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Influence of the rainfall measurement interval on the erosivity determinations in the Mediterranean area

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Summary The single-storm erosion index, EI, of the USLE and RUSLE models may vary appreciably with the rainfall measurement interval, Δt. However, the effect of Δt on EI has not been investigated in the Mediterranean area. Approximately 700 erosive events and 1.5 years of rainfall energies measured by a rainfall impact measurement device were used to evaluate the effect of the rainfall measurement interval ($5\ \text{min} \leqslant \Delta t \leqslant 60\ \text{min}$) on the erosivity determinations in the Mediterranean semi-arid area of Sicily. According to both literature and practical considerations, a reference time interval equal to 15 min was used in this investigation. Hourly rainfall data led to an appreciable underestimation of the mean value of EI (i.e., by also a factor of two, depending on the location). In the range $5\ \text{min} \leqslant \Delta t \leqslant 15\ \text{min}$, the effect of the rainfall measurement interval on the predicted erosivity was negligible (i.e., mean values differing by a maximum factor of 1.10) as compared with the uncertainties in the soil loss predictions. Two methods were developed for estimating the reference single-storm erosion index, $(\text{EI})_{15}$, from hourly rainfall data in Sicily. Method 1 converts the erosion index calculated on a 60-min measurement interval basis to $(\text{EI})_{15}$. Method 2 estimates $(\text{EI})_{15}$ by using the storm rainfall depth and the maximum rainfall intensity. Testing the two methods against two independent data sets produced a maximum difference between the estimated and the calculated mean values of $(\text{EI})_{15}$ equal to 7% for method 1 and 11% for method 2. Both methods may be applied in practice, depending on the available rainfall data. For a given rainfall intensity, the specific power, *P*, measured at eight time intervals ($5\ \text{min} \leqslant \Delta t \leqslant 60\ \text{min}$) was in the range ±10% of the mean of the eight *P* values.

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Introduction

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its revised version (RUSLE) (Renard et al., 1997) are widely applied for estimating the average annual soil loss from rainfall. The rainfall factor, *R*, of both the USLE and the RUSLE is a numerical descriptor of the ability of rainfall to erode soil (Wischmeier, 1959). The *R* factor has been shown to be correlated to soil loss in many areas of the world (Wischmeier, 1959; Stocking and Elwell, 1973; Wischmeier and Smith, 1978; Lo et al., 1985; Renard and Freimund, 1994; Bagarello and Ferro, 2004).

The rainfall factor is calculated from a series of single-storm erosion index or EI-values, obtained by multiplying the total storm kinetic energy, *E*, calculated by an empirical relationship, by the measured maximum 30-min rainfall intensity, I_{30} (Wischmeier and Smith, 1978). Many empirical relationships have been developed in different areas of the world for calculating *E* from the measured intensities. A comprehensive examination of these relationships has been recently presented by Salles et al. (2002).

By definition, EI should be computed from rainfall measurements at short time intervals during which the intensity is essentially constant, i.e. using the breakpoint data (Wischmeier and Smith, 1978; Istok et al., 1986; Williams and Sheridan, 1991). The sensitivity of the EI estimates to the depth and time resolution of rainfall measurement has been studied in the USA. In particular, assuming that a 15-min rainfall measurement interval is reasonably short to obtain constant intensity rainfall data, regression equations have been developed to estimate EI values corresponding to this measurement interval, $(\mathrm{EI})_{15}$, as a function of EI calculated for the same storm on the basis of hourly data, $(\mathrm{EI})_{60}$ (Istok et al., 1986; Williams and Sheridan, 1991; Renard et al., 1997). The most complete investigation was conducted for 713 stations as a part of the RUSLE development procedure (Renard et al., 1997). Values of the coefficient of determination greater than 0.8 were obtained by the model $(\mathrm{EI})_{15} = b_1(\mathrm{EI})_{60}$, where b_1 is a regression parameter summarizing the sensitivity of both *E* and I_{30} to the rainfall measurement interval. The values of b_1 ranged from 1.08 to 3.16, varying widely with the climatic zone. Therefore, the temporal resolution of rainfall data may affect appreciably the estimated soil loss. Furthermore, the site-dependence of the b_1 coefficient suggests that the $(\mathrm{EI})_{15}$ vs. $(\mathrm{EI})_{60}$ relationship has to be locally calibrated. Little information on the effect of the rainfall measurement time interval on the erosivity calculations is available for the Mediterranean area.

The b_1 parameter derived for a given area may vary with the relationship used to calculate *E*. In other words, using an untested relationship for calculating *E* from the measured rainfall intensity, which is common in different parts of the world, may introduce uncertainties in the evaluation of the sensitivity of EI to the rainfall measurement interval. These uncertainties may be reduced if the effect of the rainfall measurement time interval on the kinetic energies measured by rainfall impact measurement devices is known. However, this evaluation may be carried out only at a local scale within an area of interest since measuring rainfall kinetic energy is much more expensive than measuring rainfall intensity. Furthermore, a very few kinetic energy data are available compared to the rainfall intensity data.

