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Spatial assessment of areas vulnerable to water shortages in Slovakia

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A map of drought prone areas of Slovakia vulnerable to water shortages has been developed by combining the changes in the mean long-term discharges 1991–2020 against the reference period 1961–2000, with the runoff distribution of the period 1961–2000 on the territory of Slovakia. The results of the analysis have been classified into the five categories, with the southern lowlands identified as the most vulnerable and the northern mountainous areas as moderate to low vulnerability areas. The observed changes are based on the mean long-term discharges, with low flows requiring a further analysis. Despite the limitations, including the exclusion of groundwater impact, the maps at the district level resolution provide a practical tool for water planning, resource management, and decision-making at a district level for drought mitigation.

KEY WORDS: long-term discharge changes, spatial analysis, water planning

Introduction

Historically, Slovakia has not been considered a country at high risk of the drought, although the episodic drought events have been well documented especially in the last decades (Fendeková et al., 2018; Rakovec et al., 2022). Furthermore, the occurrence and timing of the droughts in Slovakia have become an increasing concern in climatological research (Rattayová et al, 2024). In the recent decades, the notable changes in the hydrological regime have been observed in Slovakia, including the changes in the low-flow conditions (Fendeková, 2018; Blaškovičová et al., 2019; Blaškovičová et al., 2020; Danáčová et al., 2021; Blaškovičová et al., 2022; Pekárová et al., 2025). Central Europe has been experiencing an increase in the drought frequency, which is linked to the potential evapotranspiration and the mean air temperature, while the potential evapotranspiration is projected to increase (Ionita and Nagavciuc, 2021). The prolonged drought period between 2018 and 2020 in Europe has significantly impacted the water availability and highlighted the increasing vulnerability of the region to the hydrological extremes and it is considered a new benchmark for the future drought events (Rakovec, 2022). This drought event has affected Slovakia as well (Jeneiová et al, 2019). These recent developments have served as a motivation for this study, as a comprehensive understanding of the drought risks is crucial for the municipalities for developing the effective water management strategies.

In Slovakia, at the national level, the drought mitigation efforts have gained an increasing attention, demonstrated by the adoption of the Action plan in 2018, to address the consequences of the drought and water scarcity (MŽP SR, 2018) and also by the identification of drought-related concerns in the strategic planning documents (e.g., Water Plan of the Slovak Republic – Update 2021; MŽP SR, 2021). For the upcoming Water Management Planning Cycle (2028–2033), an updated assessment of the drought prone areas is required. The national evaluation of the drought prone areas, created at the time of the latest revision of the reference period used for a hydrological practice in Slovakia around the year 2006, based on comparison of two periods 1931–1980 and 1961–2000, needs to be updated in the light of the observed changes.

To support this need, in this article the spatial analysis at the district level is presented, identifying the drought prone areas in Slovakia. It is based on the identification of the changes in the long-term mean discharges of the period 1991–2020, compared with the reference period 1961–2000. This analysis is further contextualized by analysing these results against the runoff distribution characterising the natural hydrological situation in the area during the reference period, thus providing insight into the long-term hydrological trends.

Material and methods

In this study, we have focused on the hydrological drought, as indicated by the changes in the mean long-term discharges. The assessment has been based on the analysis of the changes in this hydrological characteristic between the periods 1991–2020 and 1961–

2000, the latter of which is still used as the reference period in the Slovak water management frameworks for setting the design parameters for the water treatment infrastructure, dam operations, and long-term planning. The detailed analyses of these changes have been conducted in the previous studies (e.g., Blaškovičová et al 2019, Blaškovičová et al 2020), which have demonstrated the significant trends in decreasing discharges and increasing frequency of low-flow conditions in several river basins. By mapping the extent and intensity of these changes, this study has aimed to provide a robust base for updating the strategic drought assessments documents.

In the first step, 46 water gauging stations (covering 45 watercourses) with near natural observations, with minimal or no human influence on the hydrological regime (e.g. no large water withdrawals, dams upstream, etc.), available since 1961 have been primarily selected for the study. Given the relatively smaller coverage of some areas of the Slovak Republic by such stations, we have later added 66 water gauging stations with the beginning of observation between 1962 and 1970, and also 24 stations with a hydrological regime minimally influenced by the human activity (for example the known water use, like water withdrawal).

The results from the added stations have been considered taking into the account their limitations and marked in the overall assessment of the changes. The spatial distribution of 136 selected water-gauging stations is shown in Fig. 1.

