Article

Analyses of monthly discharges in Slovakia using hydrological exploratory methods

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Abstract: Detailed analyses of hydrological data are necessary in order to prove changes in their character. This article focuses on an analysis of average monthly discharges of 14 stage-discharge gauging stations in Slovakia. The measured period is from 1931 to 2016. The approaches used are hydrological exploration methods, which were created by hydrologists to describe the behaviour of hydrological time series. The methods are used to identify a change-point using an analysis of any residuals, Pettitt´s test, and an analysis of the relationship between the mean annual discharge deviations from the long-term annual discharge and the deviations of the average monthly discharge from the long-term average monthly discharge. A considerable number of change-points were identified in the 1970s and 1980s. The results of the analyses show changes in the hydrological regimes, but to confirm the accuracy of the outcomes, it is also necessary to examine other hydrological and meteorological elements such as, e.g., precipitation and the air temperature.

Keywords: monthly discharge; hydrological exploratory methods; change-point.

1. Introduction

Changes in natural phenomena, such as increasing sea levels, global warming and more occurrences of extremes in hydrology and meteorology affect us and the environment. Studies directed at changes in hydrological regimes are of great importance, especially in the fields of water resources management, flood protection and the revitalization of rivers; they concentrate on maintaining the quality of aquatic habitats or minimum discharges in the summer season ([1 - 3]). The article focuses on detecting changes in average monthly discharges by using two hydrological exploratory methods and Pettitt´s test. The aim of the article is to identify change-points and analyze the changes in a runoff regime. A considerable number of change-points were identified in the 1970s and 1980s. The results of the analyses show changes in the hydrological regimes, but to confirm the accuracy of the outcome, it is also necessary to examine other hydrological and meteorological elements such as, e.g., precipitation and the air temperature.

2. Materials and Methods

Slovakia belongs to the north temperate climate zone. The mean annual temperature is from 6˚C to 11˚C, and the mean annual rainfall total is from 500 mm to 2,000 mm [4]. The data series used are the mean monthly discharges of 14 stage-discharge gauging stations in Slovakia (Figure 1, Table 1); all of them were measured from 1931 to 2016. The data was provided by the Slovak Hydrometeorological Institute.

Figure 1: The localization of the 14 stage-discharge gauging stations used in Slovakia

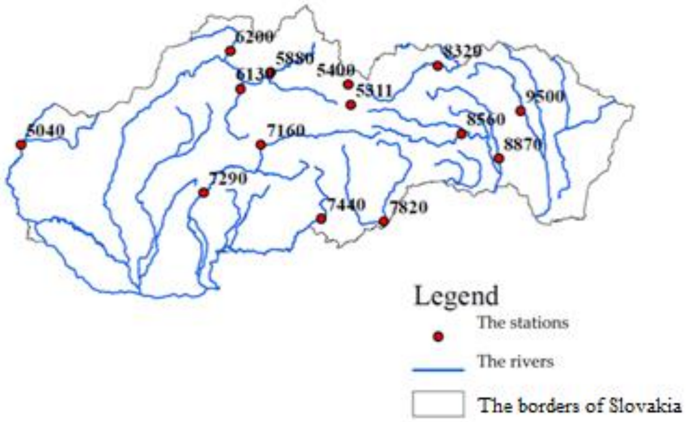


Table 1: List of the stage-discharge gauging stations with the numbering and the catchment areas

Stage-discharge gauging stations	The rivers	Number of station	Catchment area (km²)
Moravský sv. Ján	Morava	5040	24,129.30
Čierny Váh	Čierny Váh	5311	243.06
Podbánské	Belá	5400	93.49
Dierová	Orava	5880	1,966.75
Martin	Turiec	6130	827.00
Kysucké Nové Mesto	Kysuca	6200	955.09
Bánska Bystrica	Hron	7160	1,766.48
Brehy	Hron	7290	3,821.38
Holiša	Ipeľ	7440	685.27
Lenártovce	Slaná	7820	1,829.65
Jaklovce	Hnilec	8560	606.32
Košické Olšany	Torysa	8870	1,298.30
Hanušovce	Topľa	9500	1,050.03
Chmelnica	Poprad	8320	1,262.41

Two methods were used to identify the change-points. These methods use an analysis of any residuals and Pettitt´s test.

The analysis of the residuals consists of calculating the residuals. They are calculated as the differences between the mean monthly discharges and the long-term mean monthly discharge. These residuals are cumulatively added and are then are plotted on a graph. The maximal value of the cumulative curve of the residuals represents the change-point.

