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How did the aridity of the climate in Slovakia change over last decades?

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The availability of water is a crucial factor influencing the stability of an ecosystem, the vitality of its flora and fauna, and the economic growth of a society. The changes in the aridity of a climate have an important effect not only on ecosystems, but also on economies, agriculture, and the available water supply. The aridity index (AI) is one of the most frequently used indices for assessing the degree of dryness of a climate. The AI is based on long-term water deficits and therefore expresses over long periods changes. Fluctuations in aridity can also be used to quantify the impact of climate change on regional climatic conditions. Our research is focused on quantifying changes in climate conditions for 76 climatological stations in Slovakia; these changes are based on an analysis of trends in the aridity index. We also examined changes in the seasonal and long-term patterns of related variables and climate drought indexes (SPI_{10}, $SPEI_{10}$) to identify the drivers of changes in the aridity of the climate of the region. Our findings indicate rising trends in climate aridity, primarily driven by increases in air temperatures, especially the minimum air temperature, even though the trend in precipitation totals is still constant (but also increasing in some areas). Furthermore, our analysis reveals that drought has become a year-round concern over recent decades, which reinforces our assertion that certain regions of Slovakia are at risk of desertification.

KEY WORDS: aridity index, climate change, trends

Introduction

"Aridity" and "drought" are terms frequently inter-changed, but both are pertinent to the availability of water. "Drought" constitutes a short-term natural hazard, which occurs for a limited duration within a year and is characterized by its frequency, duration, and magnitude. Regions with water limitations face a heightened risk of experiencing more frequent and severe drought events due to rising temperatures, thereby potentially triggering desertification processes (Spinoni et al., 2014). Drought assessment is a frequent topic of scientific research in the region of Central Europe (Soľáková et al., 2022; Tarnawa et al., 2023). "Aridity" is a long-term condition of a climate, that affects the ecosystem and economy of a region. According to the World Atlas of Desertification (EU, 2015), arid areas globally increased between 1951–1980 and 1981–2010, and many of them have led to land degradation problems.

Recent decades have been characterized by rising air temperatures and frequent weather extremes, including drought, which significantly influence the environment and human society (IPCC Working Group 1 et al., 2013). Understanding desertification processes should drive changes in approaches to agriculture, forest management, and water management and should aim to mitigate the frequency and severity of drought events and their subsequent impacts on land. Numerous studies have demonstrated that non-adapted land uses and unsustainable practices in dry climates escalate the risk of desertification (Reynolds et al., 2007; Vogt et al., 2011). This understanding is essential for implementing sustainable measures aimed at mitigating desertification. This study is aimed at determining changes in the classification of regional climate aridity during 30-year periods based on the recommendation of the World Meteorological Organization (WMO, 2007) for a normal of climate, of 1981–2010 and the latest 30-year period 1991–2020.

Previous studies have demonstrated that the models used for the calculation of reference evapotranspiration can have significant effect on SPEI values (Beguería et al., 2014). Some authors suggest, that using of actual evapotranspiration instead of the value of reference evapotranspiration in drought assessment can provide more reliable results (Dai, 2011; Joetzjer et al., 2012). Measured values of actual evapotranspiration are not available in the climatological stations of Slovakia, therefore we decided to use values of reference evapotranspiration calculated by FAO56 Penamn-Monteith (PM) method. According the previous study of Kandra et al. (2023), the FAO-56 P-M model provide good performance compared to ET_a measurements in Petrovce nad Laborcom lysimeter station in eastern Slovakia.

We also recognized drivers of changes in aridity through an examination of temporal variations characteristics in drought (SPI_{10} and $SPEI_{10}$ index), precipitation totals and air temperature.

The main contribution of the research is determination of the changes in aridity and seasonal pattern of drought by using FAO56 Penman-Monteith reference evapotranspiration values, for stations covered whole area of Slovakia.

Using of FAO56 Penman-Monteith reference evapotranspiration values gap-filled by machine learning model in the assessing of drought bring more precise results and more objective evaluation, what parts of Slovakia are mainly affected by change of climate.

Material and methods

The research was carried out on a subset of 76 climatological stations in Slovakia, which are distributed through various altitudes (from 100 to 2635 m a. s. l.) and regions of Slovakia (Fig. 1). The climatic conditions of Slovakia are affected by the Atlantic Ocean on the west and a continental climate on the east, with different climate conditions between the lowlands on the south and mountains in the north. Over the last few decades, changes in the availability of water have been observed, with a notable increase in the frequency of dry periods (Keszeliová et al., 2022; Younus and Hassan, 2022). Measured daily data for climatological stations were acessed from database of Slovak Hydrometeorological Institute.

The solar net radiation on the Earth's surface was calculated using the FAO56 methodology. Although only stations with minimal missing climatological data were selected for the analysis, gaps in the time series were present due to missing sunshine duration data, which could potentially influence the results of the analysis. To address this issue, missing radiation data were filled in using a random forest regressor model. This model utilized related climatological variables, including minimum, maximum, and mean air temperatures, precipitation, relative air humidity, extraterrestrial radiation, and maximum possible durations of sunshine. The model parameters were set to include 150 estimators with a random state of 50.

