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ANALYSIS OF RAINFALL EROSIVITY USING DISDROMETER DATA AT TWO STATIONS IN CENTRAL SLOVENIA

ANALIZA EROZIVNOSTI PADAVIN NA DVEH MERILNIH MESTIH V OSREDNJI SLOVENIJI Z UPORABO PODATKOV Z DISDROMETROV

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Abstract

Erosive rainfall events can cause significant problems in agriculture and other fields because of fertile soil losses. Therefore, high-frequency measurements of rainfall data are useful in order to improve our knowledge about this issue. This study presents rainfall measurements in years 2013, 2014 and 2015 at two locations in central Slovenia, namely Ljubljana and Črni vrh nad Polhovim Gradcem, which are located in temperate-continental climate. 1-minute rainfall data analysed in this study was measured using optical disdrometer. Results indicate large variability in rainfall erosivity at relatively short distances. Some specific extreme events can lead to rainfall erosivity values up to average annual rates. Large seasonal variability of erosivity was also observed in the measured data. Moreover, several *KE-I* equations were tested and the results show that locally developed equations are more suitable to estimate rainfall erosivity in cases where no disdrometer data is available.

Keywords: rainfall measurements, disdrometer, rainfall erosivity, seasonal variability.

Izvleček

Erozivni padavinski dogodki lahko povzročijo velike probleme v kmetijstvu in ostalih dejavnostih zaradi izgub rodovitne zemljine. Meritve padavin z visoko frekvenco zajema podatkov so s tega vidika uporabne za izboljšanje našega razumevanja o procesih erodiranja zemljine. V prispevku je predstavljena analiza meritev padavin v letih 2013, 2014 in 2015 na dveh lokacijah v osrednjem delu Slovenije, Ljubljani in Črnem Vrhu nad Polhovih Gradcem, ki ju lahko okarakteriziramo z zmernimi celinskimi podnebnimi značilnostmi. Minutni padavinski podatki uporabljeni v tej raziskavi so bili pridobljeni z optičnima disdrometroma. Rezultati kažejo na veliko spremenljivost erozivnosti padavin na relativno kratkih razdaljah. Erozivnost posameznih ekstremnih opazovanih padavinskih dogodkov lahko doseže letne vrednosti erozivnosti padavin na posamezni postaji. Na osnovi merjenih podatkov je bila opažena tudi velika sezonska spremenljivost erozivnosti. Nadalje so bile testirane različne enačbe, ki povezujejo kinetično energijo dežnih kapljic in intenziteto padavin (t.i. *KE-I* enačbe). Rezultati kažejo, da so enačbe pridobljene na osnovi lokalno merjenih

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podatkov bolj primerne za oceno erozivnosti dežja v primerih, ko ni lokalno razpoložljivih podatkov z naprav kakršen je disdrometer.
Ključne besede: meritve padavin, disdrometer, erozivnost padavin, sezonska spremenljivost.

1. Introduction

Soil loss due to water erosion is an alarming phenomenon that leads to degradation of millions of hectares of croplands each year (Casazza, 2016). Several models for estimating soil loss are available (Angulo-Martínez et al., 2016), among these one of the most frequently used is the RUSLE method (Revised Universal Soil Loss Equation), developed by the USDA (United States Department of Agriculture) (USDA, 1997; Mikoš et al., 2006). RUSLE equation consist of six factors that take into account the effect of rainfall erosivity (*R*), soil erodibility (*K*), slope length (*L*), slope steepness (*S*), land-use cover management (*C*) and support practice (*P*) (USDA, 1997). Direct measurements of erosion are needed to calibrate these models in different environmental conditions (Todisco et al., 2009).

The erosivity of a rainfall is its ability to erode soil particles by splash and runoff (Angulo-Martínez et al., 2016). Technically it indicates detachment and transport capacity (Casazza, 2016), whereas physically it describes the process of disaggregation and detachment of soil particles due to the raindrop impact. Drop's diameter, mass, velocity, shape, fall height, force and impact pressure all influence the rainfall erosivity and consequently also soil erosion (Pandit and Isaac, 2015).

The rainfall erosivity factor can be estimated using rainfall data and is frequently analysed in different environmental studies. Moreover, due to the climate change, the rainfall erosivity factor may change, which could lead to higher soil loss rates in the future (Zhang et al., 2010). To simplify the calculation and in order to correctly identify the erosivity one should use a single or few estimators that include the most important properties of these factors (Van Dijk et al., 2002). Both momentum and kinetic energy (*KE*) are good for this purpose (Fornis et al., 2005). As an example, RUSLE methodology uses *KE* to estimate rainfall erosivity (USDA, 1997).

We can assume that each falling raindrop causes disaggregation and mobilization of soil particles because of its *KE* (Angulo-Martínez et al., 2016). Thus, the erosivity of a specific rainfall event is the sum of erosivity of all the drops (Carollo and Ferro, 2011). *KE* is a function of velocity and mass ($KE=0.5 \cdot m \cdot v^2$) and both quantities are functions of the dimension of the drops. Using the Drop-Size Distribution (DSD) and velocity data one can estimate *KE*. If the DSD is available, it is possible to calculate final fall velocity using various formulas (Kinnel, 1976; Hinkle et al., 1987; Cerro et al., 1998; Van Dijk et al., 2002; Angulo-Martínez et al., 2016; Casazza, 2016; Carollo et al., 2016).

For practical purposes, a good estimation of the *KE* can be calculated based on the rainfall intensity (*I*), because of data availability and its relationship to the DSD. However, this indicator is only an approximation, because factors other than *I* determine the DSD (Van Dijk et al., 2002; Fornis et al., 2005; Carollo and Ferro, 2011; Pandit an Isaac, 2015; Angulo-Martínez et al., 2016). Large number of papers deal with this issue and several linear, polynomial, exponential, power low and logarithmic equations has been proposed (Table 1), confirming that a single relationship valid for all climate conditions around the world does not exist. In the area close to the location of measurements, the *KE-I* relationship usually fits well. Thus, it can be useful to develop equations for regions where they are still not available (Cerro et al., 1998; Pandit and Isaac, 2015; Angulo-Martínez et al., 2016; Casazza, 2016). Sometimes also local equations show spurious fit to different kinds of measured rainfall (Cerro et al., 1998; Van Dijk et al., 2002; Fornis et al., 2005; Angulo-Martínez and Barros, 2015) or at different elevation (even though studies are discordant on this issue) (Angulo-Martínez and Barros, 2015; Pandit and Isaac, 2015; Angulo-Martínez et al., 2016).

A measuring equipment such as disdrometer is needed in the phases of developing and calibration of the *KE-I* relationship because it allows measurements of direct values of *KE* using the DSD information. Optical or laser disdrometers are the most recommended and also most widely used (Cerro et al., 1998; Fornis et al., 2005; Angulo-Martínez et al., 2016). Nevertheless, their measurements are affected by several errors due to intrinsic factors (limits of detection, simultaneous detection of drops, impact of raindrops on the device), and external factors (wind, natural coalescence and breaking of raindrops) (Salles and Poesen, 1999; Van Dijk et al., 2002; Lanzinger et al., 2006; Sasi Kumar et al., 2007; Angulo-Martínez et al., 2016). The difference among sensors causes difficulties in data comparison (Angulo-Martínez and Barros, 2015), while Lanzinger et al. (2006) showed disagreement among disdrometers of the same model. When comparing measurements of intensity and rainfall depth using disdrometers with the same data from a rain gauge, some studies noticed an overestimation (Fornis et al., 2005; Lanzinger et al., 2006, Petan et al. 2010), while others noticed an underestimation (Salles and Poesen, 1999; Sasi Kumar et al., 2007; Angulo-Martínez and Barros, 2015) of the data measured with disdrometer.

