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ORIGINAL ARTICLE

Decadal variability of floods in the northern foreland of the Tatra Mountains

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Abstract Floods in the northern foreland of the Tatra Mountains considerably contribute to the total flood damage in Poland. Therefore, the question whether the magnitude and frequency of floods have changed in this region is of high interest. This study aims at investigating the inter-decadal variability of magnitude, frequency and seasonality of floods since the mid-twentieth century, to better understand regional changes. The analysis was accomplished in a multi-temporal approach whereby trends are fitted to every possible combination of start and end years in a record. Detected trends were explained by estimating correlations between the investigated flood parameters and different large-scale climate indices for the northern hemisphere, and by trends found in intense precipitation indices, number of days with snow cover, cyclonic circulation types, temperature and moisture conditions. Catchment and channel changes that occurred in the region over the past decades were also considered. Results show that rivers in the area exhibit considerable inter-decadal variability of flows. The magnitude and direction of short-term trends are heavily influenced by this inter-decadal variability; however, certain patterns are apparent. More extreme, although perhaps less frequent floods are now likely to occur, with a shift in the seasonality, decreasing flood magnitudes in winter and increasing during autumn and spring. The identification of the factors contributing to the occurrence of flood events and their potential changes is valuable to enhance the flood management in the region and to improve the resilience of the population in this mountainous area.

Keywords River flow · Flood hazard · Climate change · Trend · Mann–Kendall test · Tatra Mountains foreland

Introduction

There has been a broadly established expectation that climatic change is likely to increase river run-off in many regions, because the warming would accelerate the hydrological cycle and projected increases in heavy rainfall would contribute to increases in local rain-caused flooding (Seneviratne et al. 2012). Impacts of climatic change particularly on mountains are of relevance because 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; Allamano et al. 2009), and due to the importance of the potential

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increase of flood risk in these areas (Olsen et al. 1998; Palmer and Ralsanen 2002; Merz et al. 2012). In recent studies of flood projections based on ensembles of general circulation model (GCM) simulations (CMIP5 results) in combination with global hydrology models, Hirabayashi et al. (2013) and Dankers et al. (2013) found the flood hazard to increase in the future in more than half of the land areas of the globe, in particular outside the European continent. In Europe, the projected situation is much more heterogeneous, with decreases over a larger part of the continent and increases over its smaller part. However, at a smaller scale, even the sign of the change does not necessarily agree among results obtained for different GCM simulations. As a conclusion, even if there have been many national studies on change detection in the long time series of high river flow records in Europe, typically, no ubiquitous, geographically organized patterns of climate-driven changes in the flood magnitude/frequency could be detected (Kundzewicz 2012).

However, climate change is not the only possible driver of change in flood time series. Flooding is a complex phenomenon, caused by a number of factors, integrating the influence of atmospheric variables over a watershed (Kundzewicz and Schellnhuber 2004). In general, land-use changes, which drive land-cover changes, induce changes of terrestrial (hydrological and ecological) systems and control the rainfall–run-off relations (change of water storage area and run-off coefficient) hence impacting on flood risk. Deforestation and urbanization, elimination of wetlands and washlands, disconnection of flood plains and the channel caused by levee construction or channel incision adversely affect flood behaviour.

Apart from the inherent complexity involved in detecting a greenhouse signal in flow records, there are serious problems related to the data and to the methodology of change/trend detection (Kundzewicz and Robson 2004). Hence, use of data from pristine (baseline) river basins is recommended, but baseline conditions are rare.

Human activity in the northern foreland of the Tatras started relatively early, reaching the highest parts of the mountains more than a century ago. The region has been typified by high population density since the late part of the eighteenth century, and this has resulted in considerable agricultural and pastoral pressure on the catchment. However, over the twentieth century, the percentage of arable land decreased significantly and forest cover increased as well (Wyżga et al. 2012). After the establishment of the Tatrzański (Tatra) National Park in 1955, restricted developments took place as a result of the national park regulations, and the state of Tatra forests improved considerably (Jahn 1979). However, other types of human impacts appeared: urbanization, channelization of rivers and streams, in-channel gravel mining and channel incision (Korpak 2007; Zawiejska and Wyżga 2010). Nonetheless, a major part of the national flood damage in Poland occurred in the basin of the Upper Vistula River (Punzet 1991), especially on its tributaries in the northern foreland of the Tatra Mountains. In the course of the twentieth century, 41 significant floods were caused by abundant rainfall in the Carpathian part of the 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). These events affected particularly the right-hand tributaries of the Upper Vistula and took place in July and May/June, respectively.

This paper aims to characterize patterns of 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 three fixed periods are influenced. The aim is to determine whether changes in recent decades are representative of the magnitude and direction of change over longer timescales. The causal aspects of 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.

The northern foreland of the Tatra Mountains

Water gauge stations analysed in the study are located in the northern foreland of the Tatra Mountains in southern Poland (Fig. 1). Nearly all the stations are situated in the upper and middle parts of the drainage basin of the Dunajec, the second largest tributary to the Upper Vistula. Only the Jabłonka station (number 7 in Fig. 1) is located to the south of the main Carpathian water divide, on the Czarna Orawa River which flows towards the Danube. The Dunajec (in its uppermost course called the Czarny Dunajec) and its major tributaries the rivers of Biały Dunajec, Białka and Poprad originate in the high-mountain Tatra massif, with elevations up to 2,655 m a.s.l. The Tatras are a young mountain range from the alpine orogeny. Their highest parts are underlain by granite and metamorphic rocks, while the northern slopes are mainly composed of carbonate rocks. Outside the Tatras, the area drained by the study rivers ranges from 277 to 1,368 m a.s.l. Most of it exhibits mountain to foothill relief and is underlain by flysch rocks.

