DOI: 10.2478/ahr-2021-0015



Acta Horticulturae et Regiotecturae – Special Issue
Nitra, Slovaca Universitas Agriculturae Nitriae, 2021, pp. 97–108

# EVALUATION OF DROUGHT – REVIEW OF DROUGHT INDICES AND THEIR APPLICATION IN THE RECENT STUDIES FROM SLOVAKIA

Slavomír Hološ[1,2]*, Peter Šurda[2]

[1]Slovak University of Agriculture in Nitra, Slovakia
[2]Institute of Hydrology, Slovak Academy of Sciences, Bratislava, Slovakia

Drought has recently become an important topic in Europe but also in Slovakia. Observed results from various studies suggest that this drought phenomenon has a serious impact on hydrology, agriculture and social and economic sectors. The first part of the paper was devoted to the study of literature from the field of existing drought indices, which serve to identify all types of drought such as meteorological, agricultural and socio-economic drought. The second part of the paper dealt with selected scientific studies on drought assessment and the use of drought indices in Central Europe and Slovakia.

**Keywords:** drought, drought index, meteorological drought, agricultural drought, socio-economic drought

### Definition and concept of drought

Climate change has led to an increasing trend of drought in the recent decades, and models predict that the global drought risk will intensify further in the 21$^{st}$ century (Dai, 2013). While mean precipitation will increase, precipitation in the subtropical latitudes tends to decrease, particularly in the Mediterranean. Precipitation changes become statistically significant only when the temperature rises by at least 1.4 °C, and in many regions, the projected changes during the 21$^{st}$ century lie within the range of the late 20$^{th}$ century natural variability (Mahlstein, Portmann, Daniel, Solomon, Knutti. 2012).

The research on drought has attracted the attention of scholars, government departments and the public. The development of drought is relatively slow, but its effects are very devastating. Drought is easily reflected in agriculture in reduced yields, but it is also associated with soil degradation and intense erosion. It could also result in the extinction of certain species of animals in the affected areas. In some areas of the Earth, drought can result in malnutrition, hunger and diseases that can lead to reduction of population. Dried soil and vegetation pose a fire hazard (Mouillot, Rambal, Joffre, 2002).

Drought is a complex phenomenon and there is no clear physical quantity or definition by which drought can be measured. The lack of precipitation, relative to the climatic average of the area, is the main cause of drought. The increased rate of evapotranspiration, which is increased especially by higher air temperature, low relative humidity, low clouds, more intense sunlight or faster air flow, contributes to a significant intensification of drought. In certain cases, drought may result from the anomaly of other variables, such as temperature or evapotranspiration (Cook, Smerdon, Seager, Coats, 2014; Livneh, Hoerling, 2016; Luo et al., 2017). Moreover, drought may not be a purely natural hazard; human activities such as land use changes and reservoir operation may alter the hydrologic processes and affect drought development (Van Loonet al., 2016a). Overall, the development of drought results from the complicated interactions among the meteorological anomalies, land surface processes and human activities (Mishra, Singh, 2010).

## Material and methods

### Drought types and characterization

Traditionally, drought can be classified into meteorological, agricultural, hydrological and socioeconomic drought, based on both physical and socioeconomic factors (Wilhite, Glantz, 1985). According to Dracup, Lee and Paulson (1980), meteorological drought is determined by the meteorological characteristics such as air temperature, total precipitation and duration of sunshine. Hydrological drought is defined as the lack of water in rivers due to normal flow, lack of groundwater and the lack of water supply in natural or artificial reservoirs. If there is lack of water in soil for animals and plants, we are talking about physiological or agricultural drought. Socio-economic drought is characterised by lack of water for normal social and economic human activities (Pedro-Monzonís, Solera, Ferrer, Estrela, Paredes-Arquiola, 2015).

According to Svoboda and Fuchs (2016), it is essential to define drought indices and indicators. Indicators are parameters used to describe drought conditions (e.g. precipitation, temperature, streamflow, groundwater and reservoir levels, soil moisture and snowpack). Indices are

**Contact address:** Slavomír Hološ, Slovak University of Agriculture, Faculty of Horticulture and Landscape Engineering, Department of Biometeorology, 949 76 Nitra, Slovakia

typically computed numerical representations of drought severity, assessed using hydrometeorological inputs.

More than 100 drought indices have been proposed so far (Heim, 2002; Liu et al., 2018; Vicente-Serrano et al., 2012; Zargar, Sadiq, Naser, Khan, 2011). These indices correspond to different types of drought, including meteorological, agricultural and hydrological drought.

With the help of drought indices, we can provide information to the decision-makers in business, government and many stakeholders. These tools can be used to provide an early drought warning system (Lohani, Loganthan, 1997) to calculate the probability of a drought ending (Karl, Quinlan, Ezell, 1987), determine drought relief (Wilhite, Rosenberg, Glantz, 1986), assess the risk of forest fires (Wheaton, 1994), predict crop yield (Sakamoto, 1978; Kumar, Panu, 1997) and examine spatial and temporal characteristics of drought, drought severity and comparison between different regions (Alley, 1985; Soule, 1992; Nkemdirim, Weber, 1999).

## Meteorological drought

The meteorological drought (or precipitation deficit) is generally caused by persistent anomalies in the large-scale atmospheric circulation patterns due to anomalous sea surface temperatures (SSTs) or other remote conditions (Dai, 2011). Globally and also in the conditions of the Slovak Republic, in the recent years, there has been a noticeable increase in the annual average air temperatures, which is closely related to a significant decrease in relative humidity (SHMÚ, 2015). The dry period can only be evaluated on the basis of total precipitation, which also takes into account the duration of precipitation-free days and the time distribution of precipitation. The meteorological drought does not result from a single cause but from a combination of multiple causes (e.g. reduced soil moisture and increased temperature), which may also contribute to the atmospheric anomaly (Dai, 2013; Kam, Sheffield, Wood, 2014). The commonly used meteorological drought indices are listed below.

### *Standardized precipitation index*

The Standardized Precipitation Index (SPI) (Figure 1A a) is a widely used index to characterise the meteorological drought in a range of timescales. McKee, Doesken, Kleist (1995) used the probability of the precipitation occurrence for 3, 6, 12, 24, 48 months, and the output values ranged from -2.0 to +2.0. It was found that the Gamma distribution fits the precipitation time series very well. The Gamma distribution is defined by its frequency or probability density function as:

$$g(x)=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}x^{\alpha-1}e^{\frac{-x}{\beta}}\ (x>0) \qquad (1)$$

