Variability of Flood Frequency and Magnitude During the Late 20th and Early 21st Centuries in the Northern Foreland of the Tatra Mountains

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Abstract Much of the flood risk in Poland is related to the Upper Vistula River Basin, and its right-bank tributaries on the northern foreland of the Tatra Mountains significantly contribute to the total flood damage. Therefore, the question whether the magnitude and frequency of floods in this region have changed in the past

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decades is of high interest. This chapter focused on the inter-decadal variability of magnitude, frequency, and seasonality of floods since the mid-20th century using a multi-temporal approach in which trends are fitted to several combinations of start and end years in a record. The correlation between flood parameters and different large-scale climate indices for the Northern Hemisphere was calculated, as well as trends of intense precipitation indices, number of days with snow cover, cyclonic circulation types, air temperature and moisture conditions were calculated to explain the detected trends. Other potential external drivers, such as catchment and channel changes were also considered. Results show that floods in the area exhibit considerable inter-decadal variability, however, certain patterns are apparent. Less frequent floods, although perhaps more extreme, are now likely to occur, with a shift in the seasonality, decreasing flood magnitudes in winter and increasing during autumn and spring.

1 Introduction

The seasonality of streamflow in mountainous basins has been found to be extremely sensitive to global warming (Diaz et al. 2003; Barnett et al. 2005; Bates et al. 2008; Marty 2008; Allamano et al. 2009) and the concern about the increase of flood risk in these areas is rapidly raising in the scientific literature (Olsen et al. 1998; Palmer and Räisänen 2002). The question whether the magnitude and frequency of floods have changed due to climate change or other drivers of change is of high interest (Merz et al. 2012). The costs of extreme weather events have exhibited a rapid upward trend in recent decades, at every spatial scale (Barredo 2007, 2009: IPCC 2009; Kron 2012). Therefore, the search for trends (or lack thereof) in flood data series has become of scientific interest and practical importance in the last years as it is essential for planning flood-protection systems, where system design has been traditionally based on the assumption of stationarity of river flow (Milly et al. 2008). Within the framework of the World Climate Programme-Water and other, national and international projects, important activities have been undertaken in the analysis of long time-series of hydrological observations to detect signals of change (Kundzewicz and Robson 2000, 2004; Robson 2002; Kundzewicz et al. 2004, 2005; Lindström and Bergström 2004; Radziejewski and Kundzewicz 2004; Svensson et al. 2004, 2005; Birsan et al. 2005; Petrow and Merz 2009). Several studies on flood trends in Europe can be found, and they usually cover large regions or entire countries (Robson et al. 1998; Helms et al. 2002; Lammersen et al. 2002; Robson 2002; Lindström and Bergström 2004; Pfister et al. 2004a, b; Mudelsee et al. 2006; Pinter et al. 2006; and national and regional chapters in the monograph edited by Kundzewicz 2012). Although there is as yet no proof that the extreme flood events of recent years are a direct

consequence of climate change, they may give an indication of what can be expected: the frequency and intensity of floods in large parts of Europe are projected to increase, even if there is a considerable uncertainty in projections (cf. discussion in Kundzewicz et al. 2016).

However, there are other important factors that may alter flood variability independently from streamflow trends and even in the absence of climate change (Slater et al. 2015). Flooding is a complex phenomenon integrating the influence of atmospheric variables over a watershed (Kundzewicz and Schellnhuber 2004). Therefore, land-use changes (e.g., reforestation and urbanization) may induce changes of terrestrial (hydrological and ecological) systems and control the rainfall–runoff relations, hence impacting on floods. In addition, changes in the capacity of river channels to convey flood flows may also change flood frequency (Wyżga 1997; Slater et al. 2015; Wyżga et al. 2016).

There are still some issues related to the data and to the methodology of change and trend detection (Kundzewicz and Robson 2004). A precise understanding of the hydroclimatic characteristics of mountain regions is complicated by a lack of observational data at the spatial and temporal resolution adequate for hydroclimatic research in regions of complex topography. In the particular case of streamflow studies, in order to detect a weak, if any, climate change component in the process of river flow, it is necessary to eliminate other influences and use data from pristine (baseline) river basins. Baseline conditions are rare, and human influence is often strong even in mountainous regions where the mountain tourism economy, largely linked to winter sports, has soared over the last 50 years.

The region of the foreland of the Tatras has been typified by high population density, with human activity in the northern foothills initiated relatively early (during the 18th century a considerable agricultural and pastoral activity was developed in the region). Over the 20th century, the use of the land changed, as the percentage of arable land decreased significantly and forest cover increased (Wyżga et al. 2012). In 1955 the establishment of the Tatra National Park restricted developments and the state of Tatra forests improved considerably (Jahn 1979). However, other types of human impacts appeared in the foreland of the high-mountain massif: urbanization, channelization of streams and rivers, in-channel gravel mining and channel incision (Korpak 2007; Zawiejska and Wyżga 2010).

During the 20th century, 41 significant floods took place in the Carpathian part of the Vistula River Basin (Cebulak and Niedźwiedź 2000). Nationwide, in the last two decades two extreme flood events (1997 and 2010) caused damages reaching or exceeding the level of 1 % of natural Polish GDP and dozens of people lost their lives (Kundzewicz et al. 2012, 2014). These events also affected the right-bank tributaries of the Upper Vistula located in the study area.

This chapter aims to analyse the flood variability in the Tatra Mountains foreland on decadal timescales and to examine, via a multi-temporal trend analysis, the extent to which observed trends in two fixed periods are influenced. The potential drivers (i.e. trend attribution) of the identified trends in floods are investigated by correlation analyses with large-scale climate indices, by identifying trends in

precipitation, snow cover duration, and cyclonic circulation types, and by analysing changes in basin attributes.

2 Study Site and Data Acquisition

The study sites are located in the northern foreland of the Polish Tatra Mountains. The highest peak Rysy, located SE of Zakopane, reaches 2499 m a.s.l. The Tatras originate from the Alpine orogeny. Their highest parts are predominantly underlain by granite and metamorphic rocks, while in the lower parts carbonate rocks dominate. Glacial transformation in the Pleistocene and periglacial processes in the Holocene produced a system of alpine cliffs and talus slopes. They indeed resemble the Alps landscape-wise, representing the only form of alpine landscape in the entire arc of the Carpathians. In the high, crystalline part of the Tatras, thick and highly porous debris cones predominate on slopes and glacial till in the valley floors, both enabling effective infiltration of water. On the northern slopes of the Tatras, limestone and dolomite bedrock favours deep, karstic water circulation. In both areas, lithological conditions slow down runoff and result in a considerable proportion (40–70 %) of underground supply of streams draining the mountains (Łajczak 1988). The foothills of the Polish Tatra Mountains are underlain primarily by flysch. This geological setting, together with considerable historical deforestation of the area results in greater flashiness of runoff (Wyżga et al. 2012).

