Changes of characteristics of daily precipitation and runoff in the High Tatra Mountains, Slovakia over the last fifty years

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Abstract: The article presents the results of the analysis of time series of daily precipitation and runoff at selected places in the highest part of the Western Carpathians. It was focused on both wet and dry periods in precipitation and runoff data series. The precipitation data were analysed for a period 1961–2010. They revealed a significant increase of the number of days with daily precipitation 40–60 mm. Trend analysis for 67 analysed flow characteristics did not show statistically significant changes over the studied period. The focus was given particularly to the characteristics of the maximum and minimum flows, i.e. 3- and 7- day minimum flows, 1-, 3- and 7-day maximum flows. We found an increase of flows classified as small floods in two of three mountain catchments in the study area in the last decade (2001–2010). It may be linked to the above increased number of days with daily precipitation reaching 40–60 mm.

Key words: time-series analysis, daily precipitation, daily runoff, wet and dry periods, mountains

1. Introduction

Climate-related risks and occurrence of extreme weather events during last years is understood as a serious problem in many countries of the world. In 2010, 385 natural (climatological, hydrological, meteorological and geophysical) disasters were reported worldwide. They killed 297 000 persons, affected more than 217 million others and caused over US$ 123.9 billion economic damages (*Guha-Sapir et al., 2011*). The United Nations International

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Strategy for Disaster Reduction (*UN/ISDR, 2010*) emphasizes the necessity to improve the knowledge-base methods and integrated frameworks for the assessment of hazards, vulnerability and risk at national and regional level.

In Europe, mountain regions along with coastal zones, wetlands and the Mediterranean region are particularly vulnerable (*EEA, 2005*). Study of extreme meteorological phenomena by *Ustrnul and Czekierda (2009)* documented occurrence of the heaviest rainfalls in southern mountainous part of Poland. *Ceglar et al. (2009)* concluded that extreme precipitation events are frequent in mountains of the north-western Slovenia. *Lapin et al. (2003)* noted that interrelations among atmospheric circulation indices, air pressure and precipitation totals show great importance of changing atmospheric circulation on climate in Central Europe, mainly in the areas with complex topography. Climate in the northern mountainous part of Slovakia has become more humid and some shifts of climatic regions and subregions towards the higher altitudes were registered in the 20^{th} and at the beginning of the 21^{st} century (*Melo et al., 2009*).

Interactions between land and atmosphere are of fundamental importance for hydrological cycle. Climate and weather drive a precipitation process in the atmosphere, while the landscape features determine distribution of water on the land surface. There are evidences of the impact of human activities and climate on changing hydrological cycle, including the observed large-scale patterns of precipitation changes over the 20^{th} century (e.g. *IPCC, 2007*). Changes in precipitation and temperature lead to changes in runoff and water availability. *IPCC (2007)* states that runoff is projected with high confidence to increase by 10 to 40% by mid-century at higher latitudes and decrease by 10 to 30% over some dry regions at mid-latitudes due to decrease in rainfall and higher rates of evapotranspiration.

While the analyses of measured data clearly indicate recent changes in air temperatures, conclusions on changes of precipitation and runoff are not so consistent (*Blöschl and Montanari, 2010*). *Mudelsee et al. (2003)* argued that observations in Europe did not show a clear increase in flood occurrence rate during the last decades. *Robson (2002)* concluded that in the UK there have been trends towards more protracted high flows in the last 30–50 years, but they could be accounted for as part of climatic variation rather than climate change. *Holko et al. (2006)* did not find changes in discharges from selected small mountainous catchments of central Slovakia, northern Czech Republic and central Germany. A number of studies related to changes in streamflow were performed in Switzerland. *Birsan et al. (2005)* demonstrated complex changes in streamflow regime in Switzerland (48 stations), especially in the more recent periods. Annual runoff increased due to increases of winter, spring and autumn runoff while the behavior in summer showed both upward and downward trends. The authors concluded that mountain areas are the most vulnerable from the point of view of streamflow change. *Allamano et al. (2009)* reported that large floods in mountain basins of the Swiss Alps are now more frequent than in the past. They have found a significant increase of flood peaks during the last century and attributed it to simultaneous increase of air temperature and precipitation. *Schmocker-Fackel and Naef (2010)* found out that annual series of streamflow from Switzerland (83 stations) showed only few negative trends. The number of stations with positive trends was especially high, when the period of 2001–2007 was included into the analysis. Over the last 150 years, periods with a large amount of larger floods (return period over 10-years) alternated with periods poor in floods. They have also documented spatial differences in the frequency of floods and indicated that changes in large-scale atmospheric circulation might be responsible for the fluctuations in flood frequency. *Cunderlik and Ouarda (2009)* reported on weak signals of climate variability and/or change present in the timing of floods in Canada during the last three decades. Most of the significant trends in the timing of spring snowmelt floods were the negative ones, i.e. earlier flood occurrence, found in the southern part of Canada. They did not find significant trends in the timing of autumn rainfall floods. However, the significance of the autumn rainfall-dominated flood season has been increasing in several analyzed watersheds. *Villarini and Smith (2010)* found little evidence for increasing flood peaks in the eastern USA. *Halmová and Pekárová (2011)* concluded that daily discharges (1928–2008) of the Belá river draining the westernmost part of the High Tatra Mts., Slovakia did not show important changes in the number of extreme floods and the temporal extent of droughts.