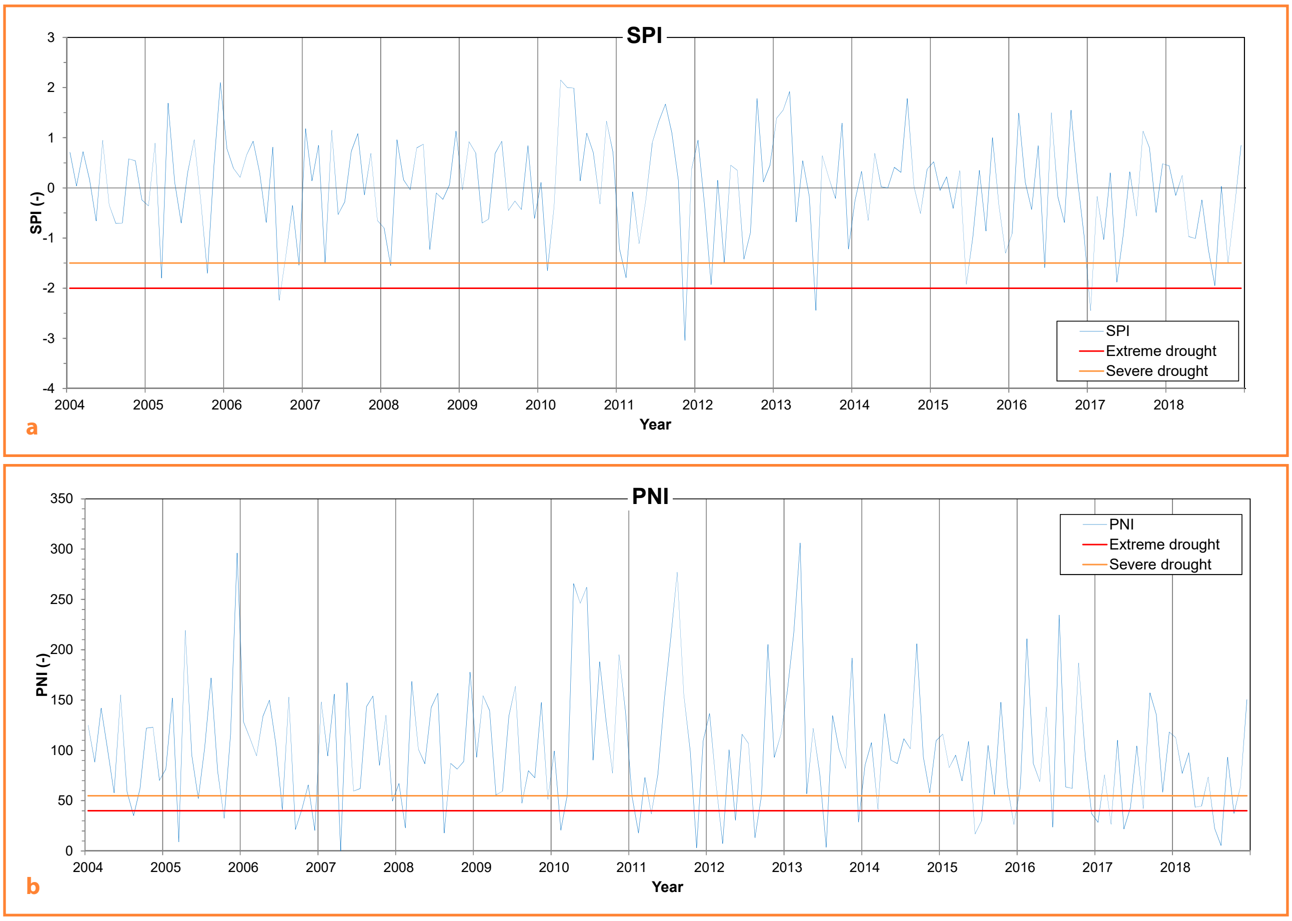


**Figure 1A** Values of SPI (a), PNI (b) index for the Malanta site, during the period 2004–2018; limit for severe (orange line) and extreme (red line) drought
Source: Šurda, Vitková, Rončák, 2020

where:

$\Gamma(\alpha)$ – for gamma function
$x$ – (mm) for precipitation amount ($x > 0$)
$\alpha$ – for shape parameter ($\alpha > 0$)
$\beta$ – for scale parameter ($\beta > 0$)

### *Percent of normal index*

Index PNI (Figure 1A b) was described by Willeke, Hosking, Wallis (1994) as a percentage of normal precipitation. It can be calculated for different time scales (monthly, seasonally and yearly). PNI (Percent of Normal Index) has been found to be rather effective for describing drought for a single region or/and for a single season (Hayes, 2006).

PNI is calculated as following:

$$\mathrm{PNI} = \frac{P_i}{P} \times 100 \quad (2)$$

where:

$P_i$ – for the precipitation in time increment (mm)
$P$ – for the normal precipitation for the study period (mm)

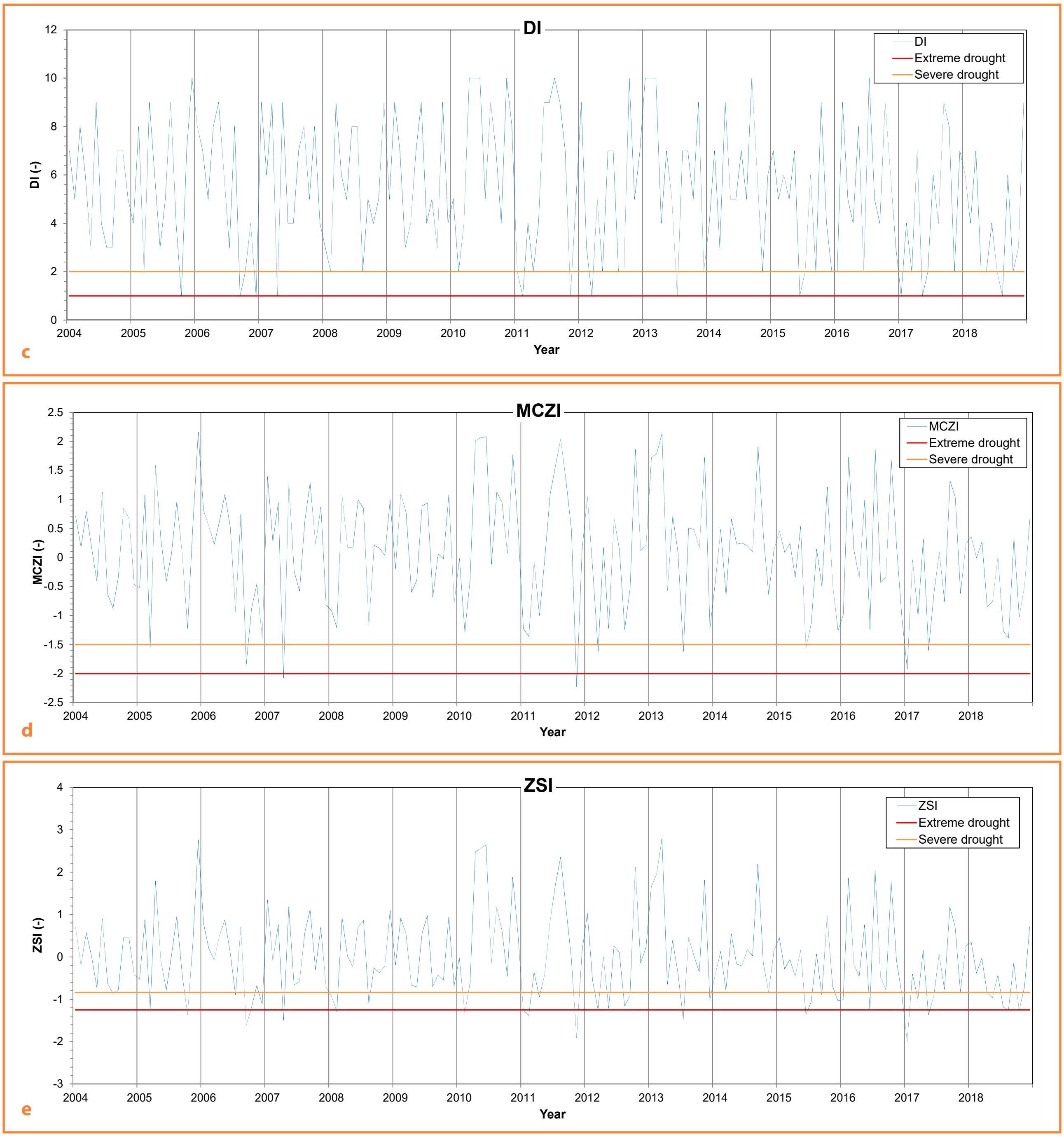


**Figure 1B** Values of DI (c), MCZI(d), ZSI(e) index for the Malanta site, during the period 2004–2018; limit for severe (orange line) and extreme (red line) drought
Source: Šurda, Vitková, Rončák, 2020

***DI (deciles)***

The DI index (Figure 1A c) was defined as a classification of precipitation totals during a time period over the whole monitoring period (Gibbs, Maher, 1967). In particular, monthly precipitation totals data are sorted from the lowest to the highest and are divided into ten equal categories or deciles. Thus, precipitation in a given month can be placed in a historical context by deciles.

***MCZI (modified z-index)***

The National Climate Centre in China developed CZI (Figure 1A d) in 1995 as an alternative to the SPI index (Ju, Yang, Chen, 1997). Assuming that the average precipitation totals have a III. Pearson distribution, the CZI is calculated as:

$$\mathrm{CZI}_{ij} = \frac{6}{C_{si}}\left(\frac{C_{si}}{2}\times\varphi_{tj}+1\right)^{1/3} - \frac{6}{C_{si}} + \frac{C_{si}}{6} \qquad (3)$$

where:

- $i$ – for the observed time span and $j$ is for the current month
- $\mathrm{CZI}_{ij}$ – for the sum of the CZI values in the current month ($j$) during the period $i$
- $C_{si}$ – for the skew coefficient
- $\varphi_{tj}$ – for a standardized variation

The MCZI is calculated using the above formula and the median prtecipitation total is replaced by the arithmetic mean value.

***ZSI (z-sum)***

The ZSI index (Figure 1A e) is sometimes confused with the SPI index. This drought index is an analogue to the CZI, but does not work with gamma or Pearson's distribution of precipitation total data. The ZSI index can be calculated according to the following formula:

$$\mathrm{ZSI} = \frac{P_i - \bar{P}}{SD} \qquad (4)$$

where:

- $\bar{P}$ – for the average monthly precipitation total (mm)
- $P_i$ – for the precipitation total in a particular month (mm)
- $SD$ – for the standard deviation of the precipitation totals over the monitoring time interval (mm)

***Standardized precipitation-evapotranspiration index (SPEI)***

The SPEI index is based on the SPI index, but the SPEI index also includes the temperature component. This component allows the index to take into account the effect of temperature on drought. The SPI index is calculated using monthly (or weekly) precipitation as the input data. The SPEI index uses the monthly (or weekly) difference between precipitation and PET. This represents simple climatic water balance (Thornthwaite, 1948) that is calculated on different time scales to obtain SPEI.

