

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

Assessing the sources of uncertainty associated with the calculation of rainfall kinetic energy and the erosivity R factor. Application to the Upper Llobregat Basin, NE Spain

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Received: 20 May 2010 – Accepted: 30 May 2010 – Published: 14 June 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

The sources of uncertainty associated with the calculation of rainfall kinetic energy and rainfall erosivity were investigated when the USLE R factor was operationally calculated for a mountainous river basin (504 km²) in the Southeastern Pyrenees. Rainfall kinetic energy was first obtained at the scale of the rainfall event by means of sub-hourly precipitation tipping-bucket rain gauge records and updates of the Kinnell (1981) equation. Annual erosivity values for the nearby pluviometric stations were then derived from the linear regressions between daily rainfall erosivity and daily precipitation, obtained for two different seasons. Finally, maps for rainfall erosivity estimates were obtained from the station values with Thiessen polygons. The sources of uncertainty analysed were i) the tipping-bucket instrumental errors, ii) the efficiency of the Kinnell (1981) equation, iii) the efficiency of the regressions between daily precipitation and kinetic energy, iv) the temporal variability of annual rainfall erosivity values, and the spatial variability of v) annual rainfall erosivity values and vi) long-term R factor values.

The results showed that the uncertainty associated with the calculation of rainfall kinetic energy from rainfall intensity at the event and station scales is highly relevant and must be taken into account for experimental or modelling purposes; for longer temporal scales, the relevance of this source of uncertainty remains high if there is a low variability of the types of rain. Temporal variability of precipitation at wider spatial scales is the main source of uncertainty when rainfall erosivity is to be calculated on an annual basis, whereas the uncertainty associated with the long-term R factor is rather low and less important than the uncertainty associated with the other RUSLE factors when operationally used for long-term soil erosion modelling.

1 Introduction

There is increasing emphasis on incorporating uncertainty estimation to the results of environmental observations and models, in order to provide decision-makers with more usable information. Nevertheless, despite the widespread use of the USLE and

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RUSLE, analyses of the uncertainty associated with the results of these models are scarce in the literature. In particular, in spite of the warning issued by Parsons and Gadian (2000), the uncertainty associated with rainfall erosivity (the only factor that can be physically derived from measurements) is commonly taken as negligible when compared to the uncertainty associated with the other model factors (e.g., Hartcher and Post, 2005; Biesemans et al., 2000), or is only analysed in terms of spatial variability when assessed for large areas (e.g., Wang et al., 2002; Falk et al., 2010).

The rainfall erosivity R factor was defined by Wischmeier and Smith (1959) as a long-term parameter based on the characteristics of rainfall storms that provided a satisfactory predictor of soil erosion in experimental plots. It is obtained by averaging annual sums of the event erosivities calculated as the product between the maximum rainfall intensity during a 30-min period (I_{30}) and the total kinetic energy of the storm. Rainfall intensity is commonly measured by a recording rain gauge, whereas the calculation of kinetic energy also needs the measurement of the distributions of raindrop sizes or terminal velocities.

Under experimental conditions, raindrop sizes are normally measured with the flour tray (Laws and Parsons, 1943) or the dyed filter paper (Marshall and Palmer, 1948) methods, although on-site continuous electromechanical, optical or microwave disdrometers (Joss and Waldvogel, 1967) and remote short radiofrequency wave attenuation methods are increasingly used. In operational soil erosion modelling studies, rainfall kinetic energy is commonly estimated at the station and event scale from sub-hourly measurements of rainfall intensity with a non-linear equation (Kinnell, 1973) that relates rainfall intensity and specific kinetic energy. Then, a relationship between (daily, seasonal or annual) precipitation depth and R factor is derived and applied for long-term and mesoscale or regional assessment with precipitation data from regular networks.

The purpose of this paper is to analyse the diverse sources of uncertainty in the estimation of the rainfall erosivity and the R factor when obtained, as commonly occurs, by applying a model such as the RUSLE to a mesoscale area (here the Upper Llobregat

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basin, 504 km²). This paper follows on from an article (Catari and Gallart, 2010) in which the uncertainty associated with the erosivity R factor was assessed by a simplified approach. Here, five sources of uncertainty are identified and assessed by statistical methods that are unsophisticated, but are designed to cover the entire expectable span. Although the example focuses on an operational use of the R factor, it intends to provide information that will be useful for a wider range of soil erosion studies that use rainfall erosivity.