Subsequently, reference evapotranspiration was calculated on a daily time step using the FAO56 Penman-Monteith methodology, which incorporates meteorological data and the gap-filled data of solar net radiation using formula:

$$ET_0 = \frac{0.408*\Delta*(R_N - G) + \Upsilon \frac{900}{T+273} * u_2 + (e_s - e_a)}{\Delta + \Upsilon*(1 + 0.34*U_2)} \qquad (1)$$

where

ET_o– is reference evapotranspiration [mm day^{-1}];
R_n – net radiation at the crop surface [MJ m^{-2} day^{-1}];
G – soil heat flux density [MJ m^{-2} day^{-1}];
T – mean daily air temperature at 2 m height [°C];
u_2 – wind speed at 2 m height [m s^{-1}];
e_s – saturation vapor pressure [kPa];
e_a – actual vapor pressure [kPa];
Δ – slope vapor pressure curve [kPa °C^{-1}];
G – psychrometric constant [kPa °C^{-1}];
R_a – extraterrestrial radiation [MJ m^{-2} d^{-1}].

To ensure consistency of time series, reference evapotranspiration data were homogenized using a random forest regression model with the same settings as in the previous task. This model utilized reference evapotranspiration data from the nearest stations for homogenization purposes, reference evapotranspiration of the target station was modelled multiple times using reference evapotranspiration data from one of the nearest stations as a feature. The resulting time series of modelled reference evapotranspiration was determined as a mean of results from models and were used for gap-filling of missing radiation values in time series calculated by FAO56 methodology.

The aridity index (AI) of each station was computed according to the methodology outlined by the United

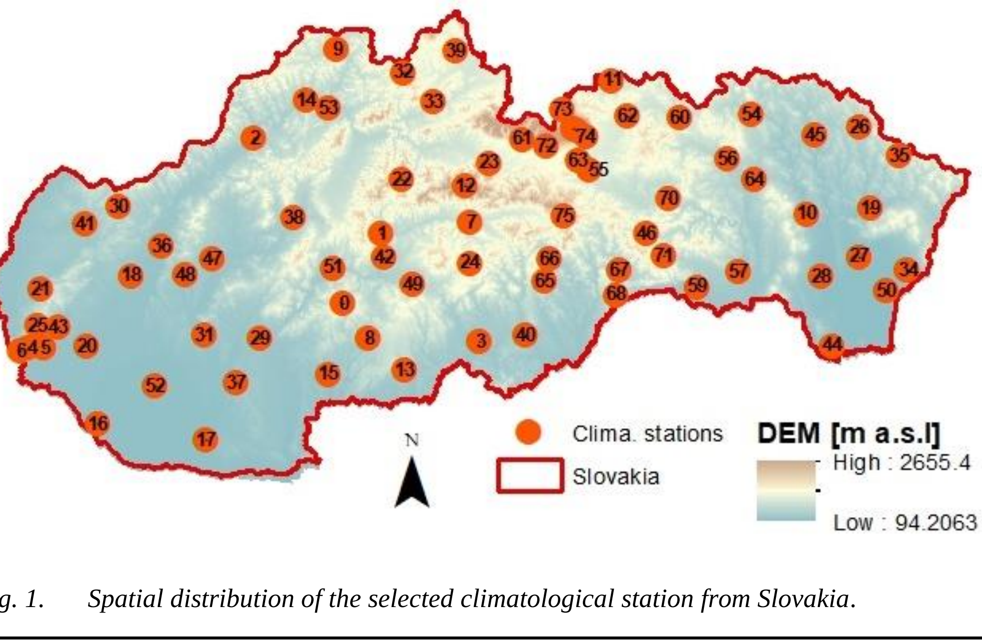

Fig. 1. Spatial distribution of the selected climatological station from Slovakia.

Nations Environment Programme (UNEP, 1997). The aridity index is determined according equation:

$$AI = \frac{P}{ET_0} \tag{2}$$

where

P –is annual precipitation totals [mm];

ET_0 –is annual reference evapotranspiration [mm year^{-1}].

Aridity index values are dimensionless and inversely related to aridity, with lower values indicating drier conditions. UNEP (1997) also introduced a classification scheme for the aridity index, as follows:

- AI<0.05 – Hyper-arid regime of a climate.
- 0.05≤AI<0.2 – Arid regime of a climate.
- 0.2≤AI<0.5 – Semi-arid regime of a climate.
- 0.5≤AI<0.65 – Sub-humid regime of a climate.
- 0.65≤AI<1 – Dry land regime of a climate.
- AI≥1 – Humid regime of a climate.

For the determination of temporal changes and their potential trajectory for the future, we employed trend analyses using the Mann-Kendall trend test (Bevan and Kendall, 1971) and Sen's slope estimator. The magnitude of the trend was derived from Sen's slope values over a 10-year period, thereby facilitating better interpretation and comparison of the results.

A seasonal drought assessment was conducted using the 10-day Standardized Precipitation Index (SPI, McKee et al., 1993) and the 10-day Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010). Changes in drought index categories were evaluated according to established criteria (Table 1.).

