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# Regionalization of the Elbe River Basin Pursuant to Flood Seasonal Analysis

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**Abstract**

This paper presents analysis of flood seasonality regional distribution in the Elbe river catchment. Three methods of flood occurrence seasonality analysis are applied – polar graph method, directional statistics method and the method of cumulative frequencies. On the basis of seasons determined for each gauging station, the Elbe river basin was divided into seven hydrologically homogenous regions. The regions do not copy natural river basin borders, but rather correspond to areas with similar characteristics as average annual precipitation or altitude.

**Key words:** floods, seasonality, regionalization, homogeneous region

## 1. Introduction

Regional flood frequency analysis is often used to enhance the estimation of flooding probabilities at locations where little or no data are available. An important component of regional flood frequency analysis is the identification of the region that is used to effect the spatial transfer of information. A region, in this context, has come to mean a collection of catchments that can be considered to be similar in terms of hydrologic response (Burn 1997; Black, Werritty 1997).

A delineation of the region is based on the request of similar characteristic within one region the same as the request of different characteristic within the different regions. The goal of this process is finding the cluster of catchments that are similar enough to transfer the extreme flow information between any locations within the region. Regions are generally formed based on some measure of the similarity between catchments. In this paper the seasonality of flood response is used as a basis for a similarity measure for grouping catchments. Specific natural conditions of each region determined a seasonal flood frequency occurrence.

Flood seasonality has formed the focus of a number of studies in the Czech republic. The seasonality analysis was employed in a given catchment (Brádka, 1967; Buchtele, 1972; Hladný, 1971, 1995; Kakos, 1983, 1985; Kašpárek, 1999, 2000; Vavruška, 1989).

The new approach presented in this paper is that the seasonality of flood response is analysed in each of selected gauging stations in order to delineate hydrologically homogeneous region.

Data sets of 110 unregulated catchments from the Czech part of the Elbe river basin were used to illustrate the methods. A brief review of methods characterizing seasonality measure is also presented.

This article terminates by an overview of findings and representation of defined regions.

## 2. Data

### 2.1. Selection of Representative Water Gauging Stations

The database used in this study was made up from river gauging station records of the statutory the Czech Hydrometeorological Institute (CHMI). Stations were selected by various criteria, e.g. natural runoff regime and sufficient data quality. Profiles with significantly affected runoff regimes or stations with interrupted or incomplete measuring series weren't considered.

In individual areas of the Czech Republic, quality and available quantity of data fairly differ. We identified in total 441 water gauging stations in the Elbe river basin. However, complete daily flow ($Q_d$) measuring series applicable to the period of 1975 – 2000 were provided only by 158 stations. With respect to the conditions stated above and trying to cover the whole area, we selected 110 river gauging stations. Most of the selected catchments are relatively small (Figure 1).

