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Comparison of two methods of erosive rains determination

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Abstract: Number of erosive rains, kinetic energy of erosive rains and factor of erosive efficiency of rains according to the USLE methodology were assessed by two methods of erosive rains determination. The first method (VAR1) defined erosive rains by intensity ≥ 0.4 mm·min^{-1}; total ≥ 12.5 mm and the second method (VAR2) by intensity ≥ 6 mm·15 min^{-1}; total ≥ 12.5 mm. Database contained one minute precipitation data from four automatic stations in the Czech Republic for the period of 2000–2005. Two-way analysis of variance (ANOVA) showed a statistically highly significant difference between the annual number of erosive rains determined by the two methods. The rains simultaneously complying with two following criteria (30 min intensity lower than 15 mm·h^{-1} and sum of 40 mm) were not generally classified as erosive rains according to VAR2. The number of erosive rains determined by VAR2 most often reached 40 to 50% of VAR1 results. Two-way ANOVA proved highly significant differences between the kinetic energy values for the erosive rains determined by VAR1 a VAR2. According to VAR2 the rains with kinetic energy lower than 3 MJ·ha^{-1} are generally not considered as erosive rains. The results of kinetic energy of the erosive rains determined by VAR2 most often reached 60 to 70% of VAR1 results. Two-way ANOVA has not proved a statistical difference between annual values of R factor of erosive rains determined by the two methods. According to VAR2 the rains with R factor lower than 5 are in general not included into annual R

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factor value. The results of annual R factor values of erosive rains determined by VAR2 are about 25% lower than the results of VAR1. Correlation between number of erosive rains, kinetic energy of erosive rains and annual R factor value assessed by both methods showed a statistically significant relationship. The conversion formulas between results of the two methods (VAR1 and VAR2) were derived by linear regression. As conclusion we can state that when using present automatic stations in R factor analyses, we have to be aware of overestimating the erosivities compared to historical data based on ombrograms, where only low temporal resolution data were available.

Key words: R factor, rain intensity, kinetic energy, erosion

1. Introduction

Water erosion on agricultural lands is extremely important degradation process worldwide. In former Czechoslovakia the soil loss has reached very high values since collectivization of agriculture in the socialist period in 20th century (*Van Rompaey et al., 2003*). To evaluate the significance of climate for erosion is quite difficult. It is not the same as to assess the overall balance of precipitation and runoff or precipitation totals.

The erosion process is episodic and is mostly caused by extreme precipitation events (summer thunderstorms and torrential rains). For the Czech Republic *Mužíková et al. (2011)* describe increase of precipitation sums in some months in the future. Procedure for the evaluation of erosion vulnerability is mostly based on the Universal soil loss equation (USLE) method (*Wischmeier and Smith, 1978*). USLE is a typical representative of empirical methods for soil loss calculation. It is a simple equation with six parameters (rainfall erosivity factor [$N \cdot ha^{-1} \cdot y^{-1}$]; soil erodibility factor [$t \cdot N^{-1}$]; slope length factor [–]; slope steepness factor [–]; crop management factor [–]; erosion control practice factor [–]), the accuracy of which, however, contributes significantly to the results obtained (average long term soil loss [$t \cdot ha^{-1} \cdot y^{-1}$]). All factors were determined empirically by statistical evaluation of the soil loss on the unit plots (22 m length and 9% slope) and on different parcels compared with the unit plots. The first two factors determine the actual soil loss on unit plots for defined soils and rainfalls and can therefore be expressed in physical units. Other factors are dimensionless and represent the ratio between soil loss on a unit plot and other parameters of analyzed parcels.

In the rainfall erosivity factor (R factor) of the USLE the episodic nature of the erosion process is being considered. The annual R factor value is given by sum of erosion efficiency of individual rainstorms. Long-term average R factor is then determined as the average of annual values for the entire period. Criteria of erosive effective precipitation are as follow: precipitation total exceeding 12.5 mm; maximum intensity exceeding 24 $\mathrm{mm \cdot h^{-1}}$.

Whereas the criterion of precipitation total is unequivocal, the criterion of maximum intensity can be practically explained by different ways. *Wischmeier and Smith (1978)* applied the value of 6 mm falling in 15 minutes, while *Hudson (1971)* 0.4 $\mathrm{mm \cdot min^{-1}}$. The way in which the intensity criterion is specifiied influences the number of erosive effective rains. As the annual R factor value is given by sum of erosion efficiency of individual rainstorms, their higher number logically increases even the long-term average value of R factor.

