Drought severity in intensive agricultural areas by means of the EDI index

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Abstract: The aim of this work was the evaluation of drought severity development in the Czech Republic for the period 1971–2015 by the means of the Effective Drought Index (EDI). Annual values of the EDI index were determined using the method of effective precipitation for 14 localities spread throughout the Czech Republic (Central Europe). The seven categories were created according to obtained index values for the drought conditions determination for years during the period 1971–2015 through the percentile method. The annual index values were compared with acquired 2nd, 15th, 45th, 55th, 85th and 98th percentiles. Both the years with precipitation unfavourable conditions: 1972, 1973, 1984, 1990, 1991, 1992, 1993 and 2015 and the years with precipitation favourable conditions: 1977, 1987, 1995, 2001, 2002 and 2010 were determined. Precipitation conditions in the growing season from 61st to 180th day of the year were also analysed. This evaluation was conducted during the period 1971–2015 through the ten-day index values which were compared with acquired 2nd, 15th, 45th, 55th, 85th and 98th percentiles. Dry growing seasons occurred in 1973, 1974, 1976 and 1993. Wet growing seasons occurred in 1987, 2006 and 2010. Trend analysis of annual index values was performed through the Mann-Kendall test. Highly statistically significant increasing linear trends ($P < 0.01$) were found for four localities (Uherský Ostroh, Vysoká, Znojmo-Oblekovice and Žatec); statistically significant increasing trends ($P < 0.05$) were found for three localities (Brno-Chrlice, Lednice and Lípa). Based on the extrapolation of the trend, a slightly higher effective precipitation can be expected during the year in a substantial part of the country. However, these findings do not necessarily mean an optimal supply of agricultural land with water. Precipitation exhibits considerable unevenness of distribution through time. Given the increasing evapotranspiration demands of the environment their availability is limited.

Key words: drought, effective precipitation, prediction, Central Europe

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1. Introduction

Drought is a sustained period of significant hydrometeorological imbalance caused by the cumulative incidence of dry periods with low or non-measurable rainfall. Generally, the drought is classified according to meteorological, hydrological, agricultural and socio-economic perspectives (*Botterill and Wilhite, 2006*). *Palmer (1965)* described drought as a significant deviation from the normal hydrological conditions of a given area. *Blinka (2005)* defines the drought more specifically as a phenomenon characterized by the slow emergence and development that takes months. Sometimes it may last throughout whole seasons, years, or even decades. Determining the start and end of a dry period is very difficult and it requires the application of a wide range of meteorological, but also hydrological variables. The effects of drought are cumulative and the magnitude of a drought intensifies with each passing day. The impacts of drought can persist for several years after the normal precipitation amounts are reached again.

Almost the entire territory of the Czech Republic is dependent on the saturation of the soil profile by precipitation, characterized by high temporal and local variability with a significant dependence on the altitude and exposure. Meteorological conditions in individual years are subject to considerable fluctuations, both in consecutive years and in comparison with multi-annual average values.

According to the results of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) the total precipitation should increase at higher latitudes, while the level of precipitation in subtropical areas should decline, especially over land. Further, more frequent occurrence of floods is assumed, but also longer periods with more intensive manifestations of drought (*IPCC, 2013*). The intensity and duration of drought periods tends to be different from short-term drought to several months or several years lasting periods of low total rainfall. Consequences and symptoms of drought can be very different, especially depending on the time period in which the drought occurs and also on the investigated agricultural crop and its current development stage etc. The crops need different amounts of water during their vegetation. Majority of the plant species are very sensitive to the lack of water in the phase of flowering and at the time when growth of vegetative organs is the most intense (*Farooq et al., 2014*).

However, we can assume that the methods for the determination of the intensity of droughts will be – given to the causes of the origins and impacts of droughts – very different and their outcomes may differ from each other (*Wilhite and Glantz, 1985*).

In the world, a number of methods for quantifying of the hydrometeorological extremes have been developed. The more simple ones take into the account only the amount of precipitation, the more complicated ones consider also the varying influence of temperature on evaporation. Other balance methods that directly calculate the evapotranspiration are applied as well, either for the standard grassland or directly for a given crop. The impact of dryness depends not only on its actual length, but also on the meteorological drought intensity and the period of occurrence. The most widely used method of drought evaluation is based on the drought index, but the subjectivity of drought definition hinders the creation of a unique and universal index.