The upper tree line (1550 m a.s.l.) is consistent with the annual isotherm of 2 °C. The subalpine belt is covered with mountain pine (*Pinus mugo*) and encompasses elevations ranging from 1550 to 1850 m a.s.l., where mean annual temperature drops to 0 °C. A belt of alpine meadows extends from 1850 to 2200 m a.s.l. Above 2200 m a.s.l. (seminival belt), bare rock and lichens predominate, and snow precipitation is more frequent than rainfall, with snow cover duration of approximately 230 days per year.

Precipitation recorded on the northern slopes of the Tatra Mountains is the highest in Poland. For the period 1951–2012, mean annual precipitation at Kasprowy Wierch (1991 m a.s.l.) was 1765 mm, but the record-high annual maximum precipitation at this station was 2599 mm in 2001 (with monthly maximum of 651 mm in July 2001). Even higher annual precipitation values were recorded in 2001 at other high-elevation locations of the Tatra Mountains, namely 2628 mm at Hala Gąsienicowa and 2770 mm at Dolina Pięciu Stawów. The flood-triggering rainfall types in this mountainous area are: (i) 2–5 days-long rainfall with intensity higher than 50–100 mm per day (maximum 300 mm day^{-1}), usually connected with circulation types Nc, NEc, NWc, Cc and Bc, often with cyclones moving by track Vb of van Bebber classification from the Adriatic Sea

through Hungary to Ukraine or eastern Poland; and (ii) heavy downpours connected with local thunderstorms, with intensity up to 100–200 mm h^{-1}, causing local flash floods.

Streamflow data series of the length of 40–60 years from 14 water-gauge stations in the northern foreland of the Tatra Mountains were analysed (Fig. 1). Two different groups of stations were distinguished: (i) a first group formed by headwater basins with variable but generally lower degree of human impact on the environment, drainage areas ranging from 34 to 210 km^2 and station altitudes between 396 and 967 m (indicated in bold in Table 1), and (ii) a second group composed of the larger basins with drainage areas from 430 to 4300 km^2 and station altitudes ranging from 277 to 581 m, with higher degree of anthropogenic disturbance. It should be emphasized that the headwater basins exhibit a wide spectrum of catchment aspect, which makes this group of basins an indicator of regional environmental changes, including climatic ones, rather than of a change in the predominant pattern of atmospheric circulation over the area. In addition, this first group shows short records of streamflows, while the second group, representing the larger basins, has longer records (going back to 1951).

While most stations have the catchments located entirely or mostly on the Polish territory, the River Poprad joining the Dunajec upstream of Nowy Sącz (station 14 in Table 1) drains mainly the territory of northern Slovakia. Some environmental changes that occurred in that area in the past few decades differed from those recorded in the Polish part of the Dunajec drainage basin. However, it has not been possible for us to acquire the complete image of environmental factors that might have been responsible for the changes in floods on the Poprad. Nevertheless, it is interesting to verify whether flood trends identified for the Nowy Sącz station are consistent with those that typify the upstream stations characterizing the runoff from the Polish part of the Dunajec basin. Table 1 summarizes the most important characteristics of the studied drainage basins derived from topographic maps and data of the Polish Hydrometeorological Service (IMGW-PIB).

The main criteria for station selection (Pfaundler 2001; Birsan et al. 2005; Stahl et al. 2010) are: (a) availability of data, (b) at least 30 years of continuous and complete observations (most of stations have 45 years of records), and (c) spatial independence between station records. Spatial independence for stations located along the same river was ensured by always choosing the upstream station. The downstream station was additionally selected only in the case of a substantial increase in drainage area between the stations or if a tributary exists between them. These conditions provide a good compromise between the assumed independence of station records and a relatively high number of stations spread fairly evenly throughout the northern foreland of the Polish Tatra Mountains.

Time series of annual and seasonal maxima, peak over threshold magnitude and peak over threshold frequency (Petrow and Merz 2009) were analysed. The analysis of floods may differentiate the flood generation mechanisms (e.g. snowmelt vs rainfall), without treating all floods as one category. Therefore, four climatological seasons may be defined and analysed separately: Winter (DJF), Spring (MAM), Summer (JJA) and Autumn (SON) and the seasonal maximum discharge was

Fig. 1 Location of the studied river catchments in the northern foreland of the Polish Tatra Mountains

analysed for each (SMW, SMSp, SMSu, and SMA for winter, spring, summer and autumn, respectively). These parameters are summarized in Table 2.

3 Flood Trend Detection and Attribution

3.1 Flood Trend Detection

For all available time series, trends can be detected and classified according to their statistical significance as: (i) tendency, a statistically still unproven development, (ii) trend, a statistically proven development (at least 80 % significance), or (iii) strong trend, a statistically well-founded development (at least 95 % significance).

First of all, an exploratory data analysis (EDA) was carried out. This study involved mainly plotting graphs, and allowed to appreciate some features in data, as well as to assess the first hypotheses to be confirmed by the statistical analysis. In addition, the linear regression gradient plot in the EDA allowed testing of potential trends of the mean.

Trend analysis in this study is conducted by the nonparametric Mann–Kendall (MK) test. The application of the MK test to hydrological series has been discussed in detail by Kundzewicz and Robson (2004) and is summarised as follows:

Table 1 Physiographic characteristics of the 14 studied basins.

	Station (river)	Highest elevation (m a.s.l.)	Lowest elevation (m a.s.l.)	Relief (m)	Mean elevation (m a.s.l.)	Catchment area (km²)	Catchment aspect	Mean catchment slope	Time period analyzed
1	**Kościelisko-Kiry** *Kościeliski Stream*	**2158**	**922**	**1236**	**1452**	**34.5**	**N**	**0.133**	**1951–2011**
2	**Zakopane-Harenda** *Cicha Woda*	**2096**	**765**	**1331**	**1320**	**58.4**	**N**	**0.126**	**1961–2011**
3	**Łysa Polana** *Białka*	**2628**	**967**	**1661**	**1660**	**63.1**	**N**	**0.151**	**1961–2011**
4	**Ludźmierz (R)** *Rogoźnik Stream*	**1124**	**596**	**528**	**832**	**125**	**N**	**0.029**	**1971–2011**
5	**Szaflary** *Biały Dunajec*	**2301**	**638**	**1663**	**1295**	**210**	**N**	**0.072**	**1961–2011**
6	**Niedzica** *Niedziczanka*	**1259**	**497**	**762**	**857**	**136.4**	**NE**	**0.049**	**1971–2011**
7	**Jablonka** *Czarna Orawa*	**1368**	**610**	**758**	**938**	**136**	**S**	**0.041**	**1961–2011**
8	**Ludźmierz (L)** *Lepietnica*	**1312**	**598**	**714**	**908**	**50.4**	**SW**	**0.056**	**1971–2011**
9	**Tylmanowa** *Ochotnica Stream*	**1288**	**396**	**892**	**791**	**107.6**	**E**	**0.050**	**1971–2011**
10	Nowy Targ *Czarny Dunajec*	2176	581	1595	1207	432	NE	0.043	1951–2011
11	Kowaniec *Dunajec*	2301	577	1724	1245	681	NE	0.046	1951–2011
12	Krościenko *Dunajec*	2628	416	2212	1199	1580	NE	0.040	1951–2011
13	Gołkowice *Dunajec*	2628	314	2314	1089	2047	NE	0.033	1951–2011
14	Nowy Sącz *Dunajec*	2655	277	2378	1100	4341	NE	0.031	1951–2011