2 Materials and methods

Rainfall erosivity R factor is a long-term estimate of the annual rainfall erosivity in an area, commonly obtained with the equation proposed by Wischmeier and Smith (1978):

$$R = \frac{1}{n} \sum_{j=1}^n \sum_{k=1}^m (E I_{30})_k \quad (1)$$

where k represents single rainstorms, E is the total kinetic energy of rainfall during a storm, I_{30} represents the maximum storm rainfall intensity in a period of 30 min, m represents the number of storms in a year and j represents the year within the record of n years. Units for storm $E I_{30}$ are usually MJ mm ha⁻¹ h⁻¹ and for R are usually MJ mm ha⁻¹ yr⁻¹.

As described below in more detail, the event rainfall erosivity ($E I_{30}$) of a set of 211 rainstorms was calculated by sub-hourly precipitation records from one rainfall recorder. Then a relationship between daily precipitation and rainfall erosivity was derived from these data and applied to the daily precipitation records in a set of stations in order to obtain estimates of daily rainfall erosivity. This made it possible to apply Eq. (1) to this set of rainfall stations with only daily data. Subsequently, the erosivity factors from the rainfall stations were aggregated in time and space to obtain the erosivity for the study area.

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The uncertainty introduced in every one of the steps was estimated separately and subsequently handled by error transmission formulas. In some steps it was necessary to decide whether the errors were due to spurious random deviations (precision errors) and could be considered to compensate and be partly cancelled out by subsequent values, or whether they were systematic deviations (accuracy errors) that were not compensated for by subsequent values. Standard deviation and standard error of the mean were commonly used to express the uncertainty of the values, although the coefficient of variation and 90% confidence bounds were used in some cases for easier understanding.

2.1 Study area and source data

The study area is located in the Pyrenees, NE Spain, at the headwaters of the Llobregat River basin (Fig. 1). This area of 504 km² constitutes a mountainous rangeland with a highly contrasted relief. Mean elevation is 1271 m and varies between 627 m and 2540 m a.s.l. and the average slope is 24° (Catari, 2010). The climate is humid Mediterranean with a mean annual precipitation of 862 ± 206 mm, with a mean of 90 rainy days. The rainiest seasons are autumn and spring; and winter is the season with least precipitation. In summer, convective storms may provide significant precipitation input and the higher rainfall intensities (Latron et al., 2010); the mean annual temperature is 9.1°C (Gallart et al., 2002).

A sub-hourly precipitation dataset from the Vallcebre research basins, located in the central part of the study area and managed by the Surface Hydrology and Erosion Research Group at IDAEA, CSIC, was used for obtaining rainfall erosivity at the event scale (EI_{30}). The data set used comprises 211 rainfall events collected between January 1994 and December 2005, with depths higher than 12.5 mm or 15-min intensity greater than 6.25 mm h⁻¹.

Rainfall datasets at daily resolution were available from seven weather stations, operated by the Spanish National Meteorological Institute (INM). Four of these stations are within the limits of the study area and three nearby; these stations are located at

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a wide range of altitudes and are relatively equidistant from each other. The coordinates of their location and altitude are shown in Table 1.

2.2 Rainfall depth and intensity measurements

Precipitation at the Vallcebre station was measured by an Institut Analític AWP-P tipping bucket stainless-steel rain recorder, with a nominal capacity of 0.2 mm per tip. The time at which each movement of the bucket occurred was recorded at a resolution of 1 s by an event-recording data logger (Chatalog, Orion Group). Calibration from tips to rainfall depths employed the approach proposed by Calder and Kidd (1978). This calibration improves the accuracy of the measurement of high-intensity values by taking into account that a certain amount of rain water may be lost to the measurement when it falls into a bucket already containing its nominal capacity and movement starts (i.e. during a “dead time”). The rainfall intensity during a time period t (h) was obtained by using Eq. (2):

$$I = n \cdot V_0 / t - (t_0 \cdot n) \quad (2)$$

where I is the measured intensity (mm h^{-1}), n is the number of tips observed during every measurement period, V_0 is the nominal capacity of the tipping bucket at null intensity (mm), t is the time span (h) and t_0 is the “dead time” when rainfall is not measured (h per tip). Parameters V_0 and t_0 , as well the residuals of this relationship, were obtained by calibration covering a wide span of simulated rainfall intensities.

The results obtained with this approach were compared to these obtained with the customary approach that considers a fixed bucket capacity. The difference was considered a systematic source of error, as the fixed bucket capacity approach means an overestimation of rainfall depth for low-intensity events and an underestimation for high-intensity ones. Subsequently, the analysis of local random errors in the measurement of precipitation proposed by Ciach (2003) was applied to estimate the random errors in the determination of rainfall erosivity at the event scale, using the common parameters of a systematic time interval of 30 min and a tip-counting procedure.

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Precipitation at the INM stations was manually measured every day at 8 a.m. CT using graduated cylinders and counted for the preceding day. The possible errors in such data were not assessed, though they may be relevant.

