estimates the rainfall aggressiveness risk.

b) To apply this methodology to a study area with a Mediterranean climate to analyse the temporal behaviour and deduce patterns in the evolution of the rainfall aggressiveness risk.

2. Study area and data

We chose the South-Atlantic region of the Iberian Peninsula for the methodological application, which is based on a long period and can help to draw conclusions about the potential risks of rainfall on the land. Spain is one of the countries most severely affected by soil erosion in the European Mediterranean region due to extreme spatial and temporal variations in its physical environment, with frequent periods of drought and torrential rainfall (Solé, 2006). The importance of erosion in the Mediterranean is related to the long history of human activity in a region characterized by low annual precipitation, the occurrence of intense rainstorms and long-lasting droughts, high evapotranspiration, the presence of steep slopes and the occurrence of recent tectonic activity, together with the recurrent use of fire, overgrazing and farming (García-Ruiz et al., 2013).

The southwestern Iberian Peninsula falls within the domain of the Mediterranean climate, although it is influenced by an oceanic effect because of its proximity to the Atlantic Ocean. The average annual rainfall is approximately 600 mm (average values are substantially higher in the mountain range separating the watersheds of the Guadiana and Guadalquivir rivers). Rainfall is subject to marked inter-annual irregularity, with great oscillations in annual totals that include multi-year periods of drought (Aguilar, 2007). In general, the profile of the intra-annual precipitation shows an asymmetric unimodal curve, ascending in autumn and descending smoothly from winter to summer, when it reaches its minimum.

The Royal Observatory of the Spanish Navy (ROA) located in San Fernando (province of Cadiz, at the southern tip of the Iberian Peninsula) includes the oldest active weather station in Spain; rainfall records have been recorded since 1805 and accessible daily data since 1870. Because of these long-term and high-quality records, different studies have used ROA data as a reference to characterize the rainfall regime (Rodrigo, 2002; Martin-Vide & Lopez-Bustins, 2006) and the inter- and intra-annual behaviour (García-Barrón *et al*., 2013) of rainfall in the study area.

The meteorological stations located in the province or district capitals of Spain and Portugal have been selected to quantify the level of regional representation of the ROA rainfall series (Figure 1). Data from the Spanish stations were provided by the Spanish Meteorological Agency (AEMET), and data from the Portuguese stations were provided by the Portuguese Sea and Atmosphere Institute (IPMA). The weather stations are distributed over different geographical areas as follows: Cadiz, Huelva and Faro in the coastal zone, Cordova and Seville in the Guadalquivir valley, and Badajoz and Beja in the Guadiana basin (Figure 1).

Figure 1. Map showing the locations of the meteorological stations used in the study area.

These series are homogeneous and have no missing data (Almarza *et al.*, 1996; García-Barrón *et al.*, 2013). We have chosen the period 1961-1990, recommended by the World Meteorological Organization, for comparing the ROA rainfall records to those of every selected regional station. Table 1 shows the representativeness of the ROA compared to every selected observatory in the area. To determine the representativeness, we calculated the proportionality of the average annual rainfall between the ROA and every selected station, the R-Pearson coefficient of the annual totals of the respective rainfall series and the R-Pearson coefficient of the monthly average of the intra-annual distribution.

Table 1. Proportionality coefficient and annual and interannual correlation between the San Fernando Observatory (ROA) and the selected regional stations.

Observatories	Country	Institution	Latitude and Longitude	Annual average rate	R-Pearson Interannual	R-Pearson Intra-annual
San Fernando (ROA)	Spain	ROA	36° 27′ 56″ N 6° 12′ 20″ W	-	-	-
Cadiz	Spain	AEMET	36° 32′ 01″ N 6° 17′ 58″ W	1.04	0.96	1.00
Huelva	Spain	AEMET	37° 16′ 30″ N 6° 54′ 35″ W	1.03	0.94	0.98
Faro	Portugal	IPMA	37° 01′ 00″ N 7° 55′ 59″ W	1.04	0.76	0.97
Seville	Spain	AEMET	37° 25′ 05″ N 5° 42′ 30″ W	1.02	0.85	0.98
Cordova	Spain	AEMET	37° 50′ 40″ N 4° 51′ 02″ W	0.96	0.86	0.98
Badajoz	Spain	AEMET	38° 43′ 02″ N 6° 49′ 45″ W	1.02	0.72	0.94
Beja	Portugal	IPMA	38° 00′ 56″ N 7° 51′ 55″ W	0.92	0.70	0.94

Table 1 shows that although the total rainfall differs among neighbouring stations and in those within the same basin, the intra- and inter-annual behaviour is similar. The high correlation of the results obtained in Table 1 shows that the region studied has the same climate and is subject to the same synoptic conditions. This corroborates the conclusions of previous studies on rainfall in the southwestern Iberian Peninsula (García-Barrón *et al.*, 2011). Therefore, we assume that the general rainfall regime of the ROA sufficiently characterizes the Atlantic southern zone of the Iberian Peninsula for analysis of its temporal variability. Consequently, this study estimated the behaviour of the temporal evolution of the aggressiveness risk using daily rainfall records of the ROA from 1870 to 2010. Absolute homogeneity tests were applied to the annual series with AnClim software (Stepanek, 2007) and the Standard Normal

Homogeneity Test (SNHT) for a single series (Alexandersson, 1986). The results support the quality of the series. The rainfall-measuring unit was mm.

The calculation of the regional erosivity, the R factor of USLE, was provided by the Environmental Information Network of the Ministry of Environment of the Andalusia Government. The automatic weather station at Cadiz (Table 1) was selected for calculating the R factor (Rodríguez Surián & Sánchez Pérez, 1995) because of the quality of its rainfall records. Because of their proximity (<12 km) and similar geographical conditions, the rainfall records of the stations at Cadiz and San Fernando (ROA) are similar and consistent. This allowed us to use the results of the R factor as an element of correspondence to establish the relationship with the R_A in the study area during the simultaneity period (1991-2010).