Blinka (2005) defined the driest months, growing season, years and dry periods in the Czech Republic during the years 1876–2003 by the means of the Effective Drought Index (EDI), which uses precipitation in daily steps. Further studies focused on the detection of drought in the Czech Republic largely analysed the Standardized Precipitation Index (SPI), recommended by the World Meteorological Organization (WMO) as the basic standard for the determination of meteorological drought, and the Standardized Precipitation Evapotranspiration Index (SPEI) (*Potop et al., 2014*). The drought index determined from rainfall data is based on assumptions that the drought follows the temporal variability of precipitation. However, the increase in temperature significantly affects the intensity of dryness. Thus, it is preferable to use drought indices that also include temperature data. The SPI (*McKee et al., 1993*) is based solely on the total rainfall and SPEI (*Vicente-Serrano et al., 2010*) includes not only rainfall, but also the potential evapotranspiration in the calculation. The Palmer Drought Severity Index (PDSI) allows the measurement of humidity and drought based on the concept of intake and output equation of water balance, and therefore includes previous rainfall, water supply, drainage and evaporation requirements at the soil surface level (*Palmer, 1965*).

Our research uses the sophisticated method of effective rainfall according to *Byun and Wilhite (1999)*, on which is based a whole range of drought indicators including the standardized drought index, EDI. The EDI value is expressed as a dimensionless number. It is a standardized value that expresses the currently available water resources and allows to compare different sites regardless of their climatic characteristics. The EDI index enables to determine the start and duration of dry periods because it uses precipitation data in daily step over the last 365 days. However, the EDI index is calculated for the entire precipitation period that monitors the continuity of the dry season during the entire computational process. This is different from the existing drought indices which only provide the calculation for a limited period (e.g. 12 months). Therefore, this index allows to diagnose prolonged droughts even if they last several years. Another advantage of this index is low demand on the input data. It requires only a long time series of total precipitation data that are more available than other meteorological data (*Byun and Wilhite, 1999*). Daily index works well for the continuous monitoring of drought or even for floods (*Lu, 2009; Lu et al., 2013*). However, it is necessary to interpret these data with caution because the impacts are usually present long after the prolonged water deficit.

2. Material and methods

2.1. Climate data and the study area

The data from the produced technical series of climatic elements created on the basis of the data measured by the network of stations of the Czech Hydrometeorological Institute (CHMI) were used for the analysis of the moisture conditions at localities of interest. The result has the form of a completely homogeneous and complemented station series. On the basis of these data, the series of climatic factors were calculated in daily step for the grid points spaced at 10 km (*Štěpánek et al., 2011*). Fourteen representative grid points were selected from the database of technical series for the evaluation of moisture conditions in the Czech Republic for the period 1971–2015. Data series were created in the grid points of the outputs of the regional climate model ALADIN-Climate/CZ. The characteristics of individual CHMI grid points are shown in Table 1. The selection of grid points was carried out on the basis of the localization of test stations CISTA (Central Institute for Supervising and Testing in Agriculture) which has significant data on yields of major field crops grown in the country. This data can then be used for further scientific exploration of the relationship precipitation index EDI and yields of major crops. The majority of grid points (9 points) is located in Moravia and the rest in the territory of Bohemia (5 points). Grid points are located at altitudes from 167 to 561 meters above sea level, in different orographic conditions. This localization of grid points does not represent completely the precipitation conditions of the Czech Republic, but it is sufficient to evaluate the precipitation conditions in intensive agricultural areas in this country (Fig. 1).

Notes to figures and tables: CHR – Chrlice, CAS – Čáslav, HRA – Hradec nad Svitavou, CHT – Chrastava, JAR – Jaroměřice nad Rokytnou, LED – Lednice, LIP – Lípa, PJA – Pusté Jakartice, STV – Staňkov, UHO – Uherský Ostroh, VER – Věrovany, VYS – Vysoká, OBL – Znojmo-Oblekovice, ZAT – Žatec.

Table 1. Characteristics of all grid points from the network of the CHMI.

Locality	**District**	**Altitude [m]**	**Long-term average temperature [°C]**	**Long-term average precipitation [mm]**
Brno-Chrlice	Brno-město	211	9.0	451
Čáslav-Filipov	Kutná Hora	247	8.9	555
Hradec nad Svitavou	Svitavy	489	7.4	616
Chrastava	Liberec	434	8.0	738
Jaroměřice nad Rokyt.	Třebíč	462	8.0	471
Lednice	Břeclav	167	9.6	461
Lípa	Havlíčkův Brod	515	7.5	594
Pusté Jakartice	Opava	322	8.3	584
Staňkov	Domažlice	417	8.1	537
Uherský Ostroh	Uherské Hradiště	208	9.1	521
Věrovany	Olomouc	219	8.7	502
Vysoká	Příbram	561	7.1	611
Znojmo-Oblekovice	Znojmo	233	9.3	435
Žatec	Louny	250	9.0	439

