REGIONAL DESIGN VALUE ESTIMATES OF EXTREME PRECIPITATION EVENTS IN THE CZECH REPUBLIC

Jan Kyselý (1), Jan Picek (2)

(1) Institute of Atmospheric Physics AS CR, Prague, Czech Republic, email: kysely@ufa.cas.cz
(2) Technical University Liberec, Czech Republic

ABSTRACT

Regional analysis is utilized to improve estimates of probabilities of extreme precipitation events in the Czech Republic. The Generalized Extreme Value (GEV) distribution was identified as the most suitable one for modelling maximum annual 1- to 7-day precipitation amounts according to the L-moment ratio diagram and goodness-of-fit tests; only in the northeast region, the Generalized Logistic (GLO) distribution should be preferred. The regional approach considerably lessens the between-site variation of estimates of the shape parameter of the GEV/GLO distribution compared to at-site procedures, and estimates of high quantiles (e.g. 50-yr return values) are more reliable and climatologically consistent in individual regions. Different shapes of the growth curves also indicate that the homogeneous regions are useful and reasonable for modelling probabilities of heavy precipitation. Particularly noteworthy is the heavy tail of distributions of multi-day extremes in the northeast region.

KEY WORDS: extreme precipitation event – regional frequency analysis – L-moments – design values – central Europe – Czech Republic

1. INTRODUCTION

A regional approach to the frequency analysis consists in supplementing at-site observations by an incorporation of spatial randomness; it has become a widely-used tool in hydrological as well as climatological studies. The approach is reasonable if one can assume that processes leading to extremes do not differ among sites in a 'region' that is 'homogeneous' according to statistical characteristics of extremes. The advantage of regional over single-site estimation is greater at distribution tails which are of interest in many practical applications, including planning for weather-related emergencies and design and operation of water reservoirs.

In this study, the regional frequency analysis based on L-moments (e.g. Hosking and Wallis 1997) is utilized to construct regional growth curves and improve estimates of design values of extreme precipitation events in the Czech Republic. After a brief description of data (Section 2) and methods used (Section 3), results of three main steps of the regional algorithm are dealt with in Sections 4 to 6; these are the formation of homogeneous regions, the choice of frequency distributions, and the estimation of parameters and quantiles of the fitted distributions. Benefits of the regional approach and concluding remarks are summarized in Section 7.

2. DATA

Daily precipitation totals measured at 78 stations operated by the Czech Hydrometeorological Institute were used as an input dataset (Fig. 1). The altitudes of stations range from 158 to 1324 m a.s.l. and the observations span the period 1961-2000. Samples of maximum annual 1-, 3-, 5- and 7-day precipitation amounts were drawn from each station records and are examined as extreme precipitation events. The data underwent standard quality checking for gross errors as well as checking in terms of a discordancy measure based on L-moments (Hosking and Wallis 1993).

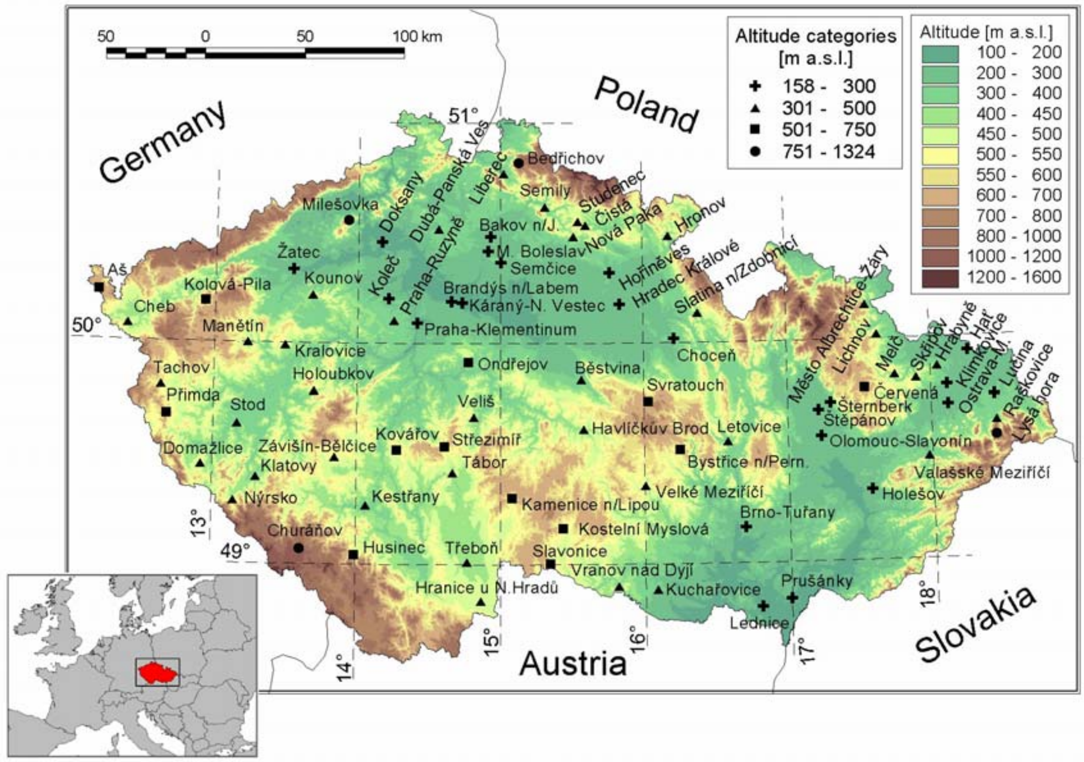

Fig. 1. Stations used in the regional frequency analysis of extreme precipitation events in the Czech Republic. Altitude categories (in m a.s.l.) are indicated by symbols.