Relief is calculated as the difference between the highest and the lowest elevation

Aspect is the averaged aspect of the basin (*N* North; *NE* North-East; *S* South; *SW* South-West). The smallest basins (group 1) are shown on bold

Table 2 Flood variables analysed in this study

	Abbreviation	Explanation
Flood variable	AMAX	Annual maximum discharge
	POTF	Peak over threshold (third quartile) frequency
	POTM	Peak over threshold (third quartile) magnitude
	SMW	Seasonal maximum discharge for winter
	SMSp	Seasonal maximum discharge for spring
	SMSu	Seasonal maximum discharge for summer
	SMA	Seasonal maximum discharge for autumn

Considering a sample $(x_1, \ldots, x_n)$ with size n, the MK statistic, S, is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}(x_j - x_i)$$

Under the null hypothesis that there is no trend within the time series:

$$E(S) = 0,$$

$$Var(S) = n(n-1)(2n+5)/18.$$

The test statistic is the standardised value calculated as

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\text{Var}(s)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ 0 & \text{if } S < 0 \end{cases}$$

The MK test has been widely used for the trend analysis of climatologic and hydrologic time series because: (i) it is a non-parametric test and does not require the data to be normally distributed, and (ii) the test has low sensitivity to abrupt breaks due to inhomogeneous time series. According to this test, the null hypothesis H0 assumes that there is no trend (the data is independent and randomly ordered) and this is tested against the alternative hypothesis H1 assuming that there is a trend. It has been demonstrated that the presence of serial correlation may lead to an erroneous rejection of the null hypothesis (Type I error; e.g. Yue and Pilon 2003). Here, detrending was accomplished by using the so called Zhang's method, described in Wang and Swail (2001). It is known that the prewhitenning reduces the rejection rate when there is no trend. However, it has been found that this may cause the deflation of an existing trend (Yue and Wang 2002), so that a trend that is not strong enough may escape detection. To check for the influence of prewhitening on the results, both original data as well as prewhitened data were analysed, and only the results obtained with the prewhitening approach were taken into consideration.

The MK Z statistic and the significance (i.e. *p*-value) were calculated from the available time series for each flood indicator, applying the MK test to two fixed

time periods (1951–2011 and 1971–2011) and to moving windows (with a minimum window length of 30 years) following the approach proposed by Hannaford et al. (2013) and Ruiz-Villanueva et al. (2016).

3.2   Flood Trend Attribution

The goal of trend studies should not be just the detection of these changes in recorded time series and the discussion of possible causes, but they should be a tool for testing hypothesis about the influences of these drivers on floods (Merz et al. 2012). The detected trends were explained by the correlation with changes in another variable (meteorological variables, such as intense precipitation indices, maximum daily precipitation, number of days with snow cover and cyclonic circulation types, and external drivers). In the large-scale climate variability, different climate indices were analysed: the North Atlantic Oscillation (NAO), the East Atlantic (EA), the East Atlantic/Western Russia (EA/WRUS) and the Scandinavia

Table 3 Large-scale climate indices, meteorological indices and terrestrial factors analysed in this study

	Abbreviation	Explanation
Large-scale climate indices	NAO	North Atlantic Oscillation
	EA	East Atlantic
	WP	West Pacific
	EP-NP	East Pacific-North Pacific
	EA/WRUS	East Atlantic/Western Russia
	PNA	Pacific/North American
	SCA	Scandinavia pattern
	TNH	Tropical/Northern Hemisphere
	POL	Polar/Eurasia pattern
	PT	Pacific transition
Meteorological indices	MDP	Maximum daily precipitation
	Snow	Number of days with snow cover
	CCT	Cyclonic circulation types
External drivers	Urbanization	
	Deforestation/afforestation	
	Agricultural practices	
	River channelization	
	River incision	
	Construction of dikes or reservoirs	

pattern (SCAND). For this latter group of large-scale climate indices, we used correlation with the flood parameters.

In addition, changes in catchment and river characteristics were investigated, such as urbanization, deforestation and reforestation, alteration in agricultural management practices and construction of dikes or reservoirs. Table 3 summarizes all the factors analysed in this study.

4 Results and Discussion

4.1 Annual Maximum Discharge

The MK test applied at each site for the two fixed periods showed a majority of non-significant trends, although some stations showed significant trends (28 % of the stations for the period 1971–2011, and 33 % for 1951–2011, p-value < 0.2), most of them being positive trends. For the most recent period, other 14.3 % of the stations showed weak increasing tendencies (with $0.2 > p$-value < 0.5 in the MK test) and other 21.4 % weak decreasing tendencies, while for the last 50 years, 22.2 % of the stations showed weak increasing tendencies. For the longest period, 50 % of the sites exhibited weak positive tendencies. The significant positive trends were found both in the first and the second group of stations, those installed in small headwater basins in the upper part of the mountainous area, but also in the larger basins. Figure 2 shows the exploratory analysis applied to the standardized annual maxima for all the studied stations.