Results and discussion

Calculation of the reference evapotranspiration via the FAO-56 Penman-Monteith methodology (Allen et al., 1998) was conducted prior to the research analysis. For this purpose, we used homogenized data of the reference evapotranspiration, based on the solar net radiation data gap-filled by the random forest regressor model. With these steps, we ensured a sufficiently long time series of reference evapotranspiration, to ensure more precise results. The aridity index was computed from annual precipitation totals and annual reference evapotranspiration values. We further analyzed trends in the yearly aridity index values using the Mann-Kendall trend test for the entire period from 1981 to 2020. Notably, significant trends in the aridity index were detected at 28 stations during this period (see Fig. 2).

We divided our study period into two 30-year intervals,

Table 1. Drought index categories

	SPI	SPEI
Extremely wet	<2	<2
Very wet	1.5 to 1.99	1.5 to 1.99
Moderately wet	1.0 to 1.49	1.0 to 1.49
Near normal	0 to 0.99	-0.99 to 0.99
Mild drought	0 to -0.99	
Moderate drought	-1.0 to -1.49	-1.0 to -1.49
Severe drought	-1.5 to -1.99	-1.5 to -1.99
Extremely dry	<-2	<-2

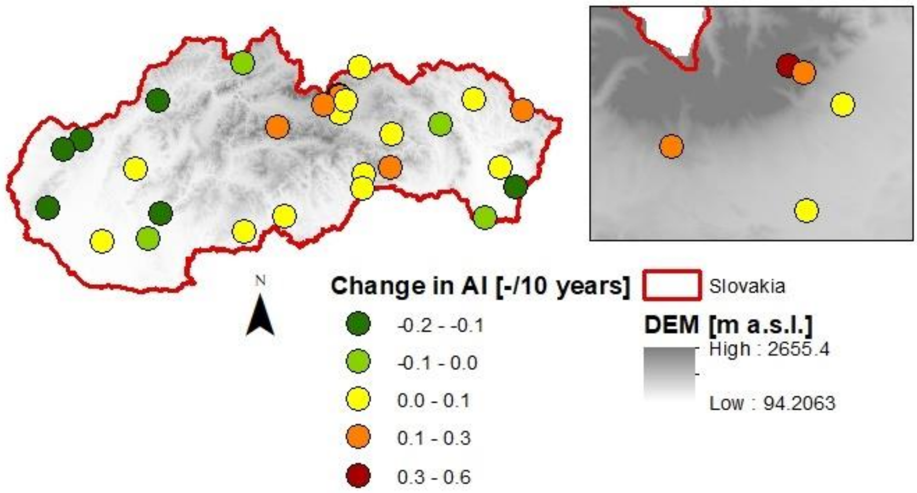

Fig. 2. Stations with significant AI trends and their magnitude (1981–2020).

spanning from 1981 to 2010 and from 1991 to 2020, to discern changes in the aridity of the climate over the past decades. Our analysis revealed significant alterations in aridity index (AI) trends during the latter period. Stations that had previously exhibited a significant trend in the aridity index saw this trend become insignificant in the most recent period, with the magnitude of the trend intensifying.

Of particular note are the significant changes observed in the western part of Slovakia – Záhorie region and Bratislava, where climatological stations such as Myjava (30), Senica (41), Kuchyňa (21), and Slovenský Grob (43) showed a significant decreasing trend in the aridity index (see Fig. 3). Similarly, in a lowland area of eastern Slovakia known as the "Dolný Zemplín" region, Somotor (44) and Vysoká nad Uhom (50) stations displayed changes in the magnitude and significance of the trends. Comparable alterations in the trends were also noted in northwestern part of Slovakia in Horné Považie region – Beluša (2) and Žilina (53), as well as in southern part of Slovakia in the Dolná Nitra region (Mochovce (29) and Podhájska (37) climatological stations). In all of these stations, decreasing trends became significant during the 1991–2020 period, with a more pronounced increase in magnitude. Remarkably, the Plaveč nad Popradom (60) climatological station in northern part of Slovakia exhibited a significant decreasing trend in both analyzed periods.

The negative magnitude of the trends in the aridity index has led to a shift in the climate's aridity towards increased aridity, particularly in the Záhorie, Horné Považie, Dolná Nitra, and Dolný Zemplín regions (see Fig. 4). We also observed a significant decreasing trend with a rising magnitude of the trend of the AI values (see Fig. 3), in the majority of the stations where changes in the climate aridity occurred (see Fig. 4), thereby indicating an increased threat of drought in these areas. This presents a significant challenge, particularly for the Senica (41), Mochovce (29), Vysoká nad Uhom (50), and Somotor (44) stations, where the climate conditions have transitioned to semi-arid conditions in the last period (1991–2020), accompanied by a significant decreasing trend in the AI values. The changes in aridity observed in these stations that could lead to increased aridity over time, could jeopardize the stability of the ecosystem and have a profound economic impact on the region.

As an example, at the Senica (41) station in western part of Slovakia, the climate aridity shifted from a dryland climate to semi-arid between the periods 1981–2010 and 1991–2020, with the trend indicating a decrease in AI values of 0.55 [-] every 10 years. If this trend in AI at the Senica station persists at the same magnitude over the next decade, the climate aridity of this station would be classified as hyper-arid. This highlights the urgent need for proactive measures to address the escalating aridity and its potential repercussions on both the environment and the economy of the region.