Pettitt's test belongs to a group of nonparametric homogeneity tests. These tests allow researchers to determine if a series can be considered as homogeneous over time or if abrupt changes have appeared over time. This test seeks to find abrupt changes in the mean of series based on the ranking of the observations. It is a widely used tool for detecting change-points in hydrological processes. The null hypothesis of this test is that there is no change in the mean of the time series. The alternative hypothesis says that there is a statistically significant change in the series. The test statistic is defined

$$\widehat{U} = max|U_k| \quad (1)$$

where U_k is given

$$U_k = 2\sum_{i=1}^{k} r_i - k(n+1) \quad (2)$$

where $k=1,2,\ldots,n$ and r_i are the ranks of the observations X_i. The most probable change-point is located where $\widehat{U}$ reaches its maximum value [5].

The test was evaluated with RStudio statistical software. Pettitt´s test obtained the most probable location of the change-point, and the significance of this change-point was evaluated by the corresponding p-value. If the p-value was less than the significance level of the test, we rejected the null hypothesis. That means there was a statistically significant change in the series. Otherwise, there was no statistically significant change-point in the series at the significance level selected.

The third method for analyzing changes in a runoff regime is based on an analysis of the relationship between the mean annual discharge deviations from the long-term annual discharges and the mean monthly discharge deviations from the long-term average monthly discharge. This method deals with the dependence of the runoff regime of each month on the runoff regime of that year. The method compares data time series divided into two periods. The mean annual discharge deviations considering the long-term mean annual discharge (Formula 3) and the mean monthly discharge deviations considering the long-term mean monthly discharge (Formula 4) were calculated. The deviations were calculated according to the formulas:

$$\Delta_1 = \frac{Q_i - Q}{Q} * 100 \quad (3) \qquad \Delta_2 = \frac{Q_j - Q_j}{Q_j} * 100 \quad (4)$$

where:

Δ_1 – the deviations of the mean annual discharges from the long-term mean annual discharge,

Q_i – the mean annual discharge for each i-year,

$\bar{Q}$ - the long-term mean annual discharge,

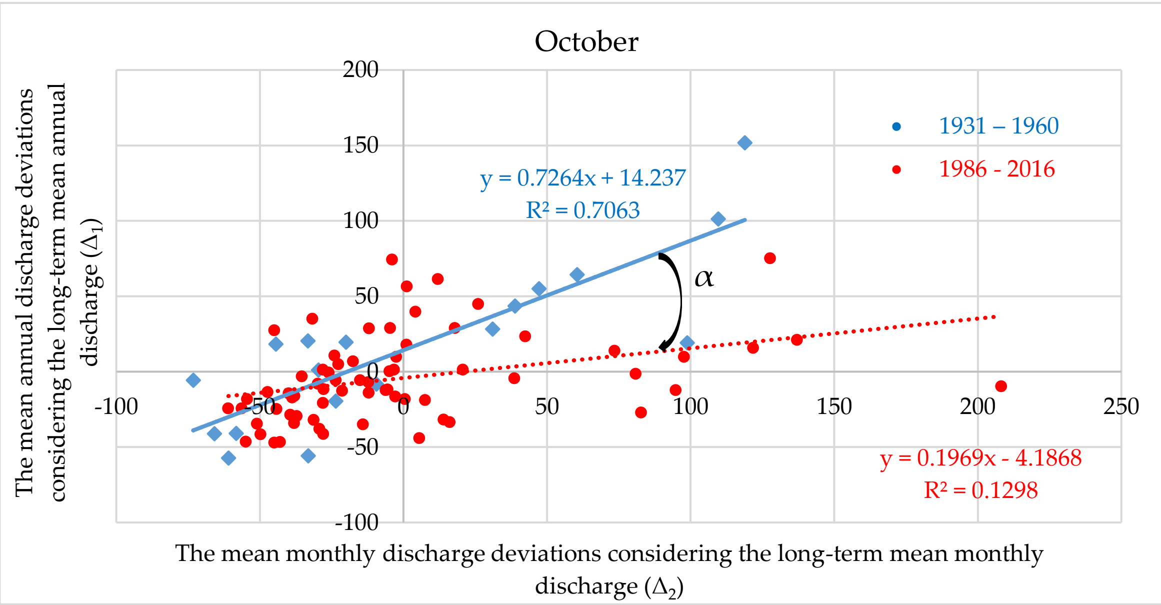
Δ_2 – the deviations of the mean monthly discharges from the long-term mean monthly discharge,

Q_j – the mean monthly discharge of the j-month in that i-year,

$\bar{Q_j}$ – the long-term mean monthly discharge of the j-month.

The trend lines which were provided for the two periods look like a closed pair of the scissors (Figure 2). The more open the scissors, the higher the changes in the runoff regime of the specific month. The scissors created forms an angle α. The angle α ranges from (10⁰, -10⁰) to (20⁰, -20⁰) and indicates a certain change; an angle greater than (20⁰, -20⁰) indicates a significant change in the runoff regime [6].

