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Estimating Rainfall Erosivity in Semiarid Regions. Comparison of Expressions and Parameters Using Data from the Guadalentín Basin (SE Spain)

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Abstract

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One of the many factors that leads to soil erosion is rainfall erosivity, which is a basic physical factor enabling us to understand the geomorphological processes that take place in a basin. Results worldwide have shown that the erosivity R factor of the Universal Soil Loss Equation (USLE) has a high correlation with soil loss. In the past there have been few pluviometers capable of recording rainfall with continuous measurements. As a result of this lack of accuracy in the available series of rainfall intensity data, the calculation of the R factor has been restricted for a long time and various simplified models were developed on an international scale that relied on information obtained from existing stations. However, the modernisation of stations over the last few decades has provided to be a valuable tool for validating models, as well as for designing others that are more hardwearing and correlate better with the available information. In this paper, we have calculated the rainfall erosivity R factor for a semiarid basin in SE Spain using the formula developed in the USLE model for a series of 20 years of rainfall with 5-minute intervals, obtaining the mean R factor value of 620 MJ/ha·mm/h per year and maximum values of up to 6000 MJ/ha·mm/h per year. In addition, a comparative analysis of various simplified expressions was carried out to obtain the R factor. To obtain this value, we came up with a simplified equation based on annual maximum daily rainfall and average monthly rainfall, which resulted in a correlation coefficient of $r = 0.936$ and a P-value of 0.033 for the basin under study. Thus, from this structure of the equation we have compiled a series of parametric maps which enable us to calculate the R factor from any position within the basin under study.

Keywords: rainfall erosivity factor; soil erosion; Universal Soil Loss Equation; water erosion

Soil erosion is a process whereby the component materials are disintegrated, transported, and deposited by the action of water (water erosion) or wind (wind erosion). If the regional climate is also arid or semiarid, as is the case in the basin under study, where the soil is poor and has little forest cover, assessing the erosivity is of utmost importance when studying the stages of territorial desertification. This desertification has a direct effect on cropland (Wijitkosum 2012), which then requires fertilizers and manures and thus increases farm production costs.

One of the many factors that leads to soil erosion is rainfall erosivity, which is a basic physical factor that enables us to understand the geomorphological processes that take place in a basin. Results worldwide have shown that the erosivity R factor of the Universal Soil Loss Equation (USLE) has a high correlation with soil loss (Wischmeier 1959; Elwell & Stocking 1973; Wischmeier & Smith 1978).

The main difficulty for obtaining this factor is the availability of sub-hourly pluviographic data on precipitation. In the past, few weather stations in Europe and in most other regions in the world were equipped with pluviometers that registered continuous measurements (De Santos Loureiro & de Azevedo Coutinho 2001; Domínguez-Romero *et* *al.* 2007; Angulo-Martínez & Beguería 2009). As a result, many authors have proposed various equations that provide an estimate of the R factor using available information at existing stations which basically include precipitation over a period of 24 h. Due to its simple calculation and the little data required, one of the most widely used parameters was the Fournier Index (Fournier 1960), based exclusively on precipitation during the rainiest month and the average annual precipitation. This was subsequently modified by Arnoldus (1977), and referred to as the Modified Fournier Index (MFI). Similarly, Renard and Freimund (1994) established other exponential ($R = 0.07397MFI^{1.847}$) and quadratic ($R = 95.77 - 6.081MFI + 0.477MFI^2$) expressions using the Modified Fournier Index. More recent research has also used this index and exponential structure, albeit with very different coefficients (Apaydin *et al.* 2006). Additional complex structures, which include sinusoidal functions and variables that depend on the longitude and latitude of the site can be found in expressions such as the one proposed by Davison *et al.* (2005), which takes into account possible monthly (Posch & Rekolainen 1993) or seasonal (Richardson *et al.* 1983) variations.

Some authors have found good relationships using linear, power or polynomial functions, such as:

$$R = aP + b,\ R = aP^b,\ \text{or}\ R = aP^2 + bP + c$$

where:

P – monthly or annual precipitation

a, b, c – constants

Cases include the studies by Grimm *et al.* (2003) in Tuscany and the correlation obtained by Torri *et al.* (2006) in the Mediterranean. Furthermore, Diodato and Bellocchi (2010) propose the Mediterranean Rainfall Erositivity Model (MedREM) using the annual maximum daily precipitation averaged over a multi-year period, site longitude and annual precipitation.

