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Analysis of changes in hydrological cycle of a pristine mountain catchment. 1. Water balance components and snow cover

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Abstract: We analyse water balance, hydrological response, runoff and snow cover characteristics in the Jalovecký Creek catchment (area 22 km^2, mean elevation 1500 m a.s.l.), Slovakia, in hydrological years 1989–2018 to search for changes in hydrological cycle of a mountain catchment representing hydrology of the highest part of the Western Carpathians. Daily air temperature data from two meteorological stations located in the studied mountain range (the Tatra Mountains) at higher elevations show that the study period is 0.1°C to 2.4°C warmer than the climatic standard period 1951–1980. Precipitation and snow depth data from the same stations do not allow to conclude if the study period is wetter/drier or has a decreasing snow cover. Clear trends or abrupt changes in the analysed multivariate hydrometric data time series are not obvious and the oscillations found in catchment runoff are not coherent to those found in catchment precipitation and air temperature. Several time series (flashiness index, number of flow reversals, annual and seasonal discharge maxima, runoff coefficients) indicate that hydrological cycle is more dynamic in the last years of the study period and more precipitation runs off since 2014. The snow cover characteristics and climatic conditions during the snow accumulation and melting period do not indicate pronounced changes (except the number of days with snowfall at the Kasprowy Wierch station since 2011). However, some data series (e.g. flow characteristics in March and June, annual versus summer runoff coefficients since 2014) suggest the changes in the cold period of the year.

Keywords: Mountain catchment; Hydrological cycle; Time series.

INTRODUCTION

Detection of changes in the long time series of hydrological data using various approaches is a traditional part of hydrological research (e.g. Buishand, 1984; Chiverton et al., 2015; Conte et al., 2019; Górnik, 2020; Hurst, 1951; Klemeš, 1974; Koutsoyiannis, 2003; Kundzewicz and Robson, 2004; Lettenmaier and Burges, 1978; Merz et al., 2012; Pettitt, 1979; Sharma et al., 2016; Xiong et al., 2015; Zégre et al., 2010; etc.). Despite caution that mathematics can tell us little about the physical signals in the nonstationary world, because "our mathematical models … by which we try to describe geophysical records are only as good as is our understanding of the processes that generated them" (Klemeš, 2000), variability and change in hydrological time series will remain important research themes also in the near future (Blöschl et al., 2019). Increasing interest in such analyses in the last two decades is related to the effort to identify the impacts of climate or global changes on the hydrological cycle.

All big river systems are born in mountain environments which are fragile and sensitive to climate or landuse changes (e.g. Kohler and Maselli, 2009; Mastrotheodoros et al., 2020). Good long-term hydrological data from the mountains are difficult to obtain due to a number of factors including the inaccessibility, harsh climatic conditions, great spatial and temporal variability of the water balance components. This study examines 30-years long time series of hydrological data from a pristine research catchment of the Jalovecký Creek in the Western Tatra Mountains. Catchment monitoring provided the long data series that are not common in many small mountain catchments, e.g. spatially distributed snow cover measurements or isotopic composition of precipitation and runoff. The main objective of this study is to investigate temporal changes in the water balance components (precipitation, runoff) and snow cover in hydrological years 1989–2018. The companion paper (Holko et al., 2020, this issue), presents the analysis of changes in isotopic composition of precipitation and runoff, examination of trends and abrupt changes in the data series and the attribution analysis.

CATCHMENT AND DATA

The Jalovecký Creek catchment (Fig. 1) has the area 22.2 km^2 and mean altitude 1500 m a.s.l. (820–2178 m a.s.l.). Crystalline rocks (schist, paragneiss, migmatite) and granodiorite build 48% and 21% of the catchment, respectively. Approximately 7% of the catchment along its western boundary is built by the nappes of Mesozoic rocks (mainly limestone and dolomite). About 24% of the catchment is covered by Quaternary sediments (morraines, slope debries, etc.). Catchment morphology is characterised by steep slopes (mean 30°) and mostly narrow valleys with missing or just small alluvium. Wider segments of the main valleys that are located in the upper parts of the catchment, were modelled by Pleistocene glaciers.

The main soil types in the catchment are cambisols, podzols and lithosols. Rendzinas occur on the Mesozoic rocks. All soils have high stoniness that is often 40–50% and more (Hlaváčiková et al., 2019; Kostka and Holko, 1997).

Forest (dominated by Norway spruce), dwarf pine and the zone of alpine meadows and bare rocks cover 44%, 31% and 25% of the catchment, respectively. Most of the forest is over 100 years old. Because the catchment is located in the protected

Fig. 1. The Jalovecký Creek catchment from the south; the light blue line indicates part of the water divide.