3. Methodology

The methodology proposed is based jointly on I_{FM} and I_{PC}. As a new contribution, the classic definition of these indices was altered to perform calculations using daily precipitation data. Both indices were used to define a unique annual parameter, the Estimated Annual Aggressiveness Risk (R_A), that calculates, accurately and synthetically, the potential effect of rainfall aggressiveness for every year in the study area using one single variable. This makes it possible to generate a multi-annual series to establish its time evolution in the study area.

From the daily rainfall series obtained for each N years of records, R_A is obtained using the indices (I_{FM*}, I_{PC*}) as follows:

$$R_A = \varphi\ (I_{FM*}, I_{PC*}) \qquad (1)$$

where I_{FM*} is a daily scale of the Modified Fournier Index,

$$I_{FM*} = (\Sigma p_d^2)/P \qquad (2)$$

and I_{PC^*} is a daily scale of the Precipitation Concentration Index,

$$I_{PC^*} = 100\ (\Sigma p_d^2)/P^2 \qquad (3)$$

where p_d is the daily precipitation (d = 1, 2,..., 365) and P is the corresponding total annual precipitation. I_{FM^*} units are the same as those of rainfall, and I_{PC^*} is dimensionless.

To mathematically estimate the values of $R_{A,}$ we established the connection with the erosivity data R of USLE for a period of simultaneous records. By linear regression, we obtain

$$\varphi\ (I_{FM^*,}\ I_{PC^*}) = R + \xi \qquad (4)$$

where the function φ is determined, with ξ being the residual deviation.

Using backwards extrapolation, the repeated application of the resulting equation to the corresponding annual values of I_{FM^*} and I_{PC^*} produces the R_A interannual series for the period. The procedure has a feature that the estimation of the R_A risk is measured in the same units and with the same scale as the R factor of USLE.

The use of daily data to calculate R_A incorporates the environmental impact caused by heavy daily rains. It also allows the use of long time series from many weather stations. Therefore, the proposed method to calculate the annual R_A improves the quality of the evaluation compared to the traditional volume models and incorporates calibration with respect to the intensity models. In view of this, we believe that the proposal is innovative, as it combines the advantages of both models and overcomes some of their limitations.

I_{FM^*} has a high dependence on total annual rainfall. In general, I_{PC^*} also depends on total annual rainfall. However, if every daily record of one year is proportional (multiple or submultiple) to those of another year, then I_{PC^*} is independent of the total rainfall and only depends on the intra-annual distribution of rainfall. Therefore, if we consider that daily rainfall (p_{di}) of the year n has its corresponding proportion ($p'_{di} = k\, p_{di}$) in the year n' (although not necessarily in the same order), where k is a constant, then the respective Fournier indices are proportional to each other, whereas the concentration indices are equal:

$$I'_{FM*} = k \cdot I_{FM*} \; ; \quad I'_{PC*} = I_{PC*} \qquad (5)$$

The theoretical limits of I_{PC*} are as follows: a higher value of 100 based on the assumption that all the annual rainfall occurs in one day and a minimum of 0.27 based on the assumption of a uniform equipartition among the days of the year. Therefore, high values of I_{PC*} indicate a heavy rainfall for a few days and thus a higher erosive power, whereas low values of I_{PC*} indicate light rainfall distributed along many days and thus less aggressiveness.

The analysis mechanism to reveal the temporal irregularity of the generated R_A series uses the linear trend and the variation and disparity coefficients of the entire series. The inter-annual behaviour is analysed using the accumulated deviations of R_A with respect to the μ_N average of the whole series, the variability for mobile periods and the Specific Disparity Index.

The accumulated value, to the year, was obtained by the sum of the annual deviations of R_A with respect to the μ_N average of the whole series, extended to all the preceding i years:

$$A_n = (\Sigma\ \delta_i) / \mu_N \qquad (6)$$

where $\delta_i = (R_{Ai} - \mu_N)$, for $i = 1, 2, \ldots n$; $n \leq N$

The R_A variation coefficient of the N-year complete series (1870-2010) is defined as the quotient of the standard deviation and the corresponding average μ_N:

$$V_N = \sigma_N / \mu_N \qquad (7)$$

Similarly, the moving variation coefficient for periods of eleven years corresponding to the year n ($1 \leq n \leq N$) is defined as the quotient of the standard deviation of the partial subseries formed by the reference year n and the previous ten years and their corresponding average:

$$V_{(11)n} = \sigma_{(n,\ n-10)} / \mu_{(n,\ n-10)} \qquad (8)$$

The methodology to calculate the I_D General Disparity Index and the I_{dn} Specific Disparity Index is available in the Supporting Information section (S1).

4. Results and assessment: application to the Southwestern Iberian Peninsula

4.1 Calculation of the indices I_{FM^*} and I_{PC^*}

Following the method shown in the Methodology section, to calculate R_A, it was necessary to first calculate the annual values of the Daily Modified Fournier Index (I_{FM^*}) and the Daily Concentration Index (I_{PC^*}). The values of these indices during the period 1870-2010 were the annual components from which the corresponding R_A values were subsequently estimated for the same period.

The values of I_{FM^*} and I_{PC^*} based on the ROA precipitation series for the period 1870-2010 showed no significant trend (Figure 2). Although the extreme values of both indices occasionally coincided, generally, there was no simultaneity in the temporal fluctuations. Values of I_{FM^*} were in a range from 10.9 to 39.3, and the actual range of the index I_{PC^*} was 2.0 to 7.4.

