Application of selected statistical tests to detect changes in the rainfall and runoff regime

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Anwendung ausgewählter statistischer Testverfahren zur Erfassung von Änderungen im Niederschlagsabflussverhalten

Introduction

The detection of changes in long-time series of hydrological data is an important and difficult issue that is of increasing interest because of its fundamental role in the planning of future water resources and flood protection. The Earth's climate system has changed considerably since the pre-industrial era. The global surface-temperature rise of 0.6+0.2 °C over the 20th century was greater than during any other century over the last 1000 years (Kundziewicz, Robson, 2004). Studies of regional scope which interpret changes in the rainfall-runoff regime are becoming more important. This study deals with an identification of inhomogeneity in time series of hydro-climatic factors and with the trend analysis of rainfall-runoff regime in selected headwater areas of the Czech Republic.

Zusammenfassung

Die Forschungsarbeit befasst sich mit der Analyse hydro-meteorologischer Trends unter Verwendung ausgewählter statistischer Verfahren. Das Hauptziel war der Vergleich von Abflusszeitreihen mit Niederschlags-, Lufttemperatur- und Schneehöhendaten und die Analyse möglicher Änderungen in den Regionen des Böhmerwaldes, des Erz- und Jeseniky-Gebirges. Die Daten wurden auf Homogenität und Trendverhalten geprüft. Dabei gelangten der Pettitt Test; der Standard Normal Homogenitäts Test; zwei Wilcoxon-Tests und der Mann-Kendall Test zur Anwendung. Weiters wurden Analysen von Einzel- und Doppelsummenkurven auf monatlicher, saisonaler und Jahresbasis durchgeführt. Seit Ende der 70er-Jahre wurde ein nennenswerter Anstieg des Abflusses in den Wintermonaten festgestellt. Dieser Anstieg korrespondiert jedoch nicht signifikant mit den Niederschlagsbeobachtungen. Seit den 80er-Jahren konnte ein Anstieg der mittleren Jahrestemperatur festgestellt werden, der eine Reduktion der Schneebedeckung zur Folge hat.

Schlagwörter: Teststatistik, Niederschlags-Abflussregime, Mittelgebirge, Böhmerwald.

Summary

The research discusses the analysis of trends of essential hydrometeorological elements using selected statistical methods. The main aim of our research project was to compare the time series of flows with an adequate series of rainfall values; air temperatures and snow cover depths, and thereby try to determine what kind of changes occur in low mountains areas (study areas: Bohemian Forest, Ore Mountains, Jeseniky Mt.). We verified the absolute and relative homogeneity of the data series, as well as the presence of a trend in the data series. The following statistical tests, in particular, were used for this purpose: Pettitt test; Standard Normal Homogeneity test; two Wilcoxon tests; and a Mann-Kendall test. Simple-mass and double-mass curves of monthly and annual values were also applied in the case of flow and rainfall values; furthermore, quarter-year as well as cold and warm half-year periods were studied. Trends in flow development do not highly correspond to rainfall tendencies. Since the end of the 70s and especially in the 80s (Bohemian Forest and Jeseniky Mt. and later in 90s Ore Mt.), a substantial increase in runoff occurred during the winter months. Starting in 1980, average annual temperatures have been rising, which corresponds very well to a reduction in snow cover.

Key words: Trend, rainfall-runoff regime, statistical test, low mountain areas, Bohemian Forest, Ore Mt., Jeseniky Mt.

Data Sources and Methods

The basic source of runoff and climate values was the Czech Hydrometeorological Institute (CHMI) database from the period 1962–2008. Hydrometeorological data of Deutscher Wetterdienst (DW) and the Technical University in Dresden (TU Dresden) were also used in transboundary regions. All series were subjected to homogeneity testing and trend analysis to determine when any given change occurred. The following statistical tests were applied: Pettitt test (KUNDZEWICZ, ROBSON, 2000); Standard Normal Homogeneity test SNHT (ALEXANDERSSON, MOBERG, 1997); and two Wilcoxon tests (ANDĚL 1985, 1998). Statistically significance tendencies in the time series were verified using the Mann-Kendall test (MK) YUE et al. (2002), ARORA et al. (2005) and PARTAL, KAHYA (2006). This analysis was moreover completed with the Kendall rank correlation coefficient τb (HENDL 2004). Simple-mass and double-mass curves of monthly and annual values were also applied in the case of flow and rainfall values; furthermore, quarter-year as well as cold and warm half-year periods were studied. Following the analysis of the trends in runoff, rainfall and air temperature regimes, an analysis of changes in landscape use, river network training, and land drainage was carried out.

