A COMPARISON OF PRECIPITATION AND RUNOFF SEASONALITY IN SLOVAKIA AND AUSTRIA

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The main goal of this study was to compare the precipitation and runoff seasonalities in Austria and Slovakia, in order to understand the differences in the climatic conditions and long term catchment characteristics using mean monthly seasonality indices and to explore the differences in the flood processes at the short term event scale. The seasonality of mean monthly precipitation and runoff was quantified by the Pardé coefficient and the seasonality of the maximum annual floods and annual maximum daily precipitation by applying the Burn's index. Altogether 555 climate stations located in Austria and 202 climate stations in Slovakia were selected for analysis of mean monthly precipitation. Annual maximum daily precipitation was available at 520 and 56 climate stations, respectively. Mean monthly runoff values and maximum annual flood records were available at 258 and 85 gauging stations in Austria and Slovakia. Even though some of the selected stations have an incomplete series of daily records in the period 1961–2000, at least 34 years of complete observations are available from all the selected stations. The estimated seasonality indices were mapped and their spatial and time distribution was discussed. The results can give insight into the main flood producing processes in Austria and Slovakia.

Článok sa zaoberá analýzou a porovnaním sezonality zrážok a odtoku v Rakúsku a na Slovensku. Sezonalita mesačných úhrnov zrážok a priemerných mesačných prietokov bola kvantifikovaná Pardého koeficientom, sezonalita maximálnych ročných prietokov a maximálnych ročných denných úhrnov zrážok bola kvantifikovaná Burnovým indexom. Pre analýzu mesačných zrážkových úhrnov bolo vybraných 555 klimatických staníc v Rakúsku a 202 staníc na Slovensku, maximálne ročné denné zrážkové úhrny boli k dispozícii v 520 staniciach v Rakúsku a v 56 staniciach na Slovensku. Priemerné mesačné a maximálne ročné prietoky boli posudzované v 258 vodomerných staniciach v Rakúsku a 85 vodomerných staniciach na Slovensku. Napriek tomu, že niektoré stanice nemali kompletné rady denných údajov z obdobia 1961–2000, každá stanica mala aspoň 34 rokov kompletných pozorovaní. Priestorové a časové rozloženie indexov sezonality bolo vyjadrené v podobe máp a diskutované v článku. Uvedené výsledky sú príspevkom k lepšiemu porozumeniu hlavných procesov tvorby odtoku a povodní v Rakúsku a na Slovensku.

Key words: seasonality, mean monthly precipitation and runoff, the maximum annual floods, annual maximum daily precipitation, Austria, Slovakia

INTRODUCTION

The seasonality of hydrological characteristics is one of the key factors controlling the development and stability of natural ecosystems. From a hydrologic perspective, seasonality analysis of runoff and precipitation is an appealing method for inferring flood producing processes, which in turn supports other hydrological applications, such as hydrological regionalisation. Recently, the assessment of hydrologic seasonality and regime stability has attracted a renewed interest especially in connection with water resource management, engineering design and climate change assessment studies.

In Slovakia, seasonality analysis of mean monthly runoff was first conducted by Dub (1957). According to the seasonality analysis the regions were delineated with similar seasonality distribution of mean monthly runoff. Since then many studies and reports dealing with seasonality of mean monthly precipitation and mean monthly runoff were published from groups of authors of the Slovak Hydrometeorological Institute. The analysis of seasonality changes in the mean monthly runoff and precipitation totals and their comparison between the representative periods 1931–1980 and 1961–2000 was performed by the authors Majerčáková et al. (2004). In Majerčáková et al. (2007), the specific seasonal analysis of mean monthly precipitation and mean monthly runoff was done for the High Tatras Mountains region. Many selected periods of observation were analysed and compared. The analysis showed a certain change in stability of the mean monthly runoff distribution on the catchment which were mostly affected by the whirlwind in November 2004.

