

Rainfall and runoff regime trends in mountain catchments (Case study area: the upper Hron River basin, Slovakia)

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Abstract: This paper presents an analysis of trends and causes of changes of selected hydroclimatic variables influencing the runoff regime in the upper Hron River basin (Slovakia). Different methods for identifying trends in data series are evaluated and include: simple mass curve analysis, linear regression, frequency analysis of flood events, use of the Indicators of Hydrological Alteration software, and the Mann-Kendall test. Analyses are performed for data from two periods (1931–2010 and 1961–2010). The changes in runoff are significant, especially in terms of lower Q_{Max} and 75 percentile values. This fact is also confirmed by the lower frequency and extremity of flood events. The 1980s are considered a turning point in the development of all hydroclimatic variables. The Mann-Kendall test shows a significant decrease in runoff in the winter period. The main causes of runoff decline are: the considerable increase in air temperature, the decrease in snow cover depth and changes in seasonal distribution of precipitation amounts.

Keywords: Trend analysis; Rainfall-runoff regime; Mann-Kendall test; IHA software; Hron River basin.

INTRODUCTION

Assessment of climate change impacts on the hydrological regimes of water courses is of great significance. As a rule, analyses of the consequences of climatic change for the hydrological regimes of water courses are conducted 1) by modelling expected changes in the hydrological regime based on knowledge of the relationships between the characteristics of the climate and the hydrological regime, including the preparation of climate change scenarios; 2) by analyzing the hydrological regime using data from the instrumental period and proxy data, and determining indicators of changes in runoff formation. The goal is to identify possible changes in the statistical characteristics of these variables which could be used as a model of how hydrological regimes behave in an environment affected by climate change. Both approaches require consideration of the relationships between climate variables on the one hand and the hydrological regime on the other hand.

There are numerous studies analyzing the potential impact of climate change on water resources in Slovakia. The first group of research includes climate projections for Slovakia, which typically indicate an increase of air temperature of 2°C to 4°C by 2075 (Lapin et al., 2012) and depending on climate model and emission scenario a change in precipitation typically ranging from –15% to 10% (Szolgay et al., 2008). The modelling of impacts of such projections then translates into a general tendency of decreasing future annual runoff and a change of runoff regime, particularly in the mountains. However, the uncertainty of these model scenarios is rather large. Models of long-term mean annual runoff in Slovakia predict an increase in runoff throughout the winter and its decrease in the summer until 2075 (Hlavčová et al., 1999, 2000, 2008; Szolgay et al., 1997).

The second group of studies includes the assessment of changes and trend detection based on the observed data. Often, these variables are studied separately and the study of mutual relationships between individual hydroclimatic variables is missing. The assessment of long-term trends and cyclicity in Slovakia has been analyzed in Pekárová (2000). The results indicate a clear decrease in the precipitation time series in period 1900–1990 and an increase in period 1990–2000.

We can observe a decreasing trend in mean annual runoff using a linear trend analysis of the measured data. Mindáš et al. (2011) report that the smallest decrease in period 1961–2009 has occurred in northern Slovakia (13%); in the basins of central and southern Slovakia the decrease is more noticeable (between 16% and 24%, in period 1931–2009). The decrease of the mean annual runoff was also reported by Šipikalová et al. (2006). With the exception of the northern areas of Slovakia, mean annual runoff values in 1961–2000 are lower than in 1931–1980. This decrease is attributed mainly to lower annual precipitation.

The effect of changing climate on hydrological characteristics in the upper Hron River basin has been explored in several studies. Runoff change scenarios on the upper Hron have been modelled by Daníhlík et al. (2004), Daníhlík and Trizna (2005), Pekárová and Szolgay (2005), and Szolgay et al. (2008). The runoff change scenarios were developed for time horizons 2010, 2030, and 2075 by using data from the reference period 1951–1980. The results show the decrease in the long-term mean annual runoff and changes in the seasonal runoff distribution. The southern part of the basin and lowland areas should be more sensitive to the decrease in runoff.

The changes in the seasonal runoff distribution are shown also by Hlavčová et al. (2008). A conceptual hydrological balance model calibrated with data from the period 1971–2000 was used for modelling changes in runoff for the time horizons 2025, 2050 and 2100. The results show the Hron River basin could become vulnerable to drought in the summer and early autumn and during the winter and early spring periods, an increase in runoff could be assumed. Štefunková et al. (2014) suggest an increase in runoff in the autumn and winter and a decrease in the spring and summer for the period 2011–2100 by using data from reference period 1961–1990.

Based on analyses of recorded values, the Hron River basin is categorized as a basin with a decreasing to significantly decreasing long-term discharge trend (Poárová et al., 2013a). It is also categorized as a very vulnerable from the perspective of the mean long-term discharge. In 1961–2012 there were no significant changes in minimum monthly and annual discharge trends in the upper Hron River basin (Poárová et al., 2013b). Mann-Kendall test results demonstrate that some stations on the upper

Hron indicate a significant decreasing trend in maximum annual discharge. A slightly decreasing trend in mean monthly discharge in 1931–2008 was detected in Banská Bystrica and linear trends for each month were determined by Tegelhoffová (2010).

The changes in snow cover, characterized by simulated snow water equivalent (*SWE*) in the upper Hron River basin were examined by Juričeková et al. (2013). The results indicate a decrease in simulated *SWE* in the period of 1961–2000. A significant decrease of snow cover is mainly due to rising air temperature. Estimation of climate change impacts on the snow cover in the Hron River basin was carried out also by Holko et al. (2005). Possible snowmelt-runoff scenarios for the upper Hron were constructed by Hrušková (2006). It was found that both initial *SWE* and precipitation have dominant influence on flood peak and volume. Air temperature has impact on timing of snowmelt. The effect of air temperature on the development of runoff is observed in our study.

