Hydrological situation on Slovak rivers from the point of view of hydrological drought assessment in the period 2011–2020

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In this paper, the occurrence of the area-wide droughts during the years 2011 to 2020 in Slovakia is assessed on the data from 164 water gauging station displayed online on the drought monitoring webpage of Slovak Hydrometeorological Institute and further analysed on 43 selected water-gauging stations. The mean monthly discharges are compared with the long-term mean monthly discharges for the reference period 1961–2000. Trend detection analysis of the mean monthly discharges in period 1961–2020 was concluded by Mann-Kendall trend test. The months of April, June, July, August and October were detected as the months with the highest occurrence of mean monthly discharges below 40% long-term mean monthly discharges for the reference period. The trend analysis of the mean monthly discharges confirmed a significant decreasing trend in April, May, June, July and August. These results reinforce the need of continuous monitoring of the mean monthly discharges. Results of the monitoring available online in form of simple graphical output can present a tool for the timely detection of the incoming long-term drought periods with possibility of implementation of appropriate measures.

KEY WORDS: hydrological drought, mean monthly discharge, online monitoring, Mann-Kendal trend test

Introduction

Due to climate change, the topic of drought and water scarcity is an important issue in water management, including for example water resources for agriculture, various industries and surface water utilization in navigation, fishing, etc. The runoff regime in Slovak streams is generally characterized by increased runoff in the spring months and minimal flows in the summer-autumn season or in winter for mountain streams. Trend analysis of total annual precipitation at 48 stations in Slovakia for time period from 33 to 119 years (end year 2019) showed no significant changes (Repel et al., 2021). A study for the time period 1981–2013 points to a change in the distribution of precipitation during the year in Slovakia. Observed was an increasing trend of precipitation in June, July and January and a decreasing trend of precipitation in December, April, May and August (Zeleňáková et al., 2017). In recent years several hydrological droughts occurred in Slovakia in 2003, 2011–2012, 2015 (Fendeková et al., 2017) and 2018 (Jeneiová et al., 2019). By analysis of precipitation records from 1981 to 2013 at 491 stations in Slovakia, Fendeková et al. (2018) analysed drought events in 21st century in Slovakia, among the results the water balance components analysis for the time period 1931–2016 revealed decreased runoff in Slovakia, mainly due to increased air temperature and balance evapotranspiration. According to Blaškovičová (2020), changes in long-term discharges in the years 2001–2015 compared to the reference period 1961–2000 coincide relatively well with the hydrological drought vulnerability map of Slovakia, which was created based on analyses of changes in long-term discharges for the reference period 1961–2000 compared to 1931–1980 time period. In this analysis, there was a decrease in the values of mean annual discharges in the areas originally designated as areas with low vulnerability: Orava and Kysuce region (both located in the north Slovakia) and tributaries of the Váh River from the Carpathians. The evaluation of mean monthly discharges in the period 2001–2015 compared to the reference period 1961–2000 in this study showed a significant increase in discharges in January for almost the entire territory of Slovakia and a decrease in April and October. A study on long-term fluctuations of low flows based on analysis of daily flow and precipitation series from 1980 to 2019 on the Laborec River (eastern Slovakia) by Kubiak-Wojcika et al. (2021) identified August and September as the months with the greatest culmination of flows below 95% quantile. Monitoring and studying long-term droughts gives the valuable inputs for setting up the measures to improve the hydrological situation in surface waters. Since 2017 the Slovak Hydrometeorological Institute
(SHMI), online on its website, is presenting the Drought monitoring and evaluation based on operational data from selected water-gauging stations, with little or no human impact on the hydrological regime (SHMI, 2021). This enables a daily assessment of the current situation on Slovak streams during the year, with an emphasis on the assessment of hydrological drought on surface waters.

The presented paper deals with the evaluation of the occurrence of the area-wide droughts during the years 2011 to 2020 in Slovakia by the analysis of mean monthly discharges during a time period between 2011 and 2020 in comparison with long-term mean monthly discharges for the reference period 1961–2000. Trend analysis of the mean monthly discharges in period 1961–2020 was concluded to assess the potential change in the hydrological regime of Slovak rivers. This evaluation shows the potential of the real time data use for continuous hydrological drought assessment available online on the SHMI web page (SHMI, 2021), which is important for planning and proposals of appropriate measures for timely drought mitigation measures.

