

# FORMATION OF HOMOGENEOUS REGIONS FOR REGIONAL FREQUENCY ANALYSIS OF EXTREME PRECIPITATION EVENTS IN THE CZECH REPUBLIC

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## ABSTRACT

*Extreme high precipitation amounts are among environmental events with the most disastrous consequences for human society. This paper deals with the identification of 'homogeneous regions' according to statistical characteristics of precipitation extremes in the Czech Republic, i.e. the basic and most important step toward the regional frequency analysis. Precipitation totals measured at 78 stations over 1961–2000 are used as an input dataset. Preliminary candidate regions are formed by the cluster analysis of site characteristics, using the average-linkage clustering and Ward's method. Several statistical tests for regional homogeneity are utilized, based on the 10-yr event and the variation of L-moment statistics. In compliance with results of the tests, the area of the Czech Republic has been divided into four homogeneous regions. The findings are supported by simulation experiments proposed to evaluate stability of the test results. Since the regions formed reflect also climatological differences in precipitation regimes and synoptic patterns causing high precipitation amounts, their future application may not be limited to the frequency analysis of extremes.*

**Key words:** extreme precipitation event, regional analysis, L-moments, Central Europe, Czech Republic

## 1. INTRODUCTION

High precipitation amounts and floods rank amongst the extreme environmental events that severely affect human society. Their disastrous impacts may become even more pronounced in a future climate since an increase in the severity of heavy precipitation is expected and/or observed over large parts of Europe (IPCC, 2001; Frich *et al.*, 2002; Christensen and Christensen, 2003; Klein Tank and Koennen, 2003; Pal *et al.*, 2004; Semmler and Jacob, 2004; Zolina *et al.*, 2005). Probability estimates of events with a given magnitude are of primary importance, e.g., in planning for weather-related emergencies, engineering practice for water resources and reservoirs, design of urban

drainage systems etc. However, the estimation of frequencies of extremes is difficult due to the fact that data records are usually short.

The current study was predominantly inspired by the recent occurrence of massive summer floods in the Czech Republic and central Europe in 1997 and particularly 2002, and the development of a new method for the estimation of probabilities of extremes based on a regional analysis combined with an L-moment approach during the 1990s (Hosking, 1990; Pilon and Adamowski, 1992; Hosking and Wallis, 1997). A regional frequency analysis has not yet been applied in studies dealing with return periods of hydrological extremes in the area under study.

The main goal of the present analysis is to form groups of sites ('regions') that satisfy the 'homogeneity condition' that their frequency distributions of extreme precipitation amounts are identical except for a site-specific scaling factor (Hosking and Wallis, 1997). After a brief description of the background methodology and datasets used (in Sections 2 and 3), the paper presents findings concerning the formation of candidate regions using cluster analysis (Section 4) and statistical tests for the regional homogeneity (Section 5). Geographical and climatological description of the final homogeneous regions is given in Section 6.1, and two statistical issues that concern a failure of Hosking-Wallis tests with the kappa distribution under special conditions and an evaluation of stability of final homogeneous regions are discussed in Section 6.2.

## 2. REGIONAL FREQUENCY ANALYSIS BASED ON L-MOMENTS

### 2.1. Regional frequency analysis

In a regional approach to the frequency analysis, data from several sites (forming a region) are used in estimating frequencies at any one site. The assumption of the 'index flood'/'index storm' procedure is that frequency distributions at  $N$  sites from a homogeneous region are the same apart from a site-specific scaling factor, usually termed the 'index flood' in a streamflow analysis and the 'index storm' in a precipitation analysis. Because of scarcity of data, the use of the regional compared to the 'at-site' estimation is particularly advantageous at distribution tails (i.e., extremes) focused in practical applications. Another advantage of the regional approach is that distributions at ungauged locations can be more easily estimated (Pilon and Adamowski, 1992; Kjeldsen et al., 2001). That is why many methods recommended by national organizations for general use in hydrology and/or climatology have a regional component.

Although the method is still more popular in studies dealing with high and low extremes of streamflow, regional frequency analysis of heavy precipitation events has been performed for many parts of the world including the U.S. (e.g. Guttman et al., 1993; Naghavi and Yu, 1995; Sveinsson et al., 2001, 2002), Canada (Alila, 1999, 2000), South Africa (Smithers and Schulze, 2001), Belgium (Gellens, 2002) and the UK (Fowler and Kilsby, 2003a,b). The methodology has also been applied to investigate projected future changes in extreme rainfall return levels in the UK from regional climate model intergrations (Fowler et al., 2005; Ekström et al., 2005). Most frequently an algorithm

based on probability-weighted-moments (PWMs; *Greenwood et al., 1979*) and/or L-moments (*Hosking, 1990; Hosking and Wallis, 1997*) is utilized.

## 2.2. L - moments

L-moments are a recent development in mathematical statistics that facilitates the estimation process in the frequency analysis (see e.g. *Hosking, 1990* for the definition). They are derived from PWMs and represent an alternative set of scale and shape statistics of a data sample or a probability distribution. Their main advantages over conventional (product) moments are that they are able to characterise a wider range of distributions and (when estimated from a sample) are less subject to bias in estimation and more robust to the presence of outliers in the data (e.g. *Royston, 1992; Sankarasubramanian and Srinivasan, 1999; Ulych et al., 2000*). The latter is because ordinary moments (unlike L-moments) require involution of the data which causes disproportionate weight to be given to the outlying values.