3. METHODS

3.1 L-moments

Several steps of the regional analysis incorporate L-moments, an alternative set of scale and shape statistics of a data sample or a probability distribution (e.g. Hosking 1990). Their derivation is based on order statistics obtained by sorting the sample $\{X_1, X_2, ..., X_n\}$ of n independent realisations of variable X in ascending order $\{X_{1:n}, X_{2:n}, ..., X_{n:n}\}$; the subscript $k{:}n$ denotes the k-th smallest number in the sample of length n. L-moments λ_k are defined as expectations of linear combinations of these order statistics,

$$\lambda_k = \frac{1}{k}\sum_{j=0}^{k-1}(-1)^j \binom{k-1}{j} E(X_{k-j:k}),$$

where E stands for expectation operator. L-moment ratios are the L-coefficient of variation $\frac{\lambda_2}{\lambda_1}$ (L-CV), the L-skewness $\frac{\lambda_3}{\lambda_2}$ (τ_3) and the L-kurtosis $\frac{\lambda_4}{\lambda_2}$ (τ_4); except for some special cases of small samples, they take values between -1 and +1.

The k-th sample L-moment λ_k ($k \le n$) can be estimated as

$$l_k = \sum_{l=0}^{k-1}(-1)^{k-l-1}\binom{k-1}{l}\binom{k+l-1}{l} b_l\,,$$

where

$$b_l = \frac{1}{n}\sum_{i=1}^{n}\frac{(i-1)(i-2)...(i-l)}{(n-1)(n-2)...(n-l)}X_{i:n}\,,\ l \geq 1, \text{ and } b_0 = \frac{1}{n}\sum_{i=1}^{n}X_{i:n}\,.$$

3.2 Testing for regional homogeneity

The regional homogeneity tests applied to samples of annual maxima of 1- to 7-day precipitation amounts were those of Lu and Stedinger (1992) and Hosking and Wallis (1993). (Note that 'regional homogeneity' means that probability distributions at individual locations in a region are identical except for a site-specific scaling factor.) Generally, the tests are based on a quantity that measures a selected aspect of the frequency distribution (a 10-yr event in the Lu-Stedinger test, and L-moment ratios in the Hosking-Wallis tests), and compare the 'at-site' estimates with the regional estimate of this quantity. Simulations of homogeneous regions with sites having record lengths the same as the observed data are necessary to estimate the variance of 90% sample quantiles at individual sites (in the Lu-Stedinger test), and the mean and variance of a dispersion measure (in the Hosking-Wallis tests). We performed 500 realisations of homogeneous regions in all Monte Carlo experiments; the GEV and kappa distributions (Hosking 1994) were used in the Lu-Stedinger and Hosking-Wallis tests, respectively. Three versions of the Hosking-Wallis tests were applied, based on combinations of L-CV, L-skewness and L-kurtosis.

3.3 Goodness-of-fit test based on L-kurtosis

Goodness-of-fit of various candidate 3-parameter probability distributions is evaluated in terms of the difference between L-kurtosis τ_4 of the fitted distribution and the regional average L-kurtosis τ_4^R (Hosking and Wallis 1997). A comparison with the sampling variability of τ_4^R is carried out to assess the significance of this difference. The test statistics is

$$Z = \frac{\tau_4 - \tau_4^R + B_4}{\sigma_4}$$

where B_4 denotes the bias and σ_4 the standard deviation of τ_4^R, both obtained by simulations of a homogeneous region with sites having the kappa distribution. The number of replications was 500. The distribution is rejected at the 0.10 (0.05) level if $|Z|$ >1.64 ($|Z|$ >1.96).

4. REGIONALIZATION

In climatologically homogeneous areas with a simple orography (e.g. Belgium; Gellens 2002) the issue of regionalization is bridged easily and all available data may be usually considered to be drawn (after rescaling) from the same sample. Since an area with spatially variable mechanisms leading to heavy precipitation amounts (e.g. Štekl et al. 2001) and with a relatively complex orography (Fig. 1) is under study, the basic step of the regional analysis consisted in a formation of regions that are homogeneous according to statistical characteristics of precipitation extremes.

In compliance with a common practice (Hosking and Wallis 1997; Smithers and Schulze 2001; Kjeldsen et al. 2002), a cluster analysis of 'site characteristics' (longitude, latitude, elevation, mean annual precipitation, mean ratio of summer half-year to winter half-year precipitation, and mean annual number of dry days) was used as an auxiliary tool that yielded a number of preliminary partitionings into groups of sites. The most promising one originated from Ward's method of the cluster analysis with 4 clusters, two of them forming large homogeneous areas comprising more than 80% of sites. A number of adjustments and relocations were tested to improve the homogeneity of regions and to make them geographically and climatologically coherent; altogether 35 different partitionings of stations into regions were examined in terms of the Hosking-Wallis and Lu-Stedinger regional homogeneity tests (Section 3.2).