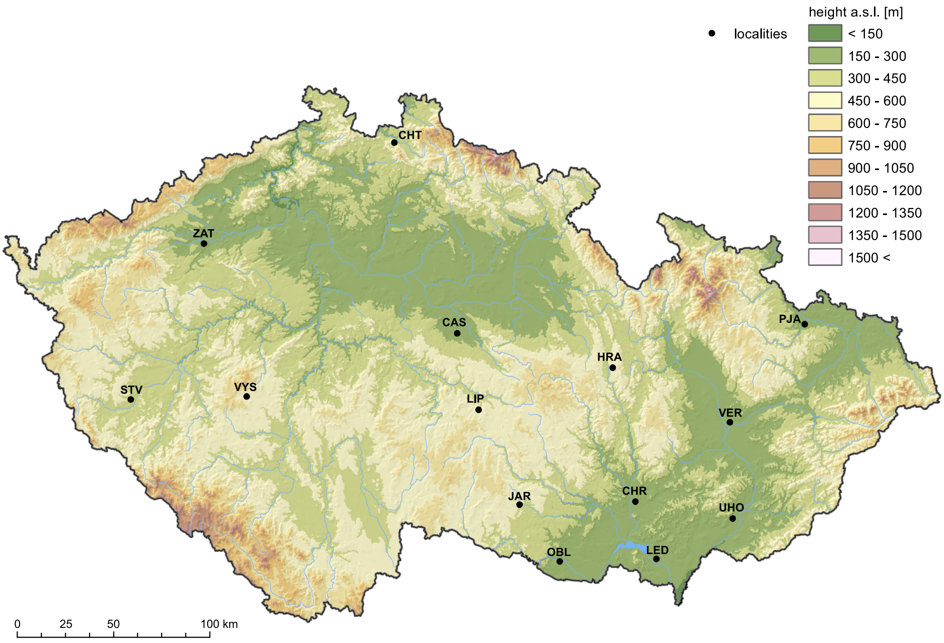

Fig. 1. Localization of the grid points used in evaluation.

2.2. The Effective Drought Index

The quantification of the EDI index is based on the method of effective precipitation, which includes the following several steps (*Byun and Wilhite, 1999*):

(i) the calculation of the daily effective precipitation (EP), which represents a daily loss of water resources (1);

(ii) the calculation of the 30-year average values of the EP (Mean of EP – MEP) for each calendar day;

(iii) the calculation of the deviation of EP (DEP), which represents the difference between EP and MEP (2);

(iv) the calculation of the EDI index: dividing the daily values of DEP by the standard deviation (SD) of the DEP indicator for the 30-year period (3).

$$EP_i = \sum_{n=1}^{i} \left(\frac{\sum_{m=1}^{n} P_m}{n} \right) , \tag{1}$$

where $i = 365$ represents the time for which the summation of daily precipitation was carried out, because the year has a characteristic variation in precipitation. P_m represents the precipitation before m days. This equation is based on the assumption that the runoff occurs during the first days after the rain. This is also proven by the results of different rainfall-runoff models (*Lee, 1998; Shim et al., 1998*). The value EP_{365} is used for the evaluation of drought in the terms of accumulated water supply.

$$DEP = EP - MEP \, . \tag{2}$$

The DEP expresses lack or excess of water resources on a specific date or place.

$$EDI = \frac{DEP}{SD(DEP)} \, . \tag{3}$$

2.3. Evaluation of drought severity by EDI index

Annual EDI index values were calculated based on the daily EDI index values for all CHMI grid points for the period 1971–2015. The method assumes that the precipitation data on which the EDI index is based have a gamma distribution – the precipitation indices can be well described by this asymmetric division. Percentile method of gamma distribution used *Středová et al. (2013a)* to evaluate the extremity of total precipitation for the period 1961–2010 in two climatologically dry areas (Břeclav and Kladno county in the Czech Republic). *Mužíková et al. (2013a)* also applied percentile method to define the categories of the number of days with dry soil condition in the early spring period (March and April) for the period 1961–2010. Individual annual EDI index values are compared with obtained 2nd, 15th, 45th, 55th, 85th and 98th percentiles from which the categories of precipitation ratios for individual years are specified. Annual EDI index values lower than the second percentile express very dry conditions (VDC) for precipitation, the values lower than the 15th percentile mean moderately drought conditions (MDC) and the values lower than the 45th percentile indicate slightly dry conditions (SDC). Similarly the categories are set above the 55th, 85th and 98th percentiles as slightly wet conditions (SWC), moderately wet conditions (MWC) and very wet conditions (VWC) for precipitation.