L-moment ratios are frequently employed as useful combinations of L-moments; except for some special cases of small samples they take values between  $-1$  and  $+1$ . If the  $k$ -th L-moment is denoted  $\lambda_k$ , the L-moment ratios (termed also standardized L-moments) are the L-coefficient of variation  $\lambda_2/\lambda_1$  (L-CV), the L-skewness  $\lambda_3/\lambda_2$  ( $\tau_3$ ) and the L-kurtosis  $\lambda_4/\lambda_2$  ( $\tau_4$ ).

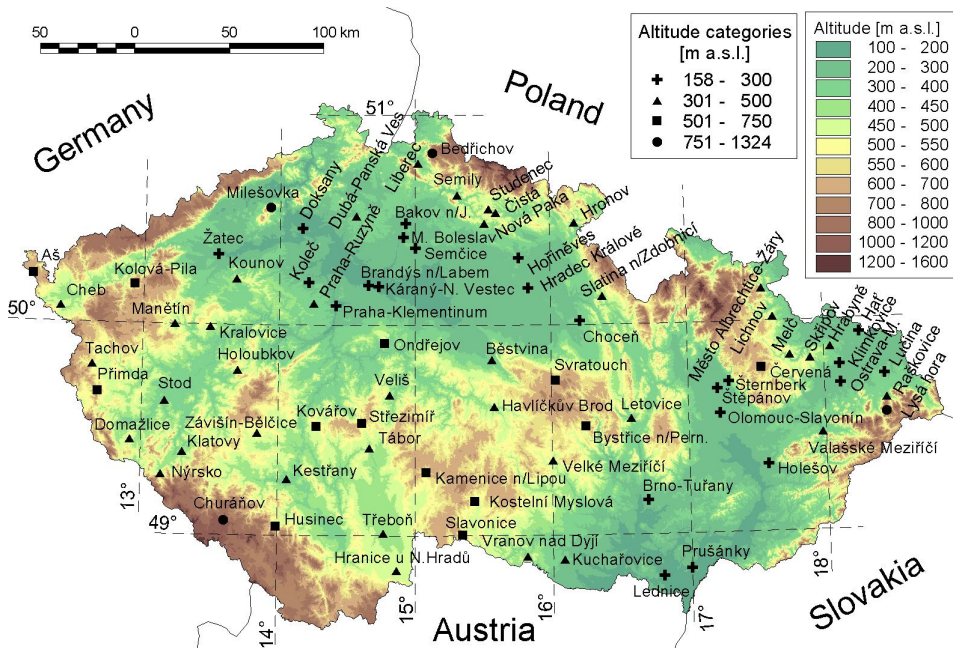
## 2.3. L - moments and regional frequency analysis

L-moments may be applied in four steps of the regional frequency analysis (*Hosking and Wallis, 1997*); these are (i) screening of the data, (ii) identification of homogeneous regions, (iii) choice of a frequency distribution, and (iv) estimation of the frequency distribution. The present study deals with the first two steps in which L-moments are utilized to construct a discordancy measure that identifies unusual sites with sample L-moment ratios markedly different from the other sites (i), and summary statistics in testing homogeneity of regions (ii).

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. Here an area with spatially variable mechanisms leading to extreme high precipitation totals (*Hanslian et al., 2000; Štekl et al., 2001*) and a relatively complex orography is under study; hence the basic step of the regional analysis, consisting in the identification of regions that are homogeneous according to statistical characteristics of extreme precipitation events, is of primary importance.

## 3. DATA

Daily precipitation amounts measured at 78 stations covering the Czech Republic (area of 78 864 km<sup>2</sup>), with altitudes ranging from 158 to 1324 m a.s.l., were used as an input dataset (Fig. 1). The data were provided by the Czech Hydrometeorological Institute where they underwent standard quality checking (cf. *Coufal et al., 1992*). The period



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

covered is 1961–2000; the main criterion applied when forming the dataset was that no significant station moves (exceeding 50 m in altitude) occurred during this period.

Samples of maximum annual  $k$ -day precipitation amounts ( $k = 1, 3, 5$  and 7 days) were drawn from each station's data and are examined as extreme precipitation events. There are no significant and spatially uniform trends in precipitation extremes over the period under study (in annual data), so the basic assumption of the regional analysis, which relies on stationary processes, is not violated.

Sites grossly discordant with the group as a whole were identified using the discordancy measure ( $D$ ) based on the dispersion of L-moment ratios among stations; see *Hosking and Wallis (1993)* for a formal definition of the discordancy statistic and critical values. Sites recognized as discordant ('outlying' according to L-moment ratios) were examined for errors or sources of unreliability in data. However, all values of the discordancy measure larger than a critical value have originated from real observed outliers, mostly extraordinarily high 1997 precipitation totals at a few stations in the northeast part of the Czech Republic (e.g. *Štekl et al., 2001*), and there is no physical reason to exclude these stations from further analysis.