To express the changes in the hydrological characteristics in the assessed periods, the deviations of the mean long-term discharges (ΔQ_a in %) for the period 1991–2020 ($Q_{a,1991-2020}$) from the reference period 1961–2000 ($Q_{a,1961-2000}$) have been quantified:

$$\Delta Q_a = \frac{Q_{a,1991-2020} - Q_{a,1961-2000}}{Q_{a,1961-2000}} 100 \quad (1)$$

The initial assessment of the deviations of the period 1991–2020 from the reference period 1961–2000 has been carried out in the ten individual main river basins of the Slovak Republic (while the Nitra and Malý Dunaj sub-basins were assessed separately from the rest of the Váh River basin due to the different hydrological regime). The spatial interpolation method (a combination of geographical weighted regression and inverse distance weighting method - IDW, an ArcGIS toolbox based on Šercl, 2008 was developed at the Slovak Hydrometeorological Institute) has been used on the values of ΔQ_a to create the rasters using the digital elevation model. The results of this map processing have been further used, taking into the account the limitations and disadvantages of the method used (the method had been developed for the rainfall data, the catchment barrier could not be set to prevent the interpolation between the basins with different hydrological regimes, the IDW method assumes an isotropy, which does not always reflect the reality in the hydrological data, the uneven distribution of the input field of the points affects the quality of the output raster, the creation of "bulls eyes" – features that arise due to the strong relative weights of the values in their vicinity, or higher values of the power parameter, in our case there is no obvious correlation between the altitude and the value of the percentage differences between the periods 1961–2000 and 1991–2020, which has affected the results mainly in the places with a higher altitude).

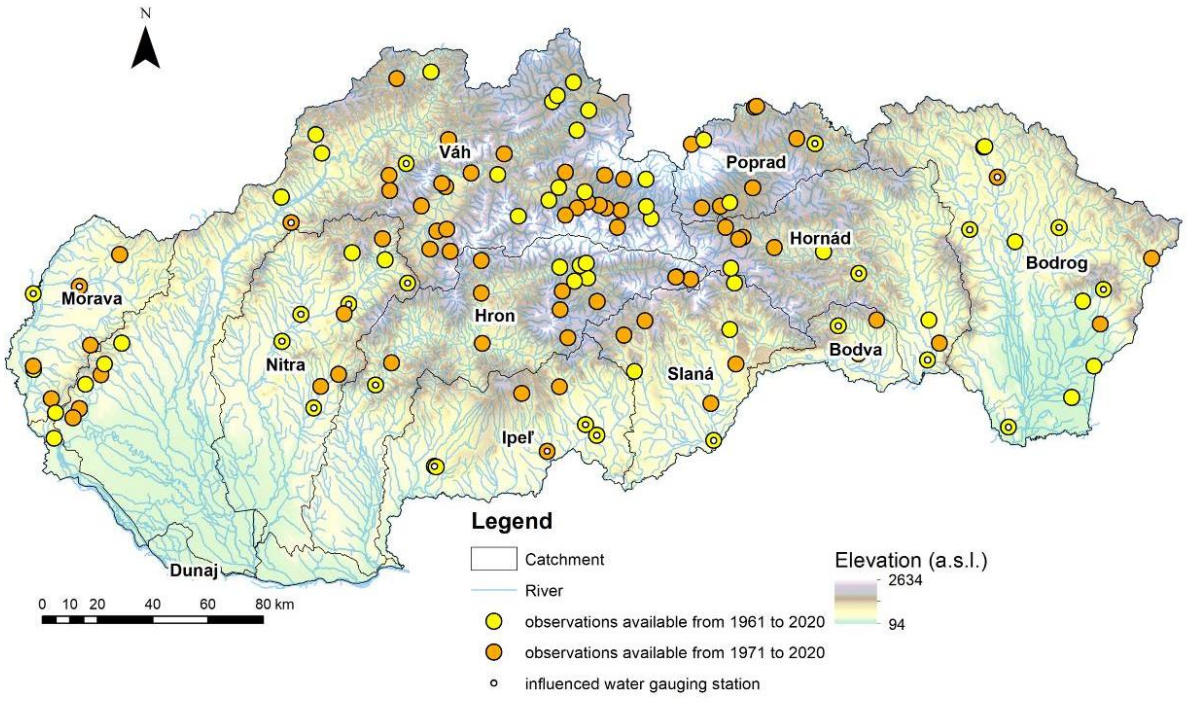


Fig. 1. Location of selected water gauging stations.