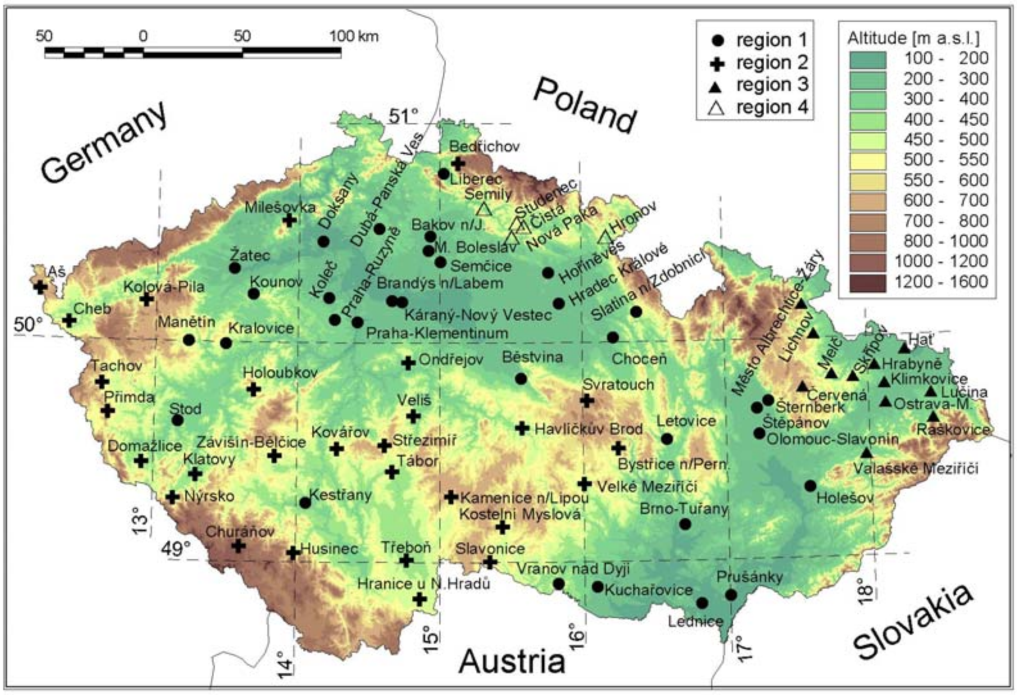

Fig. 2. Formation of homogeneous regions for the regional frequency analysis of precipitation extremes.

The final partitioning recognizes 4 homogeneous regions (Fig. 2) that reflect also climatological differences in precipitation regimes and synoptic patterns associated with heavy precipitation. The two large regions distinguish between lowland (region 1) and higher-elevated (region 2) locations in most of the area of the Czech Republic while the two smaller areas possess distinctly different precipitation regimes: Enhanced mean annual precipitation as well as heavy k-day amounts, due to orographic effects and an increased influence of Mediterrenean cyclones, is characteristic of region 3 in the NE part of the Czech Republic; and enhanced mean annual precipitation, small number of dry days and increased precipitation (including extremes) in winter, due to a larger influence of cloud belts and atmospheric fronts associated with Atlantic cyclones, are particular features of region 4 in the N part of the Czech Republic.

The fact that the regions do not depend on the duration of events (in accord with results of the statistical tests, they are identical for 1- to 7-day precipitation totals) is useful from the practical point of view (cf. Smithers and Schulze 2001). The most elevated and easternmost station, Lysá hora (in Beskydy Mts., the NE part of the Czech Republic), cannot be classified into any of the regions; its inclusion in region 3 (to which it might be geographically allocated) distorts the regional homogeneity. It cannot be concluded without additional precipitation data from the complex terrain of the NE region whether this is only due to sampling variability or reflects real different features of the distribution of precipitation maxima.

Considering the area of the Czech Republic, the number of clusters is reasonable compared to other studies (e.g., 9 regions entering the regional frequency analysis of precipitation extremes in the UK – Fowler and Kilsby 2003; 3 regions in Slovakia – Gaál 2006; 15 regions in South Africa – Smithers and Schulze 2001).

Stability of results of the regional homogeneity tests on the final partitioning was examined by a Monte Carlo simulation that consisted in repeatedly removing a given portion of data (stations) from each region, and performing the tests on the remaining part of the regional sample. These experiments fully support homogeneity of the regions formed; there are no occurrences of values of the test statistics of the Hosking-Wallis test based on L-CV larger than or equal to 2 (‘definite heterogeneity’) throughout the perturbed samples for all variables (1- to 7-day amounts) and in all regions.

5. IDENTIFICATION OF REGIONAL DISTRIBUTIONS

L-moment ratio diagrams (an example is shown in Fig. 3) and goodness-of-fit tests were applied for various candidate extreme value distributions: generalized extreme value (GEV), generalized logistic (GLO), lognormal (LN3) and Pearson type III (PE3).

The applicability of individual distributions was evaluated in terms of Z-statistics based on a difference between L-kurtosis of the fitted distribution and regional average of L-kurtosis (see Section 3.3). The GEV distribution is appropriate for most durations of extreme precipitation events and in most regions, and it is not rejected for any region-duration pair at the 0.10 significance level. All the other distributions are rejected for at least 35% of region-duration pairs at the 0.10 level, and at least 28% of pairs at the 0.05 level. Comparison of absolute values of the Z-statistics for individual distributions also supports superiority of the GEV distribution, with an exception of region 3 where GLO is preferred. The tests with the kappa distribution were impracticable in region 3 for 5-day and 7-day events; if the GEV or GLO distribution is employed instead of the kappa distribution in the tests, values of the Z-statistics support superiority of the GLO distribution in this area.