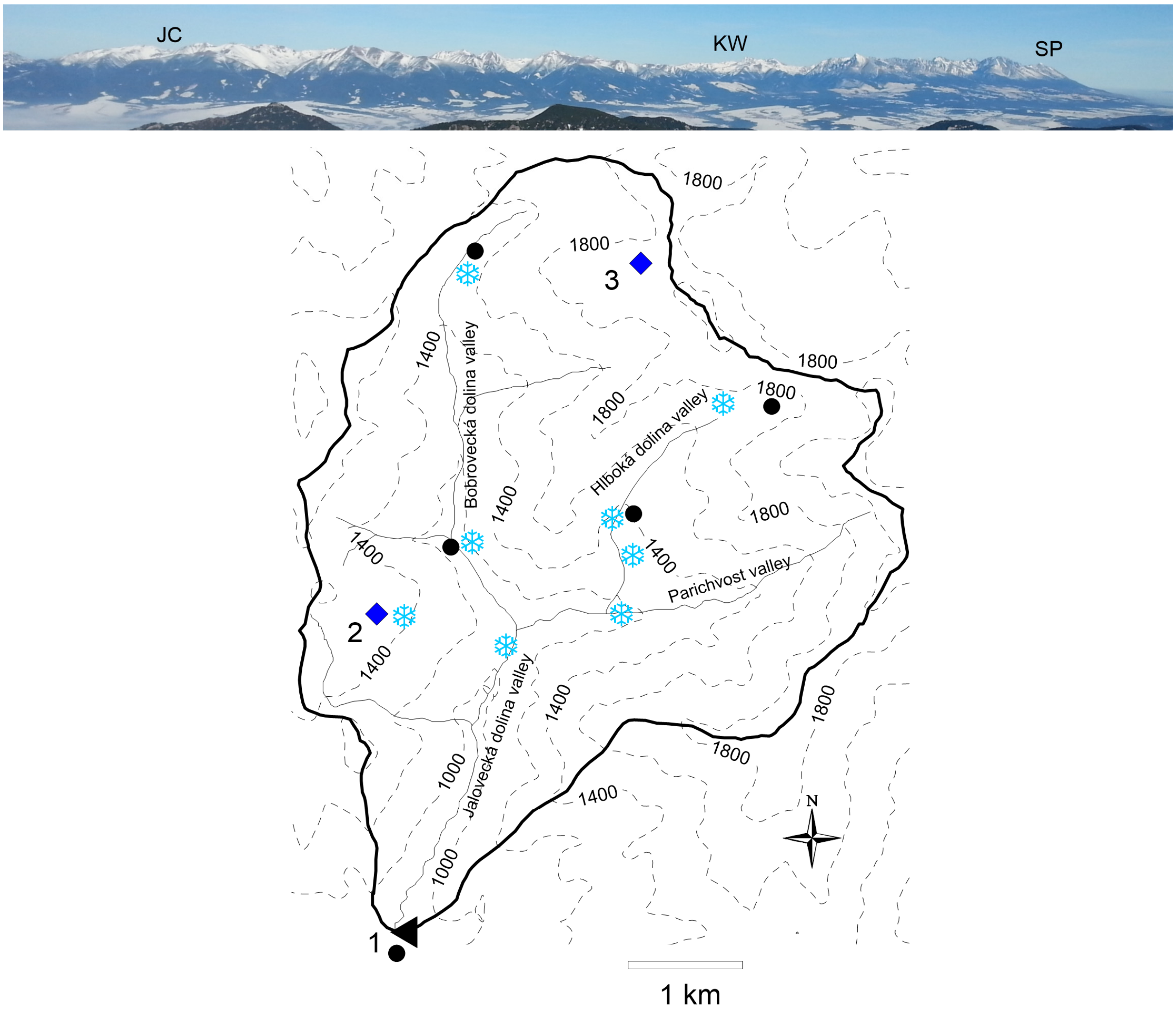

Fig. 2. Basic hydrological monitoring network in the Jalovecký Creek catchment; 1 – stream gauge (triangle) and meteorological station nearby (black circle), 2– the main meteorological station located at catchment mean elevation, 3 – meteorological station at 1875 m a.s.l. providing the air temperature data since the hydrological year 2003; snow courses (snowflakes) and storage gauges (1989–2008; black circle), water divide (thick black line) and contour lines; the photo on the top gives an idea on the approximate distance of the Jalovecký Creek Catchment (JC) from meteorological stations at Kasprowy Wierch (KW, 20 km) and Skalnaté Pleso (SP, 38 km).

area of the Tatra National Park (TANAP), human activities in the last decades are strongly restricted (absence of paved roads, occasional removal of wood after calamities, hiking on a sparse network of marked trials). However, larger scale forest dieback that started approximately in 2013 after greater windthrows and bark beetle outbreak are rapidly changing the forest structure (Bartík et al., 2019).

The basic monitoring network is shown in Fig. 2. Catchment runoff is measured at 820 m a.s.l. The main meteorological station (precipitation, air temperature and humidity, snow course) is located at catchment mean elevation (1500 m a.s.l.). Additional meteorological stations providing precipitation and air temperature data are located near the catchment outlet at 750 m a.s.l. and in the foreland part of the catchment at 570 m a.s.l.

(not shown in Fig. 2). The air temperature data are available also from the elevation of 1875 m a.s.l. since hydrological year 2003. Precipitation network in the years 1989–2008 (20 hydrological years) included four additional storage gauges at elevations 1100–1775. The tipping bucket gauges have been operating at the same points in summer months (June-September) since 2013 (e.g. Holko et al., 2014). Snow depth and water equivalent are measured at the end of January, February and March at snow courses located at elevations 1100–1700 m a.s.l. More frequent snow measurements (every two weeks during snow accumulation, every week since the snow water equivalent maximum) are conducted near the main meteorological station at 1500 m a.s.l. and in the nearby forest at 1450 m a.s.l. (e.g. Holko and Kostka, 2008; Holko et al., 2009).

Catchment areal precipitation and air temperature for this study were obtained by interpolation of point measurements using the elevation gradient. The air temperature data from elevations 570, 750 and 1500 m a.s.l. were used in the interpolation. Elevation gradients for the precipitation interpolation were based on data measured at 570, 750, 1100, 1400, 1500 (two gauges) and 1775 m a.s.l.

Information about the snow cover is obtained from the snow water equivalent (SWE) measured at varying time interval (from monthly to weekly) at snow courses located at 1100, 1400, 1500 and 1700 m a.s.l. This information is supplemented by simulated daily values of catchment SWE. Because catchment SWE cannot be obtained from direct measurements in larger mountain catchments, it was simulated by the spatially distributed hydrological model MikeSHE. The model was calibrated and validated against SWE data measured at ten snow courses located at the elevations 1100–1900 m a.s.l. (five of them were in the open area, five in the forest) and catchment runoff (Danko et al., 2015). The volume of snowmelt water measured at the elevations 1000–1500 m by six snow lysimeters in winter 2012 was used in the calibration as well. The model was calibrated for the period 2010–2014 and validated for the period 2002–2009.

Hydrological cycle of small mountain catchments (elevation ranges approximately 800–2200 m a.s.l.) in the Tatra Mountains is significantly affected by climatic conditions at higher elevations. Therefore, daily data on precipitation, air temperature and snow depth from the high-elevation meteorological stations at Kasprowy Wierch (Poland, 1991 m a.s.l., mountain ridge position) and Skalnaté Pleso (Slovakia, 1778 m a.s.l., the leeward side of the mountains) from period 1951–2018 are used to characterize climatic conditions in the Tatra Mountains in the study period from the longer time perspective. Although the Kasprowy Wierch and Skalnaté Pleso stations are about 20 and 38 km from the study catchment, respectively (Fig. 2), they are the only representative meteorological stations in the Tatra Mountains with the long-term data that are located at higher altitudes. The observations are carried out there by the permanent professional staff and both stations operate since the 1940's.

METHODOLOGY

A time series analysis should consist of exploratory data analysis, application of statistical tests and interpretation of tests results (e.g., Kundzewicz and Robson, 2004). Kundzewicz and Robson (2004) listed some commonly used tests, proposed greater use of the distribution-free testing methods and pointed at the role of exploratory data analysis as an essential part of any statistical analysis. They reminded that climate variability can cause an apparent trend and obscures other changes. Therefore, we start the analysis of data from the Jalovecký Creek catchment by characterizing climatic conditions in the study period (1989–2018) with respect to the longer time period (1951–2018) and estimation of structural changes (cycles) in the data series. Then, we analyse the water balance, hydrological response of the catchment, runoff and snow cover variability.

Climatic conditions in the study period

The long-term means representing the climatic standard are calculated for the air temperature, precipitation and snow cover data from meteorological stations at Kasprowy Wierch and Skalnaté Pleso for the period 1951–1980. This period is a good representation of climate in Slovakia in the 20th century (1901–1980) due to stationarity and absence of trends in air temperature and precipitation (Lapin, 2013).

Anomalies (deviations from the long-term means) of annual precipitation, air temperature, permanent snow cover duration, maximum winter snow depth and the number of days with new snow as a surrogate for the number of days with solid precipitation at both stations are calculated and analysed. Permanent snow cover is defined in agreement with previous climatological studies in the Tatra Mountains as a period (in days) with snow cover depth 1 cm and more that was not interrupted for more than 3 successive days (Briedoň et al., 1974). Number of days with snowfall is calculated from the daily snow depth records as a positive difference of snow depth on the current and previous days.

Daily precipitation data from Kasprowy Wierch and Skalnaté Pleso are also used to analyse the frequency of wet and dry periods with varying durations and days with precipitation that could cause flood hazard. Such an analysis could indicate changes in temporal variability of the main driver of floods and droughts (precipitation). Number of short-(uninterrupted duration of 1–5 days), mid- (6–9 days) and long term- (more than 10 days) wet and dry periods in individual years are calculated. Small, medium and extreme risk of flooding is assumed when daily precipitation is 40–60 mm, 60–90 mm and above 90 mm, respectively. The criteria defining the above wet/dry periods and flood hazards are taken from a similar analysis conducted by Bičárová and Holko (2013).

Structural changes in the time series

Meteorological and hydrological data vary in cycles (e.g., Pekárová and Pekár, 2007). We use the wavelet transform (WT) method to determine oscillations and periodicities in daily time series of catchment precipitation, air temperature and runoff in the Jalovecký Creek catchment. The same analysis is conducted for the time series of point precipitation and air temperature from meteorological stations at Kasprowy Wierch and Skalnaté Pleso to compare the catchment (interpolated) and station (directly measured) climatic data.