KE itself is not sufficient to represent rainfall erosivity. Another factor that should be taken into account is the temporal distribution of rain intensity. Usually rainfall has low average intensity with some peaks. In order to obtain the rainfall erosivity index (*EI*) for RUSLE equation, *KE* must be multiplied with the highest thirty-minute intensity (I_{30}) (USDA, 1997; Van Dijk et al., 2002; Mikoš et al., 2006; Angulo-Martínez et al., 2016; Casazza, 2016).

The main aim of this study was to analyse rainfall erosivity using 1-minute rainfall data measured at two locations in Slovenia. The specific aims of the study were as follows: (i) to calculate the *KE* and *EI* using the DSD data for the stations in Ljubljana and Črni vrh nad Polhovim Gradcem, (ii) to evaluate suitability of several *KE-I* equations and (iii) to analyse temporal variability in the rainfall erosivity.

2. Methodology

Data from two optical disdrometers located in Črni vrh nad Polhovim Gradcem and in Ljubljana (Figure 1) was used in this study in order to observe and analyse properties of rainfall erosivity. Rainfall depth data from these two disdrometers are available in real-time at (KSH, 2016): http://ksh.fgg.uni-lj.si/avp/DisCrniVrh/ (more information about these disdrometers including photos is also available). The elevation of the disdrometers is about 310 and 810 m.a.s.l. for the Ljubljana and Črni vrh disdrometer, respectively.

Figure 2 shows the annual precipitation for these two stations for the period from 1981 to 2010 (ARSO, 2016). Average annual precipitation in the period from 1981 to 2010 was about 1360 and 1580 mm for the Ljubljana and Črni vrh stations, respectively. The rainfall variability at both locations is generally large, whereas summer thunderstorms mostly have the maximum rainfall erosivity. The intensity-duration-frequency curves derived for these two stations are available at: http://meteo.arso.gov.si/uploads/probase/www/climate/table/sl/by_variable/return-periods/Ljubljana%20Bezigrad.pdf and http://meteo.arso.gov.si/uploads/probase/www/climate/table/sl/by_variable/return-periods/Crni%20Vrh%20nad%20Polhovim%20Gradcem.pdf for the Ljubljana and Črni vrh stations, respectively.

Disdrometer data from Ljubljana was collected in the periods from 08/08/2013 to 14/07/2014, from 12/08/2015 to 08/09/2015, and from 01/10/2015 to 25/01/2015. Parsivel 1 disdrometer by OTT, which classifies the raindrops into 32 classes of diameter and 32 classes of speed, producing 1024 classes in total, was used (OTT, 2008). This disdrometer was used in previous studies of rainfall erosivity in Slovenia (e.g., Petan, 2010).

Data from Črni vrh nad Polhovim Gradcem was collected in the period from 16/07/2014 to 17/12/2015. Laser Precipitation Monitor 5.4110 by Thies Clima, which classifies raindrops in 22 classes of diameter and 20 classes of speed, producing 440 classes in total (Thies Clima, 2006), was used in this case study.

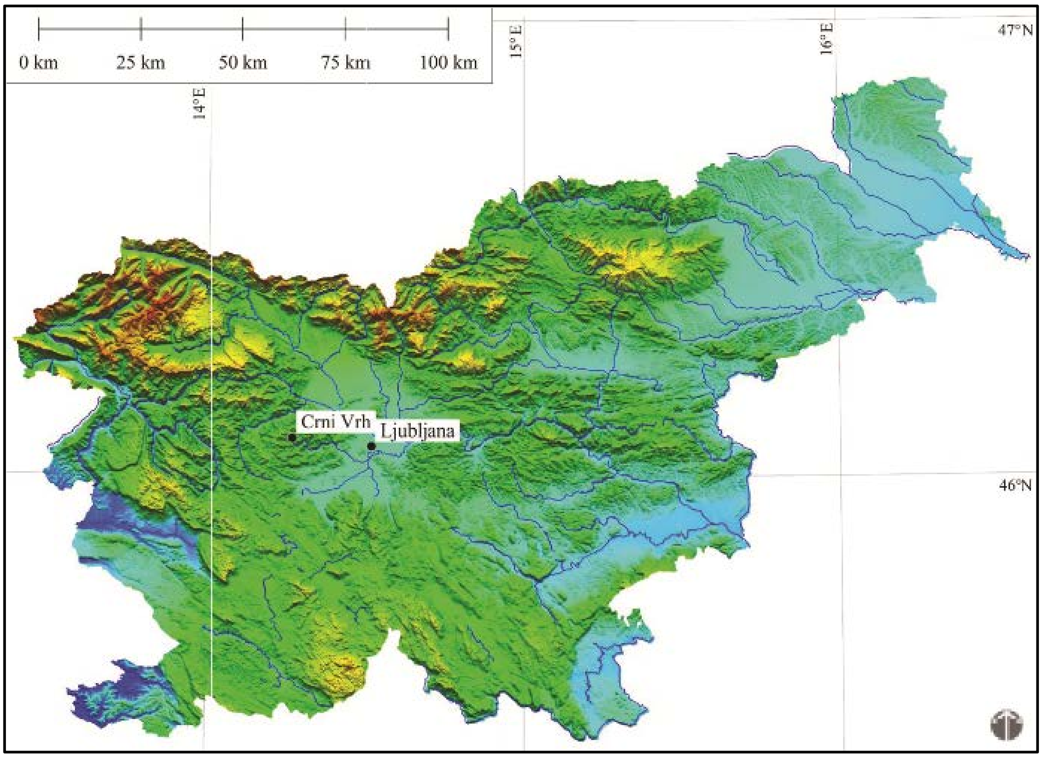


Figure 1: *Location of the optical disdrometers on the topographic map of Slovenia.*
Slika 1: *Lokacija dveh optičnih disdrometrov na topografski karti Slovenije.*

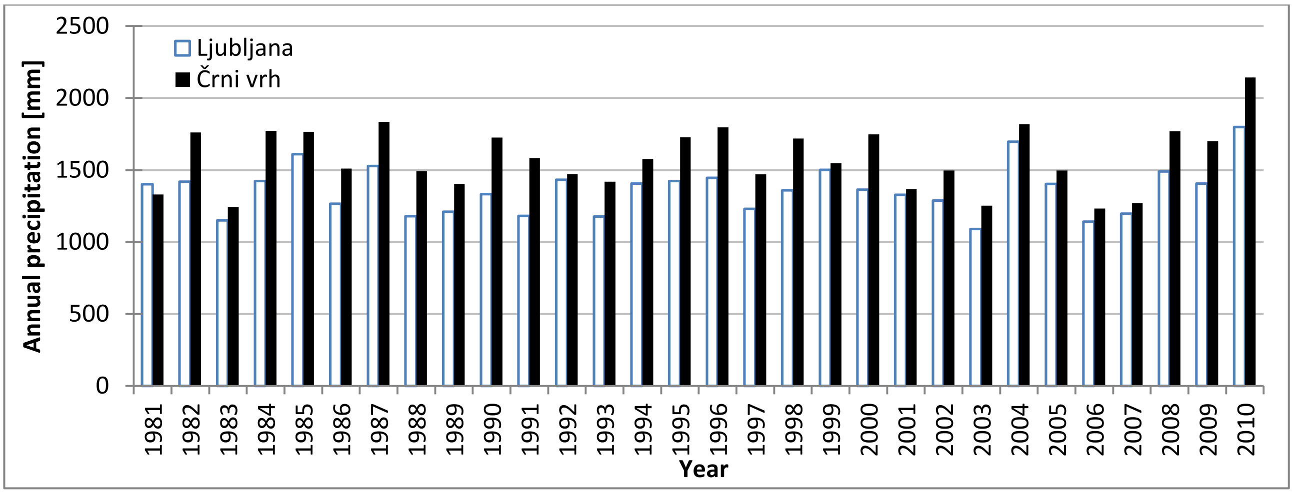


Figure 2: *Annual precipitation values for the Ljubljana and Črni vrh nad Polhovim Gradcem stations.*
Slika 2: *Povprečne letne vrednosti padavin za postaji Ljubljana in Črni vrh nad Polhovim Gradcem.*