The results of changes in the climate classification have prompted a detailed examination of the drivers behind these changes. Our focus was on determining seasonal and long-term changes in the variables and drought indicators related to climate aridity. To this end, we employed two drought indexes, i.e., SPI and SPEI, along with four related meteorological variables: precipitation totals, minimum and maximum air temperatures, and the mean air temperature, all of which are in a relationship with the energy crucial for

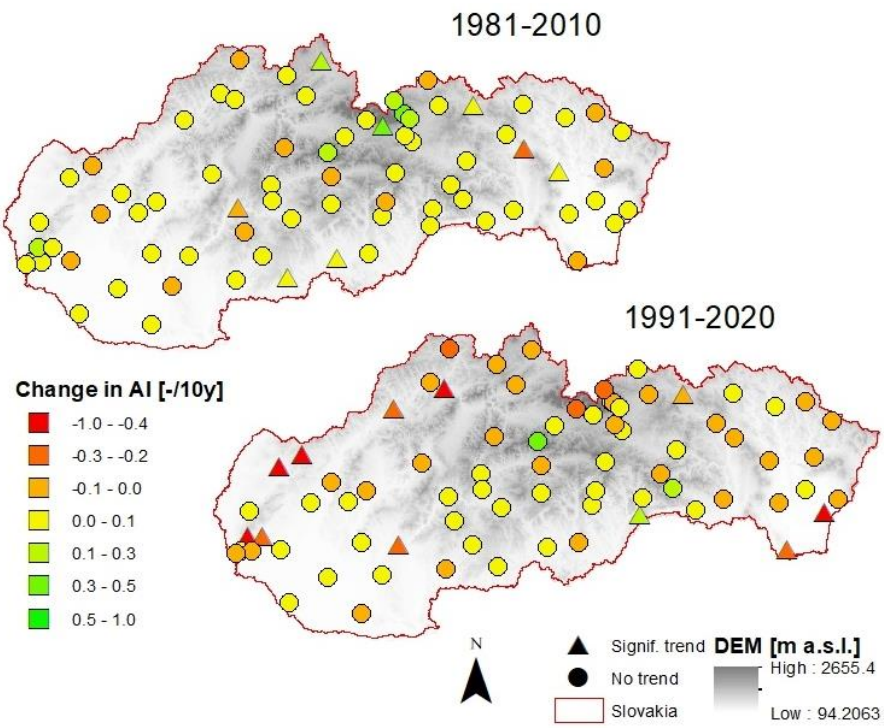

Fig. 3. Changes in the magnitude of the AI trends between two the periods examined.

evapotranspiration processes.
The SPEI and SPI indices for the stations studied reveal significant changes in moisture seasonality across various locations in Slovakia. The analysis identified a significant change in the trend of the aridity index for nine stations from 1981 to 2020. A comparison of the SPEI index for these stations confirmed rapid changes in the moisture conditions between the normal periods of 1981–2010 and 1991–2020 (see Fig. 5). For instance, at the Slovenský Grob (43) station in the Pudunajská nížina lowland, the long-term mean annual precipitation decreased by -15 mm, while the mean annual air temperature increased by +0.6°C on average (ME SR, 2019; 2023). Consequently, drier conditions have emerged in the winter and spring months, leading to potentially reduced water available for vegetation. Coupled with the rain shadow effect caused by the Little Carpathian Mountains, this could pose a significant challenge for agriculture in the region in the future.
A similar situation has been observed at the Senica (41) and Myjava (30) stations in the Záhorie Region, where conditions have become even drier over the same short

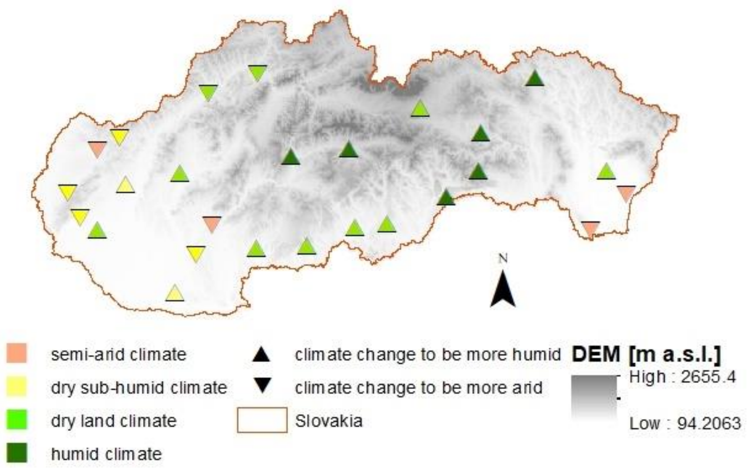

Fig. 4. Stations with a change in the class of climate aridity between two the periods examined, the climate class in the last period (1991–2020), and the tendency of this change.