Figure 2: The sample of the analysis of the runoff regime changes by the deviations



Four approaches were used to divide the time data series into two periods:

- A division of the time data series into two 30-year periods. The first period was from 1931 to 1960, and the second period was from 1986 to 2016.
- A division of the time data series into two halves; the first period was from 1931 to 1973, and the second period was from 1974 to 2016.
- A division of the time data series by an analysis of the residuals. The change-point of the summer and winter periods determines the division of the time data series (Table 2, the columns *Qsum* and *Qwin*). The summer period was defined as May to October and the winter period from November to April.
- A division of the time data series also by an analysis of the residuals. The change-point of the mean monthly discharge period determines the division of the time data series (Table 2, the last column *Qm*).

3. Results

3.1. The analysis of the residuals

The results of the analysis of the residuals showed change-points in 1941 for September and change-points in 1952 for November (Table 2). A considerable number of change-points were identified in the 1970s and 1980s. The range of colors from green to red represents the period from the earliest change-point year to the latest change-point year.

Table 2: The change-points identified of each station and each month.

Stat.	Jan.	Feb.	Mar	Apr.	May	Jun	Jul	Aug	Sep.	Oct.	Nov	Dec.	Qsu	Qwi	Qm
5040	1974	1988	1948	1970	1987	1987	1952	1987	1941	1941	1952	1988	1942	1948	1948
5311	1953	1977	1983	1972	1979	1989	1975	1972	1984	1980	1952	1966	1979	1980	1980
5400	1947	1944	1953	1953	1974	2002	1985	1981	1975	1962	1952	1952	1964	1953	1981
5880	1954	1954	1951	1956	1986	1954	1993	1978	1941	1981	1952	1962	1945	1983	1949
6130	1974	1965	1951	1970	1972	1968	1966	1966	1941	1980	1952	1976	1966	1977	1967
6200	1973	1965	1976	1970	1938	1954	1975	1986	1941	1981	1952	1989	1987	1965	2002
7160	1953	1977	1981	1972	1996	1989	1966	1966	1941	1984	1952	1966	1985	1970	1981
7290	1953	1977	1983	1970	1987	1989	1966	1966	1941	1984	1952	1980	1985	1981	1981
7440	1982	1979	1970	1980	1942	1994	1952	1970	2009	1973	1952	1976	2009	1980	1981
7820	2008	1979	1941	1961	1969	1964	1952	1970	1944	1963	1952	1976	1953	1980	1980
8560	1953	1977	1945	1980	1945	1975	1960	1960	1941	1984	1952	1952	1955	1953	1955
8870	1953	1965	1945	1980	1974	2004	1996	1985	1941	1973	1952	1985	1969	1981	1945
9500	1953	1977	1986	1980	1973	1964	1996	1985	1941	1980	1980	1987	1969	1981	1981
8320	1975	1969	1946	1970	1982	1967	1996	1960	1941	1973	1952	1950	1949	1970	1949

3.2. Pettitt´s test

Pettitt´s test showed similar results in its analysis of the residuals. The underlined years in Table 3 are change-points with a p-value ≤ 0.15. The change-points in September are not so significant, but November has six significant change-points in 1952. Overall, there were 8 change-points in 1952. The entire measured period of the mean monthly discharges (*Qm*) has 4 statistically significant change-points out of a total of 9 change-points in 1980. More than a quarter of the change-points are statistically significant (58 change-points out of 210).

Table 3: The change-points identified by Pettitt´s test. The underlined years are change-points with p-value ≤ 0.15.