Sicily is a semi-arid Mediterranean region of South Europe affected by severe erosive phenomena. For this region, accurate estimation procedures of soil loss have to be developed. Much work has been carried out in the past to determine rainfall erosivity and to develop simplified methods to estimate both EI and *R* in Sicily (D'Asaro and Santoro, 1983; Ferro et al., 1991, 1999; Bagarello, 1996; Bagarello and D'Asaro, 1994; Agnese and Corrao, 2003). Most rainfall data used for these studies were collected by mechanical raingauges. These devices use a chart placed on a clock-driven drum that has to be replaced weekly. A day of record is plotted on a 55 mm wide portion of the chart. Rainfall intensity determinations corresponding to time periods shorter than 20 or 30 min are very uncertain because the real time interval (<0.8–1.1 mm on the time scale of the chart) cannot be measured accurately. A few meteorological stations using electronic raingauges were installed in the 1990s. These devices record accumulated rainfall depth on a 5 min time interval basis with a depth resolution of 0.2 mm. Therefore, rainfall data of different nature are now available to update the existing Sicilian isoerodent maps (D'Asaro and Santoro, 1983; Ferro et al., 1991) and to analyze time series of storm EI values.

The general objective of this investigation was to evaluate the influence of the rainfall measurement interval on the erosivity determinations in Sicily. The specific objectives were to: (i) explore the effect of the rainfall measurement interval in the range from 5 min to 60 min on the single-storm erosion index calculations for approximately 700 erosive events, (ii) derive estimation procedures of the single-storm erosion index corresponding to short measurement intervals from hourly rainfall data, and (iii) establish the effect of the rainfall measurement interval on the storm energy measured by a rainfall impact measurement device.

Materials and methods

Effect of rainfall measurement interval on the single-storm erosion index calculations

The data for this study were obtained from seven electronic rain-gauge stations operating in Sicily with some breakdown during the period 1990–1999 (Fig. 1). Rainfall data were recorded with a temporal resolution $\Delta t = 5$ min. Storms separated from other rain periods by more than six hours were considered distinct and a rainfall threshold of 13.0 mm was considered to select the erosive storms to be included in this study (Wischmeier and Smith, 1978). The number of selected storms varied from a minimum of 51 (Enna station) to a maximum of 125 (Palermo station). For each station, Table 1 lists the summary statistics of the storm rainfall depth, duration, mean and maximum intensity.

For each storm, rainfall data were aggregated at $\Delta t = 15$ and 60 min and the total storm kinetic energy, *E* (MJ ha^{-1}), maximum 30-min rainfall intensity, I_{30} (mm h^{-1}), and storm erosion index, EI (MJ mm $\mathrm{ha}^{-1}\,\mathrm{h}^{-1}$), were calculated for each Δt value ($\Delta t = 5$, 15 and 60 min). The original, discon-

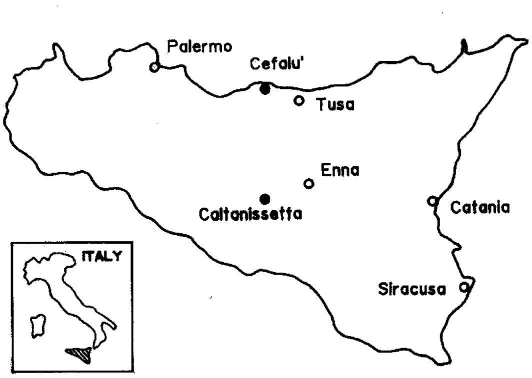

Figure 1 Sicilian stations considered in this study.

tinuous unit energy equation (Wischmeier and Smith, 1978) was applied to calculate E:

$$e = 0.119 + 0.0873 \log I \quad I \leqslant 76\ \text{mm h}^{-1} \tag{1a}$$

$$e = 0.283 \quad I > 76\ \text{mm h}^{-1} \tag{1b}$$

where e (MJ ha^{-1} mm^{-1}) is the rainfall kinetic energy per unit area and unit rainfall depth and I (mm h^{-1}) is the rainfall intensity.

For Δt = 5 min and 15 min, the I_{30} term was calculated from the maximum rainfall depth measured in a 30-min period. For Δt = 60 min, I_{30} was set equal to the maximum 60-min accumulated depth (Williams and Sheridan, 1991). Storm durations <30 min were occasionally detected for temporal resolutions $\Delta t \leqslant 15$ min. In this case, I_{30} was twice the amount of the rain (Wischmeier and Smith, 1978). A limit of 63.5 mm h^{-1} was placed on the I_{30} term (Wischmeier and Smith, 1978). In the following, the term ''calculated'' was used to denote the variables (E, I_{30}, EI) determined according to Wischmeier and Smith (1978).

Only the original procedure suggested by Wischmeier and Smith (1978) was considered in this study to calculate storm erosivity values notwithstanding that a different rainfall threshold (i.e., zero instead of 13 mm) and a different unit energy equation (Brown and Foster, 1987) have been used in the RUSLE (Renard et al., 1997). A reason was that the ori-

Table 1 Statistics of the erosive events measured with a temporal resolution of 5 min at different Sicilian locations during the period 1990–1999

Station	Sample size	Statistic[a]	Variable			
			Rainfall depth (mm)	Duration (h)	Mean intensity (mm h^{-1})	Maximum intensity (mm h^{-1})
Caltanissetta	74	Min	13.2	0.67	0.5	2.4
		Max	220.2	54.17	34.0	255.6
		Mean	29.7	12.84	4.4	41.9
		CV (%)	107.0	78.9	137.1	99.8
Catania	91	Min	13.0	0.42	0.4	7.2
		Max	206.6	47.92	51.4	172.8
		Mean	32.7	14.35	4.9	36.1
		CV (%)	93.8	73.6	162.2	81.8
Cefalù	117	Min	13.0	0.75	0.4	2.4
		Max	136.2	56.50	24.8	120.0
		Mean	26.3	15.64	3.1	35.5
		CV (%)	66.1	74.1	124.3	76.3
Enna	51	Min	13.0	0.58	0.5	4.8
		Max	59.6	41.08	41.5	141.6
		Mean	25.2	13.43	5.0	39.5
		CV (%)	49.7	81.1	148.2	82.8
Palermo	125	Min	13.0	0.67	0.4	4.8
		Max	86.4	65.83	30.0	160.8
		Mean	25.1	15.56	3.6	30.6
		CV (%)	60.0	82.4	131.8	82.6
Siracusa	115	Min	13.0	0.50	0.5	7.2
		Max	182.8	88.33	34.0	141.6
		Mean	37.1	14.78	4.7	43.1
		CV (%)	74.4	83.0	125.1	67.0
Tusa	115	Min	13.0	0.50	0.3	2.4
		Max	128.0	53.00	50.0	139.2
		Mean	26.3	12.02	5.1	37.8
		CV (%)	63.3	83.5	147.2	74.0

