Extreme large-scale precipitation events within Czech river basins

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Abstract The presentation is aimed at comprising a set of extraordinary precipitation events which affected large parts of the Czech territory since 1961. We proposed a criterion to evaluate the extremity of a precipitation event. The criterion is based on areal three-day precipitation amounts within Czech river basins and it takes into account also the temporal distribution of daily precipitation totals. We determined eight clusters of river basins of the second order with respect to the statistical similarities in daily areal precipitation amounts. We applied the proposed criterion to each of these clusters and selected objectively a set of extreme large-scale precipitation events. These events are presented and discussed from the viewpoint of the extremity and spatial distribution of precipitation. There were identified a few events during which extreme precipitation affected a substantial part of the Czech territory. In addition, several groups of the events were characterised by the similar characteristics in spatial distribution of heavy precipitation which indicate that they could be caused by the same variants of synoptic conditions.

Key words: *extreme precipitation, Czech river basins, summer flood, synoptic settings*

1. Introduction

Flooding belongs to the most damaging natural hazards. Because of disastrous summer floods in 1997 and 2002, the relations between meteorological conditions and hydrological processes became an intensively studied topic in the Central European countries (e.g. Mudelsee, 2004). The dependence of a flood occurrence on the weather patterns is frequently explored using various subjective as well as objective circulation type classifications and other techniques. These studies usually employ the runoff data as the basis for the hydro-synoptic research. However, the extremity of a flood depends on many factors and not all of them are connected with the meteorological conditions. Subsequently, if selected according to the peak flow values, the set of events embraces significant components of variance which can not be explained from the meteorological point of view.

This fact motivated our research whose main object is to comprise a set of extraordinary precipitation events (*EPEs*) which have hit large parts of the Czech territory since 1961. Three-day precipitation amounts were considered because a large summer flood arises as a consequence of a precipitation event lasting usually two or more days. However, there is no exact criterion which is generally used to evaluate the extremity of a precipitation event. Obviously, areal precipitation amounts (section 2) have to be used to formulate the criterion (section 3).

Although the area of the Czech Republic is less than 79,000 km^2, a precipitation event never hits the whole country with the same intensity. For this reason, *EPEs* have to be selected separately within particular river basins. Section 4 contains our effort to distinguish the groups of river basins where extreme precipitation usually occurred simultaneously. Finally, the *EPEs* were selected within eight clusters of river basins. Considering each of them, *EPEs* are presented and shortly studied from the viewpoint of the distribution of precipitation (section 5).

2. Areal precipitation

There have been already done a comprehensive study of *EPEs* in the Czech Republic by Štekl et al. (2001). Unfortunately, the daily precipitation totals (*R*) from gauge stations served as the criterion to define an EPE. It can demonstrate quite well the extremity of torrential rain caused by convection if a gauge station is located within the area of heavy rain. Nevertheless, the extremity of large-scale precipitation would be better expressed with areal precipitation amounts in a longer period (see the section 5).

We employed daily precipitation totals from individual gauge stations as the input into the computation of daily areal precipitation amounts within Czech river basins. The data from roughly 600 stations were at our disposal (only from the Czech territory). The stations are operated by the Czech Hydrometeorological Institute and are relatively well-distributed over the Czech Republic (Fig. 1). Firstly, the precipitation amounts were interpolated into regular grid with the horizontal resolution of 2 km. We applied pure kriging as the gridding method with no orography forcing. This simplification is sufficient for our purpose, i.e. to compare the extremity of the precipitation events

