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Precipitation trends detection as a tool for integrated water resources management in Slovakia

Martina Zeleňáková[a,*], Pavol Purcz[b], Peter Blišťan[c], Ibrahim Alkhalaf[a], Helena Hlavatá[d], Maria Manuela Portela[e], Artur Tiago Silva[e]

[a]*Department of Environmental Engineering, Faculty of Civil Engineering, Technical University of Košice, Košice, Slovakia, Tel. +42155 6024270; emails: martina.zelenakova@tuke.sk (M. Zeleňáková), ibrahim.alkhalaf@tuke.sk (I. Alkhalaf)*
[b]*Department of Applied Mathematics, Faculty of Civil Engineering, Technical University of Košice, Košice, Slovakia, email: pavol.purcz@tuke.sk*
[c]*Faculty of Mining, Ecology, Process Control and Geotechnologies, Technical University of Košice, Košice, Slovakia, email: peter.blistan@tuke.sk*
[d]*Slovakian Hydrometeorological Institute, Branch Office Košice, Slovakia, email: helena.hlavata@shmu.sk*
[e]*Department of Civil Engineering, Technical University of Lisbon, Lisbon, Portugal, emails: maria.manuela.portela@ist.utl.pt (M.M. Portela), artur.tiago.silva@tecnico.ulisboa.pt (A.T. Silva)*

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ABSTRACT

The aim of this study was to determine trends in gauging stations in Slovakia to support integrated water resources management in the country. We investigated 487 stations during the period 1981–2013. Monthly rainfall trends were detected by non-parametric Mann-Kendall and Spearman's Rho statistical test. Precipitation trends show high variability. The precipitation time series in Slovakia in gauging stations in particular have an increasing trend, especially in the month of July. Achieved results can be the basis for the development of river basin management plans and within the framework of risk assessment they will address all aspects of environmental risk management focusing on prevention, protection, preparedness (including forecasts and early warning systems) and taking into account the characteristics of each river basin. It is highly desirable but also feasible to limit the risk of adverse consequences, especially for human health and life, the environment, the cultural heritage, the economic activity and the infrastructure associated with extreme hydrological phenomena in the river basins. However, measures to reduce these risks if they are to be effective must be as far as possible coordinated throughout the river basin.

Keywords: Precipitation time series; Mann-Kendall test; Spearman's Rho test; Trend analysis; Water resources management

1. Introduction

Integrated water resources management we understand as a process of comprehensive impact assessments removal of water from ecosystems and water return back to them, including water use and protection of water resources in the area, while respecting the water circulation patterns in ecosystems territories and safeguarding the stability of the water circulation in the country. This process promotes the coordinated development and management of water and land resources in order to maximize the resultant economic and social welfare in an equitable manner, without compromising sustainability of vital ecosystems. Integrated water

* Corresponding author.

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resources management is the topic of many scientific studies [1–10]. The knowledge of temporal and spatial distribution of meteorological and hydrological time series in the country is the primary condition for water resources management. Prediction and knowledge of hydro-meteorological trends plays an important role in the economic development of a country.

The temporal variability in the precipitation time series was investigated in Ahmad et al. [11], at 15 stations over the study period of 51 years (1961–2011) in the Swat River basin, Pakistan. The non-parametric Mann-Kendall (MK) and Spearman's Rho (SR) statistical tests were applied at 5% significance level for the detection of trends in monthly, seasonal and annual precipitation. The results pointed out a mixture of positive (increasing) and negative (decreasing) trends in the monthly, seasonal and annual precipitation series.

In Shadmani et al. [12] temporal trends of reference evapotranspiration values were investigated in arid regions of Iran. For this purpose, meteorological observations collected from 11 high-quality meteorological sites over a 41-year period (1965–2005) were used and statistically significant evapotranspiration trends in the monthly, seasonal and annual time basis were detected using non-parametric MK and SR tests at the 5% significant level. The results of this study indicated that the evaporation trends for some cities were increasing (positive); however, for some sites, they showed decreasing (negative) trends. Statistical methods are very often used for solving various complex tasks of water management [13–17].