The objective of this paper was to investigate temporal variability of daily precipitation and runoff in the highest part of the Carpathian Mountains (the High Tatra Mts., Slovak Republic) over the last almost 50 years. Changes in occurrence of potentially hazardous rainfall events (from the point of view of possible flood generation), and wet and dry periods in both precipitation and runoff data series were examined as well.

2. Study area and data

The High Tatra Mountains are located in northern part of Slovakia on the border with Poland (Fig. 1). They are the highest part of the whole Carpathians. The main ridge of the High Tatra Mts. has the west-east direction. It is 26 km long and 17 km wide. Its mean elevation is about 2300 m a.s.l. and it varies from 2200 m a.s.l. (saddles) to 2400 m a.s.l. (peaks).

Šamaj (1973) reported that the first meteorological measurements (air temperature) in the High Tatra Mts. and its vicinity were made in the year 1720. The oldest documented observations are from the years 1789–1800 and systematic measurements are archived since 1873. Meteorological measurements in Starý Smokovec started in 1875. Stations in Tatranská Lomnica, Poprad and Štrbské Pleso were established at the turn of the 19^{th} and 20^{th} centuries. Important high mountain stations were established between 1936 and 1940 at the Kasprowy Wierch mountain (Poland), the Skalnaté Pleso lake and at the Lomnický štít mountain (all above information from *Šamaj, 1973*).

We analysed daily precipitation from six stations located in the central, western and eastern parts of the Slovak High Tatra Mts. (Fig. 1). Data from years 1961–2010 were used in the study. The altitude of the precipitation stations varied from 694 to 2635 m a.s.l., mean annual precipitation ranged from 600 to 1500 mm (Table 1). Precipitation was measured by standard rain gauge of the Czechoslovak meteorological service with orifice 500 cm^2 that is elevated 1 m above the ground. All stations are part of the national network of the Slovak Hydrometeorological Institute (SHMI).

The High Tatra Mts. create part of the European water divide between the Black Sea and the Baltic Sea. Most of the area in Slovakia is drained by the Poprad river which is one of only two Slovak rivers that are in the Baltic Sea basin. The western part of the High Tatra Mts. is drained by the longest Slovak river Váh that flows to the Danube river and eventually to the Black Sea. In this study we focused on the upper Poprad river catchment and

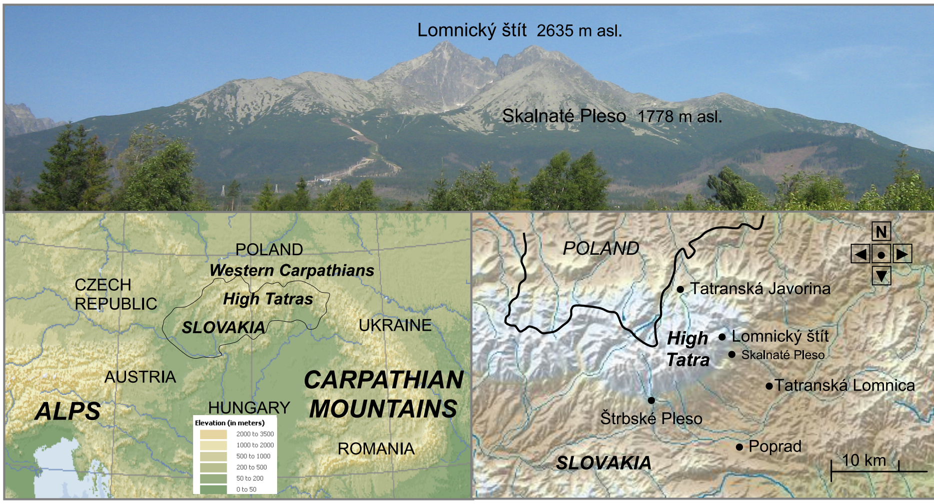

Fig. 1. The geographical position of the High Tatras in the Carpathian Mountains (left) and location of precipitation stations (right).

its subcatchments. While meteorological measurements in the High Tatra Mts. started already in the 19$^{\text{th}}$ century, hydrological measurements in the Poprad river catchment are much younger. The gage at Poprad-Matejovce was installed in 1921 (*Pacl, 1973*) and other gages in the area were installed in the following decades. We have analysed daily runoff from four catch-

Table 1. Precipitation stations used in the study; P is the mean annual precipitation (1961–2010)