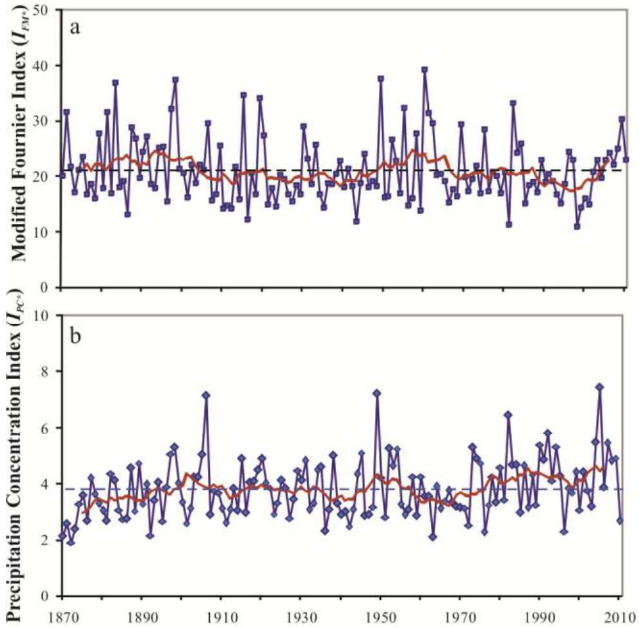

Figure 2.a) Temporal evolution of the I_{FM*} and b) the I_{PC*} showing the average value and mobile average for periods of eleven years.

The behaviours of I_{FM*} and I_{PC*} have been jointly analysed year-by-year. The r^2 interannual variability between I_{FM*} and I_{PC*} was low (r^2<0.4) (T-test for Paired Values: T = 36.633, $T_{crit\_97.5\%}$ = 1.977, *p-value* = 0.00 < 0.05). This was confirmed in the pairwise scatterplot that showed a wide range of points where the slightly ascending trend explained only 12% of the total variance (Figure 3). The temporal evolutions of both indices (I_{FM*} and I_{PC*}) were therefore independent of each other, as García-Barrón *et al.* (2015) found for the Spanish hydrographic basins. This shows that, as previously noted, each index reflects different characteristics of the rainfall regime. With no collinearity, it was confirmed that the respective contributions of both indices to the calculation of the R_A are complementary.

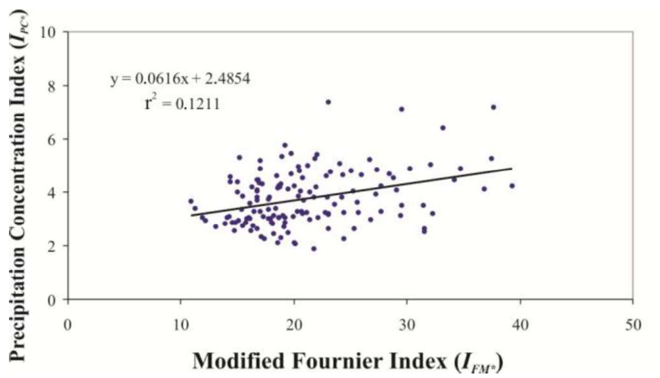

Figure 3. Pairwise scatterplot of the time series I_{FM*} and I_{PC*} for the period 1870-2010.

4.2 Characterization of the Estimated Annual Aggressiveness Risk

The function φ (I_{FM*}, I_{PC*}) that establishes the balance between both indices was obtained by multiple linear regression with respect to the local erosivity during the interval of simultaneity (1991-2010).

The equation of multiple linear estimation was as follows:

$$R_A = 145.24\ I_{FM*} - 341.56\ I_{PC*} \qquad (9)$$

The determination coefficient r^2 was 0.86. The substitution of values for I_{FM*} and I_{PC*} in equation 9 during the years of simultaneity allowed for the relation of the actual values of the R factor to the corresponding R_A values. Figure 4 shows the relationship of the adjustment for a level of significance $p = 0.05$.

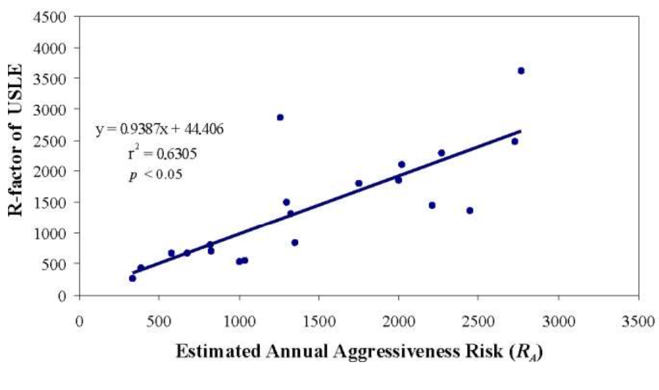

Figure 4. Pairwise scatterplot of the USLE R factor and the R_A time series for the period 1991-2010.

Applying equation 9 to the respective annual values of I_{FM*} and I_{PC*} for the entire study period allowed extrapolation and thus generation of the interannual estimated series of R_A from 1870 to 2010. The units for R_A are the same as those for R [(megajoules · mm) / (hectare · year hour)] and are on the same scale. Figure 5 graphically represents the evolution of the annual risk estimated for the period 1870-2010 with the corresponding trend line.

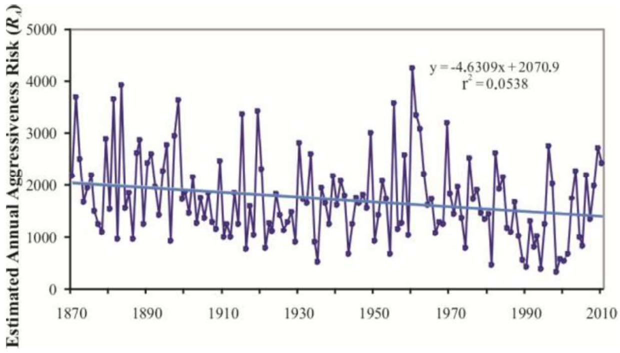

Figure 5. Temporal evolution of R_A in the SW Iberian Peninsula.

