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Estimation of IDF curves of extreme rainfall by simple scaling in Slovakia

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Abstract: Scaling properties of the short term extreme rainfall has not been investigated so far in Slovakia. In this study the simple scaling theory is applied to the intensity-duration-frequency (IDF) characteristics of short duration rainfall. The rainfall data for the analysis consists of rainfall intensities of durations ranging from 5 minutes to 180 minutes and daily rainfall amounts for 55 stations from the whole territory of Slovakia, respectively, taken from the historical dataset of *Šamaj and Valovič (1973)* and from the database of the Slovak Hydrometeorological Institute (SHMI). The scaling behaviour of rainfall intensities was examined and it was shown that for time scaling, the statistical properties of rainfall follow the hypothesis of simple scaling. The scaling exponents were derived in all the analysed stations. In the selected test stations, the influence of excluding the 5 min duration on the derived IDF curves was also examined. The possibility of using wide sense simple scaling in Slovakia was demonstrated.

Key words: rainfall intensity, simple scaling, IDF curves

1. Introduction

Information on quantiles of extreme rainfall of various durations is needed in the hydraulic design of structures that control storm runoff, such as flood detention reservoirs, sewer systems etc. Such information is in engineering hydrology usually expressed as a relationship between intensity-duration-frequency (IDF) of extreme rainfall. The establishment of such relationships goes back to the 1930s *(Bernard, 1932)*. Since then, different forms of relationships have been constructed for several regions of the world.

Since the 1960s, the regional properties of IDF relationships have been studied in several countries, and in general, maps have been constructed to provide the rainfall intensities or precipitation totals for various return periods and durations. IDF relationships were mostly estimated by at-site statistical analysis of rainfall data for different durations of intensive rainfall. The IDF curves are constructed by performing statistical analysis either on annual maxima series (AMS) or partial duration series (POT) by fitting curves to empirical quantiles or fitting probability distributions for several pre-selected rainfall durations *(Bougadis and Adamowski, 2006).*

IDF curves received considerable attention in engineering hydrology over the past decades. Approaches based on statistical analysis of data were developed, e.g. *Bell (1969)* and *Chen (1983)* derived the IDF formulae for the United States, *Baghirathan and Shaw (1978), Gert et al. (1987)* and *Niemczynowicz (1982)* developed IDF formulas for ungauged sites, *Sivapalan and Bloeschl (1998)* proposed a method of constructing IDF curves based on the spatial correlation structure of rainfall, *Koutsoyiannis et al. (1998)* proposed a new generalizing approach to the formulation of IDF curves using efficient parameterization.

The first attempts to construct regional IDF curves for Slovakia were made by *Dub (1950). Šamaj and Valovič (1973)* presented a comprehensive IDF study based on 68 stations covering the area of Slovakia using data mostly from the period 1931–1960. Their results were re-evaluated by Urcikán and Horváth (in *Urcikán and Imriška, 1986*); however, the analysis mostly concentrated on the different formal presentations of IDF curves. They also proposed a method for the spatial interpolation of IDF curves for sites with no direct observations. These procedures were data and time demanding, therefore, it seemed advantageous to develop models which would describe rainfall characteristics through a number of timescales including interpolation or extrapolation at time resolutions that may not have been observed.

In the last years, the properties of extreme rainfall in Slovakia were studied e.g. by *Faško et al. (2000), Cebulak et al. (2000), Gaál and Lapin (2000)* and *Kohnová et al. (2005).* Statistical characteristic of 1-day precipitation totals were analysed e.g. in *Pekárová et al. (2008)* and *Pekár et al. (2008).* In these studies only smaller regions were examined, but since the 1980's the short-term rainfall and its IDF characteristics has not been globally processed for the whole teritorry of Slovakia.

In recent decades, hydrological research has devoted considerable attention to improving the representation of precipitation fields both in time and space. One of the most important issues recently is the development of various simple and multiscaling models. They recognize rainfall organization at different scales through the concept of mesoscale precipitation areas and the clustering of cells in space and time; see e.g. *Waymire and Gupta (1981), Waymire et al. (1984), Rodriguez-Iturbe et al. (1984), Marien and Vandewiele (1986), Sivapalan and Wood (1987), Veneziano et al. (1996).*

Consequently, alternative approaches to construct IDF relationships, based on the fractal properties of rainfall, which implies scaling invariance, were developed. In these studies scaling formulas were proposed to extend the IDF relationships from (usually) daily time scale to shorter time intervals based on scaling properties of rainfall in recent studies. E.g., *Gupta and Waymire (1990)* studied the concepts of simple and multiple scaling to characterize the probabilistic structure of the precipitation process, *Koutsoyiannis and Foulfoula-Georgiu (1993)* used a scaling model to predict storm hyetographs. *Menabde et al. (1999)* showed that based on the empirically observed scaling properties of rainfall and some general assumptions about the cumulative distribution function for the annual maxima of mean rainfall intensity, it is possible to derive simple IDF relationships. *Bendjoudi et al. (1997)* used a multifractal point of view on rainfall IDF curves, *Rosso and Burlando (1990),* and later *Burlando and Rosso (1996)* used this concept to study traditional forms of depth-duration-frequency relationships. *De Michele et al. (2002)* developed IDF curves for design storms, *Yu et al. (2004)* developed regional IDF formulas for non-recording sites in Taiwan, *Molnar and Burlando (2005)* examined the variability of scaling exponents in a mountainous region, *Nhat et al. (2007)* developed regional relationship for ungauged locations based on the scaling theory in Japan, *Acar et al. (2008)* used a multilayer perception artificial neural network model to assess IDF relationships for short duration rainfalls. In Slovakia the scaling properties of extreme rainfall were tested in studies of *Bara (2008, 2009)* and *Bara et al. (2008).*

In this study, scaling properties of extreme rainfall are examined in Slovakia in order to establish scaling behavior of statistical moments over different durations. Such scaling or scale-invariant models enable us to scale data from one temporal resolution to another, and thus, help to overcome the lack of the extreme rainfall data of sub-daily durations. The simple scaling concept is explored using the historical dataset of *Šamaj and Valovič (1973)* and the scaling relationships are used for downscaling the daily rainfall intensity for the derivation of scaled IDF curves.

2. Methodology

The basic theoretical development of scaling has been investigated by many authors and considerable amount of studies were devoted to extreme rainfall and its scaling properties, including *Waymire and Gupta (1981), Waymire, et al. (1984), Rodriguez-Iturbe et al. (1984), Marien and Vandewiele (1986), Sivapalan and Wood (1987), Gupta and Waymire (1990), Rosso and Burlando (1990), Smith (1992), Koutsoyiannis and Foulfoula-Georgiu (1993), Burlando and Rosso (1996), Veneziano et al. (1996), Bendjoudi et al. (1997), Willems (2000), Hubert et al. (2002), De Michele et al. (2002), Molnar and Burlando (2005).* In this work the simple scaling hypothesis is adopted to test the scaling behaviour of rainfall in Slovakia, following the methodology described e.g. in *Menabde et al. (1999), Yu et al. (1994)* and *Nhat et al. (2007).*

2.1. The simple scaling hypothesis

Let I_d and $I_{\lambda d}$ denote the annual maximum rainfall intensity series for the time durations d and λd, respectively. The two random variables I_d and $I_{\lambda d}$ are said to have the following scaling property *(Menabde et al., 1999; Yu et al., 2004)* if

$$I_{\lambda d} \stackrel{dist}{=} \lambda^{\beta} I_d. \tag{1}$$

In equation (1) the equality is meant in the sense of the equality of the probability distributions of both variables and β represents the scaling exponent. Such behaviour is denoted as simple scaling in the strict sense (see *Gupta and Waymire, 1990*).