Position of measurement sites in the High Tatra Mts.			Latitude	Longitude	Altitude [m a.s.l.]	P [mm]
Central part The Skalnatá dolina valley	LS	Lomnický štít	49°12' 00" N	20°13' 00" E	2635	1496
	SkP	Skalnaté Pleso	49°11' 22" N	20°14' 03" E	1778	1345
	TL	Tatranská Lomnica	49°09' 46" N	20°17' 17" E	827	794
The Popradská kotlina basin	PP	Poprad	49°04' 06" N	20°15' 58" E	694	598
Western part	StP	Štrbské Pleso	49°07' 09" N	20°03' 26" E	1354	1025
Eastern part	TJ	Tatranská Javorina	49°15' 02" N	20°09' 29" E	1030	1303

ments in the High Tatra Mts. area that had data series comparable in length with those of precipitation. Three of them were smaller catchments nested within the fourth one – the Poprad river at Matejovce (Fig. 2). The data series did not have the same length, because the measurements in the catchments started in different years. Furthermore, measurements at Poprad-Matejovce had to finish at the end of 2009 due to infrastructure construction. Therefore, the daily runoff was analysed only for hydrological years 1963–2010 (1963–2009 for the Poprad-Matejovce catchment). Hydrological year in Slovakia starts on 1st November and ends on 31st October. Basic characteristics of the catchments are given in Table 2. Mean annual runoff in the catchments varied between 219 and 504 mm. Mean evapotranspiration calculated from the water balance equation varied approximately between 351 and 572 mm (*Holko et al., 2009*).

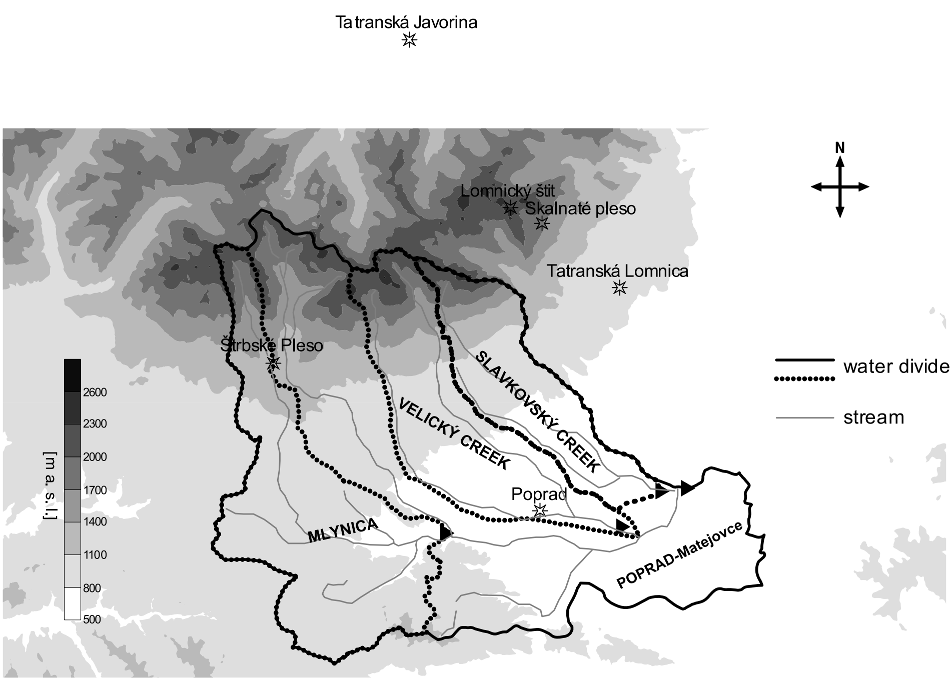

Fig. 2. Water divides of the studied subcatchments of the upper Poprad river and precipitation stations (asterisks); the stream gages are marked by the triangles.

Table 2. Studied catchments and their basic characteristics derived from gridded digital maps with resolution 50 m, R is mean annual runoff for the period given in the table; C is runoff coefficient, NA means there were no data available to calculate catchment mean precipitation

Catchment – gage	Area [km^2]	Mean altitude [m a.s.l.]	Mean slope [°]	Runoff data from period	R [mm]	C [–]
Mlynica – Svit	83	991	9.2	1963 – 2010	219	0.28
Velický creek – Veľká	58	1094	9.3	1963 – 2010	505	0.59
Slavkovský creek – Matejovce	43	1017	8.6	1963 – 2010	358	0.43
Poprad – Matejovce	315	1018	9.2	1963 – 2009	399	0.50

3. Methodology

The purpose of the work was to analyze both precipitation as the input into the hydrological cycle of a catchment and runoff representing integrated result of all processes acting in a catchment. The rationale behind including runoff is that runoff and its extremes, i.e. floods and droughts, have a direct impact on catchment environment including human society. It is therefore important to study the evolution of this phenomenon over time.

Statistical analysis was used to obtain characteristics of daily precipitation and runoff and their variability in the studied period. Daily runoff was expressed for some analysis as runoff depth in millimeters, e.g. to allow intercomparison of the catchments and comparison with precipitation.

Directly measured data are the best descriptors of natural phenomena. However, they inevitably include uncertainties. In case of precipitation and runoff the uncertainties or even errors may arise, e.g. from measurement methods, equipment, changes of sensors, replacement of stations, etc. Therefore, the analysis of the long-time data series should be accompanied by the tests of homogeneity. A number of methods were used to test the homogeneity of meteorological data (*Kang and Yousuf, 2012*). Bivariate test, standard normal homogeneity test (SNHT), von Neuman ratio test, Pettit test, Kruskal-Wallis test are perhaps the ones which have been mostly used in the analysis of precipitation and runoff data (e.g. *Firat et al., 2010; Kang and Yousuf, 2012*). In this study, the homogeneity of the precipitation data was tested by means of the SNHT Alexandersson tests (*Alexandersson, 1986*) and Bivariate test Maronny and Yohaie (*Maronna and Yohai, 1978*) method using the ProClimDB software (*Štepánek, 2010*). Homogeneity of runoff data was tested by the von Neumann test, because the data did not have normal distribution required for the SNHT test.