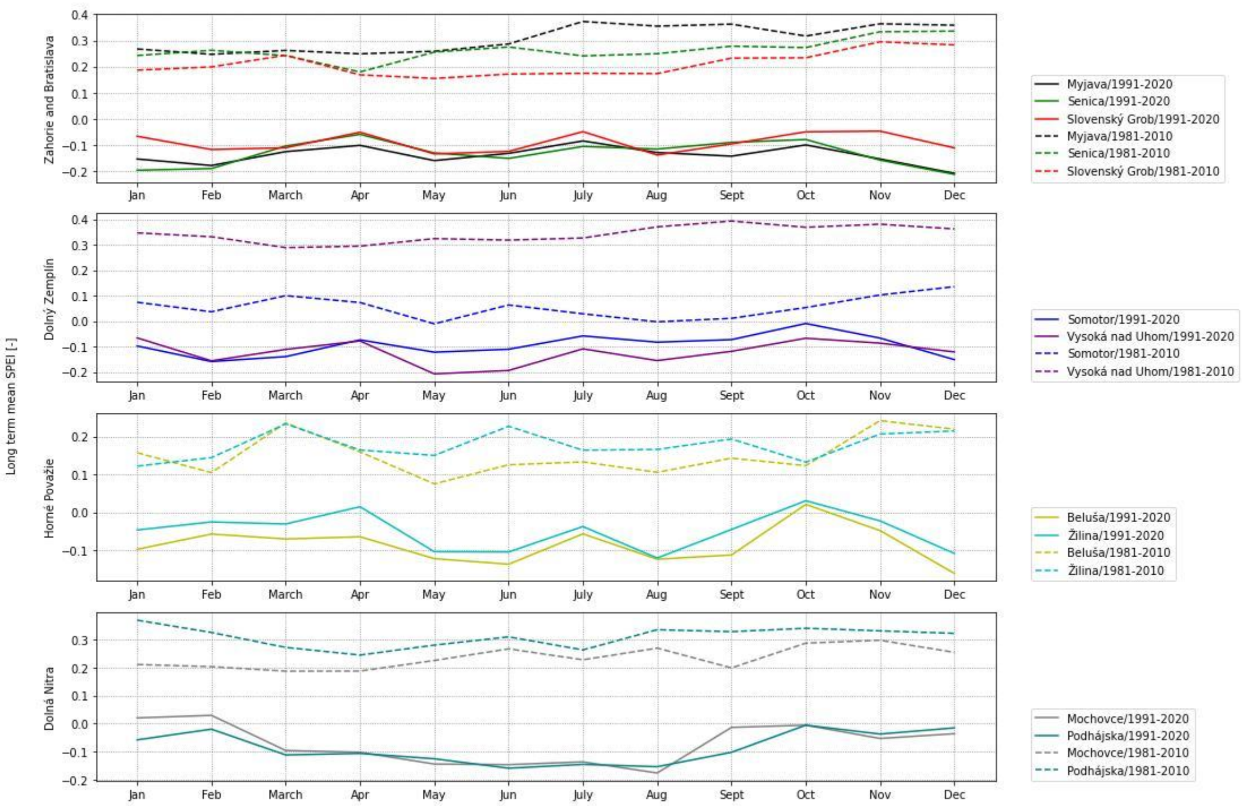

Fig. 5. Seasonal long term means of $SPEI_{10}$ index.

period. The SPI index for these areas has rapidly decreased in winter months, particularly in the Myjava subregion, where moisture conditions in the winter shifted from normal to extremely dry (see Fig. 6) based on drought index categories (see Table 1). Precipitation totals and the aridity index have exhibited a slight decreasing trend in this area, while the mean air temperature has continued to increase over the last four decades.

The eastern part of Slovakia is encountering a very similar situation. The Vysoká nad Uhom (50) station in the Východoslovenská nížina lowlands has transitioned from normal conditions to extremely dry conditions in all the seasons except for the summer, as indicated by the mean monthly SPI index (see Fig. 6). This transition corresponds to a shift towards a more arid climate. Although the amount of the long-term mean annual precipitation has remained constant, there has been a notable increase in the air temperature by +0.6°C (ME SR, 2019; 2023) compared to the climatological normals. This rise in the air temperature has intensified the reference evapotranspiration and exacerbated the aridity conditions. Additionally, periods without any precipitation have become more frequent in recent decades and are leading to moisture deficits and recurrent meteorological and hydrological droughts throughout the year.

Another region that has shifted towards more arid climate conditions, as indicated by the aridity index, is Dolná Nitra. The Mochovce station (29) has transitioned to a semi-arid climate (see Fig. 4) with a magnitude of the aridity index trend of -0.3 per decade (see Fig. 3). Similarly, the Podhájska station (37) has become drier and shifted towards a dry sub-humid climate. Nevertheless, there are also localities in Slovakia that have experienced increasing moisture conditions over recent decades, leading to a more humid climate. Stations such as Silica (68), which is located in the Slovenský Kras National Park, have seen an increase in the amount of the mean annual precipitation by +25mm compared to the two selected climatological normals, while Štós-kúpele (71) has experienced an even greater increase of +42mm (ME SR, 2019; 2023). Despite the upward trend in the air temperature values at these stations, it has not significantly affected the aridity of the climate, thanks to the concurrent increase in the precipitation totals.