***Reconnaissance drought index (RDI)***

The RDI index includes potential evapotranspiration and precipitation based on a simplified water balance equation, and the index also contains three outputs: a standardized value, normalized value and an initial value. If the standardized RDI value has a similar character as the SPI index, then it can be directly compared with it. RDI is more representative than SPI, because it uses complete water balance instead of precipitation itself. The parameters that enter the RDI index are: monthly precipitation temperatures and temperatures (Svoboda, Fuchs, 2016).

***Effective precipitation concept (DEP)***

Byun and Wilhite (1999) used the term of Effective Precipitation to describe the summed value of daily precipitation with a time-dependent reduction function, representing the daily depletion of water resources. The choice of the best reduction function (equation) remains an unsolved problem, because many parameters, like topography, soil characteristics, ability to keep water in reservoirs, air temperature, humidity, and wind speed, must be considered together precisely to represent the depletion of water resources in nature by runoff and evapotranspiration (Akhtari, Morid, Mahdian, Smakhtinm, 2009; Kalamaras, Michalopoulou, Byun, 2010; Kim, Byun, 2009; Kim, Byun, Choi, 2009; Morid, Smakhtin, Moghaddasi, 2006; Roudier, Mahe, 2010).

The EPI index is calculated in a daily time step to overcome the big limitation of other indices – the long-time unit of assessment (most of the current drought indices use a monthly or longer time period as a unit).The EP index is based on the calculation of the effective precipitation during the selected time period. For the purposes of this work, 365-day effective precipitation ($EP_{365}$) and a linear reduction function were selected, representing uniform loss of water resources throughout the year.

$$\mathrm{EP}_i = \sum_{n=1}^{i}\left[\left(\sum_{m=1}^{n} H_{zm}\right)/\,n\right] \qquad (5)$$

where:

- $i$ – number of days whose total precipitation is included in the EP calculation
- $H_{zm}$ – total precipitation $m$-days before the first day included in the EP calculation (mm)

For the needs of the complex drought diagnosis, it is necessary to supplement the EP index with other derived values. The first is the value of the long-term EP average for each day of the calendar year (MEP). In this work, the average value of the effective precipitation was calculated from the 14-year series $EP_{365}$ (period 2004–2018) (Figure 2). Long-term EP ($MEP_n$) for a normal (slightly humid) period was computed for the years 2005–2012 and long-term EP ($MEP_d$) for a long-term dry period for the years 2012–2018, in this work. This time periods were selected according to the DEP index (Figure 3). With respect to the long-term average, the surplus or scarcity of water resources (DEP) for each day of the analysed period can be evaluated, according to the equation:

$$\mathrm{DEP} = \mathrm{EP}_{365} - \mathrm{MEP} \qquad (6)$$

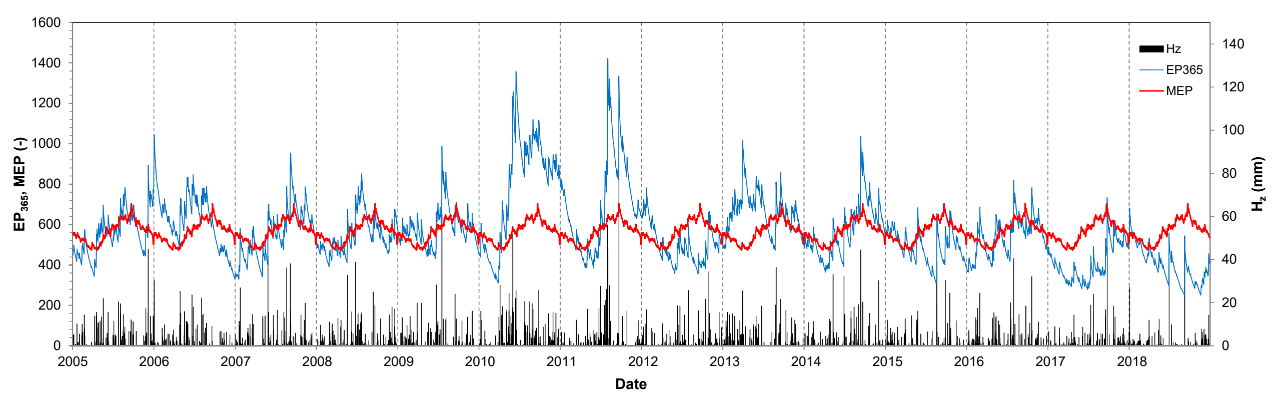


**Figure 2** Daily values of *Hz*, MEP and $EP_{365}$ for the meteorological station of Nitra, for the period 2005–2018
Source: Šurda, Rončák, Vitková, Tárnik, 2019

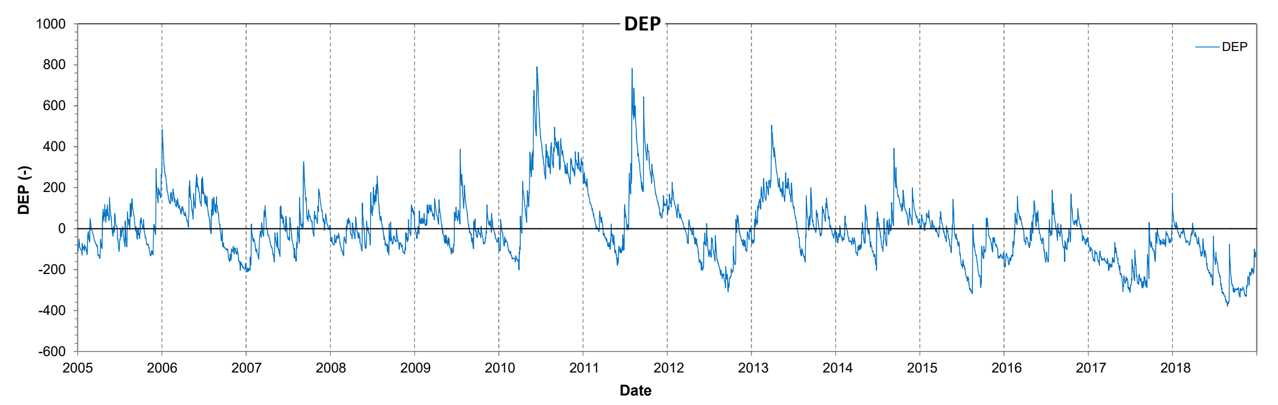


**Figure 3** Daily values of the DEP index for the meteorological station of Nitra, for the period 2005–2018
Source: Šurda, Rončák, Vitková, Tárnik, 2019

## Agricultural drought

Agricultural drought is commonly related to the deficit in soil moisture, which affects plant production and crop yield. This occurs mainly because the soil moisture availability governs the physiological processes in plants, and any paucity of water content in the crop root-zone can impede productivity (Wang, Lettenmaier, Sheeld, 2011; Mannocchi, Todisco, Vergni, 2004). A drought index using soil moisture would be directly related to the crop growth potential and could provide a decision supporting tool. The commonly used agricultural drought indicators according to Ajaz, Taghvaeian, Khand, Gowda, Moorhead (2019), are listed below.

### *Palmer drought severity index (PDSI)*

This index was developed by Palmer (1965) as one of the first attempts to identify droughts using more than just precipitation data. Monthly precipitation and temperature along with the latitude and the available water capacity of the soil are the input data. PDSI has been used to identify droughts affecting agriculture, and also for identifying and monitoring droughts associated with other types of impacts. It takes into account received moisture (precipitation) as well as moisture stored in the soil, accounting for the potential loss of moisture due to the temperature influences (Svoboda, Fuchs, 2016; Wells, Goddard, Hayes, 2004).

### *Palmer's Z-Index*

Palmer's Z-Index (Z-Index) is a derivative of PDSI, and the *Z* values are s part of the PDSI output. It is sometimes referred to as the 'Moisture Anomaly Index', and the derived values provide comparable measure of the relative anomalies of a region for both dryness and wetness when compared to the entire record for that location. The moisture loss is multiplied with empirically derived climatic characteristics, and the monthly moisture anomaly index known as Z-Index is estimated (Karl, 1986). Z Index responds to short-term conditions better than PDSI and is typically calculated for much shorter timescales, enabling it to identify rapidly developing drought conditions (Svoboda, Fuchs, 2016).