The WT method searches for wavelet coefficients which are used to estimate the power spectrum. The wavelet coefficients form a scalogram which characterises distribution of the spectral density of the time series (Fig. 3). The horizontal axis of a scalogram denotes time (i.e., the duration of a signal), while the vertical axis denotes period (i.e., the cyclical components). The values of the wavelet coefficients are identified by the colour – the highest values are shown in red. The white line in the scalogram encompasses an area with statistically significant periodicity (i.e., the cycle with certain period). The global wavelet spectrum (averaged scalogram) on the right side of the scalogram indicates the periodicity. The section of the

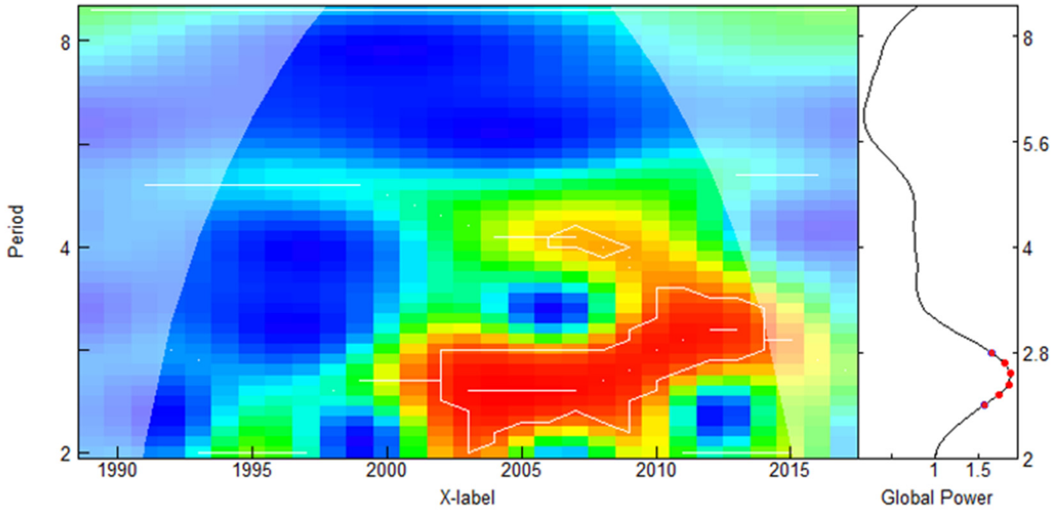

Fig. 3. Scalogram and its components (explained in the text); the red points shown on the right side of the scalogram identify the cycle with a statistically significant period of duration approximately 2.6 years that started approximately in 2003 and ended in 2013 (as indicated by the white line in the coloured raster encompassing the red wavelet coefficients).

scalogram outside the cupola shape represents an area with problematic counting of wavelet coefficients (e.g., because of the edge effects; Sabo, 2012). The WaveletCo package (Tian and Cazelles, 2013) in R software environment is used in the WT method application. More details about the scalogram and the WT method can be found in Daubechies et al. (1992) and Torrence and Compo (1998).

Water balance

Temporal variability of annual catchment precipitation, runoff and runoff coefficients in the Jalovecký Creek catchment is explored first. Then, the same data aggregated for the summer months (June to September) are examined. The idea behind the analysis is to check if the storage/release of water from the catchment given by the relationship between catchment precipitation and runoff changed in the study period.

Hydrological response of the catchment

Runoff response to snowmelt or rainfall is another indicator of changes in catchment hydrological cycle. We use flashiness index calculated from daily discharges and characteristics of runoff events derived from hourly discharges to investigate possible changes in catchment hydrological response.

Flashiness index

Flashiness index of streamflow is quantified by the ratio of absolute day-to-day fluctuations of streamflow relative to total flow in a year (Baker et al., 2004):

$$FI_y = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \qquad (1)$$

where FI is the flashiness index, q is the mean daily discharge, i is day, n = 365 (366) and y indicates the year of estimation.

The flashiness index is a dimensionless index which ranges between 0 and 2 (Fongers et al., 2007). Zero represents an absolutely constant flow; increasing FIy values indicate increasing flashiness (fluctuations) of streamflow.

Runoff events characteristics

Catchment hourly discharge in the period 1989–2018 was about 0.73 m^3 s^{-1}. About 80% of measured discharges were smaller than 1.0 m^3 s^{-1} and discharges exceeding 2.2 m^3 s^{-1} represent only about 6% of measured values. These values help to determine the criteria for selection of runoff events which is a subjective procedure. The hourly discharge data are used to analyse the total number of runoff events with peakflow exceeding 1 m^3 s^{-1} in the entire hydrological year and in the summer period (June to September). Annual and seasonal maximum discharges and the date of their occurrence in winter (December–February), spring (March–May), summer (June–September) and autumn (October–November) periods of individual years are evaluated as well.

Runoff response to rainfall does not reflect only current meteorological and catchment conditions such as rainfall amount, intensity and spatial distribution, catchment wetness state, etc. It can also indicate the change in conditions affecting runoff formation such as increasing areas producing overland flow (deforested or compacted areas), change in catchment storage, vegetation cover, etc. Summer is the period of maximum annual precipitation in the study catchment. Frequent occurrence of summer rains results in complex runoff events. Determination of characteristics of such events is complicated, because the ends and beginnings of the events overlap. Therefore, we select and analyse only simple runoff events in summer periods (June-September). Runoff events that start and end at discharges less than 1 m^3 s^{-1} and have peak discharge at least two times greater than the discharge at the beginning of the event are taken into account. The following characteristics of the simple runoff events are determined from the hourly discharge data:

- date and discharge at the beginning of an event (T_0 and Q_0)
- date and discharge at the peak (T_{max} and Q_{max})
- date of the quick flow termination (T_{end} and Q_{end})
- daily catchment rainfall on the day when the peakflow occured (hourly rainfall data are not available for the entire study period)

The quick flow is separated by the Eckhardt filter (Eckhardt, 2005) that was previously shown to provide results similar to isotopic hydrograph separation in the Jalovecký Creek catchment (Holko and Španková, 2014). The filter has two parameters. The value of filter parameter alpha is set to 0.95, maximum baseflow index is set to 0.90. Intersection of the hydrograph with the quick flow given by the Eckhardt filter determines the quick flow termination.

The above listed runoff events characteristics allow calculation of hydrograph increasing limb duration, rate of discharge increase until the peakflow, duration and intensity of discharge decrease until the quick flow termination, total duration of an event and the rough estimate of the runoff coefficient (having only daily precipitation). Variability of all characteristics in summer periods 1989–2018 is examined with the aim to search for trends or changes.

Runoff variability

Catchment runoff represents a spatially integrated characteristic which is measured with the highest accuracy compared to other components of the water balance equation. Daily discharge is used in this study to examine a number of runoff characteristics. They include monthly flows (i.e., mean monthly discharges) and flow minima and maxima (1-day, 3-day, 7-day, 30-day and 90-day), baseflow, dates of minimum and maximum annual discharges, number of flow reversals (changes from increasing to decreasing discharge and vice versa) and characteristics of extreme low flows, high flow pulses, small floods and large floods (peak, duration, time, frequency). The analysis is conducted using the IHA software (The Nature Conservancy, 2009). Classification of flows into extremely low, low, high and of floods into small and large, is given by statistics of measured discharge data mentioned above and the threshold values shown in Fig. 4. Variability of all characteristics in the study period is examined.