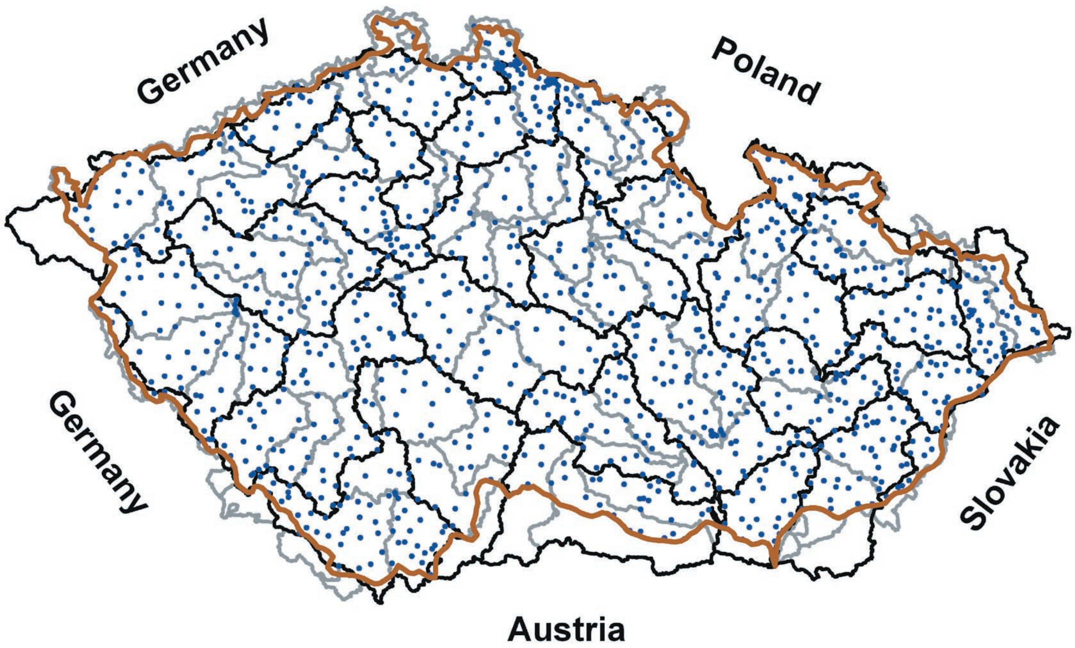

Fig. 1 The spatial distribution of the gauge stations used in the study. Black and grey lines denote the boundaries of the Czech river basins of the second order and of the third order, respectively.

for every single river basin. Finally, the areal precipitation amount within a river basin was expressed as the mean precipitation total calculated from grid-points located within the basin.

3. Selection of extraordinary precipitation events

From the pragmatic point of view, there is a problem of the accessibility of long precipitation data series. Daily totals from Czech gauge stations were at our disposal since 1996. Before 1996 it was necessary to make firstly a rough set of events when heavy precipitation had possibly occurred within the Czech territory since 1961. The selection of events was done using the ECMWF database ERA-40 (www.ecmwf.int) which contains the re-forecasted grid data of 6h precipitation totals. As the horizontal resolution of the data is 2.5°, only several grid points represent the Czech territory.

In twelve grid points over the Czech Republic or close to it, the precipitation totals from three days were considered (for an example see Fig. 2). Weighted means were computed in six grid boxes of 2x2 grid points, with the double weight of grid points along 50°N. The list of 91 potential EPEs was completed. For each of six grid boxes, it includes 32 events when the re-forecasted three-day precipitation amounts were the highest. Naturally, only summer events (1st May – 31st October) were taken into account.

We decided to consider the periods of three days to evaluate the extremity of precipitation events. Nevertheless, the temporal distribution of the precipitation during the days has to be regarded because higher intensity of rain makes the event more dangerous from the hydrological point of view. The only mean value does not express it, so we designed a criterion

$$R_x = \frac{R_3 + R_2 + R_1}{6} \qquad (1)$$

where R_3 is the three-day areal precipitation amount, R_2 is the maximal two-day precipitation amount and R_1 the maximal daily areal precipitation amount during the three-day period.

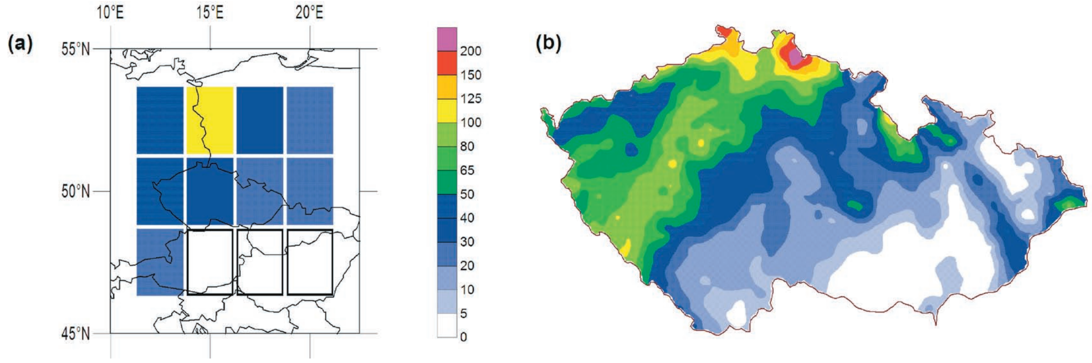

Fig. 2 An example of re-forecasted three-day precipitation totals [mm] according to ERA-40 (7 – 9 August 1978) utilised to select the potentially extreme precipitation events (a); three-day precipitation totals [mm] measured within the Czech Republic (b).