This type of scaling implies that both variables have the same probability distribution function, if finite moments of an order q exist for both. The relationship between the moments of the order q can be obtained after raising both sides of equation (1) to power q and taking the expected values of both sides *(Menabde et al., 1999; Yu et al., 2004)*:

$$E[I^q_{\lambda d}] = \lambda^\beta E[I^q_d], \tag{2}$$

where β represents the scaling exponent of order q. In order to obtain the value of β, we can simply take the logarithm of both sides of Eq. (2), which transforms it into:

$$\log E[I^q_{\lambda d}] = \log E[I^q_d] + \beta \log \lambda. \tag{3}$$

In this form of Eq. (2) the scaling exponents, β, regarded as the slope of the linear relationships between the log-transformed values of the moments ($\log E[I^q_{\lambda d}]$) and scale parameters ($\log \lambda$) for various orders of the moments (q), can be estimated e.g. by linear regression. When the scaling exponent and the corresponding order of moment have a linear relationship, one usually speaks of 'simple scaling in the wide sense' *(Gupta and Waymire, 1990)*. Both properties can be checked from sample data by using the sample averages instead of the ensemble averages *(Menabde et al., 1999)*.

Furthermore, *Menabde et al. (1999)* showed that the scaling behavior can also be found for the parameters of a fitted cumulative distribution function (CDF) (if CDF has an appropriate standardized form - such as in the case of the Gumbel distribution) and for the quantiles estimated from the fitted CDF, corresponding to different return periods T.

3. Data analysis

For the analysis in this study, 55 raingauge stations were selected from the historical dataset of *Šamaj and Valovič (1973)*, covering the whole territory of Slovakia. The location of the analysed stations is shown in Fig. 1. The primary data set of quantiles of rainfall intensities derived by *Šamaj and Valovič (1973)* including durations 5, 10, 15, 20, 30, 40, 50, 60, 90, 120 and 180 min were completed by daily data from the archive materials of SHMI. Generally, the periods of observation in this dataset range from the 1930s till the 1960s of the 20th century, with the average record length of 17 years (see Table 1).

For the validation of the simple scaling hypothesis, three raingauge sta-

Table 1. List of the analysed raingauge stations with the number of complete years of observations (Record length); these are then specified in the last column (Years of observation)

Nr.	Station	Record length	Years of observation
1	Banská Bystrica	18	1946-1954, 1957-1965
2	Banská Štiavnica	14	1952-1965
3	Bratislava VÚ	43	1922-1944, 1946-1965
4	Brezno	19	1946-1949, 1951-1965
5	Čadca	17	1949-1965
6	Čížž	12	1954-1965
7	Dobšinská Ice Cave	21	1930-1948, 1950-1951
8	Gelnica	29	1935-1944, 1947-1965
9	Hliník n/Hronom	17	1949-1965
10	Holíč	18	1946-1949, 1951-1961, 1963-1965
11	Hrachovo	15	1945-1949, 1951-1960
12	Humenné	24	1937-1943,1947-1948, 1951-1965
13	Hurbanovo	64	1901-1938, 1940-1965
14	Ilava	22	1944-1965
15	Jarabá	32	1924-1930, 1932-1944, 1947-1952, 1960-1965
16	Košice - Bankov	13	1923-1935
17	Košice - airport	20	1946-1965
18	Kšinná	12	1931-1940, 1943-1944
19	Kuchyňa Nový Dvor	21	1934-1937, 1946-1949, 1951-1955, 1958-1965
20	Ladzany	16	1950-1965
21	Liptovsky Hrádok	32	1931-1944, 1948-1965
22	Liptovská Teplička	19	1925-1930, 1932-1944
23	Lom nad Rimavicou	27	1924-1926, 1929-1944, 1946-1953
24	Lučenec	28	1931-1938, 1946-1965
25	Malé Bielice	13	1948-1949, 1955-1965
26	Modra - Pánsky dom	20	1925-1939, 1941-1944, 1946
27	Motešice - Letný dvor	14	1931-1944
28	Motičky	18	1946, 1948-1955, 1957-1965
29	Nenince	16	1950-1965
30	Nitra	21	1933-1943, 1949-1951, 1959-1965
31	Nitrianske Pravno	17	1925-1941
32	Nový Tekov	13	1952-1955, 1957-1965
33	Oravská Lesná	16	1944, 1946-1949, 1952-1954, 1956-1957, 1960-1965
34	Oravský Podzámok	14	1944-1948, 1951, 1953, 1955, 1957-1962
35	Oravská Polhora	23	1930-1952
36	Papín	13	1923-1929, 1933-1938
37	Piešťany	13	1949, 1951-1959, 1963-1965
38	Poprad - airport	20	1946-1965
39	Prešov - airport	18	1946-1956, 1959-1965
40	Prievidza	14	1951-1961, 1963-1965
41	Starý Smokovec	43	1923-1965
42	Svätuša (Podhájska)	12	1953-1964
43	Štós	24	1929-1937, 1950, 1952-1965
44	Štrbské Pleso	41	1922-1944, 1948-1965
45	Štúrovo	17	1949-1965
46	Švermovo (Telgárt)	14	1947-1951, 1957-1965
47	Tesárske Mlyňany	14	1951-1965
48	Trebišov	16	1949-1963, 1965
49	Trenčianske Biskupice	12	1940-1943, 1946-1952, 1955
50	Trnava	22	1930-1952
51	Valašská Belá	16	1949, 1951-1965
52	Veľké Rovné - Podivor	27	1935-1938, 1940-1944, 1946-1953, 1956-1965
53	Víglaš - Pstruša	16	1949-1958, 1960-1965
54	Zvolen (Sliač)	32	1927-1941, 1943, 1947-1957, 1962-1966
55	Žilina	19	1946-1949, 1951-1965

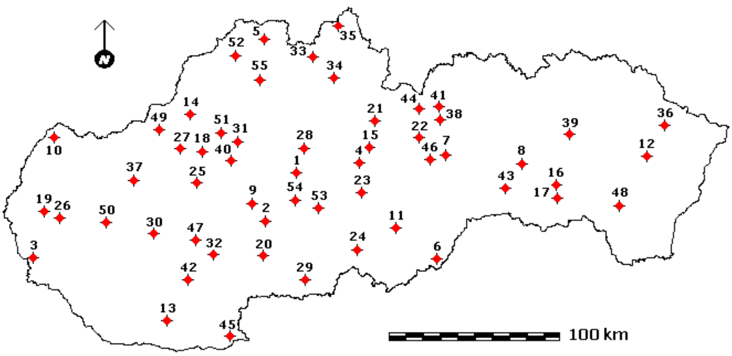


Fig. 1. Location map of the raingauge stations analysed.