**Data and methods**

The assessment is based on hydrological data from selected 164 water-gauging stations of the Slovakian hydrological network. The operational data (not verified) from these stations are used for the online evaluation and presentation of hydrological drought situation on the SHMI website. The criterion for selection the stations for hydrological drought monitoring was minimal or no human impact on the hydrological regime. Water-gauging stations affected, for example by abstractions could appear to be significantly dry due to the abstractions and not due to the hydrological situation. On the SHMI website, the current hydrological situation is displayed on a simple map of Slovakia, with the possibility of zooming onto a specific region, as well as with the possibility of selecting a water gauging station for a detailed view of the discharges (SHMI, 2021). Currently the website is only available in Slovak language, an example of output is shown in Fig. 1. In this paper, we focus on the assessment of the mean monthly discharges ($Q_m$), during time period between 2011 and

![Fig. 1. Example of the online data from hydrological drought monitoring on the SHMI webpage (SHMI, 2021).](image-url)
2020 in comparison with long-term mean monthly discharges ($Q_{ma}$) for the reference period 1961–2000. In this article the $Q_m$ for selected year in the range of 80–120% $Q_{ma}, 1961-2000$ are considered to be the values close to the relevant long-term values and months with $Q_m$ higher than 120% $Q_{ma}, 1961-2000$ to be above normal to extreme (more than 200%). As subnormal are rated the months with $Q_m$ in the range from 60–80% $Q_{ma}, 1961-2000$ and significantly below normal from 40 to 60% $Q_{ma}, 1961-2000$. The $Q_m$ lower than 40% $Q_{ma}, 1961-2000$ is considered to be a manifestation of the dry month and months with $Q_m$ lower than 20% $Q_{ma}, 1961-2000$ are considered to be extremely dry.

As the first step in assessment of the occurrence of the hydrological drought we used graphical outputs from the online version of the drought monitoring, where we visually selected periods and areas with a predominant occurrence of $Q_m$ below 40% of the relevant $Q_{ma}, 1961-2000$ for the hydrological years 2011 to 2020. These were further analysed with verified discharge data from 43 representative water-gauging stations (Fig. 2), with long-term observations at least since 1961 and with the minimally affected hydrological regime. The basic characteristics (average elevation, catchment area range) for the main river basins in Slovakia based on 43 selected stations are displayed in table 1.

The mean monthly discharge data from the 43 selected gauging stations for the period 1961–2020 were further tested for the occurrence of the trend in the $Q_m$. The rank based non-parametric Mann-Kendall trend test (Mann, 1945; Kendall, 1975), which is widely used trend detection test, was used for the analysis.

### Table 1. Catchment characteristics of analysed water gauging stations

| Catchment | Number of water gauging stations | Catchment area [km²] | Average elevation [m a.s.l.] |
|-----------|----------------------------------|-----------------------|-----------------------------|
| Morava    | 1                                | 47.1                  | 144.3                       |
| Dunaj     | 2                                | 7.25–131331.1         | 224.8                       |
| Nitra     | 2                                | 136.08–181.57         | 310.7                       |
| Váh       | 17                               | 8.4–1107.21           | 528.7                       |
| Malý Dunaj| 3                                | 19.09–37.86           | 247.8                       |
| Hron      | 6                                | 36.01–582.08          | 565                         |
| Ipeľ       | 1                                | 214.27                | 142                         |
| Slaná     | 3                                | 31.97–148.95          | 334                         |
| Hornád    | 3                                | 68.23–1298.3          | 434.1                       |
| Bodrog    | 3                                | 173.94–2915.46        | 110.8                       |
| Poprad    | 2                                | 34.89–44.64           | 781.7                       |

![Fig. 2. Water gauging stations selected for the analysis.](image-url)
The test statistic $S$ equals to:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sign}(x_j - x_k)$$  

(1)

Where

$$x_j$$ – are the values of the data;

$n$ – is the length of the time series and

$$\text{Sign}(x_j - x_k) = 1; \text{ if } x_j-x_k > 0;$$

$$= 0; \text{ if } x_j-x_k = 0;$$

$$= -1; \text{ if } x_j-x_k < 0.$$  

(2)

In case the time series has $n\geq8$, the statistic $S$ has and almost normal distribution, and its variance is computed as:

$$\text{VAR}(S) = \frac{1}{8n(n-1)(2n+5) - \sum_{p=1}^{g}(tp-1)(2tp+5)}$$  

(3)

where

$g$ – is the number of tied groups,

$tp$ – the amount of data with the same value in the group $p=1...g$.