In Spain, the former Institute for the Conservation of Nature (ICONA 1988) put forward the proposal to divide the Iberian Peninsula into three zones, with three different equations to calculate the R factor. In the zone under study, the proposed expression was as follows:

$$R = e^{-1.235}(PMEX)^{1.297}(MR)^{-0.511}(MV)^{0.366}(F24)^{0.414} \quad (1)$$

where:

MV – average rainfall for the period June–September (mm)

MR – average rainfall for the period October–May (mm)

$PMEX$ – average rainfall for the monthly maximum during the series (mm)

$F24$ – concentration factor of the maximum daily rainfall defined as:

$$F24 = \frac{(\text{annual daily maximum rainfall})^2}{(\Sigma\text{maximum monthly rainfall in 24 h})} \quad (2)$$

MATERIAL AND METHODS

The investigated zone (Guadalentín River Watershed) is located in SE Spain (Figure 1). It covers an area of 3340 km^2 and is situated in the SW of the Region of Murcia at an average height of 1000 m a.s.l. Over recent years this area, the basin of the River Guadalentín, has been of interest to many researchers. Various national (LUCDEME, HISPASED, etc.) and international research projects and programmes financed by the European Commission (MEDALUS, MEDACTION, DESERTLINKS, etc.) have included this basin as a pilot area for studying erosion and desertification in the Mediterranean region (López Bermúdez *et al.* 1988), which urgently needs to improve its water resources (transfers, desalination plants, the reuse of purified water, etc.) to achieve a higher level of socio-economic development in an increasingly globalized and competitive world. The basin houses 12 weather stations, distributed as shown in Figure 1. The data provided by the Basin Authority consists of a 20-year database with precipitation data in 5-minute intervals from hydrological years 1992–1993 to 2012–2013. To calculate the R factor of a storm, the Wischmeier and Smith (1978) formula developed in the USLE method was used. The R factor of an erosive storm is calculated using

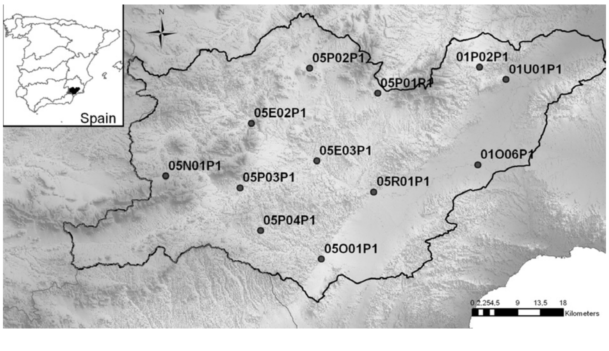

Figure 1. Location of the study zone and pluviometer stations

Table 1. Statistics of the erosive events at Guadalentín Basin during the period 1992–2012