4. Clustering of river basins

It is evident that a precipitation event is not generally accompanied by the same precipitation amounts within all river basins. On the other hand, there are groups of river basins where the extremeness of precipitation is closely correlated. In order to identify such groups where the correlation is statistically significant, we used the hierarchical cluster analysis.

In the first step, for every single river basin considered, we selected the days when daily areal precipitation amounts exceeded the percentile of 0.99. Each river basin was then characterised by daily amounts on all selected days. In the second step, we evaluated the proximity of every pair of basins in terms of normalised daily areal precipitation amounts using Minkowski metric. Then we successively clustered each two river basins whose proximity was maximal. These simple clusters and single river basins were grouped into larger clusters until a hierarchical tree have been formed.

We applied the hierarchical cluster analysis to two sets of river basins (26 river basins of the second order and 94 river basins of the third order). After evaluating both analyses we decided to concentrate further on the larger river basins of the second order. In that case, the clustering was more compact and more comprehensible to hydrologists than in the case of clustering the smaller river basins.

The complete hierarchical, binary cluster tree is depicted by the dendrogram plot in Fig. 3. By assessing the threshold value of the relative measure of proximity between clusters, we defined altogether 8 clusters (Table 1). The geographical location of the clusters is depicted in Fig. 4. In both figures, the clusters are distinguished by the same colours.

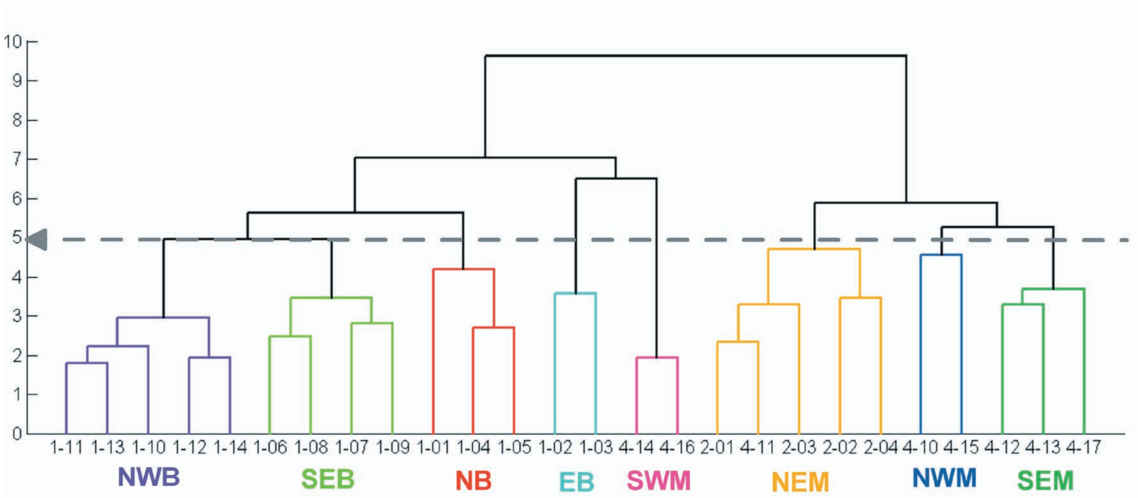

Fig. 3 The dendrogram plot of the hierarchical, binary cluster tree of 26 Czech river basins of the second order. The vertical axis represents the relative measure of the proximity between individual river basins and/or clusters in terms of normalised high areal daily amounts of precipitation. The river basins are marked by their indicatives at the horizontal axis. The further considered clusters are distinguished by colours. The threshold value of the relative measure of proximity between clusters is indicated by the horizontal grey dashed arrow.