[a] Min = minimum value; Max = maximum value; CV = coefficient of variation.

ginal USLE procedure was used in the past to calculate the existing EI data for Sicily (D'Asaro and Santoro, 1983). Another reason was that the choice of both the unit energy equation and the rainfall threshold does not seem to affect substantially the calculated *R* factor (McGregor et al., 1995; Yu, 1999).

For each station, the effect of the temporal resolution of rainfall measurement on the *E*, I_{30} and EI values was evaluated by comparing the means and the coefficients of variation (CV) determined for different Δt values. Due to the *R* factor and soil loss calculation procedures used in the USLE (Wischmeier and Smith, 1978), a given difference between mean values of EI corresponding to different Δt values coincides with the difference between the *R* factor and soil loss calculations corresponding to different rainfall measurement intervals.

Predicting the reference single-storm erosion index from hourly rainfall data

Two methods were tested to derive an estimation procedure of the single-storm erosion index corresponding to a 15-min measurement interval basis, $(\mathrm{EI})_{15}$, from hourly rainfall data. The choice of a reference time interval of 15 min was made to maintain methodological consistence with other investigations carried out in other areas of the world (Istok et al., 1986; Renard et al., 1997) and because this time interval appears to be the shortest one that can practically be considered for reasonably accurate erosivity calculations over large areas of the world.

The first method (method 1) converts the single-storm erosion index calculated on a 60-min measurement interval basis, $(\mathrm{EI})_{60}$, to $(\mathrm{EI})_{15}$ by using the following model:

$$(\mathrm{EI})_{15} = b_0 + b_1(\mathrm{EI})_{60} \tag{2}$$

where b_0 and b_1 are empirical coefficients. These coefficients were determined by three different approaches. The first approach consisted in determining b_0 and b_1 by linear regression of $(\mathrm{EI})_{15}$ against $(\mathrm{EI})_{60}$ (Two Coefficients – Linear Regression analysis, TCLR, approach). With the other two approaches, b_0 was set equal to zero and b_1 was determined (i) by linear regression of the two variables (One Coefficient – Linear Regression analysis, OCLR, approach) and (ii) as the median of the calculated $(\mathrm{EI})_{15}/(\mathrm{EI})_{60}$ ratios (One Coefficient – Median, OCM, approach). The OCLR approach was also applied by Istok et al. (1986) and Renard et al. (1997) to develop a relationship between $(\mathrm{EI})_{15}$ and $(EI)_{60}$. This approach appears more sound than the TCLR one given that $(\mathrm{EI})_{15} = 0$ is expected when $(\mathrm{EI})_{60} = 0$. The OCM approach was applied since b_1 can be viewed as a scale factor between $(\mathrm{EI})_{15}$ and $(\mathrm{EI})_{60}$.

The second method (method 2) estimates separately the two factors of the EI index, i.e. the total storm kinetic energy, $(E)_{15}$, and the maximum 30-min rainfall intensity, $(I_{30})_{15}$, corresponding to $\Delta t = 15$ min. According to Bagarello and D'Asaro (1994), a linear regression analysis was carried out to determine the b_1 coefficient of the relationship:

$$(E)_{15} = b_1 h_{\mathrm{ev}} \tag{3}$$

where h_{ev} (mm) is the event rainfall depth. The following model was considered for I_{30} (Istok et al., 1986):

$$(I_{30})_{15} = b_0 + b_1(I_{30})_{60} \tag{4}$$

The TCLR, OCLR and OCM approaches were applied to determine the coefficients b_0 and b_1 of Eq. (4). The limit of 63.5 mm h^{-1} was placed on the $(I_{30})_{15}$ term estimated by Eq. (4).

The two methods tested in this investigation differ by the required input data. For a given storm, a continuous record of rainfall intensity has to be available to apply method 1. Only the storm rainfall depth and the maximum rainfall intensity are necessary to apply method 2.

Five locations (Catania, Enna, Palermo, Siracusa and Tusa) were randomly chosen among the seven locations included in this investigation (Fig. 1) and the data were pooled to form a single data set ($N = 497$ erosive storms, i.e. storms with $h_{\mathrm{ev}} \geqslant 13$ mm). The coefficients of Eqs. (2)–(4) were derived by using this data set. The empirically derived relationships were then tested against the independent data sets collected at Caltanissetta and Cefalù. The reasons for applying this approach were the following: (i) a single relationship usable over a relatively large area has more practical interest than locally calibrated relationships, and (ii) previous work showed that data from different locations can be pooled to derive indirect estimation procedures of both *E* and EI in Sicily (Bagarello and D'Asaro, 1994). Using a relatively low number of stations was unavoidable due to the scarcity of high resolution rainfall data. Only in the last few years, different stations collecting data at short time intervals are starting to operate in Sicily. In the following, the term ''estimated'' was used to denote the variables (*E*, I_{30}, EI) determined by methods 1 and 2.