The normalised test statistic $Z$:

$$Z = \begin{cases} 
\frac{S-1}{\sqrt{\text{VAR}(S)}} 
& \text{for } S > 0 \\
0 
& \text{for } S = 0 \\
\frac{S+1}{\sqrt{\text{VAR}(S)}} 
& \text{for } S < 0 
\end{cases}$$  

(4)

If the Mann-Kendall test statistic $Z$ equals to zero, it is expected that the data are normally distributed and there is no trend present in the time series. Positive values of the $Z$ statistic point to increasing trend and negative ones to decreasing trend in the time series. The detected trend was evaluated on the significance level of $p=0.05$.

**Results and discussion**

Online monitoring of hydrological drought offers simple map overview of the $Q_m$ during time period 2011–2020 in comparison with $Q_{ma,1961-2000}$. By the visual analysis of the maps in selected time period we have identified the periods from October 2011 to September 2012 and from April 2018 to January 2019 as the periods with the highest occurrence of respective $Q_m$ below 40% $Q_{ma,1961-2000}$. During these time periods the mean monthly discharges were continuously below 40% $Q_{ma,1961-2000}$ also in areas of Slovakia, which are usually not particularly prone to low flow occurrence, for example the north-west part of Slovakia.

Table 2 contains the percentage of 43 analysed water gauging stations with $Q_m$ lower than 40% $Q_{ma}$. The results of the analysis of the data shows that between 2011–2020 the years with the highest occurrence (more than 40% of evaluated stations) of $Q_m$ lower than 40% $Q_{ma}$ were the years 2012, 2015, 2018, 2019 and 2020. In addition, it confirms the results of the visual analysis of the longest time events of respective $Q_m$ below 40% $Q_{ma,1961-2000}$ from October 2011 to September 2012 and from April 2018 to January 2019.

Months of April, June, July, August and October were the months with the highest occurrence of $Q_m$ below 40% $Q_{ma,1961-2000}$ (more than 20% of analysed water gauging stations, Table 2.). The percentage of mean monthly discharges in April in time period 2011–2020 in comparison with $Q_{ma,1961-2000}$ is shown in the Table 3.

The increasing occurrence of drier months in last years is clearly visible. The highest country-wide (all areas except of High Tatras mountains region) occurrence of $Q_m$ below 40% $Q_{ma,1961-2000}$ was in April 2020 at 70% of analysed stations (Fig. 3). These results confirm the study of Blaškovičová (2020). Especially the higher occurrence of values under the average in April signifies the change

| Month/Year | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|------------|------|------|------|------|------|------|------|------|------|------|
| 11         | 0%   | 67%  | 7%   | 5%   | 7%   | 5%   | 2%   | 7%   | 51%  | 5%   |
| 12         | 0%   | 47%  | 16%  | 19%  | 7%   | 9%   | 5%   | 2%   | 40%  | 5%   |
| 1          | 0%   | 14%  | 0%   | 5%   | 0%   | 2%   | 21%  | 0%   | 23%  | 16%  |
| 2          | 0%   | 33%  | 0%   | 0%   | 0%   | 0%   | 0%   | 2%   | 2%   | 2%   |
| 3          | 12%  | 16%  | 0%   | 21%  | 2%   | 5%   | 12%  | 7%   | 12%  | 2%   |
| 4          | 23%  | 35%  | 0%   | 47%  | 2%   | 28%  | 26%  | 23%  | 53%  | 70%  |
| 5          | 37%  | 44%  | 0%   | 2%   | 5%   | 2%   | 9%   | 47%  | 0%   | 58%  |
| 6          | 19%  | 21%  | 0%   | 23%  | 28%  | 23%  | 30%  | 26%  | 12%  | 0%   |
| 7          | 0%   | 30%  | 23%  | 12%  | 40%  | 7%   | 28%  | 33%  | 42%  | 12%  |
| 8          | 0%   | 42%  | 33%  | 2%   | 44%  | 7%   | 26%  | 35%  | 16%  | 14%  |
| 9          | 19%  | 53%  | 7%   | 0%   | 35%  | 7%   | 2%   | 23%  | 9%   | 5%   |
| 10         | 37%  | 9%   | 30%  | 2%   | 26%  | 5%   | 2%   | 47%  | 23%  | 0%   |
of the yearly hydrological regime. If a snow cover is not formed in the winter season (December–February), or sudden increase of temperatures happens (years 2011 to 2020 are the warmest decade on record according to 2020 WMO provisional report) then the condition for spring season, usually typical for higher runoffs in Slovakia (March–May) are not met. This, in combination with the changing climatological regime influence the hydrological regime and its distribution during the year.