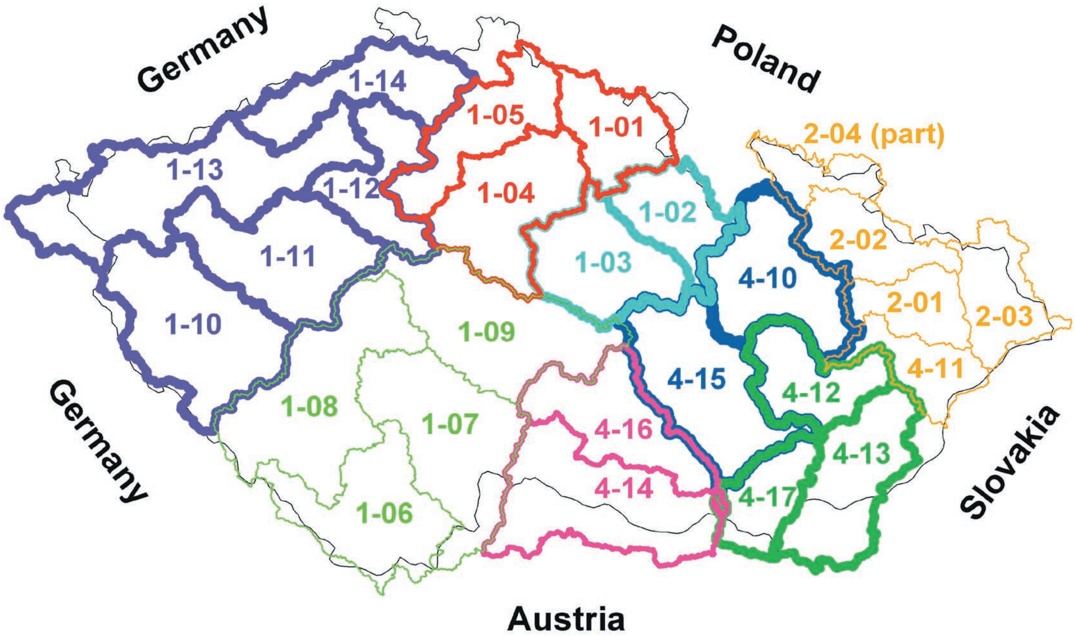

Fig. 4 The geographical location of the clusters defined in Fig. 3. The river basins of the second order constituting the individual clusters are marked by their indicatives.

Table 1 Description of the clusters defined in Fig. 3.

Cluster	Location	Indicatives of river basins	Description
NWB	North-western Bohemia	1-10, 1-11, 1-12, 1-13, 1-14	Berounka, lower reach of Vltava, Labe downstream from the mouth of Vltava (including Ohře)
SEB	South-eastern Bohemia	1-06, 1-07, 1-08, 1-09	Vltava as far as the confluence with Berounka
NB	Northern Bohemia	1-01, 1-04, 1-05	North-western part of the Labe catchment as far as the confluence with Vltava
EB	Eastern Bohemia	1-02, 1-03	South-eastern part of the Labe catchment as far as the confluence with Vltava
NWM	North-western Moravia	4-10, 4-15	Morava as far as Haná without Bečva, Svratka as far as Jihlava
SWM	South-western Moravia	4-14, 4-15, 4-16	Dyje as far as Svratka, Jihlava, Svratka from Jihlava as far as its mouth
NEM	North-eastern Moravia and Czech part of Silesia	2-01, 2-02, 2-03, 2-04, 4-11	Odra in the Czech part of Silesia, Bečva
SEM	South-eastern Moravia	4-12, 4-13, 4-17	Morava from Haná, lower reaches of Jihlava, Svratka and Dyje

5. Extraordinary precipitation events since 1961

We apply the criterion (1) to each of 8 clusters and to 26 river basins of the second order in Fig. 4 to discuss the extremity and spatial distribution of precipitation among the *EPEs*. We considered only those precipitation events with five highest values of R_x within at least one cluster. Table 2 contains the values of R_x within the clusters and also within the respective river basins of the second order for such selected *EPEs*. There are the maximal values of R_x during the events in the table. The possible time shift in precipitation onset within the Czech Republic has to be taken into account. For this reason, if the local maximum of R_x in time occurred on day earlier or later than the given day in various clusters, it was considered as only one EPE.

The main characteristics of the spatial extent and distribution of extraordinary large-scale precipitation can be summarised as follows.

- Heavy large-scale precipitation usually hits an area which is larger than a cluster (the number of *EPEs* is only 20 although five events within each of eight clusters were selected).
- There are several events (in 1981, 1985, 1997, and 2002) when extreme precipitation affected the large

part of the Czech Republic (two highest values of R_x from each of eight clusters are concentrated only into seven *EPEs*).