Numerous indices are used in different studies to monitor changes of daily precipitation (e.g. *Zhang et al., 2011*). In this study we have calculated 1^{st} and 3^{rd} quartiles (q1, q3), median, mean, 95^{th} and 99^{th} percentiles (p95, p99) for the daily precipitation and daily runoff data. They were used to characterize the differences among the precipitation stations and catchment runoff from different subcatchments. Quartiles are special percentiles corresponding to 25% (q1) and 75% (q3) cumulative relative frequency. Second quartile or median is the number in the middle of sorted dataset. The 95^{th} (99^{th}) percentile is the value of precipitation or runoff such that 95% (99%) of the relevant population is below that value.

Analysis of temporal variability of precipitation and runoff focused on dry and wet periods. In case of precipitation we counted the frequency of successive periods without precipitation (dry periods) and frequency of successive periods with precipitation (wet periods), respectively. The results were then summarized for each station and duration of dry and wet periods in the following categories:

- ST (short-term wet/dry period) with duration in range between 1 and 5 days,
- MT (middle-term wet/dry period) with duration in range between 6 and 10 days,
- LT (long-term wet/dry period) with duration more than 10 days.

Temporal evolution of the wet and dry periods was evaluated for decades (1961–1970, 1971–1980, 1981–1990, 1990–2000, 2001–2010). Relation between decadal wet/dry period frequency and decadal precipitation totals was examined by correlation analysis and the P-values (see below).

Daily discharge data (i.e. catchment runoff expressed in m^3s^{-1}) was analysed with the IHA (Indicators of Hydrologic Alteration) software (*The Nature Conservancy, 2009*). Daily discharges for hydrological years 1963–2010 (1963–2009 for Poprad-Matejovce) were processed as one period. The IHA provides a number of statistics and metrics. After the non-parametric analysis of the data we first found all characteristics that had exhibited a statistically significant trend in the studied period. The criterion was that the coefficient of correlation (linear regression between time and studied statistics) exceeded the value of 0.55 and the P-value was below 0.05. Second analysis was focused on characteristics of minimum and maximum discharges (3– and 7– day minimum flows, 1–, 3– and 7–day maximum flows) and the following flow components:

- duration of extreme low flows – extreme low flow was the flow less than or equal to the 10th percentile of daily flows,
- duration of small floods – a small flood was a flow event that had flows exceeding the 75^{th} percentile of the daily flows and the return interval of the peak flow greater than 2 years,
- duration of high floods – a high flood was a flow event that had flows exceeding the 75^{th} percentile of the daily flows and the return interval of the peak flow greater than 10 years.

Classification of the Integrated Warning Service System (*IWSS*) of the Czech Hydrometeorological Institute (`http://pocasi.chmi.cz/en/`) was used for evaluation of the number of potentially dangerous rainfalls. Only data from warmer period of the year (May to October) were analyzed, because solid precipitation may be rather frequent in the High Tatra Mts. in the other months. Three degrees of the risk were determined:

1. low risk – daily precipitation between 40 and 60 mm (occurrence of potentially dangerous situation),
2. high risk – daily precipitation from 60 to 90 mm (potential of material damage on large area),
3. extreme risk – daily precipitation above 90 mm (potential of enormous material damage and hazard to human life).

The IWSS criteria assess the risk of damages in human society including disruption of settlements, commerce and transport due to flooding, waterlogging and erosion of soil, contamination of surface and groundwater sources, increased risk of injuries, infectious, skin diseases and deaths (public health).

4. Results and discussion

4.1. Homogeneity of the data series

Data quality control of the precipitation series did not indicate any suspicious values. Detection of inhomogeneities was done on monthly, seasonal and annual precipitation totals. The test found great inhomogeneity at station Lomnický štít mountain in 1991. Correction of the inhomogeneity was done with the help of reference series from neighbouring stations (SkP, TL, PP, StP, TJ). After the correction, correlation between homogenized values of annual precipitation for the Lomnický štít mountain and reference series slightly increased (+0.044). The increase was bigger for the winter (+0.100) than for the summer (+0.008) periods (*Mačutek et al., 2011*).

All runoff data series exhibited inhomogeneities. Data from the Mlynica, Velicky creek and Poprad-Matejovce catchments had inhomogeneities in the first 7, 5 and 5 years, respectively. Data from the Slavkovsky creek catchment had inhomogeneities in the first 17 and last 5 years. Since the independent homogeneous data from a neighbouring catchment were not available, we have excluded the first seven years from the runoff data series of Mlynica, Velicky creek and Poprad-Matejovce. Data from the Slavkovsky creek were not further analyzed. The High Tatra Mts. region was hit by an extraordinary wind in November 2004 that caused spacious forest destruction. The highest windfall-induced deforestation occurred in the Slavkovsky and the Velicky creek catchments. Although the data measured in the following years did not indicate significant impacts on the runoff regime (*Holko et al., 2009*), the homogeneity test performed here indicated inhomogeneities in the runoff data series of the Slavkovsky creek.