### *Soil waterdeficit index*

The SWDI was developed by Martínez-Fernández, González-Zamora, Sánchez, Gumuzzio (2015) and was estimated as:

$$\mathrm{SWDI} = \left( \frac{\theta - \theta_{FC}}{\theta_{AWC}} \right) \times 10 \tag{7}$$

where:

$\theta$ – for the aggregated volumetric water content (VWC) of soil profile

$\theta_{FC}$ – for the VWC at field capacity (*FC*)

$\theta_{AWC}$ – for the available water content estimated as the difference between VWC at *FC* and wilting point (WP) (all in $m^3.m^{-3}$)

***Water deficit index***

This index was developed by Cammalleri, Micale, Vogt (2016):

$$d = \frac{1}{1 + \left(\frac{\theta}{\theta_{50}}\right)^n} \tag{8}$$

where:

$n$ – for an empirical exponent (unitless)

$\theta_{50}$ – estimated by averaging VWC between the soil moisture thresholds as described by Cammalleri et al. (2016)

$\theta$ – aggregated for the soil profile based on depth

***Normalized soil moisture***

The NSM was proposed by Dutra, Viterbo, Miranda (2008) as:

$$NSM_{m,y} = \frac{\theta_{m,y} - \overline{\theta_m}}{\sigma_m} \tag{9}$$

where:

$\theta_{m,y}$ – for VWC for the month *m* and the year y ($m^3.m^{-3}$)

$\overline{\theta_m}$ – for mean monthly VWC ($m^3.m^{-3}$)

$\sigma_m$ – for the standard deviation for all studied years

Finally, remote sensing-based indicators such as the Normalized-Difference Vegetation Index (NDVI) or the fraction of the Absorbed Photosynthetically Active Radiation (*f*APAR) are used to monitor drought impacts on the vegetation cover.

***The normalized difference vegetation index (NDVI)***

NDVI is defined as:

$$NDVI = \frac{(\alpha_{nir} - \alpha_{vis})}{(\alpha_{nir} + \alpha_{vis})} \tag{10}$$

where:

$\alpha_{nir}$ and $\alpha_{vis}$ represent surface reflectance averaged over ranges of wavelengths in the visible ($\lambda$ ~0.6 μm, "red") and near infrared, IR ($\lambda$ ~0.8 μm) regions of the spectrum, respectively

It is clear from its definition that NDVI (like most other remotely sensed vegetation indices) is not an intrinsic physical quantity, although it is indeed correlated with certain physical properties of the vegetation canopy: leaf area index (LAI), fractional vegetation cover, vegetation condition and biomass.

***Fraction of absorbed photosynthetically active radiation (fAPAR)***

The quantity *f*APAR is defined as the fraction of incident photosynthetically active radiation (PAR) that is absorbed by a canopy, which usually includes the overstory and sometimes the understory and ground cover (e.g. moss). *f*APAR is calculated using:

$$f\,APAR = \frac{\left[\left(PAR_{\downarrow AC} - PAR_{\uparrow AC}\right) - \left(PAR_{\downarrow BC} - PAR_{\uparrow BC}\right)\right]}{PAR_{\downarrow AC}} \tag{11}$$

where:

$PAR_{\downarrow AC}$ and $PAR_{\uparrow AC}$ – incident (downward) and reflected (upward) PAR above the canopy, respectively

$PAR_{\downarrow BC}$ and $PAR_{\uparrow BC}$ – the corresponding terms for the below of the canopy

## Hydrological drought

Hydrological drought is associated with deficiency in the bulk water supply, which may include water levels in streams, lakes, reservoirs and aquifers. Since it is directly linked to the drought impacts, it is argued that more attention is needed to study the hydrological drought (Cloke, Hannah, 2011; Mishra, Singh, 2010; Pozzi et al., 2013). From the major drought forms, the hydrological drought may be the slowest to develop (Soule, 1992). For example, a shortage of snowfall may not manifest itself as depressed runoff until half a year later. It is possible to minimise the negative impacts of the hydrological drought on the environment and society through the analysis of the minimum flows. These minimum flows are one of the characteristics that can define hydrological drought.

The commonly used hydrologic drought indicators include Palmer hydrologic Drought Severity Index (PHDI), Standardized Runoff index (SRI), or reservoir level (Hayes, Svoboda, Wall, Widhalm, 2011).

***Total water deficit***

Total water deficit is a traditional assessment of the hydrological drought, synonymous with the drought severity *S*. This severity is the product of the duration *D*, during which flows are consistently below a truncation level (e.g., the hydro-climatic mean), and the magnitude M, which is the average departure of streamflow from the truncation level, during the drought period (Dracup et al., 1980). After the drought ends, the total water deficit resets to 0.

***Cumulative streamflow anomaly***

A cumulative departure of streamflow from mean conditions can show long-term tendencies in the water availability.

***Palmer hydrological drought severity index***

The Palmer Hydrological Drought Severity Index (PHDI) is very similar to PDSI, using the identical water balance assessment. Specifically, PDSI considers drought finished when the moisture conditions start an uninterrupted rise that ultimately erases the water deficit, whereas PHDI considers drought ended when the moisture deficit actually vanishes (Heim, 2000, 2002). This retardation is appropriate for the assessment of the hydrological drought, which is slower in developing than the meteorological drought.

***Surface water supply index***

The Surface Water Supply Index (SWSI) explicitly accounts for snowpack and its delayed runoff (Garen, 1993; Doesken, McKee, Kleist, 1991). SWSI is a suitable measure of the hydrological drought for regions, such as the mountainous catchments, where snow contributes significantly to the annual streamflow. Computations require measurements for snowpack, precipitation, streamflow and reservoir storage.

***Standardized runoff index (SRI)***

Shukla and Wood (2008) applied the concept for SPI in defining a standardized runoff index (SRI) as the standard normal deviation unit associated with the percentile of hydrologic runoff accumulated over specific duration. Different duration (e.g., 1-month, 9-month) and different spatial aggregations of the index can be calculated, depending on the source data resolution and desired application.

### Socioeconomic drought

The socioeconomic drought incorporates features or impacts of three other types of drought. Drought impacts span a wide range of societal (e.g., health), economic (e.g., water supply, agricultural production and recreation), and environmental (e.g., forest productivity and wildfires) systems. The subject of the socio-hydrology, firstly conceived by Sivapalan, Savenije, Blöschl (2012), seeks to understand the 'dynamics and co-evolution of coupled human-water systems', including the impacts and dynamics of the changing social norms and values, system behaviours such as tipping points and feedback mechanisms, some of which may be emergent (unexpected), caused by non-linear interactions among processes occurring on different spatiotemporal scales. According to Van Loon et al. (2016b), human activities influence water input and output, and storage, and therefore modify the propagation of drought and can even be the cause of drought in the absence of natural drivers of drought. The drought typology based on natural processes should therefore be complemented with drought types based on human processes. According to Pedro-Monzonís et al. (2015), socio-economic drought is associated with the impact of water scarcity on people and the economic activity causing socio-economic, social and environmental impacts. To assess water scarcity, the water resource vulnerability index (Raskin, Gleick, Kirshen, Pontius, Strzepek, 1997), water stress index (Falkenmark, Lundqvist, Widstrand, 1989), critical ratio (Alcamo, Henrichs, Rösch, 2000), the water poverty index (Sullivan, 2002) and water footprint (Hoekstra, 2012) are the most commonly used approaches.

**Water resource vulnerability index** considers scarcity to be the total annual withdrawals, and a percent of the available water resources. It is focused on the assessment of use for being more objective than demanding.

***Water stress index***

Countries may be classified according to the renewable water resources per capita per year. It is easily understood and data are generally available. In contrast, average values may hide scarcity problems on smaller scales. It does not take into consideration the infrastructures that modify the water availability or the variations in demands among different countries.

**Critical ratio** considers scarcity to be the ratio of water withdrawals for human use to the total renewable water resources. The difficulty of distinguishing the amount of water that could be available for human use considering evapotranspiration, return flows, environmental requirements, or the possibility of the society to adapt to water scarcity, belong among its limitations.

**Water poverty index** represents the weighted average of its five dimensions: access to water; water quantity, quality and variability; water use; water management capacity; and environmental aspects. The input data are huge and expert judgments are required.

**Water footprint** is defined as the total volume used to produce goods and services. It can be divided into three types: blue water footprint, green water footprint and grey water footprint.

## Results and discussion

### Drought quantification studies for the region of Slovakia over the last decade

Despite some controversy over global drought trends (Dai, 2012; Sheffield, Wood, Roderick, 2012), climate models project increases in mean temperature in the most of the land and ocean regions, hot extremes in the most inhabited regions, heavy precipitation in several regions, and the probability of drought and precipitation deficits in some regions (IPCC, 2018). Between 1990 and 2015, drought in the European Union affected more than 37% of its territory, representing 800.000 km$^2$ and affecting 100 million people. Over a 30-year period (1985–2015), drought has cost the European Union more than € 100 billion (Andreu, Solera, Paredes-Arquiola, Haro-Monteagudo, van Lanen (Eds.), 2015). Therefore, drought has become an important research topic for scientists in the region of Central Europe and also in Slovakia.