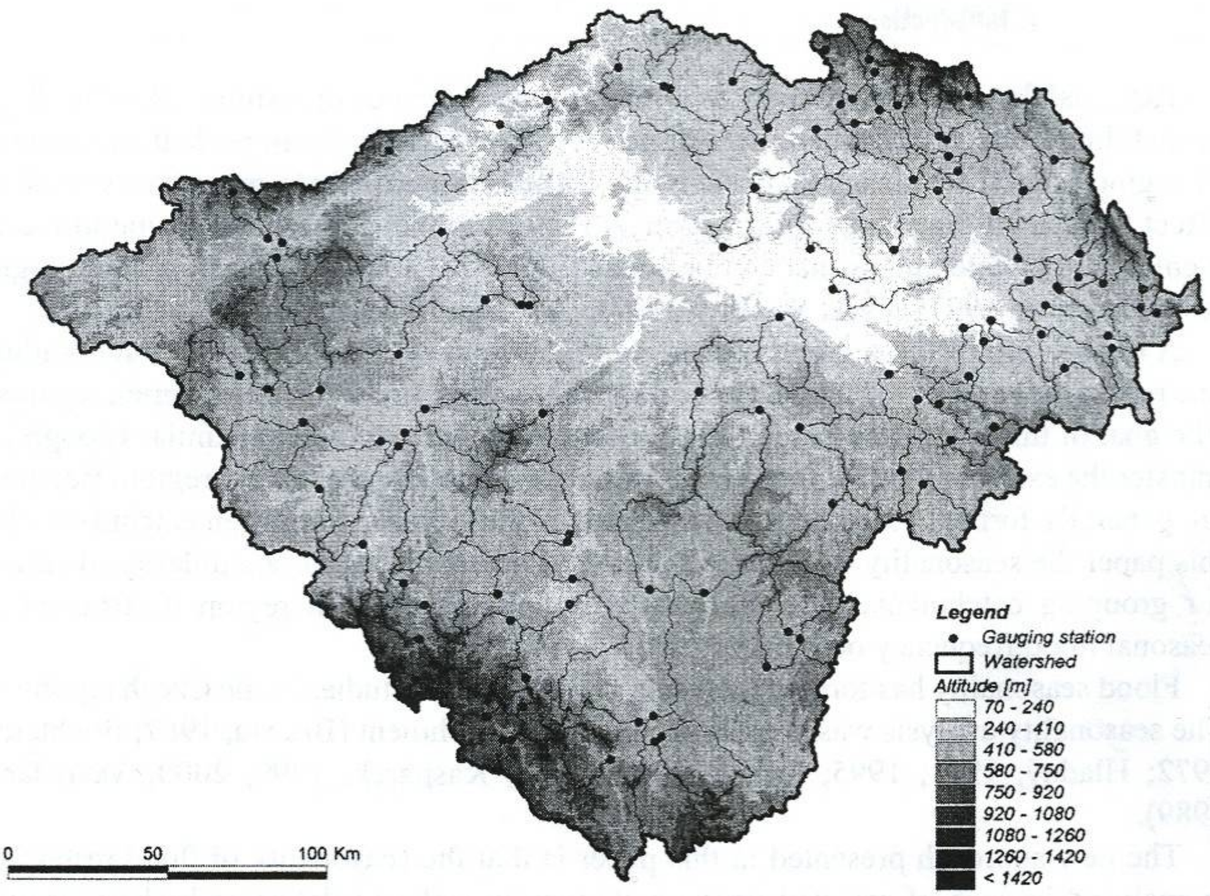


*Fig. 1* Selected water gauging stations with indication of respective divides

Final distribution of selected stations in the monitored area isn't always equally proportioned, but with respect to the scale applied by the study it is still representative.

### 2.2. Hydrological Data Selection

Monthly maximum data proved to be a too broad parameter for regionalization because in seasons with relatively higher rainfall rates, some flood events were "lost" and differences between seasons with increased and decreased probability of peak flow were blurred. Such an approach would have left aside associated floods occurring in one month, e.g. the floods in July, 1997 would have been considered as one case, while in reality there were two flood events.

Therefore, the seasonal analysis of flood occurrence was based also on daily hydrological data, particularly on records of average daily flow values. A daily peak flow data that would even better reflect runoff extremes weren't always available. For each of selected measuring stations, we applied data series from 1975–2000.

### 2.3. Selection of Physical Data

For each studied river basin represented by water gauging station, we created a database of the following characteristics:

- Catchment area,
- Average slope of terrain,
- Average altitude,
- Percentage of area covered by forest,
- Length of river valley,
- Index of the catchment shape,
- Hill aspect.

Values of catchment area and the length of river valley were taken from the CHMI database. The average altitude, slopes and aspect of hills were calculated in the GIS environment using a digital model of terrain and a layer of selected river basins' divides interpreted in vectors. Data on areas covered by forests were provided by the CORINE database.

### 2.4. Selection of Meteorological Characteristics

As a meteorological characteristics an annual precipitation amount and the snow accumulation around the end of the winter period (March 15) was considered. The data from every precipitation gauging station at the Elbe river basin area were used.

An average precipitation amount of the catchment was counted in the GIS environment using an interpolation method ("Orographic interpolation of precipitation") produced in CHMI, Prague (Šercl, Lett 2002). For the grid of average amount of snow accumulation at the end of winter the same method was employed.

## 3. Methods of Flood Occurrence Seasonal Analysis

To express differences in the space distribution of seasonality of flood response in the Elbe river basin (area 51 394 km$^2$), the daily flow data was used. Seasonality was analysed for every studied catchment in its closing cross-section.

A peaks-over-threshold database gives the data and peak flow of each event exceeding a given flow threshold, whereas an annual maximum series gives information concerning only the largest event each year (Shaw, 1993).

The method is defined by the following model (Todorovic and Zelenhasic 1970):

$$\xi_v = \begin{cases} 0 & ; Q_v \le Q_B \\ Q_v - Q_B & ; Q_v > Q_B \end{cases}$$

where $Q_B$ is a base level,
$Q_v$ the river flow at time $\tau(v)$, and
$\xi_v$ the exceedance at time $\tau(v)$.