Both devices are laser disdrometers that produce a laser beam that is detected (as voltage) by a sensor on the other side of the detection area; the reduction in voltage due to the raindrops passing through the beam makes it possible to determine the dimension of raindrops. In the same way, from the interfering time the device determines the speed of each raindrop (Thies Clima, 2006; OTT, 2008).

Both disdrometers measure several rainfall characteristics such as DSD, rainfall intensity, rainfall depth and precipitation type at 1-minute time intervals. Therefore, 1-minute disdrometer data was used in this study. Before calculating the rainfall erosivity it was necessary to pre-process the data. Classes with diameter larger than 7 mm were not considered in the calculations of the rainfall erosivity because, according to Petan et al. (2010), such large drops are often artefacts of the device, which detects multiple overlapping raindrops as one drop.

Since disdrometers detect the type of precipitation for each 1-minute time interval, it was relatively straightforward to discard minutes with solid winter precipitation (SYNOP code w_aw_a table 4680 types from 67 to 88). Hail (code SYNOP w_aw_a table 4680 types 88 and 89) is usually associated with very intense rainfall, thus it should also be considered for erosivity. Nevertheless, minutes of hail were also detected during snow events. Pre-processing of the data showed that hail events in winter were not meaningful. Thus, minutes with hail during the meteorological winter (December, January and February) (Trenberth, 1983) were not considered in further calculations.

Intensity (I in mm·h^{-1}) was calculated from DSD measured by the disdrometer using the formula from Petan et al. (2010) (equation 1):

$$I = \frac{\pi}{6 \cdot A \cdot \Delta t} \cdot \sum \frac{1}{D_{b,i} - D_{a,i}} \cdot n_i \cdot \int_{D_{a,i}}^{D_{b,i}} D_i^3 dD, \tag{1}$$

where A (mm^2) is the area of detection, Δt (1/60 h) is the interval of data collection, n_i is the number of detected raindrops in the size class I and Di (mm) is the raindrop class diameter ranging from $D_{a,i}$ to $D_{b,i}$.

According to the RUSLE methodology, minutes with rain intensity lower than 0.1 mm·h^{-1} were considered as not rainy (Petan, 2010). Furthermore, minutes with I calculated from DSD larger than the selected threshold level (0.1 mm·h^{-1}), but with zero value of I measured from disdrometer, were not considered in the analysis, because they are probably the result of an incorrect measurement.

Rainfall events were considered as separate if there was a 6-hour interval with no rain between two consecutive events. Moreover, according to the RUSLE manual (USDA, 1997) only rainfall events larger than 12.7 mm, or with more than 6.35 mm in 15 minutes were considered for the calculations of the rainfall erosivity factor (R).

The R factor of the RUSLE equation is the sum of the event's EI (multiplied by 10^{-2} to obtain the result in MJ·mm·ha^{-1}·h^{-1}). The calculation of average annual R factor is based on rainfall erosivity in multiple years (equation 2) (USDA, 1997):

$$R = \frac{\sum_1^j EI}{N}, \tag{2}$$

where j is the number of events, N the number of years, and EI (J·mm·m^{-2}·h^{-1}) the erosivity index of each rainfall event.

As stated in the introduction, EI of an event is calculated with the following equation (3) (USDA; 1997):

$$EI = KE \cdot I_{30}, \tag{3}$$

where KE (J·m^{-2}) is total kinetic energy of the rainfall and I_{30} (mm·h^{-1}) is the maximum 30-minute intensity.

KE per hour (J·m^{-2}·h^{-1}) was calculated using the disdrometer data with the formula from Petan et al. (2010):

$$KE = \frac{\rho \cdot \pi}{12 \cdot 10^3 \cdot A \cdot \Delta t} \cdot \sum_i \frac{1}{D_{b,i} - D_{a,i}} \cdot n_i \cdot \int_{D_{a,i}}^{D_{b,i}} {D_i^3}^3 dD \cdot \frac{1}{v_{b,i} - v_{a,i}} \cdot \int_{v_{a,i}}^{v_{b,i}} {v_i^2}^2 dv, \tag{4}$$

where, in addition to abovementioned terms, ρ (kg·m^{-3}) is the water density and v_i (m·s^{-1}) is the raindrop fall velocity of the class i ranging from $v_{a,i}$ to $v_{b,i}$.

The results calculated using the disdrometer data were compared with KE estimations using 13 different KE-I relationships, chosen from different references (Table 1). The equations were selected based on the geographical criterion, meaning that equations developed for regions close to Slovenia or with similar climate characteristics were used. All equations that had been developed for Europe were tested. Some others equations were also selected due to the following reasons:

- Equation from Van Dijk et al. (2002) since it was defined as general for all climate types;

- Equation from Brandt (1990) because it is used in the EUROSEM (EUROpean Soil Erosion Model) (Morgan et al., 1998);

Equations from Brown and Foster (1987), and USDA (1997) because they are used for USLE-RUSLE model, considered good for Slovenian Alps by Mikoš et al. (2006).

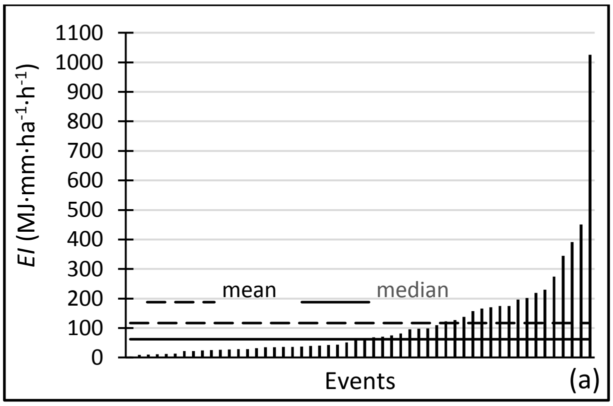
3. Results and discussion

3.1 Calculation of *KE* and *EI* using disdrometer data

As a result of the procedure described in Methodology, 39 independent rainfall events were recognised as erosive according to the mentioned criteria (RUSLE methodology) for the Črni vrh nad Polhovim Gradcem measuring station, while at the Ljubljana measuring station 52 erosive events were identified.