As Fig. 3 shows, different periods are analysed depending on availability of data. For example, the analysis applied to the Czarny Dunajec River at the Nowy Targ station (starting in 1951) resulted in a graph with numerous combinations of 30-year time windows (large number of pixels), while the result for the Lepietnica at Ludźmierz (data starting in 1970) shows a graph with less number of pixels (less time window combinations).
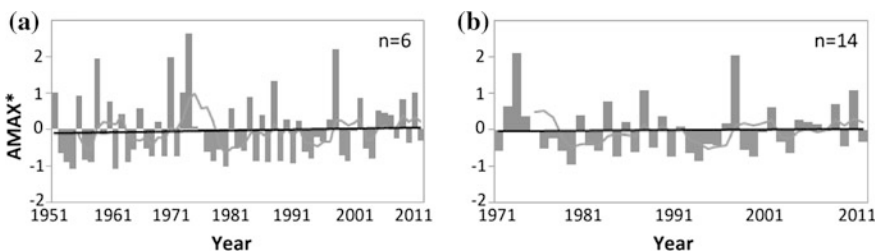

Fig. 2 Standardised annual maximum discharge (AMAX*) averaged over the studied stations for the periods 1951–2011 (**a**) and 1971–2011 (**b**). *Black line* is the linear trend, *grey curve* is the 5-year moving average, and *n* means the number of river catchments
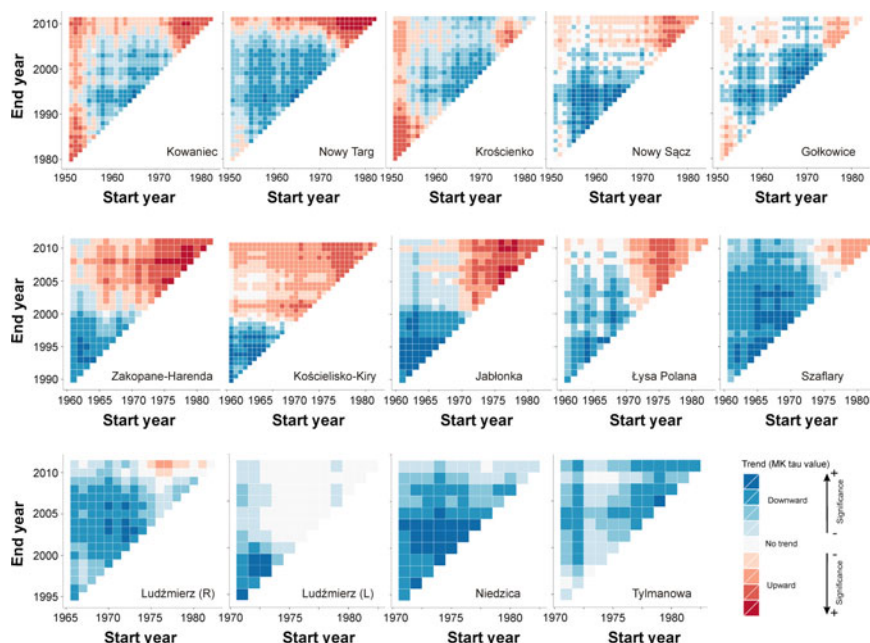
Fig. 3 Multi-temporal trend analysis for the annual maximum discharge (AMAX) for river catchments (for details on station names refer to Table 1). *Blue* and *red* cells correspond to negative and positive tau values, respectively (the darker the colour the more significant the trend)

Some conclusions can be extracted from this multi-temporal analysis. First of all, blue colours are more frequent than red colours, meaning that negative trends are more frequent than positive, especially for the most recent period (as shown on the Rogoźnik Stream at Ludźmierz and on the Lepietnica at Ludźmierz, the Niedziczanka at Niedzica and the Ochotnica Stream at Tylmanowa—Fig. 3). Second, positive trends (red colours) appear more significantly in few stations, but only in two cases the positive trend is stable over the longest time window (the Dunajec at the Kowaniec and Krościenko stations). In other cases, blue and red colours are divided along the time window, which represents a change in the general tendency, as shown in the Cicha Woda at Zakopane, the Kościeliski Stream at Kościelisko and the Czarna Orawa at Jabłonka.

4.2 Flood Frequency and Seasonality

The recorded data revealed an annual mean of 3 events with discharges higher than the third quartile (POTF) for the entire region. Some years (i.e., 1955, 1962, 1965, 1974, 1978, 1980, 1985, 1989, 2006, and 2010) were particularly rich in flood
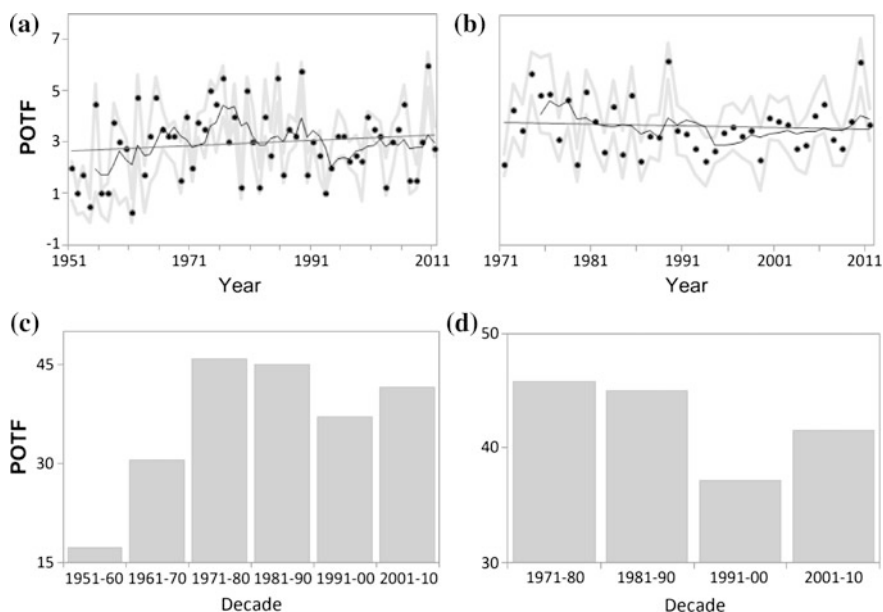
Fig. 4 Average peak over threshold (3rd quartile) frequency (POTF) plots for the periods: 1951–2011 (**a**), 1971–2011 (**b**). The plots show the mean value (*black circles*), standard deviation (*grey borders*), 5-year moving average (*black curve*) and linear regression (*black line*). Decadal averaged POTF for the periods: 1951–2011 (**c**), 1971–2011 (**d**)

events, with more than 4 events on average, and even 6 events in 2010. In contrast, in some other years (i.e., 1952, 1954, 1956, 1957, 1961, 1979, and 1993) none or just one POTF event was recorded. Interestingly, the decades when the most extreme events were recorded are not always those richest in flood events, as shown during the 1990s.

The averaged POTF for the entire studied region reveal an increasing trend (up to 35 %) of the number of events for the longest time period 1951–2011, but this tendency seems to decrease for the recent past (Fig. 4).