tions were chosen. These stations have long observation periods and their locations represent the western, central and eastern parts of Slovakia: the Humenné station at the altitude of 163 m a.s.l. in eastern Slovakia (No. 12 in Fig. 1), the Kuchyňa – Nový Dvor station situated in the western part of Slovakia at the altitude of 206 m a.s.l. (No. 19 in Fig. 1), and the Liptovský Hrádok station with an altitude of 640 m a.s.l. (No. 21 in Fig. 1). For the Humenné station 24 years of observations were available ranging from 1937 to 1965 (with 5 years missing: 1944–1946 and 1949–1950), for the Kuchyňa – Nový Dvor station 21 years of observations were available ranging from 1934 to 1965 (with 11 years missing: 1938–1945, 1950 and 1956–1957), for the Liptovský Hrádok station 32 years of observations were available ranging from 1931 to 1944 and from 1948 to 1965. The historical quantile data were checked for consistency and partially reconstructed for this scaling study by a method described in *Bara et al. (2008)*.

Figures 2 to 4 show the empirical IDF curves of *Šamaj and Valovič (1973)* extended by the daily rainfall amounts estimated using the generalised extreme value (GEV) distribution. The return periods in the historical dataset has been adjusted from empirical POT periodicities to annual maximum return periods by the well-known Langbein formula *(Langbein, 1949)*.

$$P_{AMS} = 1 - e^{P_{POT}}, \tag{4}$$

where P_{AMS} is the return period of annual maximum data series and P_{POT} the periodicity of peaks-over threshold data series.

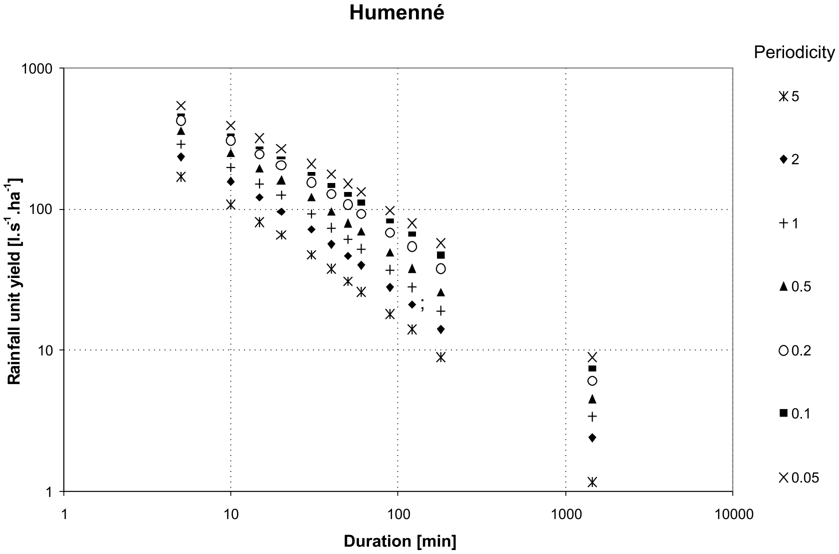


Fig. 2. The empirical IDF curves of *Šamaj and Valovič (1973)* adjusted to the annual exceedances and extended by the daily rainfall amounts in the Humenné station.

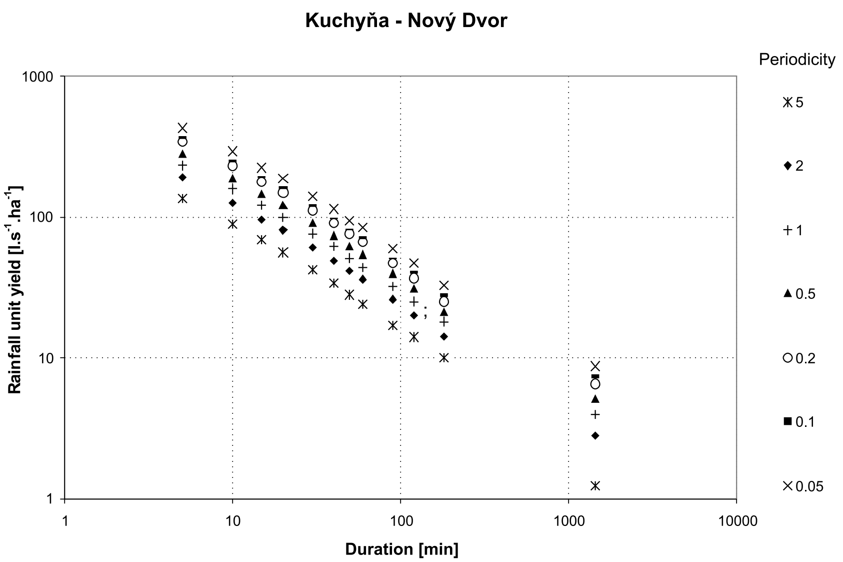


Fig. 3. The empirical IDF curves of *Šamaj and Valovič (1973)* adjusted to the annual exceedances and extended by the daily rainfall amounts in the Kuchyňa – Nový Dvor station.