Stations in western Slovakia, including the Podunajská nížina and Záhorská nížina lowlands, are particularly vulnerable to the risks of meteorological, hydrological, and soil drought, primarily due to rapid changes in the various climatological indices and variables since the year 2000. This region is predominantly influenced by an oceanic climate. The most significant precipitation deficits in this region, as indicated by SPI and SPEI, occur during the spring months (March, April, May) when comparing the periods of 1981–2010 and 1991–2020 (see Figs. 5–6). Although the long-term mean annual precipitation has remained relatively stable, there has been a dramatic increase in the mean air temperature over the last two decades. For instance, at the Kuchyňa-Nový Dvor (21) station, the long-term mean monthly air temperature has risen by +0.5°C in March and +0.7°C

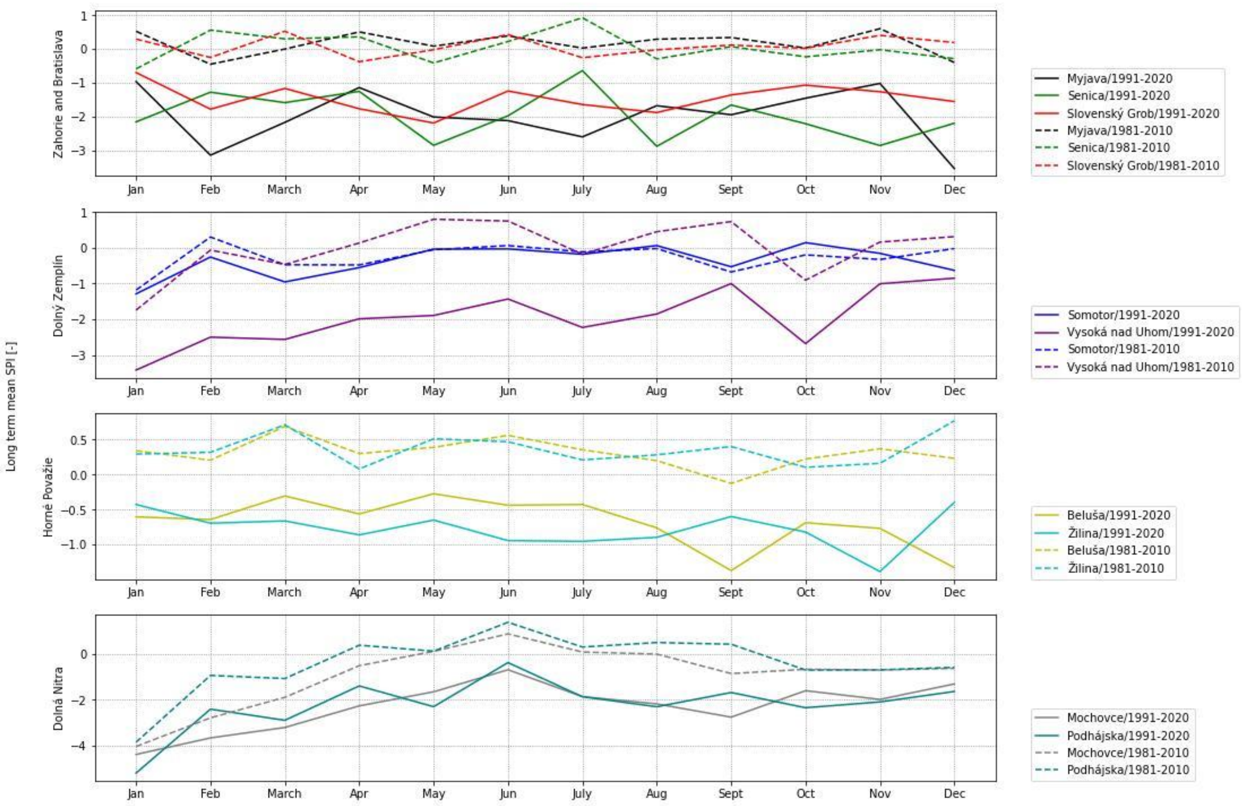

Fig. 6. Seasonal long-term means of the SPI_{10} index.

in April, when comparing the periods observed. This rise intensifies potential evapotranspiration values, thereby significantly contributing to drier conditions and shifting localities in western Slovakia towards more arid classes according to the aridity index.

On the other hand, the eastern part of Slovakia, including the Východoslovenská nížina lowland, with a more continental climate regime and higher air temperature amplitudes, is also experiencing climate change-induced drying of the land. The increase in the mean monthly air temperature is even more pronounced in this region. For example, between the periods studied, there has been an increase in the long-term mean August air temperature by +1°C, in July by +0.7°C, and in June by +0.8°C. Stations such as Vysoká nad Uhom (50) exhibit similar trends, signifying a significant and rapid change for the Dolný Zemplín region. High air temperatures in the summer season have led to a decrease in the long-term mean SPEI indices in the autumn months of September and October (see Fig. 7).

Based on the results from the analyses of the 30-year moving trends of the related variables, we can conclude that the changes in the aridity are primarily associated with changes in the air temperature. While a significant increasing trend in the minimum, maximum, and mean air temperatures were observed across the entire area of Slovakia, there has been a significant increase in the magnitude of the trend of the minimum air temperature changes in recent decades in stations where the climate has become drier. Additionally, there is an increasing trend in the maximum air temperature, although the slope of this trend has not escalated as rapidly over time.