At-site results of the MK test for the long-term period (1951–2011) showed positive trends of POTF for 50 % of the sites, while for the most recent fixed period (1971–2011) 21 % of the sites revealed significant positive trends and 28 % negative trends (mainly present in the data from the larger basins). One example of these negative trends is illustrated by the Czarny Dunajec River (at Nowy Targ) where a reduction in the frequency and magnitude of flood flows was defined for the fourth quarter of the 20th century (1974–2000) as presented by Zawiejska and Wyżga (2010).

The seasonal discharge for the two fixed time periods illustrates importance of time window in the analysis of flood trends. As Fig. 5 shows, the EDA shows that winter discharge does not present any trend in the longest period (1951–2011), while it shows a decrease in the most recent period (1971–2011).
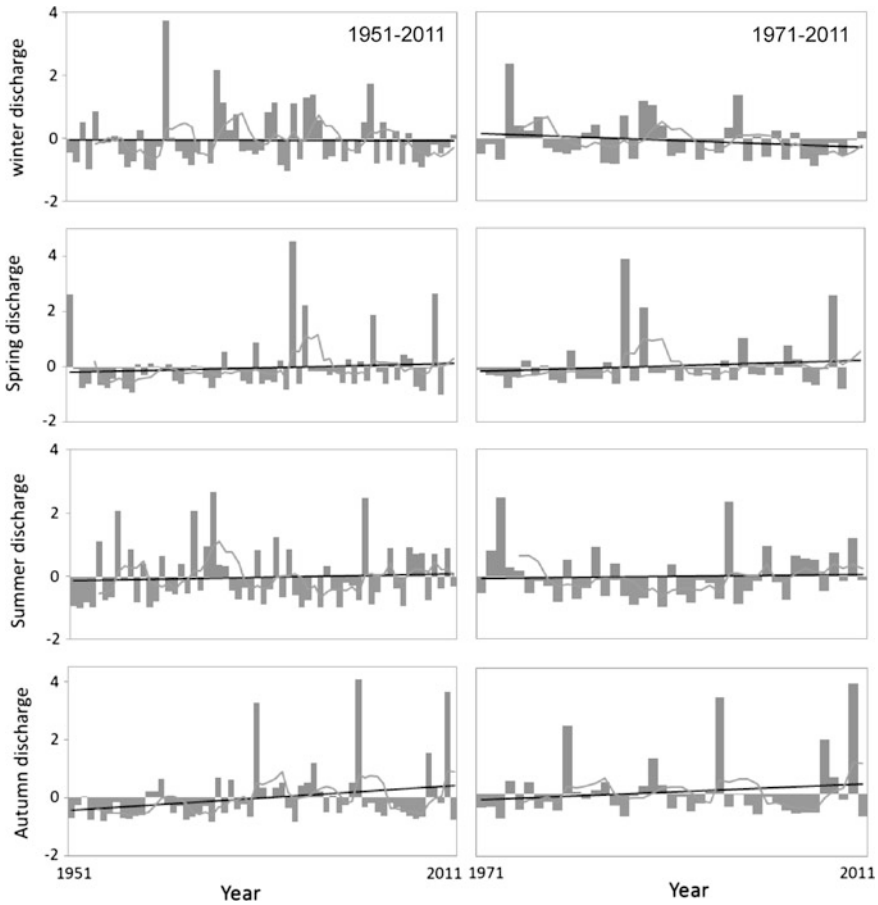
Fig. 5 Standardised seasonal maximum discharge averaged over the studied river catchments for the periods 1951–2011 and 1971–2011. *Black line* is the linear trend and *grey curve* is the 5-year moving average

The multi-temporal analysis allowed deciphering the variability (Fig. 6). Similar patterns in autumn and winter, and different in summer and spring may be observed. Darker colours show statistically significant trends, and they are more frequent in autumn and less frequent in spring. In spring, only two river catchments showed significant positive trends in the most recent period, and none for the longest period; otherwise weak, insignificant, trends were found. These stations, where strong trends were identified, belong to group 1 (small headwater basins). For autumn (SMA) significant positive trends were identified for 21 % of the river catchments in the period 1971–2011 and 50 % for the longest period, whereas in only 14 % downward trends were detected for the recent past. Although strong positive discharge trends are visible for the longest period of the autumn season, this changes to
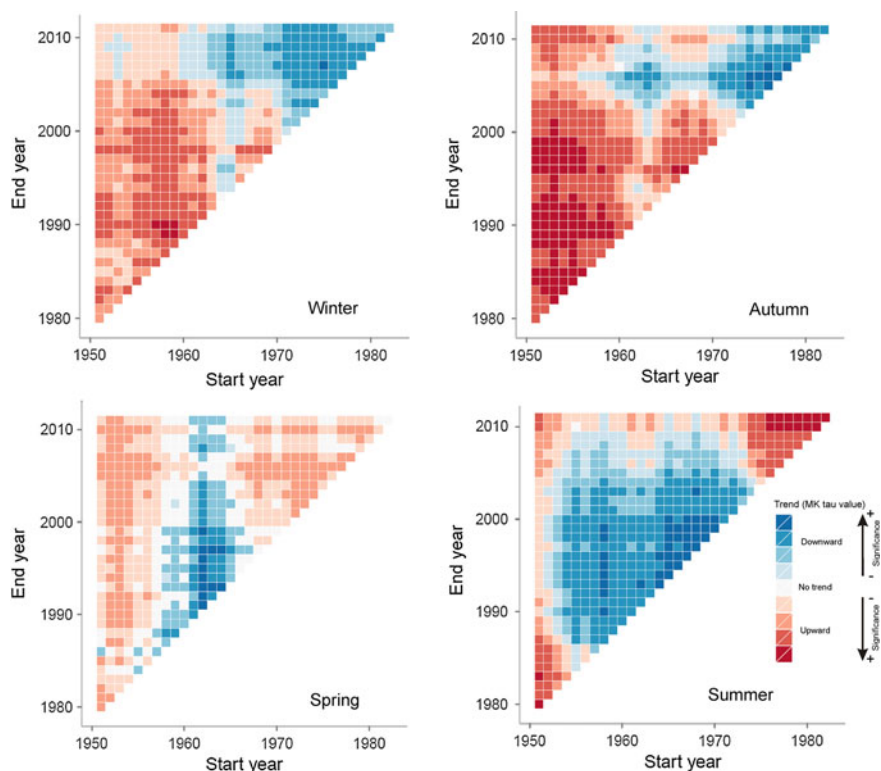
Fig. 6 Multi-temporal trend analysis for the maximum discharge in particular seasons. Legend explained in Fig. 3

a negative trend in the recent last years (Fig. 6). This pattern is even stronger in winter, when 35.7 % of the stations showed significant negative trends for the period 1971–2011, whereas only one significant positive trend and two weak negative tendencies were found for the years 1951–2011. The significant negative trends were identified in both the large and small basins. For the summer season, only 14 % of the stations showed significant positive trends for the last 40 years. The same was previously observed for the Elbe and Oder Rivers, where a significant decrease in winter floods (snowmelt related) was detected, while no significant change in summer floods was identified (Mudelsee et al. 2003). And changes of high river discharge in 20 river catchments in the Dunajec River basin revealed positive but not statistically significant trends of the majority of the runoff time series studied (1971–1990, 1984–2003, 1951–2003). The analysis was based on the normalized daily discharge data from 20 catchments with areas ranging from 58.4 to 5316 km^2. The high river discharge was defined as discharge greater than the fifth percentile of daily river discharges in a year or in a half-year seasons in particular years (Kasina et al. 2006–2007).