The Burn´s index was used for an estimation of the seasonality of maximum annual floods in Slovakia by Čunderlik (1997). Spatial and temporal changes in the mean monthly precipitation and mean monthly discharges in Eastern Slovakia were analysed in Szolgay et al. (1997). An emphasis was put on the variability of dry and wet periods in the region. Kriegerová and Kohnová (2005) estimated the seasonality index for rainfall and snowmelt floods in 142 small and mid sized catchments in Slovakia. These results were used for following regionalization and flood frequency analysis of seasonal floods in Slovakia.

Changes in annual precipitation totals caused by changes in atmospheric circulations in Slovakia for the period 1874–1993 were analysed in Lapin and Faško (1996), changes in cyclonicity, air pressure and precipitation totals in the 1901–1995 period were examined in Lapin and Pišútová (1998). Lapin at al. (2001, 2005) have also analysed changes in monthly and annual precipitation for future time horizons based on the downscaled outputs from the GCM scenarios.

An analysis of seasonality of 1 to 5-day seasonal and annual precipitation maxima in Slovakia was accomplished by Gaál (2006). The mean day of occurrence and the variability of occurrence of the seasonal precipitation maxima were initially aimed at using as input variables in a cluster analysis in the process of the regionalization of extreme precipitation. Nevertheless, Burn's vector showed a more or less uniform spatial pattern throughout the country, therefore the seasonality index of precipitation maxima has not been employed in delineation of homogeneous regions for a regional precipitation frequency analysis in Slovakia.

The seasonality assessment in Austria was recently applied mainly in connection with the regionalisation of extreme events. The studies of Merz et al. (1999) and Piock-Ellena et al. (2000) demonstrated the value of seasonality indices in the context of flood frequency regionalization in Austria. They analysed the seasonality of runoff and precipitation and related it to the main climate-driven flood-producing processes in Austria. Merz and Blöschl (2003) identified and analysed different types of causative mechanisms producing floods. In their study, the seasonality of maximum annual flood peaks was chosen as one of the flood process indicators describing the timing of floods. They found that the seasonal pattern in the flood occurrence is related to both snow processes and the occurrence of flooding in the summer months. Sivapalan et. al (2005) explored the connection between the seasonality of floods and the seasonalitiy of climatic characteristics and catchment soil moisture state using a derived quasi-analytical flood frequency model. The seasonality of low flow discharges in Austria was used for regionalisation by Laaha and Blöschl (2006). They classified the regime of 325 catchments in Austria by evaluating seasonality indices and relating them to drought processes such as retention of precipitation as snow in catchments and soil moisture depletion by evapotranspiration.

The main goal of this study is to compare the precipitation and runoff seasonalities in Austria and Slovakia, in order to understand the differences in the climatic conditions and long term catchment characteristics using mean monthly seasonality indices and to explore the differences in the flood processes at the short term event scale. It is anticipated that the combination of both concepts may give insight into the main flood producing processes in Austria and Slovakia.

The paper is organised as follows. First we describe the methods applied in the seasonality assessment. Next we present hydrologic data available for the analysis. The results section demonstrates the magnitude and spatial variability of different seasonality indices. Finally, we discuss the similarities in the hydrological regimes of both countries and present some plans for forthcoming evaluation of the issue of seasonality.

METHODS

The seasonality of the hydrologic characteristics is characterised by two indices. The first one describes the seasonality of mean monthly precipitation and runoff and is quantified by the Pardé coefficient (Pardé, 1947). For each month of the year, an index Pk_i is defined as

$$Pk_i = \frac{12}{n}\sum_{j=1}^{n}\left(Q_{ij} \Big/ \sum_{i=1}^{12} Q_{ij} \right), \qquad (1)$$

where Q_{ij} represents the mean monthly runoff (or precipitation) in month i and year j, and n is the record length. Values of Pk_i, $i = 1,\ldots, 12$ range from 1, which represents a uniformly distributed variable around the year, to 12, when all the runoff (or precipitation) occurs only in one month i_{max}. Pardé coefficient is then defined by Pk_{max} that is the maximum value of Pk_i, and the index i_{max} indicating the month, when Pk_{max} occurred:

$$Pk_{max} = \max\left(Pk_i\right). \qquad (2)$$

The Pardé coefficient in each gauging or climate station is graphically represented by an arrow, with the length of the arrow proportional to Pk_{max} and its direction representing i_{max}.