For the entire period, the average value, the coefficient of linear trend, the *Vn* coefficient of variation and the I_D general disparity index of R_A were calculated. The analysis results are shown in Table 2, which also includes the corresponding values of the indices $I_{FM*}$and I_{PC*} for comparison purposes.

Table 2. Characterization of the R_A and its comparison to the respective statistical components I_{FM*} and I_{PC*}: average, trend (linear regression), explained variance, variability and Specific Disparity Index.

	Average	**Trend**	r^2	V_N	I_D
I_{FM*}	21.0	- 0.012	< 0.01	0.28	0.40
I_{PC*}	3.8	< 0.001	< 0.001	0.27	0.35
R_A	1742	- 4.63	< 0.1	0.47	0.64

The average value of R_A was 1742 units. The linear trend (Figure 5) showed a slightly decreasing slope (-4.63 unit / year), statistically significant at the 95% level (T= -2.8 <-1.9) but climatically not relevant because the explained variance was lower than 1% (r^2<0.1). Therefore, the central value was not a sufficient predictor for the temporal estimation of the R_A; the high coefficient of variation (V_N = 0.47) and the general disparity index (I_D = 0.64) are proof of this state. This highlights the large temporary fluctuations of the R_A series, even between consecutive years. Additionally, the coefficient of variation and the general disparity index for R_A were higher than those for I_{FM^*} and I_{PC^*}.

Despite the lack of a significant trend of R_A, its accumulated relative deviations A_k allowed us to identify different multiannual sequences that characterized the interannual behaviour and, consequently, to identify sections of high and low risk of aggressiveness.

Figure 6 represents the accumulated deviations with respect to the μ_N average of the whole series of R_A. An initial upstream line was observed until the end of the nineteenth century and involved a high frequency of years with an aggressiveness risk higher than the average of the series. This period of high frequency of the aggressiveness risk coincided with the end of the Little Ice Age in Andalusia, which led to an important clogging and reduction process in lagoons and small coastal brooks (Sousa *et al.*, 2006) in the southwestern Iberian Peninsula. Diodato *et al.* (2011) noted that erosive forces increased towards the end of the Little Ice Age (~1850) over the western and central Mediterranean in general and have increased even more during the recent warming period in meridional Mediterranean regions because of a higher frequency of intense storms. On the other hand, Figure 6 shows a downward section at the first half of the 20th century, corresponding to years with aggressiveness risk below the average and that coincided with a slightly dry period with smooth annual rainfall fluctuations.

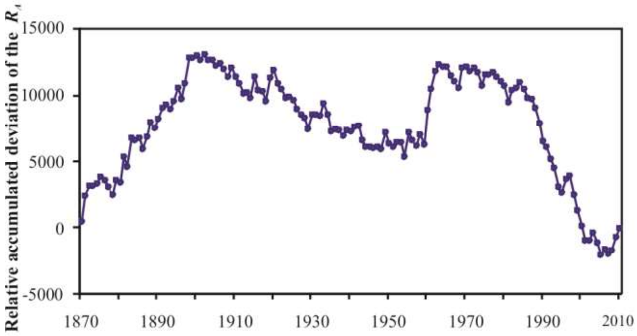

Figure 6. Evolution of the accumulated deviations with respect to the average R_A.

Finally, a steep downward phase that we associate with a period of low rainfall aggressiveness stands out during the last thirty years of the 20th century (Figure 6). This phase coincided with a dry period in which there was a greater dispersion of the intra-annual rainfall, a relative lack of rainfall in spring and a shift in rainfall towards the autumn months (García-Barrón *et al*., 2013). Data of the erosion and silting of the thalwegs of coastal brooks in the SW of Spain for this period show lower activity than that for both previously mentioned periods (the end of the 19th century and the 1960s of the 20th century), which showed high erosive activity (Figure 6). That is, phases of high rainfall aggressiveness during the 19th and 20th centuries in the SW of Europe caused wetland regression, especially in lagoons and coastal brooks (Sousa *et al*., 2013, 2015).

4.3 Temporal irregularity of the estimated risk of aggressiveness

The irregularity of the environmental effects caused by rainfall originates in the annual and intra-annual rainfall irregularity itself. In the previous sections, we discussed the general variability of R_A during the study period by means of V_N and I_D; consequently, it is necessary to analyse its interannual evolution. To do so, we calculated the mobile variation coefficients for periods of eleven years ($V_{(11)n}$) for the *n* years of the series generated (obviously with a reduction of the first ten elements) during the observation period.

The $V_{(11)n}$ variation coefficient associated with the time sequence of the R_A annual value showed peaks of the estimated risk in the years 1887, 1922, 1961 and 2002 of approximately 0.5, separated by the corresponding periods of minimum values lower than 0.30 (Figure 7), which indicates higher temporal stability of the interannual R_A values. This figure includes the representation of the values trend line. The last 25 years of the series is characterized by the greatest risk variability of the 140 years studied. Figure 7 shows a linear trend of the coefficient of variation values with a positive slope (y = 0.0009 x +0.387) significant for p = 0.05 (T_C = 3.62> 1.98), with r^2 equal to 0.09. The slope increases to 0.015 in the line that links the relative maximum values (1887, 1922, 1961 and 2002).