In the next step the *EI* values were calculated for these events for both stations. *EI* values vary among events in the range from 3.79 MJ·mm·ha^{-1}·h^{-1} to 1025.42 MJ·mm·ha^{-1}·h^{-1} in Ljubljana and from 6.08 MJ·mm·ha^{-1}·h^{-1} to 2926.96 MJ·mm·ha^{-1}·h^{-1} for the Črni vrh nad Polhovim Gradcem station. In both cases the distribution of the *EI* values is asymmetric, with median considerably lower than mean; this indicates that *EI* for the majority of events is quite low, but in the observed time periods some relatively high or even extreme events occurred (Figure 3). Furthermore, one can also see that mean *EI* value for events measured in the Črni vrh stations is higher than for the Ljubljana station. Moreover, also the maximum *EI* value for the Črni vrh station is much higher than for the Ljubljana station. This high value is associated with an extreme flood that occurred in the headwaters of the Gradaščica River catchment in August 2014 (Bezak et al., 2016). However, direct comparison of calculated *EI* values between the two stations is not possible because different time period of data was used in this study.

In the period of data collection three events occurred that had return period of maximum 30-minute intensity larger than 5 years (Table 2). These return periods were determined using the intensity-duration-frequency (IDF) curves derived by the Slovenian Environment Agency (ARSO) and are available at: http://meteo.arso.gov.si. Rainfall event that occurred on the 5th of August 2014 had a return period larger than 100 years. This event caused intense soil erosion and sediment transport processes with flash floods in the Gradaščica River catchment (Bezak et al., 2016). The consequences of this event were the worst in the headwater part of the Gradaščica catchment (e.g. Mačkov graben area). The other two events that happened in autumn 2014 were not so extreme in the headwater part and the damage was more uniformly distributed around the entire catchment. More information about these events can be found in Rusjan et al. (2015).



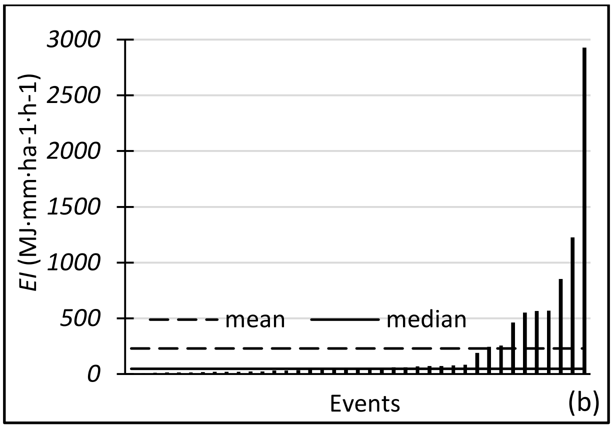


Figure 3: *EI for events recorded in Ljubljana (a) and Črni vrh nad Polhovim Gradcem (b).*

Slika 3: *EI vrednosti za erozivne dogodke, ki so bili izmerjeni v Ljubljani (a) in Črnem vrhu nad Polhovim Gradcem (b).*

Table 1: *An overview of KE-I relationships (equations in bold were used in this study).*
Preglednica 1: *Pregled enačb KE-I (enačbe označene s krepkim tiskom so bile uporabljene v tej študiji).*

Authors	Equation *KE-I* (KE: $J\cdot m^{-2}\cdot h^{-1}$)	*I* range for development ($mm\cdot h^{-1}$)	Location
Blanchard (1953)[a]	$12.7\cdot I\cdot(1\text{-}0.98\cdot e^{-0.011\cdot I})$	<25	Honolulu, HI, USA
Blanchard (1953)[a]	$23.7\cdot I\cdot(1\text{-}0.71\cdot e^{-0.031\cdot I})$	<127	Honolulu, HI, USA
Brandt (1988)[a]	$30\cdot I\cdot(1\text{-}0.56\cdot e^{-0.044\cdot I})$	<105	Manaus, AM, Brasil
Brandt (1990)[b]	$\boldsymbol{I\cdot(8.95+8.44\cdot \log I)}$		Elaboration of data from Marshall and Palmer (1948)
Brown and Foster (1987)[b]	$\boldsymbol{29\cdot I\cdot(1\text{-}0.72\cdot e^{-0.05\cdot I})}$	<250	MS, USA
Carter et al. (1974)[c]	$I\cdot(11.32+0.5546\cdot I-0.5009\cdot 10^{-2}\cdot I^2+0.126\cdot 10^{-4}\cdot I^3)$	<260	MS/LA, USA
Cerro et al. (1998)	$\boldsymbol{38.4\cdot I\cdot(1\text{-}0.528\cdot e^{-0.029\cdot I})}$		Barcellona, Spain
Coutinho and Tomás (1995)[b]	$\boldsymbol{35.9\cdot I\cdot(1\text{-}0.559\cdot e^{-0.034\cdot I})}$	0-120	Mértola, Portugal
Fornis et al. (2005)	$30.8\cdot I\cdot(1-0.55\cdot e^{-0.03\cdot I})$	2.8-142	Cebu, Philippines
Fornis et al. (2005)	$29.02\cdot I^{-71.67}\cdot 3600$	2.8-142	Cebu, Philippines
Fornis et al. (2005)	$12.05\cdot I^{1.19}\cdot 3600$	2.8-142	Cebu, Philippines
Fornis et al. (2005)	$I\cdot(11.93+7.82\cdot \log I)$	2.8-142	Cebu, Philippines
Hudson (1965)[c]	$29.89\cdot I\text{-}128.23$		Zimbawe
Jayawardena and Rezaur (2000)[d]	$36.8\cdot I\cdot(1-0.69\cdot e^{-0.038\cdot I})$	12-120	Hong Kong
Kinnel (1973)[c]	$30.13\cdot I\text{-}165.11$		Miami, FL, USA
Kinnell (1980)[d]	$29.2\cdot I\cdot(1-0.89\cdot e^{-0.048\cdot I})$	19-229	Mozowe, Zimbawe
Kinnell (1980)[d]	$29.3\cdot I\cdot(1-0.28\cdot e^{-0.018\cdot I})$	2-309	Miami, FL, USA
Laws and Parson (1943)[a]	$28.9\cdot I\cdot(1\text{-}0.54\cdot e^{-0.059\cdot I})$	0.4-114	Washington, DC, USA
Lim et al. (2015)[d]	$25.75\cdot I\cdot (1-0.54\cdot e^{-0.05\cdot I})$	0.1-142	Daejeon, Korea
Marshall and Palmer (1948)[a]	$29\cdot I\cdot(1\text{-}0.74\cdot e^{-0.039\cdot I})$	<23	Ottawa, ON, Canada
McGregor and Mutchler (1976)[c]	$I\cdot(27.3+21.68e^{-0.048I}\text{-}41.26e^{-0.072I})$		Holly Springs, MS, USA
McIsaac (1990)[b]	$28.8\cdot I\cdot(1\text{-}0.45\cdot e^{-0.033\cdot I})$	1,.5-194	Panama
McIsaac (1990)[a]	$24.6\cdot I\cdot(1\text{-}0.46\cdot e^{-0.037\cdot I})$	1-193	Franklin, NC, USA
McIsaac (1990)[a]	$29.2\cdot I\cdot(1\text{-}0.51\cdot e^{-0.011\cdot I})$	2-170	Majuro, Marshall Islands
McIsaac (1990)[a]	$25.1\cdot I\cdot(1\text{-}0.4\cdot e^{-0.045\cdot I})$	14-148	Island Beach, NL, USA
McIsaac (1990)[a]	$26.8\cdot I\cdot(1\text{-}0.29\cdot e^{-0.049\cdot I})$	13-180	Bogor, Indonesia
Onaga et al. (1988)[a]	$I\cdot(9.81+10.6\cdot \log I)$		Okinawa, Japan
Petan (2010)	$\boldsymbol{31.6\cdot I\cdot(1\text{-}0.6\cdot e^{-0.061\cdot I})}$	0.1-247	Ljubljana, Slovenia
Petan (2010)	$\boldsymbol{34.1\cdot I\cdot(1\text{-}0.6\cdot e^{-0.04\cdot I})}$	0.1-254	Bovec, Slovenia
Petan et al. (2010)	$\boldsymbol{29.8\cdot I\cdot(1\text{-}0.6\cdot e^{-0.071\cdot I})}$	0.1-288	Koseze, Slovenia
Petan et al. (2010)	$\boldsymbol{31.9\cdot I\cdot(1\text{-}0.6\cdot e^{-0.055\cdot I})}$	0.1-220	Kozjane, Slovenia
Roswell (1986)	$29\cdot I\cdot(1\text{-}0.596\cdot e^{-0.0404\cdot I})$	1-146	Gunnedah, NSW, Australia
Roswell (1986)	$26.35\cdot I\cdot(1\text{-}0.669\cdot e^{-0.0349\cdot I})$	1-161	Bisbane, QLD, Australia
Sánchez-Moreno et al. (2012)[d]	$35\cdot I\cdot (1-0.79\cdot e^{-0.03\cdot I})$	0-157	Cape Verde
Sempere-Torres et al. (1992)[b]	$\boldsymbol{34\cdot I\text{-}190}$	20-100	Cévennes, Fance
Tracy et al. (1984)[a]	$33.6\cdot I\cdot(1\text{-}0.55\cdot e^{-0.052\cdot I})$	<76	Southeast, AZ, USA
Usón and Ramos (2001)[b]	$\boldsymbol{23.4\cdot I\text{-}18}$	0-20	Anoia–Alt Penedès, Spain
USDA (1997)	$\boldsymbol{I\cdot(11.9+8.73\cdot \log I)}$	if I<76 mm/h	Washington, DC, USA
	$\boldsymbol{28.3\cdot I}$	if I>76 mm/h	
Van Dijk et al. (2002)	$\boldsymbol{28.3\cdot I\cdot(1\text{-}0.52\cdot e^{-0.042\cdot I})}$		Elaboration of published data
Van Dijk et al. (2002)	$30.4\cdot I\cdot(1\text{-}0.69\cdot e^{-0.06\cdot I})$	0.3-124	Malangbong, Indonesia
Zanchi and Torri (1980)[b]	$\boldsymbol{I\cdot(9.81+11.25\cdot \log I)}$	1-140	Firenze, Italy