Because the total soil loss defined by USLE is simply the multiplication of the individual factors, the effect of R-factor on the overall result is in direct proportion (twice the value of R-factor results in twice the soil loss). The main task of this paper is thus to compare the values of R factor (its annual value and long term average) based on those two different methods of maximum intensity criterion interpretation.

In the Czech Republic, R-factor research has been conducted at several sites continuously for the past decade and gradually brought refined results for the whole country and different regions, however the official engineering practice did not reflect the research. In late eighties the official methodologies, defining the standards for engineering practice, recommended the use of constant R-factor of 20 $\mathrm{N \cdot h^{-1} \cdot y^{-1}}$ for the entire country. This constant recommended value has been kept in practice for the last 30 years (*Janeček et al., 1992; 2012*) also at a time when the research clearly demonstrated significantly higher rainfall erosivity in the last 50 years in the Czech Republic and in its neighborhood (*Dostál et al., 2006*). High quality data from measurements at automatic precipitation and climatological stations of the Czech Hydrometeorological Institute (CHMI) has currently allowed assembling of representative maps of rainfall erosivity in the Czech Republic over the last ten years. In spite of the several systematic errors of automatic measurement the density, coverage and quality of data output from these stations significantly exceed the outputs achieved by processing of paper ombrometer data or other previous solutions based on long-term precipitation totals.

2. Material and methods

The paper compares different methods of erosive rain determination on the base of precipitation data sampled each minute from four automatic station of CHMI in the period from 2000 to 2005. Automatic stations employ tipping bucket rain gauge. Every tipping is recorded and precipitation sum is thus determined. Data is measured continuously and stored by driving computer. The measured data is revised from several aspects: by controlling formulas and by comparing with other climatic elements and phenomena as well. These revisions are applied just on daily or terms values. Ten or fifteen-minute data are not systematically checked. For purpose of this paper the databases was completely revised and no significant discrepancies were identified.

Certain parameters of erosive rains (precipitation total, kinetic energy of the rain, maximal 30 min intensity) are used for R factor assessment and for erosion intensity estimation.

The results should answer the question how the applied method of erosive rains determination will influence the R factor value.

Tested variants of critical rainfall intensity assessment:

– Variant 1 (VAR1): $i \geq 0.4$ mm·min^{-1}; U $\geq$ 12.5 mm.

– Variant 2 (VAR2): $i_{15} \geq 6$ mm·15 min^{-1}; U $\geq$ 12.5 mm.

Three parameters of R factor assessment were investigated:

– Number of erosive rains (NR).

– Kinetic energy of erosive rains (E_{kin}).

– R factor of individual years (R_A).

Applied statistical methods:

– Two-way ANOVA with repetition (one factor is a variant and the second is a year; annual values of individual stations represent a statistical repetition in frame of years).

– Correlation analyses.

– Linear regression.

Used climatological stations:
All stations are situated in South Moravia (Czech Republic) in altitude from 177 to 313 m.a.s.l. (see Table 1). The stations lay in similar climatic condition in intense agricultural areas, where the water erosion is a significant factor of soil degradation. Due to the similar natural conditions the data of all these stations could be analyzed as an internal dataset.

Table 1. Basic characteristics of analyzed climatological stations

CHMI station	*Altitude* [m a.s.l.]	*Average annual temperature*	*Average annual precipitation*
Brod nad Dyjí	177	9.5	476.3
Dyjákovice	201	9.6	486.0
Kroměříž	233	9.1	571.1
Vizovice	313	8.2	720.6

Note: Climatic data as an average for the period 1961–2012.

3. Results

3.1 Number of erosive rains (NR)

The results of two-way analysis of variance (ANOVA) show a statistically highly significant difference in NR by the use of both methods ($p < 0.01$) – see Table 2.

Figure 1 shows individual erosive rains according to their maximal 30 min intensity and total. All marks together (blue and red) represent erosive rains

Table 2. Analysis of variance (two-way ANOVA) for two variants of NR assessment

Variability source	*SS*	*Difference*	*MS*	*F*	*Value P*	*F crit*
Selection	65.35417	5	13.07083	3.391351	0.013012	2.48
Variant	111.0208	1	111.0208	28.80541	0.000005	4.11
Interaction	10.35417	5	2.070833	0.537297	0.746638	2.48
Together	138.75	36	3.854167			
Sum	325.4792	47				

Note: *SS* – sum of squares; *MS* – mean square; *F* – value (test criterion); *P* – probability; *F crit* – critical *F* value.