In the Tatra Mountains, a sequence of vegetation belts exists, starting from montane mixed forest through subalpine spruce forest, dwarf pine belt and alpine meadows to subnival zone with bare rocks. In the foreland of the Tatras,

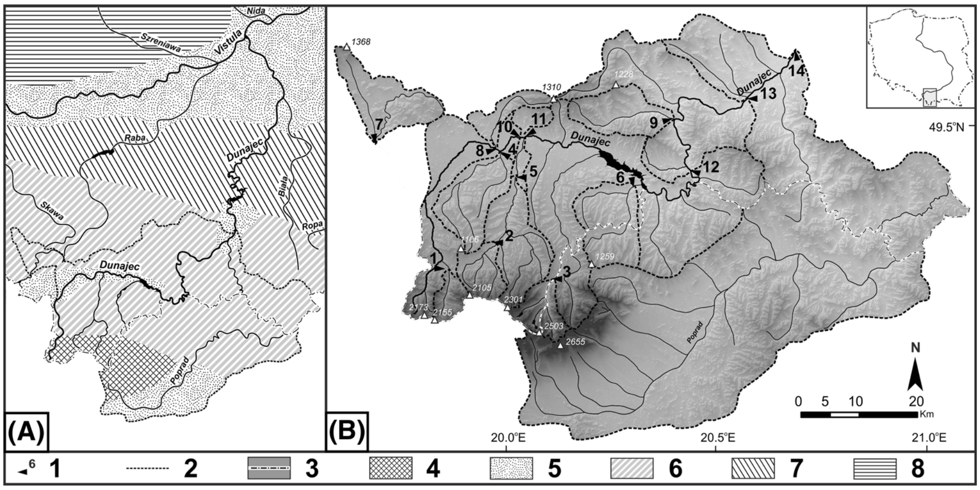

Fig. 1 **a** Location of the study area in relation to physiogeographic regions of southern Poland and **b** detailed setting of the studied catchments in the northern foreland of the Tatra Mountains. *1* water gauge stations; *2* boundaries of the studied catchments; *3* state boundary; *4* high mountains; *5* intramontane and submontane depressions; *6* mountains of intermediate and low height; *7* foothills; *8* uplands

natural vegetation belts comprise deciduous forest typical of foothill slopes, montane mixed forest and subalpine spruce forest. However, a majority of this area is deforested and either cultivated or covered with grassland.

Precipitation recorded on the northern slopes of the Tatra Mountains is the highest in Poland. Here, average annual precipitation totals range from 1,100 mm at the base of the mountains to about 1,800 mm in the summit parts. At Kasprowy Wierch (1,991 m a.s.l.), mean annual precipitation in 1951–2012 was 1765 mm, but the record-high annual precipitation total was 2,599 mm in 2001 (with monthly maximum of 651 mm in July) (Kundzewicz et al. 2014). The predominant precipitation type responsible for the generation of major floods in the entire or most of the study area is in the form of prolonged rainfalls lasting for 2–5 days, with intensities >50–100 mm d^{-1} (maximum 300 mm d^{-1}), usually associated with northern (Nc), north-eastern (NEc) north-western cyclonic (NWc), cyclone centre (Cc) and cyclonic trough (Bc) circulation types, often with cyclones following the so-called track Vb (von Bebber 1891) from the Adriatic Sea through Hungary to Ukraine or eastern Poland. Heavy downpours from thunderstorm cells, with rainfall intensity up to 100–200 mm h^{-1}, may cause local flash floods. Snow-melt floods are of minor importance due to the varying time of snow pack melting at particular elevations in the region.

Materials and methods

We used streamflow data series from 14 water gauge stations in the northern foreland of the Tatra Mountains. Table 1S in the supplementary material summarizes the most important characteristics of the studied basins. The main criteria for station selection were (a) availability of data; (b) at least 40 years of continuous and complete observations until 2011; and (c) spatial independence between station records. For stations located along the same river, spatial independence 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 exits between them. The hydrological stations can be attributed to two different groups:

- A first group formed by the 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;
- A second group composed of the larger basins with drainage areas from 430 to 4,300 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 (Table 1S), which makes this group of basins an indicator of regional environmental changes, including climatic ones, rather than a change in the predominant pattern of atmospheric circulation over the area.

Seven hydrological variables were analysed (Table 1). The analysis of floods may differentiate the flood generation mechanisms (e.g. snowmelt vs. rainfall) without treating all floods as one category. Therefore, four climatologic seasons may be defined and analysed separately: winter [December, January and February; (DJF)], spring [March, April, May; (MAM)], summer [June, July, August; (JJA)] and autumn [September, October, November; (SON)], and the seasonal maximum discharge was analysed for each (Table 1).

A multi-temporal trend analysis was conducted and then compared with three fixed periods: (i) long term, 1951–2011 for 6 sites; (ii) 1961–2011 for 10; and (iii)

Table 1 Hydrological variables, large-scale climate indices, meteorological indices and terrestrial factors analysed in this study

	Abbreviation	Explanation
Flood variable	AMAX	annual maxima
	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
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/reforestation
		agricultural management practices
		river channelization
		river incision
		construction of dikes or reservoirs

recent past, 1971–2011 for 14 sites. Multi-temporal trend analyses were conducted by the nonparametric Mann–Kendall (MK) test, often used in hydrological studies (Burn et al. 2012), detrending was accomplished by using the so called Zhang's method (described in Wang and Swail 2001) and field significance of the trends across the entire region was tested by resampling using bootstrap approach (Yue et al. 2002; Birsan et al. 2005; Petrow and Merz 2009). Multi-temporal means applying the MK test to moving windows in a time series (with a minimum window length of 30 year applied) following the approach by Hannaford et al. (2013).

In order to explain and understand the detected trends in the different hydrological parameters mentioned above, we analysed several potential drivers for attribution. First, we looked at meteorological variables (Table 1) and the already identified trends (Przybylak et al. 2007; Niedźwiedź et al. 2014). In terms of large-scale climate variability, different climate indices for northern hemisphere were analysed (Table 1). Regression models between hydrological and climate oscillation indices were tested using the Pearson's linear correlation and the Kendalĺs tau test. This latter coefficient is a rank-based alternative which may be more relevant for non-linear associations (Giuntoli et al. 2013).

