EVALUATION OF THE HYDROCLIMATIC EXTREMES IN THE UPPER HRON RIVER BASIN, SLOVAKIA

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ABSTRACT

This paper deals with the occurrence of hydroclimatic extremes in the upper Hron River basin in Slovakia in 1951/61–2010. Select trends in hydroclimatic parameters in 1931/61–2010 are also studied. Emphasis is placed on the occurrence, frequency, and seasonality of dry episodes and flood events. The de Martonne index, the relative precipitation index, base flow index, low flow index, linear regression, the Mann-Kendall test and IHA software were used in the analyses.

Mann-Kendall test pointed to significant changes in runoff of the upper Hron River basin. The annual runoff has decreased. Changes in minimums and maximums have had a fundamental influence on this decrease, particularly in the cold half year. Major changes occurred in Q_1, Q_{Max}, Q_{75pct} and 1-day, 3-day and 7-day maximum values. Approximately since the 1980s there has been a decrease in discharge events equal to or greater than one-year flood Q_1. Events where discharges were equal or greater than Q_5 occurred only in the first period 1951–1980 (in 1954 and 1974). The de Martonne index, the relative precipitation index and the low flow index show similar results, the longest above-average period of annual values reached from 2007 to 2010 and the longest below-average period from 1990 to 1993.

Keywords: drought, flood, de Martonne index, Mann-Kendall test, Hron River basin

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1. Introduction

The threat of hydroclimatic extremes, a topic of frequent discussion among experts mainly in relation to climate change, is a serious problem. Slovakia will not be able to avoid extreme droughts and floods in the future. The extremely dry year of 2003 and the very wet year of 2010 are examples. Last year, 2015, was also extremely dry. It was one of the warmest and driest years since measurements have been taken. The year 2013 also saw hydrological extremes. Most of Central Europe was hit with extensive flooding. Therefore, it is appropriate to focus attention on this problem with the realization of the lasting risks associated with these extremes.

There are few studies which would devote more complex these extremes. The presented study is an attempt to more fully evaluate hydroclimatic extremes in headwater area of the river. The aim of this study is to evaluate the incidence of hydroclimatic extremes (droughts and floods) in the upper Hron River basin in the period 1951/61–2010. The following are evaluated trends of selected hydrological parameters in the period 1931/61–2010. The knowledge gained from this study may have basic importance for risk assessment of both floods and droughts in the territory of Slovakia.

Define drought is quite difficult and therefore there are many definitions of drought. Put simply, we can say that the drought is the lack (deficit) of water. Tallaksen and van Lanen ed. (2004) define drought as a sustained and regionally extensive occurrence of below-average natural water availability, and can thus be characterized as a deviation from normal conditions of variables such as precipitation (meteorological drought), soil moisture, groundwater and streamflow (hydrological drought).

A distinction between droughts and low flows: drought is a natural event resulting from a less than normal precipitation for an extended period of time; low flows, on the other hand, is a seasonal phenomenon, and an integral component of a flow regime of any river. Various low-flow indices may be estimated from 'lowflow section' of a flow duration curve. The flows within the range of 70–99% time exceedance are usually most widely used as design low flows (Smakhtin 2001). Brázdil and Trnka et al. (2015) give a comprehensive overview of methods for determining drought and dry episodes and discuss their causes, their impact on select sectors of the national economy, their temporal and spatial variability, and finally future scenarios. Ledvinka (2015) has dealt with the development of low discharges using and comparing statistical tests.

The biggest drought events in Europe from 1950 to 2012 were examined by Spinoni et al. (2015). According to the results, Northern and Eastern Europe show the highest drought frequency and severity from the early 1950s to the mid-1970s, in Central European regions in the period 1971–1990, and in Southern Europe in the period 1991–2010. In general, it was found a small but continuous increase of the European areas prone to

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drought from the early 1980s to the early 2010s. Hisdal et al. (2001) also examined the incidence of droughts in Europe. The Mann-Kendall test and a resampling test for trend detection showed that it is not possible to conclude that drought conditions in general have become more severe or frequent. However, distinct regional differences were found. The increasing drought deficit volumes were found in Spain, the eastern part of Eastern Europe and in large parts of the UK, whereas decreasing drought deficit volumes occurred in large parts of Central Europe and in the western part of Eastern Europe. Briffa, Schrier and Jones (2009) analyzed wet and dry summers in Europe since 1750 and they observed that a major cause for the large areal extent of summer drought in the last two decades was high air temperatures. Significant decreasing trends of summer low flows and increasing winter low flows were investigated by Mann-Kendall test, using data from 144 Czech catchments for the period 1961–2005. Increasing drought duration as well as deficit volumes were observed (Fiala et al. 2010; Fiala 2011). Brázdil et al. (2009) have dealt with drought variability in the Czech Republic in 1881–2006. This study clearly confirms growth in dry episodes in the studied period as a result of growing air temperatures and decreasing precipitation.

The index for indicating hydrological drought in snow-influenced catchments was created by Staudinger et al. (2014). The study with Swiss catchments suggests a closer description of hydrological droughts by *SMRI* (the Standardized Snow Melt and Rain Index) than by *SPI* (the Standardized Precipitation Index). A decrease of snow in the cold season has a negative effect on soil and groundwater storages during spring and might cause low streamflow values in the subsequent warm season. Jeníček et al. (2016) quantified how long snowmelt affects runoff after melt-out and to estimate the sensitivity of Swiss catchments with different elevation ranges to changes in snowpack. For higher- and middle-elevation catchments and years with below-average SWE maximum, the minimum discharge in July decreased to 70–90% of its normal level. Additionally, a reduction in SWE resulted in earlier low-flow occurrence in some cases.

On the territory of Slovakia a decreasing trend of annual runoff was observed in 1961– 2000 (reference period 1931–1980 and 1961–2000), which was higher in cold half year (November–April) and smaller in warm half year (May–October), Majerčáková et al. (2004). A significant decrease in winter runoff (December–February) was observed in the upper Hron River basin in 1931–2010 (Blahušiaková and Matoušková 2015). This basin is categorized as a basin with a decreasing long-term discharge trend (Poórová et al. 2013a). Minimum discharge trends in different parts of Slovakia vary. The most favorable conditions are in the upper catchments of the Váh, Hron, and Slaná Rivers as well as in the basins of the Hornád, Poprad, Bodrog, and Danube Rivers. In contrast, southern Slovakia, that is, the basins of the lower Váh, Hron, and Slaná, and the basins of the Ipeľ, Nitra, Malý Dunaj, Bodva, and partially the Morava indicate a significant decreasing minimum discharge trend (for the period 1961–2012; Poórová et al. 2013b). Demeterová and Škoda (2009) have observed dry periods on many Slovak rivers. They also analyzed long-term dry periods (lasting more than 30 days) in the upper Hron River basin. They report one of the greatest frequencies of winter long-term dry periods in all of Slovakia (more than three times in ten years).

Floods can be characterized according to various aspects. A review of applied methods for flood-frequency analysis in a changing environment it offers by Madsen et al. (2013). A contribution includes a comparison of trend analysis results and climate change projections for 21 countries in Europe (including the Czech Republic and Slovakia). The review indicates a gap between the need for considering climate change impacts in design and actual published guidelines that incorporate climate change in extreme precipitation and flood frequency. The examination of flood frequency in central Europe (Germany, Switzerland, Czech Republic and Slovakia) using annual and seasonal maximum discharge time series was made by Villarini et al. (2011). The results show that there is a marked seasonality in the flood peak record, with a large fraction of annual maximum flood peaks occurring during the winter in the western part of the study domain, and during the summer in the southern portion of this region. A study by Svensson et al. (2005) discusses the detection of trends in flood and low-flow index series at 21 daily mean river flow stations across the world. There is no general pattern of increasing or decreasing numbers or magnitudes of floods, but there are significant increases in half of the low-flow series. For the annual maximum daily mean river flow series, the negative trends are in Northern Europe and the northwest of the Balkan Peninsula; positive trends are in central Europe and the British Isles. In the study areas of Europe (including central Europe) there are positive trends in the annual minimum 7-day mean river flow series. Yiou et al. (2006) have investigated the possible relationships between flood magnitude, climate variables (temperatures, precipitation) and atmospheric circulation patterns for the Vltava and Elbe rivers in Bohemia. The results showed that occurrence and intensity of floods have generally decreased over the 20th century. The decrease in winter is slightly correlated with the mean air temperature increase. A similar tendency is detectable in the eastern part of the Czech Republic for the Morava and Oder rivers (Brázdil et al. 2005).

Runoff extremes in Slovakia, specifically peak runoff, have been dealt with by Blaškovičová et al. (2014). Peak discharge trends were studied on the Danube River in 1877–2012; a slight increasing trend was observed. The most significant increasing trends are in December and April. In contrast, based on Mann-Kendall test results, a statistically significant decreasing trend in annual peak discharge in the basins of east and central Slovakia was detected (Jeneiová et al. 2014).