In all the years in the monitored period 1971–2015 the vegetation periods were evaluated from the 61st to the 180th day of the year (12 decades), during which the main phenological phases of agricultural crops in Central Europe occur. The evaluation of the precipitation conditions during the growing season was based on the comparison of decade (ten-day) EDI index values with calculated 2nd, 15th, 45th, 55th, 85th and 98th percentiles. The decade EDI index values were calculated from the daily index values across the localities. The decade EDI index values lower than the 2nd percentile define very dry conditions (VDC) for precipitation, the values lower than the 15th percentile indicate moderately drought conditions (MDC) and the values lower than the 45th percentile mean slightly dry conditions (SDC). Analogously, the categories above the 55th, 85th and 98th percentiles define the slightly wet conditions (SWC), moderately wet conditions (MWC) and very wet conditions (VWC) for precipitation.

Trend analysis of the time series was performed by the means of a non-parametric method: the Mann-Kendall test of the trend statistical significance (MK test) in the software XLSTAT (*Mann, 1945; Kendall, 1976*). The trend was evaluated at all selected localities.

3. Results and discussion

Based on the outputs of the method of effective precipitation, significant fluctuation of the EDI index was observed in the long term. Fig. 2 describes annual EDI index values without outlying values. The extreme annual EDI index value in the period 1971–2015 at selected localities varied in the range from −0.519 to 0.452. The highest annual EDI index (0.452) was recorded at Pusté Jakartice, a locality with average altitude, in 1977; the lowest annual value (−0.519) was found in 1973 near Hradec nad Svitavou, the site located at the higher altitude. The average values of annual index (both median and mean values) at nearly all localities except Hradec nad Svitavou varied in the ranges below zero. The lowest median value (−0.085) was achieved in Pusté Jakartice, the locality that was also characterized by

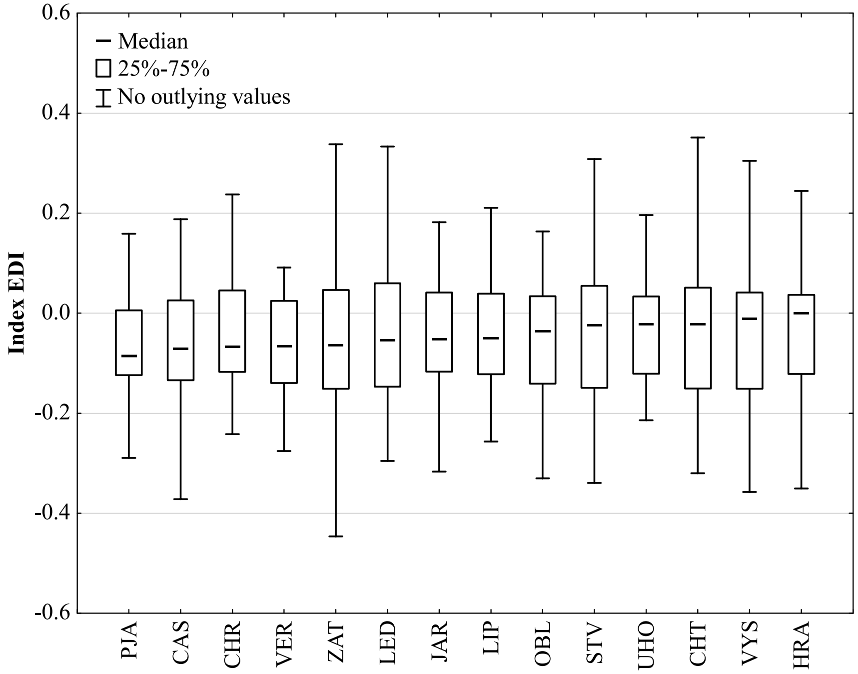

Fig. 2. Range of annual values of the EDI index at all selected localities during 1971–2015.

narrower spread of no outlying values. Conversely, the highest median value (0.0004) was observed at the locality Hradec nad Svitavou.

The localities with less rich and more rich precipitation conditions were determined based on the average long-term value of the EDI index for the period 1971–2015. Pusté Jakartice, Věrovany, Žatec and Čáslav-Filipov belong to the drier localities, where the EDI index was found to be below −0.05. These localities are typically located at lower altitudes below 322 m above sea level. Pusté Jakartice is one of the driest localities where the highest number of years with an EDI index value < 0 has been recorded (33 years). The moister localities were found at higher altitudes above 400 m above the sea level; their average long-term value of the EDI index reached more than −0.04, including the localities Hradec nad Svitavou, Chrastava, Lípa and Jaroměřice nad Rokytnou. The wettest locality is Hradec nad Svitavou where the highest number of years with an EDI index value > 0 was determined (23 years).