In addition, human-induced changes in the studied catchments and rivers (Table 1) were investigated for the last few decades. The main changes having occurred in the last 60 years were pointed out and the most important impacts on floods were discussed. These are referred to here as external drivers (Stocker et al. 2010).

Results and discussion

Multi-temporal flood trends

Annual maxima and main floods

Rivers in the northern foreland of the Tatra Mountains exhibit considerable flow variability. Even if the magnitude and direction of the identified short-term trends are heavily influenced by inter-decadal variability, certain patterns were apparent.

Positive slopes are observed for the linear trends for the periods 1951–2011 and 1961–2011 (Fig. 2a, b), whereas a clear linear trend is not observed for the shortest period (1971–2011; Fig. 2c). According to Fig. 2 and the year-to-year analysis, the annual maxima increased over the longest period (the last 60 years), although at a decadal scale, the variability in the regional time series can be observed (Fig. 2d–f). However, this variability is easily identified in the multi-temporal trend analysis (Fig. 2g–i), going to an upward trend for the last decades. The first main observation is therefore the influence of the time window, since a fixed study period represents just one pixel in the multi-temporal trend plots.

The 1950s were characterized by low (below-average) values of annual maxima, with a clear tendency to increase, ending with an important event in 1958. The 1960s were characterized by maximum discharges increasing above the average, until 1970 when a large event occurred. These two decades (1951–1970) show slightly positive linear trends (Fig. 2 d, e, g, h). Noteworthy are the 1970s, with one of the highest flood discharges in the region recorded in 1973 (maximum value recorded in 55.5 % of the stations) and showing a clear

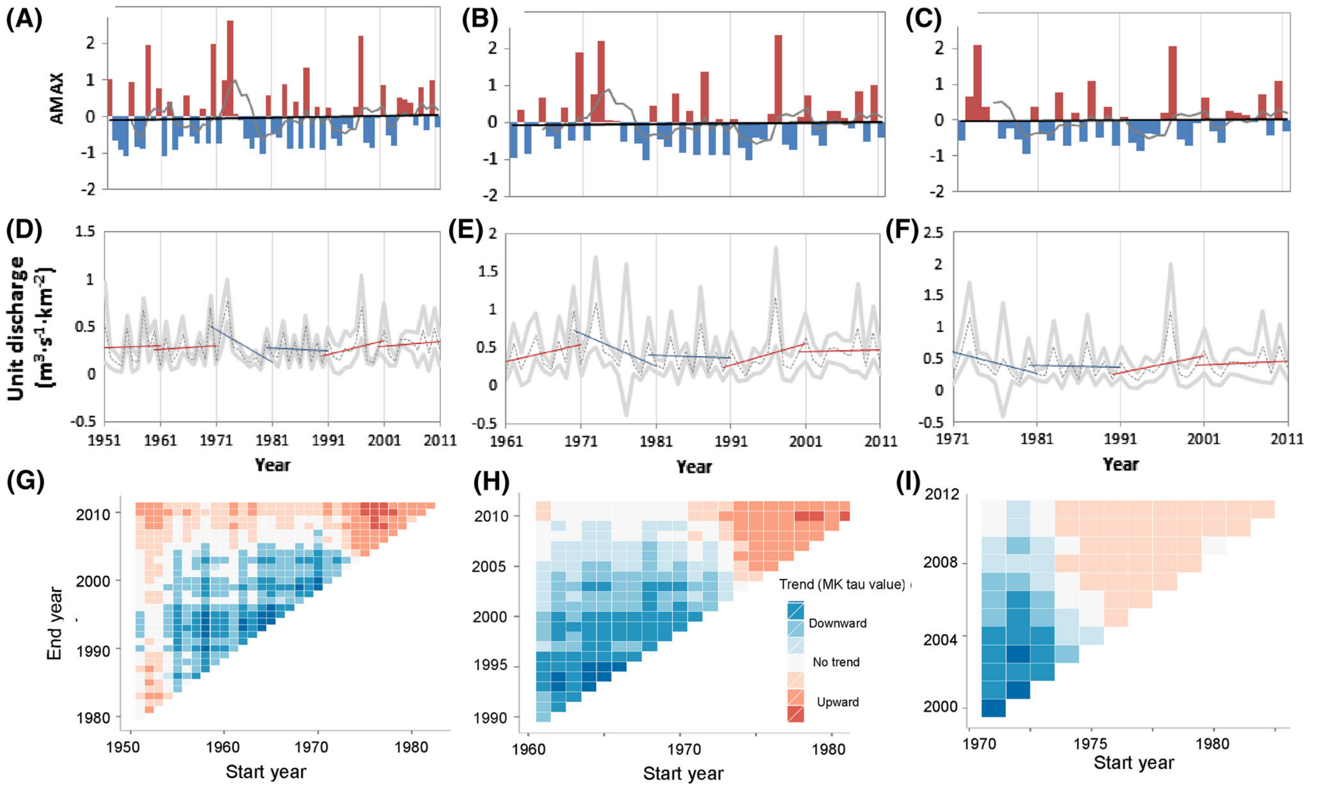

Fig. 2 Standardized annual maximum discharge (AMAX) averaged over sites for the periods: **a** 1951–2011 for six stations, **b** 1961–2011 for 10 stations and **c** 1971–2011 for 14 stations. *Grey curve* is the 5-years moving average, *black line* is the linear trend. **d**–**f** Decadal linear trends with 2 years overlapping (*black lines*) of the averaged unit (specific) discharge for the periods: **d** 1951–2011, **e** 1961–2011 and **f** 1971–2011. Mean value (*dashed grey line*), standard deviation (*grey borders*). Multi-temporal trend analysis for averaged AMAX for the same three periods: **g** 1951–2011, **h** 1961–2011 and **i** and 1971–2011. *Blue* and *red cells* correspond to negative and positive tau values, respectively (the darker the colour the more significant trend)

downward trend. In the 1980s, discharges were slightly decreasing, especially in its early part, when values were in general below the average and a weak negative trend was detected. However, it was not until 1991 when the AMAX apparently increased again (in 1997, another large flood was recorded that caused heavy damage; Kundzewicz et al. 1999). Therefore, the individual extreme events in 1958, 1970 and 1997 may largely explain the decadal behaviour and the above-mentioned changes, but the general pattern seems to be a regional upward trend in the annual maxima for the period 1951–2011. Other large events occurred in 1955, 1958, 1960, 1965, 1973, 1983, 1987, 2001, 2008 and 2010.

