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RAINFALL EROSIVITY IN THE UPPER LLOBREGAT BASIN, SE PYRENEES

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ABSTRACT.– The aim of this study was to determine the spatial distribution of rainfall erosivity in a 504 km² river basin in Eastern Pyrenees and assess its uncertainties. The study area is topographically complex and is dominated by Mediterranean climate with intense rains during summer. Available rainfall dataset includes 14 years spanning from 1991 to 2004 at daily resolution from seven weather stations and sub-hourly from one station. Daily R values were calculated from sub-hourly data, and then by using the relationship between daily R values and precipitation, the R values for weather stations having only daily rainfall resolution were calculated. The error propagation by using such upscaling approach was analyzed. The studied sources of uncertainty of R factor at annual scale were: the use of the relationship between daily R values and precipitation, the temporal averaging of R values and spatial variation. Results have shown that at annual scale the temporal averaging was the largest contributor of uncertainty (70%); however this contribution decreased significantly (14%) when R was estimated for the long term.

Keywords: R factor; error propagation; RUSLE; Pyrenees; Upper Llobregat Basin.

RESUMEN.– El objetivo de este estudio fue determinar la distribución espacial de la erosividad de precipitación en una cuenca de 504 km² en el Este de los Pirineos y evaluar sus incertidumbres. El área de estudio presenta una topografía compleja y está dominada por un clima Mediterráneo con lluvias intensas durante el verano. Los datos de precipitación utilizados abarcan 14 años, desde 1991 hasta 2004, a una resolución diaria en siete estaciones meteorológicas y minutal en una estación. Los valores diarios de R se calcularon a partir de datos con resolución minutal, y luego se estableció una relación entre valores diarios de R y precipitación, con el fin de calcular los valores de R para las estaciones meteorológicas que sólo presentan resolu-

ción diaria. Las fuentes de incertidumbre considerados para el factor R a escala anual fueron: el uso de la relación entre los valores de R diaria y precipitación, el promedio temporal de los valores de R y la variación espacial. Los resultados han mostrado que a escala anual la variación temporal fue el mayor contribuyente (70%) a la incertidumbre total, sin embargo éste disminuyó significativamente (14%) cuando R fue estimada a largo plazo.

Palabras clave: Factor R; propagación de error; RUSLE; Pirineos; Cuenca Alta del Llobregat.

1. Introduction

Uncertainty is unavoidable to some degree especially when it comes to environmental issues such as soil erosion, mainly because of system complexity, spatial heterogeneity and scarcity of data. Soil erosion is a recognized environmental problem, and its primarily driving force is rainfall because of the erosive forces of raindrop impact on soil surface (ELLISON, 1952) and generation of surface runoff (MOORE, 1979). Estimation of rainfall erosivity in large areas is often based on simplification of processes and scaling techniques, in these processes error in data and methods may be propagated into results which need to be quantified in order to give value to estimations in decision-making.

HUDSON (1995) identified three attributes of rain related to erosion (a) rainfall intensity, which is highly variable in time and space, (b) rainfall duration, and (c) rainfall kinetic energy. Rainfall kinetic energy and intensity are the most commonly used to predict soil detachment, the relationship between the two is complex since depends on the raindrop size.

Rainfall-runoff erosivity index is a basic component of empirical soil erosion models such as when modeling rill and interrill erosion with RUSLE (WISCHMEIER & SMITH, 1959; RENARD *et al.*, 1997). Within RUSLE it is known as the rainfall-runoff erosivity factor (R factor), which is defined as the product of total kinetic energy of a rainfall event and its maximum 30-minute rainfall intensity (RENARD *et al.*, 1997). To compute the R factor it is recommended at least 20 years of rainfall intensity data at sub-hourly resolution (WISCHMEIER & SMITH, 1978).

Usually sub-hourly rainfall data is not always readily available; instead, downscaling approaches are used such as from daily, monthly or annual resolution. For instance DE SANTOS LOUREIRO & AZEVEDO COUTINHO (2001) estimated the rainfall-runoff erosivity index using monthly data in Portugal; in Italy DIODATO (2004) developed a method for using annual data, obtaining satisfactory results. However, upscaling approaches may also be used when there are available sub-hourly data in one or a few weather stations and erosivity values are needed for larger areas. In the latter case, relationships at a given point are extrapolated to other locations having coarse data resolution. In both extrapolation and upscaling approaches, large errors may be expected, which need to be assessed.

The temporal scale at which the rainfall erosivity becomes interesting depends on the end-user, for instance farmers might be interested in knowing the annual R for a given year and often at small scale, and on the contrary land use planners might find more useful long term R values and at larger scale.