Cited by: [a)] Van Dijk et al. (2002) **[b)]** Petan et al. (2010) **[c)]** Roswell (1986) **[d)]** Angulo-Martínez et al. (2016) **[e)]** Morgan (2001)

Table 2: *An overview of rainfall events with return period of I_{30} larger than 5 years.*

Preglednica 2: *Pregled dogodkov, ki so imeli povratno dobo glede na I_{30} večjo od 5 let.*

Occurrence of the event	Place	I_{30} (mm·h^{-1})	Return period of the event
09/09/2013	Ljubljana	48.6	>10 years
05/08/2014	Črni Vrh	77.6	>250 years
23/06/2015	Črni Vrh	41.1	>5 years

3.2 Evaluation of the *KE-I* relationships

In the next step of the study, several KE-I equations (Table 1) were tested using the disdrometer data from the two stations. Values of one-minute I (calculated applying equation 1) were used to solve the equations; regardless of eventual ranges (shown in Table 1) of I utilized in the development of such equations. Logarithmic and linear equations yielded negative values of KE for I lower than the threshold levels shown in Table 3. These values were assumed to be zero in the calculation of the total KE for individual rainfall events.

The last two equations shown in Table 3 do not actually yield negative values because their threshold level is lower than 0.1 mm·h^{-1} and, as stated above, minutes with intensity lower than 0.1 mm/h were discarded from further analysis.

KE calculated by applying various equations shown in Table 1 were visually compared with *KE* calculated using disdrometer data (Figure 4). Equations that gave the closest fit to the measured data are those that are close to the line that connects coordinates (0,0) and (4000,4000).

In both stations the results were similar with differences in the magnitude scatter. The scatter was larger for the data from the Črni vrh nad Polhovim Gradcem than for the data from the Ljubljana station. This could be expected because for this station the *EI* and *KE* values were generally higher than for the Ljubljana station.

Moreover, we also calculated the Pearson correlation coefficients (CORREL function in Excel was used for this purpose) between measured (calculated from the data) and calculated (estimated using the proposed equations) *KE* values using several equations for both analysed stations (Table 4). The results indicate that the equation proposed by Sempere-Torres et al. (1992) gave the worst fit to the measured disdrometer data (for the Ljubljana station). Moreover, according to literature, its use is suitable only for intensities higher than 20 mm·h^{-1} (Petan et al., 2010). The best agreement between disdrometer data and equations results were obtained using the formulas developed in Slovenia by Petan (2010) and Petan et al. (2010) (Fig. 4 shows results using equation for the Ljubljana region). However, some other equations also produced a similar fit to the data (Table 4). At high values of *I* equations from Coutinho and Tomás (1995) and Cerro et al. (1998) tend to slightly overestimate the disdrometer data, while all the other tested equations shown in Table 1 tend to slightly underestimate the data obtained from the disdrometer. Furthermore, Pearson correlation coefficients shown in Table 4 can be regarded as relatively high for almost all tested equations, which also indicates that changes among compared equations are generally not significant.

Table 3: *Values of I under which KE estimated with linear and logarithmic equation tested in this study are negative.*

Preglednica 3: *Vrednosti I pri katerih so ocenjene vrednosti KE z uporabo linearnih ter logaritemskih enačb negativne.*

Equation	*KE* negative when:
Usón and Ramos (2001)	I>0.76923 mm·h^{-1}
Sempere-Torres et al. (1992)	I>5.58824 mm·h^{-1}
Zanchi and Torri (1980)	I>0.13428 mm·h^{-1}
USDA (1997)	I>0.04334 mm·h^{-1}
Brandt (1990)	I>0.08701 mm·h^{-1}

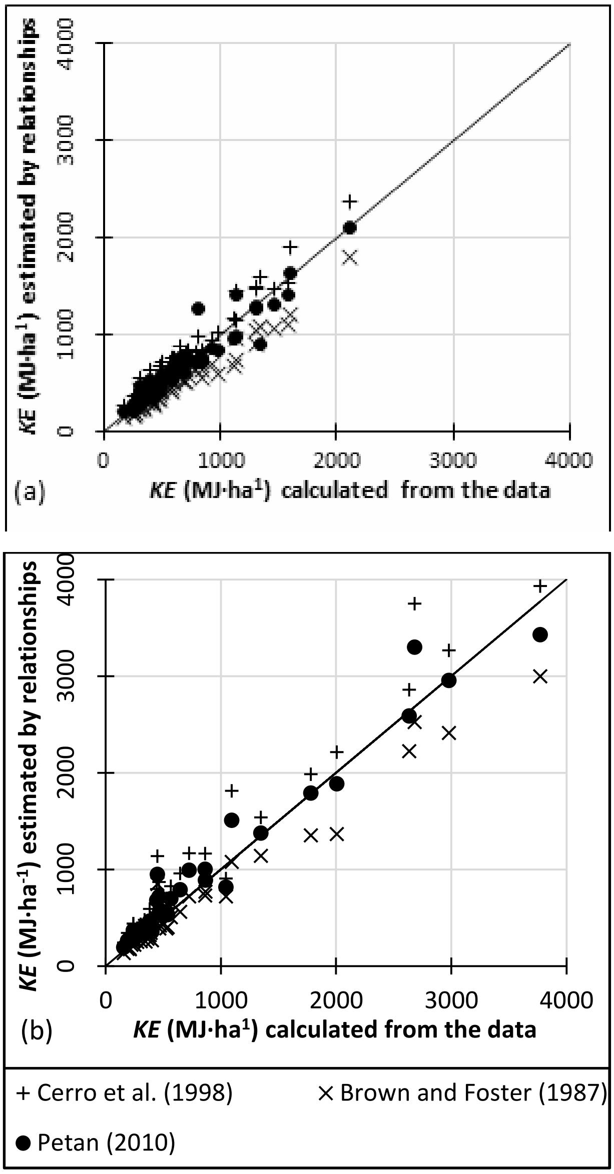


Figure 4: *Example of results for three selected KE-I relationships plotted versus KE estimated using the disdrometer data from Ljubljana (a) and from Črni vrh (b).*