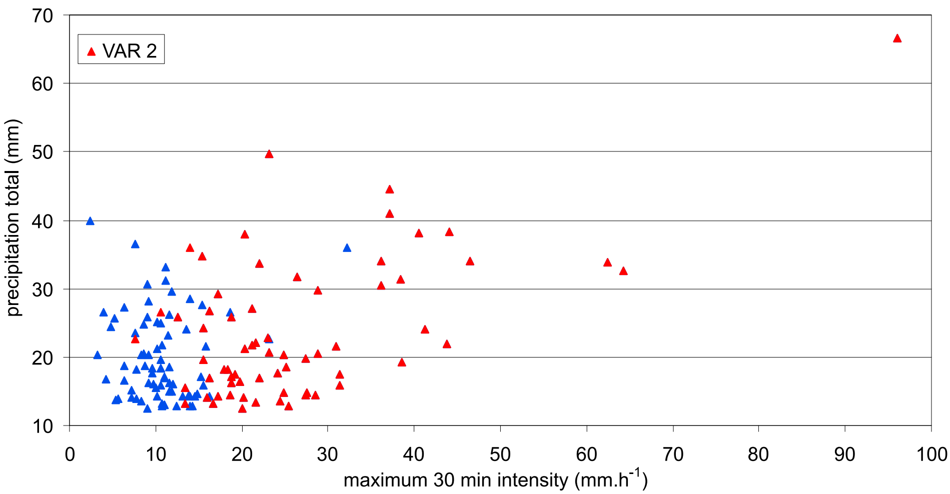

Fig. 1. Parameters of individual erosive rains according to both tested variants (VAR1 and VAR2).

according to VAR1. Erosive rains with $i_{15} \geq 6$ mm·15 min^{-1} (i.e. according to VAR2) are marked by red marks. Generally we can conclude that the rains simultaneously complying with two following criteria (30 min intensity lower than 15 mm·h^{-1} and sum of 40 mm) are not classified as erosive rains according to VAR2.

Correlation coefficient for annual NR between both methods of erosive rain assessment regardless of the year and the station is ($r = 0.6007$, $\alpha = 0.01$, $n = 25$) what means a statistically significant relationship. Convention formula for VAR2 based on results of VAR1 is:

$$NR_2 = 0.3593\ NR_1 + 0.6692\,,$$

and reverse approach based on results of VAR2 is defined by the formula:

$$NR_1 = 1.1004\ NR_2 + 3.0295\,,$$

where NR_1 – annual number of erosive rains determined according to intensity criterion $i \geq 0.4$ mm·min^{-1}, NR_2 – annual number of erosive rains determined according to intensity criterion $i_{15} \geq 6$ mm·15 min^{-1}.

Comparison of NR determined by the two methods contain Table 3 and

Table 3. Comparison of NR determined by VAR1 and VAR2

		Variant	*Brod nad Dyjí*	*Dyjákovice*	*Kroměříž*	*Vizovice*	*All stations (SUM)*
Year	2000	1	8	6	6	6	28
		2	2	2	3	3	10
	2001	1	5	4	4	7	20
		2	3	2	3	1	9
	2002	1	12	12	4	8	36
		2	8	5	2	3	18
	2003	1	3	4	5	5	17
		2	2	3	2	3	10
	2004	1	4	2	3	10	19
		2	4	1	1	3	9
	2005	1	6	4	6	5	21
		2	0	3	4	3	10
	2000–2005 (SUM)	1	38	32	28	41	141
		2	19	16	15	16	66
	2000–2005 (AVG)	1	7.6	6.8	5.6	8.2	28.2
		2	3.8	3.2	3	3.2	13.2

Fig. 2 (expressed as absolute values). The x axis states individual couples of annual values. Results of VAR2 are about 50% lower than the results of VAR1 in average.

Figure 3 shows the histogram of individual percentage categories (the intervals on x axis mean the results of NR–VAR2 as a percent of NR–VAR1). The highest frequency refers to the interval of 40 to 50%. It means the results of NR–VAR2 most often reach 40 to 50% of NR–VAR1 results.

3.2 Kinetic energy of erosive rains ($\mathbf{E_{kin}}$)

A statistically highly significant differences between E_{kin} values of erosive rains determined by VAR1 and VAR2 ($p < 0.01$) was found out by two-way ANOVA (see Table 4).