In order to effectively present the seasonal information contained in the database, it is important to employ the most appropriate statistics. Three methods are applied in this study to characterize flood seasonality. All of them work with threshold data.

### 3.1. Polar Graph Method

This method provides a graphical representation of particular variables in a polar graph where axis $x$ represents individual months (identified by Roman numerals) and axis $y$ represents values of monitored physical phenomena.

Each profile in the specific period is thus represented by a characteristic figure reflecting distribution of the monitored value. Long-term and well-proportioned dis-

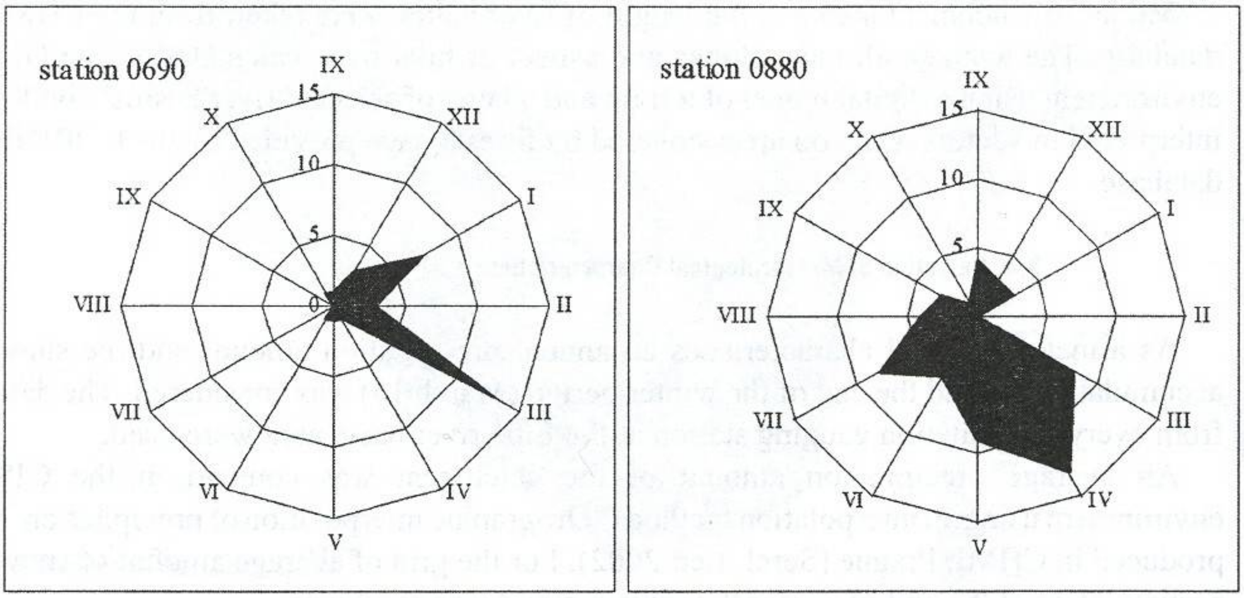


*Fig. 2* Polar graphs of extreme flow values in two selected profiles

tribution of a particular phenomenon in the course of a whole year would create a regular dodecagon. However, real phenomenon distribution is characterised by irregularity and polar coordinates thus show deviations in certain seasons of the year. Some months are marked by typical extremes and significant deviations against the average state while in others the occurrence probability is minimal (Figure 2).

Polar graphs have a high informative value and are easy to imagine, but their accuracy is lower.

### 3.2. Directional Statistics Method

Directional statistics (Mardia, 1972) form the basis for defining similarity measures derived from the timing of flood events. Following Bayliss and Jones (1993), we can define the date of occurrence of the peak flow for a flood event as a directional statistics by converting the Julian date, where the start of year is shown at its most easterly point and that the seasons proceed in a counter-clockwise sense, of the flood occurrence for the flood event $i$ to an angular value using:

$$\theta_i = (\text{Julian Date})_i \left(\frac{2\pi}{365}\right)$$

where $\theta_i$ is the angular value (in radians) for the flood date for flood event $i$.

Each flood date can now be interpreted as a vector with a direction given by $\theta_i$ and a magnitude $m$, where $m$ is a relative magnitude of a given flood flow (for the highest flood flow in a flood series $m = 1$).