Although patterns of rainfall erosivity pattern have been studied in the NE Spain especially in the Ebro Basin (LÓPEZ-VICENTE *et al.,* 2008; ANGULO-MARTINEZ *et al.,* 2009), there is scarce information for the Eastern Pyrenees and error propagation analysis for rainfall erosivity is scarcely performed. The Eastern Pyrenees present high relief, this complex topographical organization can encourage the generation of isolated extreme rainfall events (GARCIA-RUIZ *et al.,* 2000) which can strongly affect values and may be important contributors to uncertainty.

This article deals with the assessment of uncertainty of rainfall erosivity due to diverse sources in an area of the Eastern Pyrenees, using simple statistical analyses. The specific objectives are (a) to obtain the average annual R factor for each weather station and for the whole Upper Llobregat Basin, and (b) to define the magnitude of error due to up-scaling method, and temporal and spatial variations at both the weather station and Upper Llobregat Basin levels.

2. Materials and methods

2.1 Study area

The study area is located in the Eastern Pyrenees, in the headwaters of Llobregat River (Fig. 1). It comprises 504 km^2, this area constitutes a mountainous rangeland with a highly contrasted relief (elevation varies between 627 m and 2540 m a.s.l.) where the average slope is 24º (CATARI, 2009). The climate is Mediterranean with a mean annual precipitation of 862 ± 206 mm, with a mean of 90 rainy days per year, with intense summer storms; the mean annual temperature is 9.1ºC (GALLART *et al.,* 2002).

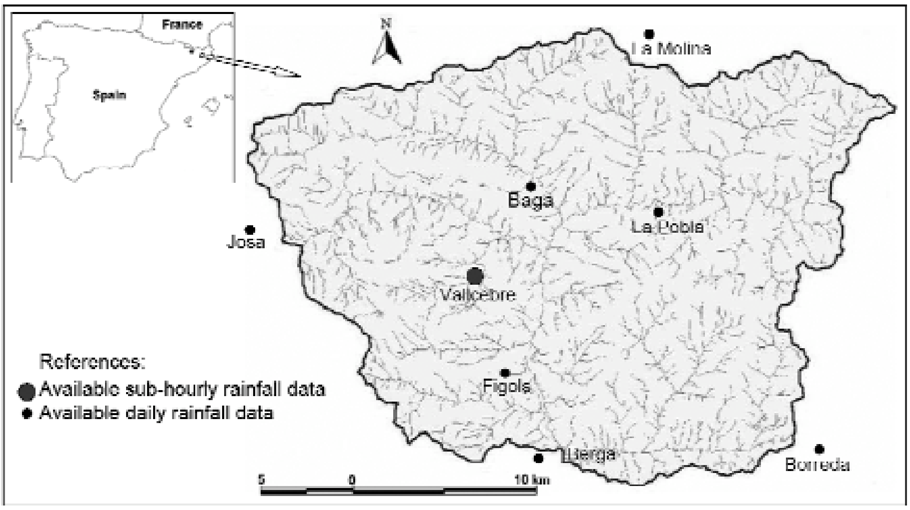

Figure 1. Location of weather stations in and nearby the study area.

2.2 Rain gauge network

Rainfall dataset was available from seven weather stations, which was provided by the Spanish National Meteorological Institute (INM). Four stations are within the limits of the study area and four nearby; these stations are located at a wide range of altitudes. The coordinates of their location and altitude are shown in Table 1. Another station (Vallcebre) belongs to the Surface Hydrology and Erosion Research Group at IDAEA, CSIC and presented sub-hourly resolution (often 15 minutes), while the remainder seven stations had only daily resolution.

2.3 Determination of R and error propagation analyses

The rainfall erosivity for the Upper Llobregat Basin was computed in two stages. Firstly, annual and seasonal relationships between daily rainfall erosivity (dependent variable) and daily rainfall depth (predictor) for the station with sub-hourly data (Vallcebre) were developed. Then these relationships were applied to stations having only daily resolution.

Table 1. Location of weather stations in or nearby the Upper Llobregat Basin.

Weather station	*INM Code*	*UTM (x)*	*UTM (y)*	*Altitude m a.s.l.*
La Molina	585	412463	4687479	1680
Josa Tuixen	632o	381765	4676545	1184
La Pobla	78u	413296	4677011	808
Baga	82	406006	4678709	795
Vallcebre	84i	402375	4673051	1133
Figols	85a	405773	4669858	754
Berga	92c	404520	4662070	664
Borreda	99	421212	4665411	845

Source: Delgado (2006) and INM (2004).