Station	Sample size	Statistic	Rainfall depth (mm)	Duration (h)	Intensity	I_{30}
					(mm/h)	
01O06P1	71	maximum	88.9	13.4	117.7	71.9
		minimum	12.8	2.0	0.3	3.6
		mean	23.7	5.9	4.2	18.8
		CV (%)	62.5	18.9	209.5	85.9
01P02P1	94	maximum	76.8	10.8	119.2	78.0
		minimum	12.7	1.3	0.7	4.0
		mean	22.4	5.9	3.8	15.0
		CV (%)	50.4	18.5	186.5	86.7
01U01P1	80	maximum	80.4	6.5	158.4	105.2
		minimum	12.7	2.9	0.2	3.6
		mean	25.9	5.9	4.6	21.1
		CV (%)	64.4	8.6	227.9	94.3
05E02P1	96	maximum	108.6	6.3	276.5	102.3
		minimum	12.0	1.1	0.0	3.2
		mean	23.0	5.7	4.2	17.2
		CV (%)	62.7	16.0	256.9	90.5
05E03P1	87	maximum	95.1	6.5	214.1	94.6
		minimum	12.7	0.2	0.1	3.5
		mean	23.3	5.7	4.1	17.9
		CV (%)	52.8	20.2	221.3	90.3
05N01P1	94	maximum	93.3	11.9	137.9	78.6
		minimum	12.7	0.9	0.4	2.4
		mean	22.4	5.9	4.0	15.6
		CV (%)	60.4	19.0	207.1	84.4
05O01P1	75	maximum	153.0	6.5	204.1	133.1
		minimum	12.7	1.0	0.0	4.7
		mean	23.3	5.6	4.0	17.5
		CV (%)	76.1	17.6	232.4	106.1
05P01P1	87	maximum	67.1	6.3	110.8	76.1
		minimum	12.8	0.3	0.4	3.6
		mean	22.2	5.7	3.9	16.8
		CV (%)	46.6	18.2	212.6	76.3
05P02P1	101	maximum	69.7	6.0	178.5	63.3
		minimum	12.9	0.3	0.1	4.0
		mean	21.6	5.6	3.7	18.0
		CV (%)	43.5	16.3	236.3	66.6
05P03P1	91	maximum	129.5	6.0	166.9	73.1
		minimum	12.7	0.3	0.3	3.3
		mean	22.9	5.6	3.9	18.7
		CV (%)	68.8	22.0	231.8	79.0
05P04P1	80	maximum	162.5	11.8	213.7	85.7
		minimum	12.7	0.3	1.9	3.6
		mean	24.5	5.7	4.4	18.0
		CV (%)	82.6	24.4	238.9	97.9
05R01P1	65	maximum	55.6	6.5	220.8	58.5
		minimum	12.8	0.5	0.3	3.5
		mean	23.0	5.7	3.9	16.0
		CV (%)	45.4	15.6	221.5	80.6

CV – coefficient of variation; I_{30} – maximum intensity of rainfall in 30 min

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$$R = [\Sigma(e_j) \times (I_j \times T_j)] \times I_{30} \text{ (MJ/ha·mm/h)} \quad (3)$$

where:
T_j – length of time estimated for each I_j intensity
I_j – intensity in j time
I_{30} – maximum intensity of rainfall in 30 min
e_j – kinetic energy of the storm

$$e_j = 0.119 + 0.0873 \log_{10} I_j \quad (4)$$

if $I_j \leq 76$ mm/h or $e_j = 0.283$ if $I_j \geq 76$ mm/h (Foster *et al.* 1980). Many researchers have evaluated the performance of several equations to predict the kinetic energy of a storm (van Dijk *et al.* 2002), and have found that the Wischmeier and Smith formula provides highly realistic results in climates similar to that of the case study (Sempere-Torres *et al.* 1992; Domínguez-Romero *et al.* 2007; Petan *et al.* 2010). For each station, Table 1 lists the summary statistics of the storm rainfall depth, duration, intensity, and I_{30}.

First of all, a storm was defined as any period of precipitation separated from preceding and succeeding precipitation by 6 h (Huff 1967). Storms of less than 12.5 mm in 30 min were omitted from the erosion index, unless at least 6.25 mm of rain fell in 15 min (Foster *et al.* 1981).

Erosivity for longer periods (daily, monthly, annually) is obtained directly from the sum of the erosivity figures of the storms that have occurred in the studied period. In fact, the R factor of the station can be calculated as the average annual erosivity for the available series.

In order to find an expression that would achieve the best correlation between the obtained values and those that result from applying a simplified expression of their calculation, a series of expressions depending on the parameters shown in Table 2 have been determined. First, a hierarchical cluster analysis was performed to determine the parameters to be used. Only those variables that produced a significant result according to an analysis of variance (ANOVA) were considered. The models of adjustment studied were polynomial, linear, exponential, potential, and logarithmic.

Once the most viable structure of the equation for the RUSLE in the basin was obtained, the adjusting coefficients for each equation corresponding to each station were individually established with the aim to compile, by means of interpolating these parameters, a series of maps to establish the erosivity of the rainfall for any area within the basin.