- They are similar features among some events from the viewpoint of spatial distribution of heavy precipitation:
  - o in 1985 and 1997 precipitation affected whole Moravia and eastern Bohemia;
  - o in 1977 and 2002 precipitation affected major part of Bohemia and also substantial part of Moravia;
  - o four EPEs from eastern Moravia (1968,1999 in SEM and 1970, 1972 in NEM) did not extent more to the west – the precipitation bands continued probably to the east over Slovakia.
- The event from July 1997 seems to be extreme because of
  - o maximum of R_x in three clusters (NWM, NEM, SEM);
  - o maxima of R_x in all river basins constituting these clusters;
  - o significantly higher precipitation amounts than during other events in these clusters.
- Considering *EPEs*, the cluster NWB is rather different from the others because *EPEs* from other clusters are not characterised by enhanced values of R_x here. The reason could be the prevailing track of Mediterranean cyclones. They are the main cause of heavy precipitation in the Central Europe. They tend to pass easterly from the Czech Republic so their influence is reduced in the north-western part of the country.

Table 2 Extraordinary precipitation events within clusters of Czech river basins (see Table 1). For each cluster, at least five events with highest R_x are listed and highlighted by colours (red – maximum R_x, orange – 2nd highest R_x, green – 3rd, 4th or 5th highest R_x). Also 6th – 10th (blue) and 11th – 20th highest values (grey) of R_x are highlighted if the event belongs to five events with highest R_x in another cluster. The pale colours depict the extremity of EPEs within individual river basins.