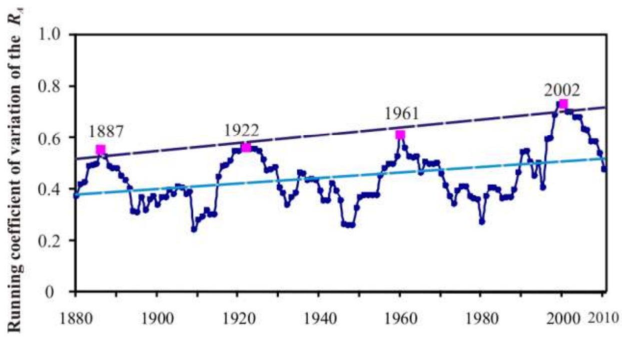

Figure 7. Mobile variation of the R_A coefficient for periods of eleven years with the trend line of the entire period analysed and that of the maximum relative values.

Therefore, the temporal analysis of R_A by means of the $V_{(11)n}$ variation coefficient shows an almost cyclical pattern with a pulsation of approximately 40 years (Figure 7). This cyclical component is unique, and we have no information indicating that it had been previously detected in the variability analysis of other climate variables in the Mediterranean environment. Equivalent results were obtained by analysing the Specific

Disparity Index (I_{dj}) are available in the Supporting Information section (S2). It is also noteworthy that the $V_{(11)n}$ variation coefficient of the R_A presents a progressive increase of its relative extremes.

5. Discussion

The proposed methodology for calculating R_A was applied to the SW Iberian Peninsula. Temporal analysis of the generated R_A series of San Fernando (ROA, 1870-2010) showed some sequences of consecutive years that, as a whole, show a frequency of annual values higher or lower than the mean value. There was a predominance of low aggressiveness during the first half of the 20th century, especially during the last thirty years; however, there were peaks of high aggressiveness in the late 19th and mid-20th centuries coinciding with periods of high soil erosion that resulted in siltation of lagoons (Sousa *et al*., 2013) and brooks (Sousa *et al*., 2015) in the southwestern Iberian Peninsula (Biosphere Reserve of Doñana).

Although this study was developed in the Iberian Peninsula, the new parameter is based on I_{FM} and I_{PC} (indices used in different edaphic and meteorological conditions), and we consider that its application is valid for analysing the potential impacts of rainfall in different climatic and geographic areas. Thus, it is necessary to develop a weighting local equation of both indices, φ (I_{FM}^*, I_{PC}^*), determined by rainfall in each region.

Several studies (Renard & Freid, 1994; Diodato y Bellocchi, 2007; Lee & Heo, 2011; Taguas *et al*., 2013; Yue *et al*., 2014) have shown a high correlation between the R factor and rainfall parameters such as the I_{FM}. For their part, Michiels *et al*. (1992) used the I_{PC} to analyse rainfall variability and considered that this index is appropriate for evaluating the erosivity, and Gabriels *et al*. (2003) used monthly precipitation data to analyse the interannual variability of erosivity. Apaydin *et al*. (2006), Elagib (2011), Elbasit *et al*. (2013) and Meshesha *et al*. (2015) used procedures based on these indices to analyse erosivity in arid regions. Based on the I_{FM}, Sauerborn *et al*. (1999) and Nearing (2001) suggested the possibility of changes in the rainfall erosivity in Europe and the USA, respectively, during the 21st century. De Luis *et al*. (2010) separately applied I_{FM} and I_{PC} to study a possible increase in erosivity in the Spanish Mediterranean area. Additionally, both indices have been used to detect changes in the temporal trend of erosivity in southern Portugal (Nunes *et al*., 2016) and, in an integrated way, analyse the spatial and temporal variability of aggressiveness in the watersheds of the Iberian Peninsula (García-Barrón *et al*., 2015).

The advantage of the proposed methodology is that it provides an accurate annual synthesis parameter of direct interpretation, potentially applicable to different geographical areas. R_A overcomes the limitations of the intensity models because of the lack of sub-hourly records (R factor) and the imprecision of the traditional volume models (I_{FM} and I_{PC}) associated with the effects of heavy rainfall episodes. Therefore, the new R_A parameter is an appropriate mechanism for estimating the potential environmental impact of rainfall aggressiveness and for performing spatial and temporal comparative analysis.

To determine the equation φ (I_{FM}, I_{PC}) with sufficient accuracy, we needed minimum simultaneous daily and sub-hourly rainfall records in addition to local erosion data. An open research line for the future is to extend the application of this methodology to other study areas with different climatic conditions, particularly in the Mediterranean, semiarid environments and environments at risk of desertification, and to compare the results to the results obtained by other methods and at other time scales.

Although the proposed methodology has theoretical foundations, it would be convenient to establish a direct empirical verification of R_A to allow for the quantification of rainfall environmental impacts (runoff, siltation of wetlands, etc.). Another aspect to consider is that although R_A estimates the rainfall potential energy, the erosive process is much more complex, and it is not always that rainfall amount and/or distribution the main factor affecting the erosive process. García-Ruiz *et al.* (2015) conducted a worldwide meta-analysis of soil erosion rates, based on data from more than 4000 sites, whose results show that there is extraordinarily high variability in erosion rates, with almost any rate apparently possible irrespective of land slope, climate, scale, land use/land cover and other environmental characteristics. Despite this variability, some general trends were found, including an increase in erosion rates with increasing land slope and annual precipitation, the association of agricultural practices with the highest erosion rates, and a correlation between shrub coverage and the lowest erosion rates. Even so, the worldwide meta-analysis of García-Ruiz *et al.* (2005) suggests that only order of magnitude approximations of erosion rates are possible. This supposes a high degree of uncertainty and causes these authors to postulate the need to develop protocols that allow the comparison of the results of different sites.