In the next step we analyzed the long term trends in

| Table 3. The percentage of mean monthly discharges in April in period 2011–2020 in comparison with $Q_{ma}$, 1961-2000 |
|---------------------------------------------------------------|
| Station ID | Station | River | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---------------------------------------------------------------|
| 5100 | Lib | Močiarka | 53 | 26 | 116 | 25 | 41 | 53 | 36 | 27 | 43 | 26 |
| 5130 | Spárská | Vydrica | 112 | 56 | 153 | 26 | 61 | 47 | 31 | 51 | 32 | 16 |
| 5140 | Bratislava | Dunaj | 60 | 87 | 102 | 55 | 92 | 72 | 72 | 87 | 85 | 56 |
| 5160 | Pezinok | Blatina | 61 | 33 | 145 | 31 | 70 | 45 | 22 | 40 | 35 | 19 |
| 5250 | Horné Oresťany | Parná | 104 | 23 | 133 | 43 | 76 | 69 | 20 | 46 | 20 | 10 |
| 5260 | Pila | Gdara | 78 | 31 | 163 | 41 | 67 | 41 | 39 | 39 | 25 | 30 |
| 6540 | Nedožery | Nitra | 33 | 42 | 163 | 38 | 106 | 43 | 81 | 45 | 37 | 36 |
| 6620 | Liesňany | Nitrica | 29 | 43 | 123 | 27 | 85 | 37 | 70 | 30 | 31 | 26 |
| 5310 | Čierny Váh | Ipoltica | 46 | 76 | 183 | 63 | 94 | 91 | 117 | 138 | 73 | 42 |
| 5330 | Východná | Biely Váh | 62 | 73 | 131 | 60 | 86 | 60 | 92 | 95 | 58 | 53 |
| 5400 | Podbanske | Belá | 95 | 123 | 136 | 122 | 102 | 143 | 142 | 197 | 127 | 134 |
| 5550 | Liptovský Mikuláš | Vih | 57 | 86 | 145 | 74 | 95 | 93 | 119 | 158 | 105 | 63 |
| 5730 | Partizánska Ľupča | Dobjušanka | 46 | 65 | 169 | 54 | 80 | 79 | 96 | 120 | 66 | 53 |
| 5740 | Podsuchá | Revúca | 35 | 81 | 138 | 44 | 95 | 57 | 78 | 92 | 75 | 40 |
| 5790 | Úlubochna | Úlubochnianska | 50 | 91 | 120 | 44 | 99 | 62 | 79 | 77 | 79 | 42 |
| 5800 | Lokea | Biela Úrva | 49 | 154 | 106 | 36 | 88 | 35 | 126 | 42 | 82 | 24 |
| 5810 | Oravská Jasenica | Veselianska | 37 | 100 | 100 | 35 | 81 | 29 | 164 | 37 | 64 | 20 |
| 5820 | Zborohľava | polohoranka | 41 | 142 | 97 | 34 | 89 | 42 | 127 | 37 | 67 | 27 |
| 5840 | Trenčená | Oravica | 55 | 88 | 121 | 72 | 94 | 47 | 149 | 54 | 66 | 34 |
| 6130 | Martin | Turiec | 40 | 88 | 149 | 48 | 118 | 53 | 82 | 75 | 55 | 36 |
| 6180 | Čadca | Kysuca | 51 | 70 | 140 | 26 | 86 | 38 | 133 | 17 | 24 | 12 |
| 6360 | Bytča | Petrovicka | 41 | 66 | 169 | 49 | 103 | 24 | 1 | 25 | 17 | 17 |
| 6390 | Vydrica | Petrová | 41 | 26 | 177 | 24 | 92 | 17 | 37 | 27 | 17 | 26 |
| 6400 | Dobšany | Biela voda | 28 | 39 | 130 | 34 | 103 | 34 | 131 | 25 | 19 | 21 |
| 6460 | Horné Smižany | Vlara | 42 | 39 | 135 | 29 | 101 | 45 | 115 | 27 | 20 | 23 |
| 6950 | Zlatno | Hron | 42 | 41 | 199 | 43 | 77 | 75 | 60 | 138 | 36 | 36 |
| 7015 | Bresno | Hron | 42 | 42 | 182 | 43 | 81 | 54 | 58 | 135 | 41 | 34 |
| 7045 | Hronec | Čierny Hron | 40 | 24 | 227 | 29 | 63 | 28 | 38 | 111 | 22 | 30 |
| 7060 | Bystrá | Bystrianska | 60 | 78 | 160 | 61 | 91 | 98 | 107 | 161 | 71 | 54 |
| 7065 | Myšto p. Žumberom | Štiavnica | 40 | 70 | 171 | 46 | 83 | 70 | 81 | 128 | 58 | 34 |
| 7070 | Dolná Lehota | Vajskovský potok | 52 | 69 | 168 | 60 | 84 | 89 | 76 | 131 | 58 | 51 |
| 7060 | Plátľovec | Lítava | 27 | 19 | 144 | 16 | 80 | 17 | 21 | 81 | 10 | 15 |
| 7160 | Dobšiná | Dobšinský potok | 49 | 31 | 239 | 55 | 67 | 85 | 47 | 166 | 25 | 36 |
| 7170 | Štiavnica | Štiavnica | 58 | 22 | 235 | 52 | 63 | 56 | 46 | 135 | 28 | 44 |
| 7860 | Lehota nad Rimavicou | Rimavica | 52 | 14 | 296 | 33 | 80 | 39 | 26 | 122 | 22 | 42 |
| 8530 | Strážňa | Humleč | 44 | 33 | 167 | 43 | 68 | 78 | 45 | 173 | 29 | 31 |
| 8560 | Jakovce | Humleč | 39 | 25 | 208 | 28 | 45 | 38 | 39 | 112 | 18 | 27 |
| 8870 | Kolíčovce | Torsya | 47 | 39 | 178 | 42 | 53 | 48 | 64 | 99 | 31 | 33 |
| 9320 | Lukavce | Uh | 42 | 99 | 160 | 27 | 53 | 29 | 37 | 98 | 40 | 22 |
| 9410 | Veľký Kapustian | Latorica | 39 | 72 | 168 | 72 | 49 | 29 | 38 | 121 | 27 | 28 |
| 9620 | Jasenovce | Orka | 49 | 56 | 182 | 37 | 34 | 45 | 72 | 147 | 31 | 29 |
| 7930 | Záhor, Podpády | Javorinka | 84 | 114 | 140 | 110 | 102 | 120 | 168 | 135 | 152 | 68 |
| 8070 | Poprad, Matejovce | Slárkovský potok | 69 | 72 | 108 | 116 | 89 | 77 | 134 | 97 | 60 | 48 |
Fig. 3. April 2020, highest occurrence of $Q_m$ below 40% $Q_{ma, 1961-2000}$.