Rainfall trend analyses conducted in mountainous areas of Slovakia, including the upper Hron, indicate no significant trends (Faško and Štastný, 2001). Bičárová and Holko (2013) reported a significant increase of the number of days with daily precipitation 40–60 mm in the area of the High Tatra Mountains (the highest part of the Carpathians) in 1961–2010. The seasonality, frequency and extremity of floods in the upper Hron River basin were assessed by Blahušiaková and Matoušková (2012). Summer flooding dominated, caused by either local, short storms with intense precipitation amount or longer-lasting regional rainfall. Winter floods resulting from melting snow in the basin and ice phenomena are also important.

The main objective of this paper is to complement existing studies by detection and analysis of key factors controlling changes in runoff regime in the upper Hron River basin. The main contribution is to study the mutual relationships between individual water balance components and link and compare existing results of climate scenarios with trend detection and attribution studies.

METHODS

The general guidance to the methodology of trend detection in time series of hydrological data is offered by Kundzewicz and Robson (2004) or Pilon and Yue (2002). The examination of the different statistical tests and their power was conducted by Helsel and Hirsch (1992), Hirsch et al. (1992), Önöz and Bayazit (2003), and Yue and Pilon (2004). A review of methods for understanding flood regime changes and preparation of scenarios for predicting future changes in floods is described in Hall et al. (2014). The examination of temporal nonstationarities in the flood peak records by using several tests was made by Villarini et al. (2011).

Several methods were applied in this study. Simple mass curves of annual precipitation amounts and discharges were used as first step to identify changes in the rainfall-runoff regime. Trends of mean annual discharges (Q_a), annual air temperatures (T_a), annual precipitation amounts (P_a) and mean annual snow cover conditions were assessed using linear regression. Furthermore, the evaluation of a trend in annual and monthly time data series of all studied hydroclimatic factors has been done using a seasonal non-parametric Mann-Kendall test (Bawden et al., 2014; Helsel and Frans, 2006; Kendall, 1975; Kliment and Matoušková, 2009; Libiseller, 2004; Mann, 1945; Murphy et al., 2013; Peters et al., 2013; Yue et al., 2002, 2012). The test 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 $MK-S$), which represents the direction and volume of the trend. The trend significance level of 0.05 has been set for all statistical analysis.

The Indicators of Hydrological Alteration (IHA) software (Richter et al., 1998) and IHA 7.1 statistics software (TNC, 2009) were used to identify changes in hydrological time series of mean daily discharges (Q_d). We compared two selected data periods 1951–1980 and 1981–2010. The IHA software calculates 67 statistical parameters, e.g. coefficient of dispersion (COD) $\rightarrow (75-25)/50pct$ ($pct \rightarrow$ percentile), extreme water conditions: the 3-, 7-, 30-, and 90-day minimums and maximums (Q_{Min} and Q_{Max}), base flow index, frequency, timing and duration of high and low pulses.

Attention was paid also to the frequency, extremity and seasonality of floods. N -year flood events (Table S1 in Supplementary material) were used as the basin selection criterion, while a flood was defined as a hydrological situation where the mean daily discharge achieved or exceeded the value Q_I (one-year flood). Evaluated flood events $\geq Q_{50}$, Q_{20} , Q_{50} , Q_{100} were included in the assessment. In order to analyze the frequency and seasonality of floods, peak discharge values were used as source data. Seasonality was assessed using data on mean Q_d that exceeded the value of Q_I . Three days preceding the day with Q_I 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.

STUDY AREA CHARACTERISTICS

The Hron River (basin area of 5.465 km²) is the second longest river in Slovakia. It 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 upper Hron River basin up to Banská Bystrica has an area of 1.766 km² and was selected as the study basin (Figure 1). The Ďumbier Mountain (2043 m a.s.l.) is the highest point of the basin, and the gauging station in Banská Bystrica (334 m a.s.l.) is its outlet.

Runoff regime of the upper Hron River is nivo-pluvial. Maximum mean monthly discharges (Q_m) occur in April, minimum ones in January, February and September. The long-term (1931–2010) mean annual discharge (Q_a) of the Hron River in Zlatno is 1.4 m³·s⁻¹, in Brezno 7.6 m³·s⁻¹, and in Banská Bystrica 26.1 m³·s⁻¹.

The upper Hron River basin is located in a cool and humid to very humid climatic region; the mean annual air temperature (T_a) ranges between 4°C and 5°C. July is the warmest month, in which the mean monthly air temperature (T_m) ranges from 14°C to 16°C. January is the coldest month, when the T_m ranges from -4°C to -6°C (Pekárová and Szolgay, 2005). The area shows a relatively well-preserved natural runoff regime. Forest covers 66% of basin area (Holko and Kostka, 2008). It exceeds the mean value of forestation for Slovakia, which is 41% (NFC, 2011).

Runoff is also influenced by flood protection measures, especially those implemented since the second half of the 20th century. The modification of the Hron River bed and an increase in its capacity in several towns (Banská Bystrica, Brezno – capacity approx. Q_{50}) were of particular importance, as they made it possible to reduce peak discharge to a high extent. Currently, the construction of dry or half-dry polders, e.g. on tributaries of Kabátovský Brook – Drábsko, Lúčky is considered an effective means of increasing retention capacity. There is no large water reservoir in the upper Hron River basin.