The present study analyses the trends in the precipitation data series in Slovakia. The non-parametric MK statistic test and SR test were applied to detect trends and to assess the significance of the trends in the precipitation time series. The site significance of trends in a 33-year time series was assessed using the statistical tests at the significance level of 0.05.

2. Theory

Spatial distribution of average annual precipitation totals points to several regions with relatively low amount of rainfall. The most extensive region is located within a large part of the Podunajska nižina lowland and in the south of Považie region. Likewise dry, but smaller areas are also at the far northwest of Zahorie region and also at the boundary of basins Hornadska kotlina and Popradska kotlina, where the values of precipitation are less than 550 mm. However, less precipitation in Spiš region does not have such a big impact on potential drought, as in the west and southwest regions of Slovakia. The average annual precipitation totals above 1,500 mm occur in the highest locations of the Mala Fatra, Veľka Fatra, Oravske Beskydy, Nizke Tatry and Tatra Mountains. On Tatra Mountains peak, the precipitation reaches up to about 2,000 mm. The average monthly precipitation for individual months of the year is affected by specific variations in the annual precipitation regime. This regime is influenced by continentality of climate in Slovakia and also by the orientation of the mountains towards the flow of humid air masses bringing precipitation. Contrast between northern and southern regions of Slovakia in the average rainfall is also visible. The average monthly precipitation totals are lowest in January and partially in February, mainly in the Hornadska kotlina basin in Spiš region, where their values do not even reach 20 mm in certain locations of these regions. In May, June and July, on the highest mountains of Slovakia (which are the most exposed areas to precipitation), the average monthly precipitation totals exceed the value of 200 mm. In October and November there are relatively high average monthly precipitation totals mainly in the southern and south-eastern windward mountain slopes, especially in the southern half of central Slovakia. This is related to the above mentioned increased seasonal activity of low pressure centres bringing precipitation from the Mediterranean. In December, there is a similar effect in the far northwest of Orava region, associated with a stronger flow of humid air masses from the west respectively northwest. The above mentioned peculiarities are manifested more or less strongly in the fields of average precipitation totals for different seasons, respectively in the warm months (April–September) and the cold months (October–March) [18,19].

3. Materials and methods

3.1. Study area and precipitation dataset

The locations of gauge stations in Slovakia are shown in Fig. 1.

The temporal variation of precipitation in the Slovak Republic was investigated by utilizing datasets from the Slovak Hydrometeorological Institute (SHMI) rain gauge network consisting of 634 rain gauge stations [20]. From all operated stations exactly 487 stations were without daily gaps or with a negligible number of daily gaps over the period of 33 years. Dataset was compiled for temporal trend analysis for the period of November 1981 to October 2013. The length of the data set satisfies the minimum required when searching for evidence of climate change in hydroclimatic time series, as proposed by Burn and Hag Elnur [21]. The missing data in the previous rain gages were filled in based on linear regression analysis [22,23]. Monthly data were compiled from daily data; seasonal data (winter, spring, summer and autumn) and annual data (in hydrologic year, from November to October) were derived from monthly data.

The precipitation time series (average, maximum and minimum values) from 487 evaluated gauging stations during the period from 1981 to 2013 in Slovakia are presented in Fig. 2.

3.2. Statistical analysis – non-parametric trend test and stationarity test

For detecting trends in hydro-meteorological variables, various statistical methods have been developed and used over the years [24–29]. The non-parametric MK trend test [30,31] is the most common of the various statistical procedures used to analyse time series datasets [32–38]. SR test [39,40] is another rank-based non-parametric method used for trend analysis [11,12,41] and was applied as a comparison with the MK test in this study. The use of non-parametric techniques tends to be a more robust option when testing data that differ from "normality." Furthermore, the use of