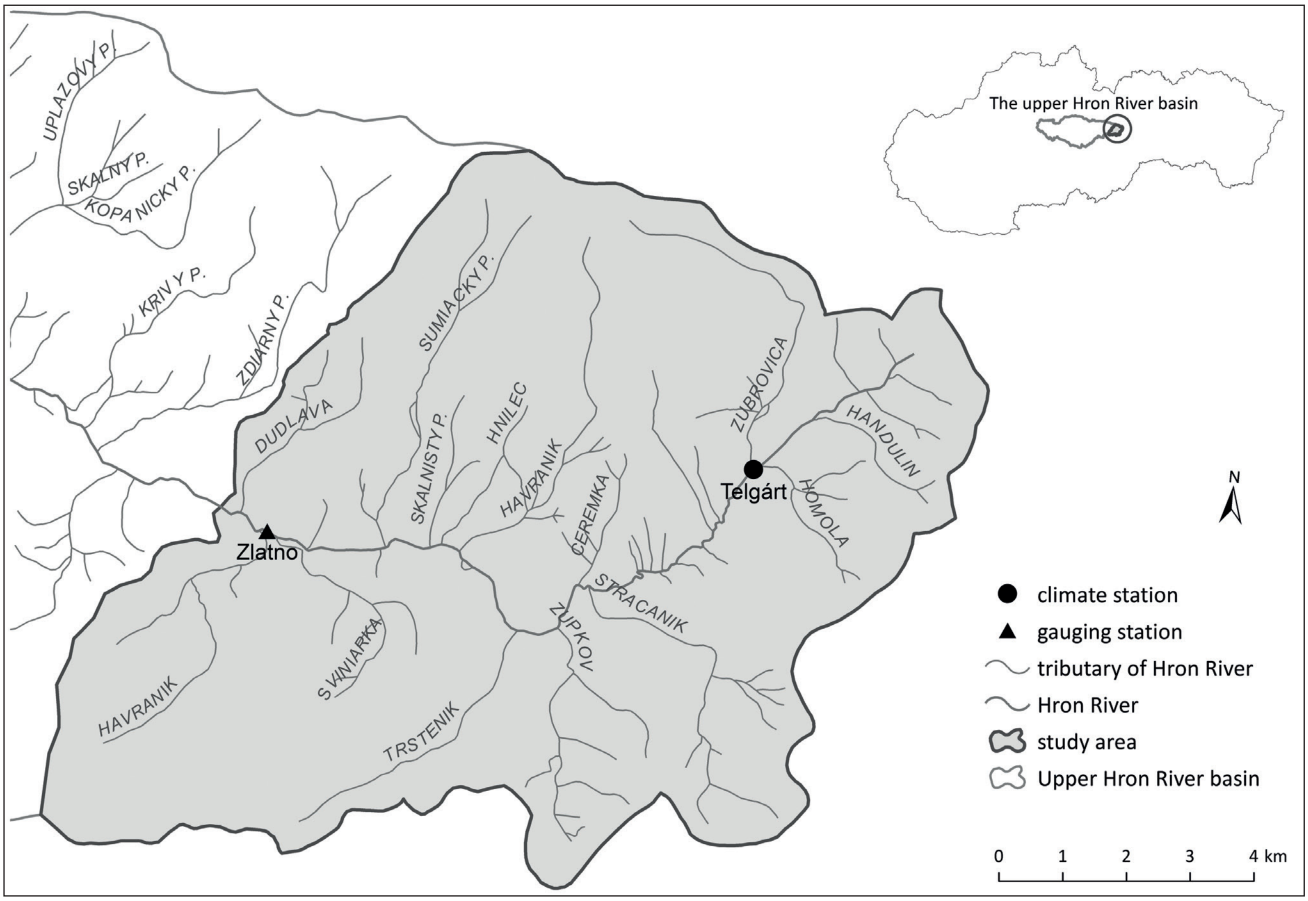

Fig. 1 Study area – the upper Hron River basin, Slovakia. Data source: SHMI, B. Bystrica

Tab. 1 The individual characteristics of the study basin.

Study area characteristics	Data from station	Time	Value	Note
Area	Zlatno	–	83.7 km^2	from the source to Zlatno station
Altitude	Telgárt	–	901 m a.s.l.	–
Altitude	Zlatno	–	733 m a.s.l.	–
Long-term annual precipitation (P_a)	Telgárt	1961–2010	853 mm	–
Maximum annual precipitation total	Telgárt	2010	1282 mm	150% of long-term precipitation normal (1961–2010)
Minimum annual precipitation total	Telgárt	2003	528 mm	62% of long-term precipitation normal (1961–2010)
Long-term mean air temperature (T_a)	Telgárt	1961–2010	5 °C	–
Maximum mean annual air temperature	Telgárt	2007	6.4 °C	for the period 1961–2010
Minimum mean annual air temperature	Telgárt	1965, 1980	3.6 °C	for the period 1961–2010
The warmest month of the year	Telgárt	July	from 12.2 °C to 17.6 °C	for the period 1961–2010
The coldest month of the year	Telgárt	January	from –10.7 °C to –0.1 °C	for the period 1961–2010
Mean annual snow cover depth (SCD_r)	Telgárt	1961–2010	24 cm	from November to April
Maximum mean annual snow cover depth	Telgárt	1963	67 cm	from November to April (1961–2010)
Minimum mean annual snow cover depth	Telgárt	1989	5 cm	from November to April (1961–2010)
Long-term mean annual discharge (Q_a)	Zlatno	1961–2010	1.4 m^3 s^{-1}	–
Specific runoff (q)	Zlatno	1961–2000	16.41 s^{-1} km^{-2}	average value of Slovakia is 8.61 s^{-1} km^{-2}
Annual runoff coefficient (φ)	Zlatno	1961–2000	0.55%	–
Maximum mean annual discharge (Q_{rMax})	Zlatno	1965	2.4 m^3 s^{-1}	for the period 1961–2010
Minimum mean annual discharge (Q_{rMin})	Zlatno	1993	0.8 m^3 s^{-1}	for the period 1961–2010
The most water month	Zlatno	October 1974	6.5 m^3 s^{-1}	37% of annual runoff
The least water month	Zlatno	February 1984	0.3 m^3 s^{-1}	1.5% of annual runoff
Maximum mean monthly discharge	Zlatno	April	2.8 m^3 s^{-1}	for the period 1961–2010
Minimum mean monthly discharge	Zlatno	January, February	0.7 m^3 s^{-1}	for the period 1961–2010

Source: SHMI, B. Bystrica; Pekárová and Szolgay 2005

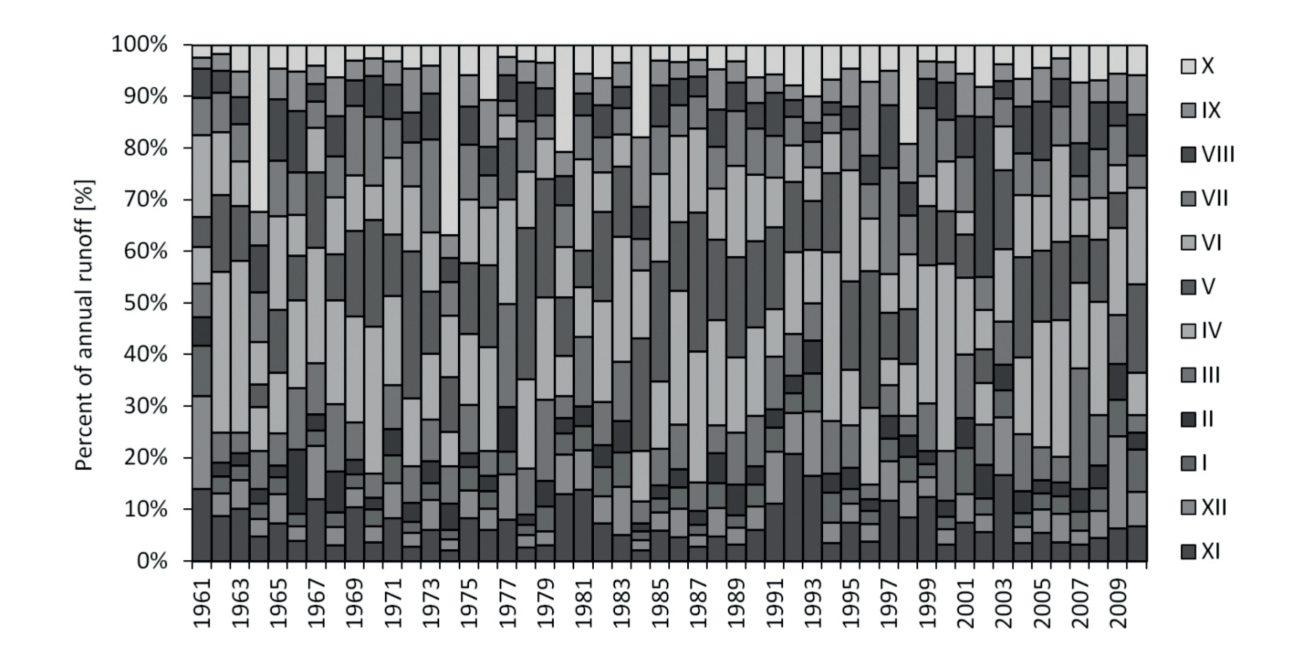

Fig. 2 Seasonal changes in runoff in Zlatno (1961–2010). Data source: SHMI, B. Bystrica

2. Study area characteristics

The Hron River (basin area of 5465 km^2) springs under the Kráľova hoľa Mountain in the Low Tatras at 934 m a.s.l. and flows into the Danube near Štúrovo at 103 m a.s.l. The source section of the upper Hron River basin up to Zlatno gauging station (altitude 733 m a.s.l.) has an area of 83.7 km^2 and was selected as the study basin (Figure 1).

The basin is located in a cold and humid to very humid climatic region. The area shows a relatively well-preserved natural runoff regime. Runoff regime of the upper Hron River is nivo-pluvial. Forest covers 59% of basin area (Holko and Kostka 2008). It exceeds the mean value of forestation for Slovakia, which is 41% (NFC 2011). Figure 2 shows seasonal changes in runoff in Zlatno during 1961–2010. The individual characteristics of the river basin are listed in Table 1.

3. Data and Methods

3.1 Used data

Climate extremes are evaluated on climate station Telgárt for the period 1961–2010. The analyzed dataset included daily (P_d), monthly (P_m), annual (P_r) precipitation amounts and the long-term annual precipitation (P_a) in millimeters (mm); mean daily (T_d), monthly (T_m), annual air temperature (T_r) and the long-term mean air temperature (T_a) in Celsius degrees (°C). Snow cover conditions were evaluated for days with permanent snow cover, i.e. period in which the snow cover was not interrupted for more than three consecutive days and a minimum height of snow cover was 1 cm. We processed data on daily snow cover depth (SCD_d), mean monthly and annual snow cover depth (SCD_m, SCD_r) in centimeters (cm), and number of days with snow cover in the month/year (SCN_m, SCN_r). The SCD_r was calculated for a winter season (November–April).