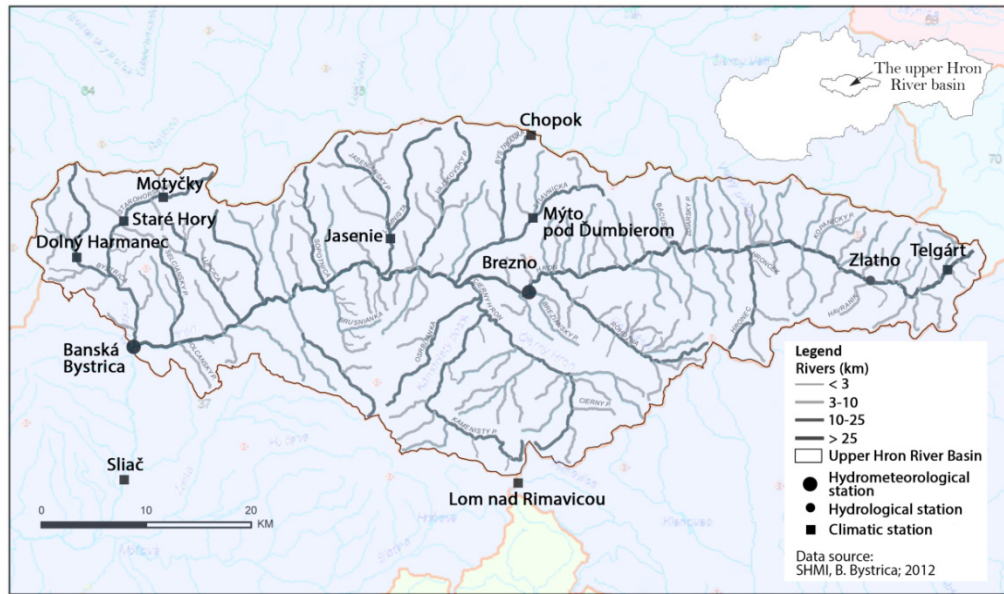


Fig. 1. Study area – the upper Hron River basin, Slovakia.

Table 1. Gauging stations in the study basin.

DB	Gauging site	Area [km ²]	Altitude [m a.s.l.]	Q_a [m ³ .s ⁻¹]	q [l.s ⁻¹ .km ⁻²]	φ [%]	Q_{rMax} [m ³ .s ⁻¹]	Q_{rMin} [m ³ .s ⁻¹]
6950	Zlatno	83.7	733	1.4	16.4	0.55	3.27 (1945)	0.72 (1947)
7015	Brezno	582.1	491	7.6	14.0	0.43	15.47 (1945)	3.48 (1943)
7160	Banská Bystrica	1766.5	334	26.2	15.9	0.47	46.14 (1965)	12.93 (1943)

DB – database number; Q_a – long-term mean annual discharge (1931–2010); q – specific runoff for the period 1961–2000 (Zlatno) and 1931–1980 (Brezno, Banská Bystrica); φ – annual runoff coefficient for the period 1961–2000 (Zlatno) and 1961–1980 (Brezno, Banská Bystrica); Q_{rMax} – maximum of mean annual discharge and Q_{rMin} – minimum of mean annual discharge (1931–2010)

Table 2. Climatic stations in the study basin.

Station	Altitude	Data from			Mean			Median			Maximum			Minimum		
	[m a.s.l.]	T	P	SC	T [°C]	P [mm]	SCD [cm]	T [°C]	P [mm]	SCD [cm]	T [°C]	P [mm]	SCD [cm]	T [°C]	P [mm]	SCD [cm]
Sliač	313	1961	1961	1961	8.2	705	12	8.2	705	11	9.7	1076	24	5.4	496	3
Banská Bystrica	343, 427*	1931	1931	1961	8.2	828	16	8.3	827	14	9.7	1388	39	5.7	541	5
Staré Hory	475		1961	1961		1024	28		1030	27		1482	82		674	5
Dolný Harmanec	481		1961	1961		1066	27		1056	24		1585	78		727	6
Brezno	487	1931	1931	1961	6.9	751	15	6.8	747	12	8.6	1236	37	4.4	482	4
Jasenie	540		1961	1961		848	19		830	16		1272	49		533	4
Králiky	627		1961	1981		1060	26		1036	23		1685	67		731	6
Mýto pod Ďumbierom	630		1961	1961		883	20		886	18		1235	50		554	3
Motyčky	688		1961	1961		1031	35		1052	36		1481	81		755	7
Telgárt	901	1931	1961	1961	5.0	853	24	5.0	853	20	6.4	1282	67	3.2	528	5
Lom nad Rimavicou	1018	1961	1961	1961	5.2	928	33	5.2	908	32	7.0	1793	98	2.9	607	6
Chopok	2005	1961	1961	1961	−0.9	1072	96	−0.9	1055	89	0.4	1421	187	−2.2	832	19

* Data from two stations in Banská Bystrica, T – air temperature, P – precipitation amount, SC – snow cover, SCD – snow cover depth

All data provided by the Slovak Hydrometeorological Institute (SHMI) in Banská Bystrica was homogenized. Values of Q_d (mean daily discharge), Q_m (mean monthly discharge) and Q_r (mean annual discharge) from three gauging stations: Zlatno (upper course), Brezno (middle course) and Banská Bystrica (lower course) in the period 1931–2010 (Table 1) were used. Mean monthly and annual climatic data from 12 climate stations and daily data from 1 climate station (Telgárt) available from the beginning of measurements: 1931 and 1961, respectively,

until 2010 (Table 2), were used as well. The analyzed dataset included mean monthly air temperature (T_m) from 6 stations and mean daily air temperature (T_d) from 1 station, monthly precipitation amounts (P_m) from 12 stations and monthly snow cover conditions from 12 stations. 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) for one sta-

tion, and mean monthly snow cover depth (SCD_m), and number of days with snow cover in the month (SCN_m) for each station. Mean snow cover depth SCD_m was calculated as a ratio of sum of snow depths and number of days with snow in particular month. For annual analyses, mean snow cover depth (SCD_r) values were used along with the number of days with snow cover (SCN_r). The SCD_r was calculated for a winter season (November–April) as the ratio of the sum of snow cover depth (SCS_r) and number of days with permanent snow cover (SCN_r).

RESULTS

Trend detection in the annual data series

Simple mass curves of the Q_r at the stations Zlatno, Brezno and Banská Bystrica in 1931–2010 were constructed. Annual precipitation data from station Brezno in the same period was also taken into account. From the perspective of mass curve analysis, changes in the Q_r are not particularly significant (Figure S1 in Supplementary material). The period of increased runoff occurred approximately from the second half of the 1960s until the beginning of the 1980s, when it began to gradually decrease with a more marked decrease after 1990. The 1980s can be considered a turning point in the development of hydroclimatic characteristics of the upper Hron. The Mann-Kendall test results (Table S2 in Supplementary material) also indicate an apparent declining trend of Q_r in 1931–2010, namely for the stations Zlatno, Brezno and Banská Bystrica. In the upper course (at Zlatno station), continuously increasing Q_r could be observed from the mid-1940s until the beginning of the 1980s. For the period 1961–2010, the statistically significant declining trend of Q_r is only at Banská Bystrica station.