Figure 4 shows E_{kin} of individual erosive rains. All marks together represent erosive rains according to VAR1. E_{kin} of erosive rains with $i_{15} \geq 6$ mm$\cdot$15 min^{-1} (i.e. according to VAR2) are marked by red marks. Gen-

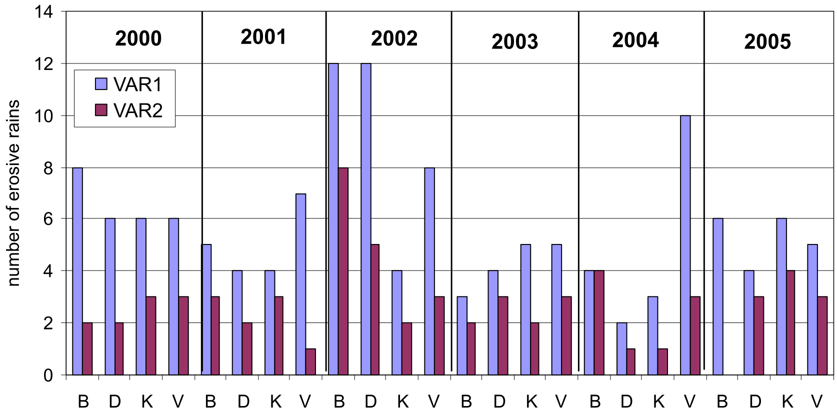

Fig. 2. NR of erosive rains determined by VAR1 and VAR2; B – Brod nad Dyjí, D – Dyjákovice, K – Kroměříž, V – Vizovice.

erally we can say that according to VAR2 the rains with E_{kin} lower than 3 MJ·ha^{-1} are not considered as erosive rains.

Correlation coefficient between E_{kin} of erosive rains determined by both methods (VAR1 and 2) of erosive rain assessment regardless of the year and

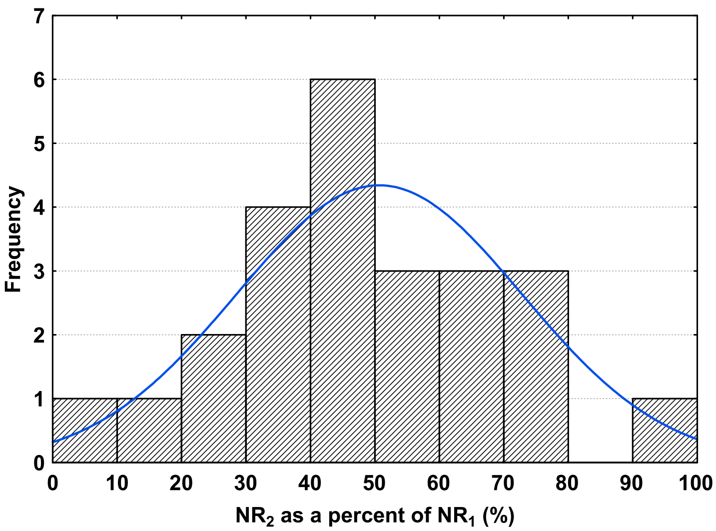

Fig. 3. Histogram of frequency of individual percentage categories NR–VAR2 as a percent of NR–VAR1.

Table 4. Analysis of variance (two-way ANOVA) for two variants of E_{kin} assessment

Variability source	*SS*	*Difference*	*MS*	*F*	*Value P*	*F crit*
Selection	2861.72	5	572.34	4.97	0.001464	2.48
Variant	979.85	1	979.85	8.51	0.006112	4.11
Interaction	97.08	5	19.42	0.17	0.972552	2.48
Together	4146.79	36	115.19			
Sum	8085.43	47				

Note: *SS* – sum of squares; *MS* – mean square; *F* – value (test criterion); *P* – probability; *F crit* – critical *F* value.

the station is ($r = 0.8735$, $p = 0.01$, $n = 25$) what means a statistically significant relationship. Convention formula for VAR2 based on results of VAR1 is:

$$E_{kin2} = 0.7735\ E_{kin1} - 3.7963\,,$$

and reverse approach based on results of VAR2 is defined by the formula:

$$E_{kin1} = 0.9864\ E_{kin2} + 9.2278\,,$$

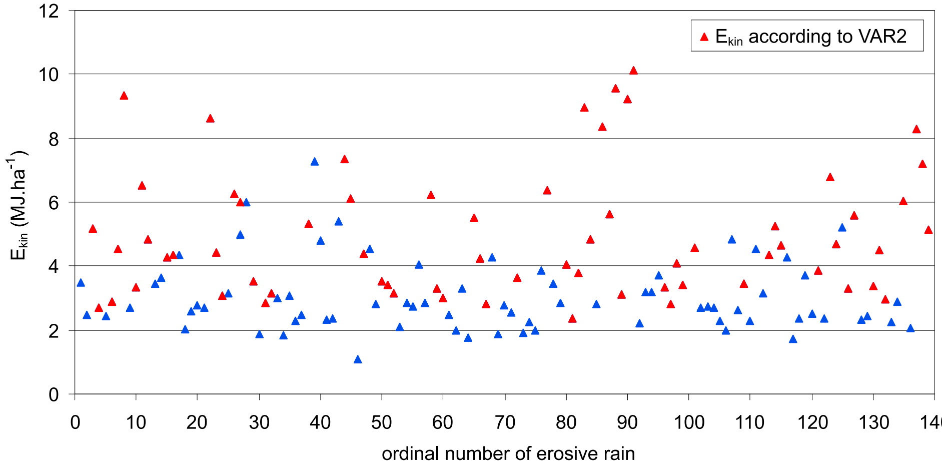

Fig. 4. E_{kin} of individual erosive rains according to both tested variants (VAR1 and VAR2). Note: One rain with $E_{kin} = 16.3$ MJ·ha^{-1} was not included into figure because of better visual expression (more detailed scale). This rain was classified as erosive by both tested method.

where E_{kin1} – annual kinetic energy of erosive rains determined according to intensity criterion $i \geq 0.4$ mm·min^{-1}, E_{kin2} – annual kinetic energy of erosive rains determined according to intensity criterion $i_{15} \geq 6$ mm·15 min^{-1}.

Comparison of annual E_{kin} of erosive rains determined by VAR1 and 2 methods is shown in Table 5 and Fig. 5 (expressed as absolute values). The x axis states individual couples of annual values. Results of E_{kin}–VAR2 are about 40% lower than the results of E_{kin}–VAR1 in average.

Table 5. Comparison of E_{kin} of erosive rains determined by VAR1 and VAR2

		Variant	*Brod nad Dyjí*	*Dyjákovice*	*Kroměříž*	*Vizovice*	*All stations (SUM)*
Year	2000	1	25.32	20.40	19.15	16.26	20.28
		2	10.01	7.82	10.76	9.56	9.54
	2001	1	16.52	15.89	19.90	27.53	19.96
		2	10.20	9.89	17.20	5.30	10.65
	2002	1	71.25	45.19	18.46	34.10	42.25
		2	59.86	24.23	11.37	17.86	28.33
	2003	1	9.86	13.07	17.58	15.04	13.89
		2	6.15	10.84	8.62	10.10	8.93
	2004	1	28.39	8.93	14.01	31.75	20.77
		2	28.39	6.04	8.61	12.55	13.90
	2005	1	17.25	22.69	27.90	18.74	21.65
		2	0.00	20.62	19.73	12.60	13.24
	2000–2005 (AVG)	1	28.10	21.03	19.50	23.90	23.13
		2	19.10	13.24	12.72	11.33	14.10

Figure 6 shows the histogram of individual percentage categories (each interval on x axis represents the results of E_{kin}–VAR2 as a percent of E_{kin}–VAR1). The highest frequency refers to the interval of 60 to 70%. It means the results of E_{kin}–VAR2 most often reach 60 to 70% of E_{kin}–VAR1 results.

3.3 Annual value of R factor (R_A)

Two-way ANOVA proved the R_A–VAR1 and R_A–VAR2 do not differ from each other statistically significantly ($p > 0.05$) – see Table 6.

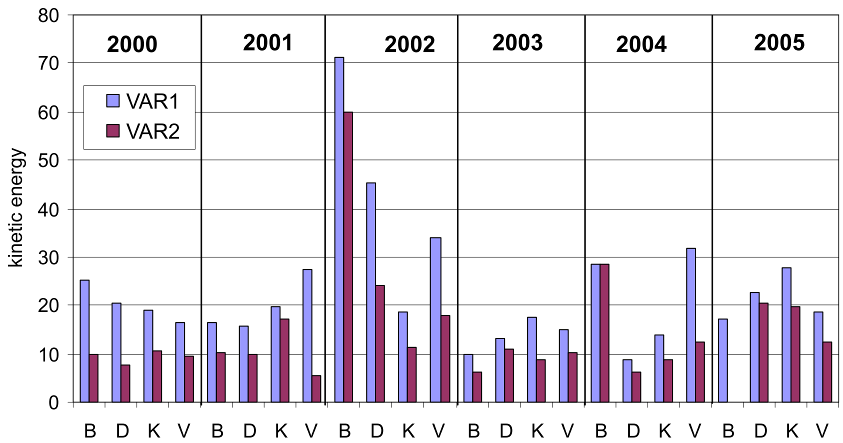

Fig. 5. Annual E_{kin} of erosive rains determined by VAR1 and VAR2; B – Brod nad Dyjí, D – Dyjákovice, K – Kroměříž, V – Vizovice.