The MK test applied at each site for the three fixed periods showed that not many cases are statistically significant (28 % of the stations for the period 1971–2011, 11.1 % for 1961–2011, and 33 % for 1951–2011, p value < 0.2). In all the cases, the significant trends in AMAX were upward trends. For the most recent period, other 14.3 % of the stations showed weak upward tendencies (with $0.2 > p$ value < 0.5 in the MK test) and other 21.4 % weak downward tendencies, while for the last 50 years, 22.2 % of the stations showed weak upward tendencies. For the longest period, 50 % of the sites exhibited weak positive tendencies. The significant upward trends were defined both in the first and the second group of stations, those installed in small head-water basins in the upper part of the mountainous area, but also in the larger stations. Figure 2S in the supplementary material shows the multi-temporal trend analysis applied in all sites.

Flood frequency and magnitude

The POTF annual mean is approximately three events for the entire region (29 events on average every 10 years). Some years were particularly rich in flood events, for instance 1955, 1962, 1965, 1974, 1978, 1980, 1985, 1989, 2006 and 2010 with more than four events on average (six events in 2010). Interestingly, the decades when the most extreme events were recorded are not always those richest in flood events, e.g. the 1990s (Fig. 3). In contrast, in some other years, e.g. 1952, 1954, 1956, 1957, 1961, 1979 and 1993, there is none or one flood event.

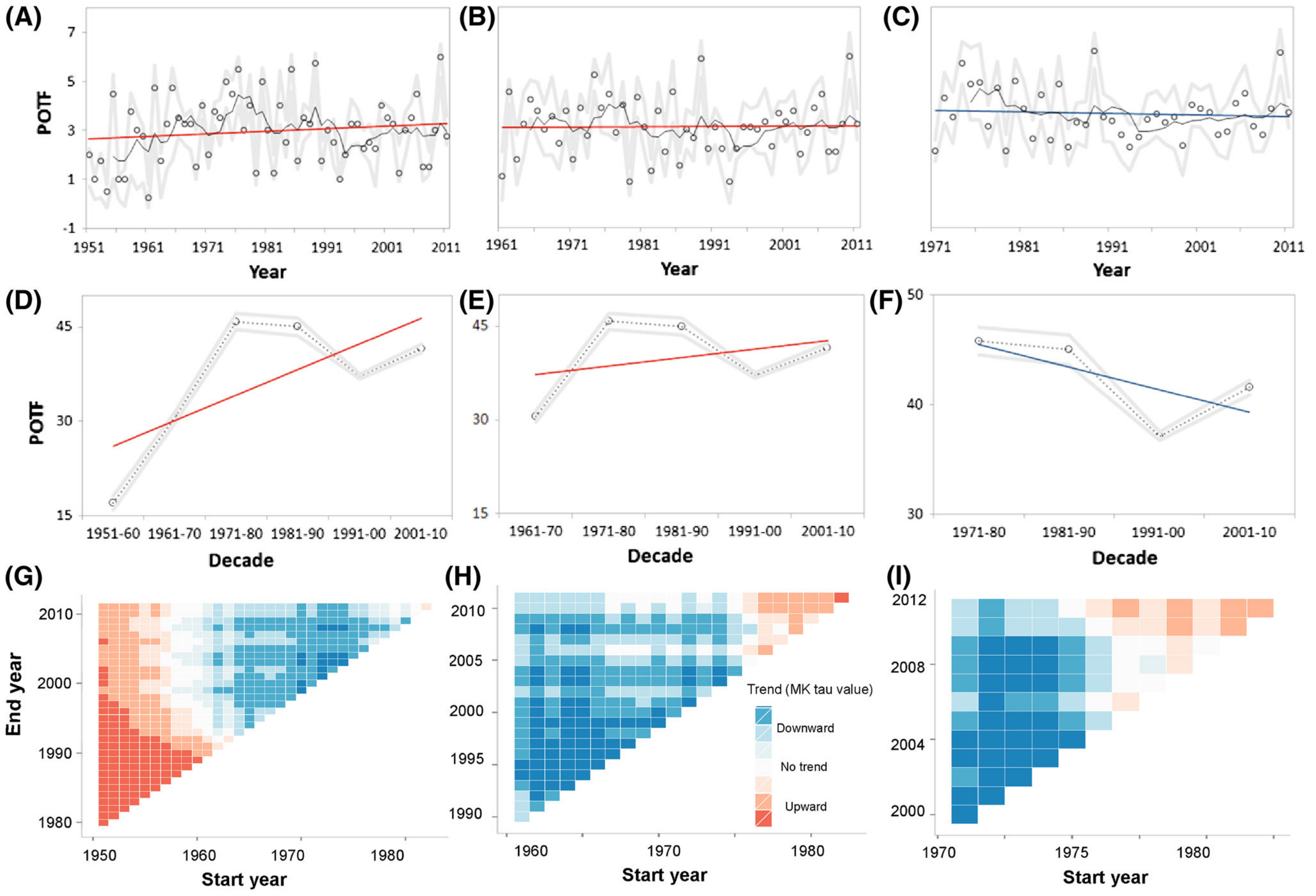

Fig. 3 Average peak over threshold (third quartile) frequency (POTF) plots for the periods: **a** 1951–2011, **b** 1961–2011 and **c** 1971–2011. **d–f** Decadal averaged POTF for the region for the three study periods. The *plots* show the mean value (*grey circles* and/or *dashed grey line*), standard deviation (*grey borders*) and linear regression (*red* and *blue line*). **g–i** Multi-temporal trend analysis for averaged POTF for the same three periods. *Same colour* legend as for Fig. 2

The averaged POTF for the studied area reveal a significant increasing trend in flood frequency for the long-term period 1951–2011, with a 35 % increment of the number of the events above the third quartile that occurred over the six last decades. While this tendency seems to decrease for the recent past, it is again increasing in the last 15 years (Fig. 3).