A rising trend of T_r by 1.1°C (Lapin et al., 2012) was observed in Slovakia in the last 100 years. This trend could also be seen in the upper Hron River basin, as illustrated in Figure 2. This trend has been most pronounced at low and middle altitudes and south located stations. The highest increase was detected for stations Lom nad Rimavicou and Brezno. The T_r rose from 4.5°C to 5.7°C between 1961–1980 and 1981–2010 at the most southern station, Lom nad Rimavicou. The T_r at Brezno rose from 6.5°C to 7.3°C between 1931–1980 and

1981–2010. No evidence of statistically significant changes was found in the assessment of P_r . Significant increase of P_r was recorded only at one station, Králiky. A slight decrease in precipitation totals in the cold half of the year (September–February) could be observed at the Brezno and Banská Bystrica stations (Figure S2 in Supplementary material). The long-term annual precipitation amount (P_a) during the cold half of the year was 325 mm at Brezno station and 400 mm at Banská Bystrica station (1931–1980). In 1981–2010 they decreased by 21 and 8 mm, respectively.

In terms of SCD_r , its gradual decrease can be seen at most stations. This trend was recorded at lower and middle altitudes, being most pronounced at stations Dolný Harmanec (481 m a.s.l.), Motyčky (688 m a.s.l.), Staré Hory (475 m a.s.l.) and Telgárt (901 m a.s.l.). The trend could not be detected at the higher located stations Chopok (2005 m a.s.l.) and Lom nad Rimavicou (1018 m a.s.l.). It was indicated only by a lower SCN_r such as at the station Lom nad Rimavicou, which is due to the more southern location of this station. In the past 30 years, the most abundant mean SCD_r was observed in the winter season of 2004–2005 (44 cm) and 2005–2006 (64 cm). These winter periods (November–April) could be classified as above average. The average SCD_r value for the upper Hron River basin (1981–2010) is 27 cm. Winters of 1988–1989 and 1997–1998 were below average; SCD_r was only 13 and 12 cm (SHMI, BB). In Telgárt SCD_r value decreased by approximately 10 cm (when 1961–1980 and 1981–2010 are compared). The highest SCD_r values in the upper course of the Hron River (at Telgárt station) were recorded in 1963, 2006 and 1970 (Figure 3). The relatively high SCD_r value of 1963 corresponds with the below-average air temperatures and concurrent above-average precipitation amount between November and April. In 2006 slightly higher air temperatures were recorded, which were however still below the freezing point. Therefore, the reason for high SCD_r values were long-lasting, low-temperature periods, during which snow in upper courses accumulated. In 2007 higher air temperatures occurred but an average snow cover depth was recorded. It was caused by higher precipitation from the middle of January until the end of February, which resulted in higher accumulation of snow cover.

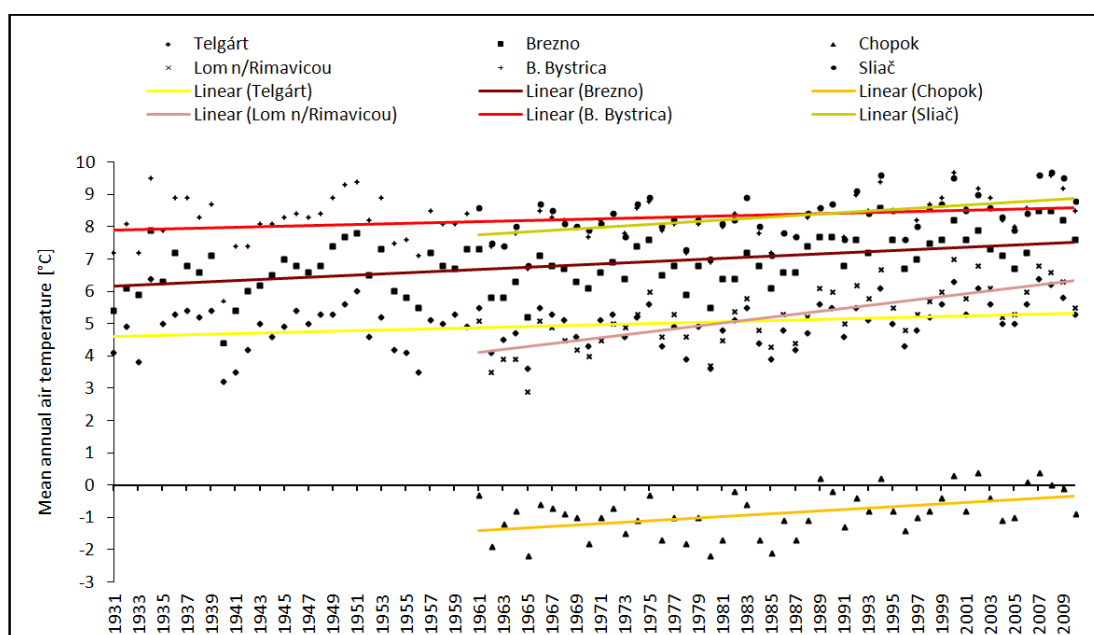


Fig. 2. Mean annual air temperature at selected climatic stations in period 1931/1961–2010.