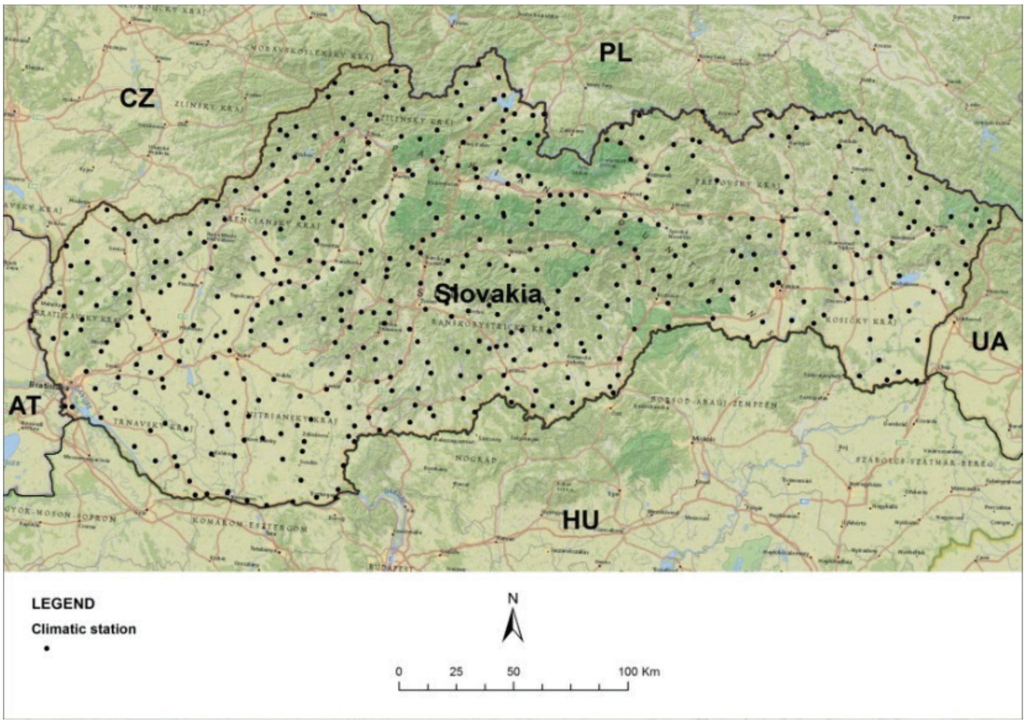

Fig. 1. Study area – location of the 487 rain gages in Slovakia.

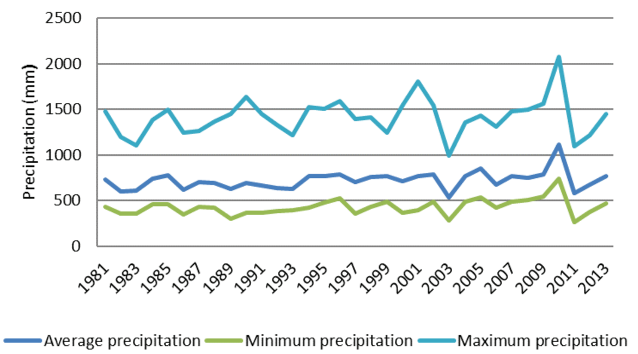

Fig. 2. Average, maximum, minimum precipitation of 487 stations in annual time scales.

non-parametric techniques is known to be more resilient to outliers [42].

The MK test follows statistics based on standard normal distribution (Z), using Eq. (1) [30,31]:

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

in which,

$$S = \sum_{k=1}^{n-1} \sum_{k+i}^{n} \mathrm{sgn}(x_j - x_k) \tag{2}$$

$$\mathrm{sgn}(x_j - x_k) = \begin{cases} +1 & \text{if} (x_j - x_k) > 0 \\ 0 & \text{if} (x_j - x_k) = 0 \\ -1 & \text{if} (x_j - x_k) < 0 \end{cases} \tag{3}$$

$$\mathrm{Var}(S) = \left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i (t_i - 1)(2t_i + 5) \right] \Big/ 18 \tag{4}$$

where n is the number of data points and m is the number of tied groups (a set of sample data having the same value).