2.3 Deriving rainfall kinetic energy from rainfall depth/intensity records

Rainfall kinetic energy is used by most erosion models for assessing rainfall erosivity. As usual in the application studies, rainfall kinetic energy was derived from an empirical equation that allows the specific kinetic energy per unit of rainfall depth to be obtained from the instantaneous rainfall intensity. More recent studies proposed the alternative use of equations using specific kinetic energy per unit time (Salles et al., 2002), but these equations are still of limited practical application and may be analytically derived from the classic ones. Currently, the most commonly accepted kinetic energy-intensity relationship is the one with two terms, a fixed value and a negative exponential of the intensity (Eq. 3), proposed by Kinnell (1981):

$$E_{kd} = e_{\max}[1 - a \cdot \exp(-b \cdot I)] \quad (3)$$

where E_{kd} is the specific rainfall kinetic energy per rainfall depth, e_{\max} is the maximum specific kinetic energy, I is rainfall intensity, and a and b are constants, experimentally obtained using measurements of the distribution of rainfall drop sizes. Diverse values for these parameters have been proposed by several authors from measurements at diverse sites and under a range of rainfall conditions (McGregor and Mutchler, 1976; Rosewell, 1986; Brown and Foster, 1987). According to the user's guide of the RUSLE2 model (Foster, 2004), the calculation of the kinetic energy of rainfall was obtained from Eq. (4), which includes the modification suggested by McGregor et al. (1995):

$$E_{kd} = 0.29[1 - 0.72 \exp(-0.082I)] \quad (4)$$

where E_{kd} is in $\text{MJ ha}^{-1} \text{mm}^{-1}$ and I is in mm h^{-1} .

Diverse published graphs of the relationships observed between E_{kd} and intensity, from diverse sites around the world, were examined (summarised in Table 2). The

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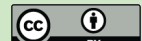
scatter of the kinetic energy – intensity relationship, for such a global dataset, is low at high-intensity values owing to the dynamic equilibrium of raindrop distribution (Zawadzki and Antonio, 1988), but it increases for decreasing intensities because raindrop distribution depends on the diverse mechanisms of drop formation or “type of rain” (e.g., Salles et al., 2002; van Dijk et al., 2002) and may even suffer dramatic changes within storms (Sempere-Torres et al., 1994).

An empirical relationship between the dispersion of the specific kinetic energy and intensity was therefore sought by re-constructing the data shown in the graphs. Assuming a log-normal distribution of the point measurements of specific kinetic energy E_{kd} , the variances of the logarithms of these measurements were derived from the information given in the graphs and averaged for narrow ranges of rainfall intensity. Then, a non-linear equation was fitted to describe the relationship between intensity and dispersion. It is worth mentioning that, when we used this latter equation to derive the scatter of the kinetic energy from the value given by Eq. (4) for every time step of the storms, the scatter was taken as systematic (accuracy error) because it is primarily a bias from the mean line, owing to the (unknown) type of storm analysed.

The question then arises whether, when event rainfall erosivity EI_{30} estimates are to be accumulated to obtain the annual totals, it can be assumed that the diverse events during the year belong to diverse types of precipitation and the errors may be therefore considered as random (precision) ones and are partly cancelled out; or whether the errors should still be seen as systematic (accuracy) ones because there is not sufficient variability in types of rain. As this is mainly a methodological analysis, both possibilities were considered. Thus, two different estimates of the uncertainties derived from the use of Eq. (3) were obtained: (i) systematic errors during the events and systematic errors between the events, and (ii) systematic errors during the events and random errors between the events.

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2.4 Upscaling rainfall erosivity from sub-hourly to daily values

Sub-hourly rainfall data, to use within RUSLE for obtaining event rainfall erosivity, are not always readily available; instead, downscaling approaches, such as those for daily, monthly or annual resolution, are used. For instance, de Santos Loureiro and Azevedo Coutinho (2001) estimated the rainfall-runoff erosivity index by using monthly data in Portugal; in Italy, Diodato (2004) developed a method for using annual data, obtaining satisfactory results.

The 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 with only daily resolution (Upper Llobregat basin). After the first trials, as it was evident that the relationship between rainfall depth and erosivity varied seasonally, two different regressions, one for summer and the other for the rest of the seasons, were computed.

The uncertainty associated with the use of these regressions was obtained from the analysis of the residuals and through error propagation formulas.

2.5 Temporal and spatial aggregation

The annual rainfall erosivity (Eq. 1) was calculated for every rainfall station by cumulating the m storm (daily) erosivities occurring in that year. On the other hand, the basin-scale erosivity for every year was obtained using the Thiessen polygon method (Thiessen, 1911) for weighing the annual erosivity values obtained at the stations. This allowed the analysis of the temporal and spatial variability of erosivity values. The contribution of every station to spatial variability was assessed by calculating the variance of the areal average on the basis of the Thiessen weighted contributions from the pluviometric stations.