Although the precipitation totals have shown a slight increasing trend at many stations, this trend has not exhibited a tendency to accelerate over time. We can infer that the changes in aridity are a consequence of the imbalance between the constant increase in the magnitude of the air temperature changes and the fairly slight increase in the precipitation totals, which has contributed to the desertification of the land. This issue was detected in numerous stations, as exemplified in Fig. 8, which illustrates the 30-year moving trends of the aridity index and related variables for the climatological station in Myjava.

The problem of increasing aridity in certain areas exacerbates the phenomenon of seasonal drought, which is now present in all seasons of the year (see Figs. 5–6). This underscores the urgency of addressing these trends and implementing measures to mitigate the impacts of climate change on the aridity of the land and drought conditions.

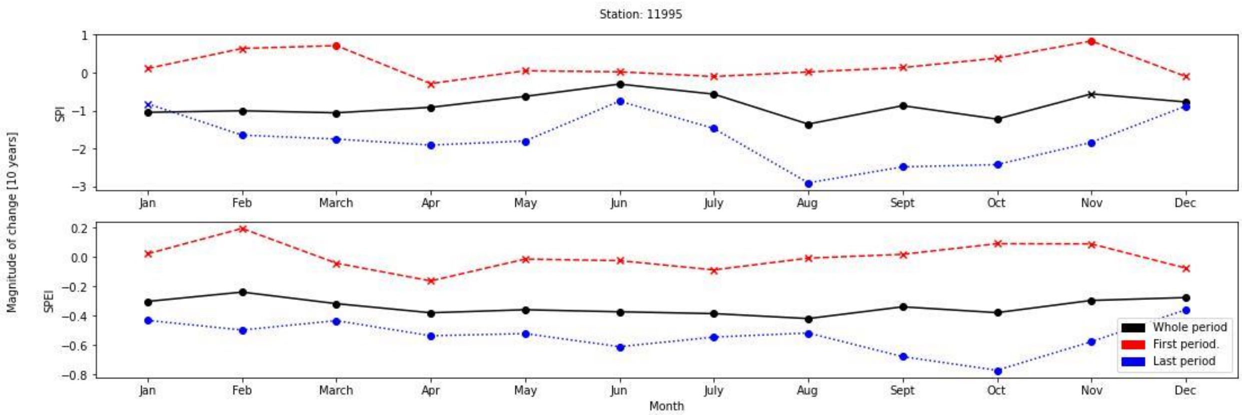

Fig. 7. Seasonal magnitude of $SPEI_{10}$ and SPI_{10} trends for the Vysoká nad Uhom climatological station (●-significant trend; x-no significant trend).

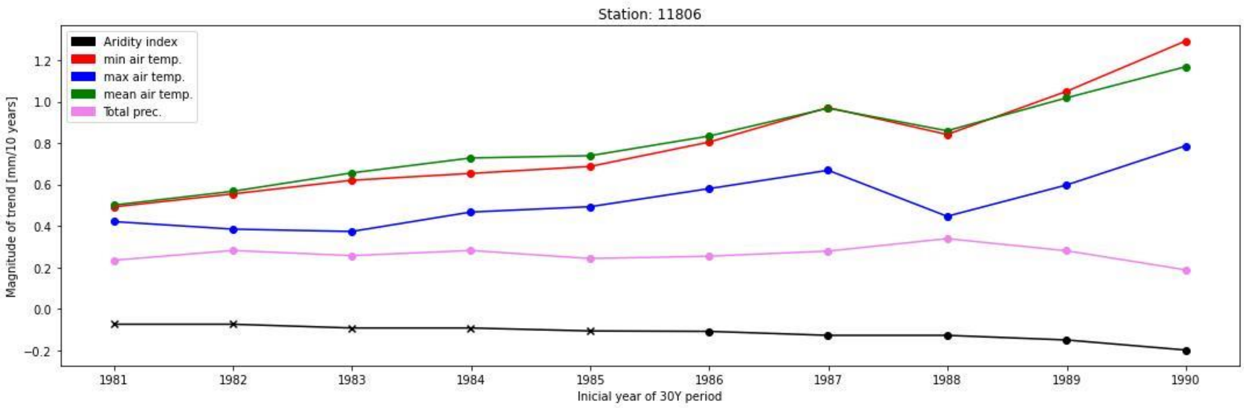

Fig. 8. Magnitude of the moving trends in AI and related variables (30 years).

Conclusion

The rapid changes in the moisture conditions observed in Slovakia over the past few years are unprecedented. Our findings are consistent with research conducted by Faško et al. (2022) and Markovič et al. (2020), which indicate that the western and eastern parts of Slovakia, particularly in the low altitudes (<200 m a.s.l.), have experienced a decrease in the long-term mean annual precipitation and have become drier according to the aridity index. Conversely, the central Slovakia and higher altitude stations have transitioned to more humid climate conditions.

The increasing magnitude of the air temperature change, especially the minimum air temperature, alongside the relatively constant trends in precipitation totals, have significantly influenced the aridity of the climate. This has resulted in the disappearance of periods with sufficient moisture in the soil throughout the year, with drought even occurring during traditionally moist months in recent decades.

However, it is noteworthy that in some climatological stations, increasing humidity in the climate is driven by rising precipitation totals. Although air temperatures are also increasing, they do not significantly affect the aridity of the climate. This underscores the need for further research to investigate how changes in the seasonal pattern of precipitation affect the long-term aridity of the climate.