Effect of rainfall measurement interval on the measured energy

The influence of the rainfall data measurement interval on the measured energy was investigated for the storm events occurred at the Faculty of Agriculture of the University of Palermo from January 2000 to May 2001 (Agnese and Corrao, 2003), in an area characterized by an almost uniform distribution of wind direction and intensity.

During this period, an electronic raingauge and a synchronized rainfall impact measurement device were used to measure the rainfall depth and the associated kinetic energy at the pre-established time interval, Δt, of 1 min. Details on the development and the testing of the impact measurement device can be found in the literature (e.g., Battista et al., 1994; Agnese and Corrao, 2003). Therefore, only a short description of the device will be given here.

The sensitive unit is composed by a rainfall receiving surface that is rigidly connected to a piezoelectric impact transducer. The slightly convex rainfall receiving surface is in sintered bronze and it has a diameter of 0.1 m. The characteristics of the surface minimize the risk of both water ponding occurrence and raindrop rebound. The energy of the rainfall falling on the exposed surface is transmitted to the transducer that produces a voltage signal related to the impulses received at a given instant. The signal is then transmitted to an integrating unit. This unit produces a voltage signal proportional to the energy received by the exposed surface in the pre-established time interval, Δt. Finally, the electric signal is converted to an energy va-

Table 2 Statistics of the rainfall intensity (*I*) and power (*P*) data obtained with a temporal resolution of 5 min at the Faculty of Agriculture of the Palermo's University

Variable	Maximum	Mean	Coefficient of variation (%)
I (mm h^{-1})	81.6	2.37	180.0
P (mW m^{-2})	1565.6	14.17	340.0

lue by a calibration relationship developed by Battista et al. (1994).

The rainfall depth and energy data collected during the study period (15 storm events) were aggregated at different time intervals, equal to 5, 10, 15, 20, 30, 40, 50 and 60 min ($N = 8$ values of Δt). For a given Δt, the following variables were determined for each rainy period:

$$I = \frac{h}{\Delta t} \tag{5}$$

$$P = \frac{E}{3600\sigma_{es}\Delta t} \tag{6}$$

where I (mm h^{-1}) is the rainfall intensity, h (mm) is the rainfall depth in the selected time period, Δt (h) is the duration of the time period, P (mW m^{-2}) is the specific power of rainfall, E (mJ) is the accumulated energy in the time period, and σ_{es} (m^2) is the area of the exposed surface of the device. For a given intensity, a representative value of P was then determined by averaging the P data corresponding to that rainfall intensity. For a given Δt, the relationship between P and I was determined. The $P(I)$ relationships corresponding to different Δt values were then compared. Data aggregated at time intervals shorter than 5 min were not included in this analysis given that a minimum time interval of 5 min was considered to evaluate the sensitivity of the EI calculations to the rainfall measurement interval. The basic statistics of the I and P values obtained for $\Delta t = 5$ min are listed in Table 2.

The energy data used in this investigation were also used by Agnese and Corrao (2003) to assess the applicability of the unit energy equation suggested by Wischmeier and Smith (1978) in Sicily. Rainfall energy corresponding to high intensities was slightly underpredicted (Fig. 2). In general, however, the agreement between measured and calculated energies was satisfactory (Agnese and Corrao, 2003).

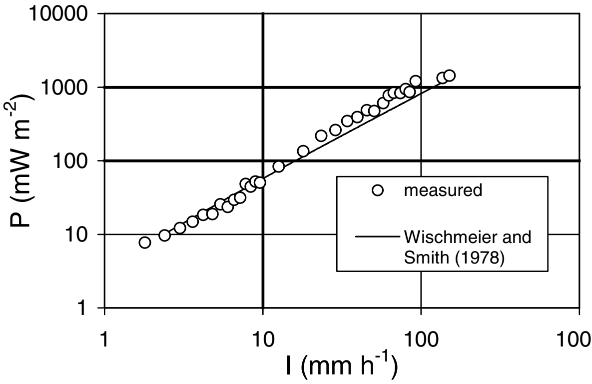

Figure 2 Comparison between the power-rainfall intensity (P, I) data pairs measured in Sicily and the relationship proposed by Wischmeier and Smith (1978) (Agnese and Corrao, 2003).

Results and discussion

Effect of rainfall measurement interval on the single-storm erosion index calculations

As expected, the calculated values of E, I_{30} and EI decreased as the rainfall measurement interval increased from $\Delta t = 5$ min to $\Delta t = 60$ min (Table 3). The decrease of Δt from 15 to 5 min determined an increase of EI by a maximum factor of 1.10 (Table 3). The increase of Δt from 15 to 60 min produced a maximum underestimation of EI by a factor of nearly two and this decrease was essentially due to the decrease in the calculated I_{30} (Table 3), confirming previous investigations (Istok et al., 1986). In most cases, the relative variability of the individual determinations of E, I_{30} and EI did not vary substantially with the rainfall measurement interval (Table 3).

The evaluation of the effect of Δt on a given variable (E, I_{30}, EI) was based on practical considerations rather than on a data statistical analysis. The reason for this choice was that the sign of the differences between two data sets did not vary with the event. In this case, the null hypothesis (no difference between two groups of data) is rejected independently of the level of the differences by common statistical procedures (e.g. paired *t*-test, sign test).