#### 4. IDENTIFICATION OF CANDIDATE REGIONS USING CLUSTER ANALYSIS

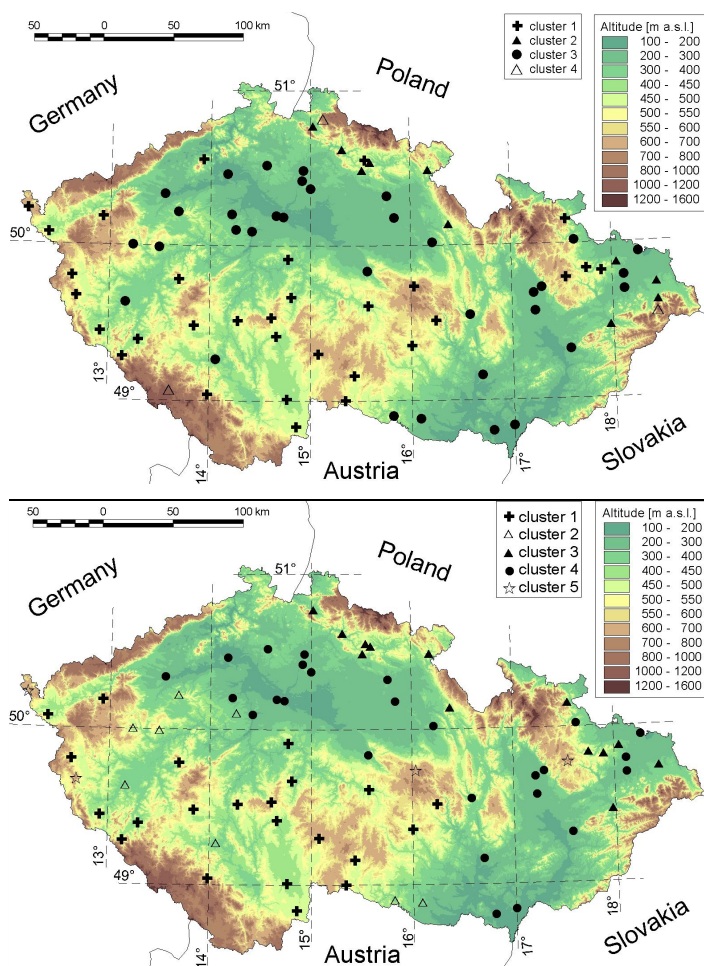
The formation of candidate regions was based, in accordance with common practice (e.g. *Hosking and Wallis, 1997*), on the cluster analysis of ‘site characteristics’: longitude, latitude, elevation, mean annual precipitation, mean ratio of summer half-year (May to October) to winter half-year (November to April) precipitation, and mean annual number of dry days (defined as days with precipitation amount  $\leq 0.1$  mm). This set of ‘site characteristics’ is similar to those utilized in other studies dealing with the regional analysis of extreme precipitation (e.g. *Smithers and Schulze, 2001*). We avoided using ‘at-site statistics’ (quantities calculated from at-site values of the analysed variables) together with the ‘site characteristics’ at this stage in order not to compromise results of the tests: otherwise there would be a tendency to group together all sites that have high outliers, even though these outliers result from random fluctuations, and testing for the homogeneity of the formed regions by a statistic calculated from the ‘at-site statistics’ would be misleading (*Hosking and Wallis, 1997*).

The average-linkage clustering (which yields clusters with equal within-cluster variance) and Ward’s method (which tends to form clusters with equal number of sites) were applied as clustering algorithms (cf. *Guttman, 1993*). The latter one yields slightly superior results, particularly because of the undesirable ‘snowball effect’ (*Kalkstein et al., 1987; Huth et al., 1993*) present in the average-linkage clustering outputs (one big cluster is produced to which smaller clusters are stuck, more and more dissimilar from the mean). The number of clusters to form is a subjective choice. Here the reasonable numbers of clusters were 8, 4 and 3 for Ward’s method, and 5 and 3 for the average-linkage, with 5 and 4 sites, respectively, unclassified in the latter. Too many clusters (more than about 10 in the present analysis) would lead to regions consisting of too few stations, and little gain in the accuracy of regional estimates compared to the ‘at-site’ analysis would be achieved. That is why possible classifications yielding more than 10 clusters were not considered. Examples of unadjusted partitionings based on both methods are depicted in Fig. 2.

#### 5. TESTING FOR HOMOGENEITY OF REGIONS

##### 5.1. Methods

Statistical tests for the homogeneity of regions are usually based on a quantity that measures some aspect of the frequency distribution, e.g. the 10-yr event (*Lu and Stedinger, 1992*), the combination of the L-coefficient of variation L-CV and the L-skewness  $\tau_3$  (*Chowdhury et al., 1991*) or the combination of L-CV,  $\tau_3$  and the L-kurtosis  $\tau_4$  (*Hosking and Wallis, 1993; Adamowski, 2000*), and compare the ‘at-site’ estimates with the regional estimate of this quantity (see *Hosking, 1990* for a formal definition of L-CV,  $\tau_3$  and  $\tau_4$ ). The variance of the 90% sample quantiles at individual sites (utilized in the test according to *Lu and Stedinger, 1992*) or the mean and variance of the chosen dispersion measure (in *Chowdhury et al., 1991* and *Hosking and Wallis, 1993*) are obtained by a simulation of a homogeneous region with sites having record lengths the same as the observed data (Monte Carlo method; see Appendix).



**Fig. 2.** Examples of unadjusted partitionings based on Ward's method (**top**, 4 clusters) and the average-linkage method (**bottom**, 5 clusters but several sites unclassified) of the cluster analysis.

The regional homogeneity tests employed in the present study were those of *Lu and Stedinger (1992)* and *Hosking and Wallis (1993)*; their brief description is given in Appendix. Three versions of the Hosking-Wallis test were applied, based on L-CV,  $\tau_3$  and  $\tau_4$  or their combinations.