The variability of the Pk_{max} occurrence of Pk_{max} is evaluated by a stability index S, which counts the frequency P of agreement in the month of occurrence of Pk_{max} between the 40-year period and each of the 10-year periods. The stability index S was estimated for each precipitation and gauging station using the following relation:

$$S = \sum_{k=1}^{4} \mathrm{P}\left(M_{Pk_{\max,k}} = M_{Pk_{\max}} \right), \qquad (3)$$

where $M_{Pkmax,k}$ represents the month of occurrence of the maximum Pk index obtained for one of the four 10-year periods (1961–70, 1971–80, 1981–90 and 1991–2000), and M_{Pkmax} represents the month of Pk_{max} in the period 1961–2000.

The second index describes the seasonality of the maximum annual floods and annual maxima of daily precipitation, respectively. It is based on Burn's index (1997), which indicates the mean date and variability of occurrence of the extreme events. The mean date of occurrence (D) at a given site is obtained following a transformation of the dates of the occurrence D_i of the event in the i-th year of observation to the directional statistics:

$$\Theta_i = D_i \frac{2\pi}{365}, \quad i = 1, ..., n, \tag{4}$$

where D_i is expressed as Julian date (D_i = 1 for January 1st, and D_i = 365 for December 31st). The dates of occurrence D_i are represented in polar coordinates as vectors of unit lengths and of direction given by (4). The average direction $\overline{\Theta}$ is calculated as the average of the projections of the individual vectors D_i to the x and y axis, respectively. The mean date of occurrence D is then obtained using the inverse form of (4):

$$D = \overline{\Theta} \frac{365}{2\pi}. \tag{5}$$

The length of the mean vector r represents the variability of the date of occurrence. It ranges from $r = 0$ (uniform distribution around the year) to $r = 1$ (all extreme events of precipitation or floods occur on the same day).

DATA

The seasonalities of runoff and precipitation totals were compared over the regions of Austria and Slovakia (Figure 1). Both countries are similar in terms of large topographical variability which has a strong influence on the seasonality of hydrologic and climatic variables. The elevation in Austria ranges from 115 to 3798 m a.s.l., while in Slovakia it varies from 94 to 2655 m a.s.l. All hydrologic data used in this study are from the period 1961–2000. The seasonality of mean monthly precipitation was analyzed at 555 climate stations located in Austria and 202 climate stations in Slovakia (Figure 1). Annual maximum daily precipitation was available at 520 and 56 climate stations, respectively. Mean monthly runoff values and maximum annual flood records were available at 258 and 85 gauging stations in Austria and Slovakia, respectively, with a catchment area ranging from 10 to 100000 km^2 with the median of 170 km^2. The record length of all the stations was at least 34 years in the period 1961–2000.

RESULTS

The seasonality of mean monthly precipitation is presented in Figure 2. The maxima of mean monthly precipitation generally occur in summer with the exception of the very south of Austria (southern Carinthia) where the maximum mean monthly precipitation is in November. In the western and central parts of Slovakia the maximum mean monthly precipitation occurs in June, while a July maximum is observed in the eastern parts of Slovakia. In Austria, a July maximum occurs especially in the central Alpine regions, June maxima occur mainly in the eastern part (Burgenland province) and northern pre-alpine area. An August maximum is observed mostly in the high Alps of the Tirol region. The November maximum in south Austria is observed only on a few climate stations and is likely caused by weather patterns from the south. The comparison of maximum Pardé's indices (Pk_{max}) shows that for most of the climate stations the Pk_{max} values are in the range from 1.4 to 1.7. This implies that the monthly maximum is 40 to 70 % larger then the average monthly value in the year and represents relative uniform precipitation around the year.