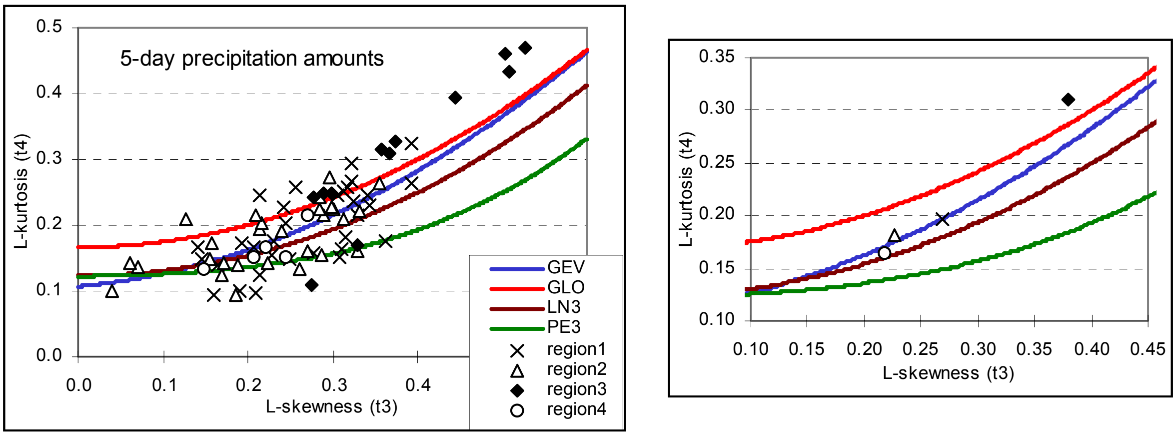

Fig. 3. L-moment ratio diagram for maximum annual 5-day precipitation amounts. Theoretical L-kurtosis/L-skewness curves for various candidate 3-parameter distributions are depicted; station values (regional means) are shown on the left (right) figure.

Note that the PE3 distribution (frequently termed also gamma) is unsuitable for modelling extreme precipitation amounts in the Czech Republic, the only exception being minor region 4 in the north. Since the PE3 distribution was applied in a previous study on probabilities of 1-day precipitation maxima in former Czechoslovakia (Šamaj et al. 1982), following a general recommendation of WMO, the results published therein (and cited in several recent studies on extreme precipitation events) should be considered unreliable.

6. REGIONAL GROWTH CURVES AND ESTIMATES OF DESIGN VALUES

To estimate parameters of regional distributions we utilized a regional algorithm based on L-moments (Hosking and Wallis 1997). Sample L-moment ratios calculated from the data at different sites were combined to give regional averages; analogously to the method of conventional moments, the first three L-moments were used to estimate parameters of a given distribution. Two variants of the scaling factor, the mean and median of at-site data, were tested. The accuracy of estimates was determined using a Monte Carlo simulation (bootstrap resampling), taking into account the intersite dependence in terms of correlation matrices (Hosking and Wallis 1997). We performed 10000 realisations of all regions, with the GEV (GLO) distribution applied to fit the generated data in regions 1, 2 and 4 (3). The regional relative RMSE of the estimated growth curves are shown in Table 1.

Table 1. RMSE for estimated regional growth curves based on the GEV (GLO) distributions in regions 1, 2 and 4 (3). *q(F)* denotes the quantile function; R1 (R5) stands for 1-day (5-day) precipitation amounts.

a. region 1 (GEV)

variable	*F*	*q(F)*	RMSE	variable	*F*	*q(F)*	RMSE
R1	0.500	0.906	0.009	R5	0.500	0.912	0.011
	0.900	1.486	0.010		0.900	1.456	0.013
	0.980	2.149	0.032		0.980	2.075	0.038
	0.990	2.483	0.041		0.990	2.386	0.049
	0.999	3.874	0.080		0.999	3.672	0.093

b. region 2 (GEV)

variable	*F*	*q(F)*	RMSE	variable	*F*	*q(F)*	RMSE
R1	0.500	0.916	0.009	R5	0.500	0.928	0.009
	0.900	1.479	0.010		0.900	1.439	0.013
	0.980	2.080	0.030		0.980	1.962	0.036
	0.990	2.370	0.039		0.990	2.206	0.045
	0.999	3.505	0.076		0.999	3.127	0.083

c. region 3 (GLO)

variable	*F*	*q(F)*	RMSE	variable	*F*	*q(F)*	RMSE
R1	0.500	0.929	0.018	R5	0.500	0.878	0.050
	0.900	1.398	0.022		0.900	1.439	0.034
	0.980	1.982	0.063		0.980	2.332	0.135
	0.990	2.307	0.083		0.990	2.908	0.189
	0.999	3.881	0.160		0.999	6.360	0.415

d. region 4 (GEV)

variable	*F*	*q(F)*	RMSE	variable	*F*	*q(F)*	RMSE
R1	0.500	0.901	0.024	R5	0.500	0.948	0.012
	0.900	1.443	0.024		0.900	1.327	0.018
	0.980	2.130	0.077		0.980	1.706	0.053
	0.990	2.500	0.108		0.990	1.881	0.071
	0.999	4.191	0.222		0.999	2.528	0.146

The regional approach considerably reduces between-site variability of the estimates of the shape parameter (k) of the GEV/GLO distribution. While the at-site analysis (estimation of parameters independently site-by-site) leads to estimates of the shape parameter of the GEV distribution for 1-day precipitation amounts in a broad range between –0.37 and +0.16 (yielding different extreme value types with $k<0$ / $k>0$), the values of k in the four regions lie in a relatively narrow band between –0.21 and –0.11. The differences among estimates at individual sites become even larger for multi-day extremes; the regional algorithm lessens the variations efficiently again although they become more pronounced due to real climatological differences among regions.

Regional estimates of k are negative for all regions and durations, and except for multi-day events in region 4 their 90% error bounds do not contain zero (Table 2). A particularly conspicuous deviation of region 3 appears for distributions of multi-day (3- to 7-day) precipitation amounts, tails of which are much heavier (corresponds to pronounced negative values of *k*) compared to other parts of the Czech Republic (cf. Fig. 4). While in all other regions the upper tails of regional distributions are heavier for 1-day than multi-day events, the opposite pattern is observed in region 3 (Table 2).