All study catchments are located in low mountains areas in the Czech Republic. Three of them in the Šumava Mt. (Bohemian Forest) (Ostružná, Upper Blanice and Vydra River), two in the Jeseníky Mt. (Opava and Opavice Rivers) and one in the Krušne hory (Ore Mt.) (Rolava River, see Figure 1). A basic hydrological characteristic of studied catchments is described in Table 1.

Nr – number of catchment (See Figure 1), A – area of a basin (ZABAGED 1:10000), P – mean annual precipitation amount for a basin for the hydrological period 1962–2008 (CHMI, DW and TU Dresden), Q_a – mean annual discharge from the beginning of measurement until year 2008 (CHMI), φ – annual runoff coefficient for the period 1962-2008, R_{max} and R_{min} – maximum and minimum altitude, FA – forest area, AL – arable land (CORINE, 2000), DA – drained area (Agricultural Water Management Agency).

Results

The results have been influenced by the quality and the length of time series. Despite the above mentioned fact it is possible to prove certain deviations and trends which are similar to each other in the observed areas. To this effect, the identification of increased mean discharges for the period of time 1974–1982 has been marked, less or more, in all of the observed streams, except for the Vydra River (see Figure 2). This identification seems to be the most significant trend KLIMENT, MATOUŠKOVÁ (2006). It is evident that the deviation has been more noticeable in low lying areas as well as in the less forested areas and areas with a stronger anthropogenic influence. Main reasons are to be found in the development of climate, especially in higher, relatively equally spread precipitation, then also in a higher snow cover together with moderate behaviour of winter temperatures and finally in relatively low air temperature in summer.

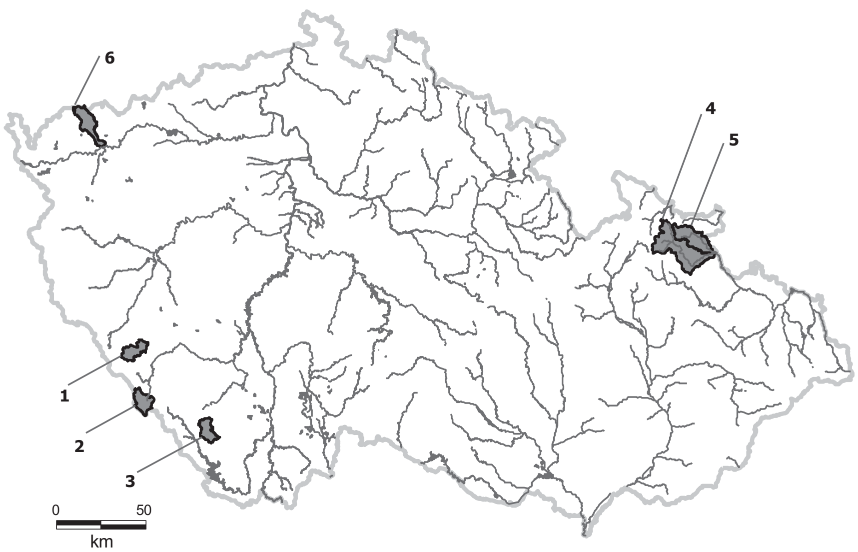

Figure 1: Delimitation of study river basins in the Czech Republic. 1 – Ostružná basin, 2 – Vydra basin, 3 – Upper Blanice basin, 4 – Upper Opava basin, 5 – Opavice basin, 6 – Rolava basin

Abbildung 1: Einzugsgebietsgrenzen der Untersuchungsgebiete in der Tschechischen Republik

Table 1: Basic characteristic of study river basins
Tabelle 1: Gebietskenngrößen der Testgebiete