Hydrological extremes were evaluated on Zlatno gauging stations in the period 1951/61–2010. Values of Q_d (mean daily discharge), Q_m (mean monthly discharge), Q_r (mean annual discharge) and Q_a (the long-term mean annual discharge) in cubic meters per second (m^3 s^{-1}) were used. Analyzed are the maximum (Q_{Max}) – the highest mean daily discharge and the minimum (Q_{Min}) – the lowest mean daily discharge. In the evaluation were added mean daily discharges Q_{330}, Q_{355} and Q_{364}. The Q_{330} refers to mean daily discharge that was reached or exceeded 330 days in the year, the Q_{355} was reached or exceeded 355 days in the year and the Q_{364} was reached or exceeded 364 days in the year.

All data provided by the Slovak Hydrometeorological Institute (SHMI) in Banská Bystrica were homogenized.

3.2 Methods for investigating climate indicators

The occurrence of drought was evaluated based on the two selected indexes and seasonality achieved on the basis of the total precipitation and the number of days without precipitation respectively, with only a small amount of precipitation.

The de Martonne Aridity Index (Sobíšek 1993) indicates the degree of dryness, or humidity, of the climate in relation to various climatic elements and factors. In this study we used the de Martonne Aridity Index as modified by Reichel (eMS 2015), which is calculated based on a formula

$$i = \frac{R}{T+10} \cdot \frac{N}{180} \qquad (1)$$

where i is the aridity index; R is annual precipitation in mm; N is the number of days with precipitation at the given location; T is the mean annual air temperature in °C; and the figure 180 represents the average number of days with precipitation in Central Europe. Each year is categorized based on this index (Table 2). Although calculating this index requires two or three meteorological variables, it can still be considered simple, and it takes into account not just precipitation but also air temperature. The number of days with precipitation emphasizes the significance of the distribution of daily precipitation.

Tab. 2 Annual de Martonne Aridity Index (dMi).

dMi	Climate classification
I<10	Dry or arid
15≤I≤24	Semiarid
24<I≤30	Moderately arid
30<I≤35	Slightly humid
35<I≤40	Moderately humid
40<I≤50	Humid
50<I≤60	Very humid
60<I≤187	Excessively humid

Source: HOA 2016

The Relative precipitation index is also used; it is calculated as the percentage of current precipitation in a given period divided by the long-term mean. It is calculated using a formula

$$I = \frac{P}{Pa} \cdot 100 \qquad (2)$$

where I is the relative precipitation index, P is current precipitation and P_a is the long-term annual precipitation for the given period (1961–2010). Values lower than 100 (%) indicate below-average precipitation. When the index value decreases, the probability of drought increases (Novický et al. 2008).

The seasonality of dry episode occurrences (in cold half year: November–April and warm half year: May–October) is analyzed on the basis of the number of days without precipitation, or rather, the number of days with precipitation, with a predetermined threshold value (the minimum duration of the dry period 15 days and maximum precipitation 8.5 mm). On the basis of these data, dry episodes are defined and classified into four groups A–D (Table 3). The advantage of defining episodes in this way is that it allows researchers to determine the beginning and end of dry periods, their frequency during the studied period and their seasonality.

Tab. 3 Definition of dry episodes in Telgárt (1961–2010).

Group	Duration (days)	Maximum precipitation (mm)
A	15 and more	to 1.0
B	20 and more	to 2.5
C	30 and more	to 5.0
D	40 and more	to 8.5

3.3 Methods for investigating hydrological indicators

For identifying changes in hydrological time series were used values of mean daily discharges (Q_d). Of these values were calculated median values, monthly discharges (Q_m), annual discharges (Q_r); maximums (Q_{Max}) and minimums (Q_{Min}) of discharges were determined, coefficient of dispersion, base flow index and daily discharges Q_{330}, Q_{355} and Q_{364}, which are frequently used as a threshold value for determining drought. N-year flood events and values of Q_{Max} and high flows were used for determining floods. Detection of trends in hydrological parameters was determined using non-parametric statistical Mann-Kendall test and linear regression.

An easy-to-use tool for calculating the characteristics of natural and altered hydrologic regimes is the Indicators of Hydrological Alteration (IHA) software (Richter et al. 1998) and IHA 7.1 statistics software (TNC 2009). The power of the IHA is that it can be used to summarize long periods of daily hydrologic data into a much more manageable series of relevant hydrologic parameters. Using this software, we evaluated the values of Q_d during the period 1951–2010, which we divided into two time periods (1951–1980 and 1981–2010), and those we compared. Selection period 1951–2010 was influenced by the availability of climate data (order to allow a comparison of climate and hydro results), and also the fact that we wanted to compare the same long period. As a turning point, the year 1980 was chosen. The IHA software calculates 67 statistical parameters. The following parameters were used in our study: median values (the 50th percentile of daily flows), Q_{75pct} (the 75th percentile of daily flows), coefficient of dispersion (COD) → (75th pct-25th pct)/50th pct (pct → percentile), minimums and maximums (Q_{Min} and Q_{Max}), the 1-, 3-, 7-, 30-, and 90-day minimums and maximums, base flow index (7-day minimum flow/mean flow for year), frequency, timing and duration of high and low pulses. The initial separation between high and low flows is done using a single fixed threshold, which was 1.6 $m^3 s^{-1}$ (this is Q_{75pct}). All flows greater than this value are classified as high flows, and all flows less than or equal to this threshold are classified as low flows. For comparison with the results of climatic indexes was added low flow index (Poff and Ward 1989). It is calculated using a formula:

$$LOWFLOW = Q_{Min} / Q_a \qquad (3)$$

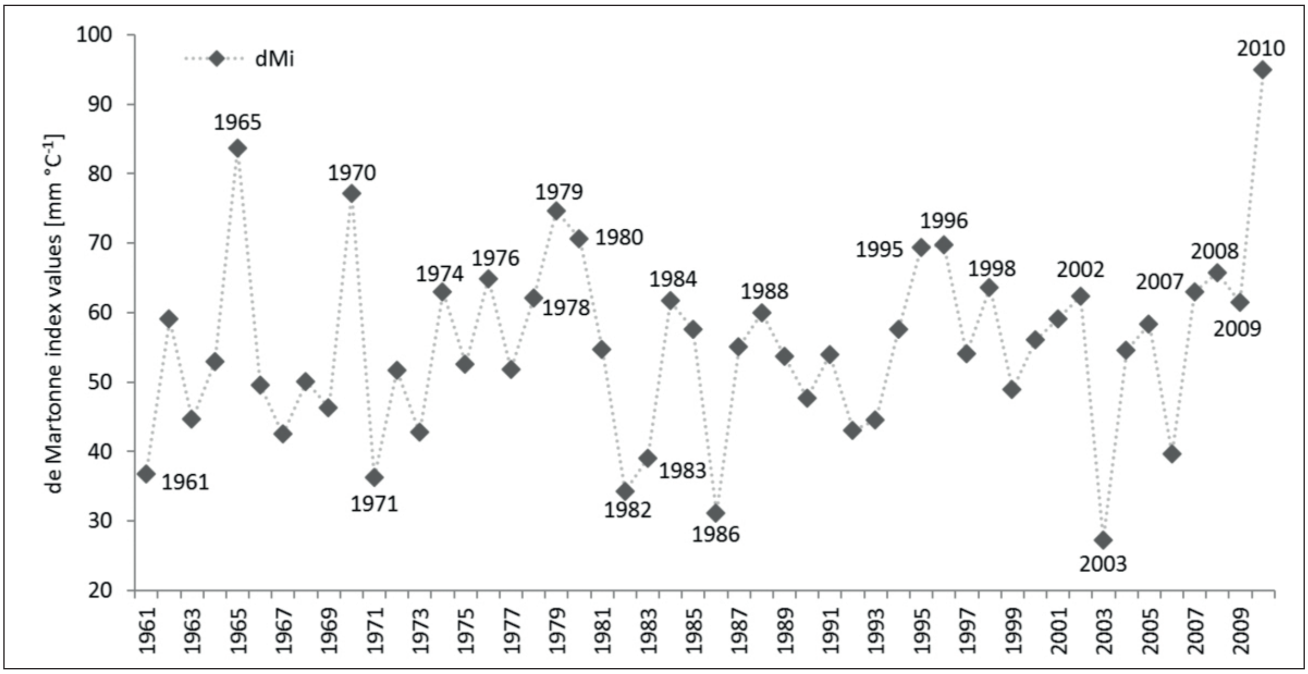

Fig. 3 The distribution of years based on the de Martonne index in Telgárt (1961–2010). Data source: SHMI, B. Bystrica

where LOWFLOW is low flow index, Q_{Min} is the lowest mean annual daily discharge and Q_a is the long-term mean annual discharge (1951–2010).

Detection of trends of selected hydrological parameters was detected using the Mann-Kendall test and linear regression. A seasonal non-parametric Mann-Kendall test (Bawden et al. 2014; Helsel and Frans 2006; Kendall 1975; Libiseller 2004; Mann 1945; Yue et al. 2002, 2012) has two parameters important for the trend detection: a significance level (p), which represents the power of the test, and a slope magnitude estimate (Mann-Kendall statistics *MKS*), which represents the direction and volume of the trend. The trend significance level of 0.05 has been set for all statistical analysis. The duration of observations plays an important role in the assessment of trends in hydroclimatic factors. If the goal of research is to identify the changes of the hydrological regime, then it is justifiable to use a time series that is as long as possible. In the upper Hron River basin, there are hydrological data available since 1931, so the MK test was run for the two periods 1931–2010 and 1961–2010.

N-year flood events (Table 4) were used as the basic selection criterion, while a flood was defined as a hydrological situation where the Q_d achieved or exceeded the value Q_1 (one-year flood). Evaluated flood events ≥ Q_5, Q_{20}, Q_{50}, Q_{100} were included in the assessment. In order to analyze the frequency and seasonality of floods, peak discharge values (Q_{Max}) were used as source data. Seasonality was assessed using data on Q_d that exceeded the value of Q_1. Ten days preceding the day with Q_1 occurrence determined the boundaries between individual flood events. If a flood began in one month and subsided in the next, the month in which the peak flow occurred was recorded.