### 5.2. Results of the tests

At the first stage, the tests for the regional homogeneity were performed for 8, 4 and 3 clusters of Ward's method, 5 and 3 clusters of the average-linkage method (see Section 4), as well as for all sites taken as one region. As expected, none of the partitionings based

entirely on the cluster analysis yields only homogeneous regions in any of the four variables examined (maximum annual 1-, 3-, 5- and 7-day precipitation totals). All stations taken together cannot be regarded as a homogeneous region either. Note that 'more regions' do not necessarily mean 'more homogeneity' owing to different sample sizes, different parameters of the distributions used in the simulations, and different means and variances of the dispersion measure in the simulated homogeneous regions.

Generally, the Hosking-Wallis test based on the L-CV (the  $H_1$  test; see Appendix) indicates heterogeneity or potential heterogeneity more often than the other two Hosking-Wallis tests. Since the discriminatory power of the  $H_2$  and  $H_3$  tests is much smaller (cf. *Hosking and Wallis, 1997*), they were evaluated as auxiliary tests only. There is no general agreement between the results of the Lu-Stedinger and Hosking-Wallis tests since they examine different characteristics of distributions of extreme precipitation amounts: The Lu-Stedinger test rejects the null hypothesis that a region is homogeneous most frequently (in 26% of all the tests performed on different candidate regions and the four variables; the percentage of heterogeneous or potentially heterogeneous regions according to the  $H_1$  test is 21%), and the regions from the various candidate partitionings heterogeneous according to the Lu-Stedinger test are in 42% acceptably homogeneous according to the  $H_1$  test.

The most promising partitioning stemming from the cluster analysis was obtained by Ward's method with 4 clusters (Fig. 2 top): two of them form large regions (comprising 83% of sites; clusters 1 and 3 in Fig. 2) that are homogeneous according to a majority of the tests and tested variables. A number of subjective modifications (mainly according to site locations and climatological characteristics) were evaluated to improve the geographical and climatological coherence of regions and to avoid their heterogeneity.

The final partitioning based on adjustments to the output of Ward's method of the cluster analysis with 4 clusters leads to 4 regions that are homogeneous according to all tests and tested variables (Table 1) with one exception: the largest Region 1 is heterogeneous according to the Lu-Stedinger test for extreme high 1-day precipitation amounts. However, the other tests on this region (the Hosking-Wallis tests for 1-day annual maxima, and all tests for 3- to 7-day annual maxima) do not reject its homogeneity. Within Region 1, sites most discordant with the region as a whole were examined for suspicious data in the samples of heavy 1-day precipitation totals and for climatological differences, but no variations in characteristics of the distribution of precipitation extremes reflecting patterns related to precipitation climatology and/or orography were found. Moreover, the two sites least similar according to the shape of the distribution of 1-day precipitation maxima are located close to one another in an area without distinct orographic influences.

It is very likely that the differences resulting in the regional heterogeneity according to the Lu-Stedinger test for 1-day events stem from sampling variability only. Considering the large number of tests and tested variables, and the 5% significance level of the Lu-Stedinger test, it is reasonable to treat this region as being homogeneous, too (cf. a discussion on physical versus statistical arguments in *Hosking and Wallis, 1997*, p.70). Note that even a possible slight heterogeneity (indicated by results of the Hosking-Wallis tests in Region 3, too; see Table 1) usually does not inhibit the regional analysis from being beneficial compared to the at-site analysis (*Hosking and Wallis, 1997; Smithers and Schulze, 2001*).

**Table 1.** Results of homogeneity tests on final regions. *R1* (*R3*, *R5*, *R7*) denotes maximum annual 1- (3-, 5-, 7-) day precipitation amounts;  $H_1$  ( $H_2$ ,  $H_3$ ) are test statistics of the Hosking-Wallis tests;  $\chi_R^2$  is the test statistics of the Lu-Stedinger test;  $\chi_{0.95}^2$  stands for the critical value of the Lu-Stedinger test. For the description of tests see Appendix. The test results yielding heterogeneity or possible heterogeneity ( $H_1$  ( $H_2$ ,  $H_3$ )  $\geq 1$ ;  $\chi_R^2 \geq \chi_{0.95}^2$ ) are shown in bold. Values of test statistics  $H_1$ ,  $H_2$  and  $H_3$  for variables *R5* and *R7* in Region 3 were calculated after year 1997 was excluded from the data.

Region	Variable	$H_1$	$H_2$	$H_3$	$\chi_R^2$	$\chi_{0.95}^2$
1	<i>R1</i>	0.98	-1.05	-1.56	<b>54.4</b>	45.0
	<i>R3</i>	-0.54	-3.04	-3.42	37.3	45.0
	<i>R5</i>	0.48	-1.17	-1.77	43.1	45.0
	<i>R7</i>	-0.62	-1.53	-2.21	36.1	45.0
2	<i>R1</i>	-0.23	0.37	0.60	35.0	40.1
	<i>R3</i>	-0.39	-0.33	-0.80	28.4	40.1
	<i>R5</i>	-0.66	-0.33	-1.22	28.0	40.1
	<i>R7</i>	-1.21	0.51	-0.40	21.0	40.1
3	<i>R1</i>	0.13	<b>1.17</b>	<b>1.12</b>	15.8	19.7
	<i>R3</i>	-1.18	-1.18	-0.97	11.2	19.7
	<i>R5</i>	0.76	-1.07	-0.79	11.5	19.7
	<i>R7</i>	<b>1.07</b>	-1.45	-2.22	8.1	19.7
4	<i>R1</i>	-0.51	-1.32	-1.74	3.2	9.5
	<i>R3</i>	-1.29	-1.88	-1.52	1.1	9.5
	<i>R5</i>	-1.88	-1.76	-2.20	0.4	9.5
	<i>R7</i>	-1.83	-1.30	-1.99	0.4	9.5