According to this test, the null hypothesis H0 states that the depersonalized data (x_1, …, x_n) consist of a sample of n independent and identically distributed random variables. The alternative hypothesis H1 of a two-sided test is that the distributions of x_k and x_j are not identical for all k, $j \leq n$ with $k \neq j$.

The null hypothesis H0 (no trend) is accepted if $Z < Z_{\alpha/2}$ and rejected (hypothesis H1) if $Z > Z_{\alpha/2}$ where α is the significance level and $Z_{\alpha/2}$ the standard normal distribution for $\alpha/2$. The applications carried out considered $\alpha = 0.05$ and, accordingly, $Z_{\alpha/2} = 1.645$.

Positive values of Z indicate increasing trends, while negative values of Z show decreasing trends.

In SR test [39,40], which assumes that time series data are independent and identically distributed, the null hypothesis (H0) again indicates no trend over time; the alternate hypothesis (H1) is that a trend exists and that data increase or decrease with i [24]. The test statistics R and standardized statistics T are defined as [12,39,40]:

$$R = 1 - \frac{6\sum_{i=1}^{n} (D_i - i)^2}{n(n^2 - 1)} \tag{5}$$

$$T = R\sqrt{\frac{n-2}{1-R^2}} \tag{6}$$

In these equations, D_i is the rank of i^{th} observation, i is the chronological order number; n is the total length of the time series data, and Z is distribution with (n – 2) degree of freedom. The positive values of Z represent an increasing trend across the hydrologic time series; negative values represent the decreasing trends. The critical value of t is stated at a 0.05 significance level. If, $Z > Z_{\alpha/2}$ where α is the significance level and $Z_{\alpha/2}$ the standard normal distribution for $\alpha/2$, H0 is rejected and a significant trend exists in the time series.

The MK test as well as SR test does not provide an estimate of the magnitude of the trends themselves. For this purpose, another non-parametric method referred to as the Theil–Sen (TS) approach is very popular among the researchers to quantify the slope of the trend (magnitude). TS approach is originally described by Theil [43] and Sen [44]. This approach provides a more robust slope estimate than the least-square method because it is insensitive to outliers or extreme values and competes well against simple least squares even for normally distributed data in a time series [42]. Both the MK test and TS require time series to be serially independent, which can be accomplished using the pre-whitening technique [41,45,46]. Sen's method assumes a linear trend in the time series and has been widely used for determining trend magnitude in hydro-meteorological time series. In this method, the slopes (β) of all data pairs are first calculated by Theil [43] and Sen [44]:

$$\beta = \text{Median}\left(\left(x_j - x_k\right)/\left(j-k\right)\right) \tag{7}$$

for j = 1, 2, ..., N, where x_j and x_k are data values at time j and k ($j > k$) respectively, and N is the number of all pairs x_j and x_k. A positive value of β indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series.

While the purpose of a trend test is to determine whether the values of a series have a general increase or decrease with the time increase, the purpose of stationarity test is to determine whether the mean values and variances of a series vary with time [47–49]. We carried out the stationarity test with the Augmented Dickey–Fuller (ADF) unit root test first proposed by Dickey and Fuller [50] and modified by Said and Dickey [51], which tests for the presence of unit roots in the series. ADF test is conducted through ordinary least square estimation of regression models incorporating either an intercept or a linear trend. Consider the autoregressive model

$$x_t = \rho x_{t-1} + \varepsilon_t \tag{8}$$

where t = 1, 2, ..., N; $x_0 = 0$; $\left|\rho\right| \le 1$; ε_t is a real valued sequence of independent random variables with mean zero and variance σ^2.

If $\rho = 1$, the process $\{x_t\}$ is non-stationary and it is known as a random walk process. In contrast, if $|\rho| < 1$, the process $\{x_t\}$ is stationary. The maximum likelihood estimator of ρ is the least squares estimator:

$$\hat{\rho} = \left(\sum_{t=2}^{N} x_{t-1}^2\right)^{-1} \sum_{t=2}^{N} x_t x_{t-1} \tag{9}$$

The statistic for testing the null hypothesis that $\rho = 1$ is based on the usual ordinary least square t test of this hypothesis:

$$t = \frac{\hat{\rho}-1}{\hat{\rho}_{\hat{\rho}}} \tag{10}$$

where $\hat{\rho}_{\hat{\rho}}$ is the usual ordinary least square standard error for the estimated coefficient.