	12.5.1962	8.8.1964	8.10.1964	8.6.1968	16.7.1970	20.8.1972	15.9.1976	31.7.1977	7.5.1978	7.8.1978	16.6.1979	18.7.1981	2.8.1983	6.8.1985	5.7.1997	20.6.1999	18.7.2001	5.8.2002	11.8.2002	5.8.2006
NWB	**3.3**	**10.1**	**10.6**	**6.1**	**2.1**	**0.6**	**4.9**	**18.4**	**26.3**	**28.7**	**13.3**	**43.8**	**31.6**	**10.6**	**9.5**	**3.2**	**4.3**	**14.9**	**38.3**	**14.7**
1-10	5.0	9.8	10.4	5.0	1.7	0.5	5.9	18.7	27.5	31.2	22.7	42.9	32.8	15.8	8.3	4.3	3.7	28.2	41.8	16.1
1-11	4.2	8.6	11.4	4.9	2.0	0.5	5.4	23.9	30.4	30.0	20.9	50.7	37.9	12.0	13.1	3.8	4.8	19.1	43.0	13.1
1-12	4.9	14.5	14.3	9.1	2.2	0.6	4.8	26.7	21.1	30.4	19.5	57.9	33.1	10.9	13.4	2.6	10.2	5.0	31.3	13.3
1-13	2.2	8.1	6.2	6.4	2.5	0.6	5.1	11.5	27.6	23.0	1.6	34.0	27.9	6.1	6.9	3.0	1.4	10.3	36.5	14.0
1-14	3.2	18.2	14.6	7.9	2.8	1.1	2.8	14.6	20.3	32.7	1.6	43.3	27.2	7.0	7.6	2.5	5.1	0.0	35.3	17.0
SEB	**16.8**	**12.3**	**19.8**	**6.0**	**4.5**	**3.1**	**5.8**	**38.1**	**12.8**	**11.1**	**32.8**	**41.8**	**30.3**	**21.6**	**18.8**	**5.5**	**20.7**	**35.0**	**49.6**	**24.0**
1-06	19.1	9.1	17.7	6.1	5.7	4.1	3.7	37.7	5.2	5.2	35.1	35.0	19.7	24.8	20.8	5.8	20.4	57.4	57.9	24.5
1-07	16.8	10.1	18.7	3.9	4.4	3.1	5.7	31.2	9.9	6.9	25.6	38.9	30.2	17.8	20.7	5.9	24.7	36.3	50.6	23.2
1-08	14.5	10.2	17.4	7.9	2.4	1.9	4.7	40.8	17.5	17.4	40.3	54.2	34.5	21.9	15.2	0.0	10.4	41.1	49.8	23.5
1-09	17.7	19.1	25.1	7.4	6.3	3.8	9.4	41.3	15.8	11.9	28.8	35.9	33.4	22.1	22.2	6.6	29.2	10.7	43.8	29.6
NB	**10.7**	**24.4**	**25.3**	**9.7**	**4.4**	**1.8**	**5.4**	**27.6**	**12.7**	**25.9**	**35.0**	**34.3**	**21.4**	**18.4**	**14.0**	**4.1**	**22.4**	**9.9**	**22.0**	**22.3**
1-01	11.7	31.3	25.7	12.7	6.0	1.0	6.8	23.5	10.7	21.3	42.1	18.4	11.6	30.2	24.4	7.2	31.0	6.2	19.1	25.9
1-04	12.6	24.3	24.7	9.4	4.3	2.2	6.5	31.5	12.1	18.8	40.7	35.6	26.5	17.3	11.9	3.0	22.3	1.0	21.1	20.5
1-05	8.0	20.0	25.7	8.5	3.4	2.0	3.5	25.4	14.9	39.3	22.3	44.8	23.9	11.4	12.0	3.3	16.3	13.2	25.8	22.3
EB	**18.4**	**41.3**	**18.2**	**15.8**	**18.7**	**4.5**	**20.2**	**29.1**	**9.4**	**16.8**	**23.6**	**19.3**	**18.5**	**39.0**	**32.8**	**10.9**	**31.9**	**5.8**	**34.8**	**34.0**
1-02	16.2	49.5	15.5	16.2	18.2	3.2	22.5	21.9	9.1	21.4	21.6	15.5	15.5	38.5	39.3	13.3	28.8	8.1	31.3	30.6
1-03	19.8	36.9	20.6	15.5	19.0	5.3	18.8	34.6	9.7	13.9	24.8	22.7	21.7	39.3	28.7	9.6	33.9	4.3	37.1	36.2
NWM	**23.6**	**25.2**	**15.0**	**15.7**	**17.4**	**2.8**	**20.5**	**20.5**	**6.9**	**7.8**	**17.8**	**10.8**	**5.9**	**30.1**	**44.0**	**16.3**	**20.7**	**2.1**	**23.3**	**30.6**
4-10	23.7	30.2	13.4	19.5	16.7	4.4	24.6	21.9	7.2	11.1	18.6	8.4	8.0	29.6	51.8	17.7	21.6	2.4	24.6	27.9
4-15	23.6	21.4	16.4	12.8	18.2	1.4	17.9	19.2	6.6	5.0	17.2	12.5	4.3	30.5	37.1	15.1	19.9	2.6	22.9	33.4
SWM	**19.5**	**15.8**	**12.8**	**5.7**	**10.4**	**1.1**	**11.6**	**21.6**	**9.3**	**2.9**	**14.1**	**17.5**	**5.2**	**29.3**	**27.4**	**9.6**	**25.3**	**22.4**	**29.1**	**25.7**
4-14	16.6	14.4	10.3	6.3	10.1	1.3	11.4	20.9	8.5	2.0	15.0	16.8	4.4	28.1	27.4	10.0	24.6	27.5	29.2	25.3
4-16	22.1	17.0	14.9	6.1	10.6	0.9	12.0	22.2	10.1	3.8	13.4	18.0	6.0	30.3	27.3	9.3	25.9	18.1	29.1	26.1
NEM	**22.1**	**22.8**	**5.7**	**35.0**	**38.7**	**39.7**	**27.4**	**37.1**	**6.9**	**8.1**	**20.9**	**15.9**	**6.6**	**41.1**	**75.6**	**24.4**	**20.0**	**2.0**	**19.0**	**22.1**
2-01	26.7	19.5	4.6	36.9	32.6	33.5	30.5	33.0	6.6	4.9	20.5	18.3	6.0	38.8	74.4	20.3	18.3	1.3	16.0	20.0
2-02	21.4	27.4	7.9	30.4	28.3	20.5	19.1	31.1	7.9	5.7	22.8	11.9	6.9	32.3	66.3	18.0	19.9	1.9	18.5	23.8
2-03	18.4	15.4	3.3	43.5	61.2	73.4	34.4	43.8	6.2	11.7	13.1	14.0	4.6	63.7	79.9	36.5	18.3	3.2	24.8	27.7
2-04	27.5	40.3	9.2	37.2	50.1	32.4	37.0	67.5	12.4	10.6	31.2	16.6	12.1	44.8	98.8	25.4	27.4	2.7	36.5	23.0
4-11	20.7	18.5	5.5	30.7	38.5	40.0	22.6	30.5	6.0	9.7	23.8	12.1	5.9	37.0	75.5	24.2	22.7	1.6	19.0	27.8
SEM	**17.9**	**18.9**	**11.1**	**27.6**	**20.2**	**11.9**	**23.7**	**16.8**	**7.5**	**3.5**	**22.1**	**10.5**	**4.5**	**27.6**	**41.6**	**26.0**	**17.9**	**2.6**	**19.6**	**19.9**
4-12	25.1	23.9	11.5	27.8	16.3	8.6	21.8	17.3	8.1	3.6	22.7	11.9	4.5	28.2	40.8	22.9	19.1	1.2	17.8	25.2
4-13	13.4	16.5	9.8	29.6	25.6	19.9	28.0	19.3	7.9	4.2	23.3	10.8	5.2	25.8	48.1	30.5	21.2	1.0	18.1	9.2
4-17	13.1	16.0	12.6	24.3	19.9	5.5	20.7	12.7	6.2	2.3	19.6	7.9	3.5	30.3	36.9	24.2	11.9	7.5	26.5	27.0