### Meteorological drought studies

Janacova, Labudova, Labuda (2018) assessed the occurrence of the meteorological drought in the regions of the Záhorská, Danubian (Podunajská) and the Eastern Slovakian (Východoslovenská) lowlands and the Southern Slovakian (Juhoslovenská) and the Košická basins in the period 1981–2010. The analysis of the meteorological drought was evaluated on the basis of the monthly data of SPI. Areas which are the most threatened with the meteorological drought in different seasons were identified. There is greater hazard of drought for the Danubian lowland in spring and summer. On the contrary, the eastern part of Slovakia is threatened during the winter season.

Nagy, Zelenaková, Kapostasová, Hlavatá, Simonová (2020) evaluated dry and wet periods at six climatic stations in eastern Slovakia using the following indices: standardized precipitation index (SPI), streamflow drought index (SDI), drought reconnaissance index (RDI) and standardized evapotranspiration index (SPEI) in a 12-month step over the period 1960–2015. The evaluation of the results showed an alternation of wet and dry periods and proved that the dry periods also occurred in the north of eastern Slovakia.

Vido, Nalevanková, Valach, Šustek, Tadesse (2019) focused on the characterisation of the historical drought occurrences in the Horné Požitavie region, in Slovakia, over the period 1966–2013 using the Standardized Precipitation-Evapotranspiration Index (SPEI). The results showed that drought occurred in the region regularly (recurrent climate feature), while the trend analysis indicated the trend towards more arid climatic conditions. Analyses of the SPEI trends in the individual months showed a decreasing trend of drought occurrences during the cold months of the year (i.e., October to March), while an increasing trend was indicated from April to August.

Vido, Nalevanková (2020) analysed drought occurrence and trends using the SPI and the SPEI index in the upper Hron region within the 1984–2014 period. They found that:
1. drought incidence decreased with an increasing altitude;
2. increasing air temperature increased also the difference in the drought trends between lowlands and mountains during the studied period;
3. abrupt changes in the time series of drought indices, which could indicate some signals of the changing atmospheric circulation patterns, were not revealed.

Trnka et al. (2016) used the index SPI, PDSI, *Z*-index and SPEI, in their work. The time series of the drought indices were calculated for 411 climatological stations across Austria (excluding the Alps), the Czech Republic and Slovakia. Up to 45% of the evaluated stations (depending on the index) became significantly drier during the 1961–2014 period. An increase in the evaporative demand of the atmosphere, driven by higher temperatures and global radiation with limited changes in the precipitation totals, was the main driver behind this development.

The study by Vido et al. (2015) focused on how drought occurs at higher altitudes of the Tatra National Park, which is a significant biological reserve of the Central European fauna and flora. Authors used the time series of SPI from 1961 to 2010 and standard GIS methods. The results showed that the frequency of drought occurrence has a cyclic pattern with approximately a 30-year period. The spatial analyses showed that the precipitation shadow of mountains influences the risk of drought occurrence.

Zelenáková et al. (2018) evaluated the trend analysis applied to the precipitation and temperature monthly data for the period from 1962 to 2014 at sixteen climatic stations in eastern Slovakia. All climatic stations in eastern Slovakia show a positive trend in temperature during the year. Trends in precipitation are also mostly positive during winter and spring. An abrupt shift in precipitation at the highest climatic station, Lomnický peak, began around 1985 (+). Abrupt shifts in temperature began around 1970 (+) at the presented climatic stations. The extremity of climate is confirmed by an analysis of the trends in wet and dry spells. Trends showed increasing tendencies in medium- and long-term wet spells.

Zelenáková et al. (2017) analysed the temporal and spatial trends in the annual and seasonal precipitation in Slovakia, in their work, utilising 487 gauging station data collected state-wide in the period from 1981 to 2013. In general, the precipitation data in the studied area have not changed during the last 33 years, and there are no big gaps. However, predominantly increasing trends in the precipitation time series were found at most of the gauging stations in Slovakia. There is also evidence of different rain distribution from the monthly point of view. Decreasing trends were detected in December in the northern part of Slovakia, while the central and southern parts revealed increasing trends. Most of the stations showed increasing summer precipitation trends, especially in July.

Nikolová, Nejedlik, Lapin (2016) analysed drought in lowlands of Slovakia on the basis of SPI and SPEI for the period 1961–2011. The results show that temperature has an important role for occurrence of moderate and severe drought at monthly level and precipitation is the main factor for occurrence of extreme drought. There are an increasing number of cases with severe or extreme drought in summer. Future projection of drought shows a general tendency to the increasing frequency of severe dry events in 2001–2050 and 2051–2100, while there will be a little decreasing of the extremely dry months in comparison to 1961–2010.

Lapin, Gera, Hrvol, Melo, Tomlain (2009) claimed that regimes of evapotranspiration, soil moisture and runoff have changed mainly in southern Slovakia. A physical model for the estimation of the energy balance equation components has been developed. Input data was gained from 31 meteorological stations in Slovakia since 1951. The 20-year period of 1988–2007 was by 0.9 °C warmer than the normal period mean. Annual precipitation totals have not changed significantly, but the substantial changes have been found in the precipitation regime. The scenarios show significant changes in the hydrological cycle not only at river basins balance but also in case of soil water balance, mainly in southern Slovakia.

### Hydrological drought studies

Fendeková, Fendek (2012) analysed groundwater drought indices, which could be derived for different groundwater parameters, among them for base flow, groundwater head stage, spring yield, or groundwater recharge. Base flow drought assessment methods were proposed in the paper. The base flow drought severity index was applied, calculated as the value of the base flow drought deficit volume divided by the drought duration. After that, the standardized base flow drought severity index was proposed as the ratio of the base flow drought index and the average long-term annual base flow. Proposed methods were applied in the Nitra River basin. Base flow drought occurrence was characterised also from the seasonality point of view.

Fendeková et al. (2018) used SPI and SPEI for assessment of the meteorological drought occurrence. The research was established on a discharge time series representing twelve river basins in Slovakia, within the period 1981–2015. Results showed that the drought parameters in the evaluated river basins of Slovakia differed in respective years, most of the basins suffered more by 2003 and 2012 drought than by the 2015 one. Water balance components analysis for the entire period 1931–2016 showed that because of the continuously increasing air temperature and evapotranspiration balance, there is a decrease of runoff in the Slovak territory.

Zelenáková et al. (2014) identified statistically significant trends in the stream flow characteristics of the low water content in eastern Slovakia, in their work, which are used in the evaluation of the hydrological drought. This analysis was carried out due to the statistical data from 63 river stations, lying in the eastern part of Slovakia. Mann-Kendall statistical test identifies the frequency of minimal stream flow trends. Obtained results from the statistically significant trends in the stream flows are in a role of a basement for the regionalisation of the eastern Slovakia territory from the point of the hydrological drought risk.

Hanel et al. (2014) used global climate models to develop climate change scenarios for four small catchments in the Czech and Slovak Republic. This method applies a nonlinear transformation to precipitation in order to match projected changes in the precipitation variability. Similarly, temperature is transformed considering the changes in mean and variability. The results show an increase in the number of minor droughts and an increase in the most severe droughts. There are clear differences in the changes of drought characteristics related to the dominant runoff regime in a catchment.

Blahušiaková et al. (2020) investigated changes in the seasonal runoff and low flows related to the changes in snow and climate variables in the mountainous catchments in Central Europe. The results showed an increase in air temperature, decrease in snowfall fraction and snow depth, and changes in precipitation. Most of the hydrological droughts were connected either to low air temperatures and precipitation during winter or high winter air temperatures, which caused below-average snow storages. Findings show that besides precipitation and air temperature, snow plays an important role in summer streamflow and drought occurrence in the selected mountainous catchments.

### Agricultural (physiological) drought studies

Labudová, Labuda, Takáč (2016) focused on the assessment of drought intensity impact on crop yields on the Danubian and the Eastern Slovakian Lowland. Limited yield data resulted in the limited length of the assessed period (1996–2013). The standardised yields of ten crops (winter wheat, spring wheat, winter barley, spring barley, rye, maize, potatoes, oilseed rape, sunflower and sugar beet) were correlated with monthly, 2-, and 3-monthly SPI and SPEI. The highest correlation was between maize and the 3-monthly SPEI. Crop yields in the Eastern Slovakian Lowland do not seem to be influenced by wet/dry periods, identified using SPI and SPEI, as their correlation with both indices is quite low and insignificant.

Čistý, Jarabicová and Minarič (2016) evaluated a spatial indicator of the threat of droughts, namely the available water capacity of soil. Data from a soil survey and data measured in a laboratory were used for the development of the pedotransfer functions with the help of the Random Forest algorithm. On the basis of the pedotransfer function, the available water capacity was spatially evaluated by geostatistical methods in the investigated area, i.e., in the Záhorská Lowland, in Slovakia.