Figure 7 shows R factor values of individual erosive rains. All marks together (blue and red) represent R factor values according to VAR1. R_A values of erosive rains with $i_{15} \geq 6$ mm·15 min^{-1} (i.e. according to VAR2)

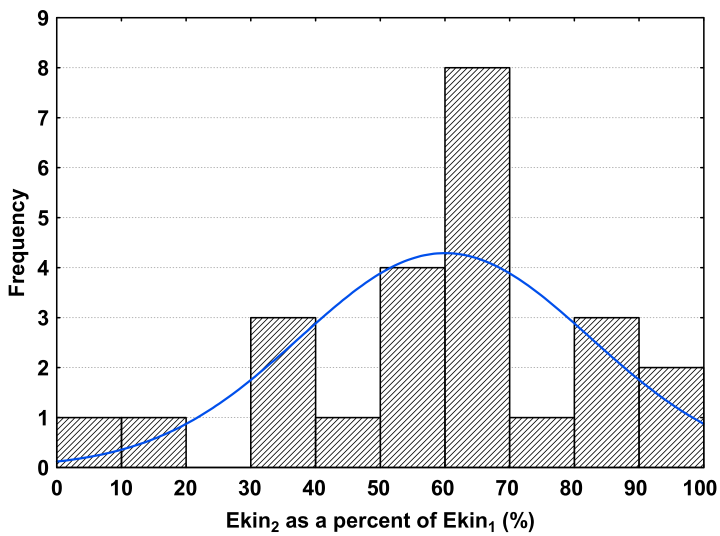

Fig. 6. Histogram of frequency of individual percentage categories E_{kin}–VAR2 as a percent of E_{kin}–VAR1.

Table 6. Analysis of variance (two-way ANOVA) for two variants of R_A assessment

Variability source	*SS*	*Difference*	*MS*	*F*	*Value P*	*F crit*
Selection	39811.49	5	7962.29	2.85	0.028654	2.48
Variant	1163.48	1	1163.48	0.42	0.522700	4.11
Interaction	167.14	5	33.43	0.01	0.999950	2.48
Together	100520.1	36	2792.23			
Sum	141662.2	47				

Note: *SS* – sum of squares; *MS* – mean square; *F* – value (test criterion); *P* – probability; *F crit* – critical *F* value.

are marked by red marks. Generally, it can be concluded that according to VAR2 the rains with R factor lower than 5 are not included into the annual R factor value.

Correlation coefficient between R_A values of erosive rains determined by both methods (VAR1 and VAR2) of erosive rain assessment regardless of the year and the station is ($r = 0.9872$, $p = 0.01$, $n = 25$) what means a statistically significant relationship. Convention formula for VAR2 based on results of VAR1 is:

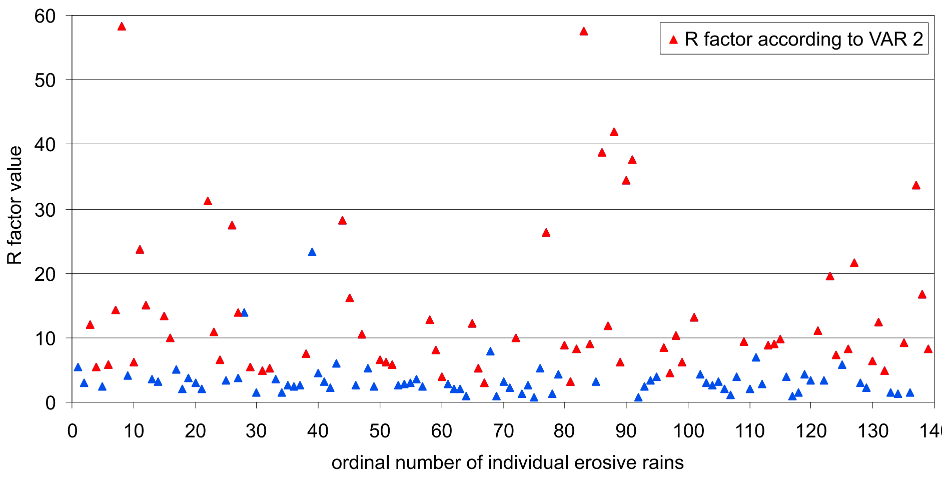

Fig. 7. R factor of individual erosive rains according to both tested variants (VAR1 and VAR2). Note: One rain with R factor 156 was not included into figure because of better visual expression (more detailed scale). This rain was classified as erosive by both tested method.