Nr.	Gauging site	River	Data since	A (km^2)	P (mm)	Qa (m^3s^{-1})	(%)	R_{max} (m)	R_{min} (m)	FA (%)	AL (%)	DA (%)
1	Kolinec	Ostružná	1949	92,42	919	1,2	44,6	1177	528	49,3	17,2	8,3
2	Modrava	Vydra	1931	93,41	1357	3,4	84,6	1373	935	59,1	0	0
3	Blanický Mlýn	Blanice	1953	85,21	837	0,93	41,1	1228	743	64,3	0,3	5,3
4	Krnov	Opava	1953	370,5	850	4,06	40,7	1492	311	61,3	6,3	4,5
5	Krnov	Opavice	1953	175,52	776	1,37	31,7	974	311	41,8	17,2	4,2
6	Stará Role	Rolava	1968	125,34	950	2,39	63,3	1008	390	34,2	21,1	-

A connection with the significant amelioration measures from 70s and 80s of the 20th century is probably random. This connection corresponds in time with the Blanice and above all with the Ostružná River basins where the largest land drainage has been done (KLIMENT, MATOUŠKOVÁ, 2009). It does not correspond with the Opava and the Opavice upstream parts of their river basins where the amelioration has been done later and with lower intensity (see Figure 3). The large scale amelioration measures were not applied in Vydra and Rolava catchments. Deviations in the runoff, which have been recorded in the mass curves, have been statistically verified to a certain level by different tests of homogeneity, mainly by Pettitt-Mann-Whitney test, Mann-Whitney test and also Kruskal-Wallis test. In the time series of mean annual discharges for the most of the selected rivers, significant inhomogeneity has been identified for the year 1983. In the series of precipitations, no significant inhomogeneity has been recognized and no direct links with inhomogeneity in runoff series have been confirmed. The homogeneity of the time series of air temperature and snow cover has been tested by SNHT test (Standard Normal Homogeneity Test). This test has been used only in a complementary way for individual climatic stations related to the areas of interest. In some climatic stations, the year of

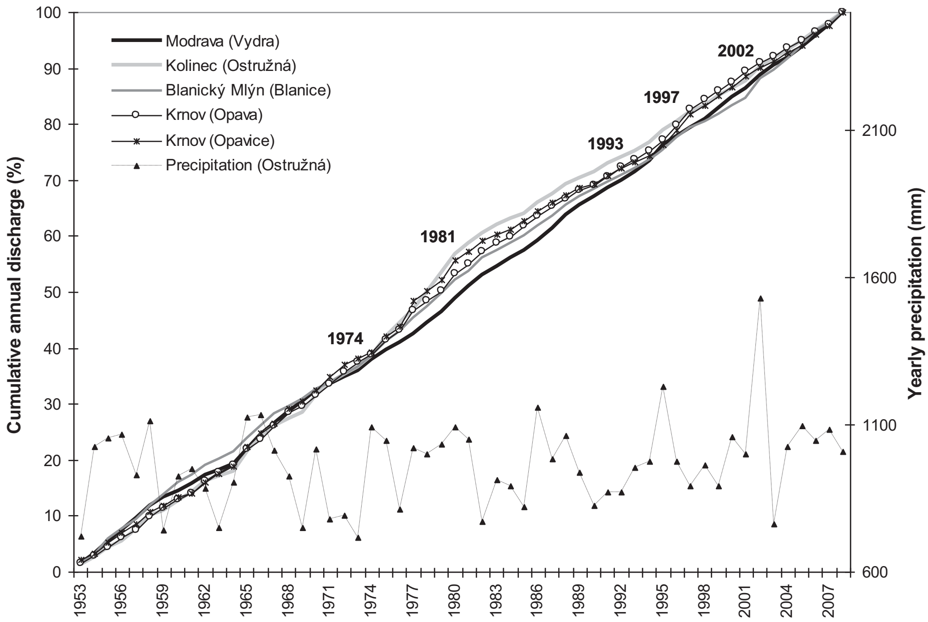

Figure 2: Simple mass curves of annual discharges
Abbildung 2: Summenkurve der Jahresniederschläge

change 1988 has repeatedly been confirmed. Since this year warming has been more evident.

Deviations in discharge series have been also verified by Wilcoxon non-parametric test. Evaluated data series have been delimitated regarding identified changes: 1967–1974, 1975–1982, 1983–1990, 1991–1998 and 1999–2006. The highest deviations of statistic significance have been recorded for the Ostružná in the period of increasing discharge from 1975 to 1982 (W0.01(8) = 0), for the Blanice (W0.01(8) = 0) and the Opavice (W0.05(8) = 3) in the period of decreasing discharge in 1983–1990. There have been proved no deviations in the river basins of the Vydra, the Rolava and the upper Opava.