The similarity in the Pk_{max} estimated from the mean monthly precipitation values observed in the period 1961–2000 and mean monthly precipitation observed in four 10-year periods (1961–70, 1971–80, 1981–90 and 1991–2000) is evaluated in Figure 3. Figure 3 shows that the Pk_{max} occurrence is the same for the longer (40 years) and all shorter (10-years) periods (i.e. $S = 4$) only in 41 climate stations, which represents approximately 5 % of all analysed climate stations. The agreement in three from four shorter 10-years periods is observed at almost 30 % (218) of the analysed stations. The climate stations with this low temporal variability in Pk_{max} occurrence are located mainly in the northern pre-alpine area and Tirol where orographic precipitation is important. In Slovakia a stabile maximum in Pk_{max} occurrence is observed in the hilly regions of the western part of the Carpathian Mountains and at climate stations in the central mountain part of the Slovak Ore Mountains (Slovenské Rudohorie). Interestingly, eight of the analysed climate stations have no agreement in Pk_{max} occurrence among the analysed periods; five of them are located close together in the southern part of Austria near Klagenfurt. This region is influenced by a mixture of different weather patterns, which cause different seasonal distributions of precipitation in different years and decades.

The seasonality of mean monthly runoff is presented in Figure 4. The spatial variability in runoff seasonality shows a more heterogeneous pattern which is a consequence of diversity in runoff generation processes. In the high Alpine catchments, maxima in runoff tend to occur in July, while in the lower Alpine catchments they tend to occur in May or June. In the Alpine catchments, Pk_{max} is in the range of 2.4 to 3.3, which represents a strong seasonality of runoff. Clearly, this is related to glacier and snowmelt being important processes in these regions. In Slovakia, a snowmelt induced maximum in May is observed only in the highest catchments in the High Tatras Mountains. In other mountain regions, snowmelt runoff dominates, but the season with maximum mean monthly runoff is shifted to April and May. Catchments with mean elevation below 600 m a.s.l., located mostly in the hilly regions of the Carpathian Mountain range, show typical runoff maxima in March. In the lowland areas, no distinct maximum can be found. In both countries the maxima are mostly in March. However, in the lowlands the Pk_{max} values vary from 1.2 to 1.5, which indicates a much more uniform seasonal distribution of runoff around the year than in the mountains. This is the results of the diversity of runoff generation processes in these regions.

The time stability in runoff Pk_{max} occurrence among different periods is presented in Figure 5. The most noticeable difference between the patterns in Austria and Slovakia is the more distinct seasonality and occurrence of mean monthly runoff maximum in the central mountainous part of Slovakia. In this region, snowmelt runoff induces seasonal runoff maxima in the spring months and these maxima are repeated in different 10-years periods. A lower agreement between different Pk_{max} occurrences is observed for the catchments located in the western part of Slovakia, where

Figure 1.
Topography of Austria and Slovakia and location of climate stations and catchment boundaries.