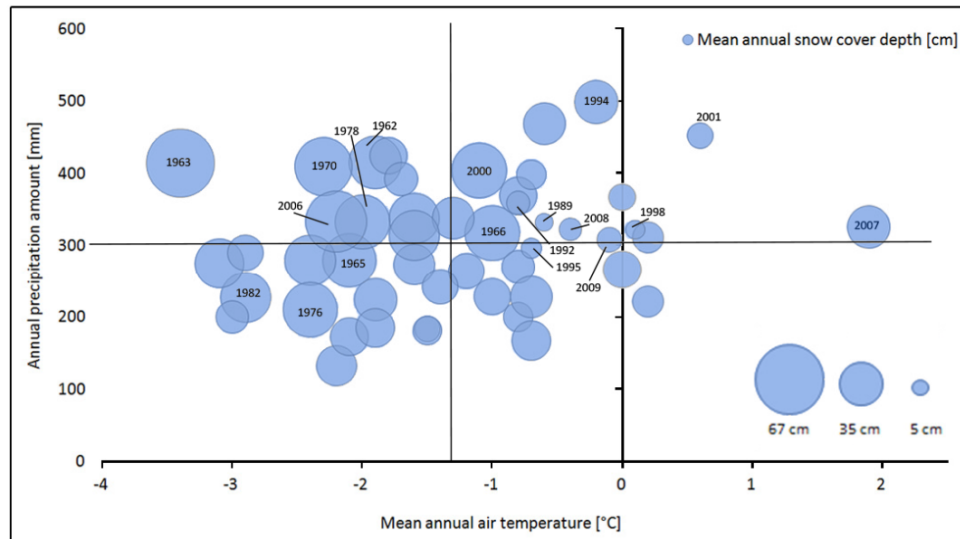


Fig. 3. The relationship between selected hydroclimatic variables at Telgárt station (1961–2010, November–April). Bubble diameter expresses snow cover depth, and the black lines represent mean annual air temperature or annual precipitation amount values in 1961–2010.

Trend detection in the monthly and seasonal data series

From the results of the Mann-Kendall test, the reduced runoff in winter months (November to February) is significant for the period 1931–2010, being most pronounced in the upper course (Zlatno), in November and February (Brezno) and in November and December (Banská Bystrica). The most significant decrease of Q_m was found in November at Banská Bystrica station (Figure S3 in Supplementary material). Almost no trend was registered for the summer months (only for Banská Bystrica – a decrease in June). The most significant trends were found in the series of T_m . In the cold half of the year, the highest increase in T_m was recorded in January. A significant increase in T_m in this month was recorded at all stations with the exception of the station at the highest elevation (Chopok), where no significant change in T_m in the winter months was recorded. The largest increase occurred at Lom nad Rimavicou, when T_m rose from -5.9°C to -3.9°C (between 1961–1980 and 1981–2010), and from -5.7°C to -4.0°C at Brezno (between 1931–1980 and 1981–2010) in this month. In other winter months, the increase in T_m is generally not significant except Lom nad Rimavicou in December and Brezno in February. In the warm half of the year, this trend was reconstructed from April to August with the highest increase in August; the greatest increases occurred at Lom nad Rimavicou and at Brezno. The T_m at Lom nad Rimavicou rose from 13.5°C to 15.3°C , and from 15.8°C to 17.0°C at Brezno in this month in the compared periods.

Seasonal fluctuations in P_m can be observed with a greater percentage of spring and summer precipitation amounts since 1990. Overall, P_m in observed climate stations indicates a slightly rising trend with the greatest share in growth occurring during the warmer half of the year, primarily in July, August, and May. In the cooler half of the year, P_m at the Brezno and Banská Bystrica stations has a slightly decreasing tendency. In the months of November and February, P_m decreases at most stations. Until now, the decreasing trend of precipitation amounts assumed for the some territories of Slovakia (Lapin et al., 2012) was discovered at the most southern station Lom nad Rimavicou. Statistically, using the Mann-Kendall test, no evidence of pronounced changes was found in P_m . Higher P_m values were recorded in January at Králiky and in June at Brezno station.

A more profound decrease in both SCD_m and SCN_m was confirmed by the Mann-Kendall test. A decrease in SCD_m is clear approximately from the 1980s (Figure S4 in Supplementary material). The most profound decrease of SCD_m was recorded in December at most stations and in February and April at others. At the Telgárt, Brezno and Banská Bystrica stations, this decrease is reflected in the SCD , although on SCN , this trend was not confirmed. The most significant decrease in both of these variables occurred at the Dolný Harmanec and Staré Hory stations. In 1989–2010 mainly the months of January through March contributed to snow totals in Telgárt, whereas in 1961–1980 snow totals in December were significant as well. The duration of snow cover has reduced gradually (snow disappears in April), and there has been a shift in the beginning of snow cover from December–February to January–March.

Trend detection in the extreme data series

Runoff in the upper Hron River basin is predominantly winter-spring runoff. Floods are the most common due to the high amount of precipitation or snowmelt in connection with the rain. The most events during which the N_I value was exceeded in the 1931–2010 period occurred in the month of April (35 events), followed by May (20 events). A reduction in the frequency of discharge $\geq Q_I$ can be observed, which is also documented by comparing the 1951–1980 and 1981–2010 periods (Figure 4). The frequency of the occurrence of Q_I events shifted from April to May to late summer.

A higher frequency of flood events was observed approximately until the beginning of the 1980s (Figure S5 in Supplementary material), associated with a period of increased runoff. A considerable decrease of flood events $\geq Q_I$ from October until April occurred in 1981–2010. Rising air temperatures have an effect on the decreasing number of winter-spring floods. Take, for example, the comparison of SCD_d in winter of 2000/2001 and in winter of 2005/2006 at Telgárt station (Figure S6 in Supplementary material). Already at the beginning of the winter of 2005/2006, air temperatures were below the freezing point, and thus, snow cover could begin accumulating earlier than in the winter of 2000/2001 (when snow began to accumulate in the second half of December). During the entire winter season of 2005/2006, air temperature contributed to the accumulation and duration of snow cover. Air temperatures were below the freezing

point for nearly the entire winter. Significant snow volume in the whole basin in March 2006, together with the increase of air temperatures in the third week of March, resulted in flooding. In the winter of 2000/2001, air temperatures fluctuated more greatly. As a result, snow cover depth was low to inconsistent and had no significant effect on spring runoff. Winters with very similar characteristics could also be observed in the following years.