Almost all of the *EPEs* produced flooding in Czech rivers. Upper mentioned four dominant events were extraordinary also from the hydrological point of view. Catastrophic floods in July 1997 and in August 2002 are well known. In July 1981 the return period of the floods in some tributaries of Berounka river (Úhlava, Úslava, Litavka) exceeded 50 years. The peak flow of Vltava in Prague would be 2480 $m^3.s^{-1}$ (periodicity of 10 years, without the impact of reservoirs) which would be the highest value after 1961 and before August 2002. In August 1985 e.g. the periodicity of the peak flow of Olše in Věřňovice also exceeded 50 years. It was the only event after 1961 and before 1997 when the flow of Odra in Bohumín got over 1000 $m^3.s^{-1}$; it means the periodicity of 10 years (Brázdil et al., 2005).

6. Conclusions + outlook

The aim of our study was to comprise a list of extraordinary precipitation events within the Czech territory since 1961. Because no exact indicator of the extremity of a precipitation event exists, we suggested such criterion (R_x). It is based on areal three-day precipitation amounts and it takes into account the temporal distribution of daily precipitation totals. The areal precipitation amounts were computed within river basins of the second order which were clustered into eight clusters with respect to similarities in daily precipitation totals.

Considering five events with the highest R_x within each cluster, we got a set of 20 events which can be assumed to be the extreme large-scale precipitation events within Czech river basins. During several dominant events extreme precipitation affected a substantial part of the Czech territory and produced floods with the return period of at least 50 years in rivers with catchments about 1000 km^2 or more. Similarities of spatial distribution of heavy precipitation among some events were probably caused by similar synoptic settings – it will be an object of further research. It should be aimed at defining variants of synoptic conditions which cause heavy rain within particular areas of the Czech Republic. Each variant will be represented by a part of detected extraordinary precipitation events during which anomalies of thermodynamic quantities will be searched. The evaluation of conditional extremity of these anomalies will be used to assess the extremity of an upcoming precipitation event (Müller and Kašpar, 2006).

Acknowledgment

The contribution was prepared under the support of GAASCR KJB300420701. The ECMWF is acknowledged for the data from the database ERA-40, the Czech Hydrological Institute for the runoff data.

References

[1] Brázdil, R., Dobrovolný, P., Elleder, L., Kakos, V., Kotyza, O., Květoň, V., Macková, J., Müller, M., Štekl, J., Tolasz, R., Valášek, H., 2005: Historické a současné povodně v České republice. Masarykova univerzita a ČHMÚ, Brno a Praha, 370 pp.

[2] Mudelsee, M., Börngen, M., Tetzlaff G. and Grünewald, U., 2004: Extreme floods in central Europe over the past 500 years: Role of cyclone pathway „Zugstrasse Vb". Journal of Geophysical Research, 109: D23101, 21 pp.

[3] Müller and Kašpar, 2006: Extremeness of meteorological quantities as an indicator of extreme precipitation events. In: Extreme precipitation, multisource data measurement and uncertainty. 7th international workshop on precipitation in urban areas, St Moritz, 7. – 10.12.2006, ISBN 3-909386-65-2, 175-179.

[4] Štekl, J., Brázdil, R., Kakos, V., Jež, J., Tolasz, R., Sokol, Z., 2001: Extrémní denní srážkové úhrny na území ČR v období 1879–2000 a jejich synoptické příčiny. Národní klimatický program České rpubliky, 31, Český hydrometeorologický ústav, Praha, 128 pp.