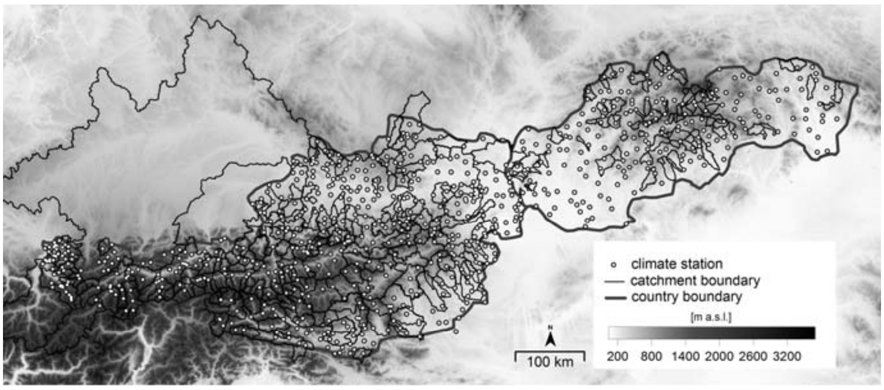


Figure 2.
Seasonality of mean monthly precipitation in the period 1961–2000. The direction of the arrows indicates the month with maximum Pardé coefficient (Pk), and the length of the arrows is a measure of the strength of the seasonality.

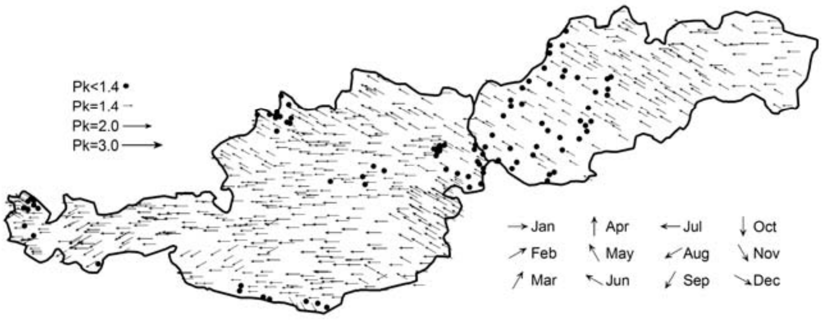


Figure 3.
Stability (S) of the mean monthly precipitation seasonality. Stability is expressed as the frequency of agreement in the occurrence of the maximum Pardé coefficient Pk_{max}, estimated in the period 1961–2000 and in four 10-year periods (1961–70, 1971–80, 1981–90, 1991–00).

Figure 4.
Seasonality of mean monthly runoff in the period 1961–2000. The direction of the arrows indicates the month with maximum Pardé coefficient (Pk_{max}), and the length of the arrows is a measure of the strength of the seasonality.

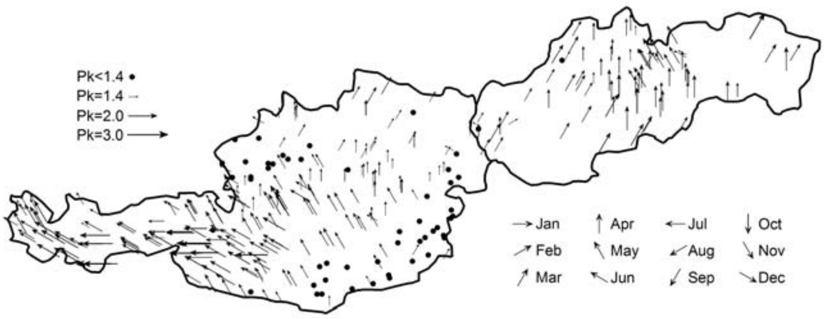


Figure 5.
Stability of the mean monthly runoff seasonality. Stability is expressed as the frequency of agreement in the occurrence of the maximum Pardé coefficient $Pk_{,max}$, estimated in the period 1961–2000 and in four 10-year periods (1961–70, 1971–80, 1981–90, 1991–00).

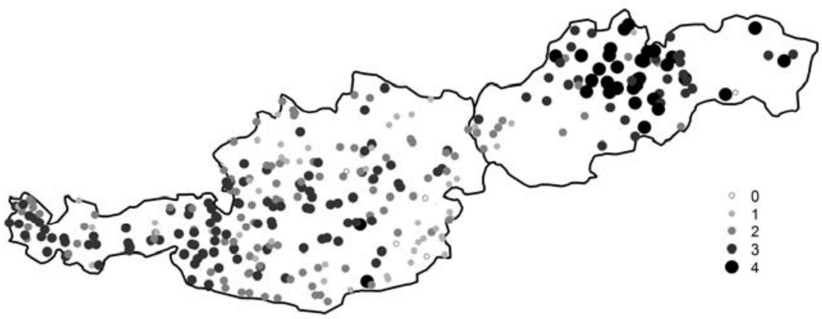


Figure 6.
Seasonality of annual maximum daily precipitation in the period 1961–2000. The direction of the arrows indicates the average occurrence of extreme precipitation in a year, and the length of the arrows (r) is a measure of the strength of the seasonality.