Dickey and Fuller [49] derived the limiting distribution of the statistic t under the null hypothesis that $\rho = 1$. The test rejects $\rho = 1$ when t is "too negative." The basic autoregressive unit root test can be augmented (referred to as ADF test) to accommodate general autoregressive models with unknown orders [51]. The ADF test is based on estimating the test regression:

$$x_t = \beta D_t + \phi x_{t-1} + \sum_{j=1}^{p} \psi_j \nabla x_{t-1} + \varepsilon_t \tag{11}$$

where t = 1, 2, ..., N; D_t is a vector of deterministic terms (constant, trend, etc.). The p lagged difference terms, ∇x_{t-1} are used to approximate the autoregressive moving average process structure of the errors, and the value of p is set so that the error ε_t is serially uncorrelated. Said and Dickey [51] show that the Dickey–Fuller procedure, which was originally developed for autoregressive representations of known order, remains valid asymptotically for general autoregressive integrated moving average process in which parameters are of unknown orders.

The statistics (in our study MK statistics) can be plotted on a map in order to show the spatial distribution of the significant precipitation trends. A spatial trend precipitation data map over Slovakia was developed in ArcGIS software. For spatial distribution of trends in maps, contours are generated using an inverse-distance-weighted algorithm based on magnitude of the trends.

4. Results

The study of the 33 years of records in 487 Slovakian rain gauges revealed an increase in the summer precipitation and, conversely, a decrease in the autumn precipitation. Table 1 summarizes the results from the trend analysis based on the MK and SR non-parametric statistical tests for a critical probability level of 5% coupled with the TS approach applied to the previous dataset. Table 1 also presents results from stationarity test: ADF test which proves absence of unit roots in the most of precipitation series observed at rain gauge stations in Slovakia.

Table 1 shows that for the annual precipitation 157 (MK test), respectively 148 (SR test) rain gauge stations proved significant trends. From those stations 155/146 showed an increasing trend and only 2 stations showed a decreasing trend.

Regarding the seasonal precipitation trends – winter and spring precipitation showed more increasing (in 68/59 + 20/17 rain gauge stations) than decreasing (in 3/2 + 1/1 rain gauges) trends. The MK test found significant increasing trends in

Table 1
Precipitation trends and stationarity in the annual, seasonal and monthly data series for 487 stations in Slovakia during period of record 1981–2013

Precipitation	Number of decreasing trends		Number of significant decreasing trends		Number of increasing trends		Number of significant increasing trends		Number of stations with stationary data
	MK	SR	MK	SR	MK	SR	MK	SR	ADF
Annual	29	29	*2*	*2*	301	310	*155*	*146*	487
Winter	99	100	*3*	*2*	317	326	*68*	*59*	487
Spring	53	56	*1*	*1*	413	413	*20*	*17*	487
Summer	17	17	*0*	*0*	347	355	*123*	*115*	487
Autumn	165	165	*0*	*0*	321	322	*1*	*0*	487
November	146	146	*0*	*0*	340	340	*1*	*1*	103
December	279	284	*15*	*11*	157	165	*36*	*27*	126
January	8	6	*0*	*0*	374	400	*105*	*81*	366
February	65	65	*0*	*0*	396	399	*26*	*23*	325
March	83	83	*0*	*0*	391	396	*13*	*8*	167
April	326	309	*3*	*3*	158	175	*0*	*0*	130
May	362	346	*2*	*0*	123	141	*0*	*0*	255
June	71	71	*1*	*1*	367	365	*48*	*51*	282
July	3	3	*0*	*0*	239	271	*245*	*213*	478
August	272	300	*3*	*0*	211	186	*1*	*1*	482
September	157	93	*0*	*0*	330	380	*0*	*14*	204
October	67	96	*0*	*0*	418	377	*2*	*14*	456

Note: Italic values are 95% significance level.