4.2. Ranges of measured precipitation and runoff

The Box-Whisker plots in Figs. 3 and 4 show the ranges of daily precipitation and runoff. Precipitation at the lowest altitude (PP) had the smallest range (Fig. 3). The highest ranges and the highest number of outliers were not observed at the highest station (LS). They occurred at station of TJ which is on the windward side of the High Tatra Mts. and at station SkP which is located at high altitude on the leeward side of the Lomnický Štít mountain. Mean values of precipitation did not significantly vary among

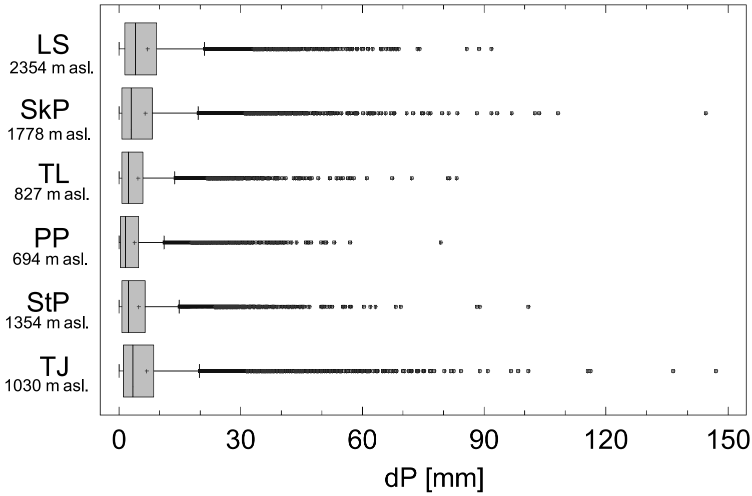

Fig. 3. Box-Whisker plot of daily precipitation at the studied stations in period 1961-2010; the statistics from the left to right represent QL-1.5*IRQ (the left whisker), 25% quartile, median, mean (the plus sign), 75% quartile, QU+1.5*IRQ (the right whisker); outliers (circles) are the points that fall below QL-1.5*IRQ or above QU+1.5*IRQ, where IRQ is the interquartile range (the difference between the first and the third quartiles), QL and QU are the values of the lower and upper quartiles, respectively.

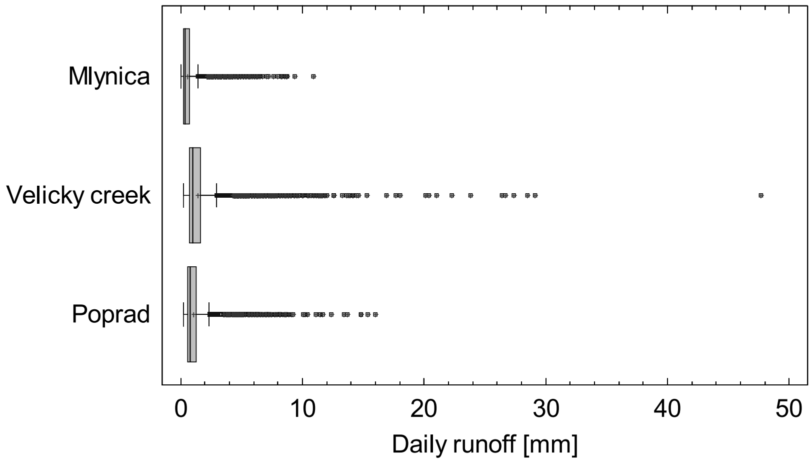

Fig. 4. Box-Whisker plot of runoff in the upper Poprad river subcatchments in hydrological years 1970–2010 (Mlynica, Velicky creek) and 1970–2009 (Poprad-Matejovce); descriptions of individual parts of the graphs are given in Fig. 2.

the stations (Table 3). Median values were lower than the means. Station StP seems to have comparatively less precipitation considering its altitude.

Figure 3 shows that 75% of daily precipitation (the 3rd quartile) was below 10 mm. Moderate precipitation between 10–20 mm was still relatively frequent at all stations. Higher daily precipitation in range from 20 to 30 mm and above 30 mm, respectively was less frequent – from statistical point of view these values appeared as outliers. Maximum daily precipitation was close to 150 mm. Such an extreme value was observed only at two stations (TJ, SkP). Maximum precipitation at other four stations (LS, TL, PP, StP) ranged from about 90 mm to about 110 mm. TJ is the only station where daily precipitation above 110 mm was observed more than once. This is consistent with the results published by *Cebulak et al. (2000)* and *Faško et al. (2000)*, focused on extreme precipitation events and daily precipitation maxima, respectively. Both concluded that events with precipitation equal or higher than 100 mm are rare. Such precipitation was usually observed in mountainous region at the border between Poland and Slovakia.