RESULTS AND DISCUSSION

After evaluating the R parameter, the results obtained for each station are as shown in Table 3. As can be seen, the erosivity values vary between 385 and 830 MJ/ha·mm/h per year with extreme annual values that are very different from the average value of the studied series. On the one hand, this is one of the consequences of the uneven distribution of the precipitations and, on the other, of the high values in certain years, associated with the high-

Table 2. Parameters used in the expressions to obtain the erosivity R factor

Concept
Annual precipitation (PA, mm)
Annual daily maximum precipitation (PMD, mm)
Monthly precipitation (PM, mm)
Average monthly precipitation (PMM, mm)
Maximum monthly precipitation (PMmax, mm)
Modified Fournier Index (MFI, mm)
Average rainfall June-September (MV, mm)
Average rainfall October-May (MR, mm)
Average rainfall of the monthly maximum for the years in the series (PMEX, mm)
Concentration factor of daily maximum rainfall (F24, mm)
Erosivity according to the ICONA expression (ICONA, MJ/ha·mm/h per year)

Table 3. Values of the erosivity factor R (MJ/ha·mm/h per year) at the stations in the Guadalentín Basin 1992–2013

Station	R_{medium}	$R_{maximum}$	$R_{minimum}$
01O06P1	524.602	1674.642	9.546
01P02P1	530.719	1502.927	53.659
01U01P1	830.349	2765.552	85.717
05E02P1	722.533	3317.699	21.523
05E03P1	657.629	2272.988	33.272
05N01P1	593.599	1812.679	58.120
05O01P1	716.847	5698.645	58.768
05P01P1	522.241	1319.669	58.887
05P02P1	617.235	1152.034	14.260
05P03P1	663.322	1748.167	20.747
05P04P1	717.074	2733.979	14.669
05R01P1	385.317	879.854	52.478

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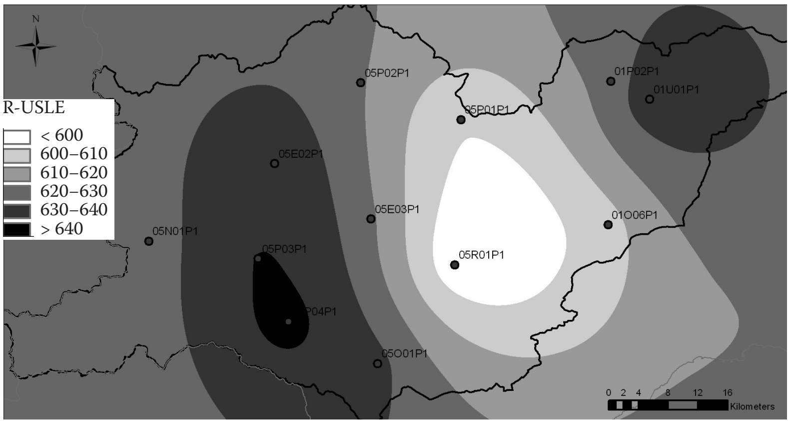