## 6. DISCUSSION

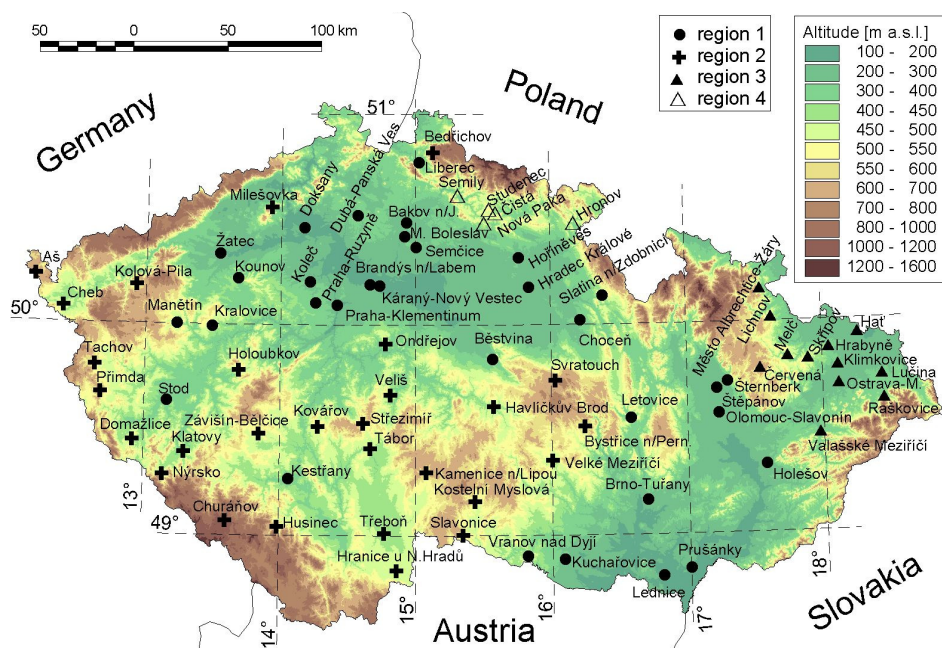
### 6.1. Geographical and climatological description of homogeneous regions

The partitioning of the area of the Czech Republic according to statistical characteristics of extreme precipitation events recognizes 4 (homogeneous) regions ranked with respect to the number of sites (Fig. 3, Table 2):

**Region 1 (main lowland region):** lowland stations in the area stretching from northwest to southeast (32 stations; the elevation range from 158 to 468 m a.s.l., the mean elevation 284 m a.s.l.; corresponds approximately to cluster 3 of Ward's method with 4 clusters); the region is homogeneous according to all tests and variables except for the Lu-Stedinger test for 1-day annual maxima.



*Homogeneous Regions for Analysis of Extreme Precipitation in the Czech Republic*



**Fig. 3.** Final formation of the homogeneous regions according to statistical characteristics of extreme precipitation events.

**Region 2 (higher-elevated west-central region):** higher-elevated stations in the west and central parts of the Czech Republic (28 stations; the elevation range from 429 to 1118 m a.s.l., the mean elevation 561 m a.s.l.; corresponds approximately to cluster 1 of Ward’s method with 4 clusters); the region is homogeneous according to all tests and variables.

**Region 3 (northeast region):** northeast Moravia and Silesia (12 stations; the elevation range from 220 to 750 m a.s.l., the mean elevation 391 m a.s.l.; typical for the region are enhanced extreme *k*-day precipitation amounts as well as mean annual precipitation (relative to the elevation of sites; Table 2, Fig. 4), and the region covers the area most affected with the 1997 record-high precipitation totals); the region is homogeneous according to all tests and variables with the exception of the  $H_2$  and  $H_3$  tests that indicate a slight heterogeneity for 1-day annual maxima.

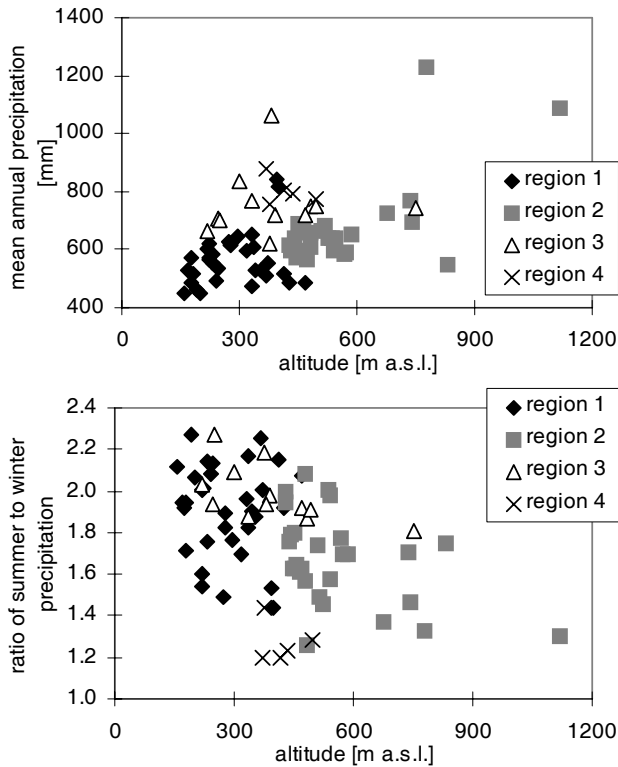
**Region 4 (north region):** north Bohemia (5 stations; the elevation range from 370 to 495 m a.s.l., the mean elevation 419 m a.s.l.; stems from the west part of cluster 2 of Ward’s method with 4 clusters; typical for the region are enhanced mean annual precipitation, small number of dry days, reduced ratio of summer to winter precipitation, and increased occurrence of precipitation extremes in winter months, see Fig. 5); the region is homogeneous according to all tests and variables.