The uncertainties of the final R value due to temporal and spatial variability were obtained as the standard errors of the mean. Nevertheless, in order to consider applications in which rainfall erosivity might be used at the annual scale, as to estimate

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annual soil erosion hazard, the standard deviation from annual erosivity was also considered.

3 Results and discussion

The average annual R factor value for the Upper Llobregat basin was 1986 MJ mm ha⁻¹ yr⁻¹. This value is between values estimated for the NE of Spain, such as 1400 MJ mm ha⁻¹ yr⁻¹ given by Usón and Ramos (2001) for a single year (1996) and 2628 MJ mm ha⁻¹ yr⁻¹ given by MMA (2004). At Vallcebre, summer precipitation contributed to 58% of the annual rainfall erosivity, though it represented only about 26% of the annual rainfall depth.

3.1 Rain depth and intensity measurements

When a fixed volume of the tipping bucket of the rain recorded was held, the volume was optimised to obtain the best estimate of the total rainfall depth. The error analysis showed a bias of the depth and intensity estimates negatively proportional to the rainfall intensity that resulted in a slight overestimation of precipitation for low intensities and a fair underestimation for high intensities (Fig. 2). Subsequently, when the analysis was applied to the precipitation recorded at Vallcebre, the higher precipitation intensity in summer meant a slight underestimation of both rainfall kinetic energy and erosivity (-1.3 and -1.7%, respectively), whereas for the rest of the seasons, there was a slighter overestimation of both values (0.12%). These low error values led us to discard the analysis of this source of error in the subsequent analyses, though it is worth to state that the underestimation of volumes during heavy intensity events may be of some relevance.

Errors in the calculation of rainfall erosivity at the event scale due to the random local errors in the tipping-bucket rain gauges, in terms of root mean squares, were nearly proportional to the rainfall depths. The slope of the relationship was a little higher for

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the summer events than for the events in the other seasons. Nevertheless, the relative errors (variation coefficients) were on average less than 7% for summer events and 10% for the rest of the year, with trends decreasing with event depths. When these errors were propagated to the long-term R value, the resulting coefficients of variation were 1.2% if random compensation of the errors was assumed and 4.5% if a persistent bias of the rain gauge is to be considered. Taking into account that only one source of errors was considered in the determination of rainfall volumes and intensities; the last value was retained for the overall analysis.

3.2 Rainfall kinetic energy calculation

The relationship between the dispersion of specific kinetic energy and rainfall intensity when the Kinnell (1981) expression is used (Eq. 3 and Table 2) was fitted with a logarithmic equation, explaining 81% of the original gross variance (Eq. 5 and Fig. 3):

$$\sigma_{ekd} = -0.0679 \cdot \ln(I) + 0.4245 \quad (5)$$

where σ_{ekd} is the standard deviation of the natural logarithm of the specific rainfall kinetic energy E_{kd} , which takes values numerically close to the values of the variation coefficient of the physical variable, and I is rainfall intensity (mm h^{-1}). This equation affords good fit to the data for all the measured ranges, although it would give odd negative values for intensities larger than 519 mm h^{-1} , much beyond the observed range.

This relationship is consistent with the physical grounds of rainfall kinetic energy mentioned in Materials and Methods. Relative dispersion is minimal for high-intensity rainfalls which have fairly similar drop-size distribution functions owing to the dynamic equilibrium of drops, whereas the variability of drop-size distribution functions increases with decreasing rainfall intensity owing to the increasing diversity of “types of rain” included in the analysis.

As is commonly done in operational use, Eq. (3) was applied to the sub-hourly precipitation data in order to obtain the event rainfall kinetic energy and its erosivity,

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regardless of the type of rain concerned. Consequently, the dispersion obtained from Eq. (5) was used as “systematic error”, the squared errors being accumulated for every time step and rainfall depth, without allowing the compensation usual in random errors.

When this analysis was applied to the rainfall events recorded at Vallcebre, the results showed that the event-averaged values of both σ_{ekd} and the coefficient of variation of K_e had mean values of 0.26 for summer events and 0.31 for the rest of the seasons. The difference, statistically significant, was attributed to the higher intensity of summer events. At the annual scale, the uncertainty associated with the determination of kinetic energy and rainfall erosivity depended on the relative weight of summer events and, if a random occurrence of types of rain is assumed, on the total number of events.

Figure 4 shows the rainfall kinetic energy (K_e) values and the corresponding 90% confidence intervals obtained for a random sample of 90 rainstorms recorded at Vallcebre, using Eqs. (3) and (5). This graph shows a relevant range of error of the estimates of K_e and the fair seasonal differences. This error could be reduced either by obtaining direct measurements of raindrop size/energy during storms, as recommended by Parsons and Gadian (2000) or using diverse Kinnell-type equations fitted to the corresponding types of rainstorms, along with a correct identification of the storm type in order to apply the right equation.