Snow cover

Climatic variability affects snow cover and the changes in snow cover can be manifested in catchment runoff. Examination of measured SWE data in this study is focused on the variability of maximum winter SWE at different elevations (measured) and in the entire catchment (simulated). We also examine the total amount of snow accumulated in the catchment (simulated) in individual winters defined as periods from November 1st until May 31st. The number of days with negative mean daily air temperature in December to April and total precipitation amount on those days at catchment mean elevation (1500 m a.s.l.) are examined as well.

RESULTS

Climatic conditions in the study period with regard to the climatic standard

Air temperature data from the high-elevation meteorological stations at Kasprowy Wierch and Skalnaté Pleso show that study period 1989–2018 is warmer compared to the climatic standard period 1951–1980 (Fig. 5). Air temperature in the study period is in almost all years 0.1°C to 2.4°C higher than in the climatic standard period. In contrast to air temperature, the two stations give a different message about precipitation. While annual precipitation at Kasprowy Wierch (the mountain ridge position) in the study period does not differ from that in the climatic standard period, at Skalnaté Pleso (the lee position) it is in the majority of years greater than during the climatic standard period.

Similarly to precipitation, anomalies of snow cover characteristics (Fig. 6) do not indicate clear changes with regard to the climatic standard period. The patterns at Kasprowy Wierch and Skalnaté Pleso differ. Duration of permanent snow cover at Kasprowy Wierch is much less variable than at Skalnaté Pleso, but clear trends are not visible at any of the two stations. Maximum winter snow depth (SD_{max}) at Skalnaté Pleso is smaller than the mean of climatic standard period already since the 1960'. Such a behavior is not observed at Kasprowy Wierch where positive and negative deviations are more regular during both climatic standard and study periods. Negative deviations are prevailing at both stations in the period 1968–1991.

Patterns of the number of days with new snow during the winter used as a surrogate for the frequency of snowfalls (on the daily scale) at the two stations differ approximately until the mid-1970's (Fig. 7). The Kasprowy Wierch station exhibits a relatively regular variability of positive and negative anomalies while the Skalnaté Pleso station shows positive deviations until

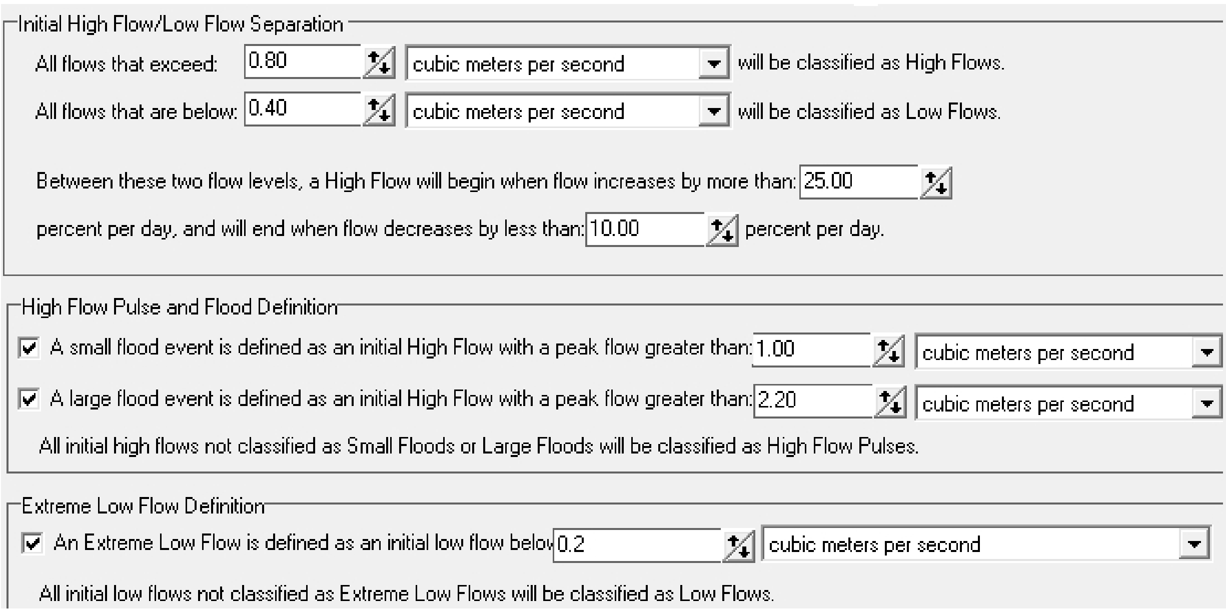

Fig. 4. Criteria for classification of flows and flood events; a window from the IHA software.

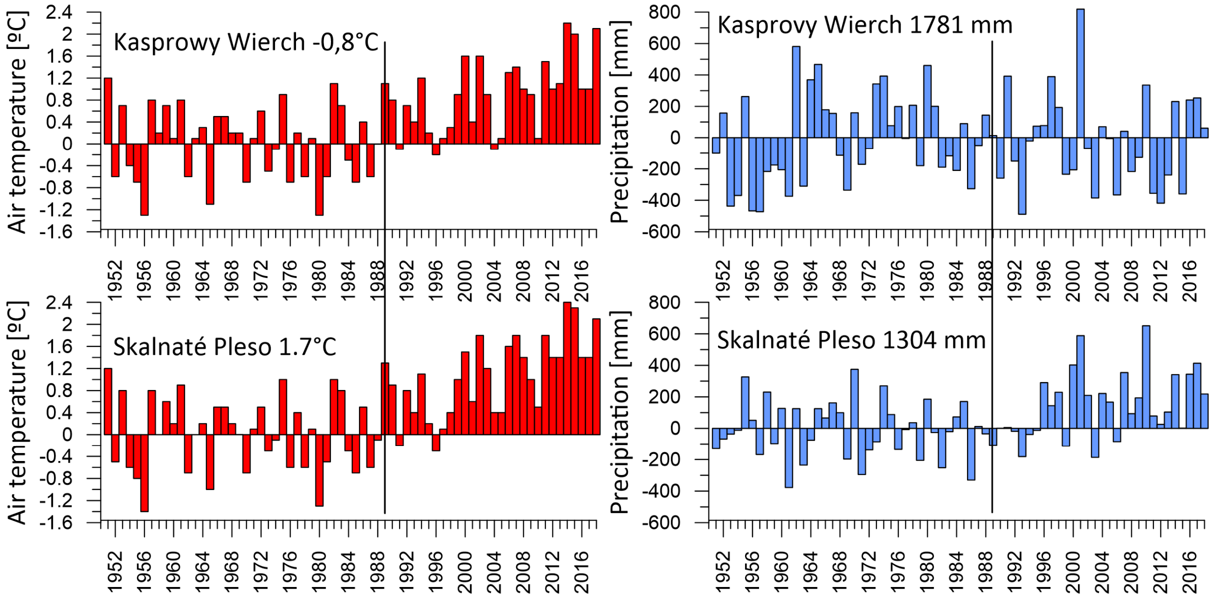

Fig. 5. Anomalies of mean annual air temperature (left) and annual precipitation (right) at the high-mountain meteorological stations Kasprowy Wierch and Skalnaté Pleso in the years 1951–2018; the numbers show the mean values calculated for the climatic standard period (1951–1980); the vertical lines indicate the beginning of the study period (1989–2018).