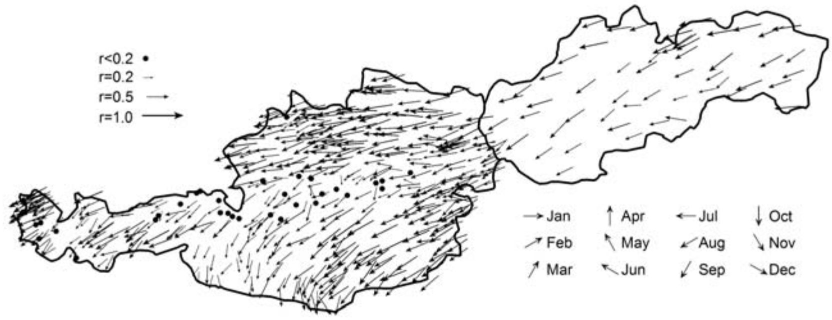
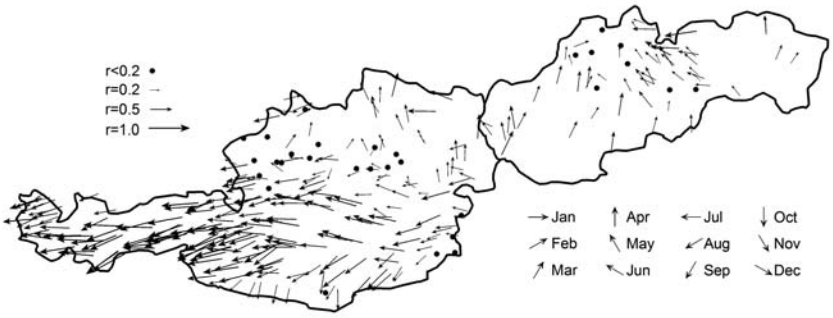


Figure 7.
Seasonality of maximum annual flood peaks in the period 1961–2000. The direction of the arrows indicates the average occurrence of floods in a year, and the length of the arrows (r) is a measure of the strength of the seasonality.

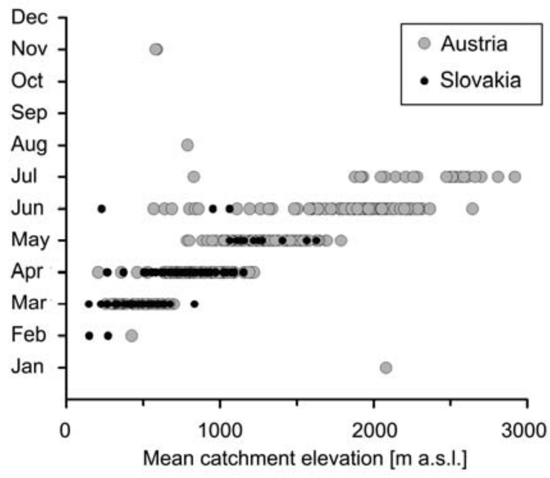


the runoff maxima occur from February to April. Similar findings are observed in Austria, where the lowest stability in the flatland regions is related to the weak mean monthly runoff seasonality. In the flatland regions, a mixture of different weather patterns and catchment conditions results in different maximum runoff seasonalities. In contrast in the high Alpine catchments the occurrence of Pk_{max} is similar across the years, which is induced by the stable snowmelt and glacier melt regime.