The uncertainty of the long-term total R value attributed to the calculation of the rainfall kinetic energy was $206 \text{ MJ mm ha}^{-1} \text{ yr}^{-1}$ (10.7% of the R value), expressed in terms of the standard error of the mean value when the rigorous criterion of event systematic error (invariance of types of rain) was applied; and $43 \text{ MJ mm ha}^{-1} \text{ yr}^{-1}$ (2.2% of the R value), when the more relaxing criterion of event random error (variability of types of rain among the events) was applied.

3.3 Daily values of rainfall erosivity

In Vallcebre, the rainy seasons are usually autumn and spring. However, during the summer short intense convective storms provide significant rainfall amounts (Latron et al., 2003). Therefore, the relationships between rainfall depth and erosivity were

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analysed separately (Fig. 5 and Eqs. 6 and 7) for the summer and the rest of the seasons. An ANOVA test indicated that the residual variance was significantly lower when two equations were used instead of one ($F=310.4$, $p < 0.05$).

$$E_s = -98.52 + 10.34P \quad R^2 = 0.55 \quad n = 61 \quad (6)$$

$$E_s = -23.48 + 2.54P \quad R^2 = 0.60 \quad n = 150 \quad (7)$$

where E_s are the daily values of storm erosivity (EI_{30} , $\text{MJ mm ha}^{-1} \text{h}^{-1}$) and P are the values of daily precipitation (mm). Daily precipitation values include snow precipitation, but snowfalls were not analysed separately because of both the low precipitation during winter and the fair erosivity of events during the colder seasons.

The absolute residuals of the daily erosivity (EI_{30}) values estimated by means of Eqs. (3) and (4) were roughly proportional to the daily rainfall depth. The corresponding factors were 3.1 for summer events and 0.87 for the rest of the seasons.

The uncertainty of the long-term total R value attributed to the simplification from sub-hourly to daily precipitation data, assuming that there was a random compensation of the errors, was $58 \text{ MJ mm ha}^{-1} \text{ yr}^{-1}$ (3% of the R value) expressed in terms of the standard error of the mean value. If a single annual equation instead of two seasonal equations was used, this source of uncertainty would be increased to a value of about 7.8% of the mean R value.

3.4 Spatial and temporal averaging

Table 3 shows the annual rainfall erosivity obtained for the stations and years analysed. Annual erosivity values obtained at the stations showed large spatial variability, which clearly varied between years: coefficients of variations ranged between 12% and 66%, with a mean value of 35%. Nevertheless, spatial variability decreased when the inter-annual R values were considered, as the coefficient of variation dropped to 18%. This result may be seen as a consequence of the importance of summer rainstorms in the annual erosivity values. These storms are known to occur a few times every year but not at the same time at all stations, as they cover only a reduced area (Latron, 2003). In

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the long term, spatial variability is reduced because of the random spatial occurrence of storms.

The uncertainty of the long-term total R value attributed to spatial variability was $125 \text{ MJ mm ha}^{-1} \text{ yr}^{-1}$ (6.4% of the R value), expressed in terms of the standard error of the mean because the stations were considered as nearly random observations of the average value, whose error would decrease with a denser rainfall recording network.

Temporal variability of the annual erosivity values at the stations was diverse, with variation coefficients between 33 and 52% and a weighted mean of 44%.

The uncertainty of the long-term R value attributed to temporal variability was $175 \text{ MJ mm ha}^{-1} \text{ yr}^{-1}$ (8.9% of the R value), expressed in terms of the standard error of the mean.

4 Summary and conclusions

The analysis presented above shows that the roles of the diverse sources of uncertainty in the estimation of rainfall erosivity depended on the spatial and temporal scales considered.

When rainfall erosivity measurements were determined at the plot and event scales, as are commonly needed for experimental or modelling purposes, instrumental errors induced a coefficient of variation of up to 10%, and the determination of kinetic energy from rainfall measurements induced a further coefficient of variation of about 30%. Better estimates of the event rainfall erosivity would need direct or indirect information on the drop size distribution.

Table 4 shows the variation coefficients estimated for rainfall erosivity at the annual scale and R factor at the long term scale, taking into account the diverse sources of uncertainty investigated. When rainfall erosivity was determined at the scale of the year, the temporal variability was the main source of uncertainty, whereas the calculation of rainfall kinetic energy from rainfall measurements was the second source of uncertainty when it can not be assumed that there are diverse types of rain along the year.

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When the long term R factor was sought, the relative importance of these uncertainty sources was reversed.