Table 3. Summary statistics of daily precipitation (dP) for period 1961–2010 and polynomial regressions of mean, 95p and 99p with altitude

Site	Altitude H [m a.s.l.]	dP > 0 mm rel. freq. [%]	q1	median	mean	q3	95p	99p	Maximum
LS	2635	59	1.4	4.1	6.9	9.3	23.5	41.2	92
SkP	1778	56	0.8	3.1	6.5	8.3	24.8	43.7	145
TL	827	46	0.8	2.4	4.7	6.0	17.3	30.4	83
PP	694	42	0.5	1.6	3.9	4.8	15.6	28.4	79
StP	1354	57	0.7	2.4	4.9	6.4	17.9	30.9	101
TJ	1030	52	1.2	3.5	6.9	8.7	24.4	50.0	147

Skalnatá dolina valley (LS, SkP, TL, PP) elevation profile: relation between x = H and y = dP

dP statistics	Regression	R	P-value
number of dP [%]	**y = 38.08 + 0.008542*x**	**0.9614**	**0.0386**
q1	y = 0.32 + 0.000376*x	0.9034	0.0966
median	**y = 1.12 + 0.001133*x**	**0.9680**	**0.0320**
mean	y = 3.28 + 0.001497*x	0.9479	0.0521
q3	**y = 3.84 + 0.002198*x**	**0.9661**	**0.0339**
95p	**y = 3.29 + 0.021259*x - 5.157E-6*x^2**	**0.9999**	**0.0077**
99p	y = 7.07 + 0.036187*x - 8.810E-6*x^2	0.9984	0.0557

R – correlation coefficient
P-value < 0.05 – statistically significant relationship

Prevailing flow of humid air originated over Atlantic Ocean invokes more effective formation of precipitation on the northern slopes of the High Tatra Mts. compared to the southern slopes (*Konček et al., 1974*). Summer heavy rainfalls over the High Tatra Mts. were formed in air masses controlled particularly by the northeastern cyclonic situation (NEc) and other air circulation types as eastern cyclonic situation (Ec), wake of low pressure (Bp) and southwestern anticyclonic situation (*Bičárová and Čepčeková, 2011*). Windward position of the TJ station is probably the reason for higher precipitation maxima compared to the SP, LS or StP stations. It is in agreement with observation of maximum daily precipitation in Poland (*Ustrnul and Czekierda, 2009*) that shows high frequency of daily precipitation exceeding 100 mm in the Polish part of the mountains. Absolute daily maxima 232 mm and 300 mm recorded at the Kasprowy Wierch mountain and the nearby station Hala Gasienicova, respectively in June 1973 represent the highest recorded daily precipitation in Poland. Both stations are situated in the Western Tatra Mts. that form one mountain range with the High Tatra Mts. Substantially lower daily precipitation (between 47 and 103 mm) occurred at the same time in the Slovak High Tatra Mts.

Daily runoff in the studied catchments was most frequently below 1 mm (Fig. 4). The observed range was smallest in the Mlynica catchment, which has the lowest mean altitude. It may be caused by comparatively smaller precipitation in the western part of the High Tatra Mts. (precipitation at station StP was mentioned above). The highest number of outliers as well as the highest observed daily runoff (47.7 mm) occurred in the Velicky creek catchment.

Statistics of daily precipitation show high correlations with altitude (Table 3). Statistically significant correlations with the altitude were found for the relative frequency of days with precipitation, median and 3rd quartile of daily precipitation. Polynomial regressions for 95th and 99th percentiles reflect slight decrease of high dP values in altitude between 1800–2600 m a.s.l. Statistics of the daily runoff are given in Table 4. The highest values of all statistics were found in the Velicky creek catchment that has the highest mean altitude.

The IHA software calculated regression parameters for 67 flow statistics. When we applied the criteria given in the Methodology, we did not find any strong statistically significant trend for the calculated statistics.

Table 4. Summary statistics of daily runoff; hydrological years 1970–2010 for the Mlynica and the Velicky creek catchments, hydrological years 1970–2009 for the Poprad-Matejovce catchment

Catchment	Statistics of daily runoff [mm]						
	q1	median	mean	q3	95p	99p	Maximum
Mlynica	0.2	0.4	0.6	0.7	1.7	3.3	10.9
Velicky creek	0.7	1.0	1.4	1.6	3.5	6.5	47.7
Poprad-Matejovce	0.6	0.8	1.1	1.3	2.6	4.5	16.0

4.3. Occurrence and duration of dry and wet periods

As expected, the total number of dry and wet periods that varied between 540 and 650 was similar for individual decades and precipitation stations (Table 5). The longest period without precipitation that lasted 36 days was observed at the lowest station PP. The longest wet period (43 days) occurred at the highest station LS. Not-pronounced changes were found for the short-term dry and wet periods. Dry/Wet share for middle-term and long-term periods suggest more frequent occurrence of wet periods at stations situated in altitude above 1000 m a.s.l. (LS, SkP, StP, TJ). Substantial increase of decadal precipitation during the last decades was observed at these stations. The increase of decadal precipitation may be associated with higher frequency of the long-term wet periods in the higher layer of the lower troposphere that is illustrated in Fig. 5. The correlation coefficient ($R = 0.913$) indicates a strong relationship between the variables.