Results and discussion

In the first step, the map of the areas vulnerable to the changes in the long-term mean discharges (Fig. 2) has been created. It has been based on the calculated values of ΔQ_a, spatially interpolated as described in the methods section and also by using an expert knowledge of the hydrological regime in the area. The three categories of the vulnerability have been defined: low-vulnerability area, medium-vulnerability area and high vulnerability area.

The average value, median and extreme values of ΔQ_a from the assessed water gauging stations, falling into the designated areas based on the vulnerability categories, are shown in Tab. 1.

The vulnerability map expresses the rate of the change in the long-term discharges for the assessed period 1991–2020 compared to the reference period 1961–2000. However, it does not take into the account the naturally present runoff distribution, which significantly contributes to whether the recorded decrease in the discharges in a given area, designated as a high/medium vulnerable, represents the real risk of the water shortage. Therefore, in the next step, we have combined the vulnerability map with the map of the runoff distribution in the territory of Slovakia (expressed in the map in mm) in the period 1961–2000 (Šipikalová, 2005).

The distribution of the runoff for the period 1961–2000 is mainly related to the altitude, which is highly correlated with the precipitation totals and slope of the territory. Lower values of the runoff (up to 125 mm) are mainly observed in the southern lowland part of Slovakia and in some basins, where the effect of the precipitation shadow is evident. The highest values of the runoff correspond mainly to the high mountain areas, such as the High and Low Tatras, where in the most water rich areas these values reach in average 950 to 1520 mm. The runoff has been reclassified into 3 categories for this assessment, with values 0–150 mm, 151–350 mm and more than 351 mm (Fig. 3). These categories have been selected after assessing the several different combinations of the distributions, based also on the expert knowledge of some areas in the lowest runoff category, where the problems with the water shortage (based on the field surveys and measurements by Slovak Hydrometeorological Institute experts, outputs of national water balance over multiple years and information reported by the media) have already been recorded.

Further the map of the areas vulnerable to the water shortages in Slovakia (Fig. 4) has been created by combining the reclassified raster map of the runoff in the period 1961–2000 with the map of the vulnerable areas derived from ΔQ_a. To reduce the noise effects originating from the runoff raster, the resulting dataset has been subsequently smoothed. Based on the combination of the categories (Table 2), the territory has been classified into the new five vulnerability levels: critical, high, medium, moderate, and low.