Vido et al. (2016) analysed the physiological response of tree species in central Slovakia to the driest months of 2012.

Lukasová et al. (2020) focused on the onset of leaf colouring-LCO-((BBCH)92) of the European beech (*Fagus sylvatica*, L.). The limiting climate conditions for LCO were defined by the meteorological drought indices: climatic water balance (CWB), standardized precipitation index (SPI), standardized precipitation-evapotranspiration index (SPEI), dry period index (DPI), and heat waves (HW). During 23-year period (1996–2018) of ground-based phenological observations, the timing of LCO was significantly delayed at the middle to high altitudes. Over the last decade, LCO at the middle altitudes started at comparable to low altitudes. This resulted mainly from the significant negative effect of drought prior to this phenological phase. The ongoing warming trend of summer months suggests further intensification of drought spreading from the continual increase of evapotranspiration over the next decades.

Bernáth et al. (2020) evaluated the drought impact on the quality parameters of grapes in the locality of the Cultivar Testing Station, Dolné Plachtince. Interanual variability of the drought impact on the grape quality was evaluated according to PDSI. The 1990–2014 period was used as a basis for the evaluation. The PDSI values as well as the sugar and acid contents were correlated to find the strength of relation between them. Short drought periods did not influence the grape quality significantly, while long drought periods caused a decrease of the acid content and an increase of the sugar content.

Tuzinsky, Gregor, Tuzinsky, Homolak (2018) analysed the balance of soil water in the spruce stand mountain conditions in the Upper Orava region. The long-term research (1991–2014) shows that the predominant moisture interval in the vegetation period is semi-uvidic soil interval with good or sufficient supply of usable water. Ongoing climatic conditions with a gradual reduction of precipitation and increase of air temperature pose danger, associated with the development of dry periods, to the spruce. Under such conditions, the spruce is threatened with drought, and physiological weakness, reduced evapotranspiration, increased fall of the assimilation organs, reduced increment, degradation of physical and hydrological properties of soil, and reduction of transport of mineral and organic substances are all its responses.

Takac, Moravek, Klikusovska, Skalsky (2014) assessed drought severity in the agricultural regions of Slovakia in the years 2011–2013. Standardized index based on the daily available soil water content was used for drought severity classification. The results of the analysis confirmed the occurrence of the meteorological drought in the years 2011 and 2012 and the occurrence of the agronomic drought in the years 2011–2013. Greater areal extension of the impact of drought on crop production was observed only in the years 2012 and 2013.

Šiška, Takáč (2009) estimated the climatic index of drought and evapotranspiration deficits for the agricultural regions of the Slovak Republic. Climate change conditions were generated by general circulation model CCCM for emission scenario SIZES B2. Five categories of drought conditions were recognized in the reference period 1961–1990, and additional two very dry categories can be recognized in the agricultural regions of Slovakia, according to both estimated climatic indices.

Šustek, Vido, Škvareninová, Škvarenina, Šurda (2017) documented the impact of the 2012 dry season on the decline in the beetle species (*Carabids*) in the High Tatras. The Standardized Precipitation Evapotranspiration Index was shown, using the cross-correlation of SPEI and number of individuals and species of *Carabids* as a suitable means to explain and predict such changes for the period of 1–2 years.

Brezianská, Vitková, Šurda (2018) analysed the occurrence of drought and reduced soil water storage in the Záhoská Lowland, in 1961–2010.

## Conclusions

1. Drought is a consequence of climate anomalies, as well as of (wrong) human water use practices. This paper has reviewed the literature concerning the existing drought indices. Thus, they serve to identify and quantify all types of drought (meteorological, agricultural, hydrological or socio-economic). The paper has presented a vast number of indices demands by collecting information related to a huge variety of disciplines and representing a complex challenge.
2. The second part of paper has been devoted to an overview of the selected scientific studies about the use of various drought indices (and indicators) and drought assessment in the conditions of Slovakia and Central Europe. Most of the studies are focused on meteorological, less on hydrological or agricultural drought and on the impacts of the increased incidence of drought on flora (alternatively fauna).

Major conclusions from the reviewed studies:

- an increase in air temperature, changes in precipitation patterns, a decrease in snowfall fraction and snow depth
- a trend towards more dry (arid) climatic conditions
- catchments are becoming drier and runoff is decreasing – an increase in the evaporative demand of the atmosphere, driven by higher temperatures and global radiation with limited changes in precipitation totals are the main drivers behind this development
- an important role of snow in summer streamflow and drought occurrence in the mountainous catchments
- an increasing number of severe drought events during summer in lowlands
- a cyclic pattern of drought events in the High Tatras
- delayed phenological phases and lower quality of grapes, caused by drought at some localities.

## Acknowledgments

This contribution was supported by the Scientific Grant Agency VEGA Project No. 2/0150/20.

## References

Ajaz, A., Taghvaeian, S., Khand, K., Gowda, P.H., Moorhead, J.E. (2019). Development and evaluation of an agricultural drought index by harnessing soil moisture and weather data. *Water, 11*, 1375.

Akhtari, R., Morid, S., Mahdian, M.H., Smakhtinm, V. (2009). Assessment of areal interpolation methods for spatial analysis of SPI and EDI drought indices. *Int. J. Climatol.*, *29*(1), 135–145. https://doi.org/10.1002/joc.1691

Alcamo, J., Henrichs, T., Rösch, T. (2000). World water in 2025 – global modeling and scenario analysis for the world commission on water for the 21st century. In: *Report A0002, Center for Environmental Systems Research*. Kassel, Germany: University of Kassel, Kurt Wolters Strasse 3.

Alley, W.M. (1985). The Palmer Drought Severity Index as a measure of hydrologic drought. *Water Resour. Bull.*, *21*(1), 105–114.

Andreu, J., Solera, A., Paredes-Arquiola, J., Haro-Monteagudo, D., van Lanen, H. (Eds.). (2015). *Drought: Research and Science-Policy Interfacing*. London: CRC Press. https://doi.org/10.1201/b18077

Bernáth, S., Šiška, B., Paulen, O., Zuzulová, V., Pintér, E., Žilinský, M., Tóth, F. (2020). Grape Quality Parameters in Western Carpathian Region under Changing Climatic Conditions as Influenced by Drought. *Journal of Ecological Engineering*, *21*(4), 39-45. https://doi.org/10.12911/22998993/119796

Blahušiaková, A., Matoušková, M., Jenicek, M., Ledvinka, O., Kliment, Z., Podolinská, J., Snopková, Z. (2020). Snow and climate trends and their impact on seasonal runoff and hydrological drought types in selected mountain catchments in Central Europe. *Hydrological Sciences Journal*, *65*(12), 2083–2096. https://doi.org/10.1080/02626667.2020.1784900

Brezianská, K., Vitková, J., Šurda, P. (2018). Drought analysis and the impact of climate change on soil water supply in the Záhorská lowland. In *Aktuálne problémy zóny aerácie pôdy v podmienkach prebiehajúcej klimatickej zmeny, Veda* (pp. 307–335) (in Slovak).

Byun, H.R. and Wilhite, D.A. (1999). Objective quantification of drought severity and duration. *Int. J. Climatol.*, *12*(9), 2747–2756.

Cammalleri, C., Micale, F., Vogt, J. (2016). A novel soil moisture-based drought severity index (DSI) combining water deficit magnitude and frequency. *Hydrol. Process.*, *30*, 289–301.

Čistý, M., Jarabicová, M., Minarič, P. (2016). Spatial Assessment of Soil Water Storage as an Identifier of Areas Threatened by Drought. *Procedia Engineering*, *161*, 1738–1744. https://doi.org/10.1016/j.proeng.2016.08.768

Cloke, H.L., Hannah, D.M. (2011). Large-scale hydrology: Advances in understanding processes, dynamics and models from beyond river basin to global scale. *Hydrological Processes*, *25*, 991–995. https://doi.org/10.1002/hyp.8059

Cook, B. I., Smerdon, J. E., Seager, R., Coats, S. (2014). Global warming and 21st century drying. *Climate Dynamics*, *43*(9–10), 2607–2627. https://doi.org/10.1007/s00382-014-2075-y

Dai, A. (2011). Drought under global warming: A review. *Wiley Interdisciplinary Reviews: Climate Change*, *2*, 45–65.

Dai, A. (2012). Increasing drought under global warming in observations and models. *Nat. Clim. Change*, *3*, 52–8.