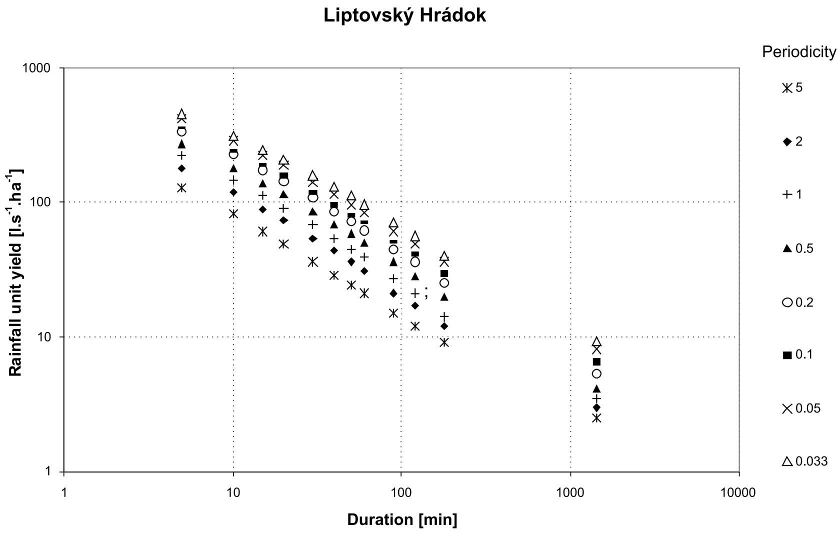
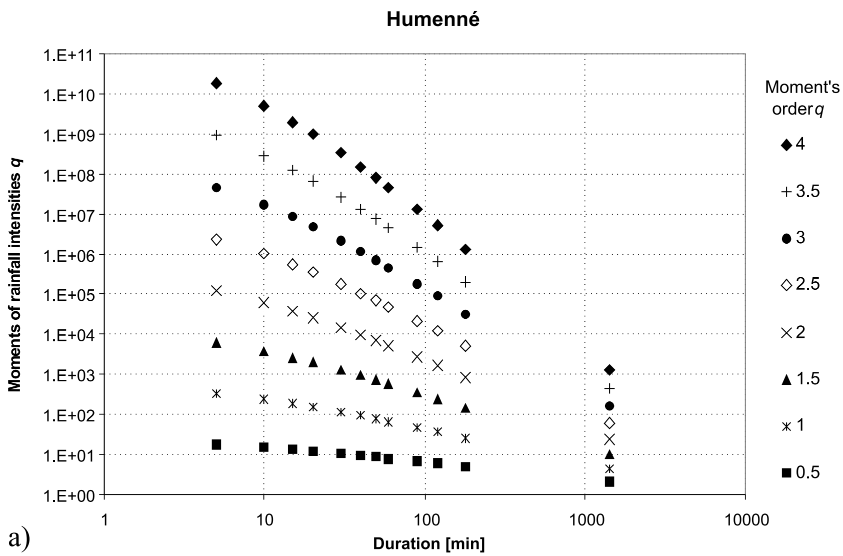


Fig. 4. The empirical IDF curves of *Šamaj and Valovič (1973)* adjusted to the annual exceedances and extended by the daily rainfall amounts in the Liptovský Hrádok station.

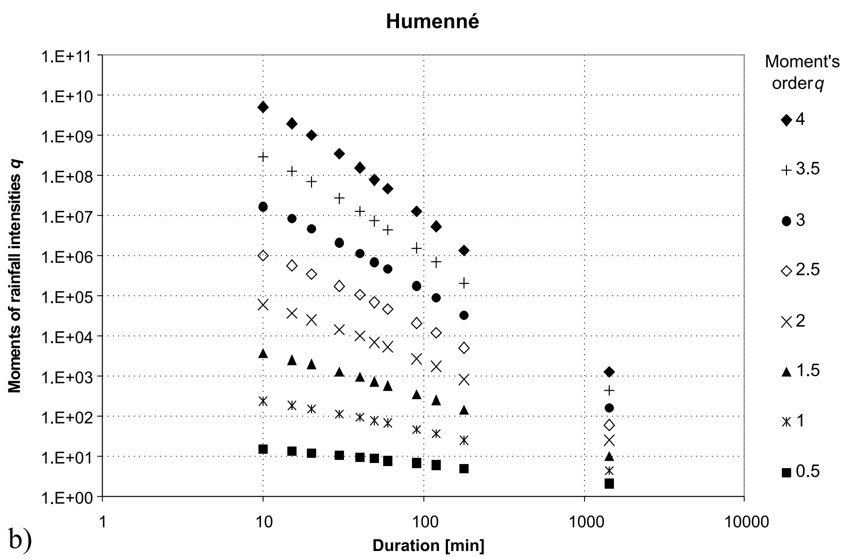
Despite of the slight inconsistency in both methods of dataset derivation, it can be seen, that the newly added daily data are consistent with the trend of the historical dataset. This also implies the existence of some scaling behavior in the data, which will be investigated below.

4. Empirical verification of the scaling hypothesis

The property of simple scaling of rainfall intensities in the wide sense is demonstrated in the three selected sample stations. First, the scaling exponents were derived by including all the analyzed durations of rainfall (5, 10, 15, 20, 30, 40, 50, 60, 90, 120, 180 and 1440 min) to the analysis and consequently by excluding rainfall units of 5 minute duration. Fig. 5 displays the relationships between the log-transformed values of moments of various orders against various rainfall durations at the Humenné station and Fig. 6 and 7 the same relationship at the Kuchyňa – Nový Dvor and Liptovský Hrádok station, respectively. The scaling exponents of the moments of various orders were estimated as the slopes of the linear regression between



a)



b)

Fig. 5a-b. The relationships between the log-transformed values of moments of various orders and various rainfall durations at the station Humenné: a) for all durations of rainfall units, b) without 5 min duration.

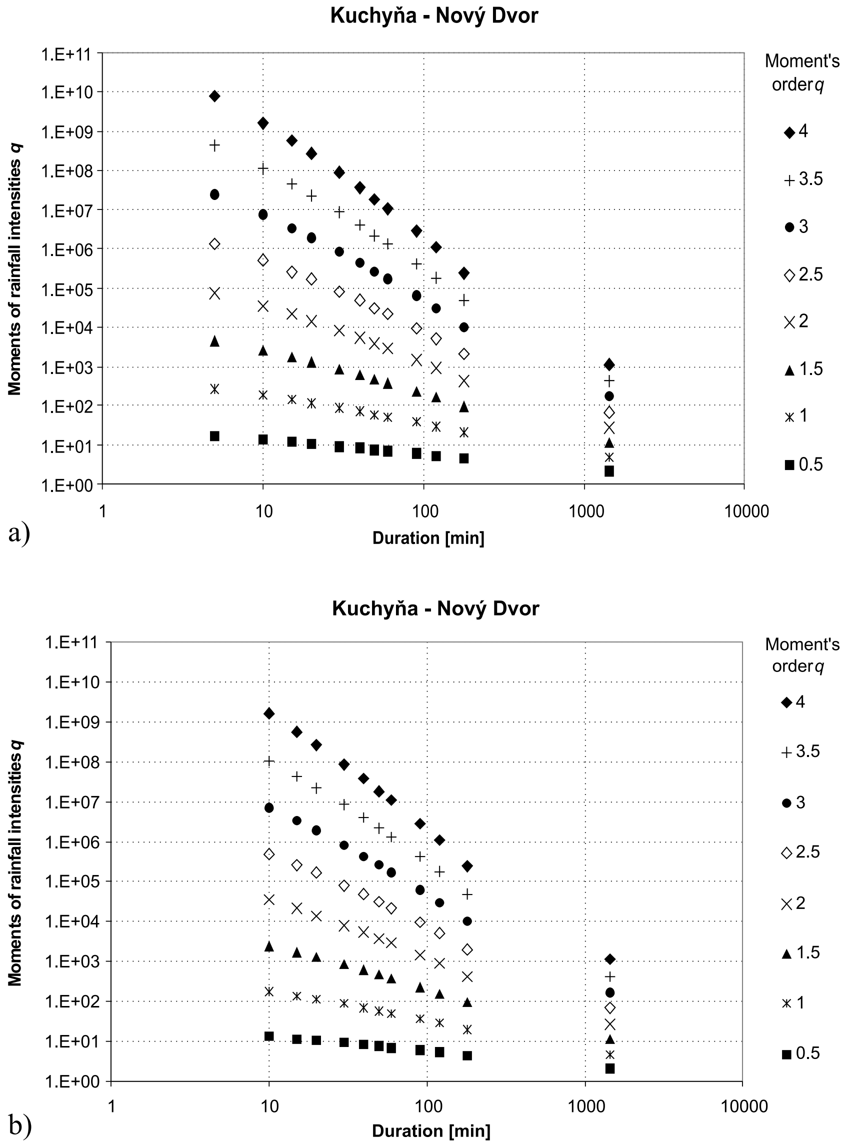


Fig. 6a-b. The relationships between the log-transformed values of moments of various orders and various rainfall durations at the station Kuchyňa – Nový Dvor. a) for all durations of rainfall units, b) without 5 min duration.