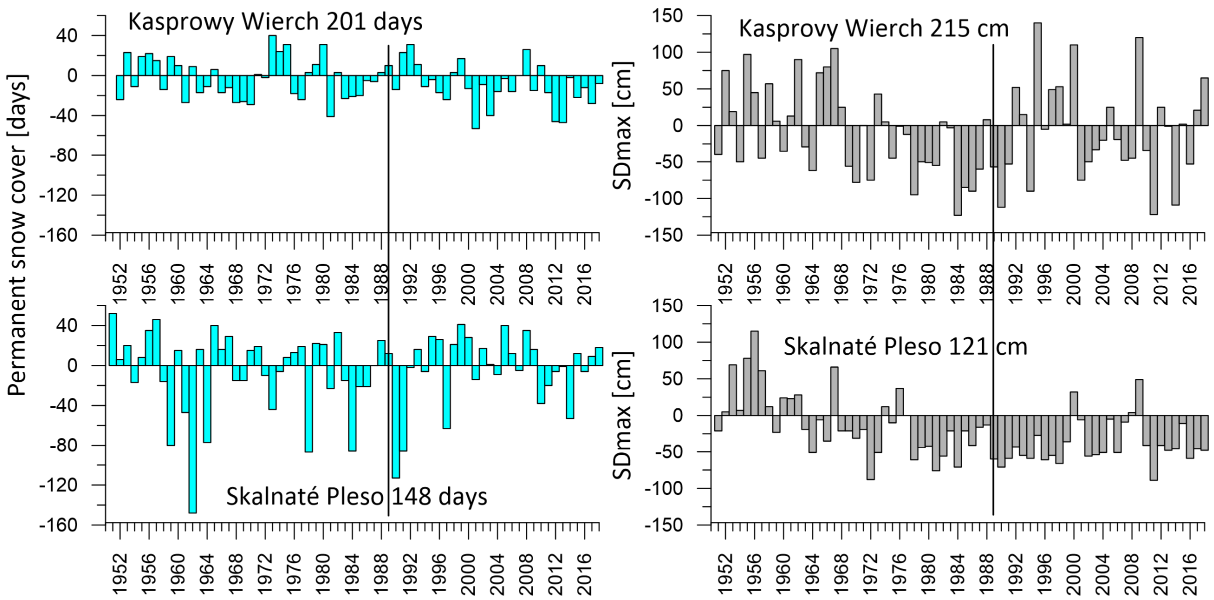

Fig. 6. Anomalies of permanent snow cover duration (left) and maximum winter snow depth (right) at Kasprowy Wierch and Skalnaté Pleso in the years 1951–2018; the numbers show the mean values calculated for the climatic standard period (1951–1980); the vertical lines indicate the beginning of the study period (1989–2018).

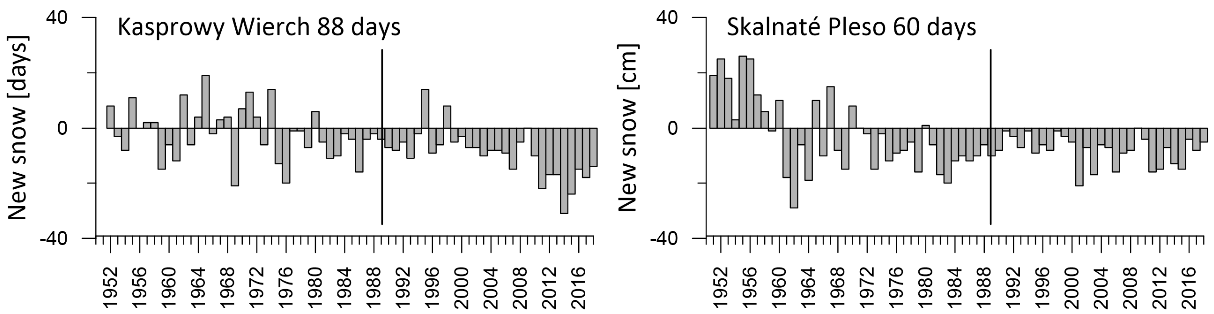

Fig. 7. Anomalies of the number of days with new snow (a surrogate for the number of daily snowfalls during a winter) at Kasprowy Wierch and Skalnaté Pleso in the years 1951–2018; the numbers show the mean values calculated for the climatic standard period (1951–1980); the lines indicate the beginning of the study period (1989–2018).

1962 and mostly negative variations after that. Negative deviations, i.e. fewer days with new snow are recorded at Skalnaté Pleso since the beginning of the 1970's and at Kasprowy Wierch since the mid-1970's. Greater negative deviations are observed at Kasprowy Wierch since 2011.

The snow cover data show that duration of permanent snow cover during the study period was similar to that of the climatic standard. Maximum snow depth at Skalnaté Pleso and number of days with new snow at both stations in the study period were smaller than during the climatic standard period, but it was like that already since the 1970's, i.e. almost two decades earlier. Negative deviations of the number of days with new snow at Kasprowy Wierch became greater since 2011.

Numbers of wet and dry periods (see Methodology) do not indicate trends or abrupt changes in the study period. According to precipitation data from Kasprowy Wierch (and Skalnaté Pleso), there are on average 43 (47) short-term wet periods, 9 (9) mid-term wet periods and 4 (2) long-term wet periods in a year. Average numbers of the short-, mid- and long term- dry periods are 51 (52), 4 (5) and 1 (1) per year, respectively. There are about 2–3 days with precipitation at each station representing small and medium flood risk per year. The number of days with precipitation representing extreme flood risk varies from 0 to 3 per year, but in most years such a precipitation does not occur. Greater number of days with low flood risk precipitation was recorded at Skalnaté Pleso in 2010 (9 days) - the year when a number of floods in the entire Slovakia was observed, in 2014 (7 days) and in 2016 (5 days). In all other years there are no more than four such days at the two stations.

Structural changes in the time series

The scalogram of daily air temperatures in the Jalovecký Creek catchment (Fig. 8a left) indicates a significant cycle with period ranging between 6 and 8 years that occurred approximately between the years 1995–2010. Daily precipitation data do not indicate any significant cycles. Daily runoff (Fig. 8a right) shows a significant cycle with period of 4 years that occurred approximately between 2000 and 2013.

Scalograms for daily precipitation and air temperature at Kasprowy Wierch and Skalnaté Pleso indicate significant cycles only for precipitation at Kasprowy Wierch with period of about 3 years in 1997–2004 (Fig. 8b). Snow depth at both stations shows significant cycles (Fig. 8c) with shorter period at