Tab. 4 N-year maximum and minimum discharges ($m^3 s^{-1}$) in Zlatno.

Zlatno (N-year)	1	5	20	50	100
Max (1931-1987)	10	23	38	49	58
Min (1931-2004)	0.26	–	0.23	0.20	0.18

Source: Pekárová and Szolgay 2005

4. Results

4.1 Analysis of extremes based on annual and monthly climate data

By calculating the selected indices it was possible to determine the character of each year in the studied period 1961–2010. The results of the de Martonne index (Figure 3, Table 2) indicate that longer wet periods occurred at the end of the studied period (from 2007 to 2010, all years with a value over 60 mm $°C^{-1}$), with 2010 being the highpoint (95 mm $°C^{-1}$). A three-year period from 1978 to 1980 follows, and then 1995 and 1996 (all with a value above 60 or 70 mm $°C^{-1}$). In contrast, 2003 was one of the driest years (27 mm $°C^{-1}$), followed by 1986, 1982, 1971, 1961, and 1983 (all below 40 mm $°C^{-1}$).

Similar results were obtained from calculating the relative precipitation index, which classifies each year as above-average, average, and below-average, where average equals 100%. Years with values below this threshold are below-average and those above it are above-average. The longest above-average period was from 2007 to 2010, when, for example, the exceptionally wet 2010 was 150% of the long-term mean. The longest below-average period was from 1990 to 1993, when, for example, 1993 was 78%

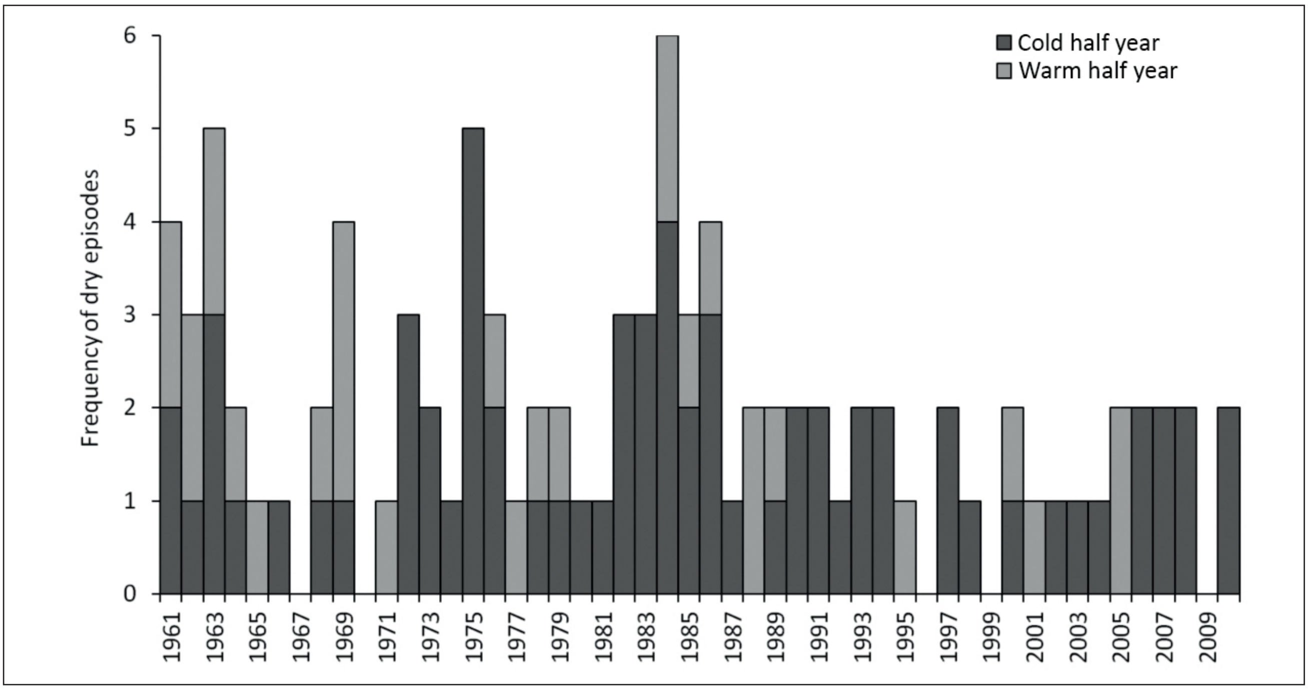

Fig. 4 Frequency of dry episodes lasting 15 days and more with a maximum precipitation to 8.5 mm in cold and warm half years in Telgárt (1961–2010). Data source: SHMI, B. Bystrica

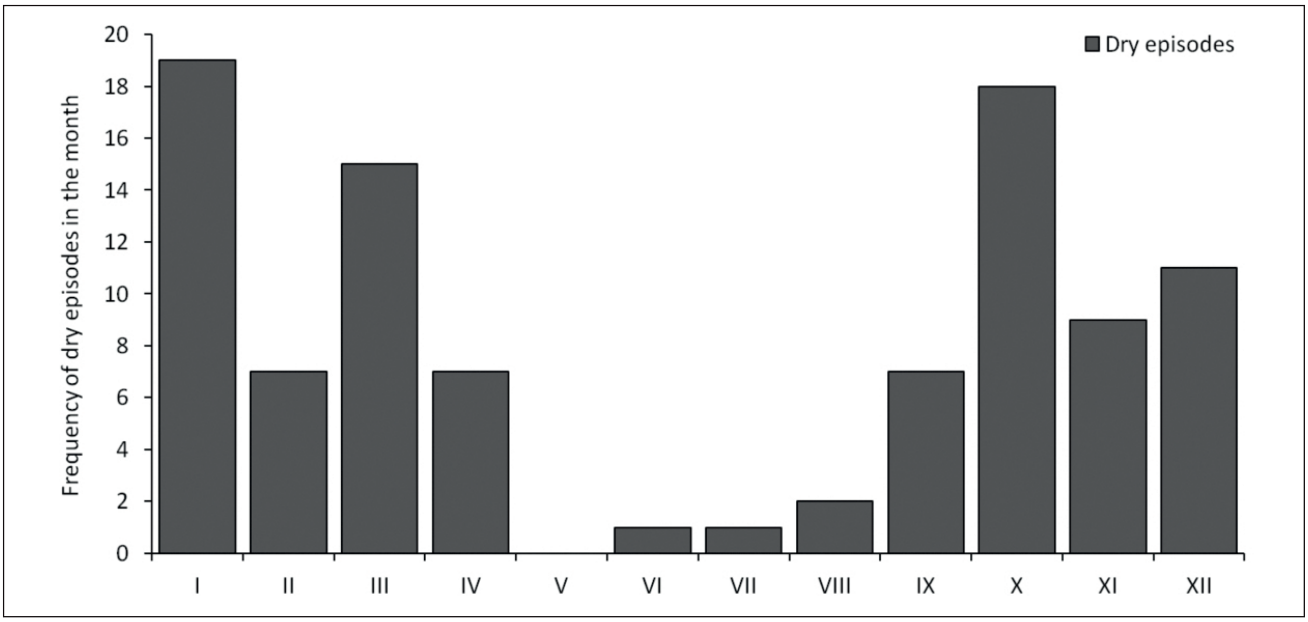

Fig. 5 The frequency of dry episodes lasting 15 days and more with a maximum precipitation to 8.5 mm in Telgárt in each month during the period 1961–2010. Data source: SHMI, B. Bystrica

of the long-term mean. The driest year, 2003, was only 62% and 1986 68% of the long-term mean.

Figure 4 indicates that dry episodes (episodes lasting 15 days or more with a maximum precipitation 8.5 mm) were more frequent in the cold half year (November–April), and they were most frequent in 1975 and 1984. Dry episodes in this period were prevalent primarily in the 1970s, 1980s, and early 1990s. In contrast, in the warm half year (May–October), dry episodes occurred mainly in the 1960s, with the most occurring in 1969. Nineteen dry episodes occurred in January, followed by October (18) and March (15). In the period from May to August they were much fewer in number. Their overall frequency is depicted in Figure 5. The longest dry episode occurred from 16 February to 23 April 1974, with 8.5 mm of precipitation. A drought occurred at the similar time of year 2003, lasting from 6 February until 2 April with 6.4 mm of precipitation. Droughts also frequently occur in autumn. The third-longest-lasting dry episode occurred from 5 October to 26 November 1978