The shift towards a more arid climatic region, which has been characterized by a constant increase in aridity over the years, poses a significant threat to ecosystems, agriculture, and other sectors of the economy. It is imperative to implement practices aimed at maintaining moisture in the land to prevent desertification and mitigate the adverse effects of climate change on the environment and society.

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References

Allen, R. G., Pereira, L. S., Raes, D., Smith, M. (1998): Crop evapotranspiration - Guidelines for computing crop water requirements – FAO Irrigation and drainage paper 56. Irrigation and Drainage. https://doi.org/10.1016/j.eja.2010.12.001

Beguería, S., Vicente-Serrano, S. M., Reig, F., Latorre, B. (2014): Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology*, *34*(10). https://doi.org/10.1002/joc.3887

Bevan, J. M., Kendall, M. G. (1971): Rank Correlation Methods. The Statistician, 20(3). https://doi.org/10.2307/2986801

Dai, A. (2011): Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. *Journal of Geophysical Research Atmospheres*, *116*(12). https://doi.org/10.1029/2010JD015541

EU (2015): Mapping land degradation and sustainable land management opportunities. In European Union (p. 16). Publications Office of the European Union.

Faško, P., Bochníček, O., Markovič, L. (2022): Evolution of long-term average values of air temperature and atmospheric precipitation in Slovakia. Meteorologický Časopis, 25, 79–88.

IPCC Working Group 1, I., Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. M. (2013): IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, AR5.

Joetzjer, E., Douville, H., Delire, C., Ciais, P., Decharme, B., Tyteca, S. (2012): Evaluation of drought indices at interannual to climate change timescales: a case study over the Amazon and Mississippi river basins. *Hydrology and Earth System Sciences Discussions*, *9*(11).

Kandra, B., Tall, A., Gomboš, M., Pavelková, D. (2023). Vybrané parametre vodnej bilancie pôdy získané výpočtom a lyzimetrickými meraniami. *Hydrologie Malého Povodí*. 257–264.

Keszeliová, A., Výleta, R., Danacova, M., Hlavčová, K., Sleziak, P., Gribovszki, Z., Szolgay, J. (2022): Detection of Changes in Evapotranspiration on a Catchment Scale Under Changing Climate Conditions in Selected River Basins of Slovakia. Slovak Journal of Civil Engineering. 30. 55–63. 10.2478/sjce-2022-0029.

Markovič, L., Pecho, J., Faško, P. (2020): Zmeny v skupenskom zastúpení atmosférických zrážok v zime na území Slovenska. Meteorologické Zprávy. CHMÚ, 73–2020/1.

McKee, T. B., Nolan, J., Kleist, J. (1993): The relationship of drought frequency and duration to time scales. Preprints, Eighth Conf. on Applied Climatology, Amer. Meteor, Soc., January.

Ministry of Environment of the Slovak Republic (MŽP SR) (2019): *Národný klimatický program Slovenskej republiky, zv. 14/19, Klimatologické normály za obdobie 1981–2010 na Slovensku*.

Ministry of Environment of the Slovak Republic (MŽP SR) (2023): *Národný klimatický program Slovenskej republiky, zv. 16/22, Klimatologické a fenologické normály v období 1991–2020 na Slovensku*.

Reynolds, J. F., Stafford Smith, D. M., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P. J., Downing, T. E., Dowlatabadi, H., Fernández, R. J., Herrick, J. E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F. T., Ayarza, M., Walker, B. (2007): Ecology: Global desertification: Building a science for dryland development. In Science (Vol. 316, No. 5826). https://doi.org/10.1126/science.1131634

Soľáková, T., Zeleňáková, M., Mikita, V., Hlavatá, H., Simonová, D., Elhamid, H. A. (2022): Assessment of meteorological and hydrological drought using drought indices: SPI and SSI in eastern Slovakia. Acta Hydrologica Slovaca, 23(2). https://doi.org/10.31577/ahs-2022-0023.02.0030

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., Vogt, J. (2014): World drought frequency, duration, and severity for 1951–2010. International Journal of Climatology, 34(8). https://doi.org/10.1002/joc.3875

Tarnawa, Á., Kassai, K. M., Kende, Z., Jolánkai, M. (2023): Changes of drought indices in relation with the geographic altitude of the crop site. Acta Hydrologica Slovaca, 24(2). https://doi.org/10.31577/ahs-2023-0024.02.0020

UNEP (1997): World atlas of desertification 2ed. United Nations Environment Programme.

Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I. (2010): A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate, 23(7). https://doi.org/10.1175/2009JCLI2909.1

Vogt, J. V., Safriel, U., Von Maltitz, G., Sokona, Y., Zougmore, R., Bastin, G., Hill, J. (2011): Monitoring and assessment of land degradation and desertification: Towards new conceptual and integrated approaches. In Land Degradation and Development (Vol. 22, Issue 2). https://doi.org/10.1002/ldr.1075

WMO (2007): The role of climatological normals in a changing climate. https://community.wmo.int/en/wmo-climatological-normals

Younus, M., Hassan, S. (2022): The Impact of Climate Change on Stochastic Variations of the Hydrology of the Flow of the Indus River. Slovak Journal of Civil Engineering. 30. 33-41. 10.2478/sjce-2022-0004.

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