Slika 4: *Primer treh rezultatov izračunov z uporabo 3 izbranih KE-I enačb in KE vrednosti, ki so bile ocenjene z uporabo podatkov z disdrometra za postajo v Ljubljani (a) in Črnem vrhu nad Polhovim Gradcem (b).*

3.3 Temporal variability of erosivity

In the last part of the study the variability in rainfall erosivitiy was observed. Since a complete series of data is not available, it was not possible to determine the *R* factor for complete calendar years, but monthly *R* was determined for each month or part of the month, with data from at least one station (Figure 5).

One can notice that rainfall erosivity in winter is generally smaller than in summer months, which can be expected for the climatic characteristics of Slovenia.

In Ljubljana the average monthly *R* value for about 16 months was 380.1 MJ·mm·ha^{-1}·h^{-1}. This means that average annual *R* value for this period for the Ljubljana station was 4561.0 MJ·mm·ha^{-1}·h^{-1}·y^{-1}.

For the Črni vrh nad Polhovim Gradcem station the average monthly *R* value for about 17 months of records was 527.4 MJ·mm·ha^{-1}·h^{-1} and the average annual value was 6320.9 MJ·mm·ha^{-1}·h^{-1}·y^{-1}.

The computation of average monthly *R* was based on data collected in different periods, and some months are more represented than others. This impedes the direct comparison with average values from other studies (Petan, 2010; Panagos et al., 2015) and also between the two stations. However, these results give an idea about the order of magnitude of erosivity in central Slovenia during the period considered.

4. Conclusions

Disdrometer data used in this study allows an accurate estimation of *KE* and I_{30} factors that determine *EI* (Cerro et al., 1998). *EI* does not consider intra-storm intensity pattern (Angulo-Martínez et al., 2016) and intermittency (Dunkerley, 2015), and is not the most representative for the Mediterranean climate (Pandit and Isaac, 2015). Todisco (2014) showed that in central Italy the parameters used in RUSLE methodology to discern erosive and non-erosive events are not always correct; she proposed an adaption of the theory of runs to compare the patterns of intra storm intensity, given a threshold level of instantaneous intensity.

However, *EI* can still be considered a good indicator of rainfall erosivity (Van Dijk et al., 2002), and it is used in RUSLE methodology (USDA, 1997) that has often been applied all over the world. However, Casazza (2016) suggests going beyond this semi-empirical model and replacing it with a more physical-based model. However, modelling rainfall erosivity using the RUSLE methodology is relatively straightforward despite its drawbacks; it is less data demanding and will probably remain frequently used in the future.

Table 4: *Pearson correlation coefficients between measured and calculated KE values using several equations for the Ljubljana and Črni vrh nad Polhovim Gradcem stations.*

Preglednica 4: *Izračunane vrednosti Pearsonovih koeficientov korelacije med izmerjenimi ter izračunanimi KE vrednostmi za postaji Ljubljana ter Črni vrh nad Polhovim Gradcem.*

Authors	Equations		Stations	
			Ljubljana	Črni vrh
Petan et al. (2010)	$29.8 \cdot I \cdot (1-0.6 \cdot e^{-0.071 \cdot I})$		0.984	0.980
Petan et al. (2010)	$31.9 \cdot I \cdot (1-0.6 \cdot e^{-0.055 \cdot I})$		0.984	0.982
Usón and Ramos (2001)	$23.4 \cdot I - 18$		0.979	0.966
Sempere-Torres et al. (1992)	$34 \cdot I - 190$		0.787	0.923
Coutinho and Tomás (1995)	$35.9 \cdot I \cdot (1-0.559 \cdot e^{-0.034 I})$		0.982	0.980
Cerro et al. (1998)	$38.4 \cdot I \cdot (1-0.538 \cdot e^{-0.029 \cdot I})$		0.981	0.978
Zanchi and Torri (1980)	$I \cdot (9.81+11.25 \cdot \log I)$		0.983	0.984
Wischmeier and Smith (1958)	$I \cdot (11.9+8.73 \cdot \log I)$	if I<76mm/h	0.984	0.977
	$28.3 \cdot I$	if I>76mm/h		
Brown and Foster (1987)	$29 \cdot I \cdot (1-0.72 \cdot e^{-0.05 \cdot I})$		0.976	0.986
Brandt (1990)	$I \cdot (8.95+8.44 \cdot \log I)$		0.984	0.982
Van Dijk et al. (2002)	$28.3 \cdot I \cdot (1-0.52 \cdot e^{-0.042 \cdot I})$		0.982	0.977
Petan (2010)	$31.6 \cdot I \cdot (1-0.6 \cdot e^{-0.061 \cdot I})$		0.958	0.981
Petan (2010)	$34.1 \cdot I \cdot (1-0.6 \cdot e^{-0.04 \cdot I})$		0.957	0.983

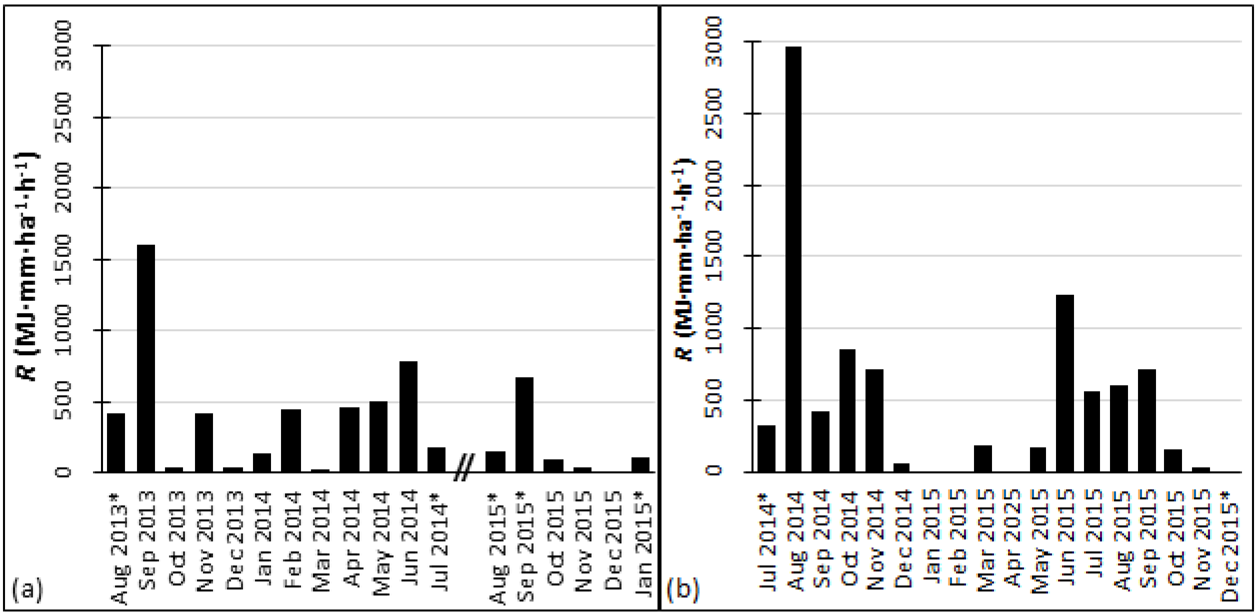


Figure 5: *Monthly R in Ljubljana (a) and in Črni vrh nad Polhovim Gradcem (b). Data for months indicated with asterisk were incomplete.*