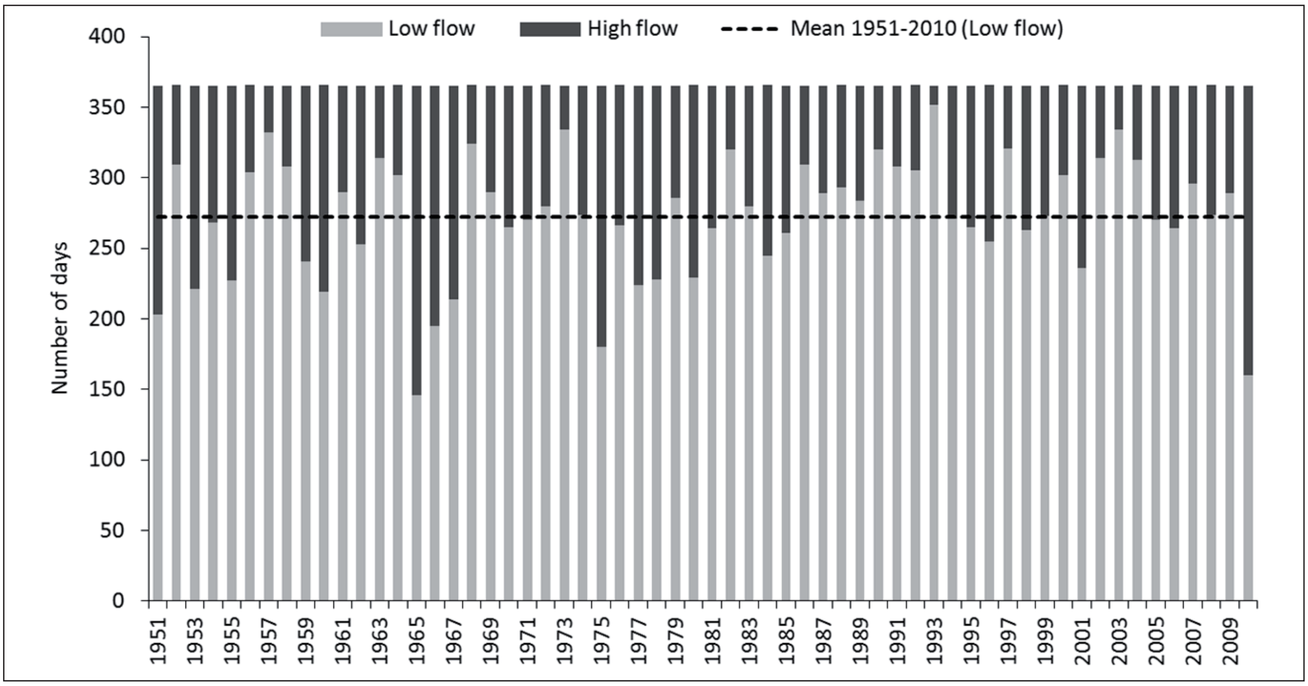

Fig. 6 The frequency of days with low and high flow in Zlatno (1951–2010); a threshold between low and high flow is 1.6 m³ s⁻¹; an average number of days with a low flow was 272 and with a high flow was 93 (1951–2010). Data source: SHMI, B. Bystrica

with 5.5 mm of precipitation. The fourth longest episodes occurred from 7 September to 29 October 1985 with 7.6 mm of precipitation. All dry episodes categorized in group D are displayed in Table 5.

Tab. 5 The duration of the dry episodes (Group D; maximum precipitation 8.5 mm) in 1961–2010.

Start	End	Precipitation (mm)	Days
19.09.1962	29.10.1962	1.6	41
18.12.1963	31.01.1964	3.4	45
04.12.1972	15.01.1973	4.4	43
16.02.1974	23.04.1974	8.5	67
01.02.1982	12.03.1982	6.7	40
05.10.1978	26.11.1978	5.5	54
07.09.1985	29.10.1985	7.6	53
07.01.1989	19.02.1989	3.9	44
13.12.1992	21.01.1993	7.2	40
06.02.2003	02.04.2003	6.4	56
02.10.2005	15.11.2005	2.5	45
24.03.2007	03.05.2007	6.2	41

Data source: SHMI, B. Bystrica

4.2 Analysis of extremes based on annual and monthly hydrological data

Detecting high and low flows using IHA is one of the preconditions for evaluating hydrological extremes. In Figure 6 it can be seen that the second half of the studied period, 1981–2010, was in total less wet at Zlatno station. The least wet period was the second half of the 1980s and the early 1990s (from 1986 to 1993) as well as from 2002 to 2004 (mainly 2003). In contrast, the wettest periods were in the mid-1960s (from 1965 to 1967), the second half of the 1970s (1974 to 1981), and the 1990s (1994 to 1996 and 1998, and 1999) in addition to 2001, 2005, 2006, and 2010. Exceptionally dry years in 1951–2010 were, in order from driest, 2003, 1993, and 1973, and exceptionally wet years were, in order from wettest, 1965, 2010, and 1975. Low flow index also indicates that the driest period was the second half of the 1980s and the early 1990s (Figure 7). Other dry years were 1967, 1974, 2000, 2003, 2004 and 2007. Among the wettest years belonged 1953, 1959, 1967 and 2010. These results are similar with the results of climate indices.

The decrease in wetness in the second half of the studied period is connected with a decrease in frequency and extremity of flooding as depicted in Figure 8. The figure shows that approximately until the 1980s the frequency and extremity of events where discharge was $\geq Q_1$ and Q_5 was greater. The greatest peak discharge (27.3 $m^3 s^{-1}$) occurred during a flood in 1954 with a value equal to Q_5. The flood in 1974 reached the same N-year value, with a peak discharge 26.5 $m^3 s^{-1}$. In the 1958 hydrological year, Q_1 was exceeded, moreover, for a total of seven days. In 1964 it was six days and in 1967 and 2002 it was five days. In 1951–1980 there were 18 such events, in 1981–2010 there were only seven, which the linear trend line also demonstrates. The seasonal distribution of events where discharge was $\geq Q_1$ in 1951–1980 and 1981–2010 is displayed in Figure 9. The month of April is of great importance for spring runoff on the upper Hron. Its

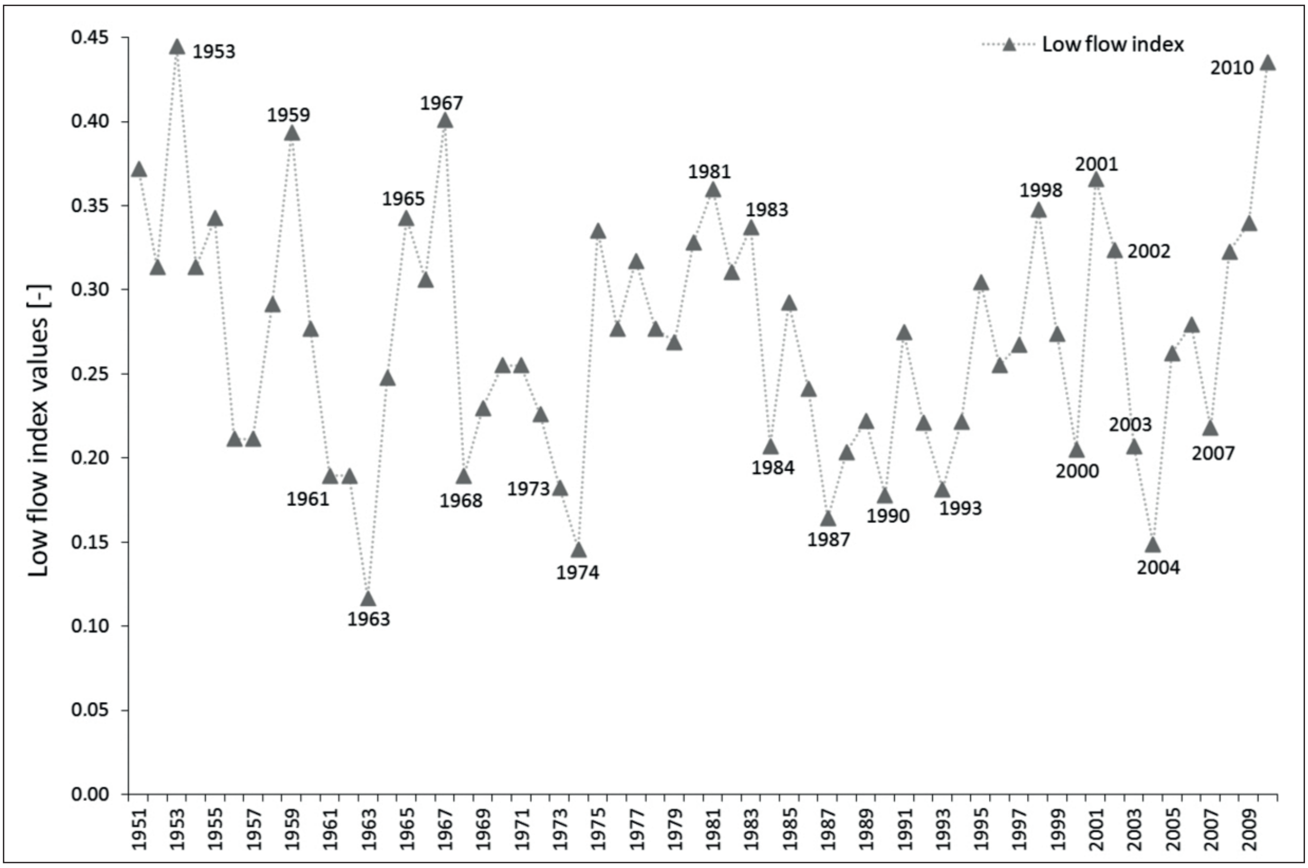

Fig. 7 The distribution of years based on the low flow index in Zlatno (1951–2010). Data source: SHMI, B. Bystrica