**Table 2.** Geographical and precipitation characteristics of the four regions identified for the regional frequency analysis of extreme precipitation events in the Czech Republic.

	Region			
	1 Main Lowland	2 Higher-Elevated West-Central	3 Northeast	4 North
Altitude Specification	lowland stations	higher-elevated stations	–	–
Number of Stations	32	28	12	5
Mean Altitude [m a.s.l.]	283.7	561.2	391.0	418.8
Altitude Range [m a.s.l.]	158–468	429–1118	220–750	370–495
Mean Maximum Annual 1-Day Precipitation [mm]	36.4	38.0	44.0	38.6
Mean Maximum Annual 5-Day Precipitation [mm]	60.4	66.0	80.0	68.7
Mean Annual Precipitation [mm]	565	674	753	801
Mean Annual Number of Dry Days	223	203	210	201
Ratio of Summer to Winter Precipitation	1.91	1.67	1.99	1.27
Percentage of Maximum Annual 1-Day Precipitation Occurring in Nov–Mar	4.8	9.7	4.2	18.5
Percentage of Maximum Annual 5-Day Precipitation Occurring in Nov–Mar	6.6	12.3	6.3	32.0

The mountain station Lysá hora (1324 m a.s.l.) remains unclassified; its inclusion in Region 3 leads to a considerable distortion of the homogeneity. Whether this is only due to sampling variability, or reflects real different features of the distribution of extreme precipitation cannot be concluded without additional precipitation data from the complex terrain of the northeast region.

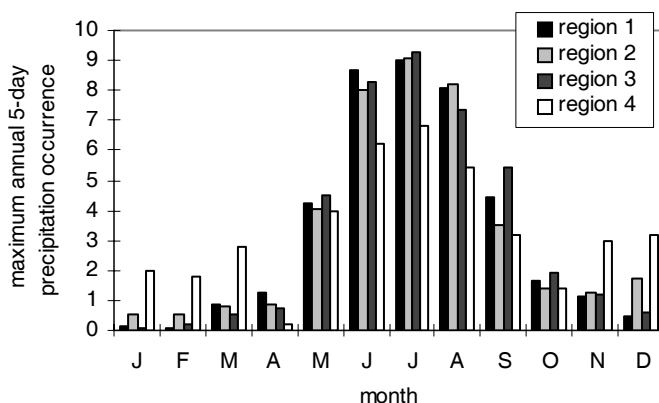
A major advantage of the 4 regions formed is that – apart from their homogeneity in statistical characteristics of extreme high *k*-day precipitation amounts – they are reasonable also from the point of view of precipitation climatology. The two main regions (that are not geographically contiguous) distinguish between lowland (Region 1) and higher-elevated (Region 2) locations in most of the area of the Czech Republic; taken together they do not form a homogeneous area. Climatological differences between these two regions consist mainly of larger mean annual precipitation totals, smaller number of



**Fig. 4.** Dependence of mean annual precipitation (**top**) and ratio of summer to winter precipitation (**bottom**) on elevation in individual regions (depicted by symbols).

dry days, and a lower ratio of summer to winter precipitation at the higher-elevated sites, whereas  $k$ -day precipitation extremes are comparable in both regions. The two smaller regions possess distinctly different precipitation regimes, with enhanced mean annual precipitation and extreme high  $k$ -day precipitation amounts (Region 3), most likely due to orographic effects combined with an enhanced influence of slowly moving Mediterranean cyclones in the northeast part of the Czech Republic (Hanslian *et al.*, 2000; Štekl *et al.*, 2001); and with enhanced mean annual precipitation, small number of dry days and increased precipitation (including extreme events) in winter at the expense of summer (Region 4), due to a larger influence of cloud belts and atmospheric fronts associated with Atlantic cyclones in the prevailing southwestern to northwestern flow over the north part of the Czech Republic (which is close to the climatological location of the storm track over Europe in winter).

Note that two northernmost stations Bedřichov and Liberec might rank among Region 4 according to their locations as well as distinct characteristics of the precipitation regime, mainly a large percentage of precipitation, including extreme amounts, falling in winter months. Nevertheless, their incorporation into Region 4 distorts the regional



**Fig. 5.** Distribution of occurrences of maximum annual 5-day precipitation amounts over 1961–2000.

homogeneity, and the statistical characteristics of extreme precipitation events at these sites seem to agree with the patterns of Regions 1 (Liberec) and 2 (Bedřichov).

### 6.2. Statistical issues

To our knowledge, the following issues have not yet been dealt with in applications of the regional homogeneity tests:

**Impacticability of the Hosking-Wallis tests with the kappa distribution under special conditions.** In Region 3, the tests for 5- and 7-day precipitation amounts were impracticable because L-moment ratios estimated from the data were incompatible with any set of parameters of the four-parameter kappa distribution (Hosking, 1994). To our knowledge, this statistical issue has not yet been pointed to in any practical analysis. Note that the L-moment ratios  $\tau_3$  and  $\tau_4$  determine parameters of the kappa distribution used in the simulations. To enable the four parameters to be estimated from the L-moment ratios, the parameter space must be restricted and certain conditions ensure the existence of the L-moments and the uniqueness of the parameters, given the first four L-moments. This restricted parameter space corresponds to the condition  $\tau_4 < (1 + 5\tau_3^2) / 6$  (Hosking, 1994).