Dai, A. (2013). Increasing drought under global warming in observations and models. *Nature Clim Change*, *3*, 52–58. https://doi.org/10.1038/nclimate1633

Doesken, N.J., McKee, T.B., Kleist, J. (1991). Development of a Surface Water Supply Index for the western United States. *Climatology Rep. 91–93,* Colorado Climate Center, Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO (76 p.).

Dracup, J.A., Lee, K.S., Paulson, E.G.J. (1980). On the definition of drought. *Water Resour. Res.*, *16*(2), 297–302.

Dutra, E., Viterbo, P., Miranda, P.M.A. (2008). ERA-40 reanalysis hydrological applications in the characterization of regional drought. *Geophys. Res. Lett.*, *35*, 2–6.

Falkenmark, M., Lundqvist, J., Widstrand, C. (1989). Macro-scale water scarcity requires micro-scale approaches. *Nat. Res. Forum*, *13*, 258–267.

Fendeková, M., Fendek, M. (2012). Groundwater drought in the Nitra River Basin – identification and classification. *J. Hydrol. Hydromechanics*, *60*, 185–193. https://doi.org/10.2478/v10098-012-0016-1

Fendeková M., Gauster T., Labudová L., Vrabliková D., Danáčová Z., Fendek M., Pekárová P. (2018). Analysing 21st century meteorological and hydrological drought events in Slovakia. *J. Hydrol. Hydromech.*, *66*(4), 393–403.

Garen, D.C. (1993). Revised Surface-Water Supply Index for western United States. *Water Resour. Plan. Manage.*, *119*, 437-454.

Gibbs, W., Maher, J. (1967). *Rainfall Deciles as Drought Indicators*. Melbourne: Bureau of Meteorology (117 p.).

Hanel, M., Vizina, A., Martínková, M., Horáček, S., Porubská, D., Fendek, M., Fendeková, M. (2014). Changes of drought characteristics in small Czech and Slovakian catchments projected by the CMIP5 GCM ensemble. In: *Hydrology in a changing world: environmental and human dimensions*, IAHS (pp. 78–83).

Hayes, M.J. (2006). Drought Indices. *Van Nostrand's Scientific Encyclopedia*. Hoboken: John Wiley & Sons, Inc.

Hayes, M., Svoboda, M., Wall, N., Widhalm, M. (2011). The Lincoln declaration on drought indices: Universal meteorological drought index recommended. *Bulletin of the American Meteorological Society*, *92*, 485–488. https://doi.org/10.1175/2010BAMS3103.1

Heim, R.R. (2000). *Drought indices: A review*. Drought: A Global Assessment, D. A. Wilhite, Ed., Routledge (pp. 159–167).

Heim, R.R. (2002). A Review of Twentieth-Century Drought Indices Used in the United States. *Bull. Amer. Meteor. Soc.*, *83*, 1149–1166. https://doi.org/10.1175/1520-0477-83.8.1149

Hoekstra, A.Y. (2012). Water footprint accounting. In: Godfrey, J.M., Chalmers, K. (Eds.). *Water Accounting. International Approaches to Policy and Decisionmaking*. Edward Elgar Publishing Limited, Cheltenham, UK – Northampton, MA, USA (pp. 58–75).

IPCC (2018). Summary for Policymakers. *Global Warming of 1.5 °C*. Geneva, Switzerland: World Meteorological Organization (32 p.).

Janáčová, T., Labudová, L., Labuda, M. (2018). Meteorological drought in the parts of Slovakia with lowland features in 1981–2010. *Geographia Cassoviensis, 12*(1), 53–64.

Ju, X.S., Yang, X.W., Chen, L.J. (1997). Research on determination of station indexes and division of regional flood/drought grades in China. *Quarterly Journal of Applied Meteorology*, *8*(1), 26–33.

Kalamaras, N., Michalopoulou, H., Byun, H.R. (2010). Detection of drought events in Greece using daily precipitation. *Hydrol. Res.*, *41*(2), 126–133. https://doi.org/10.2166/nh.2010.001

Kam, J., Sheffield, J., Wood, E.F. (2014). A multiscale analysis of drought and pluvial mechanisms for the southeastern United States. *Journal of Geophysical Research: Atmospheres*, *119*, 7348–7367. https://doi.org/10.1002/2014JD021453

Karl, T.R. (1986). The sensitivity of the Palmer Drought Severity Index and Palmer's Z-Index to their calibration coefcients including potential evapotranspiration. *J. Clim. Appl. Meteorol.*, *25*, 77–86.

Karl, T., Quinlan, F., Ezell, D.S. (1987). Drought termination and amelioration: its climatological probability. *J. Climate Appl. Meteor.*, *26*, 1198–1209.

Kim, D.W. and Byun, H.R. (2009). Future pattern of Asian drought under global warming scenario. *Theor. Appl. Climatol.*, *98*(1–2), 137–150. https://doi.org/10.1007/s00704-008-0100-y

Kim, D.W., Byun, H.R., Choi, K.S. (2009). Evaluation, modification, and application of the effective drought index to 200 – year drought climatology of Seoul Korea. *J. Hydrol.*, *378*(1–2), 1–12. https://doi.org/10.1016/j.jhydrol.2009.08.021

Kumar, V., Panu, U. (1997). Predictive assessment of severity of agricultural droughts based on agro-climatic factors. *J. Am. Water Resour. Assoc.*, *33*(6), 1255–1264.

Labudová, L., Labuda, M., Takáč, J. (2016). Comparison of SPI and SPEI applicability for drought impact assessment on crop production in the Danubian lowland and the east Slovakian lowland. *Theor. Appl. Climatol.*, *128*, 491–506.

Lapin, M., Gera, M., Hrvol, J., Melo, M., Tomlain, J. (2009). Possible impacts of climate change on hydrologic cycle in Slovakia and results of observations in 1951–2007. *Biologia*, *64*, 454–459.

Livneh, B., Hoerling, M. P. (2016). The physics of drought in the U.S. Central Great Plains. *Journal of Climate*, *29*(18), 6783–6804. https://doi.org/10.1175/JCLI-D-15-0697.1

Liu, X., Zhu, X., Pan, Y. Bai, J. Li, S. (2018)Performance of different drought indices for agriculture drought in the North China Plain. *J. Arid Land, 10*, 507–516. https://doi.org/10.1007/s40333-018-0005-2

Lohani, V.K., Loganathan, G.V. (1997). An early warning system for drought management using the Palmer Drought Index. *J. Am. Water Resour. Assoc.*, *33*(6), 1375–1386.

Lukasová, V., Vido, J., Škvareninová, J., Bičárová, S., Hlavatá, H., Borsányi, P., Škvarenina, J. (2020). Autumn phenological response of european beech to summer drought and heat. *Water*, *12*(9), 2610.

Luo, L., Apps, D., Arcand, S., Xu, H., Pan, M., Hoerling, M. (2017). Contribution of temperature and precipitation anomalies to the California drought during 2012–2015. *Geophysical Research Letters*, *44*, 3184–3192. https://doi.org/10.1002/2016GL072027

Mahlstein, I., Portmann, R.W., Daniel, J.S., Solomon, S.,,Knutti, R. (2012). Perceptible changes in regional precipitation in a future climate. *Geophysical Research Letters*, *39*, L05701. doi:10.1029/2011GL050738

Mannocchi, F., Todisco, F., Vergni, L. (2004). Agricultural drought: indices, definition and analysis. *Basis Civ. Water Sci.*, *286*, 246–254. http://hydrologie.org/redbooks/a286/iahs_286_0246.pdf

Martínez-Fernández, J., González-Zamora, A., Sánchez, N., Gumuzzio, A. (2015). A soil water-based index as a suitable agricultural drought indicator. *J. Hydrol.*, *522*, 265–273.

McKee, T.B., Doesken, N.J., Kleist, J. (1995). Drought monitoring with Multiple Time scales. *Proceeding of the 9th Conference on Applied Climatology*. Dallas, TX: American Meteorological Society (pp. 233–236).

Mishra, A.K., Singh, V.P. (2010). A review of drought concepts. *J. Hydrol.*, *391*(1–2), 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Morid, S., Smakhtin, V., Moghaddasi, M. (2006). Comparison of seven meteorological indices for drought monitoring. Iran. *Int. J. Climatol.*, *26*(7), 971–985. https://doi.org/10.1002/joc.1264

Mouillot, F., Rambal, S., Joffre, R. (2002). Simulating climate change impacts on fire frequencyand vegetation dynamics in a Mediterranean-type ecosystem. *Global Change Biology*, *8*, 423–437.

Nagy, P., Zelenaková, M., Kapostasová, D., Hlavatá, H., Simonová, D. (2020). Identification of dry and wet years in eastern Slovakia using indices. *Advances in Environmental Engineering: proceedings*, IOP Publishing (pp. 1–6).

Nikolová, N., Nejedlík., P., Lapin, M. (2016). Temporal variability and spatial distribution of drought events in the lowlands of Slovakia. *Geofizika*, *33*(2), 119–135.