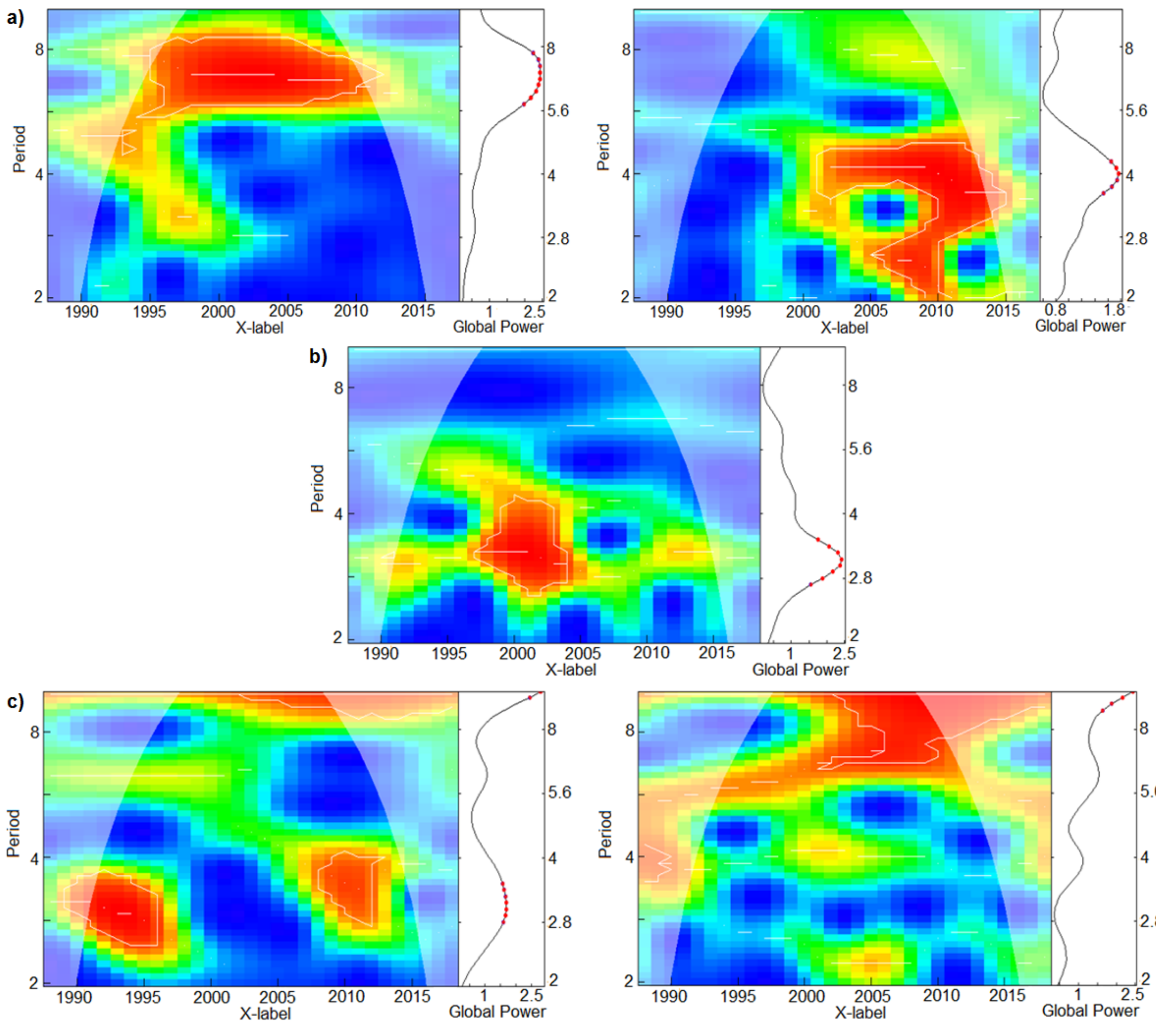

Fig. 8. Scalograms indicating cycles with significant periods revealed from daily data in the hydrological years 1989–2018; a) air temperature (left) and runoff (right) in in the Jalovecký Creek catchment; b) daily precipitation at Kasprowy Wierch c) daily snow depths at Kasprowy Wierch (left) and Skalnaté Pleso (right).

Kasprowy Wierch (about 3–4 years in the years 1990–1997 and 2008–2014) and an insignificant cycle with period of about 8 years in 2004–2010 at Skalnaté Pleso.

Water balance

Annual catchment precipitation and runoff are relatively stable until the mid-1990' (Fig. 9a). Annual runoff coefficients do not vary much until 2001 (Fig. 9b). However, since 2014, they are clearly and permanently higher than before. The annual runoff coefficient was high also in 2010 which was the wettest year on record.

Precipitation and runoff in the summer period (June to September) exhibits a regular variability. Summer runoff coefficients since 2012 (Fig. 9b) are in most years close to the lower range of the values (40% to 50%) calculated for the entire study period. A significant difference between the annual and summer runoff coefficients is visible since 2014.

Scatterplots of precipitation against runoff have smaller vertical scatter in the summer compared to the annual data (Fig. 10). The annual data clearly show higher runoff coefficients in years 2015, 2016, 2017 and 2010. Wetter summers that plot apart from the points representing other years occurred in 2010 and 2001. The driest year on the record is the year 2003.

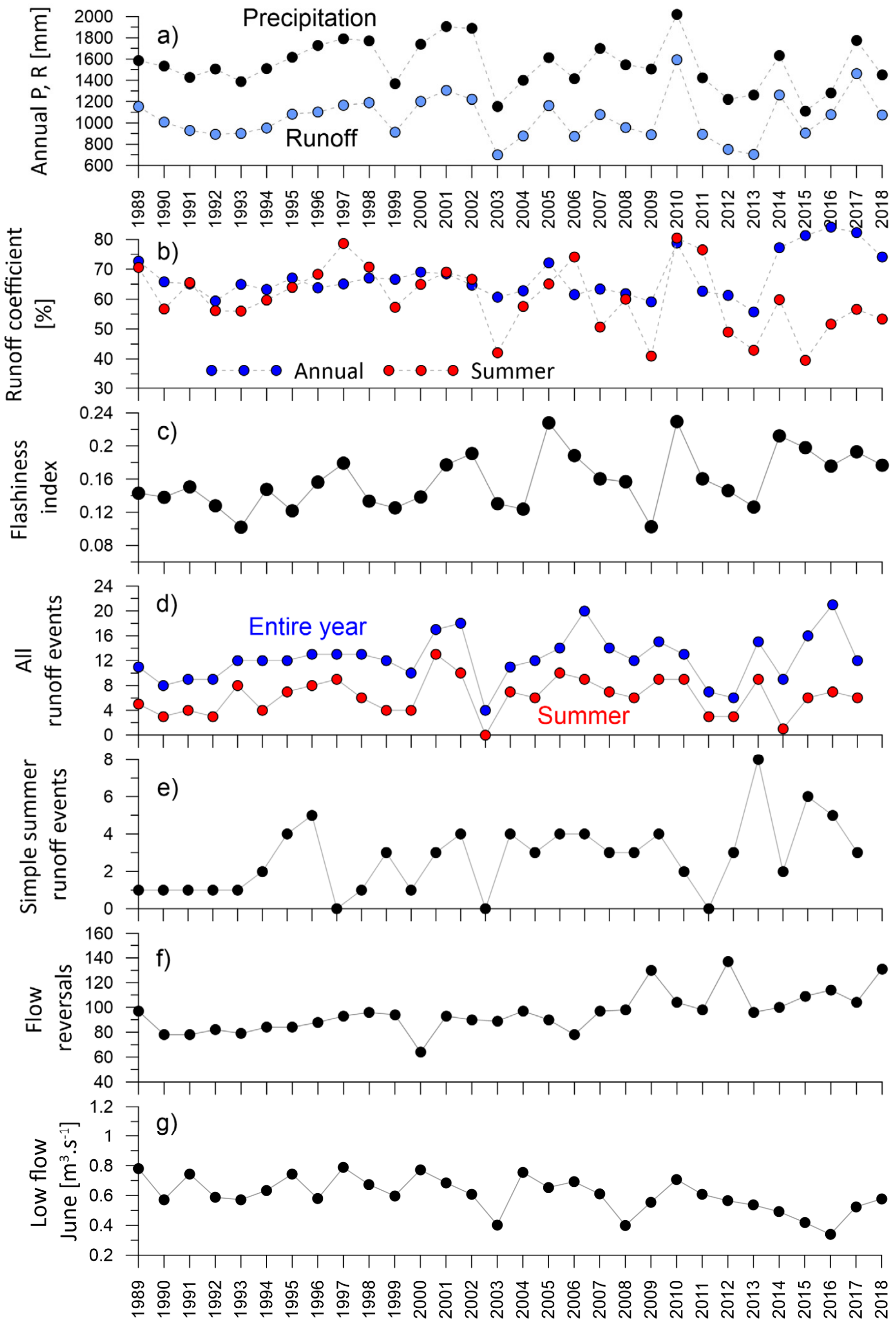

Fig. 9. Temporal variability of selected characteristics in the hydrological years 1989–2018; a) annual precipitation and runoff; b) annual and summer (June to September) runoff coefficients; c) flashiness index; d) number of runoff events (both simple and complex) in the entire hydrological year (November–October) and in the summer period (June–September); e) number of simple summer runoff events; f) number of flow reversals; g) June low flow.