4.3 Summary of Flood Trends

The presented results showed that there has been no ubiquitous increase in the flood frequency and/or magnitude over the second half of the 20th century for the entire region analysed. However, significant trends, both positive and negative, were detected for a considerable proportion of the studied stations (Ruiz-Villanueva et al. 2016). In a regional perspective, decreasing trends of annual maxima (especially for the headwater small basins) and winter seasonal maxima were slightly dominant in the northern foreland of the Tatra Mountains during the last 60 years, while increasing frequency of floods was observed. It is also evident that changes in floods were not uniformly distributed between sites and between seasons. It is partially consistent with earlier studies conducted at various scales. Kundzewicz et al. (2004, 2005) examined a set of 195 long-time series of annual values of maximum daily discharge worldwide, therein 70 series from European rivers, of which only 20 showed statistically significant changes. Therefore, the potential response of river runoff to climate change in Poland is still uncertain (Pociask-Karteczka 2011). However, changes in the hydrological regime, as expressed by the increasing contribution of mean and high rates of discharge and a decreasing contribution of low rates of discharge have been observed, particularly in the second part of the 20th century (Pociask-Karteczka et al. 2010; Pociask-Karteczka 2014).

There have been many other national studies analysing long time-series of high river flow records in Europe, aimed to detect signals of change. There are 14 national and regional chapters in the book edited by Kundzewicz (2012), examining the changes in flood hazard in European countries and regions, but, typically, no ubiquitous, geographically organized, uniform increasing patterns of climate-driven changes in the flood magnitude/frequency could be detected. However, less frequent is the multi-temporal analysis which shows the inter-decadal variability and highlights considerable variability of trends in time (Petrow et al. 2009; Schmocker-Fackel and Naef 2010). According to Hannaford et al. (2013), fixed periods are essential for trend analysis, but a question could arise as to how representative is the found trend? With the approach used in this study, the decadal variability and determining some representative changes over long timescales were investigated.

4.4 Potential Drivers of Flood Trends

4.4.1 Meteorological Drivers

According to previous studies, after a dry period between 1951 and 1957 a frequency of high daily precipitation totals increased in the years 1958–1980 (Niedźwiedź et al. 2015). Analysis of the number of days with precipitation sum of ≥ 50 mm in Poland in the years 1971–2000 leads to the conclusion that the

number of such days is growing at a rate of 2 days per decade, especially in the southern and central parts and locally in the north of the country. These trends are persistent in the first decade of the 21st century. Moreover, the number of days with precipitation sum of ≥30 mm is also increasing, while the number of days with precipitation sum of ≥20 mm is increasing almost all over the country at a rate of 4 days per decade (Lorenc et al. 2012). This increase was associated with an occurrence of the highest flood discharges in the region. The last decade may also be considered wet. In turn, decreases in maximum daily rainfall in the years 1981–1996 resulted in a significant lowering of flood discharges of the studied rivers. This would be in agreement with our findings regarding the frequency of flood events above the threshold of the third quartile, although they do not entirely explain discovered trends.

Statistically significant trends were not found for the maximum 24 h precipitation (Łupikasza 2010), although some short-term fluctuations might be evident with clustering of extreme events (Starkel 2001). These findings mean that annual high precipitation is not the only factor responsible for the flood variability in the studied region. The occurrence of floods also depends on seasonal precipitation totals. Recent data indicates a clear decrease in the summer precipitation (JJA) since 2011 with the summer of 2015 being the driest of the last 65 years. In summer 2015 a seasonal total precipitation reached only 182 mm (34 % of the 1951–2015 total) in Zakopane while 281 mm (46 % of the average) at the Kasprowy Wierch station. On the other hand, extremely high precipitation generating flood can also occur during dry periods.

The number of days with snow cover and maximum snow depth might be important to the streamflow contribution, especially in spring when snow-melt floods are expected. A previous study revealed a statistically significant decreasing trends in the number of days with snow cover for the period 1961–1990 (Falarz 2002), while at the decadal scale the duration of snow cover was more stable particularly in the years 1954–1960, 1970–1980 and 1990–1998 (Falarz 2013). The decrease in the number of days with snow cover could mean that snow melting takes place earlier in the year, which corresponds with a slight increase in flood discharge in spring and a decrease in winter, as it has been observed.

There is no significant trend in the summer discharge, however, the frequency of floods in summer is usually linked to three cyclonic circulation types (Niedźwiedź 2003a, b): north cyclonic (Nc), north-east cyclonic (NEc) and cyclonic trough (Bc), and the frequency of these types of air circulation increased by about 20 % over the second half of the 20th century (Niedźwiedź et al. 2015). There is a significant decrease ($p < 0.001$) in meridional westerly circulation index (Wi) which is inversely correlated with the frequency of the summer flood precipitation over the Tatra Mountains. Decreasing trends in this index mean the intensification of air advection from the eastern sector including the air advection from NE direction. A significant increase in the frequency of cyclonic situations is noticeable in the warm half-year (May–October). These trends may indicate a possible increase in the occurrence of floods. However, flood precipitation occurrence is determined, among others, by synoptic conditions in particular years and may not follow the

general trends. For example, extremely dry 2015 year was accompanied by an exceptionally low value of cyclonicity index (Niedzwiedz and Lupikasza 2016).

Temperature is a factor indirectly influencing streamflow as it is responsible for the evaporation and moisture. The study carried out by Przybylak et al. (2007) described an increase of the maximum temperature in terms of average annual values and the number of days exceeding commonly used threshold values, i.e., 25 °C (hot days), 30 °C (very hot days) and 35 °C (extremely hot days). According to this work, this trend is particularly strong from the beginning of the 1990s, while extremely hot days occurred very rarely prior to 1985. Summer 2015 brought exceptionally high frequency of hot days in the southern Poland that reached 51 days in Katowice and 34 days in Zakopane. In that year, the number of very hot summer days exceeded 28 days in Katowice. Przybylak et al. (2007) also analysed the moisture index (defined as the difference between precipitation and potential evapotranspiration) and they reported statistically significant increasing trends of extremely dry and very dry days, with an increase of 1–2 days before the 1990s to greater than 5 days afterwards. On the other hand, they observed statistically significant decreasing trends of the extremely wet days and very wet days, decreasing from 3 to 6 days in the period 1951–1980 to 1–3 days for the last 25 years. These findings could explain the trends discovered in the annual maximum discharge data sets.

