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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 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

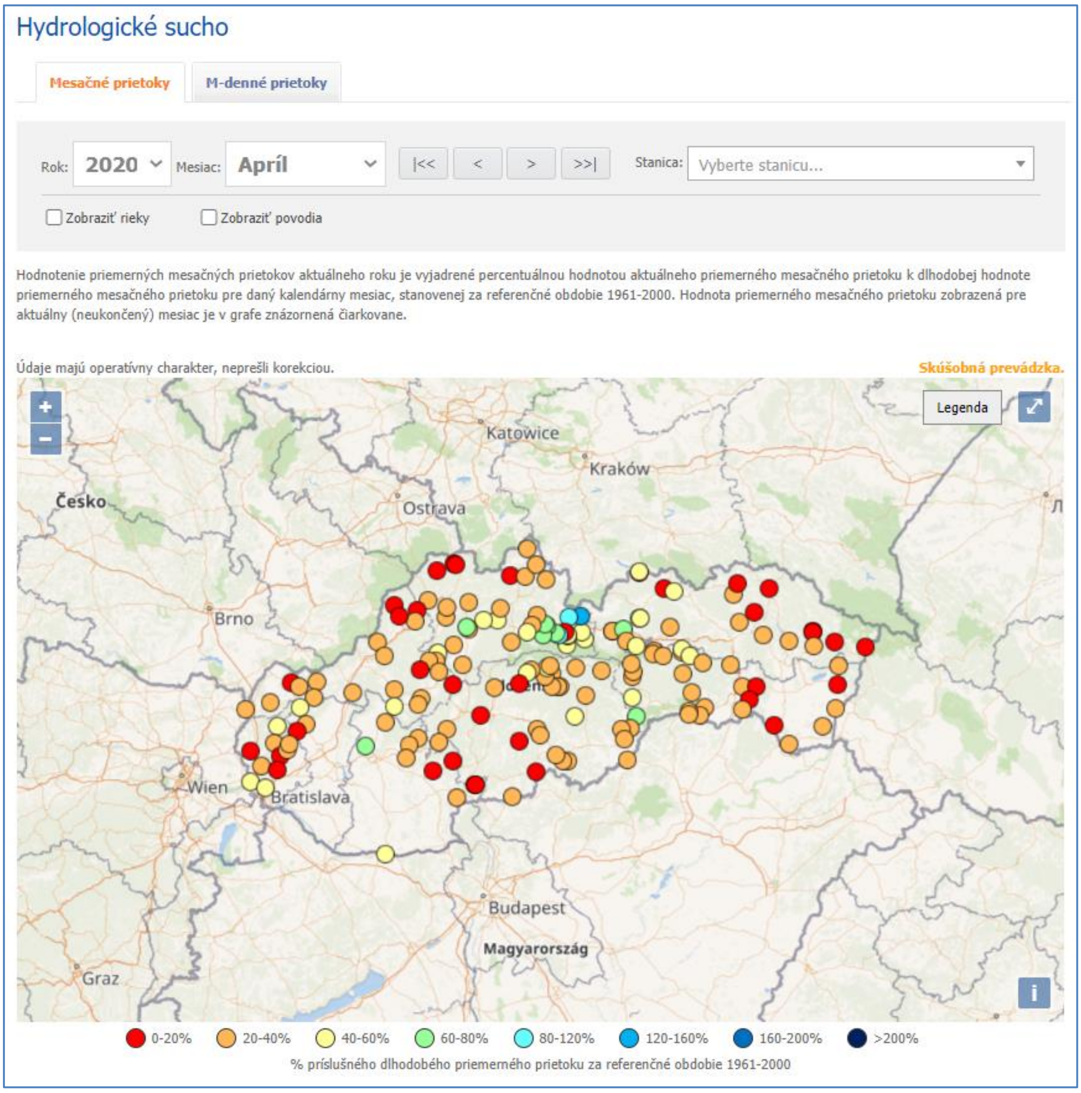

Fig. 1. Example of the online data from hydrological drought monitoring on the SHMI webpage (SHMI, 2021).

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% $Q_{ma,\ 1961\text{-}2000}$ are considered to be the values close to the relevant long-term values and months with Q_m higher than 120% $Q_{ma,\ 1961\text{-}2000}$ to be above normal to extreme (more than 200%). As subnormal are rated the months with Q_m in the range from 60–80% $Q_{ma,\ 1961\text{-}2000}$ and significantly below normal from 40 to 60% $Q_{ma,\ 1961\text{-}2000}$. The Q_m lower than 40% $Q_{ma,\ 1961\text{-}2000}$ is considered to be a manifestation of the dry month and months with Q_m lower than 20% $Q_{ma,\ 1961\text{-}2000}$ 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 $Q_{ma,\ 1961\text{-}2000}$ 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 in hydrology, was used for the analysis.