In practice, a variation in the estimated soil loss by 10% can be considered inconsequential. Due to the complexity of the erosive phenomenon and the empirical nature of the USLE, soil loss estimates differing by a factor of two could also be considered practically similar. However, much work has been carried out recently to improve the prediction of specific factors of the USLE and the updated factors often differ by much less than a factor of two from the old ones (Renard et al., 1991, 1997; Yu, 1999). On the basis of the previous remarks, using hourly rainfall data in place of the reference ones to calculate EI should be avoided, since the level of underestimation may be appreciable. In the range 5 min $\leqslant \Delta t \leqslant$ 15 min, rainfall data measured at different time intervals may be used indifferently since the R factor values varied negligibly with Δt. Istok et al. (1986) suggested that the single-storm erosion index is expected to increase as the size of the measurement interval decreases below 15 min because this interval can be too long to include really constant intensity periods in the calculations. This investigation did not support the conclusion by Istok et al. (1986). A time interval of 15 min was found to be short enough to obtain rainfall periods of reasonably constant intensity, given that the EI values calculated for $\Delta t = 15$ min were similar to the ones obtained with a much shorter time interval (i.e., $\Delta t = 5$ min).

Predicting the reference single-storm erosion index from hourly rainfall data

The three approaches for determining the coefficients b_0 and b_1 of Eq. (2) (method 1) produced different estimates

Table 3 Mean values and coefficients of variation (%, in parenthesis) of the total storm kinetic energy, E, maximum 30-min rainfall intensity, I_{30}, and single-storm erosion index, EI, corresponding to different rainfall measurement intervals, Δt

Station	E (MJ ha^{-1})			I_{30} (mm h^{-1})			EI (MJ mm ha^{-1} h^{-1})		
	$\Delta t = 5$ min	$\Delta t = 15$ min	$\Delta t = 60$ min	$\Delta t = 5$ min	$\Delta t = 15$ min	$\Delta t = 60$ min	$\Delta t = 5$ min	$\Delta t = 15$ min	$\Delta t = 60$ min
Caltanissetta	6.30 (125)	6.04 (127)	5.62 (130)	18.2 (75)	17.6 (77)	10.8 (73)	183.9 (260)	173.5 (267)	105.7 (306)
Catania	6.83 (109)	6.52 (111)	6.04 (115)	17.6 (78)	16.9 (78)	10.4 (88)	189.1 (243)	174.1 (247)	116.0 (317)
Cefalù	5.37 (71)	5.05 (73)	4.59 (76)	15.8 (72)	15.1 (72)	9.0 (71)	107.1 (158)	97.5 (165)	55.1 (197)
Enna	5.30 (59)	5.03 (62)	4.63 (64)	19.6 (78)	18.9 (78)	11.2 (77)	141.3 (139)	131.5 (142)	73.0 (149)
Palermo	5.01 (64)	4.73 (66)	4.31 (68)	14.4 (69)	13.8 (70)	8.3 (62)	88.1 (131)	80.5 (131)	44.6 (130)
Siracusa	7.80 (78)	7.48 (80)	6.98 (83)	21.5 (68)	20.7 (68)	12.6 (72)	214.0 (141)	198.1 (142)	118.7 (160)
Tusa	5.55 (66)	5.25 (67)	4.74 (69)	17.4 (68)	16.8 (68)	9.7 (66)	119.7 (140)	109.9 (141)	58.3 (156)

of $(\mathrm{EI})_{15}$ (Table 4). In particular, the TCLR approach returned exactly the mean of the $(\mathrm{EI})_{15}$ values calculated by using rainfall data aggregated at 15-min time intervals, whereas the means obtained with the OCLR and OCM approaches were 0.79 and 1.04 times the mean of the calculated $(\mathrm{EI})_{15}$ values, respectively. The cumulative empirical frequency distribution of the $(\mathrm{EI})_{15}$ values estimated by the OCM approach was very close to the distribution of the calculated $(\mathrm{EI})_{15}$ values (Fig. 3). The OCLR approach produced higher frequencies of low values of $(\mathrm{EI})_{15}$ as compared to the calculated ones. Due to the constant term in Eq. (2), all the $(\mathrm{EI})_{15}$ values estimated with the TCLR approach were higher than 34.3 MJ mm ha^{-1} h^{-1} notwithstanding that the calculated $(\mathrm{EI})_{15}$ values were less than 34.3 MJ mm ha^{-1} h^{-1} for 164 erosive events (33% of the total). Therefore, the OCLR approach determined an appreciable underestimation of $(\mathrm{EI})_{15}$ whereas the TCLR approach did not reproduce the distribution of the calculated $(\mathrm{EI})_{15}$ values. The ability of the OCM approach to reproduce satisfactorily this distribution and to give an estimate of the mean value of EI close to the mean of the calculated values (i.e., differing by 4.2%) induced us to select this approach for further testing of method 1.

Istok et al. (1986) and Renard et al. (1997) used Eq. (2) and the OCLR approach to estimate b_1 for the US locations. By this approach, similar results were obtained in Sicily ($b_1 = 1.33$) and in selected locations of western Oregon ($1.19 \leqslant b_1 \leqslant 1.38$) (Istok et al., 1986). The scaling factor determined in Sicily was in the range of the lowest values of b_1 obtained by Renard et al. (1997) for different US climatic zones ($1.08 \leqslant b_1 \leqslant 3.16$). This last result suggested that in Sicily the variability of the EI estimates with the rainfall measurement interval may be considered relatively low if compared to the variability observed in some areas of the USA.