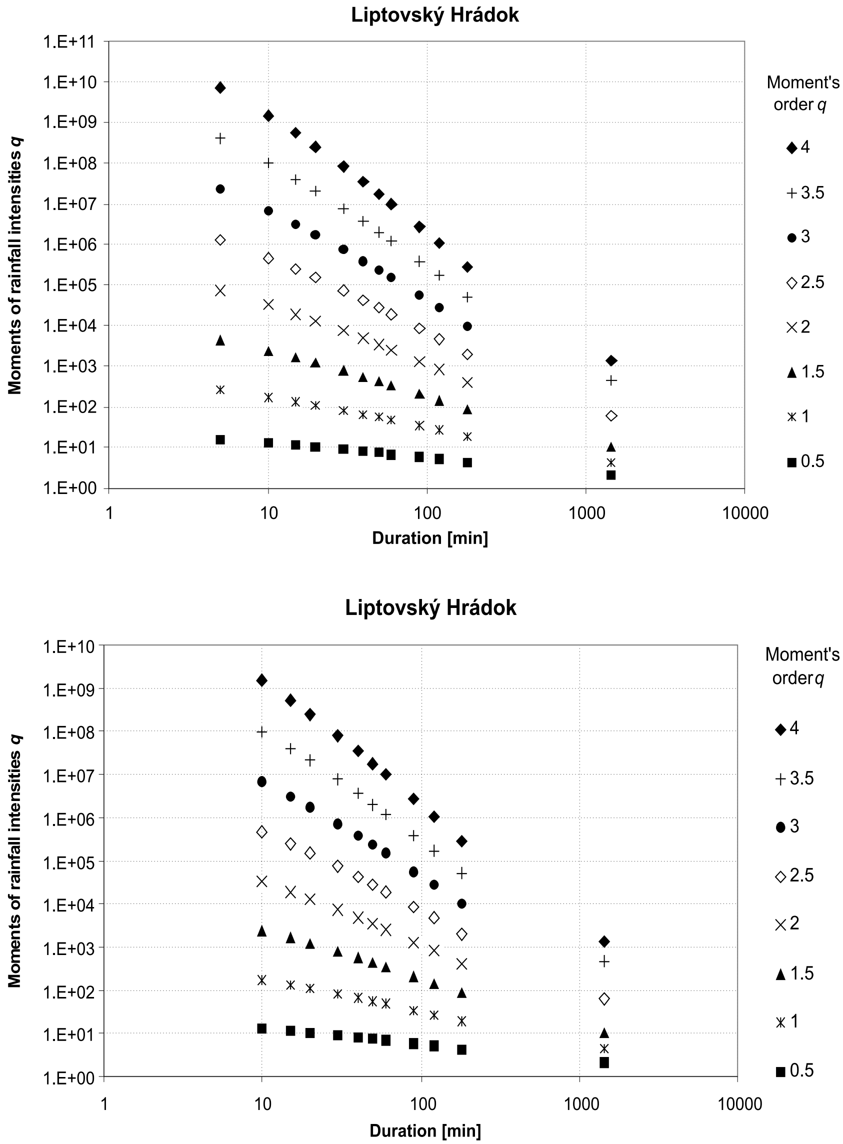


Fig. 7a-b. The relationships between the log-transformed values of moments of various orders and various rainfall durations at the station Liptovský Hrádok: a) for all durations of rainfall units, b) without 5 min duration.

these and the rainfall duration.

Figures 8–10 show the relationships between the scaling exponents of the moments and the orders of the moments at the stations. It is obvious that the scaling exponents decrease with the order of moments and a linear relationship exists between scaling exponents and the moment orders. These two properties imply that the property of simple scaling in the wide sense exists in the analyzed stations if rainfall of all durations is included and also if rainfall of 5 minute duration is excluded from the analysis. For the Humenné station the value of the scaling exponent derived including all durations is 0.7455 and excluding 5 min rainfall is 0.7768. For the Kuchyňa – Nový Dvor station these values are 0.7189 resp. 0.7337 and for the Liptovský Hrádok station 0.7151 resp. 0.7271. As can be seen, after excluding

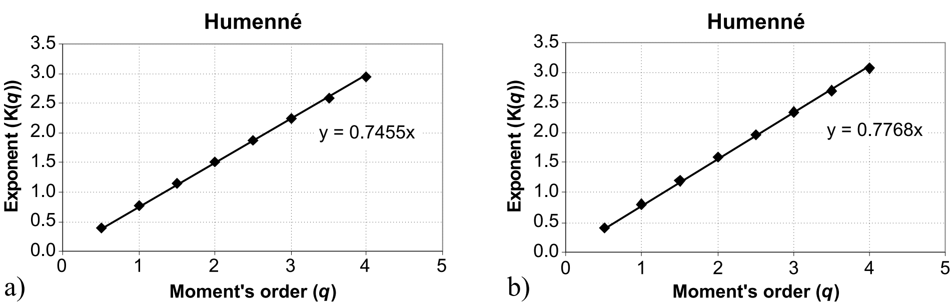


Fig. 8a-b. The relationship between the scaling exponents of the moments and the orders of the moments at the station Humenné. a) for all durations of rainfall units, b) without 5 min duration.

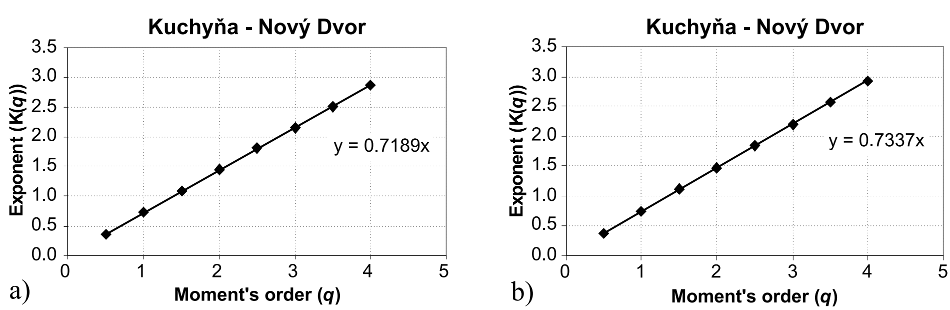


Fig. 9a-b. The relationship between the scaling exponents of the moments and the orders of the moments at the station Kuchyňa – Nový Dvor. a) for all durations of rainfall units, b) without 5 min duration.