Finally, modification of the channel (especially after the flood in 1974), its deepening and less ice-cover formation also contributed to the decrease of their incidence. These reasons could explain the reduced incidence of floods with a peak discharge above Q_1 , i.e. Q_5 , Q_{20} , Q_{50} , and Q_{100} . The most extreme flood event occurred in Banská Bystrica in October 1974. The maximum flow achieved during the flood was $560 \text{ m}^3 \cdot \text{s}^{-1}$ which is an equivalent to Q_{100} (SHMI, BB).

Trend detection in the daily data series using IHA

Changes in discharge series were confirmed using the IHA software. The entire 1951–2010 period was assessed and was divided into two equally 30-year-long time periods: 1951–1980 and 1981–2010 (Table S3 in Supplementary material). During the 1951–1980 period, runoff was overall higher; higher values were recorded for all hydrological indicators Q_{Min} , Q_{25pct} , Q_{Med} , Q_{75pct} and Q_{Max} in the months of December, February, March,

and June–August. The greatest difference in the COD was between the months of December and January. During the first period, the values for 1-, 3-, and 7-day peaks were significantly higher. A significant decrease in Q_{75pct} in the month of December is depicted in Figure 5. The decrease in minimum discharge values was practically unnoticeable. The primary causes of changes in runoff were the Q_{Max} and $75pct$ values.

DISCUSSION

From the results of our analyses and also other studies (Poárová et al., 2013a, 2013b; Tegelhoffová, 2010), it is clear that on the upper Hron there is a significant declining trend in discharges in cold half of the year during the period 1931–2010. Based on the findings of each hydroclimatic indicator, it seems as if the greatest change took place in the 1980s. Analyses and statistic tests have discovered a decrease in both Q_r and Q_m values in 1931–2010. At the Zlatno station, the decrease in Q_m was detected for the longest period, from November to February. It is the most significant decrease from all observed stations. Šipikalová et al. (2006) also demonstrate a decrease in discharge in Slovak rivers in the first half (November–April) of the hydrological year (November–October). The greatest decreases occur in November, which was confirmed in the upper Hron River basin. At the upper course (Zlatno station) the decrease was stronger in December. Comparing

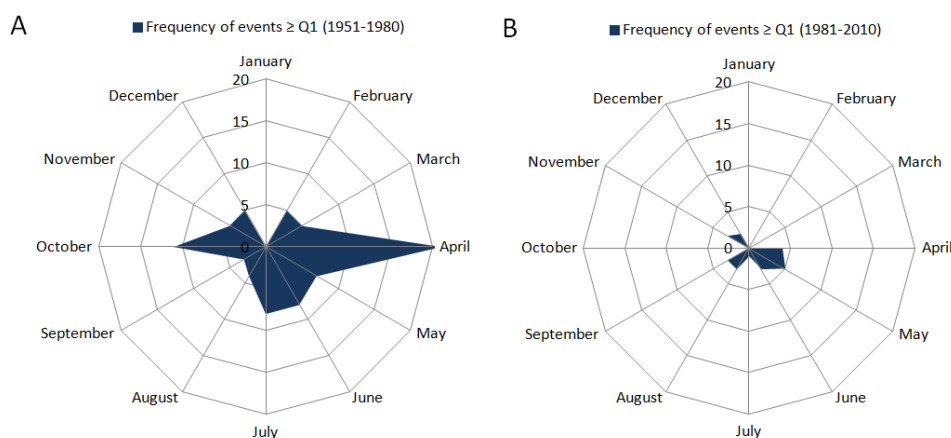


Fig. 4. Frequency of events $\geq Q_1$ in the study basin, a comparison of periods A) 1951–1980 and B) 1981–2010.

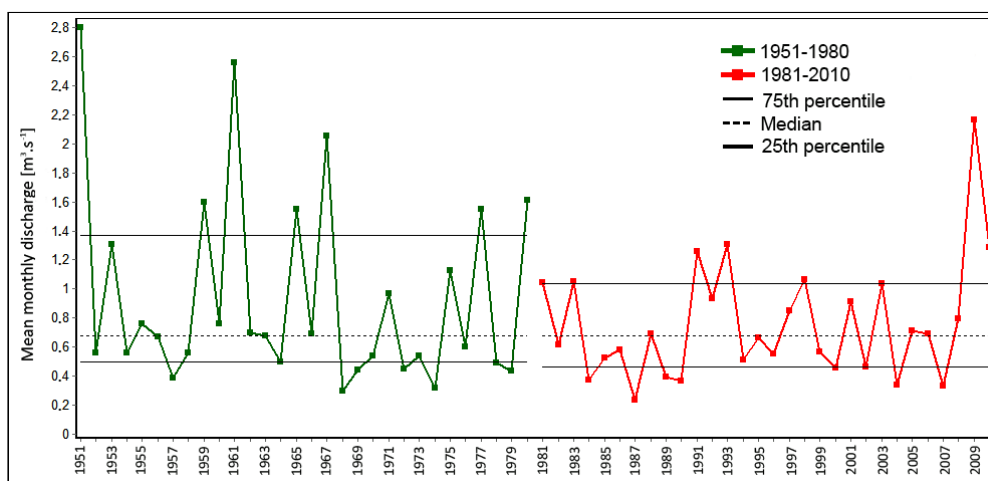


Fig. 5. The mean monthly discharge for December in Zlatno in periods 1951–1980 and 1981–2010.