An identification of trends in hydro-climatic time series, tested by the seasonal Mann-Kendall test, shows a very significant result. The test has two parameters important for trend detection: significance level (p), which represents the power of the test, and slope magnitude estimate (MK-S), which represents the direction and volume of the trend (see Table 2, 3). The significance of a trend was tested at the level of 0.05. In May and June an important runoff decrease has been confirmed in the observed streams. No direct link of statistical importance with a rainfall decrease in the mentioned months has been proved, with the only exception of the Vydra River. A significant increase in runoff during winter months has been recorded in the Rolava River and in the Šumava Mt. Rivers as well. This trend can be put in connection not only with the rising air temperature (see Figure 4), but also with increasing amount of winter precipitations in these areas. The similar phenomenon has not been proved in the Opava and the Opavice River basins. The most remarkable increase of monthly temperatures covers the period from April to August (with highest values in May and August) and also the winter season, with highest values in December and January. Generally significant trend has not been confirmed in the time series of annually or monthly areal basin precipitations. The trends in the annual and monthly air temperature series, not regarding altitude above sea level and geographical position, have been proved for all observed river basins. Warming is the most significant in the periods from April to August and from December to January.

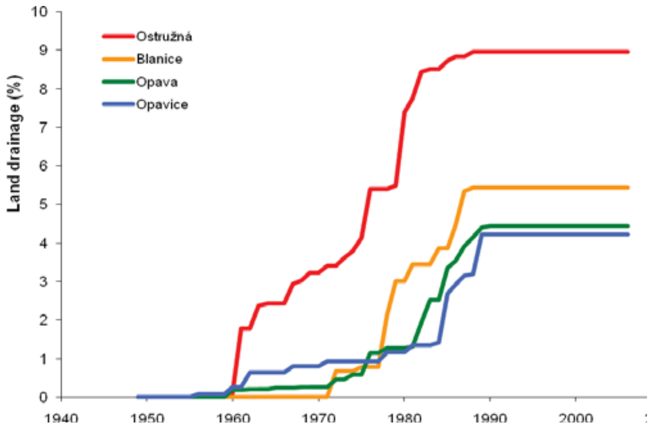

Figure 3: Amelioration measures in studied catchments, subsurface land drainage

Abbildung 3: Meliorationsmaßnahmen in den Untersuchungsgebieten (Untergrunddränagierung)

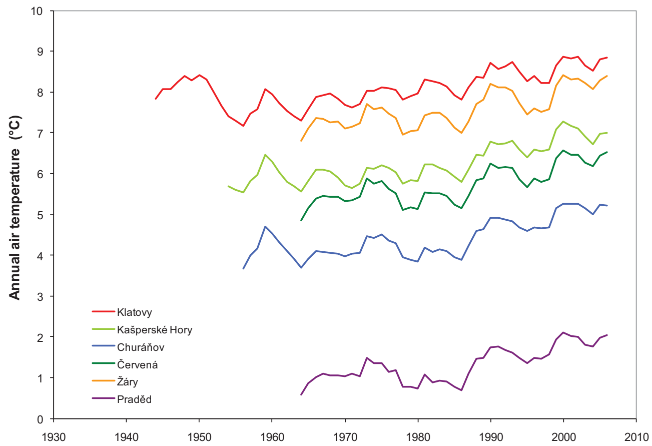

Figure 4: Development of annual air temperature for selected climatic station, 5-year moving averages (1942–2008). Prad d station finished observations in the year 1997; the data has been calculated as a multiple regression using the data of neighbouring climatic stations

Abbildung 4: Jahresmitteltemperaturen (5-Jahresgleitmittel) ausgewählter Klimastationen der Periode 1942–2008

Conclusion

During summer months higher temperature can intensify the process of evaporation-transpiration and thus it takes part in a significant decrease in runoff. The decrease in runoff and insufficient supplies of ground water can be interrelated with the trends in snow cover. These trends manifest themselves in an average decrease of snow cover depth and in a decreasing number of days with snow cover. The