4.4.2 Large-Scale Climate Drivers

Ten indices characterizing the large-scale climate variability patterns for the studied region (Table 3) were correlated with the flood parameters (for details, see Ruiz-Villanueva et al. 2016). Four out of the 10 indices were selected: the East Atlantic (EA), the East Atlantic/Western Russia (EA/WRUS), the North Atlantic Oscillation (NAO) and the Scandinavia pattern (SCA). The criterion for selection was the strength of the links between these indices and the flood variables found in our study or indicated in literature. Table 4 shows Pearson correlation coefficient (R) computed between selected climatic indices and flood-related variables for the two studied periods.

The EA pattern shows a general upward tendency for the period 1951–2011 towards the positive phase that is associated with above-average precipitation over northern Europe. A slight positive correlation of EA with flood magnitudes (AMAX) was found.

In contrast, the EA/WRUS pattern shows a linear negative trend for the last 60 years, with a tendency of its negative phase in the annual scale (related to above-average precipitation), and in all seasons except winter when the trend is towards its positive phase (reflecting below-average precipitation over Europe). In effect, in the annual scale, a positive correlation with flood magnitudes (AMAX) in the region has been revealed, while the negative trend of winter floods could be linked to the winter trend of this climate index. Similarly to EA/WURS, the SCA pattern also shows a negative linear trend, possibly related to above-average

Table 4 Pearson correlation R computed between selected climatic indices and analysed hydrological variables for the two studied periods

Index		Correlation (Pearson's R, Kendall's tau significance)			
		1951–2011		1971–2011	
Annual	Tendency	AMAX	POTF	AMAX	POTF
NAO	Up	**−0.19**	**−0.18**	**−0.35**	**−0.32**
EA	Up	+0.11	No cor.	+0.025	No cor.
EA/WRUS	Down	+0.13	+0.04	+0.051	**+0.24**
SCA	Down	−0.045	+0.11	−0.075	**+0.20**
Summer		SMSu		SMSu	
NAO	Down	−0.018		−0.04	
EA	Up	+0.07		+0.092	
EA/WRUS	Down	**+0.25**		+0.13	
SCA	Down	**+0.33**		**+0.36**	
Spring		SMSp		SMSp	
NAO	Up	+0.01		+0.014	
EA	Up	+0.037		+0.071	
EA/WRUS	No trend	−0.058		−0.033	
SCA	Down	−0.069		−0.05	
Autumn		SMA		SMA	
NAO	Down	**−0.22**		**−0.25**	
EA	Up	+0.085		+0.021	
EA/WRUS	Down	−0.16		**−0.27**	
SCA	Down	+0.031		+0.053	
Winter		SMW		SMW	
NAO	Up	+0.11		**+0.16**	
EA	Up	**+0.22**		**+0.19**	
EA/WRUS	Up	+0.14		+0.12	
SCA	Down	−0.11		−0.09	

Tendency represents the linear trend observed in the EDA. Statistically significant correlations (based on Kendall tau test p-value < 0.05) are shown in bold. Notation explained in Table 3

precipitation across central and southern Europe. However, no correlation with examined flood variables for the studied region was found, although a link between extreme discharges of some Carpathian rivers and the SCA index has been noted in other studies (Pociask-Karteczka et al. 2003; Pociask-Karteczka 2007).

The NAO pattern identified as one of the essential patterns of climate variability in the Northern Hemisphere, exhibited an increasing tendency (to the positive phase) at the annual scale for a longer period (1951–2011) that seems to slow down over the last decades. Strong positive phases of the NAO tend to be associated with below-average precipitation over southern and central Europe. Both examined flood characteristics (AMAX and POTF) are significantly correlated with negative NAO phases. This would explain the increase of both flood variables over the longer

period (1951–2011) and the decrease of flood frequency in the shorter period (1971–2011). At the seasonal scale, the increase in flood magnitude in autumn is also related to more persistent negative NAO phase, whereas the decrease in the magnitude of winter floods is related to an upward trend identified in the seasonal NAO index (associated with less snow cover).

A lag between the response of river discharge and the behaviour of the NAO index can be apparent at a monthly resolution (cf. Trigo 2011). This aspect was already investigated by relating spring maxima to winter NAO index to study snowmelt-induced floods in Poland (Kaczmarek 2003). For the Dunajec catchment, Pociask-Karteczka and Nieckarz (2010) found various relationships between 10-day high flows in spring and summer and the NAO index in preceding winter. In order to analyse this possible lag, we plotted AMAX together with the values of seasonal NAO index and analysed possible correlations for the longer period. We found a negative correlation between AMAX and NAOW (NAO winter) and positive, statistically significant, correlation with NAOA (NAO autumn). Therefore, extremely low NAOW value corresponds with the river flow increase. This is in agreement with the findings of Pociask-Karteczka (2007) who observed that considerable flooding of the Vistula and Odra occurs after winters for which the values of the NAO index are extremely low.

It may be concluded that the interpretation of links between large-scale climate anomalies and flood indices in the studied region remains a challenging research area that requires further studies since flood management practices are likely to benefit from improved medium-term (e.g. seasonal) weather forecasts that depend on forecasting of these indices, and particularly of the NAO index (Salgueiro et al. 2013). Nevertheless, it must be remembered that heavy, flood-inducing precipitation in the Upper Vistula Basin depends more on local air circulation than on macroscale circulation. Despite atmospheric circulation, orography is of crucial significance in this complex terrain.

4.4.3 Other Potential Drivers

The results have indicated the relationships between flood trends and changes in some atmospheric variables, but the latter only partly explain the variability of streamflow. Therefore, non-climatic changes in catchment and river parameters must also be taken into account.