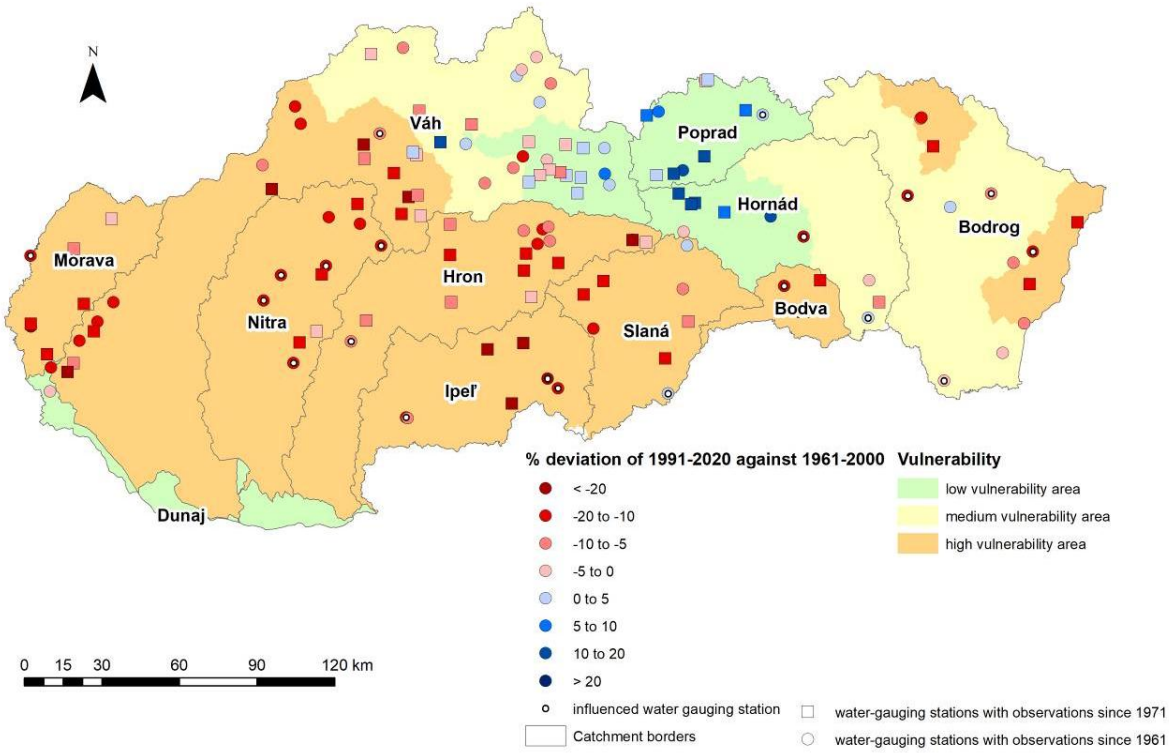


Fig. 2. Map of the vulnerability of the Slovak Republic's territories with respect to the mean annual discharges (changes in the period 1991–2020 compared to the period 1961–2000).

The map of the areas vulnerable to water shortages in Slovakia has integrated both the changes in the mean long-term discharges of the period 1991–2020 relative to the reference period 1961–2000 and the natural spatial distribution of the runoff for the period 1961–2000. The spatial patterns of the both input maps are similar, with the unfavourable categories (i.e., highly vulnerable areas and lower runoff values) concentrated in the southern lowland regions, while the more favourable categories (i.e., less vulnerable areas and higher runoff values) predominate in the mountainous regions of the northern Slovakia. The combined vulnerability map therefore highlights the southern Slovakia as the most critical area, including the Morava sub-basin, the lower sections of the Váh River basin (including a large part of the Malý Dunaj and Nitra sub-basins), the river basins of Hron, Ipeľ, Bodva, and a smaller part of the Bodrog River basin (Čierna Voda catchment). On the contrary, the least critical areas are located in the mountainous northern regions, where the naturally higher runoff is enhanced by an observed increase in the long-term discharges in the period 1991–2020 compared with 1961–2000.

To enhance the usability of this map for the decision-makers, we have applied a weighted average approach to assess the vulnerability to the water shortage across the districts of the Slovak Republic (Fig. 5), since planning and implementation of drought mitigation measures have been typically conducted at the district level. In addition, it has been considered, that the Danube region near the southern state border does not adequately represent the hydrological conditions within Slovakia, as the analysis there is based also on the Danube River itself, which is mainly influenced by the upstream inflows. Consequently, the Komárno district (KN) has been adjusted to reflect a higher drought vulnerability. Furthermore, the city municipalities have been harmonised to exhibit the consistent vulnerability levels (Bratislava districts B1–B5 and Košice districts K1–K4). Based on the expert judgement, the Pezinok district (PK) has been also reclassified as a higher-vulnerability area.

Table 1. The average values, median, minimum and maximum values of deviations ΔQ_a [%] for individual vulnerability categories of the territory

	Average	Median	Min	Max
Low	2.5	2.6	-13.5	19.5
Medium	-3.3	-5.1	-16.7	17.8
High	-13.0	-12.2	-48.9	11.3