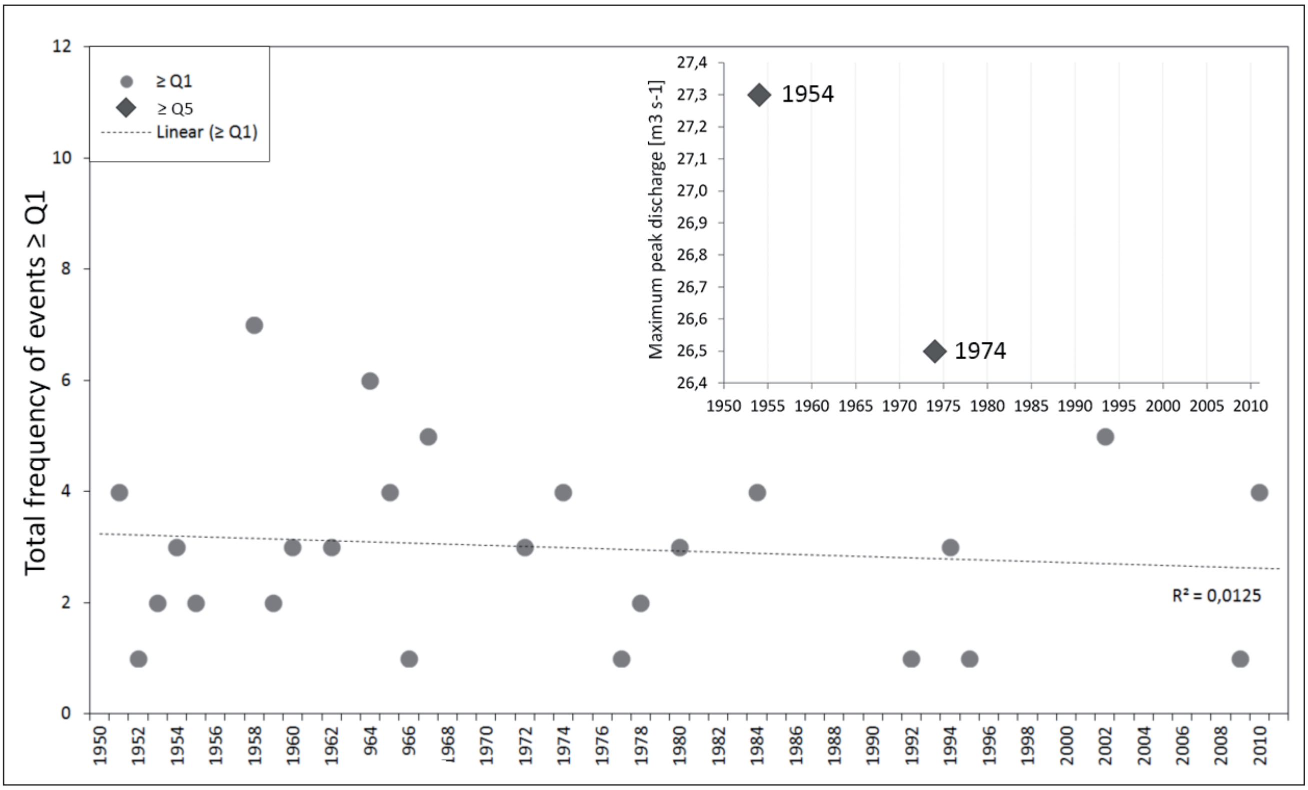

Fig. 8 The frequency of events ≥Q1 and Q5 in Zlatno (1951–2010). Data source: SHMI, B. Bystrica

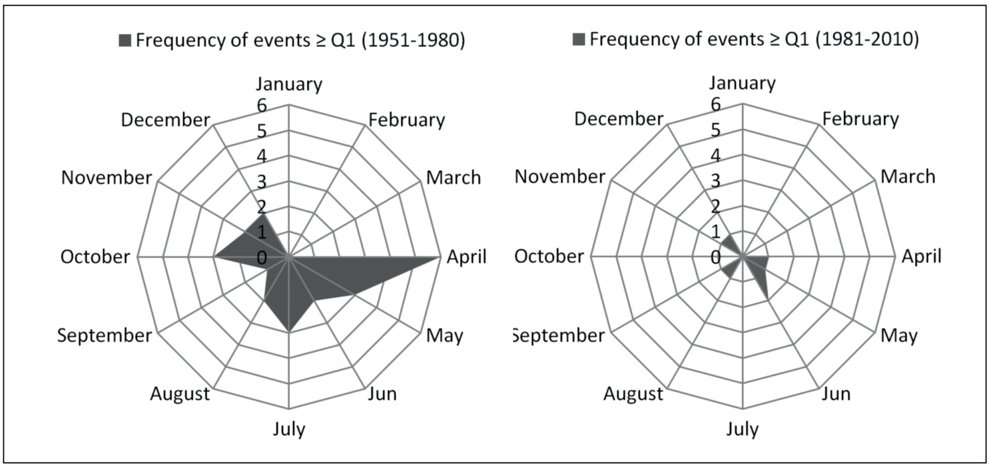

Fig. 9 A seasonal distribution and frequency of events ≥Q1 in Zlatno, a comparison of periods 1951–1980 and 1981–2010. Data source: SHMI, B. Bystrica

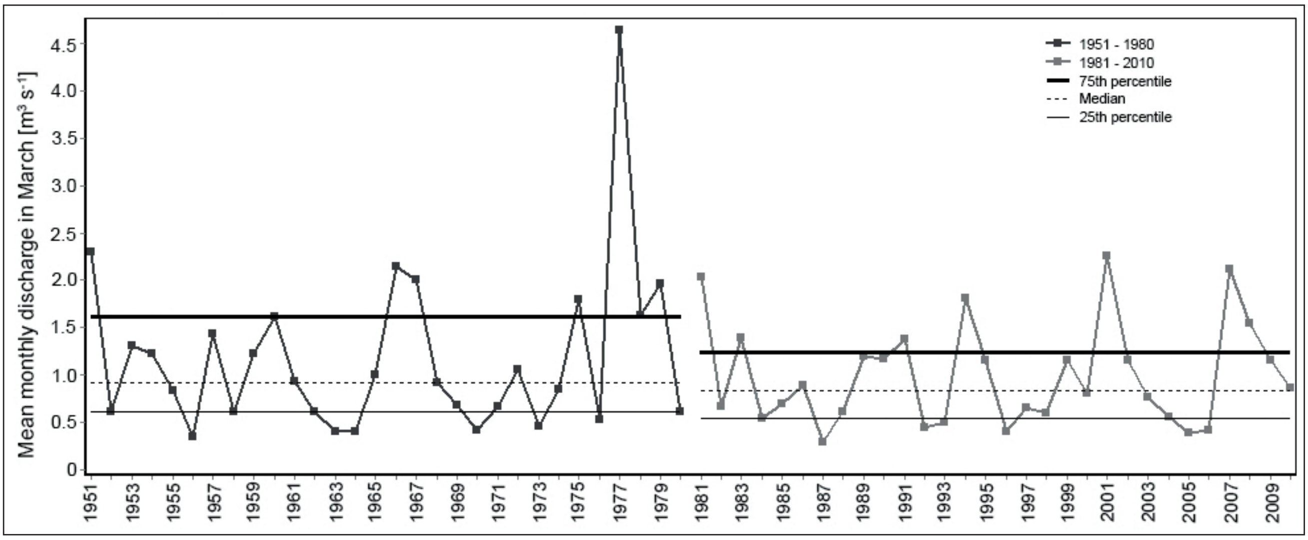

Fig. 10 The mean monthly discharge for March in Zlatno in periods 1951–1980 and 1980–2010. Data source: SHMI, B. Bystrica

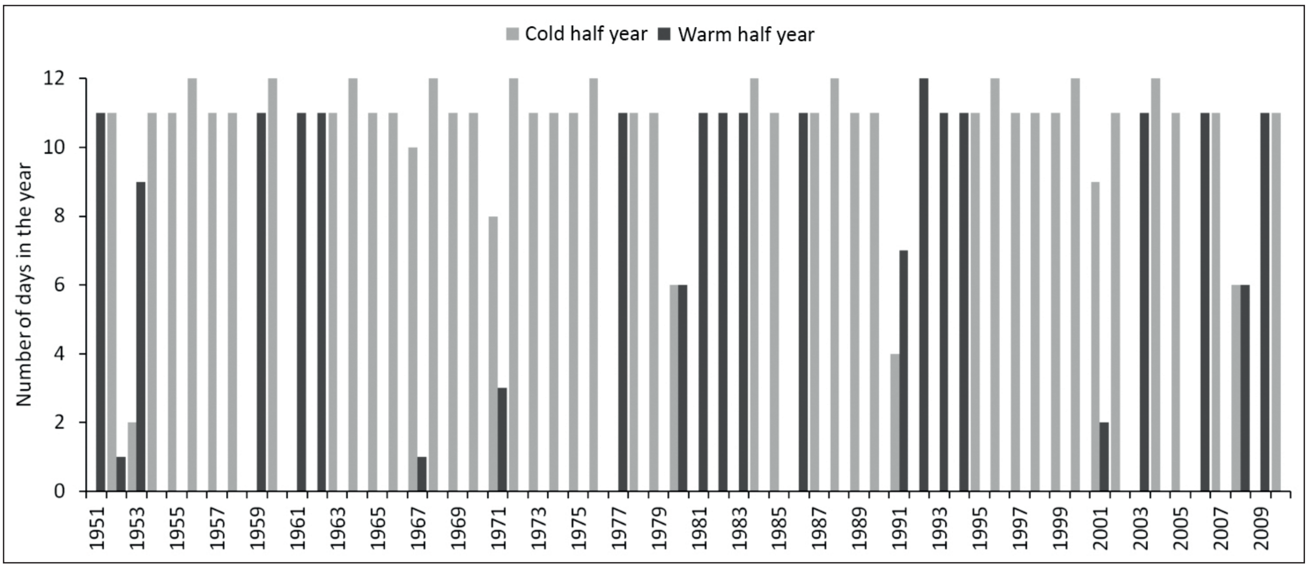

Fig. 11 Seasonality of daily discharge Q355 in Zlatno (1951–2010). Data source: SHMI, B. Bystrica

great contribution to runoff in 1951–1980 decreased in the following period of 1981–2010. The number of events decreased from six to one. A more significant decrease happened in May, July, and October.

From the results using IHA software is obvious a decrease in Q_{Max} values in March and October. In contrast, increases occurred in January and September (Table 6). In comparison with Q_{Min} and median values, more specifically values of Q_{75pct}, a more significant decrease occurred, moreover in the already-mentioned months of March (Figure 10) and October. In comparison with Q_{Min}, median values, and Q_{75pct} values, Q_{Max} values experienced the most significant decrease. The decrease in February is also significant. In contrast, the largest increase occurred in January. It is therefore possible to state that decreasing Q_{Max} values contribute to the upper Hron's decreased runoff. Using of IHA and the MK test confirmed these changes (section 4.4).

Tab. 6 Comparative analysis of monthly and daily flow parameters between 1951–1980 and 1981–2010 periods.