For a sample of $n$ flood events, this information can be plotted to provide a visual representation of the hydrologic regime for the catchment (Burn, 1997). From the sample of $n$ flood events, the $x$- and $y$-coordinates of the mean flood date can be determined using:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n}\cos(\theta_i) \qquad \bar{y} = \frac{1}{n}\sum_{i=1}^{n}\sin(\theta_i)$$

where $\bar{x}$ and $\bar{y}$ represent axis $x$- and $y$- coordinates of the mean flood date and lie within, or on, the unit circle. A measure of the variability of the $n$ flood occurrences about the mean date can also be determined. The variability measure is defined by the mean resultant as

$$\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2}$$

where $\bar{r}$ provides a measure of the spread of the data.

A value of $\bar{r}$ close to unity indicates a catchment with a strongly seasonal flood response ($\bar{r}$ equal to 1 would indicate that all floods in a given profile occurred on the same date of the year) while values close to zero indicate that there is great variability in the date of occurrence of flood events for the catchment (Burn, 1997). Figure 3 illustrates the method application in two selected stations of the Elbe river basin with *MD* indication. The position vector size is determined by $\bar{r}$ values.

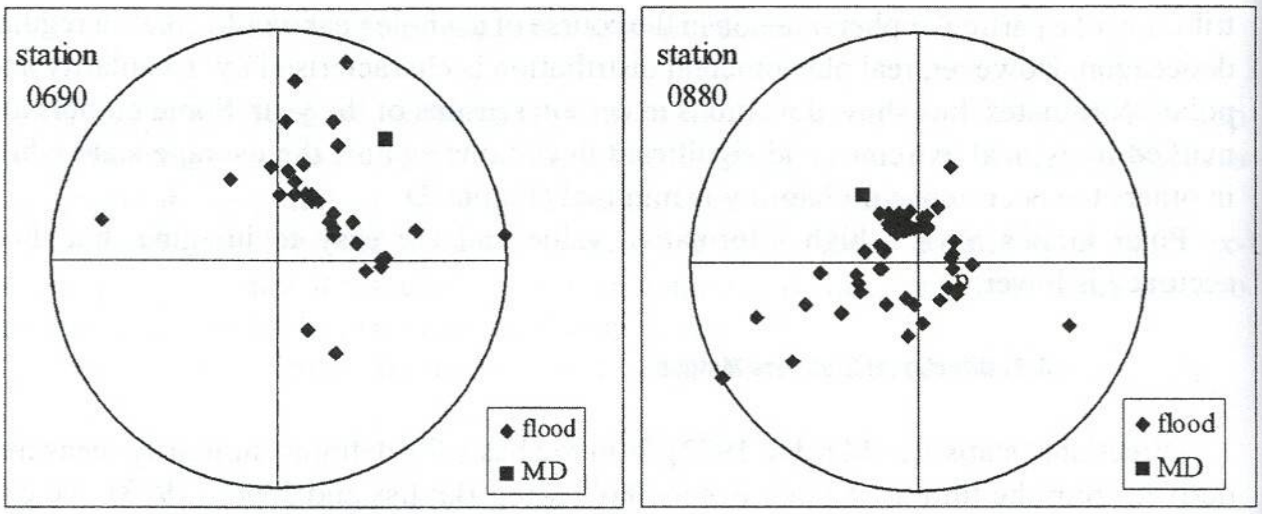


*Fig. 3* Illustration of flood dates and summary seasonality statistics for two sites

There are two main advantages of directional statistics method. First, seasonality is defined by a single numerical value and second, the result is highly illustrative. On the other hand, it distorts data by working with mean values.

### 3.3. Method of the Cumulative Frequency Curves

A method of the cumulative frequency curves consists of plotting the mean number of exceedances *L(t)* in a time interval (0,T) equal to one year, against the time *t*, for each station, and for a number of increasing levels. There where three values for $Q_B$ that corresponds to $Q_{1,1}$, $Q_{1,25}$ and $Q_{1,4}$ quantiles of statistical distribution. The graphical method was applied for each of 110 gauging stations. Figure 4 illustrates seasonality representation of two selected sites.

Where an event occurred with more than one peak in the flow hydrograph, to ensure the data are independent, the study considers only such peak flows that occurred at least seven days after their previous culmination provided that flow values in this period dropped to at least one half of the higher peak value. Per each station and each out of three $Q_B$ values, a cumulative frequency curve was made. The behaviour of these *L(t)* plots (change of slope, its beginning and end in time, piecewise linearity, etc.) indicates a significant seasons for each stations.