2.3.1 Vallcebre

Rainfall dataset for the period 01 January 1994 to December 2005 was used. Since the annual R factor must be determined from daily R values, the rainfall depth dataset of each event were split into daily precipitation, considered as the 24 hour period counted from 8:00 am until 8:00 am of the next calendar-day.

The erosive events (days) were selected according to RUSLE guidelines, which is, an event is erosive if the cumulative rainfall is greater than 12.5 mm, or if the 15 min intensity is greater than 6.25 mm. Calculation has involved the analysis of the hyetograph of every rainfall event in order to create an erosive events database, which was comprised of 211 daily rainfall episodes.

The R factor indicates that when factors other than rainfall are held constant, soil losses from cultivated fields are directly proportional to the multiplication of the total storm energy (E) times the maximum 30-min intensity (I30). The R factor in MJ mm $ha^{-1}h^{-1}$ day^{-1} was calculated from Eq. 1 (WISCHMEIER & SMITH, 1978),

$$R = \sum_{k=1}^{m} (EI_{30})_k \qquad \text{(Eq. 1)}$$

Where EI30 is the rainfall erosivity index for storm *k*, *m* is the number of storms in a day. The total storm kinetic energy E_k (MJ ha^{-1}) was obtained by Eq. 2 (MCGREGOR et al., 1995; FOSTER, 2004), where *pk* and *ik* are, the rainfall depth (mm) and rainfall intensity (mm h^{-1}) respectively for rainfall periods in which intensity was considered constant.

$$E_k = p_k\, 0.29[1 - 0.72 \exp(-0.082 i_k)] \qquad \text{(Eq. 2)}$$

In Vallcebre, rainy seasons typically are autumn and spring; however during summer short intense convective storms provide significant rainfall amounts (LATRON *et al.*, 2003). In order to determine whether the degree of variability is reduced by using separate regressions for summer (61 out of 211) and rest of the seasons (150 out of 211) an ANOVA test for regression was performed. This test has shown that variability is better explained when developing separate equations are developed for each group ($F = 310.4$, $p < 0.05$).

R factor values were computed by using equations 1 and 2. Then using the empirical relationship between daily R and daily rainfall, two linear regressions were developed. The scatter plots showing the relationship between these variables are illustrated in Fig. 2a for summer and in Fig. 2b for the rest of seasons. These regressions are shown in Eq. 3 for summer and Eq. 4 for the rest of the seasons, where P is rainfall depth in mm.

$R = -150.14+12.60P$ $\quad R^2 = 0.70 \quad n = 61$ (Eq. 3)

$R = -23.48+2.54P$ $\quad R^2 = 0.60 \quad n = 150$ (Eq. 4)

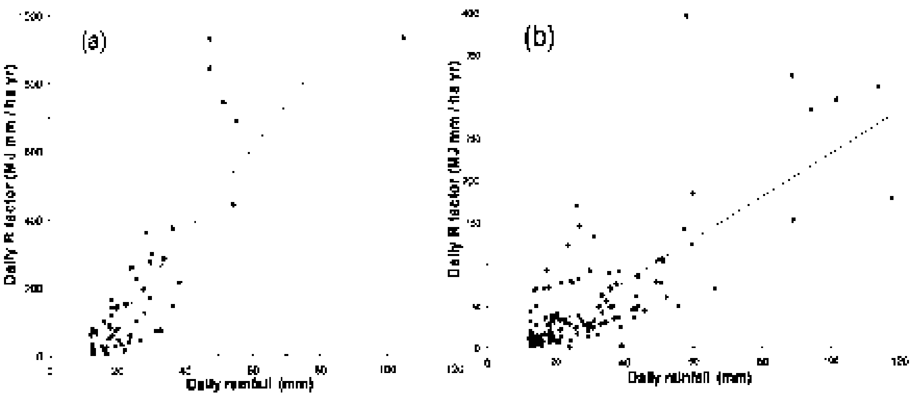

Figure 2. Scatter plots of daily R factor vs. daily rainfall for the Vallcebre weather station: (a) summer, and (b) rest of seasons.

2.3.2 Upper Llobregat Basin

The R factor values for rest of the seven stations given in Table 1, were calculated by substituting P in equations 3 and 4 with daily rainfall in order to calculate the point R values. The area of coverage of each station to the river basin was defined by obtaining Thiessen polygons, where any point at random within the polygon has a constant R value. Finally, the R value for the entire basin was obtained by weighing the R value of each station according to the area of the polygon.