Slika 5: *Mesečne vrednosti faktorja erozivnosti padavin R za postaji Ljubljana (a) in Črni vrh nad Polhovim Gradcem (b). Podatki za mesece, ki so označeni z zvezdico niso bili popolni.*

Slovenia has one of the highest rainfall erosivities among European countries. The average annual value of *R* for the Slovenian stations considered by Panagos et al. (2015) in the period 1999-2008 was 2302 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$, while the maximum was 5655.8 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$. Despite to the small size of the country, there is significant variability in the rainfall erosivity among the three climatic regions (mediterranean, alpine, and continental), with a lower *R* in the latter case, where extreme events are less frequent than in the other two climate regions.

In view of these high erosivity values, rainfall erosivity results shown in this paper are still relatively high, especially compared with some other studies (Panagos et al., 2015; Ceglar et al., 2008). Petan (2010) reported mean *R* value of 3153.8 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$ for the Črni vrh nad Polhovim Gradcem and 3625.3 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$ for the Ljubljana station. However, some extreme events that occurred in the observed periods, which could explain the high values. Moreover, the results of this study indicate that one extreme event such as the one in August 2014 in the Gradaščica River catchment (Bezak et al., 2016) can lead to rainfall erosivity higher than average annual values. Data about this event collected in Črni Vrh show an *EI* of 2727.2 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$, corresponding to about 40% of yearly *R* factor of the period August 2014-July 2015. Furthermore, 1-minute rainfall data measured with optical disdrometer was used in this study. This means that higher rainfall erosivity values can be expected than in the case of using e.g. 15 minute rainfall data where some information about the most extreme rainfall intensity can be lost.

The highest values of rainfall erosivity were observed in summer and beginning of autumn due to extreme events. Similar conclusions about the seasonal distribution of rainfall erosivity was pointed out by Ceglar et al. (2008) and Diodato and Bellocchi (2012) in their works, regarding respectively western Slovenia and the Euro-Mediterranean region.

The comparison of several *KE-I* equations (Table 1) generally confirms the best suitability of locally developed relationships (Angulo-Martínez et al., 2016; Casazza, 2016), whereas general equations showed a tendency to slightly underestimate the *KE* estimated directly from the disdrometer data. Moreover, linear relationships show a greater scatter than the exponential and logarithmic equations and this could mean that these equations are less suitable for Slovenian conditions.

References

Angulo-Martínez, M., Barros, A. P. (2015). Measurement uncertainty in rainfall kinetic energy and intensity relationships for soil erosion studies: An evaluation using PARSIVEL disdrometers in the Southern Appalachian Mountains, *Geomorphology* **228**, 28–40.

Angulo-Martínez, M., Beguería, S., Kyselý, J. (2016). Use of disdrometer data to evaluate the relationship of rainfall kinetic energy and intensity (KE-I), *Science of the Total Environment* **568**, 83–94.

ARSO. 2016. Available at: http://meteo.arso.gov.si (accessed 18/07/2016).

Bezak, N., Grigillo, D., Urbančič, T., Mikoš, M., Petrovič, D., Rusjan, S. (2016). Geomorphic response detection and quantification in a steep forested torrent, *Geomorphology* doi: 10.1016/j.geomorph.2016.06.034.

Blanchard, D. C. (1953). Raindrop size-distribution in Hawaiian rains, *Journal of Meteorology* **10(6)**, 457–473.

Brandt, J. (1988). The transformation of rainfall energy by a tropical rain forest canopy in relation to soil erosion, *Journal of Biogeography* **15**, 41–48.

Brandt, C. J. (1990). Simulation of the size distribution and erosivity of raindrops and throughfall drops, *Earth Surface Processes and Landforms* **15(8)**, 687–698.

Brown, L. C., Foster G. R. (1987). Storm erosivity using idealised intensity distribution, *Transactions of the American Society of Agricultural Engineers* **30(2)**, 379–386.

Carollo, F. G., Ferro, V. (2011). Stima della potenza cinetica della precipitazione a partire da osservazioni disdrometriche di distribuzioni dimensionali delle gocce di pioggia (Estimation of kinetic power of precipitation on the basis of disdrometer observations on raindrop size distribution), *L'Italia Forestale e Montana* **66(6)**, 499–508 (in Italian).

Carollo, F. G., Ferro, V., Serio, M. A. (2016). Estimating rainfall erosivity by aggregated drop size distributions, *Hydrological Processes* **30**, 2119–2128.

Carter, C. E., Greer, J. D., Braud, H. J., Floyd, J. M. (1974). Raindrop characteristics in south central United States, *Transactions of the American Society of Agricultural Engineers* **17(6)**, 1033–1037.

Casazza, M. (2016). Some Metrological Limitations to Rain Impact Computation in Storm Erosivity as Defined in the Revised Universal Soil Loss Equation, Version 2 (RUSLE2), *Journal of Environmental Accounting and Management* **4(1)**, 35–42.

Ceglar, A., Zupanc, V., Kajfez-Bogataj, L. (2008). A comparative study of rainfall erosivity for eastern and western Slovenia, *Acta Agriculturae Slovenica* **91(2)**, 331–341.

Cerro, C., Bech, J., Codina, B., Lorente, J. (1998). Modeling Rain Erosivity Using Disdrometric Techniques, *Soil Science Society of America Journal* **62(3)**, 731–735.

Coutinho, M. A., Tomás, P. P. (1995). Characterisation of raindrop size distribution at the Vale Formoso experimental erosion center, *Catena* **25(1)**, 187–197.

Diodato, N., Bellocchi, G. (2012). Decadal modelling of rainfall–runoff erosivity in the Euro-Mediterranean region using extreme precipitation indices. *Global and Planetary Change* **86**, 79–91.

Dunkerley, D. (2015). Intra-event intermittency of rainfall: an analysis of the metrics of rain and no-rain periods, *Hydrological Processes* **29**, 3294–3305.

Fornis, R. L., Vermeulen, H. R. Nieuwenhuis, J. D. (2005). Kinetic energy–rainfall intensity relationship for Central Cebu, Philippines for soil erosion studies, *Journal of Hydrology* **300**, 20–32.

Hinkle, S. E., Heermann, D. F., Blue, M. C. (1987). Falling Water Drop Velocities at 1570 m Elevation, *Transactions of the American Society of Agricultural Engineers* **30(1)**, 94–100.

Hudson, N. W. (1965). The influence of rainfall on the mechanics of soil erosion, M.S. thesis, University of Cape Town.

Jayawardena, A. W., Rezaur, R. B. (2000). Drop size distribution and kinetic energy load of rainstorms in Hong Kong, *Hydrological Processes* **14(6)**, 1069–1082.