Durations of extremely low flows, and small and large floods in individual decades are given in Table 6. Decrease of duration of extremely low flows in the last two decades was observed in two of the three catchments. On the contrary, significant increase occurred in the third catchment (Mlynica) in the last decade. Number of days with flows classified as small floods in the Velicky creek and the Poprad-Matejovce catchments significantly increased in the last decade. The increase should not be attributed to the windfall that hit the High Tatra Mts. in November 2004, because quite many small floods occurred also before (in June–July 2001, July–August 2002, July–August 2004). Small floods after the windfall occurred in March–July 2005 (snow-rich winter), March–July 2006 (long winter with untypical simultaneous snowmelt in both mountains and river valley), July-August 2008 and in April 2010 (snowmelt period after a snow-poor winter).

Large floods did not seem to be the best descriptors in the studied catchments, because they occurred very rarely. There were two such events in the Mlynica catchment (October–December 1974, July–August 2001). Three events were observed in the Velicky creek catchment (July 1973, July–

Table 5. Characteristics of dry and wet periods for precipitation stations (1961–2010)

site	decade	Dry periods[1]					Precipitation	Wet periods[1]				
		ST	MT	LT	total	max[2]	[mm/decade]	ST	MT	LT	total	max[2]
LS	1961-1970	546	43	11	600	24	16475	505	74	22	601	25
	1971-1980	500	50	17	567	20	14756	460	83	23	566	22
	1981-1990	504	47	8	559	21	14742	431	106	22	559	31
	1991-2000	498	53	3	554	13	17763	422	94	39	555	34
	2001-2010	513	38	8	559	13	19908	434	81	43	558	25
SkP	1961-1970	532	55	15	602	21	13024	515	72	15	602	16
	1971-1980	500	44	16	560	25	12753	438	98	24	560	19
	1981-1990	529	51	13	593	23	12526	477	102	14	593	24
	1991-2000	525	50	5	580	19	13748	464	83	34	581	23
	2001-2010	522	51	12	585	17	15194	472	83	29	584	24
TL	1961-1970	535	66	26	627	23	7954	571	52	4	627	13
	1971-1980	509	70	28	607	34	8098	556	46	6	608	22
	1981-1990	485	97	25	607	22	7353	563	38	6	607	20
	1991-2000	550	74	15	639	22	7739	583	48	8	639	18
	2001-2010	531	70	19	620	29	8622	551	60	8	619	23
PP	1961-1970	524	68	32	624	36	5933	585	38	2	625	9
	1971-1980	501	75	26	602	28	5956	550	46	5	601	16
	1981-1990	522	86	22	630	26	5484	590	37	4	631	13
	1991-2000	525	90	19	634	26	5832	592	41	1	634	11
	2001-2010	541	83	19	643	26	6706	602	37	3	642	19
StP	1961-1970	527	51	7	585	21	9898	474	84	27	585	23
	1971-1980	488	41	15	544	26	9808	409	111	24	544	20
	1981-1990	509	56	17	582	17	9094	475	88	19	582	21
	1991-2000	508	62	5	575	18	10878	470	73	33	576	26
	2001-2010	515	54	11	580	22	11583	466	83	30	579	25
TJ	1961-1970	570	66	13	649	22	12161	583	53	12	648	31
	1971-1980	474	79	25	578	26	12364	508	55	15	578	20
	1981-1990	544	65	11	620	18	12341	526	79	15	620	22
	1991-2000	536	51	12	599	15	13507	502	80	18	600	25
	2001-2010	545	59	13	617	22	15127	528	70	18	616	25

[1] number of periods per decade; ST – short-term period (duration 1-5 days); MT – middle-term period (duration 6-10 days); LT – long-term period (more than 10 days)
[2] duration of the longest period in days in a decade

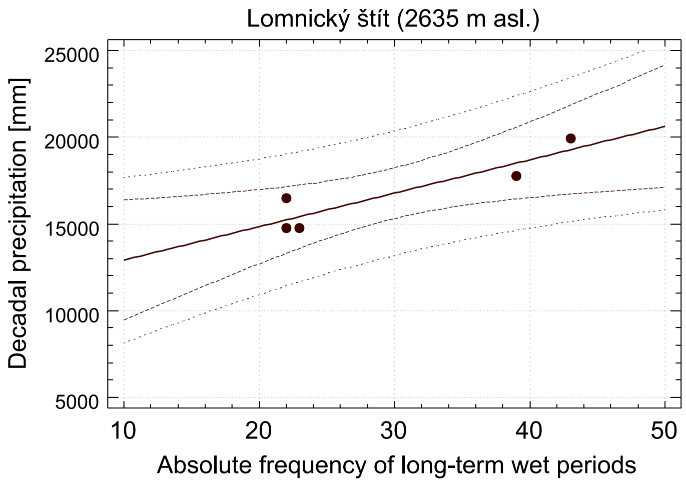

Fig. 5. Simple regression between the frequency of the long-term wet periods and decadal precipitation.