For each stations studied, three interesting observations were made:

1. all plotted curves, for various base levels, change slope at approximately the same dates, and
2. three different periods are defining at each stations (the period of an increased and the period of a decreased extreme flow value probability, and transitional period),
3. within indicated periods, the cumulative frequency curves have more or less linear character.

The piecewise linearity mentioned under clause (3) has an important significance at flood frequency analysis. It indicates that within seasons, the time distribution of flood events is largely homogeneous.

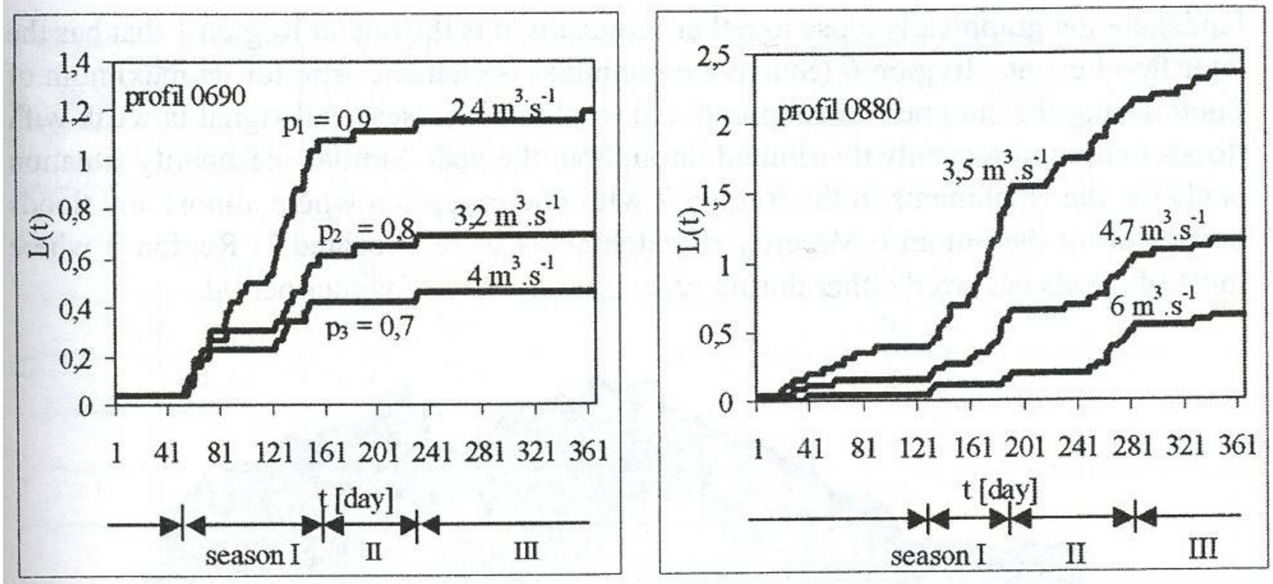


*Fig. 4* Illustration of the graphical method for two stations in elbe river basin

An advantage of the method described above is its high accuracy level while data on seasonality are maintained. Periods of an increased flood probability can be identified with accuracy of days. On the other hand, it is difficult to use resulting seasonal data for further statistical processing.

Numerous methods exist to express seasonal characteristics of flood regimes in a given region. However, due to various controls on flooding, there isn't any universal method deemed to be the best one. With respect to the objective, i.e. to depict spatial differences in extreme flow seasonal distribution, we compared three methods. The method of cumulative frequency curves proved to be most suitable.

#### 4. Results

An advantage of directional statistics method is providing the information not only about timing but also about relative magnitude of flood flows. An advantage of the method of cumulative frequency curves is an exact determination of the beginning and the duration of the flood occurrence season. For this reason the results of the second mentioned method was used.

It is interesting to note that on the basis of the seasons determined for each station, and without consideration of the geographical location of the stations, a geographical regionalization of seasonality was achieved for the Czech part of Elbe river basin. The area was divided into seven homogeneous regions (Fig. 5, Tab. 1) after carefully examining and comparing the seasonal partitioning of the year in different part of the Elbe river basin. The regions are geographically contiguous, for the most part.