Table 1. Catchment characteristics of analysed water gauging stations

Catchment	Number of water gauging stations	Catchment area [km^2]	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

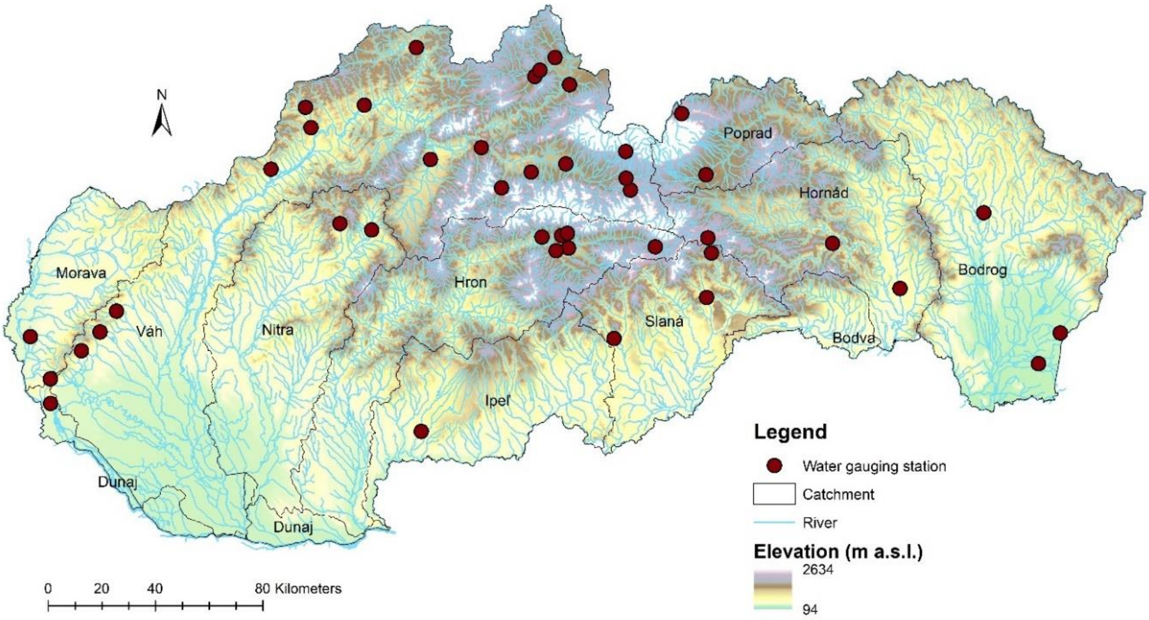

Fig. 2. Water gauging stations selected for the analysis.

The test statistic S equals to:

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

Where

x_j – are the values of the data;
n – is the length of the time series and

$$Sign(x_j - x_k) = \begin{cases} 1; & \text{if } x_j - x_k > 0; \\ 0; & \text{if } x_j - x_k = 0; \\ -1; & \text{if } x_j - x_k < 0. \end{cases} \qquad (2)$$

In case the time series has $n \geq 8$, the statistic S has and almost normal distribution, and its variance is computed as:

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p - 1)(2t_p + 5)\right] \qquad (3)$$

where
g – is the number of tied groups,
t_p – the amount of data with the same value in the group $p=1...g$.
The normalised test statistic Z:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{for } S < 0 \end{cases} . \qquad (4)$$

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 $Q_{ma,\ 1961\text{-}2000}$. 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% $Q_{ma,\ 1961\text{-}2000}$. During these time periods the mean monthly discharges were continuously below 40% $Q_{ma,1961\text{-}2000}$ 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% $Q_{ma,\ 1961\text{-}2000}$ 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% $Q_{ma,1961\text{-}2000}$ (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 $Q_{ma,1961\text{-}2000}$ 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% $Q_{ma,1961\text{-}2000}$ 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

Table 2. The percentage of analysed water gauging stations with Q_m lower than 40% of $Q_{ma,\ 1961\text{-}2000}$ (yellow 20%–40% of stations, red 40% and more of the stations)

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%	2%	0%	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 the selected 43 stations to further assess the potential of the change in the hydrological regime. Significant trend was detected by the Mann-Kendall trend test at the 95% confidence level. The highest occurrence of significant decreasing trend in the period 1961–2020 was in April in 47% of the evaluated stations (Fig. 4). Significant decreasing trend was also detected in May (28% of stations), June (40% of stations), July (23% of stations) and August (19% of stations). On the other hand significant rising trend was detected mostly in January (9% of stations) and February (19% of stations).