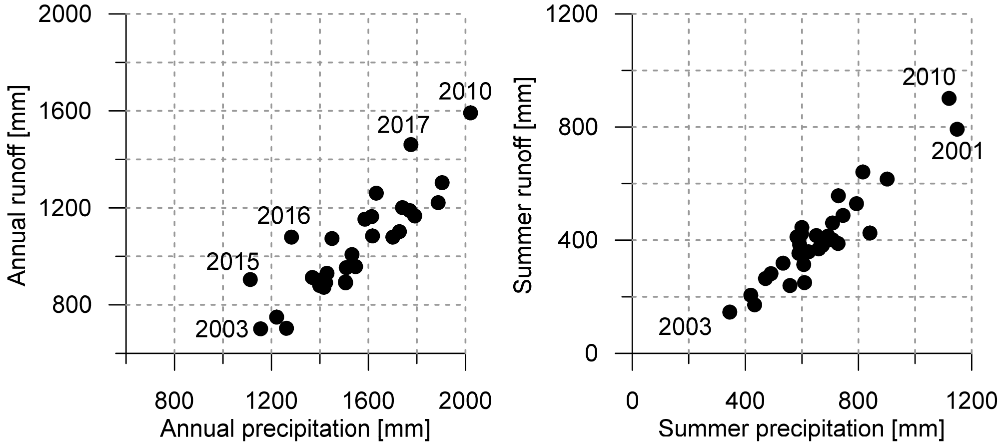

Fig. 10. Scatterplots of annual (November to October) and summer (June to September) precipitation and runoff in the hydrological years 1989–2018; note that scales of the axes differ.

The water balance data show that greater part of precipitation began to run off from the catchment in the last years of the study period. Because such a behaviour was not observed for the data from summer periods (June to September), it indicates a change in the colder part of the year. The same is suggested by the great difference between summer and annual runoff coefficients since 2014.

Hydrological response of the catchment

The flashiness index (Fig. 9c) is smaller at the beginning of the study period. Later, greater variability becomes visible between 2005 and 2013. The values since 2014 are comparatively greater and their interannual variability is smaller than before 2014.

The number of runoff events in the entire hydrological year is relatively stable (about 9–13 events per year) until the year of 2000. After 2000, the variability increases (Fig. 9d). About a half of runoff events occurs in summer. The share of summer events in the annual totals does not change over the study period. The lowest number of runoff events in the entire year is recorded in the hydrological year 2003 which was the driest year in the study period. No summer runoff events as defined in Methodology occurred in that year.

Annual and seasonal (spring, summer, autumn, winter) discharge maxima and days of their occurrence do not indicate any trend or change in variability. However, three highest annual discharge maxima (22.5 $m^3 s^{-1}$, 17.9 $m^3 s^{-1}$, and 18.0 $m^3 s^{-1}$) are recorded in 2014, 2017 and 2018, respectively, i.e. in the last five years of the study period. Annual maximum in 2014 was observed in spring (mid-May). It was caused by a combination of snowmelt and rainfall that produced the greatest peak discharge measured in the entire study period (Danko, 2014). Annual maxima in 2017 and 2018 are recorded in spring (end of April) and summer (mid-July), respectively. The analysis of seasonal maxima shows that the highest values often occurred in the last years of the study period as well (in spring 2014 and 2017, summer 2018, autumn 2016).

Majority of simple summer runoff events characteristics does not indicate trends over the study period. However, changing variability or different behaviour in some periods is found for some characteristics. Characteristics of all 82 events show greater number of events at the end of the study period (2014, 2016, 2017). Ony one simple summer runoff event is mostly recorded until 2000 (in 8 out of 12 summers between 1989 and 2000) while the typical number of events since 2001 increases to 3–4 (Fig. 9e). Characteristics of the entire pool of simple summer runoff events do not indicate any trends or changes in the study period. Therefore, we focused on the events with the fastest response, i.e. with the shortest rising limbs of the hydrographs (1–4 hours from the beginning of an event). These events represent about one third of all selected runoff events (28 out of 82). Shorter recessions of the hydrograph (until the quick flow termination) appear after 2006 (Fig. 11). The duration of runoff events becomes shorter since 2006 as well (approximately 7–8 hours instead of 12 hours).

Runoff variability

The most pronounced changes in characteristics derived from daily flows are found for the number of runoff reversals and June mean and low flows. Number of flow reversals (Fig. 9f) remains high since 2015, although the two highest values occurred in 2009 and 2012. June flows (mean discharge in June) are relatively small after 2012. Low flows in June (Fig. 9g) show similar behaviour as the June flows.

The daily flow data indicate smaller discharge increase and faster decrease during runoff events since 2003 as well. Other examined flow characteristics mentioned in Methodology, among them flow maxima and minima, do not indicate clear trends or changes in the behavior in the study period.

Snow cover

Measured data from snow courses located at the altitudes 1100 to 1700 m a.s.l. do not indicate any clear change in SWE in the study period. The data suggest that SWE maxima in the last winters (2013–2018) are smaller than in the previous period when greater SWE maxima occurred in 2000, 2002, 2005, 2009, 2012 (Fig. 12b). However, maximum in winter 2019 (the first winter after the study period) which is not shown here, is greater again.

The simulated amount of snow accumulated in the catchment in individual winters (Fig. 12c) does not show any apparent changes either. The same holds for the climatic conditions in the period which is the most important for snow accumulation and melt in the catchment (December to April; Fig. 12a). The number of days with negative/positive mean daily air temperature or total amount of solid/liquid precipitation (as suggested by the mean daily air temperature) exhibit a great variability, but no trends or abrupt changes.

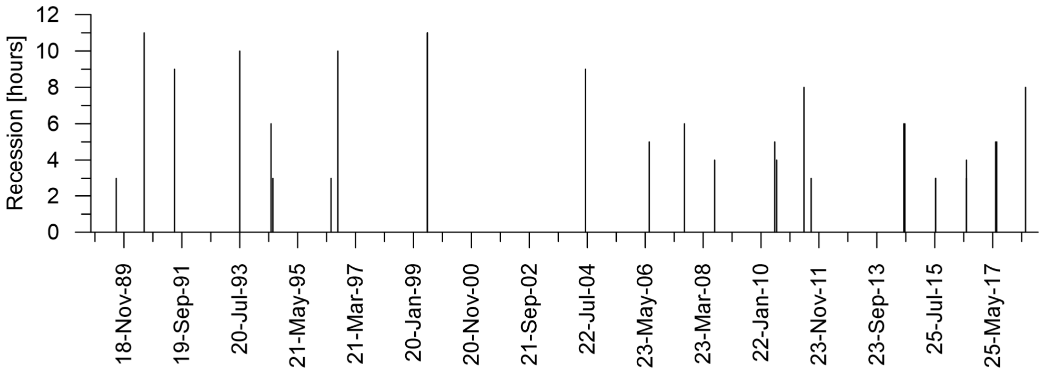

Fig. 11. Duration of runoff recession during simple summer runoff events with short time to peak (up to 4 hours) in the hydrological years 1989–2018.