Particular tests in Region 3 were impracticable because this condition was not satisfied.

The failure of the tests stems from the occurrence of extraordinarily large observations in 1997 (related to the massive summer floods that affected the NE part of the Czech Republic). When the largest event is excluded from the data, the Hosking-Wallis tests become practicable and confirm the homogeneity of the region. In the whole sample, the homogeneity of Region 3 according to statistical characteristics of extreme precipitation data is supported by the results of the Lu-Stedinger test as well as the fact that sample L-moment ratios are very similar at all stations; at each site they lie within the 95% confidence intervals of L-moment ratios at all other sites (confidence intervals were constructed using a bootstrap method).

**Table 3.** Stability of results of regional homogeneity tests on final regions.  $R1$  ( $R3$ ,  $R5$ ,  $R7$ ) denotes maximum annual 1- (3-, 5-, 7-) day precipitation amounts;  $H_1$  ( $H_2$ ,  $H_3$ ) stands for the percentage of results when the test statistic of the Hosking-Wallis tests is  $< 2/<1$ ;  $\chi_R^2$  shows the percentage of results when the test statistic of the Lu-Stedinger test is less than the critical value of the test. Values for variables  $R5$  and  $R7$  in Region 3 were calculated after year 1997 was excluded from the data.

Region	Variable	$H_1$	$H_2$	$H_3$	$\chi_R^2$
1	$R1$	100/52	100/100	100/100	5
	$R3$	100/100	100/100	100/100	100
	$R5$	100/91	100/100	100/100	73
	$R7$	100/100	100/100	100/100	100
2	$R1$	100/100	100/90	100/74	98
	$R3$	100/100	100/100	100/100	100
	$R5$	100/100	100/100	100/100	100
	$R7$	100/100	100/84	100/98	100
3	$R1$	100/100	100/47	99/55	100
	$R3$	100/100	100/100	100/100	100
	$R5$	100/56	100/100	100/100	100
	$R7$	100/20	100/100	100/100	100
4	$R1$	100/100	100/100	100/100	100
	$R3$	100/100	100/100	100/100	100
	$R5$	100/100	100/100	100/100	100
	$R7$	100/100	100/100	100/100	100

**Testing for stability of the homogeneous regions.** Stability of results of the regional homogeneity tests on the final regions was examined using Monte Carlo simulation which 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. In Regions 1 and 2 we randomly removed 20% of stations and the procedure was repeated 100 times. (Owing to the size of the regions, considering all possible combinations of sites to be removed would lead to enormous numbers of tests; note that four tests are performed on each examined set of sites, and each individual test itself involves a computationally expensive Monte Carlo simulation of a homogeneous region, see Appendix.) In smaller Regions 3 and 4 we proceeded analogously but all possible removals (of approximately 20% of stations) were considered.

The findings are summarised in Table 3; the vast majority of them are the same as in Table 1 and this confirms the homogeneity of the regions. There are no occurrences of values of the test statistic of any of the Hosking-Wallis tests larger than or equal to 2 ('definite heterogeneity') throughout the perturbed samples, with only one exception for the auxiliary  $H_3$  test and 1-day events in Region 3. Results of the Lu-Stedinger tests confirm homogeneity of the regions, too, with the exception of region 1 and 1-day annual maxima (as discussed in Section 5), so the final formation of regions is suitable from this point of view as well.

A similar sensitivity analysis should be performed in future when more data will become available (either data from other measuring sites or extending to the more recent past; note that the datasets available for the present analysis cover the period 1961–2000) so that the findings concerning homogeneity of the regions can be supported or adjusted.

## 7. CONCLUSIONS

The present study is a first part of research that utilizes the L-moment based method of the regional frequency analysis in modelling extreme precipitation events in the Czech Republic. The area of the Czech Republic has been divided into four homogeneous regions, based on the cluster analysis of site characteristics and tests for the regional homogeneity. Taking into account the area of the Czech Republic, the number of clusters is comparable with, e.g., 9 regions entering the regional frequency analysis of precipitation extremes in the UK (*Fowler and Kilsby, 2003a*) or 15 regions in South Africa (*Smithers and Schulze, 2001*). Although the regions for extreme  $k$ -day precipitation amounts may vary in dependence on the value of  $k$ , it is advantageous to use the same partitioning for one-day as well as multi-day events if a reasonable degree of homogeneity is achieved as in the present study.

The implementation of different sorts of statistical tests for regional homogeneity has proved to be beneficial, particularly since their results are not in general agreement and in special cases, the Hosking-Wallis tests with the kappa distribution may be impracticable. The regions formed in the current application may be considered homogeneous according to both the Lu-Stedinger and Hosking-Wallis tests. We recommend utilization of both the tests as complementary methods in future studies dealing with the regional homogeneity of extremes; this is not a common practice in recent applications that mostly rely on single test results (one of a few exceptions is *Gaál, 2005*).

Although L-moments are more robust to the presence of outliers in the data than conventional product moments, one observation (here in 1997) may have a large influence on the computed sample L-moments as shown by the results in Region 3. Impracticability of the Hosking-Wallis tests for 5- and 7-day precipitation totals in this region when the 1997 records are involved also indicates that the four-parameter kappa distribution may be a bad model for fitting the examined data. However, a similar problem does not appear in the Lu-Stedinger test that is based on the GEV distribution (a special case of the four-parameter kappa distribution), and a condition ensuring the existence of the L-moments is satisfied in this case. Probably a more robust and/or non-parametric method (which does not depend on a distinct distribution) would be more appropriate. To our knowledge, this issue has not yet been dealt with, and a failure of the Hosking-Wallis tests based on the kappa distribution has not been reported in any practical climatological or hydrological analysis. This point deserves further investigation.