Human activity can also significantly affect the development and evolution of denudation hot spots, especially through changes in land use (Vergari *et al.,* 2013). As these authors point out, this factor has a great importance associated with the croplands abandonment, and in general, in badlands of the Mediterranean area. The relationships among the various factors that influence the erosion intensity are very complex, and therefore new studies are needed to continue to deepen these aspects, with the support of real erosion measures taken directly from the field work.

6. Conclusions

A new synthesis parameter R_A was calculated by means of the combined use of the Fournier (I_{FM^*}) and Oliver concentration (I_{PC^*}) indices and reformulated with daily data. Weighting between both indices was obtained by multiple regression with the local erosivity. The historical extrapolation allowed the interannual series of the R_A to be obtained. A comparative analysis of the temporal evolution of I_{FM^*} and I_{PC^*} showed that they were independent of each other and that their contributions to the calculation of R_A were complementary. Obtaining the annual values of R_A in the same units and scale as the USLE R function allowed for the generalization of the results, thus increasing their applicability and establishing a link among historical rainfall records and current values of the potential rainfall aggressiveness.

In our opinion, the proposed methodology has the ability to provide consistent conclusions about historical erosive processes in each region linked to the potential rainfall aggressiveness. Therefore, it has a special relevance to the design of environmental measures and land management policies that prevent the direct and indirect impacts of rainfall.

7. Acknowledgements

We would like to thank the Navy's Royal Observatory of San Fernando (ROA) for providing the rainfall records and the Environmental Information Network of the Ministry of Environment of the Junta de Andalucía for providing the data set to calculate the erosivity. We thank María Ángeles Garrido and Alicia Cebolla for their help in data processing.

8. References

Aguilar M. 2007. Recent changes and tendencies in precipitation in Andalusia. In: Climate Change in Andalusia: trends and environmental consequences, Sousa A, García-Barrón L, Jurado V. (eds). Consejería de Medio Ambiente: Sevilla; 99-116. https://idus.us.es/xmlui/handle/11441/30483

Alexandersson H. 1986. A homogeneity test applied to precipitation data. *Journal of Climatology* **6**: 661- 675. DOI:10.1002/joc.3370060607.

Almarza C, López A, Flores C. 1996. Homogeneidad y variabilidad de los registros históricos de precipitación en España. Instituto Nacional de Meteorología, Madrid.

Angulo-Martínez M, López-Vicente M, Vicente-Serrano SM, Beguería S. 2009. Mapping rainfall erosivity at a regional scale, a comparison of interpolation methods in the Ebro Basin (NE Spain). *Hydrology and Earth System Sciences* **13:** 1907-1920. DOI:10.5194/hess-13-1907-2009.

Apaydin H, Erpul G, Bayramin I, Gabriels D. 2006. Evaluation of indices for characterizing the distribution and concentration of precipitation: a case for the region of Southeastern Anatolia Project, Turkey. *Journal of Hydrology* **328**: 726-732. DOI:10.1016/j.jhydrol.2006.01.019.

Arnoldus HMJ. 1980. An approximation of the rainfall factor in the universal soil loss equation. In: Assessment of Erosion, De Boodt M, Gabriels D (eds). John Wiley: Chichester; 127-132.

Da Silva AM. 2004. Rainfall erosivity map for Brazil. *Catena* **57**: 251-259. DOI:10.1016/j.catena.2003.11.006.

De Luis M, Gonzalez-Hidalgo JC, Longares LA. 2010. Is rainfall erosivity increasing in the Mediterranean Iberian Peninsula? *Land Degradation & Development* **21**: 139-144. DOI:10.1002/ldr.918.

Diodato N, Bellocchi G, Romano N, Chirico GB. 2011. How the aggressiveness of rainfalls in the Mediterranean lands is enhanced by climate change. *Climatic Change* **108**: 591-599. DOI:10.1007/s10584-011-0216-4.

Diodato N, Bellocchi G. 2007. Estimating monthly (R)USLE climate input in a Mediterranean region using limited data. *Journal of Hydrology* **345**: 224-236. DOI:10.1016/j.jhydrol.2007.08.008.

Diodato N, Ceccarelli M, Bellocchi G. 2008. Decadal and century-long changes in the reconstruction of erosive rainfall anomalies in a Mediterranean fluvial basin. *Earth Surface Processes and Landforms* **33**: 2078-2093. DOI: 10.1002/esp.1656.

Elagib NA. 2011. Changing rainfall, seasonality and erosivity in the hyper-arid zone of Sudan. *Land Degradation & Development* **22:** 505–512. DOI:10.1002/ldr.1023.

Elbasit AMA, Ojha CSP, Jinbai H, Yasuda H, Kimura R, Ahmed Z. 2013. Relationship between rainfall erosivity indicators under arid environments: Case of Liudaogou basin in Chinese Loess Plateau. *Journal of Food, Agriculture & Environment* **11**: 1073-1077. http://world-food.net/download/journals/2013-issue_2/2013-issue_2-environment/e55.pdf.

Fournier F. 1960. Climat et érosion. Presse Universitaire de France, Paris.

Gabriels D, Vermeulen A, Verbist K, Van Meirvenne M. 2003. Assessment of rain erosivity and precipitation concentration in Europe. In: Proceedings of the International Symposium, 25 Years of Assessment of Erosion, Gabriels D, Cornelis W (eds). Ghent; 87–92.

García-Barrón L, Aguilar M, Sousa A. 2011. Evolution of annual rainfall irregularity in the southwest of the Iberian Peninsula. *Theoretical and Applied Climatology* **103**: 13-26. DOI:10.1007/s00704-010-0280-0.

García-Barrón L, Camarillo JM, Morales J, Sousa A. 2015.Temporal analysis (1940–2010) of rainfall aggressiveness in the Iberian Peninsula basins. *Journal of Hydrology* **525**: 747-759. DOI:10.1016/j.jhydrol.2015.04.036.