Finally, these results show that, although spatial and temporal variability of the annual rainfall erosivity values was high, the averaging of 8 rainfall stations over 13yr was sufficient to afford a fair level of uncertainty in the long-term R factor for the extension and climatic characteristics of the study area.

Acknowledgements. This research was supported by the PROBASE (CGL2006-11619/HID) and MONTES (CSD2008-00040) projects, funded by the Spanish Government, and the MIRAGE (FP7-ENV-211732) project, funded by the European Commission. Research at the Vallcebre catchments is also supported by the agreement (RESEL) between the CSIC and the “Ministerio de Medio Ambiente y Medio Rural y Marino” (*Environment Ministry*). The contribution of G. Catari was made possible by a DEBEQ grant, funded by the Autonomous Government of Catalonia. J. Latron was the beneficiary of a research contract (Ramón y Cajal programme) funded by the “Ministerio de Ciencia e Innovación” (*Science Ministry*). The authors are indebted to Montserrat Soler and Juliana Delgado and the other members of the Surface Hydrology and Erosion Research Group at IDAEA, CSIC for providing the necessary data and assistance.

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Table 1. Location of weather stations in or near the headwaters of the Llobregat River basin.

Weather station	INM Code	UTM (x)	UTM (y)	Altitude m a.s.l.
La Molina	585	412 463	4 687 479	1680
Josa Tuixén	632o	381 765	4 676 545	1184
Vallcebre	84i	402 375	4 673 051	1133
Borredà	99	421 212	4 665 411	845
La Pobla	78u	413 296	4 677 011	808
Bagà	82	406 006	4 678 709	795
Fígols	85a	405 773	4 669 858	754
Berga	92c	404 520	4 662 070	664

Source: INM (2004) and Delgado (2006)

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Table 2. Sources of data used for the analysis of the uncertainty associated with the Kinnell (1981) equation.

Site	Intensities (mm h^{-1})	Number of means	Number of observations	References
Miami, Florida	1.83–200	10	200	Kinnell (1981) based on Kinnell (1973)
Miami, Florida	18.5–228.6	n.a.	30	Kinnell (1981) based on Hudson (1971)
Zimbabwe	18.5–228.6	n.a.	19	Kinnell (1981) based on Hudson (1971)
Holly Springs, Mississippi	0–257	n.a.	315	McGregor and Mutchler (1976)
Gunnedah, Australia	0–150	18	12 894	Rosewell (1986)
Brisbane, Australia	0–160	19	6360	Rosewell (1986)

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Table 3. Annual rainfall erosivity values obtained at the stations ($\text{MJ mm ha}^{-1} \text{ yr}^{-1}$).

Year	Berga	Figols	Borreda	Baga	Pobla	Vallcebre	Molina	Josa	average	var. coeff.
1991	1810	2259	1785	1130	2657	1368	1494	1034	1865	31%
1992	2135	2513	3668	3544	4426	2592	3304	4016	3462	20%
1993	925	1479	1670	805	1298	1280	1270	1031	1231	21%
1994	1201	2323	1768	1294	3066	2115	2647	3259	2270	30%
1995	2913	3968	3547	1401	2115	2123	1850	1500	2366	39%
1996	1589	3464	2523	1729	1910	2131	3025	3200	2427	28%
1997	2464	2914	2564	1106	1592	1786	2871	3739	2118	35%
1998	1100	3232	1508	651	931	764	1085	1139	1349	66%
1999	2466	5240	3137	1600	2285	1525	2815	2581	2813	43%
2000	965	1322	1261	1511	1128	1297	1358	2207	1308	13%
2001	1375	1063	2409	1171	1538	1179	1278	924	1370	25%
2002	2437	1853	2657	1303	1653	1320	1616	1542	1703	22%
2003	1941	1536	1381	1390	1462	1155	1810	1537	1536	12%
average	1794	2551	2298	1434	2005	1587	2033	2131	1986	35%
var. coeff.	37%	47%	35%	49%	47%	33%	38%	52%	44%	

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Table 4. Variation coefficients (percent values) estimated for rainfall erosivity (EI_{30}) and R factor, taking into account the diverse sources of uncertainty.

		instrument	kinetic energy	daily values	spatial	temporal	total
single year EI_{30}	single rain type	4.5	10.7	3.0	6.4	43.7	45.8
single year EI_{30}	diverse rain types	4.5	2.2	3.0	6.4	43.7	44.6
long term R	single rain type	4.5	10.7	3.0	6.4	8.9	16.3
long term R	diverse rain types	4.5	2.2	3.0	6.4	8.9	12.4