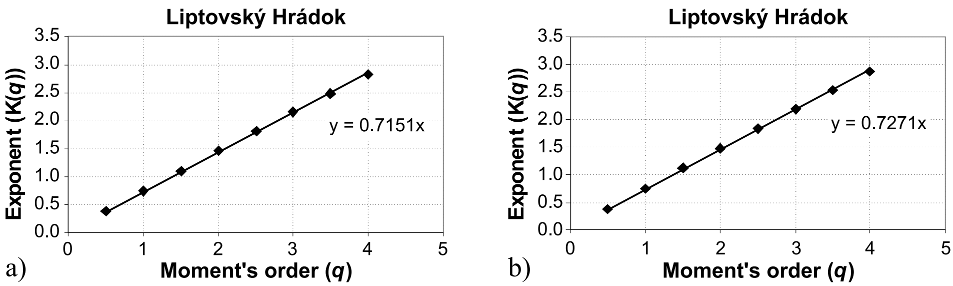


Fig. 10a-b. The relationship between the scaling exponents of the moments and the orders of the moments at the station Liptovský Hrádok. a) for all durations of rainfall units, b) without 5 min duration.

the rainfall units of 5 minute duration, the values of the scaling exponents increased. The scaling exponents of moments of the rainfall intensities were derived for the whole set of 55 stations using the same methodology and both of the aforementioned approaches: including all durations of rainfall and excluding 5 min rainfall units, respectively.

5. Comparison of IDF curves assessed by Šamaj and Valovič (1973) with IDF curves derived by the simple scaling method

In the three sample stations, the design values of precipitation were assessed using the methodology of simple scaling, by downscaling the daily precipitation data. The scaling exponents of moments of rainfall intensities derived both for all analyzed durations and also excluding 5 min rainfall were used. The downscaled data were 1-day precipitation maxima in the warm season from the same period as presented in Table 1. The quantiles of the 1-day rainfall intensities for the desired return periods were derived by the GEV distribution. Using the simple scaling methodology, the design values of the rainfall of selected recurrence intervals and for durations 5, 10, 15, 20, 30, 40, 50, 60, 90, 120 and 180 minutes were evaluated.

The downscaled design values of rainfall intensities were compared to those assessed by *Šamaj and Valovič (1973)*. The relative differences (RD) between these values in percentage were calculated using the formula

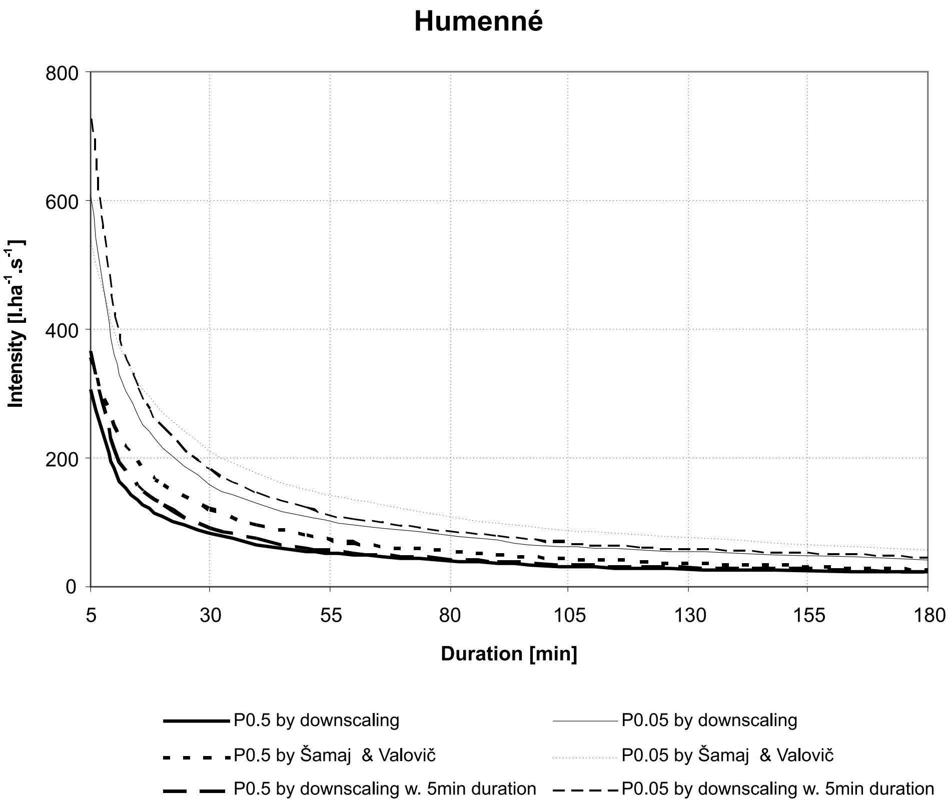


Fig. 11. Comparison of the IDF curves assessed by *Šamaj and Valovič (1973)* and obtained by downscaling for periodicities $P = 0.5$ and 0.05 at the Humenné station.

$$RD = \frac{X - Y}{Y} \,.\, 100\,[\%], \tag{5}$$

where X are the design values determined by downscaling and Y are the design values assessed by *Šamaj and Valovič (1973)*. Figs. 11–13 show the comparison of the IDF curves derived by downscaling (using scaling exponents derived for all analyzed durations and by excluding 5 min rainfall units, respectively) in the three stations selected with the IDF by *Šamaj and Valovič (1973)* for the periodicities $P = 0.5$ and 0.05. For all the analysed stations the derived downscaled values of IDF curves were lower than those published by *Šamaj and Valovič (1973)*. The absolute average RD value in