123 of the stations in summer, the SR test found significant increasing trend in 115 of the stations in summer. In autumn only one rain gauge denoted a significant trend detected by MK test.

The MK trend test proved more significant trends than SR test. Results from MK test were also applied to detect spatial trends in the monthly precipitation time series. Fig. 3 presents spatial distribution of seasonal precipitation trends in Slovakia during 1981–2013 (detected by MK test).

Table 1 gives also stationarity test results. Annual and seasonal precipitation series appear to be significantly stationary, since we cannot accept the unit root hypothesis with ADF test at 5% significance level. Most monthly series are also stationary (Table 1).

The spatial variability of precipitation has caused frequent and sometimes prolonged periods of drought, mainly in the lowlands and frequent flood events occurrence in mountainous area. In Fig. 2, almost the middle of country, mountainous area, shows significant (95% confidence level) positive trend in stations during summer and winter.

The highest magnitude of increased trend was proved in station Sumiac (situated in the middle of the country) in July and the highest magnitude of decreased trend was detected in station Oravska Polhora (situated in the north of the country) in April. The variation of the precipitation trends in mentioned stations are presented in Fig. 4.

Regarding the monthly precipitation data, the analysis showed that the highest identification of significant increasing trends occurred in July: 245 (MK test)/213 (SR test) of rain gauge stations. Also in June quite high number of stations proved significant increasing trends: 48 (MK test)/51 (SR test). The high number of significant increasing trends was proved also during winter months – exactly in December: 36 (MK test)/27 (SR test) of stations, even higher number of significant increasing trends were proved in January: 105 (MK test)/81 (SR test), in February: 26 (MK test)/23 (SR test).

5. Discussion

Average monthly precipitation totals calculated over the period of 30 years are based on a set of individual monthly precipitation totals. The values of this time series may differ significantly throughout each year. October is the typical example of such an unbalanced variation of monthly precipitation totals in climatic conditions of Slovakia (it is entirely possible the October's monthly precipitation value to be almost zero, while next year the October's monthly precipitation at the same station could reach an extraordinary high value). This is caused by the influence of semi-permanent pressure systems in Europe, and is the nature of the weather in this region. This nature of weather associated with precipitation anomalies can be manifested more frequently in the middle of autumn than in any other period of the year. At the same time, however, it should be noted that the relatively high variability of monthly precipitation totals exist also in other months of the year. At these months, either extremely low or extremely high monthly precipitation totals were registered more frequently in the late 20th and early 21st century than in the previous periods. Values of monthly precipitation totals in some cases exceeded even historic extremes, both in minimum and maximum values [18]. In the present study we found a coincidence with the rainiest period, that is, the