A reduction in the frequency and magnitude of flood flows was defined for the fourth quarter of the twentieth century (1974–2000) for the Czarny Dunajec River (Zawiejska and Wyżga 2010). But this reduction can be explained by the selection of the study period, as it is observed in Fig. 3 g–i.

At-site results of the fixed period MK test showed 21 % of significant upward trends and 28 % of downward trends for the most recent period (1971–2011), 50 % of the sites showed positive upward trends for the period 1951–2011 and no significant trends were identified for the period starting in 1961. The defined downward trends in the most recent period are mainly present in the data from the larger basins.

Regarding flood magnitude (POTM), 57 % of the stations revealed significant upward trends for the period 1971–2011, whereas such trends were identified for 11.1 % of the stations for the period 1961–2011 and for 75 % of the stations for the years 1951–2011. Other 8.3, 33 and 25 % of the stations showed weak positive trends in these periods, respectively. It is difficult to average the regional POTM, since the number of events per year depends on the site. On the other hand, the multi-temporal trend test was not applied individually since in some cases, there is more than one event per year, and some years are missing. Therefore, we provided some representative at-site results in the supplementary material (Fig. 4S). The significant upward trends in POTM were found in the larger basins. According to our findings, for the largest basins (group 2) in general, the stations with defined significant downward trends in flood frequency exhibit significant upward trends in flood magnitude. Therefore, although less frequent (at least for the last 40 years, but more frequent for the last 60, and for the last 15 years), flood events are also getting more extreme in magnitude.

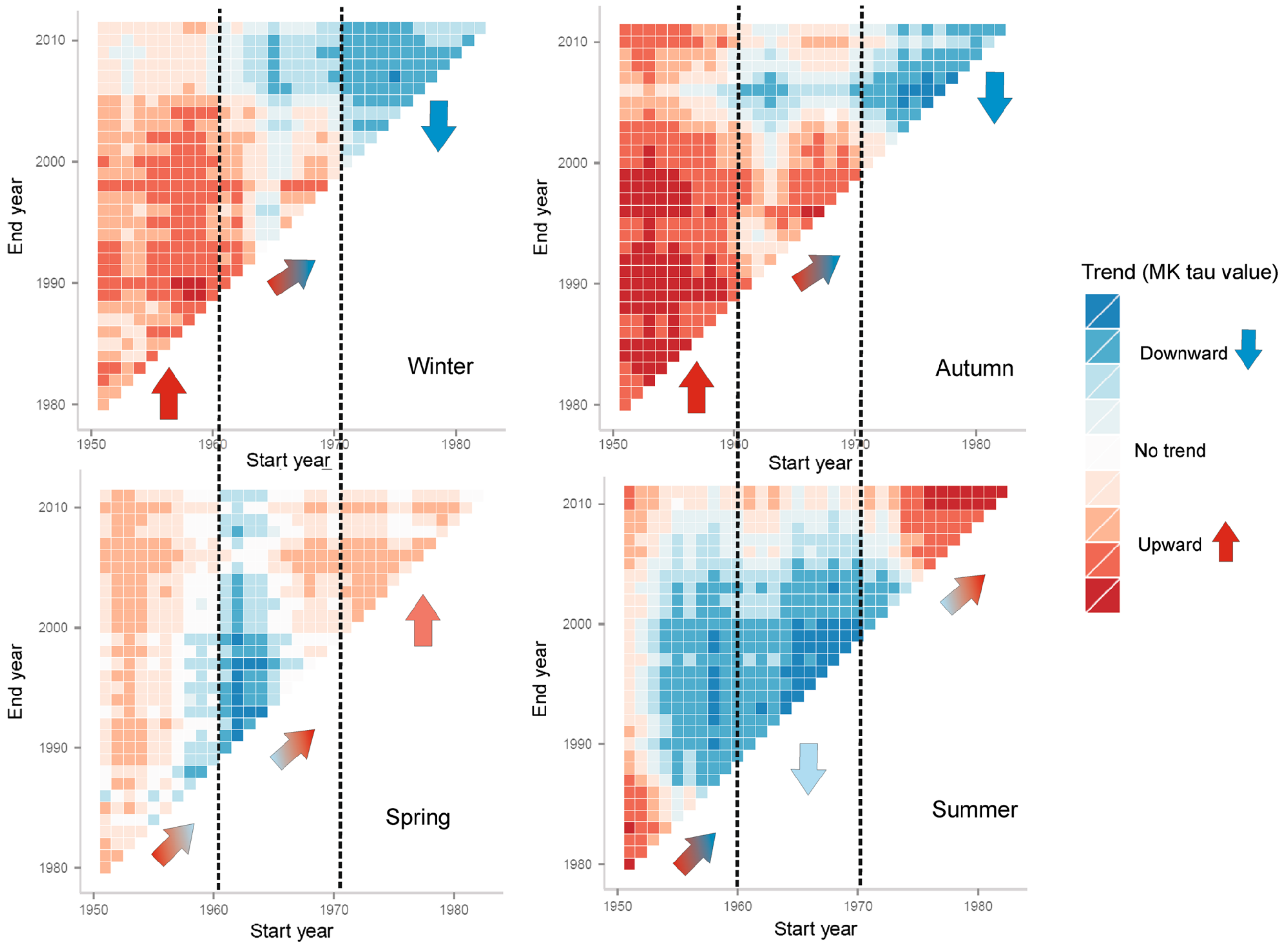

Fig. 4 Multi-temporal trend analysis for the maximum discharge of particular seasons. Legend explained in Fig. 2