$R_{A2} = 1.002\ R_{A1} - 9.8576\,,$

and reverse approach based on results of VAR2 is defined by the formula:

$R_{A1} = 0.9745\ R_{A2} + 11.003\,,$

where R_{A1}–annual value of R factor determined according to intensity criterion $i \geq 0.4$ mm·min^{-1}. R_{A2}–annual value of R factor determined according to intensity criterion $i_{15} \geq 6$ mm·15 min^{-1}.

Comparison of R_A of erosive rains determined by VAR1 and VAR2 is shown in Table 7 and Fig. 8 (expressed as absolute values). The x axis states individual couples of annual values. Results of VAR2 are about 25% lower than the results of VAR1 in average.

Table 7. Comparison of R_A values of erosive rains determined by VAR1 and VAR2

		Variant	*Brod nad Dyjí*	*Dyjákovice*	*Kroměříž*	*Vizovice*	*All stations (SUM)*
Year	2000	1	51.90	34.22	34.15	22.16	35.61
		2	36.30	18.36	23.23	15.67	23.39
	2001	1	26.00	23.65	82.97	46.33	44.74
		2	20.23	18.87	78.80	7.46	31.34
	2002	1	247.39	91.51	45.43	73.76	114.52
		2	237.72	67.69	38.60	55.03	99.76
	2003	1	16.90	25.04	34.40	24.29	25.16
		2	12.98	23.61	23.40	18.79	19.70
	2004	1	186.02	10.69	36.22	41.89	68.71
		2	186.02	9.30	31.20	24.83	62.84
	2005	1	16.55	60.19	66.00	24.83	41.89
		2	0.00	58.70	58.90	20.48	34.52
	2000–2005 (AVG)	1	90.79	40.88	49.86	38.88	55.10
		2	82.21	32.76	42.36	23.71	45.26

Figure 9 shows the histogram of individual percentage categories where the percentage categories represented on x axis are the ratios of R_{A2} as a percent of R_{A1}. The highest frequency refers to the interval of 70 to 80%. It means the results of R_A–VAR2 most often reach 70 to 80% of R_A–VAR1 results.

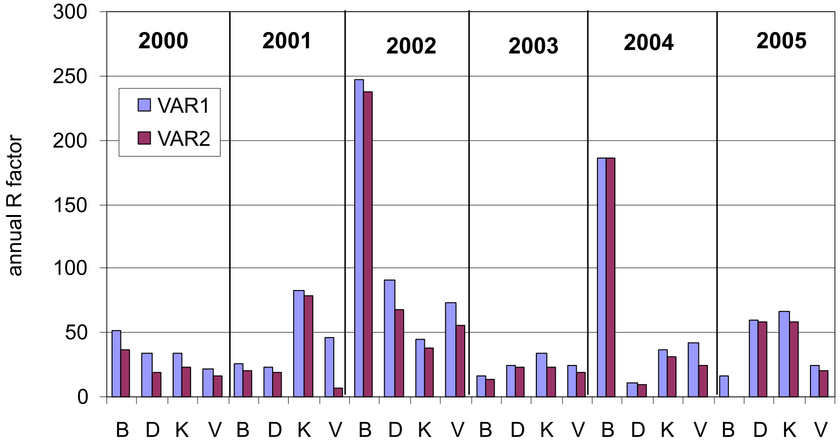

Fig. 8. R_A values of erosive rains determined by VAR1 and VAR2; B – Brod nad Dyjí, D – Dyjákovice, K – Kroměříž, V – Vizovice.

The overall comparison of all tested parameters of erosive rains (NR, E_{kin} and R_A) is shown by boxplot in Fig. 10. Results of VAR2 are expressed as a percent of VAR1 results on y axis.