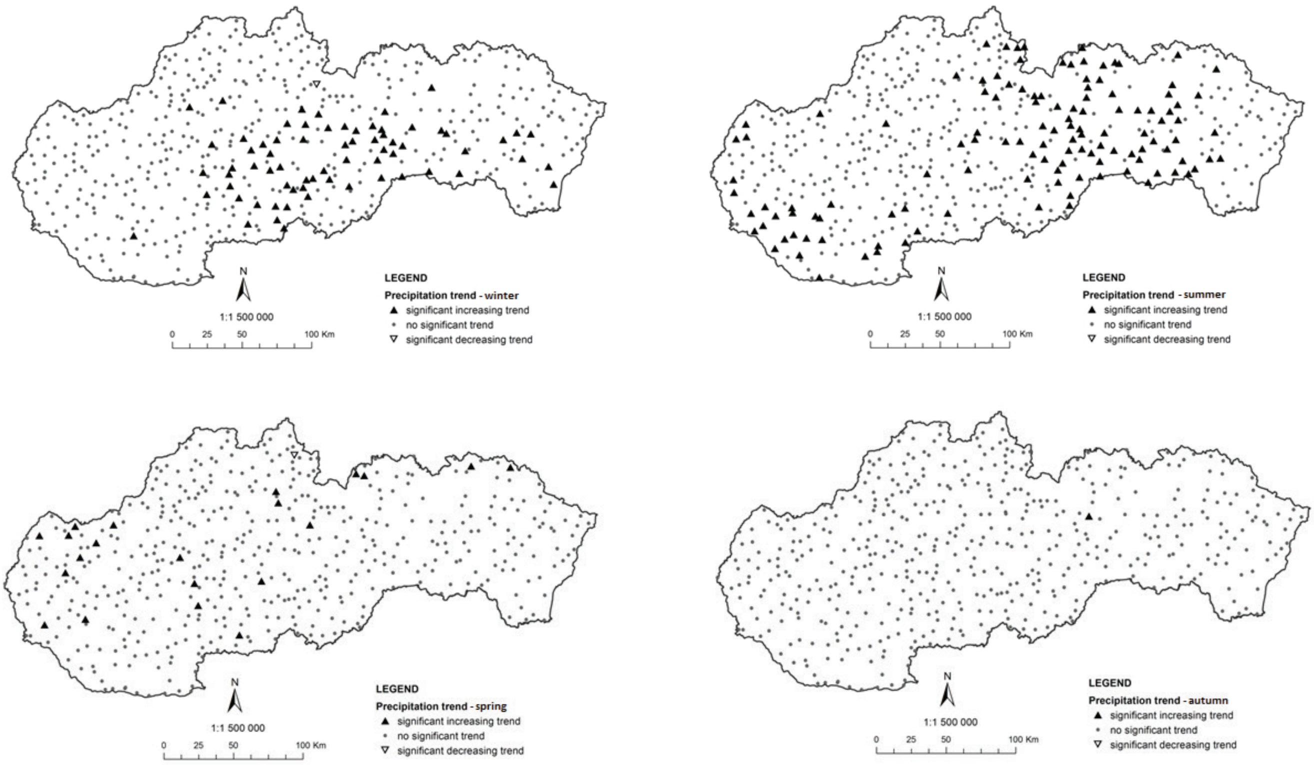

Fig. 3. Spatial distribution of seasonal precipitation trends in Slovakia during 1981–2013.

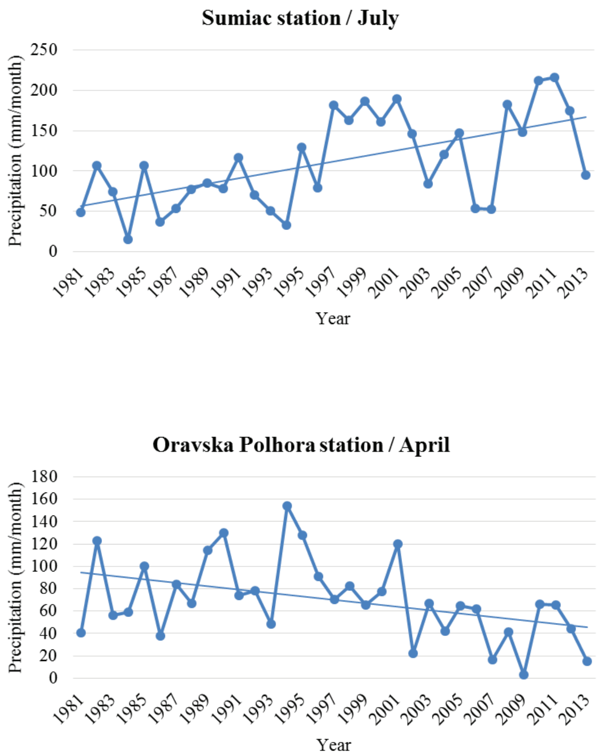

Fig. 4. Monthly precipitation variation with the most significant trends during 1981–2013.

summer season, although the most decreasing trends were related to the autumn season, which is a little different from the previous studies of precipitation time series in Slovakia. The results obtained for precipitation reveal more frequent significant increasing trends. According to SHMI statistics the rainiest month is usually June or July, and the driest period from January to March.