Flood seasonality

At the regional scale, seasonal upward trends of flood magnitude are observed for summer, spring and autumn, whereas downward trends are found for winter (Fig. 4). In spring (SMSp), only two stations showed significant trends (upwards) for the most recent period, one station for the period 1961–2011 and none for the longest period; otherwise, weak, insignificant and trends were found. These stations, where strong trends were identified, belong to group 1 (small headwater basins). For autumn (SMA), significant upward trends were identified for 21 % of the stations in the period 1971–2011, 11.1 % for the years 1961–2011 and 50 % for the longest period, whereas in only 14 % downward trends were detected for the recent past. For the summer season (SMSu), only 14, 25 and 11.1 % of the stations showed significant positive trends for the last 40, 50 and 60 years, respectively. The trends were identified in both large and small basins. Interestingly, the winter season (SMW) shows a different pattern, with 35.7 and 11.1 % of the stations showing significant downward trends for the periods 1971–2011 and 1961–2011, respectively, and only one significant upward trend was found in 1951–2011, when two weak downward tendencies were also observed. The significant downward trends were identified in both the large and small basins. The same was previously observed for the Elbe and Oder Rivers, where significant decrease in winter floods (snowmelt related) was detected, while no significant change in summer floods were identified (Mudelsee et al. 2003).

Potential drivers of flood trends

There may be several candidates for drivers of flood trends, and the significance of particular drivers may change with the catchment size (Merz et al. 2012) and location. In this section, we attempt to perform attribution by identifying potential drivers for the detected trends. Particular attention is paid to the small headwater basins where effects of land-use changes can be more active.

Meteorological and climatological drivers

Maximum daily precipitation (MDP), the number of days with snow cover and the frequency of particular cyclonic circulation types (CCT) are the regional-scale meteorological drivers considered in this study (Table 1). During the period 1951–2011, maximum 24 h precipitation in Zakopane varied from 29.8 mm (1993) to 138.9 mm (1970 and 1973). At higher parts of the Tatras, the highest daily rainfall reached 232.0 mm at Kasprowy Wierch and 300.0 mm at Hala Gąsienicowa (Cebulak and Niedźwiedź 2000; Niedźwiedź 2003a; Kundzewicz et al. 2012; Niedźwiedź et al. 2014). A long-term trend of this characteristic is not statistically significant (Łupikasza 2010); however, some short-term fluctuations are evident with clustering of extreme events (Starkel 2001). After a dry period between 1951 and 1957, a frequency of high daily totals increased in the years 1958–1980 (Niedźwiedź et al. 2014). 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 on the studied rivers.

In Zakopane, the number of days with snow cover and maximum snow depth revealed statistically significant decreasing trends of −8 and −9 days/10 years, respectively, in the period 1961–1990 (Falarz 2002). In the highest zone of the mountains, the duration of snow cover was more stable particularly in the years 1954–1960, 1970–1980 and 1990–1998 (Falarz 2013).

Most of the summer floods on the study rivers are linked to three CCT (Niedźwiedź 2003b): north cyclonic (Nc), north-east cyclonic (NEc) and cyclonic trough (Bc). The frequency of these types increased by about 20 % over the second half of twentieth century (Niedźwiedź et al. 2014).

Previous trends identified in maximum ($T_{\max}$) and minimum ($T_{\min}$) temperatures and extreme moisture index [defined as the difference between precipitation and potential evapotranspiration (P-EP)] have been also analysed (Przybylak et al. 2007). A clear rise in $T_{\max}$ was observed, in terms of both average yearly 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). This trend is particularly strong from the beginning of the 1990s, while extremely hot days occurred very rarely prior to 1985. Areal averaged annual mean number of days with $T_{\max} < 0$ °C (cold $T_{\max}$) showed downward trends (not significant), while warm $T_{\max}$ (number of days with $T_{\max} > 10$ °C) showed statically significant upward trends for the period 1951–2005. Statistically significant upward trends were observed in the average annual mean number of days with P-EP < 1st and 10th percentiles (extremely dry and very dry days), with an increase of 1–2 days before the 1990s to >5 days afterwards. On the other hand, the extremely wet days and very wet days (P-EP >90 %) showed statistically significant downward trends, decreasing from 3–6 days in the period 1951–1980 to 1–3 days for the last 25 years.

The indices describing the large-scale climate variability (Table 1) were found to be variously correlated with the analysed hydrological variables for the region (Fig. 5a). Table 2 shows values for four large-scale climate indices selected out of the 10 ones considered. Links between these four climate indices and flood variables for the studied region are considered below.

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

The East Atlantic/Western Russia (WRUS) pattern shows a linear negative trend for the last 60 years, with a tendency of its negative phase in the annual scale, and in all seasons except winter when the trend is towards its positive phase. The positive phase of this pattern reflects below-average precipitation over Europe, and the negative one is related to above-average precipitations. At the annual scale, we found a positive correlation with floods (AMAX) in the region. And the downward trend of winter floods could be related with the winter trend of this climate index (Fig. 5b).

The Scandinavia pattern (SCA) shows the same pattern as EA/WURS, with a negative linear trend, towards a more negative phase, so related to above-average precipitation across central and southern Europe. However, we found practically no correlation with the flood variables, although a link between extreme discharges of some Carpathian rivers and the SCA index has been noted (Pociask-Karteczka 2006).

Finally, the North Atlantic Oscillation (NAO), which is identified as one of the major patterns of atmospheric variability in the northern hemisphere, exhibits at the annual scale an upward tendency (to the positive phase) for the longer period (1951–2011; Fig. 6S) but with a tendency to decrease for the last decades. Strong positive phases of the NAO tend to be associated with below-average precipitation over southern and central Europe. According to the analysis, both AMAX and POTF are significantly correlated to negative NAO phases. This would explain the increase in both flood variables over the longer term and the decrease in flood frequency in the shortest period. At the seasonal scale, the increase in flood magnitude in autumn is also related to more persistent negative NAO phases, whereas the decrease in the magnitude of winter floods is related to an upward trend identified in the seasonal NAO index.