For method 2, $(E)_{15}$ was highly correlated to h_{ev} (Table 4) and the estimated slope of Eq. (3) ($b_1 = 0.20$) was close to the one obtained by Bagarello and D'Asaro (1994) on a different data set of more than 5500 erosive events ($b_1 = 0.19$). The discrepancy between the estimated and the calculated mean values of $(I_{30})_{15}$ was lowest for the TCLR approach (Table 4). The OCLR and OCM approaches produced equivalent results (Table 4) and they reproduced the frequency distribution of the calculated $(I_{30})_{15}$ values more accurately than the TCLR approach (Fig. 4). Depending on the approach used to estimate the coefficients b_0 and b_1 of Eq. (4), the mean of the estimated values of $(\mathrm{EI})_{15}$ was 0.93 to 0.95 times the mean of the calculated values (Table 4). The distributions of the $(\mathrm{EI})_{15}$ values estimated by using the OCLR and OCM results for $(I_{30})_{15}$ were closer to the distribution of the calculated values than the distribution obtained by using the TCLR approach (Fig. 5). Therefore, the OCLR and OCM approaches were selected for further testing of method 2. In practice, the OCM approach results were used in the subsequent calculations.

Method 1 overestimated the mean of the calculated values of $(\mathrm{EI})_{15}$ by 4.2% whereas method 2 underestimated this value by 7.4% (Table 4). Therefore, method 1 was more accurate than method 2. In both cases, however, the discrepancies between the estimated and the calculated values were of little practical importance.

Table 4 Intercept (b_0), slope (b_1) and coefficient of determination (r^2) of the relationships between erosivity variables corresponding to two rainfall measurement intervals, Δt (Δt = 15 and 60 min) for different approaches of analysis of the experimental data and comparison between the mean and the coefficient of variation (CV) of the calculated and the estimated erosivity data obtained by two estimation methods of the single-storm erosion index

Method	Dependent variable[a]	Independent variables[a]	Approach[b]	b_0	b_1	r^2	Calculated		Estimated	
							Mean	CV (%)	Mean	CV (%)
1	$(EI)_{15}$	$(EI)_{60}$	TCLR	34.339 (27.495–41.183)[c]	1.267 (1.235–1.300)	0.922	136.9	187.4	136.9	179.9
			OCLR		1.330 (1.297–1.363)	0.907			107.6	240.2
			OCM		1.762 (1.700–1.823)				142.6	240.2
2	$(E)_{15}$	h_{ev}	OCLR		0.205 (0.202–0.208)	0.953	5.84	85.8	6.06	76.2
	$(I_{30})_{15}$	$(I_{30})_{60}$	TCLR	1.800 (1.071–2.529)	1.492 (1.435–1.548)	0.845	17.2	73.3	17.0	63.4
			OCLR		1.603 (1.568–1.638)	0.837			16.3	70.2
			OCM		1.600 (1.514–1.686)				16.3	70.3
	$(EI)_{15}$	h_{ev}, $(I_{30})_{60}$	TCLR for $(I_{30})_{15}$				136.9	187.4	129.7	170.2
			OCLR for $(I_{30})_{15}$						127.0	177.0
			OCM for $(I_{30})_{15}$						126.8	177.1

[a] EI (MJ mm ha^{-1} h^{-1}) is the single storm erosion index, E (MJ ha^{-1}) is the total storm kinetic energy, I_{30} (mm h^{-1}) is the maximum 30-min rainfall intensity, h_{ev} (mm) is the storm rainfall depth. The subscript is the rainfall measurement interval in min.

[b] TCLR: Two Coefficients – Linear Regression analysis; OCLR: One Coefficient – Linear Regression analysis; OCM: One Coefficient – Median.

[c] Confidence intervals at the 95% level.

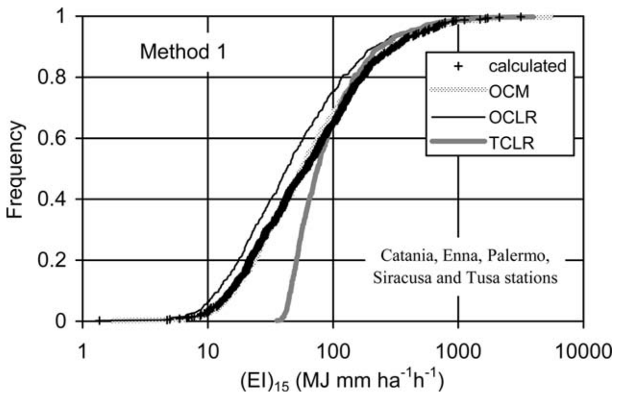

Figure 3 Comparison between the cumulative empirical frequency distributions of the calculated and the estimated (method 1) reference single-storm erosion index values, $(EI)_{15}$.

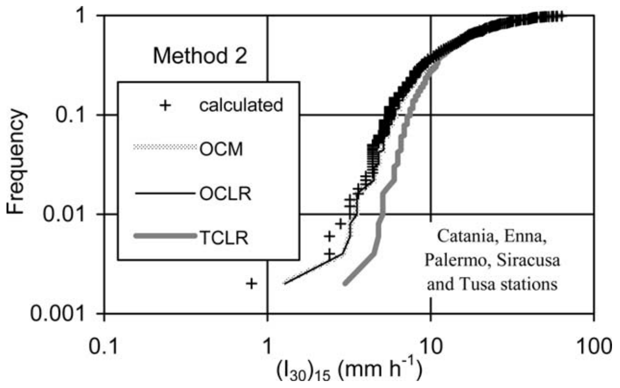

Figure 4 Comparison between the cumulative empirical frequency distributions of the calculated and the estimated (method 2) reference maximum 30-min rainfall intensity, $(I_{30})_{15}$.