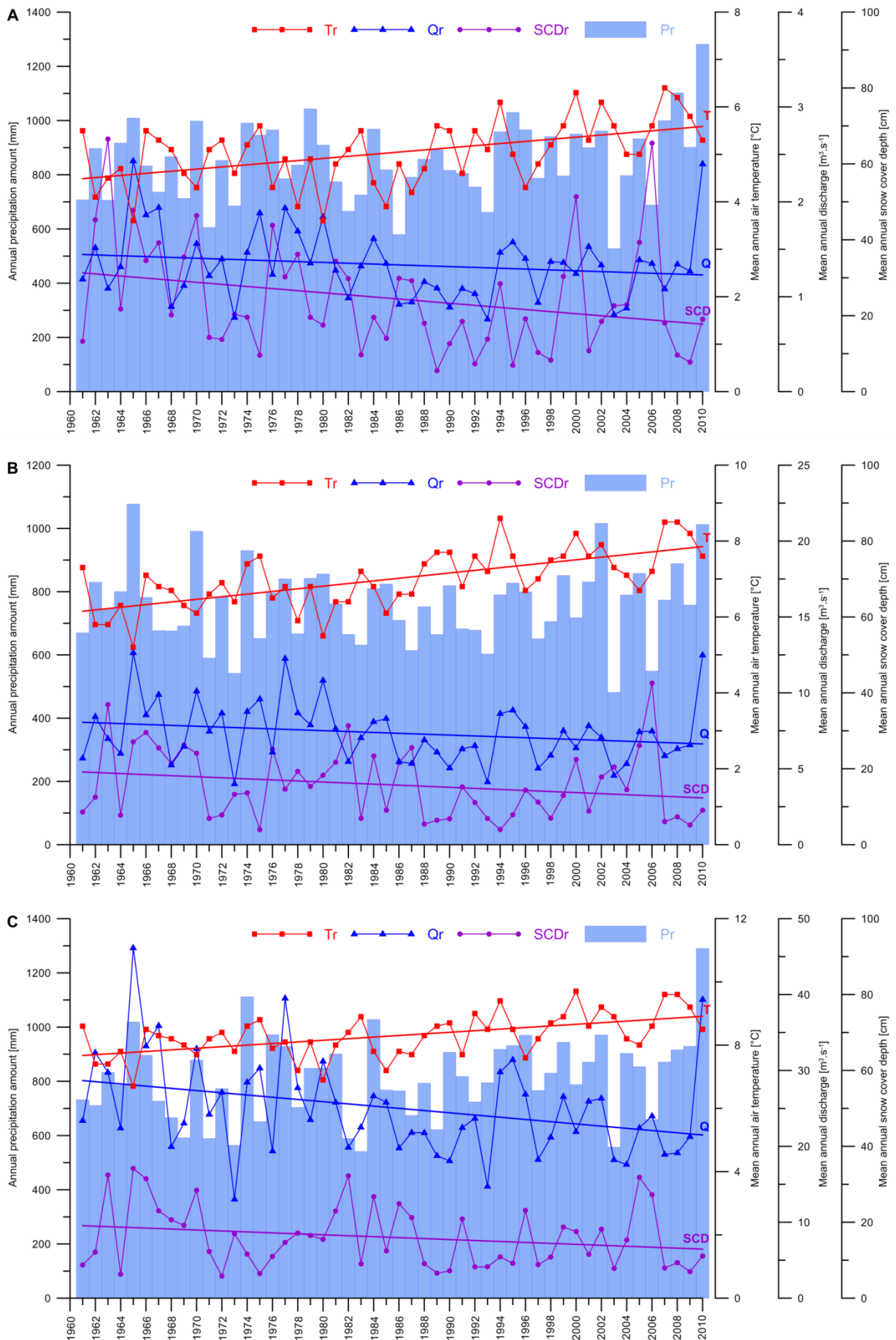


Fig. 6. Development of hydroclimatic parameters (mean annual discharge, mean annual air temperature, annual precipitation amount and mean annual snow cover depth) at Zlatno and Telgárt stations (A), Brezno (B), Banská Bystrica (C) in 1961–2010.

findings from all stations (Figure 6), we observed the greatest decrease in Q_r at the B. Bystrica station. This observation corresponds with the greater sensitivity of the southern part of the basin to runoff decreases (Daníhlík et al., 2004). This decrease is significant in the periods 1931–2010 and 1961–2010. Our findings do not completely correspond with the output of the models of Daníhlík and Trizna (2005), Hlavčová et al. (2008), Szolgay et al. (2008) or Štefunková et al. (2014), i.e., with the predicted increase of discharge during the cold half of the year and decrease in the warm half of the year, which was recorded but is significant only in Banská Bystrica (in June). The cause may be found in the differing length of input data series used to calibrate these models. These models did not use data from the past 20–30 years.

Results for the upper Hron River basin confirm the significant rising tendency of air temperature at all the stations observed, which is similar to results of Daníhlík et al. (2004), Lapin et al. (2012), Pekárová and Szolgay (2005), and Szolgay et al. (2008). This increase is most obvious from April to August and also in the winter period, particularly in December and January. The increase in observed T_r at the all stations ranges between 0.4°C and 1.2°C (comparing 1961–1980 and 1981–2010). A similar increase of air temperatures between 0.5°C and 1°C (reference dataset 1951–1980, up to 2010) was used in scenario by Daníhlík et al. (2004). The scenario assumed an increase in P_r by 0.1%. The observed P_r shows a higher increase in Telgárt (0.5%) and in Banská Bystrica (5%), but a decrease in Brezno (3%). A decreasing trend of Q_r by 6–16% was expected in the scenario while the observed Q_r indicated a decline of 17–18% (comparing 1961–1980 and 1981–2010).

Different results compared to our outputs presents study Hlavčová et al. (2008). According to the ECHAM scenario (reference period 1971–2000, scenario up to 2025), an increase in Q_m can be expected from November to March. For example an increase by 4% is expected in November's Q_m . This was achieved using the increase of T_m by 0.9°C and P_m by 0.8%. Observed data series of Q_m decreased in November more significantly (18%) by the T_m increase of 0.1°C and decrease in P_m 10–22%. The highest increase of Q_m the scenario assumed in February (16%), by the increase of T_m by 0.9°C and the decrease of P_m 1.9%.

Observed data for February show a decrease of Q_m (23–37%) while T_m increases in average only by 0.1°C, P_m decreases by 4–20% (comparing 1961–1980 and 1981–2010). Decreasing P_m affects also the decrease in snow cover depth SCD_m 6–28%. The low values of SCD were recorded especially in the period 1988–1998. Figure 7 depicts trends in all studied parameters for February in Brezno.