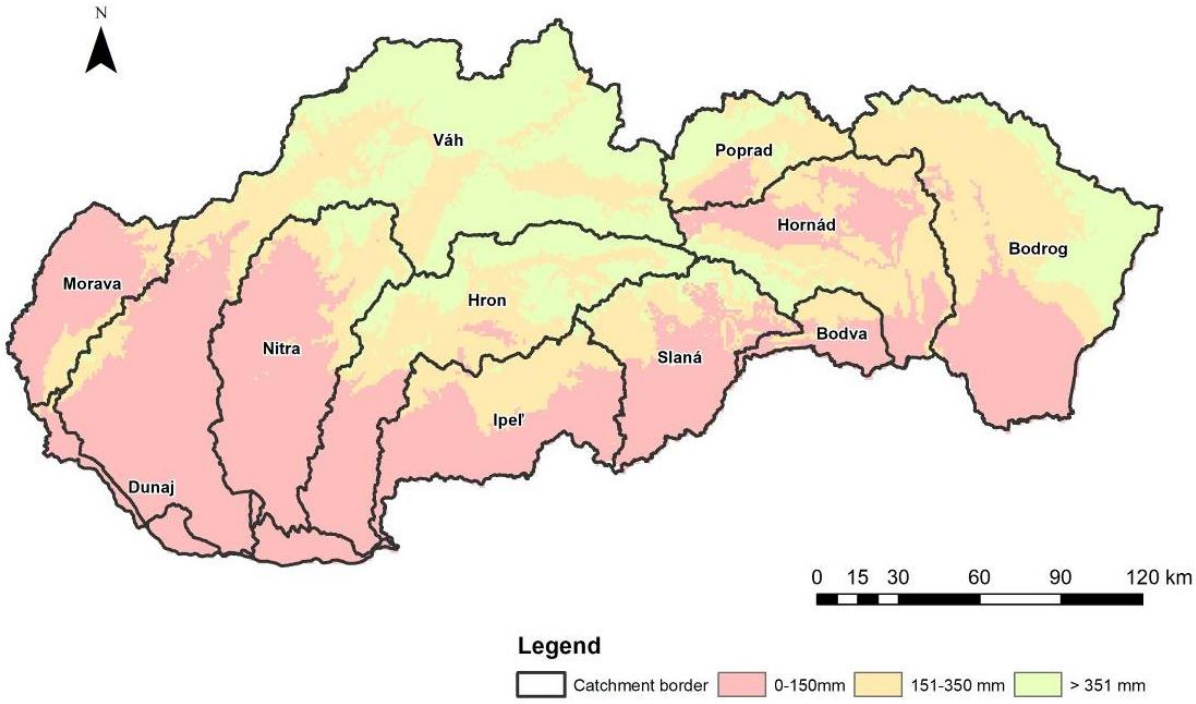


Fig. 3. Runoff distribution on the territory of Slovakia for the period 1961–2000 reclassified into three categories.

Table 2. Vulnerability levels classification

		Vulnerability derived from ΔQ_a		
		high	**medium**	**low**
Runoff [mm]	0 – 150	critical	high	medium
	151 – 350	high	medium	moderate
	> 351	medium	moderate	low

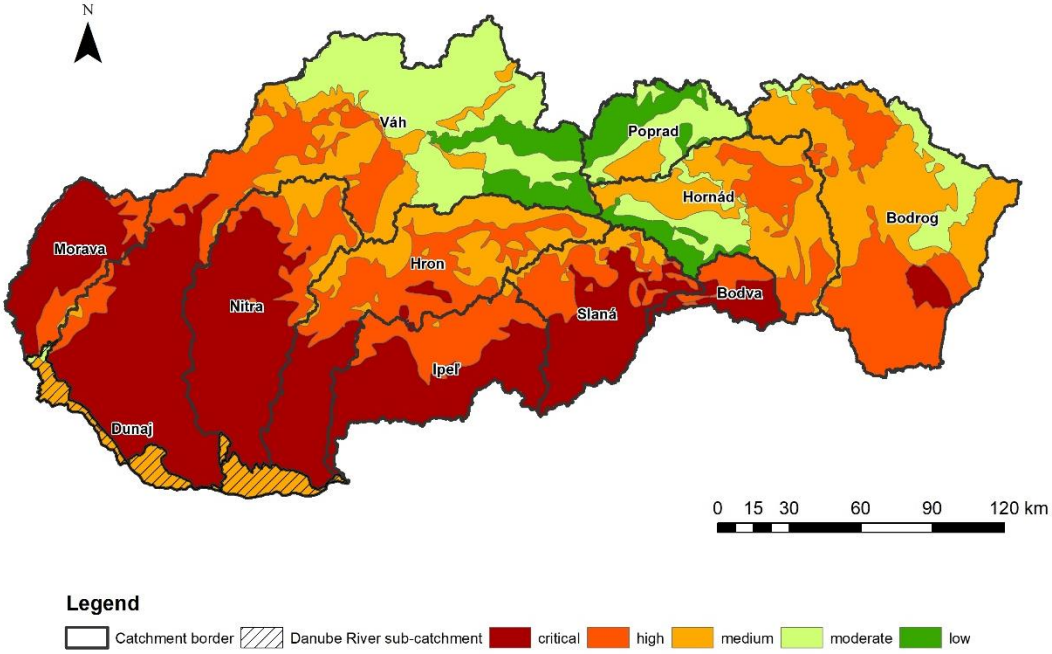


Fig. 4. Map of the areas vulnerable to the water shortage in Slovakia.