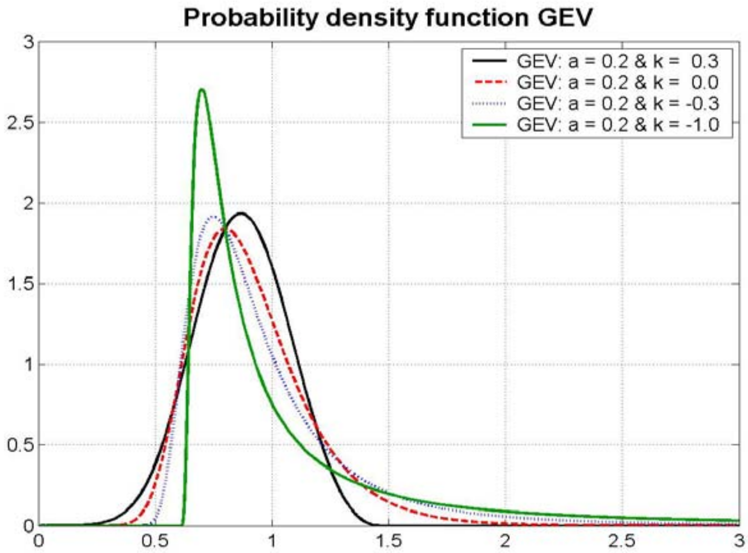

Fig. 4. Shapes of probability density functions of GEV distributions with different values of shape parameter *k*.

Table 2. Estimates and 90% error bounds of shape parameter *k* of the GEV (GLO) distributions in regions 1, 2 and 4 (3) of 1-, 3-, 5- and 7-day precipitation amounts (denoted R1, R3, R5 and R7).

	variable	*k*	90% error bounds	
region 1 (GEV)	R1	-0.151	-0.092	-0.176
	R3	-0.176	-0.110	-0.207
	R5	-0.147	-0.084	-0.184
	R7	-0.129	-0.061	-0.166
region 2 (GEV)	R1	-0.112	-0.051	-0.138
	R3	-0.117	-0.052	-0.151
	R5	-0.087	-0.021	-0.127
	R7	-0.069	-0.004	-0.111
region 3 (GLO)	R1	-0.249	-0.170	-0.296
	R3	-0.374	-0.222	-0.472
	R5	-0.379	-0.225	-0.498
	R7	-0.342	-0.193	-0.439
region 4 (GEV)	R1	-0.210	-0.073	-0.298
	R3	-0.063	0.056	-0.153
	R5	-0.074	0.039	-0.172
	R7	-0.030	0.092	-0.124

The application of median as a scaling factor (index storm) yields underestimated design values (as expected from generally heavy tails of the fitted distributions) and mean is preferred as the index storm. The relationship between the index storm and mean annual precipitation is approximately linear in regions 1, 2 and 3, the slope being largest (smallest) in region 3 (1). The existence of these links enables one to estimate design values at ungauged sites from mean annual precipitation. In region 4, the dependence is not observed and values of the index storm are almost identical at all stations.

Main benefits of the regional compared to the at-site approach consist in reduced uncertainty of design value estimates as well as reduced between-site variability that stems from random fluctuations in a homogeneous region. This is true particularly for large regions 1 and 2 where differences between at-site estimated design values (e.g. 50-yr return values) do not reflect climatological features, but almost entirely sampling variability. E.g. in region 1 (formed by 32 stations and covering lowland areas in most parts of the Czech Republic), the at-site analysis results in 50-yr return values of 1-day precipitation amounts between 56 and 101 mm while the regional approach halves the range of estimates (69 to 92 mm) and makes them more directly related to mean precipitation pattern. The reduction of site-by-site differences (that cannot be related to climatological peculiarities and stem from random sampling variability only) occurs in all regions and for all examined durations of precipitation events.

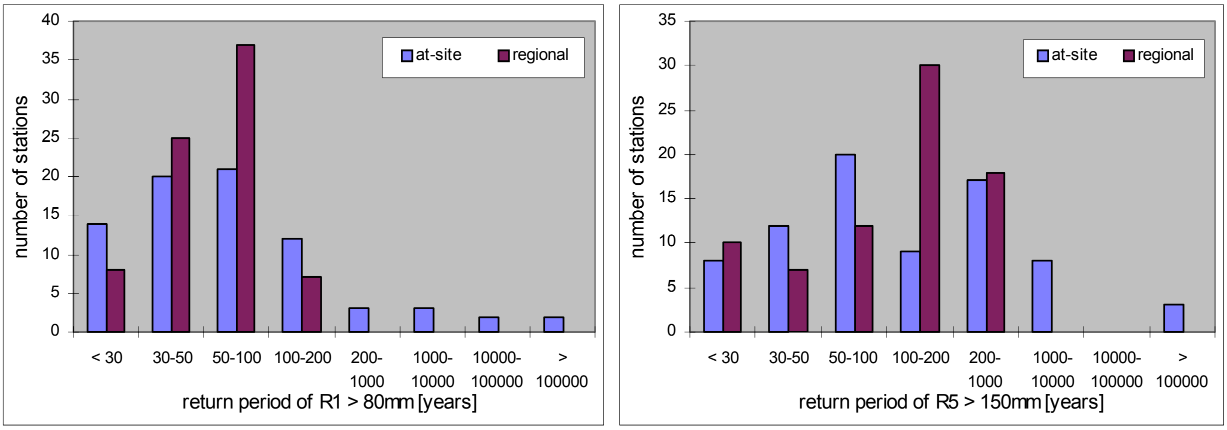

Fig. 5. Distributions of estimates of return periods of 1-day amounts exceeding 80 mm (5-day amounts exceeding 150 mm) obtained using the at-site and regional algorithms.