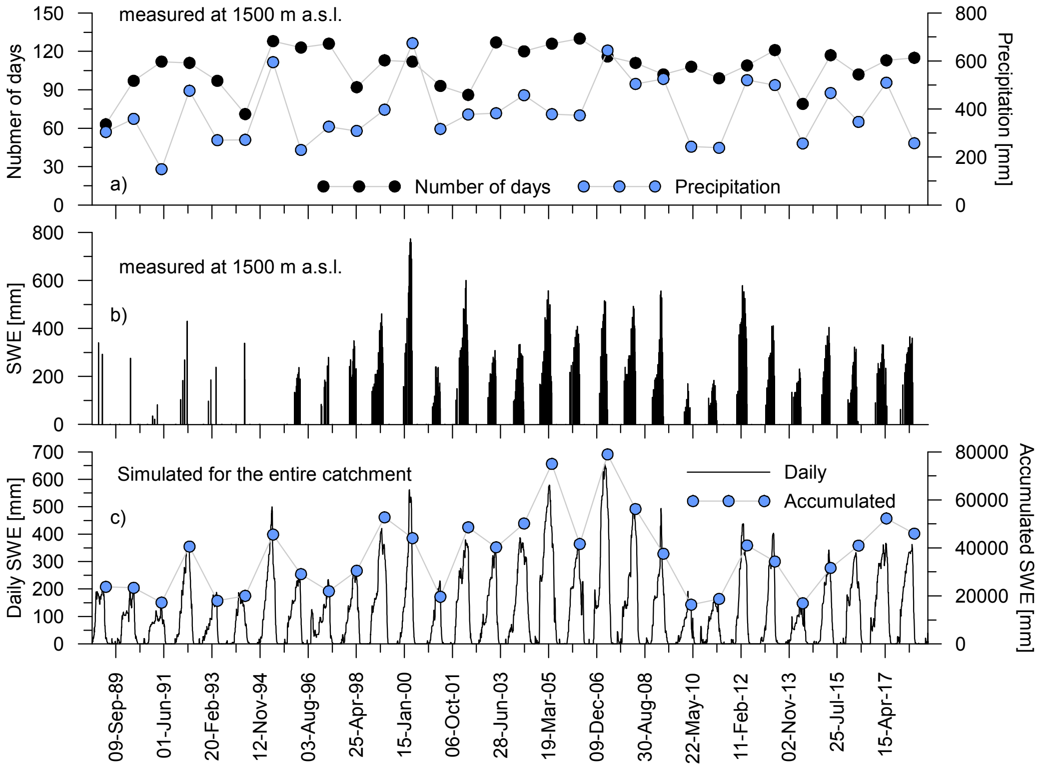

Fig. 12. a) number of days with negative mean daily air temperature in the snow accumulation and melt period (December to April) at catchment mean elevation in winters 1989–2018 and total precipitation on those days; b) SWE measured at the same site during field campaigns (i.e. approximately once in 1–2 weeks); c) MikeSHE simulated catchment daily SWE and snow accumulation over the winter period.

DISCUSSION

Numerous studies reported increasing trends in air temperature in the Tatra Mountains area in the last decades while the conclusions on trends in precipitation and runoff were not so unvivocal (a brief overview is given in Górnik et al., 2017). Precipitation, air temperature and snow cover data from the high-elevated meteorological stations Kasprowy Wierch and Skalnaté Pleso analysed in this study lead to similar result. The study period in which the hydrological cycle in the Jalovecký Creek has been monitored, is warmer than the climatic standard period and the annual air temperatures at the end of the study period are higher than at its beginning. Unlike the air temperature, precipitation patterns at Kasprowy Wierch and Skalnaté Pleso differ. Thus, precipitation data from the two stations do not provide an unambiguous information on whether the study period is wetter or drier than the climatic standard period.

It would be assumed that an increasing air temperature should result in changes of snow cover and runoff characteristics related to snowmelt. However, the changes in snow cover characteristics at Kasprowy Wierch and Skalnaté Pleso during the study period are not confirmed except the decrease in the number of days with new snow at the Kasprowy Wierch station since 2011.

Wavelet analysis is used in geophysical time series processing including climatic and hydrological data since the 1990' (e.g. Pišoft et al., 2004; Qian et al., 2014; Torrence and Compo, 1998). Oscillations found in the Jalovecký Creek catchment runoff do not correspond to the oscillations detected in the air temperature and precipitation as the main local climatic drivers. While the oscillations in the air temperature covered almost the entire study period, in catchment runoff they were found only in its second half. The periodicities in the two data series were different as well (4 years for runoff and 6–8 years for the air temperature). Precipitation did not exhibit any significant oscillations at all.

Oscillations of the areal catchment data (precipitation, air temperature, runoff) differ from those found in the data series measured at meteorological stations Kasprowy Wierch and Skalnaté Pleso. The snow depth data series at Kasprowy Wierch and Skalnaté Pleso show different oscillations as well. Processes affecting the snow cover formation at the two meteorological stations can partially differ due to different position (the mountain ridge versus the leeward, south oriented mountain slope position) and the distance between the stations.

As for the Jalovecký Creek catchment, we expected that oscillations found in catchment runoff would be consistent with those found either in the air temperature or in the precipitation data. Additional work is needed to explain the links among the oscillations found in the data series of the main water balance and climatic components and catchment hydrological cycle. Szolgayova et al. (2014) also found differences among the Danube River discharge, precipitation and air temperature oscillations and periodicities. However, they documented strong correlation between the precipitation and discharge spectra in the low frequency intervals and propagation of the long cycles from precipitation to discharge. Qian et al., 2014 found different significant periods for annual precipitation, air temperature, evapotranspiration and runoff, whereas two periods (7–8 years and 42–43 years) were the same for runoff and meteorological data. Zhang et al. (2015) employed the wavelet coherence to investigate the coherence among inconsistent changes in annual precipitation/potential evapotranspiration and annual streamflow in the Yangtze River basin.

Unlike many time series analyses studies that focused just on one or a few time series, we have attempted to analyse as many data sets describing various aspects of the hydrological cycle in the study catchment as possible. Although the clear changes in snow cover characteristics were not found, some of the time series indicate that hydrological cycle in colder part of the year might be changing (e.g., annual versus summer runoff coefficients, June flows and low flows). Others suggest that hydrological cycle in the catchment was more stable approximately until the end of the 1990‘and became more dynamic in the last years of the study period (i.e., higher runoff coefficients, number of flow reversals, flashiness index, number of simple summer runoff events and shorter runoff events recession). However, the trends over the entire study period are not very distinct. Changes in the behaviour of several characteristics are more pronounced in the last five years of the study period.

CONCLUSIONS

The exploratory analysis of numerous data sets does not confirm distinct trends or change points in the pristine mountain catchment of the Jalovecký Creek in hydrological years 1989–2018. The data indicate greater dynamics of the hydrological cycle in the last years of the study period. It is manifested in higher runoff coefficients, number of flow reversals per year or flashiness index, or the fact that most of the greatest annual and seasonal discharge maxima occurred in years 2014–2018. Regular snow cover measurements at different elevations are perhaps the only data series that are not commonly measured in similar small mountain catchments on the long–term basis. An extended snow cover monitoring based on cheap approaches like the soil surface temperature (e.g. Krajčí et al., 2016; Lundquist and Lott, 2008) or time lapse photography (Parajka et al., 2012) could be useful in the long-term monitoring and future evaluations of changes in hydrological cycle in seasonally snow-covered catchments.

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