Month	Medians	Coefficient of Dispersion	Minimum	Maximum
November	0.03	−0.22	−0.06	−0.82
December	0.00	−0.44	−0.06	−0.63
January	−0.07	−0.41	−0.04	0.48
February	−0.12	0.03	−0.07	−1.25
March	−0.09	−0.25	−0.05	−2.38
April	−0.53	−0.16	−0.33	−0.45
May	−0.24	−0.27	0.13	−0.75
June	−0.30	0.14	−0.22	−0.19
July	−0.51	−0.16	−0.20	−0.91
August	−0.12	0.05	−0.27	−0.53
September	−0.10	0.18	−0.01	0.35
October	0.04	−0.20	0.03	−2.30
1-day minimum	−0.02	0.01	0.04	−0.01
3-day minimum	−0.01	−0.02	0.03	−0.08
7-day minimum	−0.03	−0.02	0.04	−0.03
30-day minimum	−0.05	0.00	−0.05	0.12
90-day minimum	−0.06	−0.21	−0.08	0.27
1-day maximum	−3.96	−0.02	−1.43	−10.74
3-day maximum	−3.20	0.05	−1.36	−5.91
7-day maximum	−2.60	−0.04	−1.01	−1.99
30-day maximum	−1.27	−0.02	−0.17	−0.09
90-day maximum	−0.46	0.04	−0.22	−0.09
Base flow index	0.03	0.10	0.00	0.06

Notes: decrease (–) / unchanged / increase (+); input data of discharges ($m^3 s^{-1}$) dark grey – increase, light grey – decrease. Data source: SHMI, B. Bystrica

4.3 Analysis of climatological and hydrological extremes based on daily time series data

Based on precipitation data and the number of days without precipitation, or with just a small amount of precipitation (Table 3), dry episodes in the upper Hron River basin were determined in 1961–2010. The longest drought lasted from February to April of 1974 (67 days, Table 5) with 8.5 mm of daily precipitation and a mean daily discharge of 1.25 $m^3 s^{-1}$ (Figure 12 B). This year was rich in extremes as a flood occurred in October. On the graph it can be seen that at the start of the year precipitation was below-average and air temperature was above-average. Snow accumulation from November and December of 1973 melted rapidly due to higher January air temperatures, which then negatively affected the situation in the following months. More intensive precipitation began in May and continued until the end of October, when air temperatures remained below-average. These factors were behind the creation of a flood wave with a peak discharge of Q_5 (26.5 $m^3 s^{-1}$). In total, 1974 was an excessively humid year according to the de Martonne index (HOA 2016). Another excessively humid year was 1962 (Figure 12 A). In this year, the situation was reversed, with flooding in spring and drought in autumn. Significant snow accumulations in February and March and below-average air temperatures contributed significantly to spring flooding in April 1962 (peak discharge 11.8 $m^3 s^{-1}$). Groundwater supplies and more regular precipitation contributed to runoff values in summer being higher than in 1974. In mid-August, however, precipitation receded and during 41 days (from 19 September to 29 October) only 1.6 mm of precipitation fell at Telgárt. October discharges fell below the values of Q_{330} to Q_{364} (0.4 to 0.26 $m^3 s^{-1}$).

The years 2010 and 2003 saw the most extreme flooding and drought. In the studied 1961–2010 period, 2010 was the wettest and 2003 the driest. The hydrographs in Figures 12 C and D clearly demonstrate this fact. Throughout all of 2010, in May and June in particular, intensive precipitation (150% of the long-term mean) caused multiple floods. The largest peak came in early June with a discharge of 15.4 $m^3 s^{-1}$. Thus, in hydrological year 2010, daily discharge on 55 days was below 1 $m^3 s^{-1}$; in 2003 it was 244 days. It is also interesting to note that 2003 was preceded by a very wet period lasting from the late 1990s until 2002. The longest dry episode in 2003 occurred in winter and early spring (6 February to 2 April) and lasted 56 days. In this period, 6.4 mm of precipitation fell at Telgárt. Snow accumulation mainly in February only very slightly increased spring discharge values and overall snow cover depth was only 1/3 of the maximum depth of 1963. The largest decreases in discharge occurred in July, August, and September, when air temperatures were above-average and precipitation occurred only sporadically.

The findings that Q_{Max} have primarily impact on the decrease in runoff confirms when assessing the daily

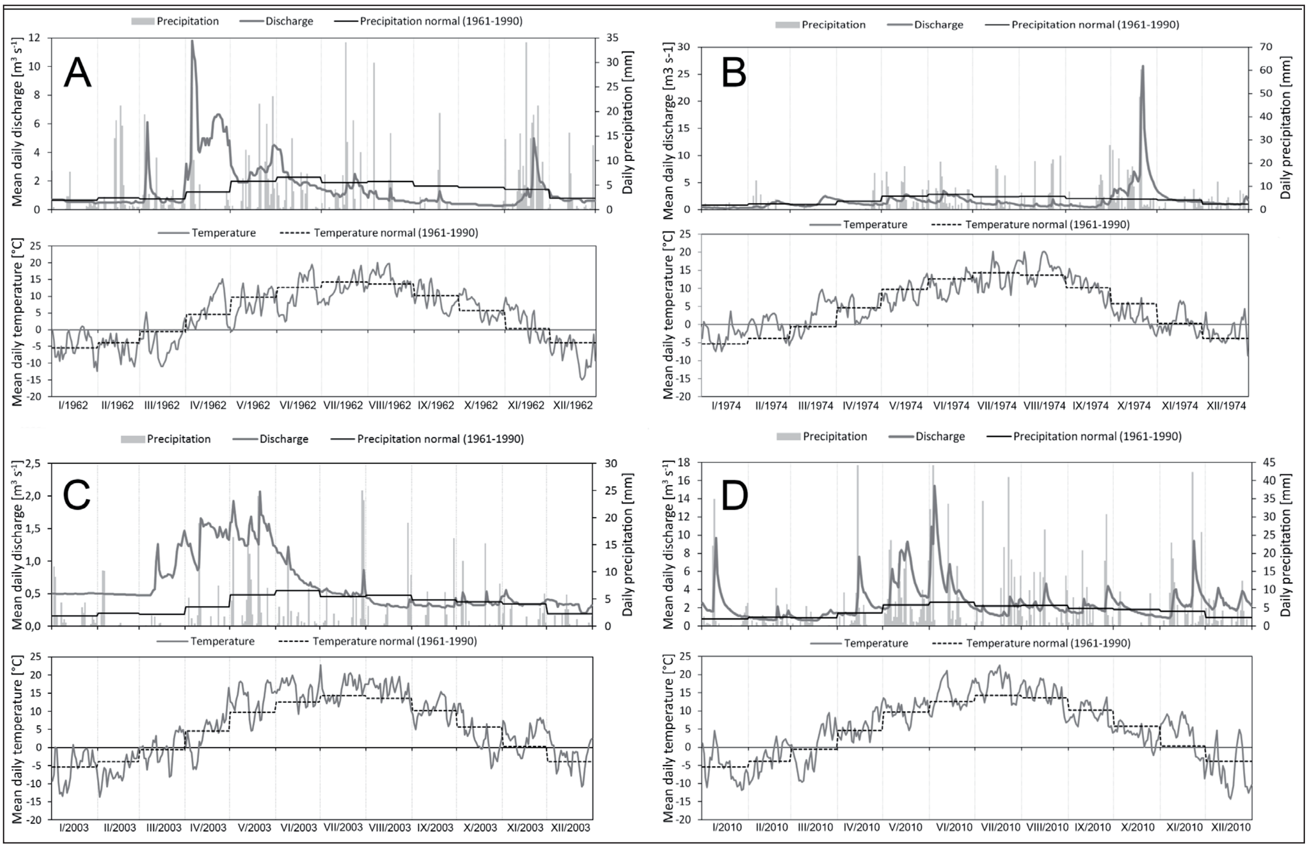

Fig. 12 Development of mean daily air temperature, daily precipitation amounts and mean daily discharge in Zlatno and Telgárt stations in 1962 (A), 1974 (B), 2003 (C) and 2010 (D). Data source: SHMI, B. Bystrica

hydrological data. The largest decrease occurred in value of 1-day maximum, but also in values of 3-day and 7-day maximum (Table 6). A slight increase occurred in 1-day, 3-day and 7-day minimum. From the values of 7-day minimum flow and mean annual flow was calculated base flow index. In medians, COD and maximum values there was only a slight increase in this index.

4.4 Statistical evaluation of extremes using Mann-Kendall test

The results of Mann-Kendall test (Table 7) revealed significant changes in the value of Q_m, Q_r, Q_{Max}, $Q_{Min\ and}$ daily discharges Q_{330}, Q_{355} and Q_{364} in Zlatno station in the period 1961–2010. Prolonged period in the past, significant changes occur.

Assessing the entire year, we can state that the greatest decreases occur in Q_r and daily discharge Q_{330}. There were slightly weaker decreases in Q_{Max} and Q_{Min} and daily discharges Q_{355} and Q_{364}.

Examining monthly time series, decreases dominated in the cold half year, in the period from November to February. We recorded the largest decrease in Q_m, and slightly weaker decreases in Q_{Max} and Q_{Min}. The decrease in Q_m is most evident in December, followed by November, February, and January. The most significant decrease in Q_{Min} occurs in December and January. In contrast a significant decrease in Q_{Max} occurs mainly in November and then in February. No significant changes occurred in the summer. Thus, long-term changes in Q_{Max} and Q_{Min} in the cold half year have an influence on the decrease in Q_r.

5. Discussion

This paper evaluates hydroclimatic extremes (droughts and floods) in the upper Hron River basin, which is classified as a basin with a decreasing long-term discharge trend (Poórová et al. 2013a). The European areas are susceptible to drought from the early 1980s to early 2010s, confirms the results Spinoni et al. (2015). On the growth of dry episodes since 1881 in the Czech Republic inform Brázdil et al. (2009). As the main cause include growth air temperature and decrease of precipitation. Conversely, a study by Hisdal et al. (2001) argues that it is not possible to conclude that drought conditions in general have become more severe or frequent. But they found distinct regional differences, for example with decreasing drought deficit volumes in large parts of Central Europe. Trends in drought deficit volumes or durations are explained through changes in precipitation or artificial influences in the catchment. Analyses from Zlatno station confirmed finding by Poórová et al. (2013a), Spinoni et al. (2015) and Brázdil et al. (2009). Overall, the second half of the studied period, that is, 1981–2010, was less wet.