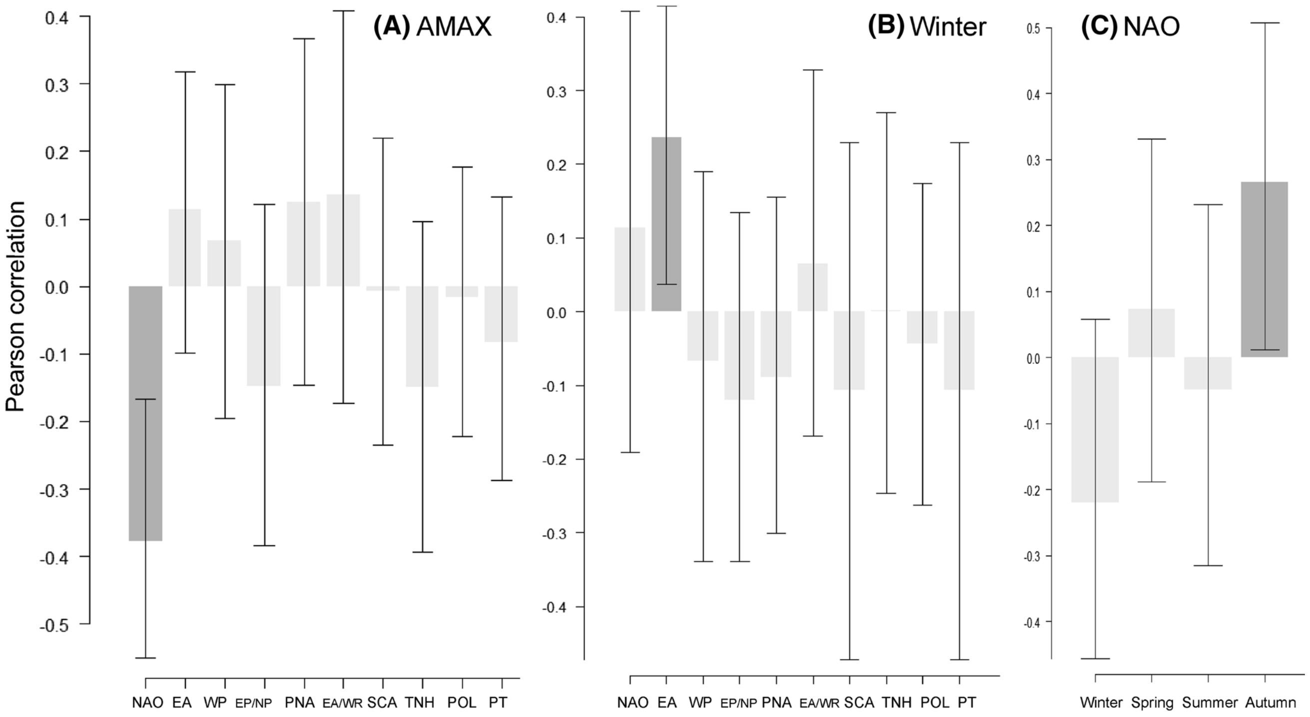

Fig. 5 Some results of the correlation analysis between: **a** averaged AMAX and the climate indices; **b** flood maxima for winter season (SAMW) and climate indices; **c** averaged AMAX and averaged seasonal NAO index. *Dark grey* means significant correlation. Whiskers are 95 % confidence intervals

As suggested by Trigo (2011), a lag between the response of river discharge and positive or negative NAO phases can be apparent at a monthly resolution. In Poland, this aspect was also investigated by relating spring maxima to winter NAO index to study snowmelt-induced floods (Kaczmarek 2003). For the Dunajec catchment, Pociask-Karteczka and Nieckarz (2010) found various relationships between 10-day high flows in spring and summer months and winter NAO index. In order to analyse this possible lag, we plotted AMAX together with the values of seasonal NAO index and analysed possible correlations for the longest period (Fig. 5C). According to the results, there is a negative correlation between AMAX and NAOW (NAO winter) and positive significant correlation with NAOA (NAO autumn). Therefore, at extremely low NAOW values, the river flow is increased. This is in agreement with Pociask-Karteczka (2006) who observed considerable high flooding of the Wisła and Odra Rivers occurs after winters that are characterized by extremely low NAO indices.

However, the impact of large-scale climate anomalies on floods remains an open question that is important to tackle since flood management practices may benefit from improved climate scenarios and forecasting of these indices, and particularly of the NAO index (Salgueiro et al. 2013).

External drivers

The results have indicated that connections exist between flood trends and changes in some atmospheric variables, but the latter only partly explain the variability in streamflow. Environmental changes that occurred in past decades in the studied catchments must have affected the conditions of flood run-off (Table 2S). A considerable increase in the forest cover and a decrease in the percentage of arable land, that took place in the Polish part of the study area (Wyżga et al. 2012), tended to slow down run-off and to reduce peak flows. On the other hand, collectivization of farms shortly after the World War II in communist Czechoslovakia resulted in the formation of large plots that induced acceleration of run-off processes, especially as a consequence of rapid development of gullies (Stankoviansky and Barka 2007). In the 2000s, a large proportion of mature spruce forest in the SE Tatras was damaged as a result of widespread wind throw and subsequent bark beetle infestation (Kopecká and Nováček 2009). This might have contributed to increase in flood peaks on the Poprad River in the past few years, especially as the forest damage took place in the area with high precipitation totals. Finally, the catchment of Cicha Woda, with its considerable proportion occupied by the town of Zakopane, was significantly affected by urbanization accelerating the run-off from the area.