Nkemdirim, L., Weber, L. (1999). Comparison between the droughts of the 1930s and the 1980s in the Southern Prairies of Canada. *J. Climate*, *12*, 2434–2450.

Palmer, W.C. (1965). *Meteorological Drought*. US Weather Bur. Res. Pap. no. 45, 58. https://www.ncdc.noaa.gov/temp-and-precip/drought/docs/palmer.pdf

Pedro-Monzonís, M., Solera, A., Ferrer, J., Estrela, T., Paredes-Arquiola, J. (2015). A review of water scarcity and drought indexes in water resources planning and management. *Journal of Hydrology*, *527*, 482–493. https://doi.org/10.1016/j.jhydrol.2015.05.003

Pozzi, W., Sheffield, J., Stefanski, R., Cripe, D., Pulwarty, R., Vogt, J.V. et al. (2013). Towards global drought early warning capability: Expanding international cooperation for the development of a framework for global drought monitoring and forecasting. *Bulletin of the American Meteorological Society*, *94*(6), 776–785. https://doi.org/10.1175/BAMS-D-11-00176.1

Raskin, P., Gleick, P., Kirshen, P., Pontius, G., Strzepek, K. (1997). *Water Futures: Assessment of Long-Range Patterns and Prospects*. Stockholm, Sweden: Stockholm Environment Institute.

Roudier, P., Mahe, G. (2010). Study of water stress and droughts with indicators using daily data on the Bani River (Niger basin, Mali). *Int. J. Climatol.*, *30*(11), 1689–1705. https://doi.org/10.1002/joc.2013

Sakamoto, C.M. (1978). The Z-index as a variable for crop yield estimation. *Agric. Meteor.*, *19*, 305–313.

Sheffield, J., Wood, E.F., Roderick, M.L. (2012). Little change in global drought over the past 60 years. *Nature, 491*, 435–8.

SHMÚ (2015). *Manifestations of climate change at the global level*. http://www.shmu.sk/sk/?page=1379 (in Slovak).

Shukla, S., Wood, A.W. (2008). Use of a standardized runoff index for characterizing hydrologic drought. *Geophysical Research Letters*, *35*, L02405. https://doi.org/10.1029/2007GL032487

Šiška, B., Takáč, J. (2009). Drought analyses of agricultural regions as influenced by climatic conditions in the Slovak Republic. *Idojárás*, *13*, 135–143.

Sivapalan, M., Savenije, H.H.G., Blöschl, G. (2012). Sociohydrology: A new science of people and water. *Hydrol. Process.*, *26*, 1270–1276. doi:10.1002/hyp.8426

Soule, P.T. (1992). Spatial patterns of drought frequency and duration in the contiguous USA based on multiple drought event definitions. *Int. J. Climatol.*, *12*, 11–24.

Sullivan, C.A. (2002). Calculating a water poverty index. *World Dev.*, *30*, 1195–1210.

Šurda, P., Rončák, P., Vítková, J., Tárnik, A. (2019). Regional drought assessment based on the meteorological indices for locality Nitra. *Acta Hydrologica Slovaca*, *20*(1), 63–73 (in Slovak).

Šurda, P., Vitková, J., Rončák, P. (2020). Regional Drought Assessment Based on the Meteorological Indices. *Bulletin of the Georgian National Academy of Sciences*, *14*(2), 69–84.

Šustek, Z., Vido, J., Škvareninová, J., Škvarenina J., Šurda, P. (2017). Drought impact on ground beetle assemblages (Coleoptera, Carabidae) in Norway spruce forests with different management after windstorm damage – a case study from Tatra Mts. (Slovakia). *J. Hydrol. Hydromech.*, *65*(4), 333–342.

Svoboda, M., Fuchs, B. (2016). *Integrated Drought Management Programme (IDMP)*. Handbook of Drought Indicators and Indices. Drought Mitigation Center Faculty Publications (117 p.). http://digitalcommons.unl.edu/droughtfacpub/117

Takáč, J., Morávek, A., Klikušovská, Z., Skalský, R. (2014). Drought severity in agricultural land of Slovakia in the years 2011–2013. *Mendel and Bioclimatology*, 488–506.

Thornthwaite, C.W. (1948). An approach toward a rational classification of climate. *Geogr. Rev., 38*, 55–94.

Trnka, M., Balek, J., Štěpánek, P., Zahradníček, P., Možný, M., Eitzinger, J. et al. (2016). Drought trends over part of Central Europe between 1961 and 2014. *Clim. Res.*, *70*, 143–160.

Tužinský, L., Gregor, J., Tužinský, M., Homolák, M. (2018). Pedohydrological cycles development in the spruce ecosystem under the current climatic conditions of Slovakia. *Reports of forestry research*, *63*(4), 299-310.

Van Loon, A.F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J. et al. (2016a). Drought in the Anthropocene. *Nature Geoscience*, *9*(2), 89–91. https://doi.org/10.1038/ngeo2646

Van Loon, A.F., Stahl, K., di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N. et al. (2016b). Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches. *Hydrology and Earth System Sciences*, *20*(9), 3631–3650. https://doi.org/10.5194/hess-20-3631-2016

Vicente-Serrano, S.M.,Beguería, S., Lorenzo-Lacruz, J., Camarero, J. J., López-Moreno, J. I., Azorin-Molina, C. et al. (2012). Performance of Drought Indices for Ecological, Agricultural, and Hydrological Applications. *Earth Interact.*, *16*, 1–27. https://doi.org/10.1175/2012EI000434.1

Vido, J., Nalevanková, P., Valach, J., Šustek, Z., Tadesse, T. (2019). Drought Analyses of the Horné Požitavie Region (Slovakia) in the Period 1966–2013. *Adv. Meteorol.*, 1–10.

Vido, J., Nalevanková, P. (2020). Drought in the Upper Hron Region (Slovakia) between the Years 1984–2014. *Water*, *12*(10), 2887.

Vido, J., Tadesse, T., Šustek, Z., Kandrík, R., Hanzelová, M., Škvarenina, J., Škvareninová, J., Hayes, M. (2015). Drought Occurrence in Central European Mountainous Region (Tatra National Park, Slovakia) within the Period 1961–2010. *Adv. Meteorol.*, 1–8.

Vido, J., Střelcová, K., Nalevanková, P., Leštianska, A., Kandrík, R., Pástorová, A., Škvarenina, J., Tadesse, T. (2016). Identifying the relationships of climate and physiological responses of a beech forest using the Standardised Precipitation Index: a case study for Slovakia. *J. Hydrol. Hydromech.*, *64*(3), 246–251.

Wang, A., Lettenmaier, D.P., Sheeld, J. (2011). Soil moisture drought in China, 1950–2006. *J. Clim., 24*, 3257–3271.

Wells, N., Goddard, S., Hayes, M.J. (2004). A self-calibrating Palmer Drought Severity Index. *J. Clim., 17*, 2335–2351.

Wheaton, E.E. (1994). *Impacts of a variable and changing climate on the Canadian prairies' provinces: A preliminary intergration and annotated bibliography*. SRC Publication No. E-2900-7-E-93, Saskatoon, SK: Saskatchewan Research Council.

Wilhite, D. A., Glantz, M. H. (1985). Understanding: The drought phenomenon: The role of definitions. *Water International*, *10*(3), 111–120. https://doi.org/10.1080/02508068508686328

Wilhite, D.A., Rosenberg, N.J., Glantz, M.H. (1986). Improving federal reponse to drought. *J. Climate Appl. Meteor*., *25*, 332– 342.

Willeke, G., Hosking, J. R. M., Wallis, J. R. (1994). The national drought atlas. *Institute for Water Resources Report 94-NDS-4*. Norfolk, VA: U.S Army Corp of Engineers.

Zargar, A., Sadiq, R., Naser, B., Khan, F.I. (2011). A review of drought indices. *Environ. Rev.*, i, 333–49.

Zeleňáková, M., Purcz, P., Blištan, P., Vranayová, Z., Hlavatá, H., Diaconu, D.C., Portela, M.M. (2018). Trends in Precipitation and Temperatures in Eastern Slovakia (1962–2014). *Water*, *10*, 727.

Zeleňáková, M., Vido, J., Portela, M.C.A.S., Purcz, P., Blištan, P., Hlavatá, H., Hluštík, P. (2017). Precipitation Trends over Slovakia in the Period 1981–2013. *Water*, *9*, 922.

Zeleňáková, M., Purcz, P., Solaková, T., Simonová, D., Harbulaková, V.O. (2014). Trends in minimal stream flows at eastern Slovakia. *Environmental Engineering 2014, 9th International Conference,* selected papers, Vilnius, Lithuania: Gediminas Technical University (pp. 1–7).