Compared to the mean of the calculated values of $(EI)_{15}$, method 1 produced an overestimation by 7.3% at the test station of Caltanissetta and an underestimation by 0.4% at Cefalù (Table 5). For method 2, the predictions were lower than the calculations by 11.0% and 4.6%, respectively (Table 5). Both methods produced empirical frequency distributions of $(EI)_{15}$ close to the ones of the calculated values (Fig. 6). Therefore, method 1 performed better than method 2 but the loss in accuracy associated to this last method was of little significance and both methods allowed to approximate satisfactorily the calculated values of the single-storm erosion index at the two test stations.

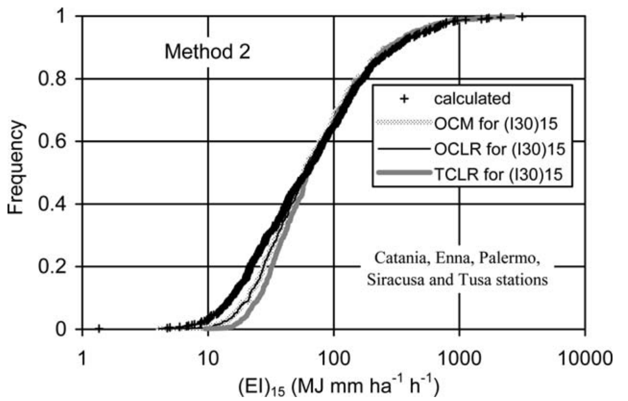

Figure 5 Comparison between the cumulative empirical frequency distributions of the calculated and the estimated (method 2) reference single-storm erosion index values, $(EI)_{15}$.

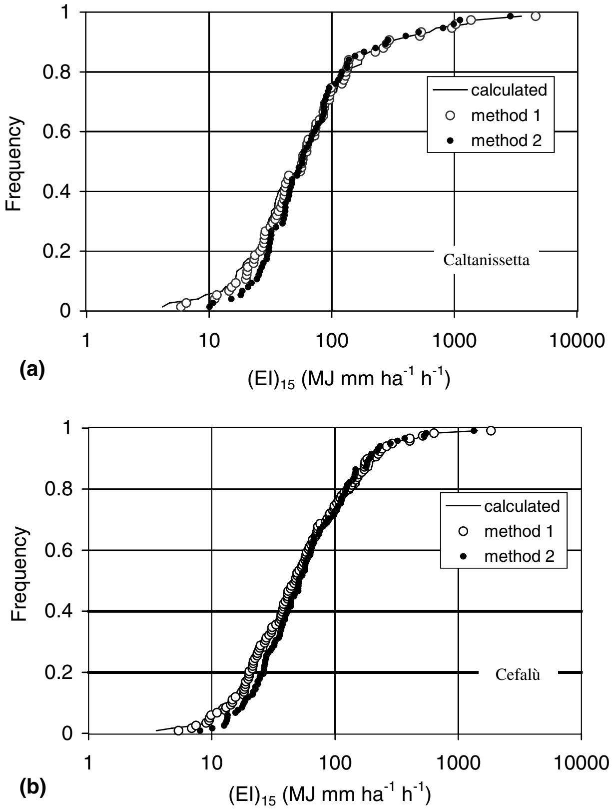

Figure 6 Comparison between the cumulative empirical frequency distributions of the calculated and the estimated reference single-storm erosion index values, $(EI)_{15}$, at the test sites of (a) Caltanissetta and (b) Cefalù.

Table 5 Calculated and estimated mean and coefficient of variation (CV) values of the single-storm erosion index corresponding to a measurement time interval of 15 min for the two test locations

Location	Calculated		Estimated			
			Method 1		Method 2	
	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
Caltanissetta	173.5	267.0	186.2	306.5	154.4	243.4
Cefalù	97.5	165.0	97.1	197.0	93.0	158.3

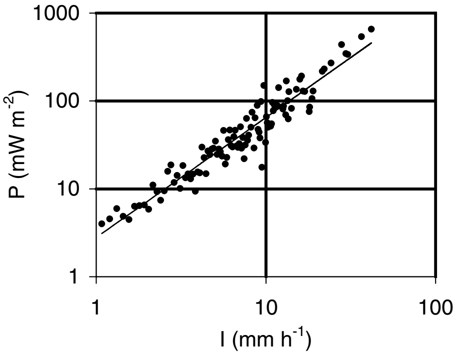

Figure 7 Power, *P*, vs. intensity, *I*, relationship for rainfall data aggregated at 5 min time intervals.

Method 1, using a continuous record of rainfall intensity, should be preferred to estimate $(EI)_{15}$ from hourly rainfall data. When only the rainfall depth and the maximum rainfall intensity are available, method 2 may be used without experiencing an appreciable loss in the accuracy of the predictions.

Effect of rainfall measurement interval on the measured energy

For each considered time interval, Δt ($5\ \text{min} \leqslant \Delta t \leqslant 60\ \text{min}$, $N = 8$), the best relationship interpolating the experimental (I, P) data had the following form:

$$P = aI^n \tag{7}$$

where a and n are empirical coefficients. The comparison between the (I,P) data pairs and Eq. (7) is shown in the example of Fig. 7 for $\Delta t = 5$ min. Eq. (7) was also applied successfully by Salles et al. (2002). For the selected events, the coefficient a increased with Δt from a minimum of 2.8 to a maximum of 3.7 (Fig. 8). The values of n were in the range 1.26–1.38 and they showed a slight decreasing trend for Δt increasing from 5 min to 60 min (Fig. 8).