Table 2 Pearson's correlation R computed between selected climatic indices and analysed hydrological variables for the three studied periods

Index		Correlation (Pearson's R, Kendall's tau significance)					
		1951–2011		1961–2011		1971–2011	
Annual	Tendency	AMAX	POTF	AMAX	POTF	AMAX	POTF
NAO	up	**−0.19**	**−0.18**	**−0.35**	**−0.29**	**−0.35**	**−0.32**
EA	up	+0.11	No cor.	+0.031	−0.09	+0.025	no cor.
EA/WRUS	down	+0.13	+0.04	+0.035	+0.16	+0.051	**+0.24**
SCA	down	−0.045	+0.11	−0.057	+0.16	−0.075	**+0.20**
Summer		SMSu		SMSu		SMSu	
NAO	down	−0.018		−0.11		−0.04	
EA	up	+0.07		+0.05		+0.092	
EA/WRUS	down	**+0.25**		+0.13		+0.13	
SCA	down	**+0.33**		**+0.34**		**+0.36**	
Spring		SMSp		SMSp		SMSp	
NAO	up	+0.01		+0.013		+0.014	
EA	up	+0.037		+0.053		+0.071	
EA/WRUS	no trend	−0.058		−0.008		−0.033	
SCA	down	−0.069		−0.031		−0.05	
Autumn		SMA		SMA		SMA	
NAO	down	**−0.22**		**−0.20**		**−0.25**	
EA	up	+0.085		+0.019		+0.021	
EA/WRUS	down	−0.16		**−0.20**		**−0.27**	
SCA	down	+0.031		+0.006		+0.053	
Winter		SMW		SMW		SMW	
NAO	up	+0.11		**+0.14**		**+0.16**	
EA	up	**+0.22**		**+0.25**		**+0.19**	
EA/WRUS	up	+0.14		+0.11		+0.12	
SCA	down	−0.11		−0.01		−0.09	

See abbreviation for acronyms in Table 1. 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: *NAO* North Atlantic Oscillation, *EA* the East Atlantic, *EA/WRUS* the East Atlantic/Western Russia; *SCA* the Scandinavia pattern (SCA)

Direct human interventions in the studied rivers constitute another group of impacts on the conditions of flood run-off (Table 2S). Channelization works on the Dunajec, conducted in the 1950–1970s, resulted in the narrowing and considerable simplification of its channel (Zawiejska and Wyżga 2010). Since the 1960s, channelization works have been undertaken in rivers and streams of the headwater basins, substantially (up to a fifth of the original value) narrowing the watercourses and replacing their former multi-thread channels by single, artificial ones along a majority of their courses (Łajczak 2007; Korpak 2007; Zawiejska and Wyżga 2010; Wyżga et al. 2012). During the 1950–1960s, rivers in the study area, especially the Czarny Dunajec, were subjected to large-scale but localized gravel mining, whereas in the following decades, it was replaced by widely distributed, illegal extraction of cobbles from the channels (Zawiejska and Wyżga 2010). An increase in transport capacity of the watercourses caused by their channelization (Wyżga 2001) and a considerable shrinkage of sediment available for fluvial transport, resulting from the gravel mining, induced rapid channel incision. To date, up to 3.5 m of bed degradation have occurred in the rivers of the study area (Wyżga 2008; Zawiejska and Wyżga 2010). 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). In the headwater catchments, run-off processes have been predominantly affected by the counteracting effects of forest cover increase that gradually progressed over the second half of the twentieth century, 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 run-off probably lowered with increasing catchment size. In turn, the effects of channelization and channel incision on flood run-off should increase with the length of modified channels hence being more pronounced in the stations located downstream. While the flood record in the stations characterizing these 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 downward trend in flood frequency coupled with a significant upward trend in flood magnitude was found for the Gołkowice gauging station. This station is located a few tens of kilometres downstream of the Czorsztyn Reservoir that started to operate in 1997. It is not surprising that the reservoir decreased the frequency of the largest floods. At the same time, the increase in flood magnitude might be attributed to the loss of floodplain water storage along the river reach where deep channel incision took place in the second half of the twentieth century (Zawiejska and Wyżga 2010).

In summary, different drivers, climatic and terrestrial (or external), 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 (Merz et al. 2012).

Conclusions

In this study, we presented a multi-temporal statistical framework for the assessment of changes in the frequency, magnitude and seasonality of floods in the northern foreland of the Tatra Mountains. The analysis of flood changes shows a complex pattern. There is no ubiquitous and compelling trend at any spatial–temporal scale. However, the main identified trends were upwards in annual maxima and magnitude, and regarding flood seasonality, we can highlight an increase in flood magnitude in the spring and autumn seasons for the last 60 years. On the other hand, we found downward trends in the magnitude of winter floods. We hypothesized then that more extreme (but less frequent since the 1950s and more frequent for recent years) floods are likely to occur, with a shift in the seasonality, decreasing the snow-melt floods in winter and increasing floods during autumn and spring.

We found positives tendencies in the MDP and upward trends in the CCT responsible for floods in the Tatras. A significant correlation exists between floods and NAO index; both AMAX and POTF are significantly correlated to negative NAO phases. In addition, the presented analysis of climatic factors clearly indicated the need of in-depth insight into terrestrial factors, especially human impacts (mainly land-use change and land-cover change, notably urbanization and river management works) in the region.

A certain level of uncertainty has always existed in flood trend analysis due to the intrinsic natural climate variability. The ongoing, and even more so the projected, climate change induces additional uncertainty. The observed variability of temporal trends confirms that the detected trends should not be extrapolated into the future, or at least, not on the basis of the results presented in this study. More stations and longer periods may be required to state credibly whether or not climate indices explain the temporal variability of floods.

However, the development of a carefully conducted analysis of instrumental data is a powerful tool enabling us to identify the factors contributing to the occurrence of flood events and their potential changes. It is believed to be a valuable contribution that enables to enhance flood management in the region, contributing to a better “adaptive and integrated water management” (AIWM; Huntjens et al. 2010) and therefore improving the resilience of the population in this mountainous area.

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