The Theil–Sen analysis method demonstrates the highest increasing (decreasing) trend magnitudes for July in Sumiac station (April in Oravska Polhora station) of +4.3 (–2.9) mm/year. Zeleňáková et al. [19] found positive (negative) trends in summer (fall and winter) precipitation for same stations at the 95% confidence interval. The season output averages 3 months, for example, winter trend averages the trends of November, December and March. This study extends the previous precipitation analysis by Zeleňáková et al. [19] and provides analysis in monthly time scale. Increasing (decreasing) precipitation trends in July (April) are consistent with the previous seasonal study for summer (spring); however, the month of July was found to have the highest numbers of stations with significant trends at the 95% confidence interval, followed by June and none in May. Likewise, April and January have higher numbers of stations with negative significant precipitation trends than other months. ADF test [49,50] is used to test for stationarity. All annual and seasonal precipitation series and the most of monthly precipitation series appear to be stationary.

The Intergovernmental Panel on Climatic Change`s Fifth Assessment Report concluded that precipitation has generally increased over latitudes north of 30° over the period of 1900–2005 [52]. Availability, and the presence of sufficient water resources in the environment and landscape is an essential condition of life, social and ecological stability as well as economic prosperity. Water is a strategic and irreplaceable natural resource. Constrains in water management are mainly due to unequal distribution of water in the area. The rational use of water is adapting to its natural occurrence in the area. This fact needs to be taken into account mainly during the development of urban areas. In the course of the year the amount of water in the area is usually significantly changing. This phenomenon is closely related to the change of water quality. Excess of water is causing problems to the population, farmers, industries and municipalities – during floods. The same problem also causes water shortages – during the dry season. The best option is if the sufficient amount of water resources throughout the year without undue variations in both terms of quality and quantity is presented in the environment. An optimal state of water resources could be approached by a long-term and sound management of water resources at the level of local municipalities, as well as at the level of the entire river. Water quality can affect the protection of water resources against pollution through strict waste water treatment, soil erosion and elimination of point and diffuse pollution sources, or other preventive measures.

6. Conclusion

In terms of global climate classification, the territory of Slovakia lies in the northern temperate climatic zone with a regular alternation of four seasons and variable weather, with a relatively even distribution of rainfall throughout the year. According to the SHMI [18], average annual rainfalls of less than 600 mm may occur in Slovakia. Generally the rainfall increases with altitude. The rainiest month is usually June or July, and the least rainfall occurs from January to March. The highest daily rainfall was 231.9 mm measured in 1957. In summer, very rainy storms occur relatively frequently over the whole country: almost every year, somewhere in Slovakia the daily rainfall exceeds 100 mm. In winter much of the rain falls in the form of snow, particularly in the middle and the high mountain ranges.

The temporal and spatial variation of precipitation in the Slovak Republic was investigated by utilizing datasets from the SHMI rain gauge network consisting of 487 rain gauges with daily precipitation values from 1981–2013. Non-parametric MK test, SR test and Theil–Sen analysis methods were applied for significant trend detection and magnitude of trends, respectively. The results from trend analysis are different from the average annual precipitation distribution in the Slovak Republic published by SHMI [18]. In this study, monthly scale precipitation data series were not significant at the 95% confidence level except for July, in which about 50% – 245 according to MK and 213 according to SR test out of 487 numbers of stations were found to have significant increasing trends. Regarding the spatial distribution of the trends it is obvious that only the stations in the middle part of the country proved increasing trends in precipitation. It is a mountainous area – Carpathian Mountains. Only a few stations proved decreasing trends in precipitation, exactly the stations in the north part of the country.

The archived results are a basement for integrated water resources management in the country. Public interest in the protection and use of water resources in the urban areas is consistent protection of water and soil, and the sustainable management of water and land resources in the individual settlements and their origin. Public interest further includes ensuring people's access to drinking water, provision of waste water treatment, minimizing flood risks in river basins and in the municipalities and ensuring appropriate protection system against floods.

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