The maps of physical geographic factors were employed to proper associate the borderline catchments with the regions. Especially map of distribution of the annual average precipitation on the Elbe river basin closely correspondents to the partitioning to the regions. Region 1 (north-eastern mountains) and Region 2 (north-eastern highlands) are geographically close together. Logically it is the higher Region 1 that has the later flood events. Region 6 (Šumava mountains) is characteristic for its maximum of flood during the summer. In Region 4 and Region 5, the seasonal signal is weak with floods being more evenly distributed throughout the year. Similar seasonality situation is also at the catchments in the Region 7 with one exception where almost any floods occur during the autumn. Majority of catchments were allocated in Region 3 where most of floods occurred either during early or at the end of winter period.

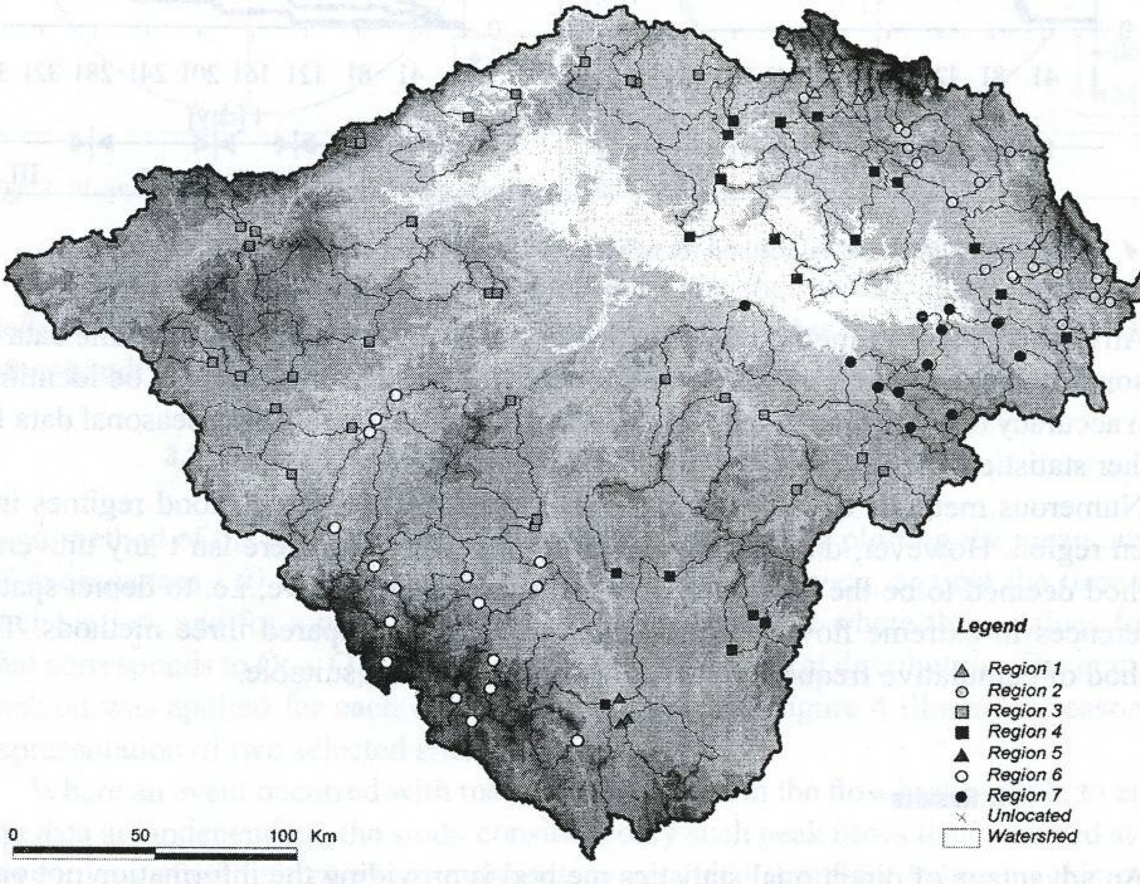


*Fig. 5* Geographic display of homogenous regions in the elbe river basin

*Tab. 1* Summary of sites in each region

| Region 1 | Region 2 | Region 3 | | Region 4 | Region 5 | Region 6 | Region 7 | Unclassified |
|---|---|---|---|---|---|---|---|---|
| 0130 | 0030 | 0210 | 1580 | 0770 | 1130 | 1060 | 0450 | 1901 |
| 0290 | 0040 | 0300 | 1610 | 1000 | 1140 | 1080 | 0460 | 1070 |
| 0830 | 0050 | 0310 | 1620 | 1020 | 1150 | 1102 | 0470 | |
| 0840 | 0060 | 0340 | 1660 | 1930 | | 1110 | 0480 | |
| 0850 | 0150 | 0350 | 1670 | 1940 | | 1350 | 0490 | |
| 0860 | 0160 | 0360 | 1710 | 2170 | | 1370 | 0520 | |
| 0880 | 0180 | 0370 | 1720 | 2180 | | 1380 | 0580 | |