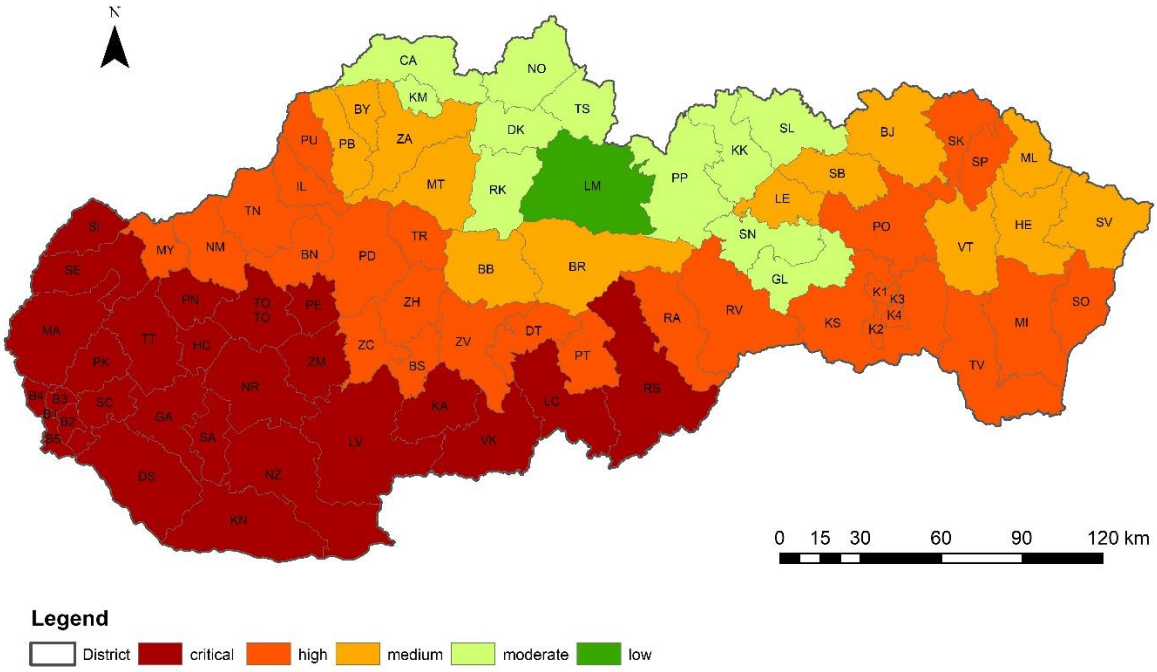


Fig. 5. Map of the areas vulnerable to the water shortage in Slovakia – division into the districts.

Conclusion

To account not only for the changes in the mean long-term discharges, as depicted in the vulnerability maps, but also for the spatial distribution of the runoff, the map of the areas vulnerable to the water shortage in Slovakia has been developed. The resulting classification divides Slovakia into the five water-shortage vulnerability categories. The most critical areas are concentrated in the southern part of the country, whereas the moderate and low vulnerability areas dominate in the northern mountainous regions with the higher altitudes.

Within the defined categories, particularly the less favourable ones, it is important to recognize that even in areas with the low natural runoff and the decreasing long-term discharges, the main rivers crossing these regions may provide the sufficient water resources for the adjacent territories. Such an assessment should therefore also be complemented by the consideration of the status of the groundwater resources. For instance, the Slovak part of the Danube River basin is classified as a low-vulnerability area in the vulnerability maps, owing to a relatively minor changes in the long-term discharges of the Danube River itself. Nevertheless, the natural runoff of this area, given by its geographic location and low elevation, is among the lowest in Slovakia. Consequently, in the combined map this basin is categorized as at the medium vulnerability. However, the availability of water in the Danube River itself and the groundwater in its adjacent alluvial deposits corresponds more closely to a favourable category. It should be added, that when the area is further subdivided at the district level, it is classified as a critical area, based on both expert judgement and the relative size of the district.

At the same time, it should be emphasized that the observed changes analysed in this article relate to mean long-term discharges; the changes of the low flows and their implications for drought vulnerability require further detailed analysis.

We recommend to use the map of the areas vulnerable to the water shortage in Slovakia while considering their limitations, such as not including of analysis groundwater resource. Nevertheless, these maps provide valuable information for water planning, resource management, and can serve as a decision-support tool for the design and implementation of the measures to mitigate the hydrological drought and the water scarcity at a district level.

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