Fig. 4. The results of the Mann–Kendall trend test for the mean monthly discharges in April in the 1961–2020 time period, detected significant trend at 95% confidence level is marked according to the legend.

Conclusion

The potential of the use of the real-time data for continuous hydrological drought assessment online on the SHMI web page (SHMI, 2021) was evaluated. The analyses show the change in the hydrological regime of the Slovak rivers and increase of the low flows occurrence in previously not prone areas. Therefore, a further analysis of the occurrence of the area-wide droughts during the years 2011 to 2020 in Slovakia was concluded by the analysis of $Q_m$ during this time period in comparison with long-term values for reference period $Q_{ma, 1961-2000}$ for selected 43 gauging stations. The results show, that the months of April, June, July, August and October were detected as the months with the highest occurrence of $Q_m$ below 40% $Q_{ma, 1961-2000}$ in the 2011–2020 time period. The trend analysis of the mean monthly discharges in the period 1961–2020 by the Mann–Kendall trend test assessed the potential change in the hydrological regime of Slovak rivers and confirmed significant decreasing trend in April, May, June, July and August for the 1961–2020 time period.
These results reinforce the need of continuous online monitoring of the mean monthly flows. The lower discharges in months where historically the highest runoff of the year is manifested are not so visible on the first sight – there are no close-to-dry riverbeds minimum discharges occurring. However, the situation with decreasing spring runoff (March, April, May) together with changing climatic conditions can introduce a critical start of a serious dry period later in summer (June, July, August) or even for a longer period. Therefore, there is a need to carefully monitor mean monthly flows in comparison with long-term mean monthly discharges (especially under 40% and 20%). Results of the monitoring available on the SHMI webpage can present a tool for the timely detection of the incoming long-term drought periods with possibility of timely implementation of appropriate measures.

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