The seasonality of annual maximum daily precipitation (Fig. 6) exhibits distinct regional patterns. Most striking is a band shaped region at the northern fringe of the Central Alps showing very little seasonality (r< 0.2). This is likely caused by orographic rainfall which may occur throughout the year. The Alps act as a topographic barrier to north westerly airflows. In the hilly region of south-eastern Austria (Styria) a distinct maximum occurs in late summer which suggests that convective precipitation is an important process. In southern Austria (Carinthia) maxima occur in autumn which is related to the characteristic weather patterns of this region. In Slovakia there is no such distinct spatial difference in the seasonality of extreme precipitation. The evaluation of Burn's index shows that the mean occurrence of extreme daily precipitation is in the summer period (July and August). The seasonal variability in the mean date of occurrence is not very large, the median of Burn's *r* over 56 stations is 0.55.

The seasonality of maximum annual floods is presented in Figure 7. It is clear that the spatial patterns are more heterogeneous than those of annual maximum daily precipitation which, again, is due to differences in the catchment processes. In the high Alpine catchments, floods tend to occur in summer showing a strong seasonality. In this region, the maxima of mean monthly runoff also occur in summer, while annual maximum daily precipitation exhibits very little seasonality. This indicates that glacier melt is an important flood producing process while convective and synoptic events are less important. The strongest flood seasonality in Slovakia is observed in the highest mountain catchments, with mean catchment elevation above 1500 m a.s.l. In these catchments, floods occur mainly in July. In other mountain regions much weaker flood seasonality exists, see also Figure 8. The floods are not related to the seasonality of extreme precipitation, but mostly are in agreement with the seasonality of mean monthly runoff, where snowmelt is found as a dominant factor. In Austria, a distinct pattern of flood occurrence in late summer is found in the south-eastern Austria (hilly region of Styria).

Figure 8. Seasonality of maximum annual flood peaks for different elevation zones in the period 1961–2000.



However, mean monthly runoff and extreme precipitation exhibits almost no seasonality and mean monthly precipitation has a weak maximum in early summer (June). This suggests that convective storms are an important flood producing process. Particular flood behaviour can be found in southern Carinthia. While the seasonality of monthly runoff is similar to that of other regions of the same altitude, the seasonality of mean monthly precipitation, annual maximum daily precipitation and annual maximum floods are very different. This suggests that this region is climatologically and hydrologically different from the rest of Austria. Indeed, weather patterns from the south are known to cause floods in this part of Austria. The region of low altitude catchments of northern Austria has similar flood seasonality as most of the catchments in western Slovakia. In this region, the mean date of occurrence of floods varies. While mean monthly runoff data (maxima in spring) do indicate that snowmelt is an important process, there exist other important flood producing processes, e.g. synoptic rainfall. In these catchments, local effects may also be important which confound the interpretation of flood processes.

DISCUSSION AND CONCLUSIONS

In this study the comparison of the precipitation and runoff seasonalities in Austria and Slovakia was performed. From the results of seasonality indices, which were mapped and are presented on Figs. 2 to 7, the following can be concluded: The spatial variability in runoff seasonality shows a more heterogeneous pattern which is a consequence of the diversity in runoff generation processes. As could be expected, the seasonality of monthly runoff in the Alpine areas is more stable than in the lowlands. Clearly this is because of snow processes which result in spring/summer maxima of runoff in all years and decades. What is more surprising is the clear pattern of the seasonality of mean monthly precipitation. Typically this is related to the precipitation generation mechanisms of the interplay of advection of air masses and orographic effects. These seem to result in a seasonality that does not vary much between the years and decades. In the lowlands in contrast, other mechanisms (convective, synoptic) may be equally important and lead to less stable seasonality. From the seasonality analysis of maximum annual floods it is clear that the spatial patterns are more heterogeneous than those of annual maximum daily precipitation which, again, is due to differences in the catchment processes.

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