García-Barrón L, Morales J, Sousa A. 2013. Characterisation of the intra-annual rainfall and its evolution (1837-2010) in the southwest of the Iberian Peninsula. *Theoretical and Applied Climatology* **114**: 445-457. DOI:10.1007/s00704-013-0855-7.

García-Ruiz JM, Beguería S, Nadal-Romero E, González-Hidalgo JC, Lana-Renault N, Sanjuán Y. 2015. A meta-analysis of soil erosion rates across the world. *Geomorphology* **239:** 160-173. DOI:10.1016/j.geomorph.2015.03.008.

García-Ruiz JM, Nadal-Romero E, Lana-Renault N, Beguería S. 2013. Erosion in Mediterranean landscapes: changes and future challenges. *Geomorphology* **198:** 20-36. DOI:10.1016/j.geomorph.2013.05.023.

Gregori E, Costanza M, Zorn G. 2006. Assessment and classification of climatic aggressiveness with regard to slope instability phenomena connected to hydrological and morphological processes. *Journal of Hydrology* **329**: 489–499. DOI:10.1016/j.jhydrol.2006.03.001.

Hernando D, Romana MG. 2016. Estimate of the (R)USLE rainfall erosivity factor from monthly precipitation data in mainland Spain. *Journal of Iberian Geology* **42**: 113-124. DOI:10.5209/rev_JIGE.2016.v42.n1.49120.

ICONA 1988. Agresividad de la lluvia en España. Valores del factor R de la ecuación universal de pérdidas de suelo. Servicio de Publicaciones del Ministerio de Agricultura, Pesca y Alimentación, Madrid.

Kinnell P. 2010. Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review. *Journal of Hydrology* **385:** 384–397. DOI:10.1016/j.jhydrol.2010.01.024.

Lee JH, Heo JH. 2011. Evaluation of estimation methods for rainfall erosivity based on annual precipitation in Korea. *Journal of Hydrology* **409**: 30-48. DOI:10.1016/j.jhydrol.2011.07.031.

Loureiro NS, Couthino MA. 2001. A new procedure to estimate the RUSLE EI30 index, based on monthly rainfall data applied to the Algarve region, Portugal. *Journal of Hydrology* **250**: 12-18. DOI:10.1016/S0022-1694(01)00387-0.

Martín-Vide J, López-Bustins JA. 2006. The western Mediterranean oscillation and rainfall in the Iberian Peninsula. *International Journal of Climatology* **26**: 1455-1475. DOI:10.1002/joc.1388.

Martín-Fernández L, Martínez-Núñez M. 2011. An empirical approach to estimate soil erosion risk in Spain. *Science of the Total Environment* **409:** 3114-3123. http://doi.org/10.1016/j.scitotenv.2011.05.010

Meshesha DT, Tsunekawa A, Tsubo M, Haregeweyn N, Adgo E. 2015. Evaluating spatial and temporal variations of rainfall erosivity, case of Central Rift Valley of Ethiopia. *Theoretical and Applied Climatology* **119**: 515-522. DOI:10.1007/s00704-014-1130-2.

Michiels P, Gabriels D, Hartmann R. 1992. Using the seasonal and temporal precipitation concentration index for characterizing monthly rainfall distribution in Spain. *Catena* **19**: 43-58. DOI:10.1016/0341-8162(92)90016-5.

Nearing MA. 2001. Potential changes in rainfall erosivity in the US with climate change during the 21st century. *Journal of Soil and Water Conservation* **56**: 229-232.

Nunes AN, Lourenço L, Vieira A, Bento-Gonçalves A. 2016. Precipitation and erosivity in southern Portugal: seasonal variability and trends (1950–2008). *Land Degradation & Development* **27**: 211-222. DOI:10.1002/ldr.2265.

Oliver JE. 1980. Monthly precipitation distribution, a comparative index. *The Professional Geographer* **32**: 300–309. DOI:10.1111/j.0033-0124.1980.00300.x.

Panagos P, Ballabio C, Borrelli P, Meusburger K, Klik A, Rousseva S, Tadic MP, Michaelides S, Hrabalíková M, Olsen P, Aalto J, Lakatos M, Rymszewicz A, Dumitrescu A, Beguería S, Alewell C. 2015. Rainfall erosivity in Europe. *Science of the Total Environment* **511**: 801-814. DOI:10.1016/j.scitotenv.2015.01.008.

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC. 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook 703, USDA.

Renard KG, Freid JR. 1994. Using monthly precipitation data to estimate the *R* factor in the revised USLE. *Journal of Hydrology* **157**: 287-306. DOI:10.1016/0022-1694(94)90110-4.

Rodrigo FS. 2002. Changes in climate variability and seasonal rainfall extremes: a case study from San Fernando (Spain), 1821–2000. *Theoretical and Applied Climatology* **72**: 193-207. DOI:10.1007/s007040200020.

Rodríguez Surián M, Sánchez Pérez JD. 1995. Distribución espacio-temporal de las pérdidas de suelo en Andalucía utilizando tecnología S.I.G. e imágenes de satélite. http://www.juntadeandalucia.es/medioambiente/web/Red_informacion_ambiental/productos/Publicaciones/articulos/articulos_pdf/Distespa.pdf.

Sánchez-Canales M, López-Benito A, Acuña V, Ziv G, Hamel P, Chaplin-Kramer R, Elorza FJ. 2015. Sensitivity analysis of a sediment dynamics model applied in a Mediterranean river basin: Global change and management implications. *Science of the Total Environment* **502**: 602-610. http://doi.org/10.1016/j.scitotenv.2014.09.074.