During the past decades some environmental changes occurred in the studied catchments that influence the conditions of flood runoff (Table 5). Land use and land cover changed and forestry has been changing in the northern foreland of the Tatra Mountains, mainly due to transformations of land use systems after 1990 (e.g. land reforms, policy changes, socioeconomic transformation, accession to the European Union, international agreements) and land use legacies from Austro-Hungarian and Socialist times. Main processes include farmland abandonment and forest expansion and agricultural parcelization. A contribution of arable land decreased considerably in favour of forested areas (Wyżga et al. 2012), with

the land use changes slowing down runoff and reducing peak flows. In the former Czechoslovakia where a large part of the Poprad catchment is located, collectivization of farms shortly after the World War II resulted in the formation of large plots of cultivated land that accelerated runoff processes, especially as a consequence of rapid development of gullies (Stankoviansky and Barka 2007). Development of the town of Zakopane increased the share of paved surfaces in the catchment of Cicha Woda, hence accelerating the runoff from the area. Since 2004 a few events of widespread windthrow of mature spruce forest have occurred in the Slovak and Polish parts of the Tatra Mountains, followed by bark beetle infestation (Kopecká and Nováček 2009). As the forest damage occurred in the area with high intensities and totals of precipitation, it must have increased and accelerated runoff from the deforested hillslopes, especially during a few years after the events.

Another group of impacts on the conditions of flood runoff encompasses direct human interventions in the studied river channels (Table 5). Channelization works on the Dunajec, carried out in the 1950s–1970s, resulted in the narrowing and considerable simplification of its channel (Zawiejska and Wyżga 2010). Since the

Table 5 Summary of main regional environmental changes since the mid-20th century and their effects on flood runoff

Regional environmental change	Time of change	Effects on floods
Reduction in the proportion of arable land coupled with increase in forest cover	Second half of the 20th century	Change in albedo, increased evapotranspiration, slowed down runoff from hillslopes
Farm collectivization (Slovak part of the Poprad catchment)	The early 1950s	Enhanced slope gullying due to the elimination of agricultural terraces, accelerated runoff from hillslopes
Urbanization	Second half of the 20th century	Significant effect on the Cicha Woda catchment where the town of Zakopane is located
Widespread forest windthrows followed by bark beetle infestation in the Tatras	2004 and the following years	Change in albedo, decreased evapotranspiration, accelerated water runoff from hillslopes
Large-scale, in-channel gravel mining	The 1950s–1960s	Channel incision leading to the concentration of flood runoff in river channels and the reduction of water storage in floodplain areas
River training works (simplification of channel pattern, channel narrowing)	The 1950s–1970s in the Dunajec, since the 1960s in headwater watercourses	Shortening of the travel time of flood waves, channel incision, both leading to increased peak flows in the downstream reaches
Construction of Czorsztyn Reservoir	1997	Reduction of peak flows of flood waves

1960s streams and rivers in the headwater catchments have also been subjected to channelization works that substantially (up to a fifth of the original value) narrowed the watercourses and replaced their former multi-thread channels by single, artificial ones along a majority of their courses (Korpak 2007; Zawiejska and Wyżga 2010; Wyżga et al. 2012).

During the 1950s–1960s, large-scale gravel mining was conducted in rivers, especially in the Czarny Dunajec. In the following decades, it was replaced by widely distributed, illegal extraction of cobbles from the river channels (Zawiejska and Wyżga 2010; Zawiejska et al. 2015). A considerable shrinkage of sediment available for fluvial transport, resulting from the gravel mining, together with an increase in transport capacity of the watercourses caused by their channelization (Wyżga 2001) induced rapid channel incision (Wyżga 2008; Wyżga et al. 2016). To date, up to 3.5 m of bed degradation have occurred in the rivers of the study area (Zawiejska and Wyżga 2010). The effect of channel incision on the resultant increase in channel capacity and reduction in the frequency of floodplain inundation was especially large in upper river courses where the initial capacity of their channels was small (Wyżga et al. 2016). Flood magnitudes in the foothill and foreland reaches of Polish Carpathian rivers were demonstrated to have increased as a result of upstream channel straightening and incision (Wyżga 1997, 2008).

The above discussion indicated complex temporal and spatial patterns of the impacts of non-climatic environmental changes on flood runoff from the catchments in the northern foreland of the Tatra Mountains. In the headwater catchments, runoff processes have been predominantly affected by the counteracting effects of forest cover increase that gradually progressed over the second half of the 20th century (but was interrupted by the windthrow events from the last 10 years), and those of channelization and channel incision. In the group of the five largest catchments, the scale of catchment reforestation diminished towards lower areas more suitable for agriculture, and thus its effect on runoff most likely lowered with increasing catchment size. In turn, the effects of channelization and channel incision on flood runoff should increase with the length of modified channels, hence being more pronounced in the stations located downstream. While the flood record in the largest catchments integrates the effects of all upstream-operating factors, analysis of the results for individual stations may reveal some specific drivers. For instance, a significant negative trend in flood frequency coupled with a significant positive trend in flood magnitude was found for the Dunajec River at Gołkowice. The station is located a few tens of kilometres downstream of the Czorsztyn Reservoir that started to operate in 1997. The reduction in the frequency of largest floods is a typical effect of the operation of dam reservoirs. At the same time, the increase in flood magnitude at some distance from the reservoir might be attributed to the loss of floodplain water storage along the river reach (Wyżga et al. 2016) where deep channel incision took place in the second half of the 20th century (Zawiejska and Wyżga 2010).

5 Concluding Remarks

The present chapter aims to analyse the inter-decadal variability of magnitude, frequency, and seasonality of floods in the Tatra Mountains foreland, on decadal timescales, since the mid-20th century. A multi-temporal approach was employed and trends were fitted to several combinations of start and end years in a record. This allowed identifying the extent to which observed trends in two fixed periods are influenced. The presented results showed that there has been no ubiquitous increase in the flood frequency and/or magnitude over the second half of the 20th century for the entire region analysed. However, even if a majority of non-significant trends were found, significant trends (both positive and negative) were also detected for a considerable number of the studied river catchments. Analysis was made for annual as well as seasonal values. It was found that changes in floods were not uniformly distributed between sites and between seasons (more details in Ruiz-Villanueva et al. 2016).

In order to explain the detected trends, the flood parameters of interest were correlated with 10 indices describing the large-scale climate variability for the Northern Hemisphere and compared with trends found in intense precipitation indices, number of days with snow cover, cyclonic circulation types, air temperature and moisture conditions. Links with four indices, i.e., NAO, EA, EA/WRUS, SCA, expressed by Pearson correlation, were interesting and promising. Other external, non-climatic, drivers, such as catchment and channel changes were also considered in the studied region. Results show that floods in the area exhibit considerable inter-decadal variability, however, certain patterns are apparent. Less frequent floods, although perhaps more extreme, are now likely to occur, with a shift in the seasonality, decreasing flood magnitudes in winter and increasing during autumn and spring.

According to Merz et al. (2012) it may be stated that different drivers, climatic and non-climatic, act in parallel and interact in a catchment, while changes in flood behaviour are the integral response of the catchment to these different drivers and to their interactions.

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