Figure 2. Distribution of R-USLE values in the Guadalentín Basin

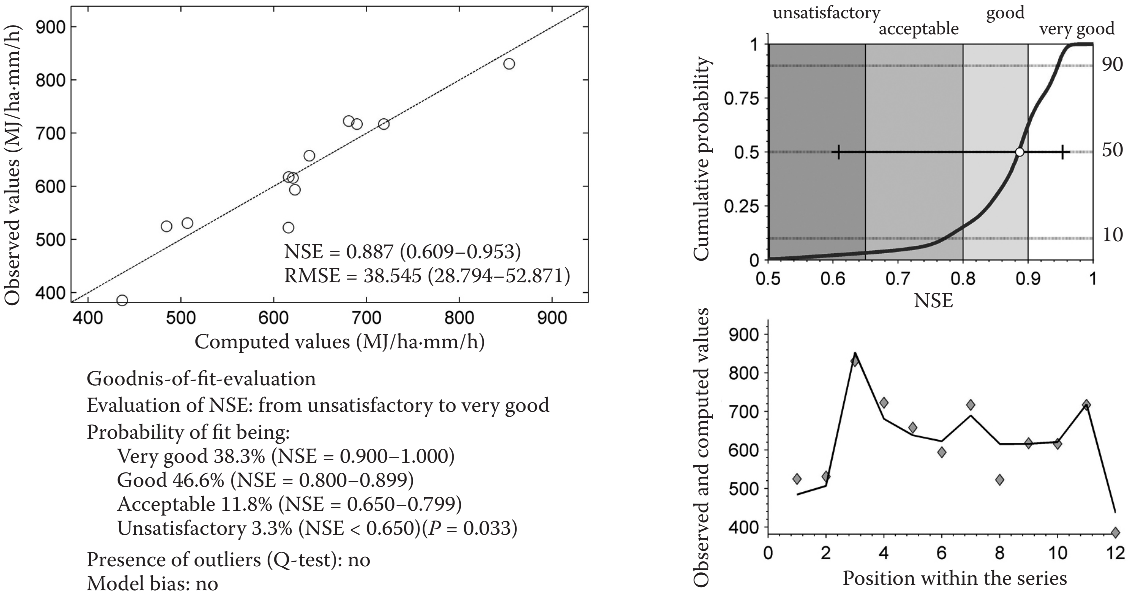
intensity rain that is occasionally characteristic of a semiarid climate such as that of the Guadalentín Basin. Similarly, to summarize the results obtained, a map has been made of the geographical distribution of the R value in the basin (Figure 2) using GIS tools and the Kriging interpolation method. It shows that, despite the extreme values, an average R factor for erosivity of around 620 MJ/ha·mm/h per year is obtained and the extreme values are located in areas that are over 1000 m a.s.l.

As precipitation data for less than 30-minute intervals have not been available in most stations, rainfall erosivity has been calculated using simplified expressions with achievable parameters, such as annual daily maximum rainfall. In Spain, rainfall erosivity is determined in most of the country by using the ICONA Eq. (1), which has been used at each of the stations in the study. The values were obtained using the formula recommended by ICONA. These values for the SE Spain are much higher (300%) than those using the Wischmeier and Smith formula. The ICONA formula overestimates erosivity twice and even thrice in comparison with the value obtained by the USLE method and it is generally closer to extreme values than to the average values that have been calculated.

Based on the parameters of the ICONA expression, the following equation was obtained:

$$R = e^{-1.235}\,(-11.92)\,(PMEX)^{1.297} + (10\,538.88)\,(MR)^{-0.511} + (549.33)\,(MV)^{0.336} + (624.42)\,(F24)^{0.414} \qquad (5)$$

This equation gives a correlation coefficient of $r = 0.936$, showing that the structure of the ICONA



Goodnis-of-fit-evaluation
Evaluation of NSE: from unsatisfactory to very good
Probability of fit being:
- Very good 38.3% (NSE = 0.900–1.000)
- Good 46.6% (NSE = 0.800–0.899)
- Acceptable 11.8% (NSE = 0.650–0.799)
- Unsatisfactory 3.3% (NSE < 0.650)($P = 0.033$)

Presence of outliers (Q-test): no
Model bias: no

Figure 3. Goodness-of-fit of the model proposed for the Guadalentín Basin; NSE – Nash-Sutcliffe Efficiency; RMSE – Root-Mean-Square-Error

equation works well with that of the RUSLE. Similarly, using the Fiteval programme proposed by Ritter and Muñoz-Carpena (2013) to determine the objective assessment of the goodness-of-fit of the model with statistical significance, a *P*-value of 0.03 is obtained, giving a NSE (Nash-Sutcliffe Efficiency) of 0.887 and a RMSE (Root-Mean-Square-Error) of 38.545, as shown in Figure 3.