Tab. 7 Results of Mann-Kendall test (*MK-S* values) for mean monthly and annual discharge, maximum and minimum in the month/year, daily discharges Q_{330}, Q_{355}, Q_{364} in Zlatno in two periods (1931–2010 and 1961–2010).

Discharge	Period	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	Year
Mean	1931–2010	−2.67	−2.70	−2.57	−2.64	−1.82	−0.47	−0.42	−1.74	−0.91	−0.60	−1.64	−1.36	−2.65
	1961–2010	−0.69	0.09	0.57	0.13	−0.37	−0.96	−0.79	−1.87	−1.22	0.09	0.23	0.77	−1.28
Maximum	1931–2010	−2.46	−2.27	−1.82	−2.44	−1.50	−0.75	−0.39	−1.31	−1.19	−1.32	−1.67	−1.28	−1.86
	1961–2010	−1.16	0.30	0.52	−0.26	−0.69	−0.91	−0.76	−1.56	−0.90	−0.09	−0.56	0.20	−0.75
Minimum	1931–2010	−2.09	−2.47	−2.28	−2.01	−1.80	0.97	−0.29	−0.52	−0.87	−0.13	−1.75	−1.63	−2.34
	1961–2010	0.66	0.14	0.36	1.17	0.73	−0.28	−0.19	−1.29	−1.13	0.67	0.64	0.72	1.16
Q_{330}	1931–2010													−3.02
	1961–2010													0.65
Q_{355}	1931–2010													−2.44
	1961–2010													1.05
Q_{364}	1931–2010													−2.08
	1961–2010													1.62

Notes: significant values are highlighted in colour, a significant decreasing trend (dark grey), a slight decreasing trend (light grey).
Data source: SHMI, B. Bystrica

A longer-lasting less wet period from 1986 to 1993, the period 2002 to 2004 with the exceptionally dry 2003, and 1982 and 1983 contributed to decreased wetness. Despite this, one of the wettest years (2010) occurred at the end of the entire study period (Šipikalová et al. 2011). We may conclude that the de Martonne and the relative precipitation index, chosen for this analysis, have brought comparable results.

Statistically decrease in wetness in the upper Hron River basin confirmed Mann-Kendall test. The most significant is the decrease in values of Q_r and daily discharge Q_{330}. There were slightly weaker decreases in Q_{Max} and Q_{Min} and daily discharges Q_{355} and Q_{364}. A clear decrease in runoff occurs at Zlatno station in the cold half year (mainly from November to February), which corresponds with the findings of Majerčáková et al. (2004) and Demeterová and Škoda (2009). According to Mann-Kendall test results, the largest decrease in Q_m was in December, which corresponds with a shift in minimum values from late November to mid-December and a significant decrease in Q_{Min} values (Blahušiaková and Matoušková 2015).

Poórová et al. (2013b) found that the most favorable conditions for the development of Q_{Min} are in the upper catchments of the Slovak rivers. But in the upper Hron tributaries (from Low Tatras and Slovak Ore Mountains) there is a decreasing trend of Q_{Min}, which changed the character development Q_{Min} on the lower flow of the river. Results using IHA demonstrate a decrease in Q_{Min} of 0.1 $m^3\ s^{-1}$ at Zlatno station between 1951–1980 and 1981–2010, in both the cold (a decrease of about 24%) and warm half years (a decrease of about 19%). Interesting would be found out what numerical impact has this decrease on the lower flow of the Hron River.

One of the greatest frequencies of winter long-term dry periods (more than three times in ten years) in Slovakia was observed in the upper Hron River basin by Demeterová and Škoda (2009). Based on our results, the dry episodes were more frequent on the upper Hron in the cold half year. The driest episodes occurred in January; the longest however occurred from February to April of 1974 and 2003. It is given to the fact that in our analyses were included autumn and spring months to the cold half year, which affected the development of drought in the winter. Great influence on the development of drought on the upper Hron has snow cover. An example were years 1974 and 2003. A decrease of snow in the cold season affects the value of runoff in the warm season (Staudinger et al. 2014). A reduction in SWE resulted in earlier low-flow occurrence (Jeníček et al. 2016). In the warm half year the dry episodes were more frequent mainly in the 1960s. But, the longest dry episodes occurred from October to November of 1978 and from September to October of 1985.

Based on the Mann-Kendall test there is a statistically significant decreasing trend in annual peak discharge in the basins of east and central Slovakia (Jeneiová et al. 2014). The same results were obtained in our analysis. Different results are in south-west region of Slovakia, where a slight increasing trend was observed (Blaškovičová et al. 2014). In a more detailed analysis, we find that the largest decrease occurred in value of 1-day maximum, but was also significant in values of 3-day and 7-day maximum. Decrease wetness was confirmed also by an analysis of the frequency of occurrences of events where discharge is $\geq Q_1$. Eighteen such events were determined in 1951–1980, compared to seven such events in 1981–2010. Moreover, the Q_1 threshold was exceeded on seven days in 1958. Events where discharge was $\geq Q_5$ occurred only in 1951–1980 (in 1954 and 1974). We observed this decrease not only at Zlatno station, but in the entire upper Hron River basin (Blahušiaková and Matoušková 2015). The results by Yiou et al. (2006) also point that occurrence and intensity of floods in Bohemia have generally decreased over the 20th century.

Seasonality of annual maximum flood peaks in Central Europe (Germany, Switzerland, Czech Republic and Slovakia) was examined by Villarini et al. (2011). The results showed that in the southern portion of this region there is a large fraction of annual maximum flood peaks occurring during the summer. For the upper Hron River basin is typical occurrence of floods at the end of winter and during spring. From our results it is significant that changes in maximum peak values have a significant impact on the decrease in runoff in the cold half year. Between the periods 1951–1980 and 1981–2010, Q_{Max} decreased in the cold half year on average by 0.8 $m^3\ s^{-1}$ (a decrease of about 25%) and in the warm half year by 0.7 $m^3\ s^{-1}$ (a decrease of about 18%). Significant decreases occur in November and February. There was a significant decrease in events where discharge is $\geq Q_1$ in April. Q_{Max} values and events where discharge is $\geq Q_1$ decrease mainly in October, May, and July. In contrast, they increase in January and September.

Studying the occurrence of past extremes can help interpret their occurrence in the present. They indicate that in the past it was not unusual for both a long-lasting drought and devastating flood to occur in the same year. A good example is 1974 when drought occurred from February to April and a flood in October. Another example is 1962 with a flood in April and drought lasting from September to October. Equally interesting is the last decade of the studied period, when two of the most extreme years occurred: the exceptionally dry 2003 and the exceptionally wet 2010.

6. Conclusion

The main conclusions of this study are:

(1) In the upper Hron basin there is a decreasing trend in runoff, which was significant in 1931–2010. The largest decrease can be observed in Q_r, Q_{75pct} and daily discharge Q_{330}. Decrease is particularly significant in the cold half year (from November to February).

(2) Q_{Min} values in both the cold and the warm half years decreased on average by 24% and 19%. The longest dry episodes lasted from February to April (in 1974 and 2003). A shift in minimum values from November to mid-December was observed. The values of base flow index do not show changes.

(3) Q_{Max} values decreased, in the cold half year on average by 25%, and in the warm half year by 18%. The largest decrease occurred in values of 1-day maximum, 3-day and 7-day maximum. In March and October was recorded the largest decrease. A decrease in events where discharge was $\geq Q_1$ was recorded from approximately the mid-1980s. There was a significant decrease mainly in April. At the same time a decrease in the extremity of flood events was observed.

(4) The de Martonne, the relative precipitation index and the low flow index show similar results in determining the character of the each year in studied periods. The longest above-average period of annual values reached from 2007 to 2010 and the longest below-average period from 1990 to 1993. In 1961–2010 exceptionally dry years were 1973, 1993, and 2003. In contrast, 1965, 1975, and 2010 were exceptionally wet years.

(5) Decreases in the occurrence of Q_{Max}, Q_{75pct}, and events where discharge is $\geq Q_1$ as well as more frequent occurrence of Q_{Min} in the cold half year contribute greatly to the decrease in runoff on the upper Hron.

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RESUMÉ

Hodnocení výskytu hydroklimatických extrémů v povodí horního Hronu, Slovensko

Článek se zabývá výskytem hydroklimatických extrémů v povodí horního Hronu na Slovensku v období 1951/61–2010. Sledované jsou trendy vývoje vybraných hydroklimatických parametrů v období 1931/61–2010. Důraz je kladen na výskyt, frekvenci a sezonalitu suchých epizod a povodňových událostí. V analýzách je použitý de Martonneho index, index relativního množství srážek, index základního odtoku, index nízkého průtoku, lineární regrese, Mann-Kendallův test a IHA software.

Mann-Kendallův test poukázal na významné změny v odtoku v povodí horního Hronu, hlavně na pokles ročního odtoku. Na tento pokles mají zásadní vliv změny v minimálních a maximálních průtocích, a to především v chladné polovině roku. K největším změnám došlo v hodnotách Q_1, Q_{Max}, Q_{75pct} a v hodnotách 1-denních, 3-denních a 7-denních maxim. Hodnoty základního odtoku nevykazují žádné změny.

Přibližně od 80. let 20. století došlo k poklesu událostí s průtokem rovnajícím se nebo větším než je jednoletý průtok Q_1. Události s průtokem $=>Q_5$ se objevily jenom v období 1951–1980 (v roce 1954 a 1974). De Martonneho index, index relativního množství srážek a index nízkého průtoku ukazují podobné výsledky při určování charakteru jednotlivých období. Mezi výrazně suchá období patřila perioda 1990–1993, naopak nadprůměrně vodným obdobím byla perioda 2007–2010. Mezi mimořádně suché roky ve sledovaném období patřily: 1973, 1993 a 2003; mezi mimořádně vodné roky: 1965, 1975 a 2010.

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