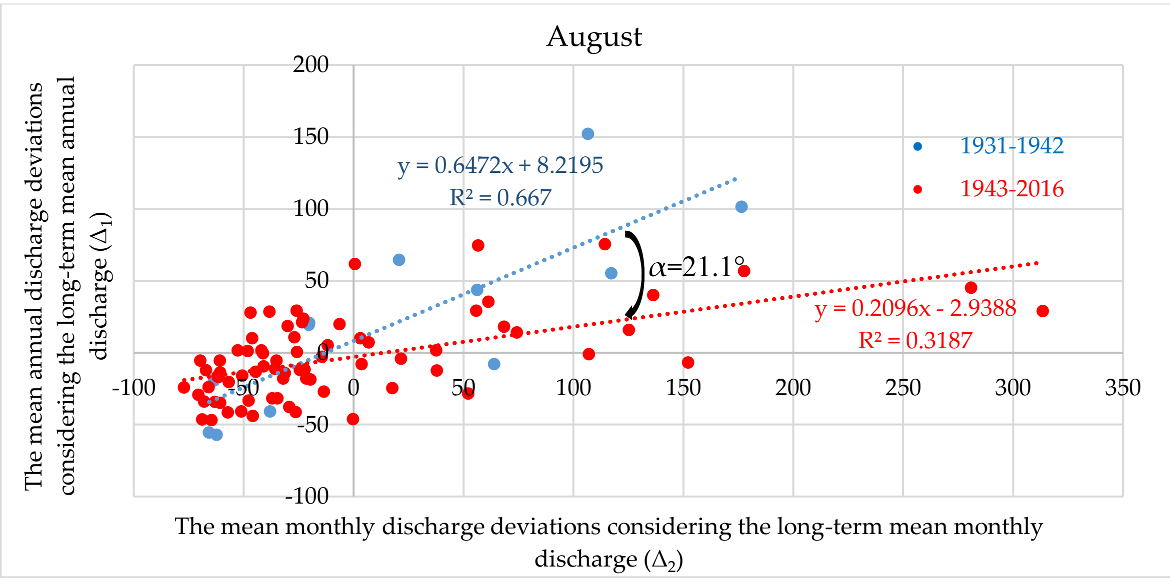
Stat.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Qsum	Qwin	Qm
5040	1973	1988	1948	1988	1997	1987	1987	1987	1954	1954	1981	1998	1987	1948	1988
5311	1953	1971	1983	1979	1996	1989	1975	1972	1980	1981	1952	1966	1980	1979	1980
5880	1954	1954	1951	1952	1986	1954	1993	1978	1941	1981	1950	1962	1945	1983	1949
5400	1947	1944	1944	1997	1974	2002	1985	1981	1941	1962	1952	1952	2002	1953	1981
6130	1992	2006	1998	1972	1987	1968	1972	1986	1942	1966	1966	1976	1966	1977	1967
7160	1983	1977	1983	1972	1996	1989	1975	1980	1981	1941	1952	1966	1980	1970	1980
6200	1973	1965	2009	1970	1938	1957	1982	1986	1941	1941	1952	1989	1987	1936	2002
7290	2000	1981	1983	1988	1987	1989	1972	1978	1981	1941	1952	1967	1985	1983	1985
7440	1982	1981	1970	1988	1991	1991	1952	1952	1950	1962	1980	1970	1950	1980	1980
7820	1983	1980	1941	1961	1964	1989	1975	1996	1980	1944	1945	1966	1950	1980	1980
8560	1983	1973	1955	1980	1991	1976	1960	1960	1955	1945	1952	1968	1980	1970	1980
8870	1953	2006	1986	2001	1969	1937	1996	1995	1941	1973	1945	1945	1969	1983	1945
9500	2004	2006	1986	2000	1969	1964	1952	1981	1996	1945	1981	1982	1969	1983	1981
8320	1961	1969	1971	1970	1936	1936	1996	1945	1941	1945	1952	1960	1949	1970	1949

3.3. An analysis of the runoff regime changes by the deviations

The analysis of the deviations compares two periods of the entire measurements for each month. The purpose of using four approaches is to analyze the differences which were visualized into the angles and then eventually into changes in the runoff regime.

The selected graph (Figure 3) shows an analysis of the deviations for the stage-discharge gauging station 5040 (Šaštín-Stráže) in August. The division of the measured period is based on the seasonal mean monthly discharges (*Qsum* vs. *Qwin*). Specifically for this graph, the first period was from 1931 to 1942 and the second period from 1943 to 2016. The change-point was in 1942 (see Table 2, row 5040, column *Qsum*). The angle between the trend lines is 21.1°. This means a significant change in the runoff regime in August.

Figure 3: The analysis of the deviations of the stage-discharge gauging station 5040 in August.



Using the four different methods for all the months at each station, angles were selected that ranged from (10⁰, -10⁰) to (20⁰, -20⁰) and then angles greater than the interval (20⁰, -20⁰). A significant number of the changes in the runoff regime were identified at the Šaštín-Stráže station (5040). Where from May to November, but excluding September, changes in the runoff regime were identified.

The method found the most changes in the runoff regime were in October, where changes in five stations were identified.

4. Discussion

The analysis of the residuals identified the most changes in September (year 1941) and in November (year 1952). A lot of the change-points were identified in the 1970s and 1980s. This simple method is applicable to hydrological data series. A disadvantage is the absence of statistical significance, but Pettitt's test, which showed statistical significance, was used in the study.

The change-points identified by Pettitt´s test show several significant change-points in November of 1952. More than a quarter of the change-points were statistically significant.

A considerable number of changes in the runoff regime were identified at the Šaštín-Stráže (5040) station and at other stations in October.

The results of the analyses show certain changes in the mean monthly discharges, but in order to confirm their correctness, it will be necessary to examine other hydrological and meteorological elements and use other methods for identifying the changes.

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