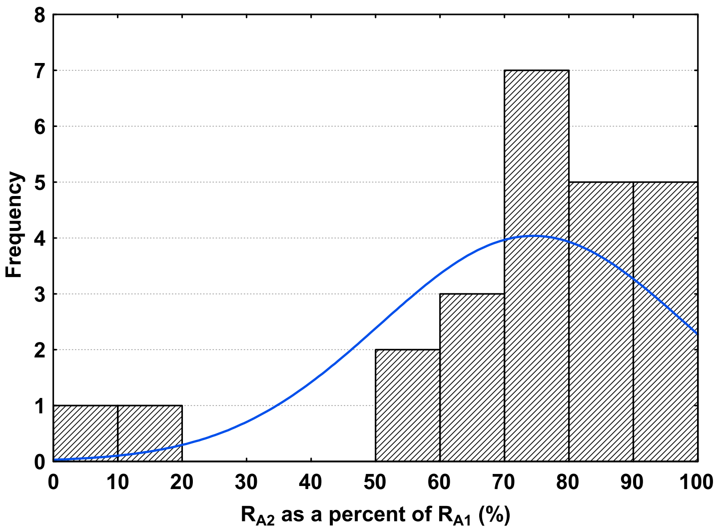

Fig. 9. Histogram of frequency of individual percentage categories NR–VAR2 as a percent of NR–VAR1.

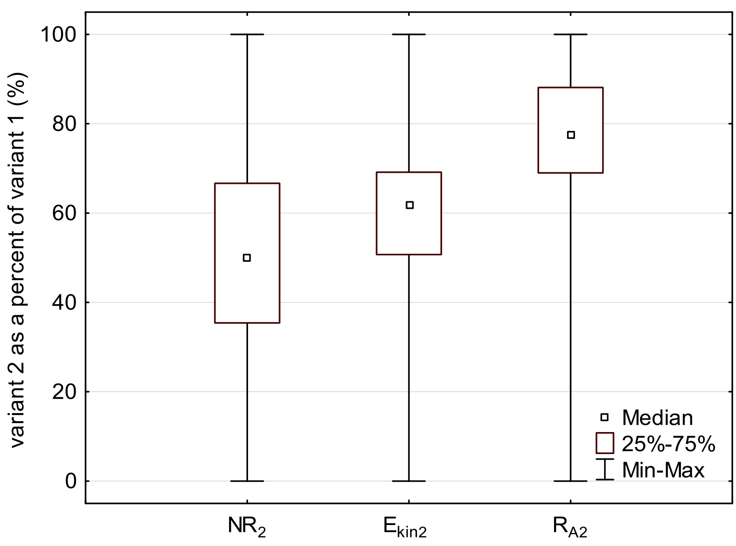

Fig. 10. Box-plot of tested parameters of erosive rains.

4. Conclusion

Comparison of two methods of erosive rain determination (VAR1: $i \geq 0.4$ mm·min^{-1}; U $\geq$ 12.5 mm and VAR2: $i_{15} \geq 6$ mm·15 min^{-1}; U $\geq$ 12.5 mm) was based on one minute data from four automatic climatological station of CHMI (the period of 2000–2005). Parameters of erosive rains such as precipitation total, kinetic energy and maximal 30 min intensity are used for R factor assessment and for estimation of erosion intensity. The paper discovered how applied method of erosive rain determination influenced the R factor value.

Three variables (number of erosive rains NR, kinetic energy of erosive rains E_{kin} and annual value of R factor R_A) in dependence on used variant of erosive rains determination were analyzed in detail.

The most significant differences were proved for NR. R_A values were statistically not significantly different from each other. While average difference in NR reached to 50%, in case of E_{kin} it was 35% and for R_A just 25%. It is given by the fact that the stricter variant of erosive rains determination VAR2 does not determine quite high number of rains as erosive compared to VAR1 (50%), but most of these rains have just low erosive efficiency. In other words, the rain with significant erosion efficiency comply with the criterion of VAR2. The rains simultaneously complying with two following criteria (30 min intensity lower than 15 mm·h^{-1} and sum of 40 mm), E_{kin} lower than 3 MJ·ha^{-1}, and factor lower than 5 were not generally classified as erosive according to VAR2.

Aim of the paper is to show that digital rain gauge data have a great potential, but we have to be careful in assessing them and relying to the original Wichmeier's erosivities without considering the differences in data acquisition and different temporal resolution of current datasets. We have to be aware that in central european region, using one minute temporal resolution, the rainfall characteristics lead to ca 25% overestimation of the R-factor comparing to the original data assessment. Due to its linear relationship with the soil loss in USLE, this is rather serious overestimation of the resulting soil loss.

Even more striking is the difference between numbers of selected "erosive" storms which is about 50%. Theoretically this means also doubled soil erosion-event frequency within a year if considering the detailed rainfall temporal resolution. Further experimental research is needed here to define the actual threshold for erosive rainfall.

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