In view of the good results obtained using expressions similar to those of ICONA, the erositivity obtained using the USLE method has been correlated linearly and polynomially with the ICONA value, achieving correlation coefficients of 0.7058 and 0.7188 respectively, lower than those obtained with the modifications made to the ICONA expression in Eq. (5) (Table 4). Other linear, exponential,

Table 4. Results of linear, polynomial, and exponential erosivity factor R adjustments in the Guadalentín Basin using one single parameter

Parameter	Regression curve	Correlation coefficients		Empirical coefficients		Adjustment curves
		r	a	b	c	
ICONA	linear	0.607	0.21	273.10	–	$R = a\,\mathrm{ICONA} + b$
	exponential	0.589	339.40	0.00	–	$R = a\,e^{b\,\mathrm{ICONA}}$
	polynomial	0.638	0.00	1.27	−664.3	$R = a\,\mathrm{ICONA}^2 + b\,\mathrm{ICONA} + \mathrm{c}$
	potential	0.596	5.19	0.64	–	$R = a\,(\mathrm{ICONA})^b$
MFI	linear	0.273	5.84	185.10	–	$R = a\,\mathrm{MFI} + b$
	exponential	0.305	265.10	0.01	–	$R = a\,e^{b\,\mathrm{MFI}}$
	polynomial	0.286	−0.31	52.16	−1 543.0	$R = a\,\mathrm{MFI}^2 + b\,\mathrm{MFI} + c$
	logarithmic	0.275	441.10	12.80	–	$R = a\ln(\mathrm{MFI}) + b$
	potential	0.309	16.01	0.84	–	$R = a\,(\mathrm{MFI})^b$
PA	linear	0.355	1.54	166.20	–	$R = a\,\mathrm{PA} + b$
	exponential	0.403	251.40	0.00	–	$R = a\,e^{b\,\mathrm{PA}}$
	polynomial	0.437	−0.04	25.57	−3 320.0	$R = a\,\mathrm{PA}^2 + b\,\mathrm{PA} + c$
	potential	0.415	3.70	0.90	–	$R = a\,(\mathrm{PA})\text{\textasciicircum}b$
PMEX	linear	0.187	2.83	383.40	–	$R = a\,PMEX + b$
	exponential	0.207	388.90	0.01	–	$R = a\,e^{b\,PMEX}$
	polynomial	0.207	0.17	−26.00	−1 597.0	$R = a\,PMEX^2 + b\,\mathrm{PMEX} + \mathrm{c}$
	potential	0.202	87.41	0.44	–	$R = a\,(PMEX)^b$
MR	linear	0.089	4.26	500.00	–	$R = a\,MR + b$
	exponential	0.151	430.90	0.01	–	$R = a\,e^{b\,MR}$
	polynomial	0.644	−13.26	770.70	−10 491.0	$R = a\,MR^2 + b\,MR + c$
	potential	0.178	157.00	0.40	–	$R = a\,(MR)^b$
MV	linear	0.430	14.94	364.80	–	$R = a\,MV + b$
	exponential	0.465	378.60	0.03	–	$R = a\,e^{b\,MV}$
	polynomial	0.474	−2.65	104.90	−369.20	$R = a\,MV^2 + b\,MV + c$
	potential	0.478	161.10	0.47	–	$R = a\,(MV)^b$
*F*24	linear	0.499	21.76	272.40	–	$R = a\,F24 + b$
	exponential	0.430	364.50	0.03	–	$R = a\,e^{b\,\mathrm{F24}}$
	polynomial	0.558	2.82	−80.09	1 162.00	$R = a\,F24^2 + b\,F24 + c$
	potential	0.401	143.60	0.52	–	$R = a\,(F24)^b$

ICONA – Institute for the Conservation of Nature; MFI – Modified Fournier Index; PA – annual precipitation; *PMEX* – average rainfall for the monthly maximum during the series; *MR* – average rainfall for the period October–May; *MV* – average rainfall for the period June–September; *F*24 – concentration factor of the maximum daily rainfall; *a*, *b*, *c* – constants