For selected rainfall intensity values ($5\ \text{mm h}^{-1} \leqslant I \leqslant 30\ \text{mm h}^{-1}$), the estimates of P obtained by Eq. (7) for different rainfall measurement intervals were nearly constant (Fig. 9). For each considered intensity, the deviations between an individual estimate of P (i.e., corresponding to a given Δt value) and the mean of the eight estimates of P fell in the range ±10%. Therefore, the rainfall measurement time interval did not affect appreciably the energy characteristics for given intensity.

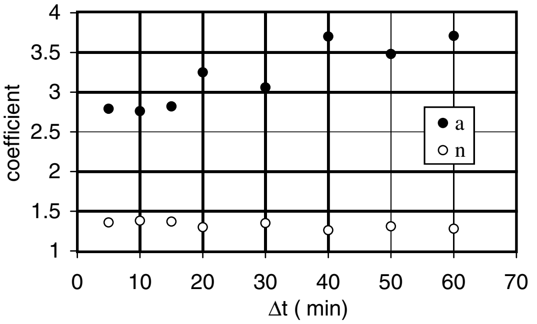

Figure 8 Coefficients a and n of Eq. (7) for different rainfall measurement intervals, Δt.

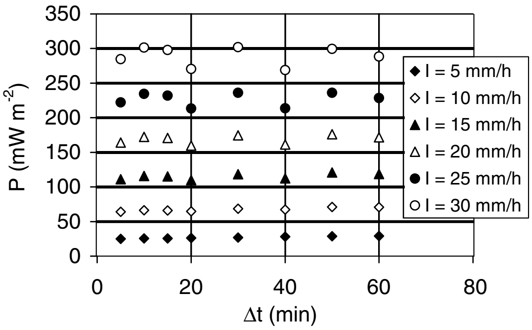

Figure 9 Power, *P*, vs. rainfall measurement interval, Δt, for selected values of rainfall intensity, *I*.

Summary and conclusions

In this investigation, the influence of the rainfall measurement interval on the determination of erosivity was evaluated for a Mediterranean semi-arid area.

The total storm kinetic energy, E, maximum 30-min rainfall intensity, I_{30}, and single-storm erosion index, EI, corresponding to three rainfall measurement intervals, Δt ($\Delta t = 5$, 15 and 60 min), were calculated for approximately 700 erosive events observed at seven Sicilian locations by applying the original procedure used in the USLE. The E, I_{30} and EI values obtained from rainfall data aggregated at 15 min time intervals were chosen as the reference data since this time interval appears to be the shortest one that can be practically considered for reasonably accurate erosivity calculations over large areas of the world.

Erosivity data obtained for both $\Delta t = 5$ min and $\Delta t = 60$ min were compared to the reference data. The decrease of Δt from 15 min to 5 min resulted in an increase of the mean value of EI by a maximum factor of 1.10. The increase of Δt from 15 min to 60 min produced, at the most, a decrease of the mean value of EI by a factor of two. The decrease of EI was essentially due to the decrease of the I_{30} determinations whereas the decrease of E had a minor impact on the EI results. It was concluded that using hourly rainfall data in place of the reference ones to estimate EI should be avoided since the level of underestimation of soil loss may be appreciable. In the range $5\ \text{min} \leqslant \Delta t \leqslant 15\ \text{min}$, the rainfall measurement interval has a practically negligible effect on the predicted erosivity and soil loss values.

The single-storm erosion index, $(EI)_{60}$, and the maximum 30-min rainfall intensity, $(I_{30})_{60}$, deduced from hourly rainfall data, and the storm rainfall depth, h_{ev}, were used for estimating the reference single-storm erosion index, $(EI)_{15}$. Two methods were developed. The first method (method 1) consists of using the $(EI)_{60}$ data for estimating $(EI)_{15}$. The h_{ev} and $(I_{30})_{60}$ data are used with method 2. Therefore, the two methods differ by the required input data. For a given storm, a continuous record of rainfall intensity has to be available to apply method 1. Only the storm rainfall depth and the maximum rainfall intensity are necessary for applying method 2. For both methods, more accurate estimates of $(EI)_{15}$ were obtained by assuming that the reference and the hourly data differed by a scale factor than by using linear regression procedures to deduce a relationship between the two variables. The estimated and the calculated values of $(EI)_{15}$ were compared for two independent data sets. A maximum discrepancy of 7% and 11% was observed for methods 1 and 2, respectively. It was concluded that both methods yielded satisfactory estimates of the calculated erosion index values. Method 1 should be preferred to estimate $(EI)_{15}$ from hourly rainfall data. When only a restricted information on the erosive event is available, method 2 may be used without experiencing substantial losses in the accuracy of the predictions.

Finally, a comparison among the experimental rainfall power, P, values deduced for different Δt values ($5\ \text{min} < \Delta t \leqslant 60\ \text{min}$) was carried out by using kinetic energy data measured at Palermo's University. For a given rainfall intensity, the discrepancies between the values of P corresponding to selected Δt values and the associated mean were in the range ±10%. Therefore, the effect of the rainfall measurement time interval on the rainfall energy characteristics was small and of little practical importance. Both the indirect approach, based on an empirical relationship for calculating E, and the direct one, based on measured kinetic energies, suggested that the effect of the rainfall measurement interval on the rainfall energy characteristics was practically negligible.

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