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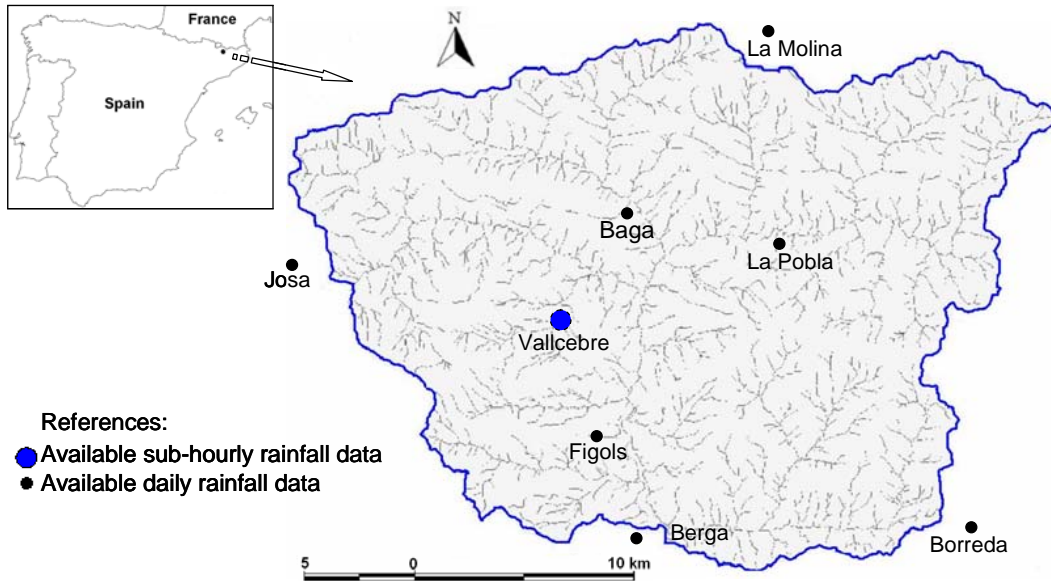


Fig. 1. Study area and locations of weather stations.

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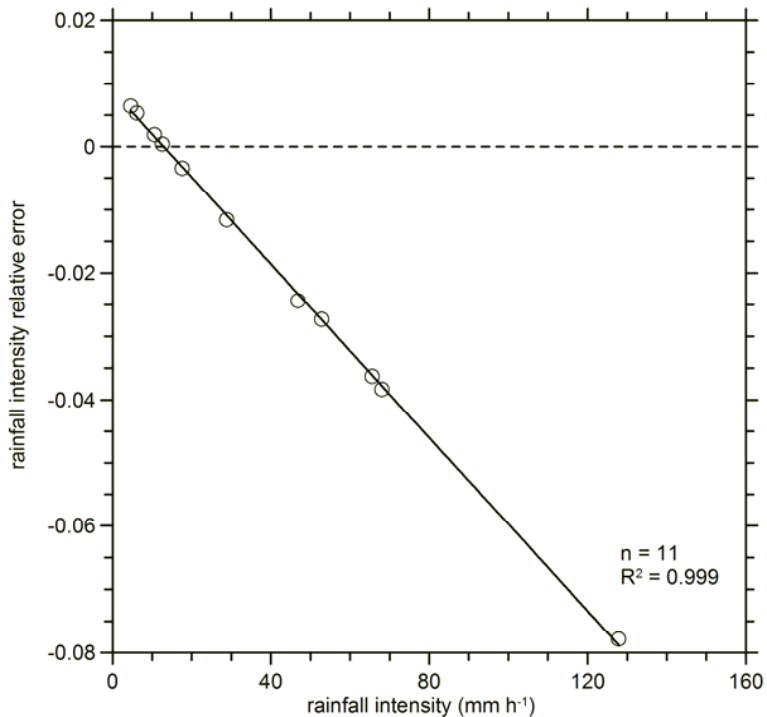
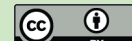


Fig. 2. Relative errors in the determination of rainfall depth (and intensity) when a fixed volume of the rain recorded tipping bucket is considered.

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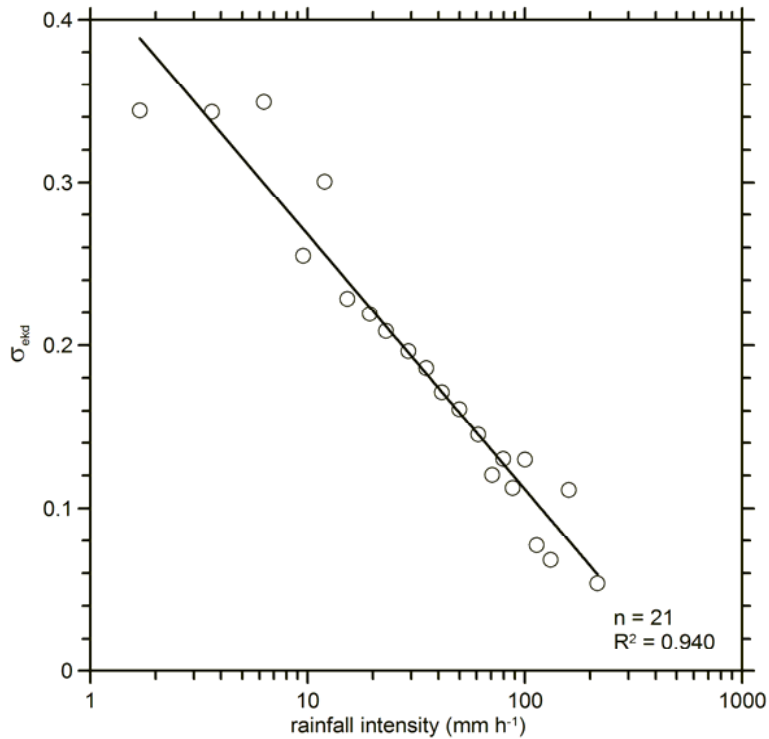