Table 2: Application of Mann-Kendall statistics, long-term trends in mean monthly discharge and precipitation time series (1962–2008)
Tabelle 2: Ergebnisse des Mann-Kendall Tests (1962–2008). Trendanalyse der mittleren Monatsabflüsse und Monatsniederschlagssummen

	Vydra – Modrava			Ostružná – Kolinec			Blanice – Blanický Mlýn			Opava – Krnov			Opavice – Krnov			Rolava – Stará Role		
	MK-S	p	Trend	MK-S	p	Trend	MK-S	p	Trend	MK-S	p	Trend	MK-S	p	Trend	MK-S	p	Trend
Q_{11}	0,798	0,4250		-0,779	0,4357		0,138	0,8906		-0,523	0,6012		-0,1742	0,8617		0,9798	0,327	
Q_{12}	0,981	0,3265		0,284	0,7762		0,101	0,9196		-1,513	0,1302		-0,8529	0,3937		1,8508	0,0642	
Q_1	1,403	0,1606		-0,009	0,9927		1,311	0,1897		1,2472	0,2123		0,6144	0,5389		1,8508	0,0642	
Q_2	1,550	0,1212		0,339	0,7344		2,137	0,0326	↑	0,8345	0,404		0,2201	0,8258		2,7944	0,0052	↑
Q_3	3,366	0,0008	↑	0,743	0,4576		3,402	0,0007	↑	0,2843	0,7762		0,1192	0,9051		2,5282	0,01146	↑
Q_4	1,953	0,0508		-0,532	0,5948		-1,000	0,3175		-1,513	0,1302		-1,7149	0,0864		-1,222	0,22179	
Q_5	-0,963	0,3356		-2,265	0,0235	↓	-2,632	0,0085	↓	-2,21	0,0271	↓	-2,3018	0,0213	↓	-2,94	0,00329	↓
Q_6	-3,109	0,0019	↓	-2,889	0,0039	↓	-2,449	0,0143	↓	-3,347	0,0008	↓	-2,6686	0,0076	↓	-1,899	0,05754	
Q_7	-0,908	0,3639		-2,357	0,0184	↓	-0,761	0,4466		-2,265	0,0235	↓	-1,8249	0,068		0,5202	0,60295	
Q_8	-0,835	0,4040		-2,155	0,0312	↓	-0,431	0,6665		-1,018	0,3087		-0,6144	0,5389		0,6412	0,52141	
Q_9	0,596	0,5511		-2,173	0,0298	↓	-0,835	0,4040		-0,046	0,9634		0,2476	0,8044		1,7978	0,07221	
Q_{10}	0,770	0,4411		-1,293	0,1960		-0,193	0,8473		-0,248	0,8044		-0,5686	0,5696		1,4709	0,14131	
Q_r	0,779	0,4357		-1,146	0,2517		-0,009	0,9927		-2,21	0,0271	↓	-1,3114	0,1897		1,6218	0,10485	
H_{11}	0,101	0,9196		0,908	0,3639		0,468	0,6400		-0,779	0,436		-0,138	0,891		1,6183	0,1056	
H_{12}	0,890	0,3737		0,816	0,4144		0,119	0,9051		0,156	0,876		0,266	0,790		1,0519	0,29285	
H_1	1,843	0,0653		1,403	0,1606		1,550	0,1212		0,614	0,539		-0,303	0,762		1,2663	0,2054	
H_2	2,008	0,0446	↑	1,366	0,1718		1,623	0,1046		-0,119	0,905		-0,835	0,404		0,7221	0,47022	
H_3	1,458	0,1448		1,697	0,0898		1,697	0,0898		1,091	0,275		0,688	0,492		0,5756	0,56489	
H_4	-0,963	0,3356		-1,421	0,1552		-0,926	0,3543		-0,211	0,833		-0,431	0,666		-1,266	0,2054	
H_5	-1,513	0,1302		-0,761	0,4466		0,138	0,8906		-1,531	0,126		-1,293	0,196		-1,79	0,07352	
H_6	-2,559	0,0105	↓	-0,578	0,5634		-1,348	0,1776		-1,036	0,300		-1,183	0,237		-0,45	0,6527	
H_7	1,146	0,2517		1,586	0,1126		0,816	0,4144		-0,963	0,336		-0,724	0,469		1,1826	0,23697	
H_8	-0,468	0,6400		0,559	0,5759		0,064	0,9488		-0,596	0,551		-0,688	0,492		0,4082	0,68316	
H_9	0,853	0,3937		0,596	0,5511		0,266	0,7903		1,165	0,244		1,348	0,178		1,2663	0,2054	
H_{10}	1,036	0,3001		1,440	0,1499		1,091	0,2751		0,028	0,978		-0,156	0,876		1,9361	0,05286	
H_r	1,862	0,0627		1,880	0,0601		1,568	0,1168		-0,798	0,425		-0,945	0,345		2,0198	0,0434	↑