The homogeneous regions were identified with the view of their utilization in the regional frequency analysis of extreme precipitation events in the Czech Republic, the next steps of which concern selection of the most appropriate regional distributions of heavy  $k$ -day amounts, and estimation of parameters and quantiles of the fitted distributions together with their uncertainty. Return periods of the 1997 and 2002 extreme precipitation events that caused massive summer floods in central Europe are expected to

be estimated with less uncertainty and more accurately from the regional than at-site data. The regional approach may also be useful in improving estimates of future changes in precipitation extremes derived from climate models (cf. *Fowler et al., 2005; Ekström et al., 2005*). Nevertheless, since the regions formed are not only homogeneous as to the statistical characteristics of extreme high precipitation totals, but also reflect climatological differences in precipitation regimes and synoptic patterns causing heavy precipitation, their future application may not be limited to the frequency analysis of extremes.

## APPENDIX STATISTICAL TESTS FOR HOMOGENEITY OF REGIONS

Suppose that the region has  $N$  sites, with site  $i$  having record length  $n_i$  and sample L-moment ratios  $t^{(i)}$  (L-CV),  $t_3^{(i)}$  (L-skewness) and  $t_4^{(i)}$  (L-kurtosis) of maximum annual  $k$ -day ( $k = 1, 3, 5, 7$ ) precipitation amounts.

### Test 1 (*Hosking and Wallis, 1993*)

The test statistic is

$$H_1 = \frac{V_1 - \mu_V}{\sigma_V},$$

where

$$V_1 = \sqrt{\frac{\sum_{i=1}^N n_i (t^{(i)} - t^R)^2}{\sum_{i=1}^N n_i}}, \quad t^R = \frac{\sum_{i=1}^N n_i t^{(i)}}{\sum_{i=1}^N n_i}$$

and  $\mu_V$ ,  $\sigma_V$  are determined from simulations (500 realisations of a homogeneous region with  $N$  sites, each having a four-parameter kappa distribution (*Hosking, 1994*) with L-moment ratios equal to regional averages of sample L-moment ratios  $t^R$ ,  $t_3^R$  and  $t_4^R$ , and the at-site mean equal to 1) as the mean and standard deviation of the simulated values of  $V_1$ .

Two other analogous tests are based on the combination of L-CV  $t$  and L-skewness  $t_3$  (test statistic  $H_2$ ), and L-skewness  $t_3$  and L-kurtosis  $t_4$  (test statistic  $H_3$ ). The heterogeneity measures are

$$V_2 = \frac{\sum_{i=1}^N n_i \sqrt{\left(t^{(i)} - t^R\right)^2 + \left(t_3^{(i)} - t_3^R\right)^2}}{\sum_{i=1}^N n_i} \quad \text{and} \quad V_3 = \frac{\sum_{i=1}^N n_i \sqrt{\left(t_3^{(i)} - t_3^R\right)^2 + \left(t_4^{(i)} - t_4^R\right)^2}}{\sum_{i=1}^N n_i},$$

respectively, and the test statistics as well as regional values of  $t_3^R$  and  $t_4^R$  are calculated in the same way as in the test based on  $H_1$ .

The region is regarded as ‘acceptably homogeneous’ according to a given test if  $H_1(H_2, H_3) < 1$ , ‘possibly heterogeneous’ if  $1 \leq H_1(H_2, H_3) < 2$ , and ‘definitely heterogeneous’ if  $H_1(H_2, H_3) \geq 2$  (Hosking and Wallis, 1993).

Test 2 (Lu and Stedinger, 1992):

The test statistic is

$$\chi_R^2 = \sum_{i=1}^N \frac{\left(\xi_{0.9}^{(i)} - \xi_{0.9}^R\right)^2}{\text{Var} \xi_{0.9}^{(i)}},$$

where

$$\xi_{0.9}^R = \frac{\sum_{i=1}^N n_i \xi_{0.9}^{(i)}}{\sum_{i=1}^N n_i}, \quad \xi_{0.9}^{(i)} = 1 + \frac{t^{(i)}}{1 - 2^{-k}} \left(1 - \frac{(-\ln 0.90)^k}{\Gamma(1+k)}\right),$$

and

$$k = 7.8590C + 2.9554C^2, \quad C = \frac{2}{t_3^{(i)} + 3} - \frac{\ln 2}{\ln 3},$$

where  $\Gamma$  stands for the gamma function.  $\text{Var} \xi_{0.9}^{(i)}$ ,  $i = 1, \dots, N$  was again determined from simulations (500 realisations of a region consisting of  $N$  sites, each having a three-parameter GEV distribution with L-moment ratios equal to  $t^{(i)}$ ,  $t_3^{(i)}$  and the at-site mean equal to 1) as the variance of the 90% sample quantiles.

If  $\chi_R^2 < \chi_{0.95, N-1}^2$  (where  $\chi_{0.95, N-1}^2$  is the 95% quantile of  $\chi^2$  distribution with  $N-1$  degrees of freedom) we do not reject the null hypothesis (the region is homogeneous) at the 5% significance level; if  $\chi_R^2 \geq \chi_{0.95, N-1}^2$  the null hypothesis is rejected and the region is heterogeneous.

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