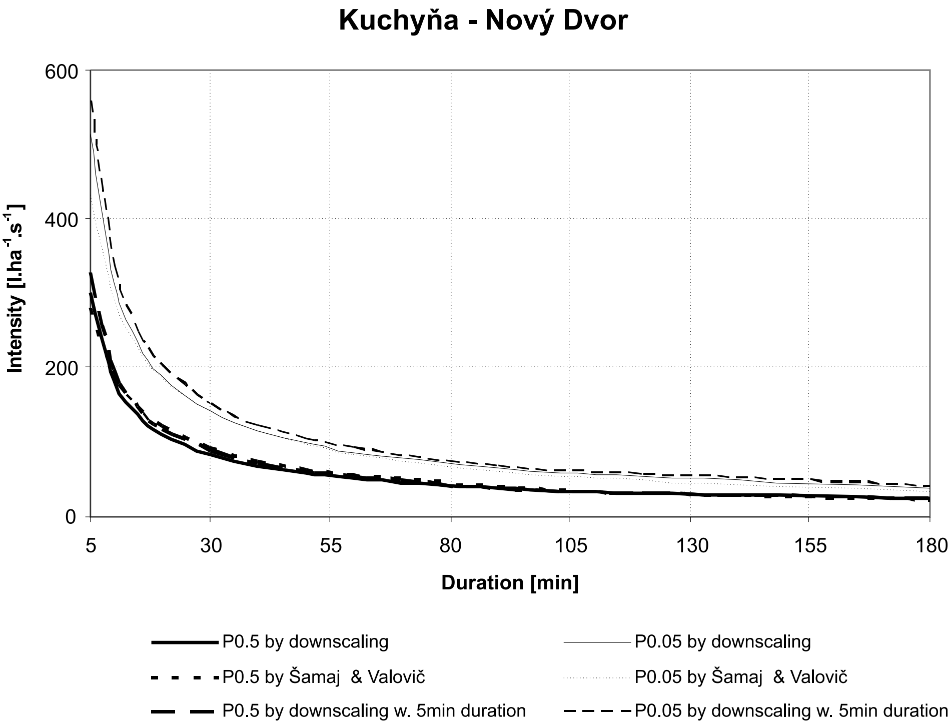


Fig. 12. Comparison of the IDF curves assessed by *Šamaj and Valovič (1973)* and obtained by downscaling for periodicities $P = 0.5$ and 0.05 at the Kuchyňa – Nový Dvor station.

the Humenné station using the scaling exponents derived for all durations of rainfall units was 30.74%, in the Kuchyňa – Nový Dvor station it was 14.98% and in the Liptovský Hrádok station it was 12.25%. Using the scaling exponents derived by excluding rainfall units of 5 min duration the average RD between the downscaled and the empirically derived design values was lower in all the selected stations: in the station Humenné 23.85%, in the station Kuchyňa – Nový Dvor 15.09% and in the station Liptovský Hrádok 10.57%. For all the tested stations, excluding the 5 min duration rainfall units from the scaling procedure resulted in the fact that the downscaled values of IDF curves lie closer to the IDF curves derived by *Šamaj and Valovič (1973)*.

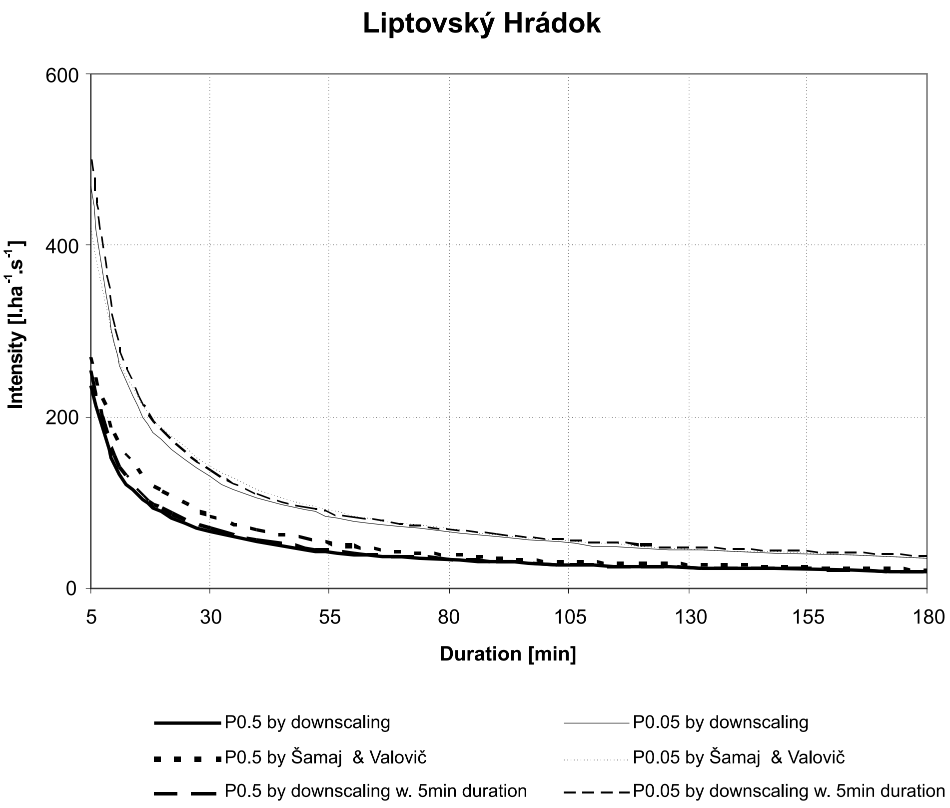


Fig. 13. Comparison of the IDF curves assessed by *Šamaj and Valovič (1973)* and obtained by downscaling for periodicities $P = 0.5$ and 0.05 at the Liptovský Hrádok station.

6. Conclusions

The main results of the presented study can be summarized as follows. The properties of the time scale invariance of selected rainfall quantiles were studied in Slovakia. It was shown that the properties of rainfall follow the hypothesis of simple scaling. Therefore, following the results of *Menabde et al. (1999)*, it was possible to derive the rainfall IDF curves for durations shorter than a day. The simple scaling properties were verified by the historical dataset of *Šamaj and Valovič (1973)*. The IDF relationships, which were deduced from daily rainfall, showed acceptable results in comparison with the IDF curves obtained from at-site short-duration rainfall data. The exclusion of the 5 min duration from the scaling procedure resulted in better estimates of IDF curves values with comparison to those derived from *Šamaj and Valovič (1973)*. Therefore, the exclusion of 5 min duration by simple scaling of extreme rainfall could be recommended also for other stations in Slovakia.

Results of this study are of significant practical importance in Slovakia because statistical rainfall inferences can be made with the use of simple scaling hypothesis from daily data, which are more widely available from standard rain gauge measurements.

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References

Acar R., Celik S., Senocak S., 2008: Rainfall intensity-duration-frequency model using an artificial neural network approach. Journal of Scientific & Industrial Research, **67**, 198–202.

Baghirathan V. R., Shaw E. M., 1978: Rainfall depth-duration-frequency studies for Sri Lanka. J. Hydrol., **37**, 223–239.

Bara M., 2008: Analysis of short-term rainfall intensities the simple scaling approach. (Analýza intenzít krátkodobých dažďov na Slovensku metódou jednoduchého škálovania.) In: 20th Conference of young hydrologists, SHMI, Bratislava, CD, 10 p. (in Slovak).

Bara M., 2009: Scaling properties of extreme rainfall in Slovakia. (Škálovacie vlastnosti extrémnych zrážok na Slovensku.) 11th International science conference of PhD students, Juniorstav 2009, VUT Brno, CD, 6 p. (in Slovak).

Bara M., Gaál L., Kohnová S., Szolgay J., Hlavčová K., 2008: Simple scaling of extreme rainfall in Slovakia: a case study. Meteorological Journal, **11**, 4, 153–157.

Bell F. C., 1969: Generalized rainfall-duration-frequency relationship. ASCE J. Hydraul. Eng., **95**, 311–327.

Bendjoudi H., Hubert P., Schertzer D., Lovejoy S., 1997: Multifractal point of view on rainfall intensity-duration-frequency curves. C. R. Acad. Sci. Paris Earth Planet. Sci., **325**, 323–326.