The superiority of the regional approach is conspicuous when probabilities of given precipitation depths are estimated (Fig. 5, Table 3). Estimates of return periods of e.g. 1-day amounts exceeding 80 mm based on the at-site analysis are on the order of thousands to millions of years at 10% of sites (left panel of Fig. 5, third column in Table 3), although it is easy to reveal that real probabilities of such events are much larger in central Europe (the observed 1-day maxima over 1961-2000 exceed 80 mm at 63% of examined sites; cf. also Šamaj et al. 1983; Štekl et al. 2001). Such an underestimation reflects properties of the particular samples that do not support heavy tails of precipitation distributions. The regional procedure leads to estimates of return periods of 1-day totals exceeding 80 mm at all stations in an acceptable range of 5 to 137 years (fourth column in Table 3). Similar results hold true for probabilities of multi-day precipitation amounts where the percentage of sites with unrealistically large return periods (based on at-site data only) of 5-day totals exceeding 150 mm is even higher (right panel of Fig. 5, last two columns of Table 3).

Table 3. Comparison of estimates of return periods (in years) of selected precipitation depths based on the at-site and regional analysis. R1 (R5) stands for 1-day (5-day) precipitation amounts.

station	region	R1 > 80 mm, at site	R1 > 80 mm, regional	R5 > 150 mm, at-site	R5 > 150 mm, regional
Stod	1	45	78	66	155
Manětín	1	42	90	81	247
Kralovice	1	41	49	89	159

station	region	R1 > 80 mm, at site	R1 > 80 mm, regional	R5 > 150 mm, at-site	R5 > 150 mm, regional
Žatec	1	57	105	115	207
Kounov	1	64	62	42	98
Kestřany	1	34	46	70	84
Doksany	1	77	84	133	203
Koleč	1	24	44	40	100
Praha-Ruzyně	1	40	49	65	127
Praha-Klementinum	1	49	82	77	180
Dubá-Panská Ves	1	>1000000	73	357	127
Brandýs n/Lab	1	33	40	73	102
Káraný-Nový Vestec	1	31	48	67	143
Mladá Boleslav	1	49	62	131	164
Bakov n/Jizerou	1	45	64	355	170
Semčice	1	27	49	75	145
Liberec	1	21	26	40	41
Běstvina	1	52	32	347	65
Hořiněves	1	67	54	>1000	143
Vranov n/Dyjí	1	122	65	>1000	151
Hradec Králové	1	24	31	88	93
Kuchařovice	1	128	59	693	166
Choceň	1	36	46	71	88
Slatina n/Zdobnicí	1	66	30	66	43
Letovice	1	212	60	466	143
Brno-Tuřany	1	119	87	208	189
Lednice	1	221	83	267	238
Prušánky	1	133	86	503	205
Štěpánov	1	>1000	79	>1000	136
Olomouc-Slavonín	1	111	52	353	119
Šternberk	1	67	56	>1000	94
Holešov	1	52	42	71	63
Aš	2	282	76	>1000000	181
Cheb	2	169	111	>1000000	454
Tachov	2	101	103	532	309
Přimda	2	>10000	137	758	187
Domažlice	2	105	71	196	116
Kolová-Pila	2	94	132	917	382
Nýrsko	2	68	50	40	80
Klatovy	2	29	44	51	113
Churáňov	2	13	13	15	13
Holoubkov	2	44	57	70	136
Závišín-Bělčice	2	32	64	103	185
Milešovka	2	55	104	86	276
Husinec	2	18	24	40	66
Kovářov	2	66	85	92	193
Střezimíř	2	65	55	81	149
Tábor	2	>10000	114	>1000	378
Třeboň	2	27	44	96	108
Ondřejov	2	29	45	43	95
Veliš	2	56	71	125	188
Hranice u N.Hradů	2	84	53	>1000000	100
Kamenice n/Lipou	2	>100000	85	>1000	232

station	region	R1 > 80 mm, at site	R1 > 80 mm, regional	R5 > 150 mm, at-site	R5 > 150 mm, regional
Bedřichov	2	7	8	7	8
Slavonice	2	73	51	153	137
Kostelní Myslová	2	53	53	167	156
Havlíčkův Brod	2	30	46	>1000	132
Velké Meziříčí	2	>1000	69	383	244
Svratouch	2	55	32	35	49
Bystřice n/Pern.	2	53	62	340	284
Červená	3	>1000	76	46	32
Město Albrechtice	3	23	37	22	24
Lichnov	3	44	72	61	45
Melč	3	59	39	46	26
Skřipov	3	31	41	22	23
Valašské Meziříčí	3	16	21	20	21
Hrabyně	3	57	45	26	27
Klimkovice	3	122	59	41	36
Ostrava-Mošnov	3	134	30	30	26
Hať	3	152	81	45	41
Lučina	3	23	21	16	17
Raškovice	3	4	5	4	5
Semily	4	106	51	242	232
Nová Paka	4	33	47	>1000	318
Studenec	4	41	46	168	333
Čistá	4	38	46	276	305
Hronov	4	46	34	314	355

Regional growth curves (derived using the GEV distribution in regions 1, 2 and 4, and GLO in region 3) for 1-day and multi-day extremes are depicted in Fig. 6; error bounds of the curves may be derived from Table 1. (In region 3, the GEV distribution was applied for comparison, too.) Note that the growth curves are dimensionless and station quantiles can be obtained by multiplication with the station's mean annual maximum of a given duration. The between-region differences in shapes of the growth curves are very similar for 3- to 7-day amounts, and upper tails of the distributions are much heavier in region 3 compared to the other ones. In region 4, multi-day extremes are almost Gumbel-distributed (corresponds to zero value of the shape parameter k, and a straight line of a growth curve); region 4 is the only one where the Gumbel distribution is not rejected at the 0.10 level (cf. 90% error bounds of the estimates of k in Table 2). In the range of return periods useful in a practical implementation of the regional analysis, deviations between the GLO and GEV distributions in region 3 are much smaller than differences among regions.