Fig. 3. Relationship between the standard deviation of the natural logarithm of the specific kinetic energy and the rainfall intensity obtained from the graphs listed in Table 2.

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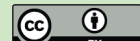
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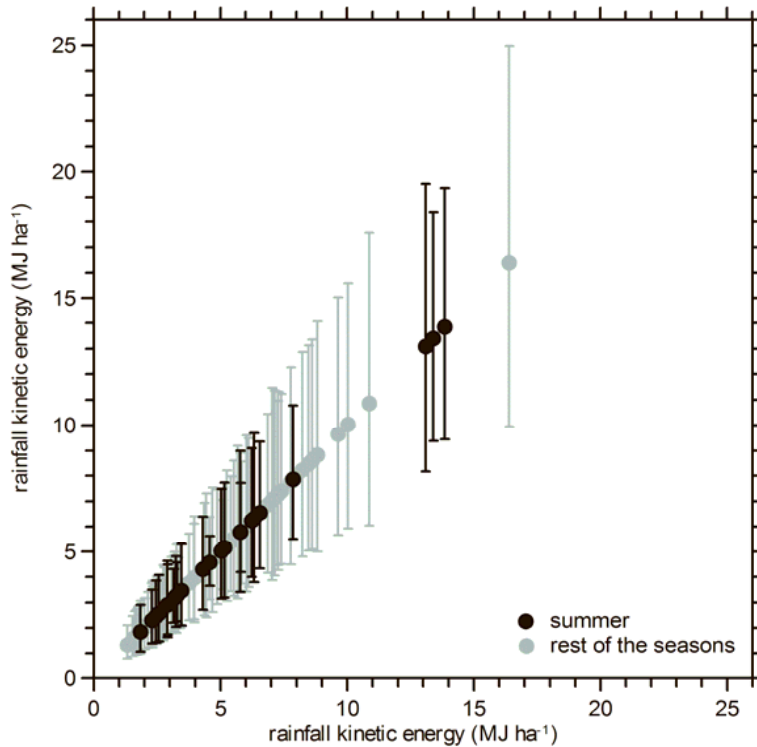


Fig. 4. 90% uncertainty bounds for a set of estimates of event rainfall kinetic energy at Vallcebre, obtained from rainfall records using Eqs. (4 and 5).

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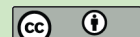
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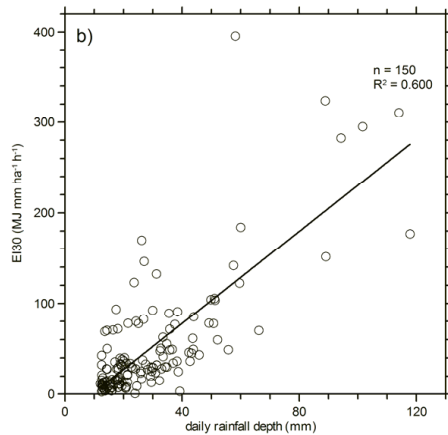
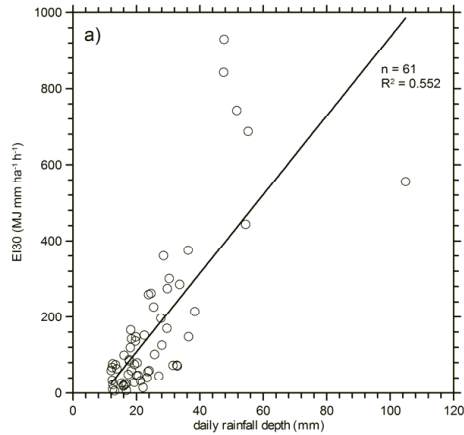


Fig. 5. Scatter plots of daily rainfall erosivity versus daily rainfall for the Vallcebre weather station: **(a)** summer and **(b)** rest of the seasons.

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