August 2001 and May–August 2010). Two events classified as large floods were observed in the Poprad-Matejovce catchment (July–August 1997, July–August 2001). The event in May-August 2010 most probably occurred at Poprad-Matejovce too, but since the measurements finished in 2009, the measured data were not at disposal. It is obvious that an apparent signif-

Table 6. Numbers of days with flows classified as extremely low, small floods and large floods; the definitions of flow characteristics are given in methodology

Catchment	Decade	Extremely low	Small floods	Large floods
Mlynica	1971-1980	283	166	80
	1981-1990	360	229	0
	1991-2000	282	141	0
	2001-2010	456	179	27
Velicky creek	1971-1980	311	109	28
	1981-1990	625	90	0
	1991-2000	360	144	0
	2001-2010	173	234	122
Poprad-Matejovce	1971-1980	287	195	0
	1981-1990	523	134	0
	1991-2000	323	51	38
	2001-2009	271	176	33

icant increase between decade 1991–2000 and 2001–2010 is caused just but the occurrence of one large flood event in the extremely wet spring 2010. Thus, such a change should not be classified as a trend.

Evaluation of precipitation data series according to the IWSS criteria shows a significant increase of the number of potentially dangerous daily precipitation, i.e. reaching 40–60 mm (Fig. 6). It may be related to the increase of precipitation at the highest altitudes. The increase of precipitation at higher altitudes may be the reason of increase of flows classified as small floods in the last two decades. Occurrence of days with precipitation exceeding 60 mm, i.e. potentially large or enormous hazard consequences suggested irrelevant changes, although approximately twofold increase of the absolute frequency was recorded at stations SkP and TJ in last two decades (Fig. 6). The highest number (4) of daily precipitation connected with the extreme risk, i.e. more than 90 mm was observed at station TJ during decade 2001–2010. Thus, the area close to the Polish-Slovak border is probably the most vulnerable area in the High Tatra Mts.

5. Conclusions

Frequent occurrence of extreme weather events reported over the world during last years is a serious reason for regional research of the associated potential hazard. It is generally acknowledged that mountains are particularly vulnerable to possible changes of weather patterns. Hydrological research performed near the study area showed that runoff response of the small mountain catchments in the warm period of a year (i.e. the one associated with precipitation maximum) primarily depends on the amount of precipitation (*Kostka and Holko, 2003*). The results of this study indicated an increased precipitation at higher altitudes in the High Tatra Mts. It may be related to a significant increase in the number of days with daily precipitation 40–60 mm and more frequent occurrence of the long-term wet periods during last two decades in the upper layer of lower troposphere. Significant increase of small flood events found for two catchments in the last decade (2001–2010) may be linked to it as well.

Simultaneous analysis of the time series of meteorological and hydrological data is useful in extending knowledge on hydrological response of

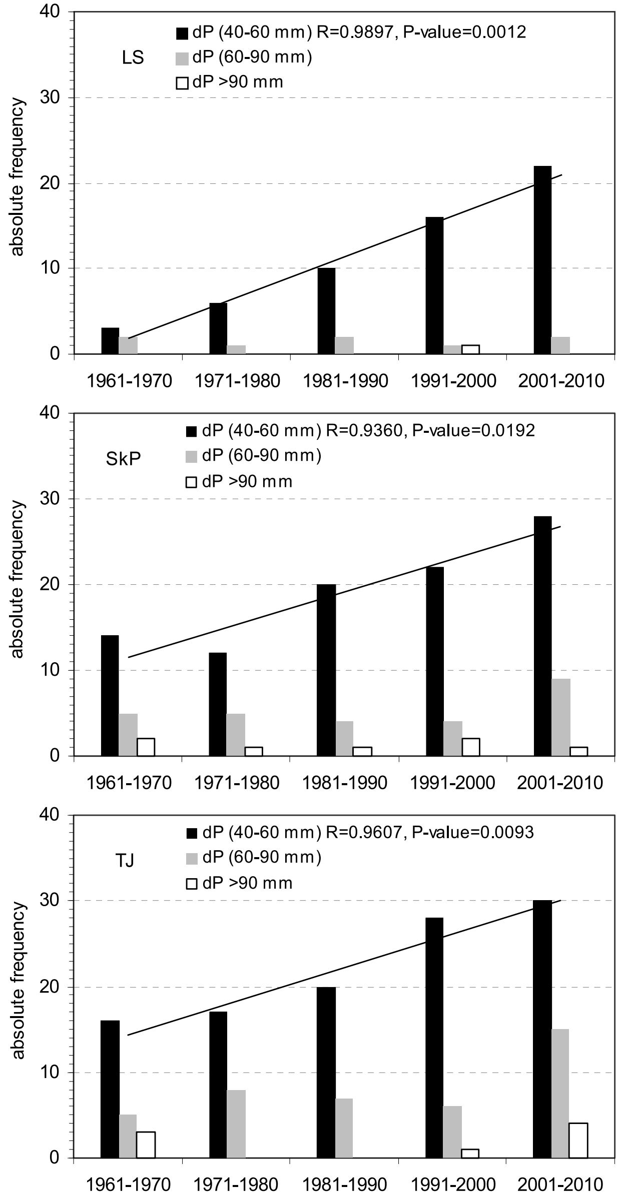

Fig. 6. Decadal changes of extreme and potentially dangerous rainfalls at the most sensitive sites LS, SkP and TJ for warm seasons (MJJASO) of period 1961–2010 (line – statistically significant increase).

mountain catchments. However, the results should not be extrapolated beyond the study period. Dry year of 2011 that was not analysed here would for example not negligibly change the statistics of the dry periods.

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