Variations in shapes of the regional growth curves are relatively minor for 1-day precipitation maxima (Fig. 6). Particularly, the growth curves in regions 1 and 4 are not distinct from each other if accuracy of the estimates is measures by RMSE, i.e. the curves overlap within RMSE bounds in a large range of return values. For multi-day precipitation amounts, the regional growth curves are distinct from each other at return levels between 20 and 100 yrs (cf. Table 1). The regional similarity of growth curves for 1-day maxima was expected since processes leading to heavy 1-day amounts, mostly related to convective systems and storms in summer half-year, are spatially less variable in the area under study compared to synoptic patterns causing extreme high multi-day totals (e.g. Štekl et al. 2001).

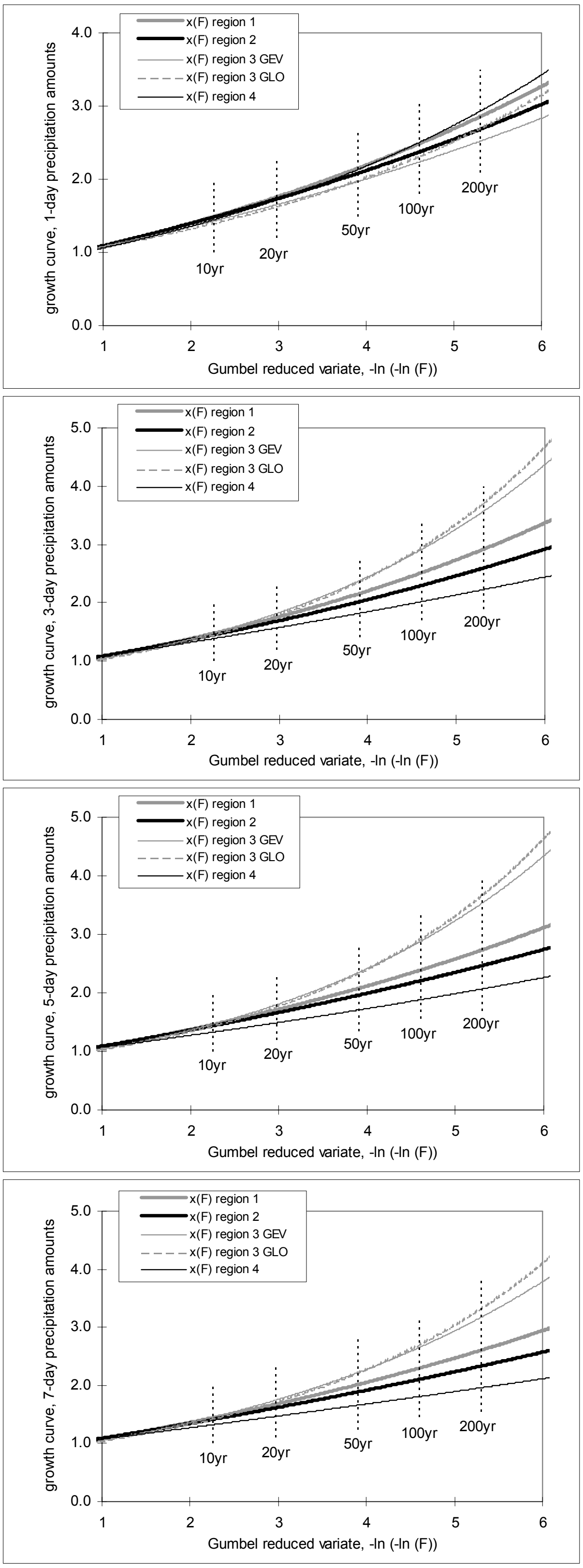

Fig. 6. Regional growth curves of 1- to 7-day precipitation amounts based on the GEV distribution; in region 3, the GLO growth curves are also depicted. The Gumbel reduced variate (-ln(-ln(F)) where F stands for the distribution function) is shown on x-axis; values corresponding to return levels of 10, 20, 50, 100 and 200 yrs are depicted by vertical lines.

7. SUMMARY

Main conclusions of the study are as follows:

- A regional methodology is shown to be beneficial compared to an at-site approach in the frequency analysis of extreme precipitation events. It leads to estimates of design values that are less uncertain, and spatial variability of which, related mostly to random fluctuations, is favourably reduced.
- The four homogeneous regions ensuing from statistical procedures (cluster analysis of site characteristics and subsequent tests for regional homogeneity) reflect also climatological differences in precipitation regimes and synoptic patterns causing heavy precipitation, and their future applications may not be limited to the frequency analysis of rainfall extremes.
- The Generalized Extreme Value (GEV) distribution was identified as the most suitable one for modelling maximum annual 1- to 7-day precipitation amounts, according to the L-moment ratio diagram and goodness-of-fit tests. This result is similar to many other parts of the world where the GEV distribution was found useful in modelling precipitation extremes. Only in the NE region 3 (which is most prone to the occurrence of high precipitation totals), the Generalized Logistic (GLO) distribution is preferred.
- Negative regional estimates of shape parameters of both distributions reflect heavy tails of precipitation extremes. Note that the GEV and GLO distributions with a negative value of the shape parameter are distributions with the same weight of the (heavy) upper tail, and their probability density functions converge to zero more slowly than those of other candidate 3-parameter distributions examined (LN3 and PE3).
- The regional approach considerably lessens the between-site variation of estimates of the shape parameter of the GEV/GLO distribution compared to the at-site procedures, and the estimates of design values are more reliable and climatologically consistent in the individual regions.
- Differences between distributions (in cases when more than one statistical model is appropriate) are generally smaller than differences between the regional and at-site approaches which further supports superiority of the regional algorithm.
- Considerable deviations between the four regions in shapes of the growth curves also indicate that the homogeneous regions are useful and reasonable for modelling probabilities of precipitation extremes. The between-region variability is almost identical for 3- to 7-day precipitation totals, and generally larger for multi-day than 1-day events. This is because the latter are related to mechanisms (mostly convective storms in summer half-year), spatial climatological variability of which is relatively minor (Štekl et al. 2001). Unlike the 1-day extremes, heavy multi-day precipitation is usually associated with slowly moving cyclones over central Europe, an influence of which tends to be enhanced in the NE part of the Czech Republic where a specific configuration of mountain ranges plays a role.

The present analysis is a first step toward regional modelling of extreme precipitation events in the Czech Republic. It is likely that appropriate modifications of the regional algorithm can improve its performance and the reliability of design values. Further directions and challenges involve incorporation of peaks-over-threshold methodology and covariates (time-dependency) into regional extreme value models (e.g. Coles and Dixon 1999; Katz et al. 2002) and development of a region-of-influence approach (Burn 1990; Gaál et al. 2006). The issue of time-dependency is particularly timely since an increase in the frequency and severity of heavy precipitation is expected and/or observed over large parts of Europe (e.g. Frich et al. 2002; Pal et al. 2004), and the currently disastrous impacts of high precipitation amounts and floods on the human society may become even more pronounced in a future climate. The present analysis constitutes bases for more sophisticated regional models of extremes in a non-stationary climate.

Acknowledgements: The study was supported by the Grant Agency of AS CR under project B300420601. Thanks are due to J.Hošek and L.Gaál for assistance in drawing the figures, and L.Gaál, R.Huth and I.Nemešová for comments on previous versions of the manuscript.

REFERENCES

Burn DH (1990) Evaluation of regional flood frequency analysis with a region of influence approach. Water Resources Research 26: 2257-2265

Coles SG, Dixon MJ (1999) Likelihood-based inference for extreme value models. Extremes 2: 5-23

Fowler HJ, Kilsby CG (2003) A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000. Int J Climatol 23: 1313-1334

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank AMG, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the 20th century. Clim Res 19: 193-212

Gaál L (2006) Estimation methods of statistical properties of several-day design precipitation. PhD thesis, Faculty of Mathematics, Physics and Informatics, Komenius University, Bratislava [in Slovak]

Gaál L, Kyselý J, Štěpánek P (2006) Region-of-influence approach to the frequency analysis of heavy k-day precipitation amounts. Proc of the Bioclimatological Workshop, Strečno, Slovakia, this volume

Gellens D (2002) Combining regional approach and data extension procedure for assessing GEV distribution of extreme precipitation in Belgium. J Hydrol 268: 113-126

Hosking JRM (1990) L-moments: Analysis and estimation of distributions using linear combinations of order statistics. J Roy Stat Soc 52B: 105-124

Hosking JRM (1994) The four-parameter kappa distribution. IBM J Res Develop 38: 251-258

Hosking JRM, Wallis JR (1993) Some statistics useful in regional frequency analysis. Water Resour Res 29: 271-281

Hosking JRM, Wallis JR (1997) Regional Frequency Analysis. An Approach Based on L-moments. Cambridge University Press, Cambridge, New York, Melbourne, 224 pp

Katz RW, Parlange MB, Naveau P (2002) Statistics of extremes in hydrology. Adv Water Res 25: 1287-1304

Kjeldsen TR, Smithers JC, Schulze RE (2002) Regional flood frequency analysis in the KwaZulu-Natal province, South Africa, using the index-flood method. J Hydrol 255: 194-211

Lu L-H, Stedinger JR (1992) Sampling variance of normalized GEV/PWM quantile estimators and a regional homogeneity test. J Hydrol 138: 223-245

Pal JS, Giorgi F, Bi XQ (2004) Consistency of recent European summer precipitation trends and extremes with future regional climate projections. Geoph Res Lett 31: L13202

Smithers JC, Schulze RE (2001) A methodology for the estimation of short duration design storms in South Africa using a regional approach based on L-moments. J Hydrol 241: 42-52

Šamaj F, Valovič Š, Brázdil R, Gulčíková V (1982) Maximum daily atmospheric precipitation totals in Czechoslovakia. Meteorol Zpr 35: 129-135 [in Slovak, with English summary]

Šamaj F, Valovič Š, Brázdil R (1983) Extreme daily precipitation totals in Czechoslovakia. Meteorol Zpr 36: 14-21 [in Slovak, with English summary]

Štekl J, Brázdil R, Kakos V, Jež J, Tolasz R, Sokol Z (2001) Extreme daily precipitation on the territory of the Czech Republic in the period 1879-2000 and their synoptic causes. National Climatic Programme of the Czech Republic, 31, 140 pp [in Czech, with English summary]