Sanchez-Moreno JF, Mannaerts CM, Jettena V. 2014. Rainfall erosivity mapping for Santiago Island, Cape Verde. *Geoderma* **217**: 74-82. DOI:10.1016/j.geoderma.2013.10.026.

Sauerborn P, Klein A, Botschek J, Skowronek A. 1999. Future rainfall erosivity derived from large-scale climate models—methods and scenarios for a humid region. *Geoderma* **93**: 269-276. DOI:10.1016/S0016-7061(99)00068-3.

Solé A. 2006. Spain. In: Soil Erosion in Europe, Boardman J, Poesen J (eds). John Wiley & Sons; 311–346.

Sousa A, García-Barrón L, García-Murillo P, Vetter, Morales J. 2015. The use of changes in small coastal Atlantic brooks in southwestern Europe as indicators of anthropogenic and climatic impacts over the last 400 years. *Journal of Paleolimnology* **53**: 73-88. DOI:10.1007/s10933-014-9809-z

Sousa A, García-Barrón L, Morales J, García-Murillo P. 2006. Post-Little Ice Age warming and desiccation of the continental wetlands of the Aeolian sheet in the Huelva region (SW Spain). *Limnetica* **25**: 57-70.

Sousa A, García-Murillo P, Morales J, García-Barrón L. 2009. Anthropogenic and natural effects on the coastal lagoons in the southwest of Spain (Doñana National Park). *ICES Journal of Marine Science* **66**: 1508-1514. DOI:10.1093/icesjms/fsp106.

Sousa A, Morales J, García-Barrón L, García-Murillo P. 2013.Changes in the *Erica ciliaris* Loefl.ex L. peat bogs of southwestern Europe from the 17^{th} to the 20^{th} centuries AD. *Holocene* **23**: 255-269. DOI:10.1177/0959683612455545.

Stepanek P. 2007. AnClim—software for time series analysis (for Windows).Department of Geography, Faculty of Natural Sciences, Masaryk University, Brno.

Taguas EV, Carpintero E, Ayuso JL. 2013. Assessing land degradation risk through the long-term analysis of erosivity: a case study in southern Spain. *Land Degradation & Development* **24**: 179-187. DOI:10.1002/ldr.1119.

Terranova O, Antronico L, Coscarelli R, Iaquinta P. 2009. Soil erosion risk scenarios in the Mediterranean environment using RUSLE and GIS: an application model for Calabria (southern Italy). *Geomorphology* **112**: 228-245. DOI:10.1016/j.geomorph.2009.06.009.

Vergari F, Della Seta M, Del Monte M, Fredi P, Palmieri EL. 2013. Long-and short-term evolution of several Mediterranean denudation hot spots: The role of rainfall variations and human impact. *Geomorphology* **183**: 14-27. DOI: 10.1016/j.geomorph.2012.08.002.

Wischmeier WH, Smith DD. 1978. Predicting rainfall erosion loss: a guide to conservation planning. Agriculture Handbook 537, Washington.

Yue BJ, Shi ZH, Fang NF. 2014. Evaluation of rainfall erosivity and its temporal variation in the Yanhe River catchment of the Chinese Loess Plateau. *Natural Hazards* **74**: 585-602. DOI:10.1007/s11069-014-1199-z.

Table 1. Proportionality coefficient and annual and interannual correlation between the San Fernando Observatory (ROA) and the selected regional stations

Observatories	**Country**	**Institution**	**Latitude and Longitude**	**Annual average rate**	**R-Pearson Interannual**	**R-Pearson Intra-annual**
San Fernando (ROA)	Spain	ROA	36° 27′ 56″ N 6° 12′ 20″ W	-	-	-
Cadiz	Spain	AEMET	36° 32′ 01″ N 6° 17′ 58″ W	1.04	0.96	1.00
Huelva	Spain	AEMET	37° 16′ 30″ N 6° 54′ 35″ W	1.03	0.94	0.98
Faro	Portugal	IPMA	37° 01′ 00″ N 7° 55′ 59″ W	1.04	0.76	0.97
Seville	Spain	AEMET	37° 25′ 05″ N 5° 42′ 30″ W	1.02	0.85	0.98
Cordova	Spain	AEMET	37° 50′ 40″ N 4° 51′ 02″ W	0.96	0.86	0.98
Badajoz	Spain	AEMET	38° 43′ 02″ N 6° 49′ 45″ W	1.02	0.72	0.94
Beja	Portugal	IPMA	38° 00′ 56″ N 7° 51′ 55″ W	0.92	0.70	0.94

Table 2. Characterization of the R_A and its comparison to the respective statistical components I_{FM*} and I_{PC*}: average, trend (linear regression), explained variance, variability and *Specific Disparity Index*

	Average	**Trend**	r^2	V_N	I_D
I_{FM*}	21.0	- 0.012	< 0.01	0.28	0.40
I_{PC*}	3.8	< 0.001	< 0.001	0.27	0.35
R_A	1742	- 4.63	< 0.1	0.47	0.64

FIGURE LEGEND

Figure 1. Map showing the locations of the meteorological stations used in the study area.

Figure 2.a) Temporal evolution of the I_{FM*} and b) the I_{PC*} showing the average value and mobile average for periods of eleven years.

Figure 3. Pairwise scatterplot of the time series I_{FM*} and I_{PC*} for the period 1870-2010.

Figure 4. Pairwise scatterplot of the USLE R factor and the R_A time series for the period 1991-2010.

Figure 5. Temporal evolution of R_A in the SW Iberian Peninsula.

Figure 6. Evolution of the accumulated deviations with respect to the average R_A.

Figure 7. Mobile variation of the R_A coefficient for periods of eleven years with the trend line of the entire period analysed and that of the maximum relative values.