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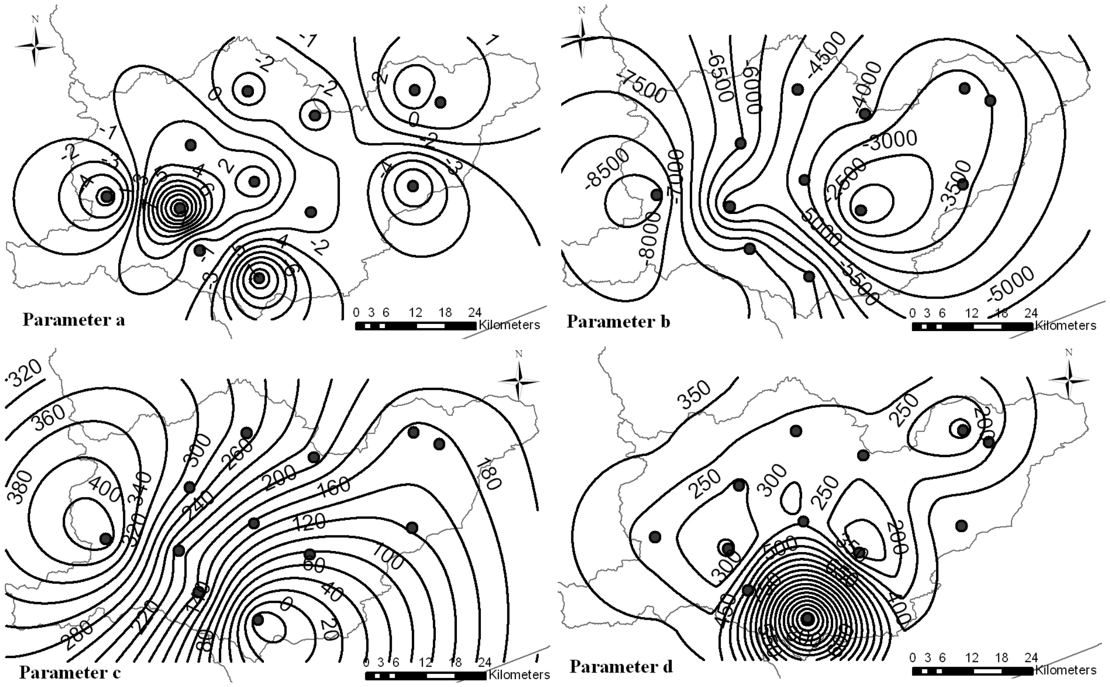

Figure 4. Parameters for calculating the erositivity factor R in the expression $R = e^{a(1.235)}(PMEX)^{1.297} + b(MR)^{-0.511} + c(MV)^{0.366} + d(F24)^{0.414}$

polynomial, logarithmic, and potential expressions have been tested with the other parameters referred to earlier (Table 4) and the correlation coefficients have not been higher than 0.30 in the entire series under analysis, together with a figure of 0.6 for annual periods. Slightly higher coefficients (0.6384) are obtained using the expression by Morais *et al.* (1991), which is a transformation of the MFI.

In view of the improved results obtained using the expression

$$R = e^{a(1.235)}(PMEX)^{1.297} + b(MR)^{-0.511} + c(MV)^{0.366} + d(F24)^{0.414} \qquad (6)$$

The coefficients *a*–*d* from the previous equations relating to each station have been individually evaluated. A series of maps has been produced (Figure 4) using the Kriging interpolation for each parameter in the expression to obtain the spatial R factor distribution in the Guadalentín Basin.

CONCLUSIONS

The R values for each of the 12 rain gauge weather stations within the Guadalentín Basin were calculated using the USLE method and data for 20 years of rainfall in time periods of 5 min. The average values were R = 600 MJ/ha·mm/h per year, with maximum values of up to 5700 MJ/ha·mm/h per year; normal results for the semiarid climate of the area. These high values show the need to quantify and determine the possible soil loss and, consequently, the R value, given the importance of the soil for productivity and biodiversity in the Mediterranean area.

The lack of sub-hourly data at many weather stations has led to the application of a series of expressions to obtain the rainfall erosivity value using more readily available parameters, such as annual daily maximum rainfall. This study evaluated the various expressions that are widely used across various European regions in a semiarid Mediterranean basin. The study confirms that the expressions based on one single parameter, such as the MFI, or annual and/or monthly average precipitations, show very low correlations in comparison with the values obtained using the USLE method. However, the highest figures ($r = 0.936$, NSE = 0.887, RMSE = 38.545) for the stations in the investigated basin were obtained by the ICONA expression modifying the coefficients that correspond to the selected parameters. The use of the proposed formula gives the R value for those stations that only have daily data. Furthermore, a series of parametric maps of the region have been made up to calculate the erositiviy of rainfall in any part of the basin using the ICONA structure.

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