Table 3. **The percentage of mean monthly discharges in April in period 2011–2020 in comparison with $Q_{ma,\,1961\text{-}2000}$**

Station ID	Station	River	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
5100	Láb	Močiarka	53	26	116	25	41	53	36	27	43	26
5130	Spariská	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	15	19
5250	Horné Orešany	Parná	104	23	133	43	76	69	20	46	20	19
5260	Píla	Gidra	78	31	163	41	67	41	18	39	25	30
6540	Nedožery	Nitra	33	42	163	38	106	43	81	45	37	36
6620	Liešťany	Nitrica	29	43	123	27	85	37	70	30	31	20
5310	Čierny Váh	Ipoltica	46	76	185	63	94	91	117	188	73	42
5330	Východná	Biely Váh	62	73	131	60	86	60	92	95	58	53
5400	Podbanské	Belá	95	123	136	122	102	149	142	249	177	134
5550	Liptovský Mikuláš	Váh	57	86	145	74	95	93	119	158	105	63
5730	Partizánska Ľupča	Ľupčianka	46	65	169	54	80	79	96	120	66	53
5740	Podsuchá	Revúca	35	81	138	44	95	57	78	92	75	40
5790	Ľubochňa	Ľubochnianka	50	91	120	44	99	62	79	77	79	42
5800	Lokca	Biela Orava	49	154	106	36	88	35	126	42	82	24
5810	Oravská Jasenica	Veselianka	37	100	100	35	81	29	164	37	64	20
5820	Zubrohlava	Polhoranka	41	142	97	34	89	42	127	37	67	27
5840	Trstená	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	Petrovička	41	66	169	29	102	48	181	25	32	17
6390	Vydrná	Petrinovec	41	26	177	24	92	17	73	27	17	26
6400	Dohňany	Biela voda	28	39	130	34	103	34	131	25	19	21
6450	Horné Sŕnie	Vlára	42	39	135	29	101	45	115	27	20	23
6950	Zlatno	Hron	42	41	199	43	77	75	60	138	36	36
7015	Brezno	Hron	42	42	182	43	81	54	58	135	41	34
7045	Hronec	Čierny Hron	40	24	223	29	63	28	38	111	22	30
7060	Bystrá	Bystrianka	60	78	160	61	91	98	107	164	71	54
7065	Mýto p. Ďumbierom	Štiavnička	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
7600	Plášťovce	Litava	27	19	344	16	80	17	21	81	10	15
7660	Dobšiná	Dobšinský potok	49	31	239	55	67	85	47	166	25	36
7730	Štítnik	Štítnik	58	22	228	52	63	56	46	135	28	44
7860	Lehota nad Rimavicou	Rimavica	52	14	288	33	80	39	26	122	22	42
8530	Stratená	Hnilec	44	33	167	43	68	78	45	173	29	31
8560	Jaklovce	Hnilec	39	25	208	28	45	38	39	112	18	27
8870	Košické Olšany	Torysa	47	39	178	42	53	48	64	99	31	33
9320	Lekárovce	Uh	42	99	160	27	53	29	37	98	40	22
9410	Veľké Kapušany	Latorica	39	72	168	27	49	29	38	121	27	28
9620	Jasenovce	Oľka	49	56	185	37	34	45	72	147	13	29
7930	Ždiar, Podspády	Javorinka	84	114	140	110	102	120	168	175	152	68
8070	Poprad, Matejovce	Slavkovský potok	69	72	108	116	89	77	134	97	68	48