| Region 1 | Region 2 | Region 3 | | Region 4 | Region 5 | Region 6 | Region 7 | Unclassified |
|---|---|---|---|---|---|---|---|---|
| 0900 | 0240 | 0390 | 1730 | 2230 | | 1390 | 0590 | |
| | 0250 | 0700 | 1740 | 2260 | | 1410 | 0630 | |
| | 0270 | 0710 | 1750 | | | 1430 | 0640 | |
| | 0280 | 0750 | 1790 | | | 1450 | 0650 | |
| | 0320 | 0870 | 1799 | | | 1470 | 0660 | |
| | 0690 | 0910 | 1900 | | | 1500 | 0820 | |
| | | 0920 | 1960 | | | 1510 | | |
| | | 0940 | 2091 | | | 1820 | | |
| | | 0960 | 2101 | | | 1830 | | |
| | | 1240 | 2120 | | | 1870 | | |
| | | 1260 | 2140 | | | 1880 | | |
| | | 1270 | 2300 | | | | | |
| | | 1310 | 2310 | | | | | |
| | | 1330 | 2350 | | | | | |
| | | 1520 | 2360 | | | | | |
| | | 1530 | 2380 | | | | | |
| | | 1560 | 2390 | | | | | |

## 5. Discussion and Conclusion

The present paper analyzed several measures of catchment similarity in order to highlight their descriptive capability when used in a flood frequency analysis framework, as the basis to classify the catchments into homogeneous regions.

The results of a study of flood seasonality, using floods defined for each gauging station by a modest flood-flow threshold are presented. Three methods of describing seasonal flood events distribution were compared.

Polar graphs have good informative value and are easy to imagine, but their statistical accuracy is low. With respect to the method of directional statistics, the main benefits include detailed and clear organisation and high reliability in identifying periods with intensified occurrence of extreme flows. Further, the method enables to add information of a relative magnitude of individual flood event. The spread illustrated by this method represents valuable information employed to assess river basins' sensitivity to maximum flow values. On the other hand, the method generalises seasonal data under a mean value that is not sufficiently representative.

The method of cumulative frequency curves proved to be most suitable and effective in dividing a year into three seasons differing by their probability of flood occurrence. A big advantage of the method is an exact determination of the beginning and the duration of the flood occurrence season, which in terms of seasonal analysis is a vital piece of information.

With respect to the objective, i.e. to depict spatial differences in extreme flow seasonal distribution, we applied the method of cumulative frequency curve. Seasonal partitioning of the year differ more or less depending on geographical location of individual water gauging stations.

On the basis of seasons determined for each station, whole studied area was divided into seven hydrologically homogenous regions. The regions don't copy natural river basin borders, but rather correspond to areas with similar characteristics as average annual precipitation or altitude. Physical and geographical controls on the timing and spatial variability of floods are subject to further research.

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**References**

BAYLISS, A. C. AND JONES, R. C. (1993): Peaks over Threshold flood database: Summary statistics and seasonality. Report No. 121. Institute of Hydrology, Wallingford, UK, 61 pp.

BLACK, A. R. AND WERRITTY, A. (1997): Seasonality of flooding: a case study of North Britain. Journal of Hydrology 195, p. 1–25.

BRÁDKA, J. (1967): Meteorologické příčiny povodní ve Slezku. Meteorologiké zprávy 20 (1), ČHMÚ, Praha, s. 3–9.

BUCHTELE, J. (1972): Kategorizace povodňového režimu na tocích vltavské kaskády. Sborník prací HMÚ, sv. 18, Praha, s. 65–139.

BURN, D. H., ZRINJI, Z. and KOWALCHUK, M. (1997): Regionalisation of Catchments for Regional Flood Frequency Analysis. Journal of Hydrologic Engineering, p. 76–82.

HLADNÝ, J. (1971): K rajonizaci povodňových situací na území ČSR pro potřeby povodňové služby. Sborník referátů z hydrologické konference v Brně, Studia Geographica 22, GÚ ČSAV, Brno, s. 221–236.