2.3.3 Error analyses

A first uncertainty source comes by the fact that R factors were estimated for a series of rainfall stations with daily records, using the relationships (regressions) between daily rainfall and the R factor for the storms in that day at Vallcebre. When the values of *mean annual R factors* from these stations are to be used for estimating soil erosion hazards, it is necessary to estimate the uncertainty of these values.

The uncertainty in these determinations for the whole river basin comes from three sources: (1) the *spurious errors of the daily R estimates using the regressions* (variance of R factor not explained by the daily precipitation), (2) the temporal variability (*interannual variability of the precipitation),* and (3) the spatial variability if R is estimated for the entire river basin.

To find the uncertainty of R factor estimates, first it was estimated the uncertainty (variance or mean square error) of every daily R value calculated from the daily precipitation, which is the square of the *standard error* of the corresponding regression used to estimate R from P (Eq. 3 and 4). Since the annual R value at a station level is the sum of the R values for every rainy day; the uncertainty of the value (variance) may be found as the sum of the variances of the daily estimates. Second, since the interannual R value is the average of the annual R estimates; the time variability would be the variance of these estimates. Third, the spatial variability is obtained by weighing the deviation of every R value from the mean in function of the relative area of the respective Thiessen's polygon. Finally, the total uncertainty of R estimate was obtained from the sum of regression, time and spatial variances.

It should be noted that when R values are estimated at the annual scale, its uncertainty is calculated as described previously; nevertheless when R is calculated for the long term, its uncertainty due to the temporal source should be calculated by using the variance of the mean. The variance of R factor at annual scale is more useful to farmers, and at the long term scale it is more useful to land use planners.

3. Results

3.1 Vallcebre

The annual average R factor calculated for Vallcebre was 1493 MJ mm ha^{-1} yr^{-1} and the standard error of the mean 277 MJ mm ha^{-1} yr^{-1}. The annual R values for the period 1994 and 2005 are illustrated in Fig. 3. R values are over 2000 MJ mm ha^{-1} yr^{-1} for 1995, 1996 and 1999; and the lowest values were between 2000 and 2003.

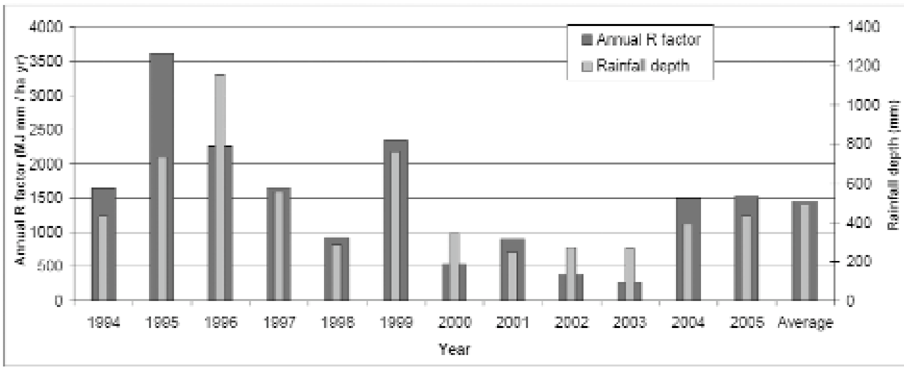

Figure 3. Rainfall depth and R factor values for Vallcebre weather station.

A large rainfall amount (depth) does not necessarily indicate a large R value; it was found that rainfall intensity is the primary driving force. For instance, for 1995 the R factor value was proportionally very large in relation to the amount of rainfall fallen during that year, where three daily rainfall events contributed almost half to the R factor, these events are characterized by high intensity and they occurred during summer. On the contrary, the R factor value for 1996 was proportionally smaller than the amount of rainfall, where 37 daily rainfall episodes were recorded (the year with the largest amount of episodes) but they had a relatively low intensity. This shows that high intensity of infrequent rainfall events strongly disrupt the direct proportionality between rainfall and erosivity factor.

3.2 Upper Llobregat Basin

The average R factor for all weather stations ranged from 1416.8 to 2496.2 MJ mm ha^{-1} yr^{-1}. The stations with the highest standard error of the mean are Figols and Josa, on the contrary Baga and Berga present the lowest variability as shown in Fig. 3 and Table 2. A clear spatial distribution of the R factor can be observed, there is more rainfall erosivity in the NE and SE of the basin than in the W.