Kinnel, P. I. A. (1973). The problem of assessing the erosive power of rainfall from meteorological observations, *Soil Science Society of America* Journal **37(4)**, 617–621.

Kinnel, P. I. A. (1976). Some Observations on the Joss-Waldvogel Rainfall Disdrometer, *Journal of Applied Meteorology* **15(5)**, 499–502.

Kinnell, P. I. A. (1980). Rainfall intensity-kinetic energy relationships for soil loss prediction, *Soil Science Society of America Journal* **45(1)**, 153–155.

KSH. 2016. Available at: http://ksh.fgg.uni-lj.si (accessed 21/07/2016).

Lanzinger, E., Theel, M., Windolph, H., (2006). Rainfall amount and intensity measured by the Thies laser precipitation monitor. TECO-2006—WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, Geneva, Switzerland, World Meteorological Organisation, Instruments and observing methods, IOM No. 94. 3(3).

Laws, J. O., Parsons, D. A. (1943). The relation of raindrop-size to intensity, *Transactions American Geophysical Union* **24(2)**, 452–460.

Lim J. S., Kim J. K., Kim J. W., Park B. I., Kim M. S. (2015). Analysis of the relationship between the kinetic energy and intensity of rainfall in Daejeon, Korea, *Quaternary International* **384**, 107–117.

Marshall, J. S., Palmer, W. M. K. (1948). The distribution of raindrops with size. *Journal of meteorology* **5(4)**, 165–166.

McGregor, K. C., Mutchler, C. K. (1976). Status of the R factor in Northern Mississipi. Procedings of National Conference on Soil Erosion, Purde university, West Lafayette, IN, pp. 135–142.

McIsaac, G. F. (1990). Apparent geographic and atmospheric influences on raindrop sizes and rainfall kinetic energy, *Journal of Soil and Water Conservation* **45(6)**, 663–666.

Mikoš, M., Jošt, D., Petkovšek, G. (2006). Rainfall and runoff erosivity in the alpine climate of north Slovenia: a comparison of different estimation methods, *Hydrological Sciences–Journal* **51(1)**, 115–126.

Morgan, R. P. C., Quinton, J. N., Smith, R. E., Govers, G., Poesen, J. W. A., Auerswald, K., Chisci, G., Torri, D., Styczen, M. E., Folly, A. J. V. (1998). The European Soil Erosion Model (EUROSEM): documentation and user guide, Version 3.6, Cranfield University, 30 pp.

Morgan, R. P. C. (2001). A simple approach to soil loss prediction: a revised Morgan–Morgan–Finney model, *Catena* **44(4)**, 305–322.

Onaga, K., Shirai, K., Yoshinaga, A. (1988). Rainfall erosion and how to control its effects on farmland in Okinawa, in: S. Ž. Rimwanich, Ed., *Land Conservation for Future Generations*. Department of Land Development, Bangkok, pp. 627–639.

OTT (2008). Operating instructions, Present Weather Sensor Parsivel. Kempten, OTT MESSTECHNIK GmbH & Co. 48 pp.

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Perčec Tadić M., Michaelides S., Harabariková M., Olsen P., Aalto J., Lakatos M., Rymszewicz A., Dumitrescu A., Beguería S., Alewell C. (2015). Rainfall erosivity in Europe, *Science of the Total Environment* **511**, 801–814.

Pandit, D. V., Isaac, R. K. (2015). A Scenario of Rainfall Erosivity Index Research, *International Journal of Engineering Research* **4(12)**, 668–672.

Petan, S., Rusjan, S., Vidmar, A., Mikoš M. (2010). The rainfall kinetic energy–intensity relationship for rainfall erosivity estimation in the mediterranean part of Slovenia, *Journal of Hydrology* **391**, 314–321.

Petan, S. (2010). Meritive in modeliranje erozivnosti padavin kot parametra erozije tal (measurements and spatial modelling of rainfall erosivity as a soil erosion factor) Doctoral Thesis, Univerza v Ljubljani, FGG, 205 pp. (in Slovenian).

Roswell, C.J. (1986). Rainfall Kinetic Energy in Eastern Australia, *Journal of Climate and Applied Meteorology* **25**, 1695–1701.

Rusjan, S., Mikoš, M., Bezak, N. (2015). Vodna erozija v porečju Gradaščice=Water erosion in the Gradaščica River catchment. *Ujma* **29**, 79–84.

Salles, C., Poesen, J. (1999). Performance of an optical spectro pluviometer in measuring basic rain erosivity characteristics, *Journal of Hydrology* **218**, 142–156.

Sánchez-Moreno, J. F., Mannaerts, C. M., Jetten, V., Löffler-Mang, M. (2012). Rainfall kinetic energy–intensity and rainfall momentum–intensity relationships for Cape Verde, *Journal of Hydrology* **454**, 131–140.

Sasi Kumar, V., Sampath, S., Vinayak, P. V. S. S. K., Harikumar, R. (2007). Rainfall intensity characteristics at coastal and high altitude stations in Kerala, *Journal of Earth System Science* **116(5)**, 451–463.

Sempere-Torres, D., Salles, C., Creutin, J. D., Delrieu, G. (1992). "Quantification of soil detachment by raindrop impact: performance of classical formulae of kinetic energy in Mediterranean storms" in: J. Bogen, D. E. Walling, T. Day, Eds., *Erosion and Sediment Transport Monitoring Programmes in River Basins*. IAHS Publ. 210, Oslo, pp. 115–124.

Thies Clima (2006). Laser Precipitation Monitor, Instruction for use 021341/02/06. Gottigen Adolf Thies GmbH & Co. 56 pp.

Todisco, F., Mannocchi, F., Vergni, L., Vinci, A. (2009). Plot scale measurements of rainfall erosion losses in central Italy. The Role of Hydrology in Water Resources Management, Capri, Italy. IAHS Publ. **327**, 324–327.

Todisco, F. (2014). The internal structure of erosive and non-erosive storm events for interpretation of erosive processes and rainfall simulation, *Journal of Hydrology* **519**, 3651–3663.

Tracy, F. C., Renard, K. G., Fogel, A. M. (1984). Rainfall energy characteristics for southeastern Arizona. Proceedings of American Society of Civil Engineering, IDD Speciality conference "Water-Yoday and Tomorrow", Flagstaff, Arizzona, pp. 559–566.

Trenberth, K. E. (1983). What are the seasons?, *Bulletin of the American Meteorological Society* **64(11)**, 1276–1282.

USDA (1997). Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE), *Agriculture handbook Number 703*, 385 pp.

Usón, A., Ramos, M. C. (2001). An improved rainfall erosivity index obtained from experimental interrill soil losses in soils with a Mediterranean climate, *Catena* **43(4)**, 293–305.

Van Dijk, A. I. J. M., Bruijnzeel, L. A., Rosewell, C. J. (2002). Rainfall intensity–kinetic energy relationships: a critical literature appraisal, *Journal of Hydrology* **261**, 1–23.

Zanchi, C., Torri, D. (1980). "Evaluation of rainfall energy in central Italy" in: M. De Boodt, D. Gabriels, Eds., *Assessment of Erosion*. Wiley, Toronto, pp. 133–142.

Zhang, Y. G., Nearing, M. A., Zhang, X. C., Xie, Y., Wei, H. (2010). Projected rainfall erosivity changes under climate change from multimodel and multiscenario projections in Northeast China, *Journal of hydrology* 384(1), 97–106.