HLADNÝ, J., CHALUŠOVÁ, J. a VLASÁK, T. (2001): Hydrosynoptické přístupy k identifikaci povodňového mechanismu. Acta Universitatis Carolinae Geographica, 2, Praha, Přírodovědecká fakulta UK (v tisku).

KAKOS, V. (1983): Hydrometeorologický rozbor povodní na Vltavě v Praze za období 1873–1982. Meteorol. Zpr. 36 (6), ČHMÚ, Praha, s. 171–181.

KAKOS, V. (1985): Hydrometeorologická analýza povodňových situací v povodí Labe. Meteorol. Zpr. 38 (5), ČHMÚ, Praha, s. 148–151.

KAŠPÁREK, L. A KOL. (1999): Hodnocení modelování srážko–odtokových vlastností povodí.VÚV T.G.M., Praha, 47 s.

MARDIA, K. V. (1972): Statistics of Directional Data. Academia Press, London, 38 pp.

OUARDA, T. B. M. J., ASHKAR, F. and EL-JABI, N. (1993): Peaks Over Threshold Model for Seasonal Flood Variations. Engineering Hydrology, USA, p. 341–346.

ŠERCL, P., LETT, P. (2002): Výpočet rastru srážek v prostředí GIS (s využitím ArcView Spatial Analyst). Uživatelská příručka verze 2.0.1, ČHMÚ, OPV, Praha, 8 s.
TODOROVIC, P., and ZELENHASIC, E. (1970): A stochastic model for flood analysis. Water Resources Research, 6 (6), p. 1641–1648.
VAVRUŠKA, F. (1989): Meteorologické příčiny povodní na Otavě a Lužnici. Meteorologické zprávy, 42. ČHMÚ, Praha, s. 111–115.

## REGIONALIZACE POVODÍ LABE NA ZÁKLADĚ SEZONÁLNÍ ANALÝZY VÝSKYTU POVODNÍ

### Résumé

Článek se zabývá sezonální analýzou výskytu extrémních průtoků v české části povodí Labe. Odlišné výstupy sezonální analýzy umožňují rozdělit sledovanou oblast na dílčí celky, hydrologicky homogenní regiony, jejichž specifické přírodní podmínky předurčují četnost výskytu povodní v konkrétním období roku.

Pro sezonální analýzu výskytu povodní byla využita hydrologická data průměrného denního průtoku z databáze Českého hydrometeorologického ústavu. Pro každou ze 110 vybraných vodoměrných stanic byla použita datová řada z období 1975–2000. Na základě metody POT (Peaks Over Threshold), data nad určitou mezí, byly analyzovány pouze kulminační hodnoty povodňových průtoků, které přesáhly zvolenou hranici průtoků $Q_B$.

K efektivní interpretaci sezonálních informací obsažených v databázi je důležité zvolit co nejpřesnější statistiky. Ve studii bylo za tímto účelem provedeno srovnání třech metod užívaných při znázornění sezonálního rozložení výskytu povodňových případů v roce. Metoda polárních grafů, metoda směrových statistik a metoda čar kumulativních četností výskytu maximálních průtoků. Všechny pracují s daty průtoků nad určitou mezí. Z hlediska přesnosti dosažených výsledků se jako nejpříhodnější jevila metoda čar kumulativních četností.

V dalším kroku byla pro všechna povodí odpovídající vybraným vodoměrným profilům vytvořena databáze následujících fyzickogeografických charakteristik: plocha povodí, průměrný sklon svahů v povodí, průměrná nadmořská výška povodí, procento plochy pokryté lesem, délka údolnice, index tvaru povodí a orientace svahů v povodí. Meteorologické veličiny byly zastoupeny údaji o ročních srážkových úhrnech a daty o výšce sněhové pokrývky na konci zimy. Průměrné srážky na povodí byly vypočteny v prostředí GIS pomocí interpolační metody „Orografická interpolace srážek" z bodových údajů jednotlivých srážkoměrných stanic.

Pro každou vodoměrnou stanici, která reprezentuje povodňový režim příslušného povodí, bylo určeno období roku, kdy se povodně vyskytují s největší pravděpodobností. Podobnost, resp. rozdílnost počátečního data a délky trvání identifikovaného období byla dále podkladem pro nalezení povodí, která jsou si vzájemně hydrologicky podobná.

Celé povodí českého Labe bylo po pečlivém zkoumání a porovnávání sezonality výskytu povodňových průtoků v jeho různých částech rozděleno do sedmi hydrologicky homogenních regionů.

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