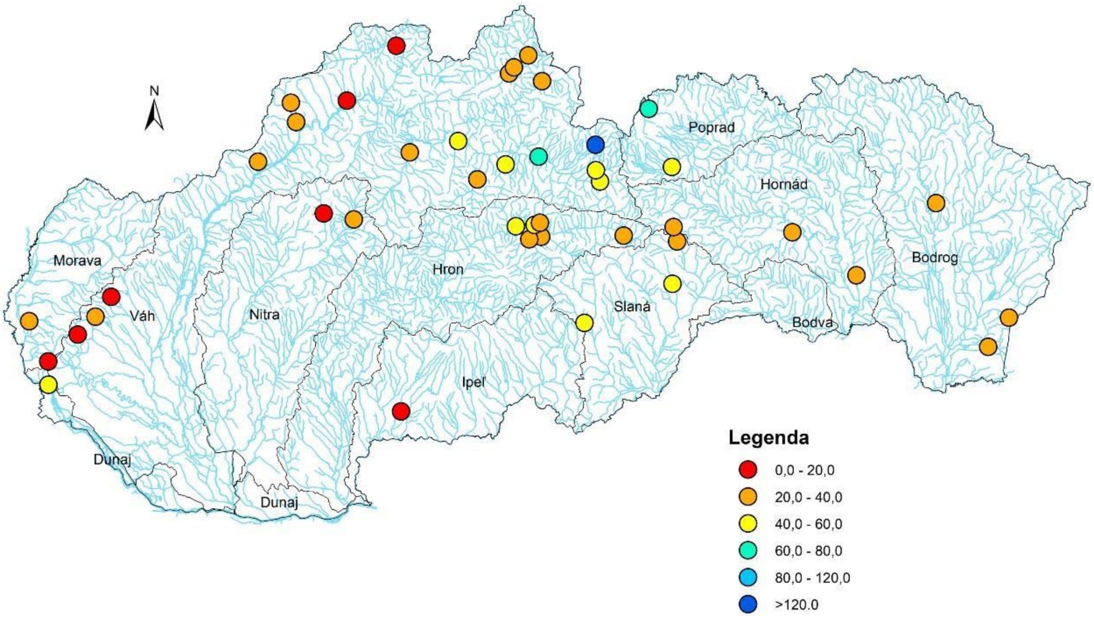

Fig. 3. April 2020, highest occurence of Q_m below 40% $Q_{ma,\ 1961\text{-}2000}$.

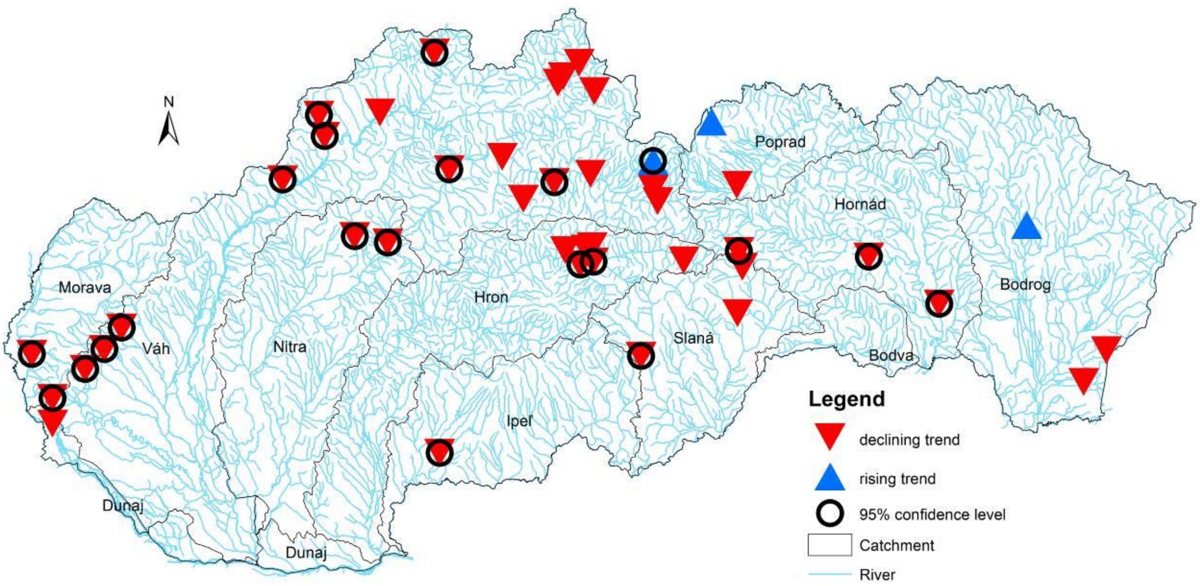

Fig. 4. The results of the Mann – Kendall trend test for the mean monthly discharges in April in the 1961–2020 time period, detected significant trend at 95% confidence level is marked according to the legend.

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 $Q_{ma,1961\text{-}2000}$ 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% $Q_{ma,\ 1961\text{-}2000}$ 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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