The Mann-Kendall test did not provide any evidence of pronounced changes in P_r . Similar result was obtained also by Faško and Štastný (2001). Further analyses have demonstrated a particular greater fluctuation in P_m and how their distribution over the year. A slight increase occurs in the warmer half of the year (July, August, May). In the cold period, P_m has a slightly decreasing tendency.

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. Runoff trends in the upper Hron River basin were also tested for different data period sets. From our point of view, at least 30 years of data is needed to obtain statistically meaningful test trends.

Parajka et al. (2009) indicate the same shift in the seasonality of floods in mountainous areas of central Slovakia. The factors that probably most likely influence the decrease in flood occurrence in the upper Hron River basin are the increase in air temperature and lower SCD . The spring thaw significantly contributes to runoff in the area. A problem may arise when the water accumulated in the snow does not contribute to river discharge. It could happen as a result of high air temperatures, the absence of precipitation amount, little cloud cover, and wind resulting in intensive sublimation. If lower precipitation occurs in subsequent months, discharge decreases significantly. Changes in snow conditions can be observed since the 1980s by our analysis; these changes include a decrease as well as greater variability in SCD . Since the end of the 1980s Holko et al. (2005) observed repeated weak winters in the southern part of the Hron River basin. As a rule, several years with low snow precipitation are followed by an above average year. Snow cover has decreased primarily in the month of December and is significant for most

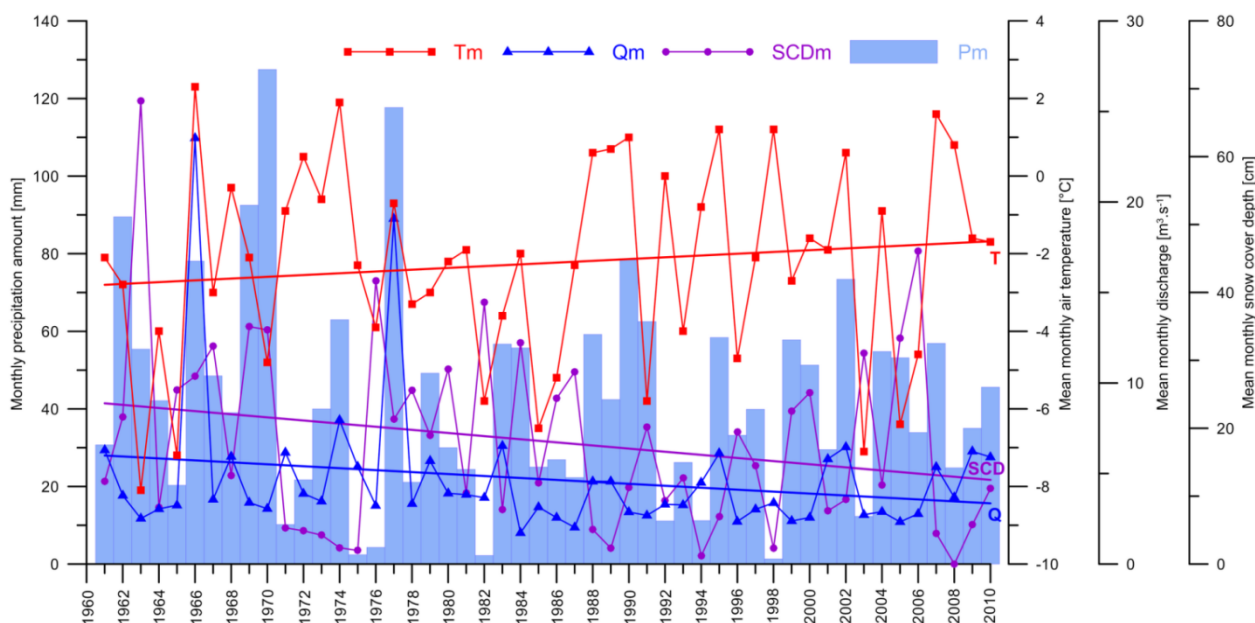


Fig. 7. Trends of hydroclimatic parameters in February (mean monthly values) in Brezno (1961–2010).

climatic stations. The statistically significant decreasing trend in *SWE* in the months of December–February is confirmed by the findings of Juričková et al. (2013). As for trend detection using statistical tests, a disadvantage is posed by the rather short duration of the data series and by being limited to the cold period of the year with snow cover.

CONCLUSION

The main results of our study are:

1) The upper Hron River basin is very sensitive, both to climate warming and changes in precipitation distribution, which have a significant effect on the runoff.

2) The 1980s can be considered a turning point in the development of all assessed hydroclimatic variables.

3) Our findings do not completely correspond with the outputs of rainfall-runoff models which predicted increase of discharge during the cold half of the year. The reason can be in different air temperature and precipitation trends. The observed datasets show more pronounced decrease of Q_r as scenarios.

4) Significant declining trends in Q_r and Q_m were detected for period 1931–2010 period. In the cold half of the year Q_m decreases from November to February.

5) A considerable significant increase in air temperature was observed at all stations. The most significant increase was detected for December and January and April to August.

6) There are no statistically significant changes in annual precipitation amounts. Seasonal fluctuations in P_m can be observed with a greater percentage of spring and summer monthly precipitation since 1990. In November and February, P_m decreased at most stations.

7) Runoff decrease seems to be influenced by the decrease in snow cover depth (*SCD*) and the decrease in the number of days with snow cover (*SCN_r*). A decrease in mean monthly snow cover depth (*SCD_m*) and number of days with snow cover in the month (*SCN_m*) is significant mainly in December, February and April.

8) The changes in the runoff regime are significant, especially the drop in Q_{Max} and *75pct* values. The fact of decreasing runoff is also confirmed by the higher frequency and extremity of flood events in the period before 1980. At the same time a shift in the seasonality of flood events has occurred.

The results of this study may provide indicators of changes in climate variability and contribute to our knowledge of the rainfall-runoff regime of the given region. They are helpful in solving questions of impacts on the hydrological cycle of rivers in mountain areas.

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Notes: Supplementary Material (Tables S1–S3 and Figures S1–S6) can be found in the web version of this article.

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