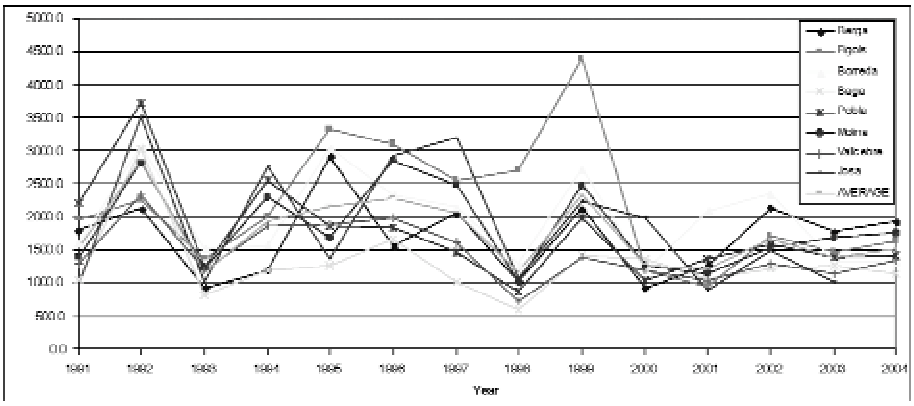

Figure 4. Annual R factor values for each weather station for the period 1991-2004.

The temporal variation of R factor reveals that, in general, years with heavy rainy days present a more spread distribution of R factor values between weather stations; on the other hand, years with small and low intensity episodes present a relatively more uniform spatial distribution. For example, during 1999 the R factor value between stations varied largely, where Figols and Borreda (both located in the SE) present the highest values. This is in agreement with the statement that the R factor values vary with the individual storm precipitation patterns and amount of rainfall (Elliot, 1995b).

The standard errors of the regressions which were developed using dataset from Vallcebre were 150.1 and 40.5 for summer and rest of seasons respectively.

Table 2. Average R factor values and related uncertainties at the weather station level, and at annual scale (RMSE (root mean square error).

Weather station	*Area (km²)*	*Average R*	*Temporal RMSE*	*Regression RMSE*	*Total RMSE*
JosA	3.4	2,131	1,107	406	1,179
Molina	106.8	2,023	714	440	839
Pobla	125.1	1,971	918	464	1,028
Baga	107.0	1,417	676	407	789
Borreda	39.5	2,236	813	448	928
Figols	86.9	2,496	1,168	468	1,259
Berga	19.6	1,828	645	393	755
Vallcebre	15.9	1,493	914	311	965

The average annual R factor values for the Upper Llobregat basin was 1956.1 MJ mm ha^{-1} yr^{-1}. The estimated R value is larger than the value estimated for the NE by USON & RAMOS (2001) which was 1400 MJ mm ha^{-1} yr^{-1} although that value was calculated for a single year (1996). The uncertainty of this value was calculated for two temporal resolutions. The first case, when in the temporal variability source, the interannual variability of R value is considered. The second case, is when the interannual variability is obtained from the variance of the mean.

For the first case, the weighted temporal variability in function of area represents 70%, the weighted regression variability represents 18% and the weighted spatial variability represents only 12% (Table 2). Therefore the R factor value and uncertainty for this case can be written as 1956.1 ± 1035.4 MJ mm ha^{-1} yr^{-1}.

For the second case, the magnitude of total uncertainty is smaller than for the first case. The weighted temporal variability is significantly reduced to 14%, the weighted variability of regression although is the same as for the first case, it proportionally increases to 52%. Similarly, the weighted spatial variability also increases in proportion to 34%. The R factor value and uncertainty for this case can be summarized as 1956.1 ± 611.7 MJ mm ha^{-1} yr^{-1} (Table 4).

Table 3. Average R factor values and related uncertainties at the weather station level and at long term scale (SEM (standard error of the mean)).

Weather station	*Area (km²)*	*Average R*	*Temporal SEM*	*Regression RMSE*	*Total RMSE*
JosA	3.4	2,131	307	406	509
Molina	106.8	2,023	191	440	480
Pobla	125.1	1,971	245	464	525
Baga	107.0	1,417	181	407	446
Borreda	39.5	2,236	217	448	498
Figols	86.9	2,496	312	468	562
Berga	19.6	1,828	172	393	429
Vallcebre	15.9	1,493	264	311	408

4. Discussion and conclusions

According to RUSLE guidelines, R factor is the result of averaging annual values of R factor in a given station. In the Eastern Pyrenees, it was found that the temporal variability is the main contributor of error (70%) to total uncertainty, when the annual variability is considered (farmer's perspective), because the R values are associated to a high interannual variation within the same station, on the contrary extrapolation method (linear regressions) and spatial variability are relatively low.

At the long term resolution (land use planner's perspective), the magnitude of error contributed to the total uncertainty by the use of regression becomes the largest (52%), compared to temporal and spatial variabilities, which are 34% and 14% respectively.

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