Q ($_{1–12}$) – monthly discharge, Q_r – annual discharge, H($_{1–12}$) – monthly precipitation amount for a basin, H_r – annual precipitation, MK-S – Mann-Kendall statistics, p – statistical significance, (↑) rising trend, (↓) decreasing trend. Data source: CHMI, DWD, TU Dresden 1962–2008

Table 3: Application of Mann-Kendall statistics, long-term trends in mean temperatures, snow cover depth and number of days with snow covers (1962–2008)
Table 3: Ergebnisse des Mann-Kendall Tests (1962–2008). Trendanalyse der mittleren Lufttemperaturen, der Schneehöhen und der Tage mit Schneebedeckung

	Karlovy Vary			Krnov			Klatovy			Kašperské Hory			Cervená			Churáňov			Fichtelberg		
	MK-S	p	Trend	MK-S	p	Trend	MK-S	p	Trend	MK-S	p	Trend	MK-S	p	Trend	MK-S	p	Trend	MK-S	p	Trend
T_{11}	0,321	0,7480		-0,110	0,9123		0,009	0,9927		-0,339	0,7344		-0,028	0,9780		0,293	0,7692		0,669	0,5032	
T_{12}	0,891	0,3731		1,303	0,1926		1,733	0,0831		1,596	0,1105		1,358	0,1744		2,063	0,0391	↑	2,283	0,0224	↑
T_1	1,615	0,1063		2,045	0,0408	↑	1,752	0,0799		2,118	0,0341	↑	2,138	0,0325	↑	1,458	0,1448		1,715	0,0864	
T_2	1,432	0,1522		1,385	0,1660		1,357	0,1747		1,311	0,1897		1,440	0,1498		1,330	0,1836		1,807	0,0708	
T_3	1,918	0,0551		1,239	0,2154		1,807	0,0708		1,770	0,0767		1,257	0,2088		1,458	0,1448		1,467	0,1423	
T_4	1,971	0,0488	↑	2,588	0,0097	↑	1,935	0,0530	↑	1,972	0,0486	↑	2,147	0,0318	↑	1,908	0,0565		2,421	0,0155	↑
T_5	3,460	0,0005	↑	3,563	0,0004	↑	3,357	0,0008	↑	3,622	0,0003	↑	2,845	0,0044	↑	3,852	0,0001	↑	3,081	0,0021	↑
T_6	2,442	0,0146	↑	3,619	0,0003	↑	1,605	0,1085		2,421	0,0155	↑	2,093	0,0363	↑	2,201	0,0277		1,275	0,2024	
T_7	2,248	0,0246	↑	3,771	0,0002	↑	1,623	0,1046		2,091	0,0365	↑	2,340	0,0193	↑	1,513	0,1302		1,311	0,1897	
T_8	3,388	0,0007	↑	4,048	0,0001	↑	2,660	0,0078	↑	2,999	0,0027	↑	3,148	0,0016	↑	3,219	0,0013	↑	2,660	0,0078	↑
T_9	0,229	0,8185		0,624	0,5324		-0,064	0,9488		0,138	0,8906		-0,156	0,8760		0,220	0,8258		0,165	0,8689	
T_{10}	0,826	0,4086		1,230	0,2188		1,220	0,2226		1,403	0,1606		0,294	0,7690		0,624	0,5329		-0,119	0,9051	
T_r	3,866	0,0001	↑	4,072	0,0000	↑	3,897	0,0001	↑	4,063	0,0000	↑	3,724	0,0002	↑	4,246	0,0000	↑	3,861	0,0001	↑
SN_{11}	0,618	0,5367		-1,035	0,3007		-0,276	0,7823		0,759	0,4481		-1,697	0,0896		-0,275	0,7836		1,431	0,1525	
SN_{12}	-0,739	0,4600		-1,009	0,3129		0,000	1,0000		-1,266	0,2057		-2,559	0,0105	↓	-1,220	0,2226		-0,257	0,7973	
SN_1	-0,413	0,6798		-0,606	0,5447		0,421	0,6740		-0,028	0,9773		-2,320	0,0203	↓	-0,945	0,3449		-1,192	0,2332	
SN_2	-1,146	0,2516		-0,248	0,8043		0,315	0,7531		-0,502	0,6158		-3,586	0,0003	↓	-1,642	0,1007		-2,228	0,0259	↓
SN_3	-1,048	0,2948		-0,046	0,9633		-0,068	0,9456		-1,127	0,2598		-2,054	0,0399	↓	-1,605	0,1085		-2,137	0,0326	↓