Bernard M. M., 1932: Formulas for rainfall intensities of long durations. Trans. ASCE, **96**, 592–624.

Bougadis J., Adamowski K., 2006: Scaling model of a rainfall intensity-duration-frequency relationship. Hydrol. Process., **20**, 3747–3757.

Burlando P., Rosso R., 1996: Scaling and multiscaling models of depth-duration-frequency curves for storm precipitation. J. Hydrol., **187**, 45–65.

Cebulak E., Faško P., Lapin M., Šťastný P., 2000: Extreme precipitations events in the Western Carpathians. In: Images of Weather and Climate. Prace Geograficzne, fasc. 108. Institute of Geography of the Jagellonian University, Cracow, 117–124.

Chen C. L., 1983: Rainfall intensity-duration-frequency formulas. ASCE J. Hydraul. Eng., **109**, 1603–1621.

De Michele C., Kottegoda N. T., Rosso R., 2002: IDAF (intensity-duration-area-frequency) curves of extreme storm rainfall: a scaling approach. Water Sci. Technol., **25**, 2, 83–90.

Dub O., 1950: Hydrological data for sewage system design. (Hydrologické podklady pre výpočet kanalizačných sietí.) Voda, 5 (in Slovak).

Faško P., Lapin M., Šťastný P., Vivoda J., 2000: Maximum daily sums of precipitation in Slovakia in the second half of the 20th century. In: Images of Weather and Climate. Prace Geograficzne, fasc. 108. Institute of Geography of the Jagellonian University, Cracow, 131–138.

Gaál L., Lapin M., 2002: Extreme several day precipitation totals at the Hurbanovo observatory (Slovakia) during the 20th century. Contr. Geophys. Geod., **32**, 3, 197–213.

Gert A., Wall D. J., White E. L., Dunn C. N., 1987: Regional rainfall intensity-duration-frequency curves for Pennsylvania. Water Resour. Bull., **23**, 479–486.

Gupta V. K., Waymire E., 1990: Multiscaling properties of spatial and river flow distributions. J. Geophys. Res., **95**, D3, 1999–2009.

Hubert P., Bendjoudi H., Schertzer D., Lovejoy S., 2002: Multifractal taming of extreme hydrometeorological events. The Extremes of the Extremes (Proceeding of Reykjavik Symposium, July 2000). IAHS Publication No. 271, 51–56.

Kohnová S., Gaál L., Szolgay J., Hlavčová K., 2005: Analysis of maximum precipitation totals in the Upper-Hron river basin. Faculty of Civil Engineering, Slovak University of Technology, Bratislava, 120 p.

Koutsoyiannis D., Foufoula-Georgiu E., 1993: A scaling model of storm hyetograph. Water Resour. Res., **29**, 7, 2345–2361.

Koutsoyiannis D., Kozonis D., Manetas A., 1998: A mathematical framework for studying rainfall intensity-duration-frequency relationships. J. Hydrol., **206**, 118–135.

Langbein W. B., 1949: Annual maximum series and the partial-duration series. Transactions, Amer. Geophys. Union, **30**, 6, 879–881.

Marien J. L., Vandewiele G. L., 1986: A point rainfall generator with internal storm structure. Water Resour. Res., **22**, 4, 5231–5238.

Menabde M., Seed A., Pegram G., 1999: A simple scaling model for extreme rainfall. Water Resour. Res., **35**, 1, 335–339.

Molnar P., Burlando P., 2005: Preservation of rainfall properties in stochastic disaggregation by a simple random cascade model. Atmospheric Research, **77**, 137–151.

Nhat L. M., Tachikawa Y., Sayama T., Takara K., 2007: Regional rainfall intensity-duration-frequency relationships for ungauged catchments based on scaling properties. Annuals of Disas. Prev. Res. Inst., Kyoto Univ., **50**, B, 33–43.

Niemczynowicz J., 1982: Areal intensity-duration-frequency curves for short rainfall events in Lund. Nord. Hydrol., **13**, 928–934.

Pekár J., Pekárová P., Olbřímek J., Miklánek P., 2008: Analysis of the statistical characteristics of daily precipitation at Hurbanovo in different periods. Part II. Frequency analysis. Acta Hydrologica Slovaca, **9**, 1, 77–88 (in Slovak).

Pekárová P., Miklánek P., Pekár J., Olbřímek J., 2008: Analysis of the statistical characteristics of daily precipitation at Hurbanovo in different periods. Part I. Multiannual variability – spectral analysis. Acta Hydrologica Slovaca, **9**, 1, 64–76 (in Slovak).

Rodriguez-Iturbe I., Gupta V. K., Waymire E. C., 1984: Scale considerations in the modeling of temporal rainfall. Water Resour. Res., **20**, 11, 1611–1619.

Rosso R., Burlando P., 1990: Scale invariance in temporal and spatial rainfall. In: Proceedings XVth General Assembly of European Geophysical Society, 23–27 April, Copenhagen, Annales Geophysical, 145 p. (abstract).

Šamaj F., Valovič Š., 1973: Intensities of short-term rainfall in Slovakia. Proceedings of works of HMI, Nr. 5, SPN Bratislava (in Slovak).

Sivapalan M., Bloeschl G., 1998: Transformation of point rainfall to areal rainfall: intensity-duration-frequency curves. J. Hydrol., **204**, 1/2, 150–167.

Sivapalan M., Wood E. F., 1987: A multidimensional model of nonstacionarity space-time rainfall at the catchment scale. Water Resour. Res., **23**, 7, 1289–1299.

Smith J. A., 1992: Representation of basin scale in flood peak distributions. Water Resour. Res., **28**, 11, 2993–2999.

Urcikán P., Imriška L., 1986: Sewage and water treatment. Tables for sewage system design. (Stokovanie a čistenie odpadových vôd. Tabuľky na výpočet stôk.) ALFA-SNTL Bratislava (in Slovak).

Veneziano D., Bras R. L., Niemann J. D., 1996: Nonlinearity and self-similarity of rainfall in time and a stochastic model. Journal of Geophysical Res., **101**, D21, 371–392.

Waymire E. C., Gupta V. K., 1981: The mathematical structure of rainfall representation, 1, A review of stochastic rainfall models, 2, A review of the point processes theory, 3, Some applications of the point process theory to rainfall processes. Water Resour. Res., **17**, 5, 1261–1294.

Waymire E. C., Gupta V. K., Rodriguez-Iturbe I., 1984: A spectral theory of rainfall intensity at the meso-β scale. Water Resour. Res., **20**, 10, 1453–1465.

Willems P., 2000: Compound intensity/duration/frequency-relationships of extreme precipitation for two seasons and two storm types. J. Hydrol., **233**, 1-4, 189–205.

Yu P.-S., Yang T.-C., Lin C.-S., 2004: Regional rainfall intensity formulas based on scaling property of rainfall. J. Hydrol., **295**, 1-4, 108–123.