SN_4	1,070	0,2845		-1,199	0,2305		1,408	0,1592		0,034	0,9731		-1,986	0,0471	↓	-1,697	0,0898		-1,917	0,0553	
SN_{5*}										-1,530	0,1260		-1,845	0,0595		-1,946	0,0516	↓	-4,025	0,0001	↓
SN_r	-1,115	0,2648		-0,110	0,9124		0,642	0,5209		0,468	0,6400		-3,476	0,0005	↓	-2,045	0,0409	↓	-2,137	0,0326	↓
SD_{11}	0,914	0,3606		-0,150	0,8806		-1,787	0,0740		-0,074	0,9413		0,349	0,7269		0,588	0,5565		0,524	0,6000	
SD_{12}	-0,797	0,4254		-0,837	0,4026		-2,913	0,0036	↓	-0,395	0,6926		-1,135	0,2564		-0,575	0,5652		-0,374	0,7081	
SD_1	-1,233	0,2177		-1,334	0,1821		-2,022	0,0432	↓	-1,221	0,2222		-1,772	0,0764		-1,475	0,1402		-1,523	0,1279	
SD_2	-0,993	0,3208		-0,901	0,3676		-1,443	0,1489		-1,018	0,3088		-1,402	0,1609		-0,067	0,9464		-0,058	0,9540	
SD_3	-0,676	0,4991		-0,700	0,4836		-2,121	0,0339	↓	-1,323	0,1859		-1,274	0,2026		-0,524	0,6002		-0,152	0,8790	
SD_4	0,994	0,3202		-0,832	0,4055		-1,778	0,0754		-1,662	0,0965		-1,625	0,1043		-0,616	0,5381		-2,163	0,0306	↓
SD_{5*}										-2,163	0,0306	↓	-2,099	0,0358	↓	-2,331	0,0198	↓	-3,670	0,0002	↓
SD_r	-1,586	0,1128		-1,450	0,1472		-3,083	0,0020	↓	-1,854	0,0638		-1,845	0,0651		-0,514	0,6074		-1,854	0,0637	

T ($_{1–12}$) – monthly air temperature, T_r – annual air temperature, SN ($_{1–5,\ 11,\ 12}$) – monthly snow cover depth, SN_r – annual snow cover depth SD ($_{1–5,\ 11,\ 12}$) – monthly number of days with snow cover, SDr – annual number of days with snow cover, MK-S – Mann-Kendall statistics, p – statistical significance, (↑) rising trend, (↓) decreasing trend, Data source: CHMI, DWD, TU Dresden 1962–2008 second finding is important especially for low elevated climatic stations.

The period of higher runoff between 1975 and 1982 is correspondent with a period of higher precipitation. However, compared to similar situations, the given period can be described as not completely adequate from the point of discharge values in relation to the amount of precipitation. Looking at the 50-year sequence as a whole, there was air temperature increase considerably from the beginning of the 1980s and furthermore during the 1990s, both for the summer and winter months. In relation with increased temperatures, reduced snow cover depths and the number of days with snow cover were observed from the end of the 1980s. This research provides the contribution of validation by the SNHT test. Although this test is a particular favourite in climatology, it has been shown capable of holding up in hydrological applications as well; it is more sensitive than the Wilcoxon single-sample test. Another advantage of the SNHT test consists in the possibility of determining the particular year of change.

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