Figure 3 shows a detailed overview of annual values of the EDI index over the period 1971–2015 for all evaluated localities. These annual values were categorized according to the precipitation conditions percentile method. As for the precipitation conditions, the least favourable year was 1973, when the annual value of the EDI index fell in all localities below −0.1, and also the lowest recorded value of the EDI (−0.519) was achieved. Other years with less favourable precipitation conditions were the years 1972, 1984, 1990, 1991, 1992, 1993 and 2015, where the value of EDI index in the majority of localities belongs to the categories: SDC, MDC and VDC. Dryness of these years in the Czech Republic is proven also in the works of other authors. *Blinka (2005)* defined dry periods: 1953–1954, 1973–1974, 1982–1984 and extremely dry years: 1943 and 1976 by the means of the EDI index. *Potop et al. (2014)* further determined the most intense episodes of drought in the Czech Republic using the SPEI index: 1970–1974, 1983–1984, 2003–2004 and 2011–2012.

On the other hand, the year 2010 was one of the wettest; with the highest average value of the EDI index found from all localities and all observed years (0.248). In this year a positive value of EDI index was detected at all evaluated localities, which belongs to the categories: SWC, MWC a VWC. *Mužíková et al. (2013b)* states that the year 2010 was one of the precipitation-richest years based on achieved high levels of water reserves available in the soil. According to the obtained values of SPEI (*Potop et al., 2014),* the wettest years in the Czech Republic were determined: 2001–2002 and 2009–2010. The years 1977, 1987, 1995, 2001 and 2002 were favourable for precipitation conditions, with average values of the EDI index from all localities found to be over 0.1.

Figure 4 shows a detailed evaluation of effective precipitation conditions during the growing season from 61st to 180th day of the year in each year during the period 1971–2015. These ten-day values of the EDI index were classified to the categories of precipitation ratios according to the percentile method. These values were calculated as the average of all localities situated at different altitudes. They represent precipitation conditions during the growing season of crops grown in the Czech Republic in which take place important growth and development phases. Nevertheless, in the monitored period we can identify considerable variability of precipitation conditions in the individual decades of the growing season. Dry growing seasons were recorded in 1973, 1974, 1976 and 1993, where the average value of the EDI index for the whole growing season was lower than −0.2. Wet growing season was found in 1987, 2006 and 2010, in which the average value was higher than 0.1. *Mužíková et al. (2013a)* analysed the occurrence of soil drought during the spring period in the years 1961–2010 in the Czech Republic. Spring with dry conditions occurred mainly in the years 1961, 1968, 1974, 1981, 1990, 2002, 2003, 2007 and 2009. Spring with wet conditions in the years 1965, 1970, 1980, 2001 and 2006. These results correspond to only some of our defined dry and wet growing seasons (1974 and 2006). We can assume that this difference was caused by the use of shorter time series data on the state of the soil surface only from the months of March and April.

The trend analysis of the annual EDI index values was performed by the means of Mann-Kendall trend test for the period 1971–2015 at all evaluated localities (Table 2). For the localities Uherský Ostroh, Vysoká, Znojmo-Oblekovice and Žatec, statistically highly significant increasing linear trends were found at the confidence level $P < 0.01$. Statistically significant increasing linear trends at the confidence level $P < 0.05$ were found at the localities Brno-Chrlice, Lednice and Lípa. The increasing trend of precipitation totals is also proven by the study of *Střeštík et al. (2014)* which found out that the total rainfall in the Czech Republic in the period from the mid-20th century has rather a slightly rising trend. *Kyselý et al. (2003)*, based on the analysis of long-term series measured in the Prague-Klementinum from the 19th century to the 1980s, state an increasing trend in the occurrence of more than one day lasting precipitation extremes in the summer half of the year. In the winter months they saw the opposite trend. *Doleželová (2014)*

Legend to the Figures 3 and 4:

Colour	**Range of percentiles**	**Abbreviation**	**Categories**
(red)	≤ 2	VDC	very dry conditions
(orange)	≤ 15	MDC	moderately dry conditions
(yellow)	≤ 45	SDC	slightly dry conditions
(white)	45 to 55	NC	normal conditions
(light cyan)	≥ 55	SWC	slightly wet conditions
(light blue)	≥ 85	MWC	moderately wet conditions
(blue)	≥ 98	VWC	very wet conditions

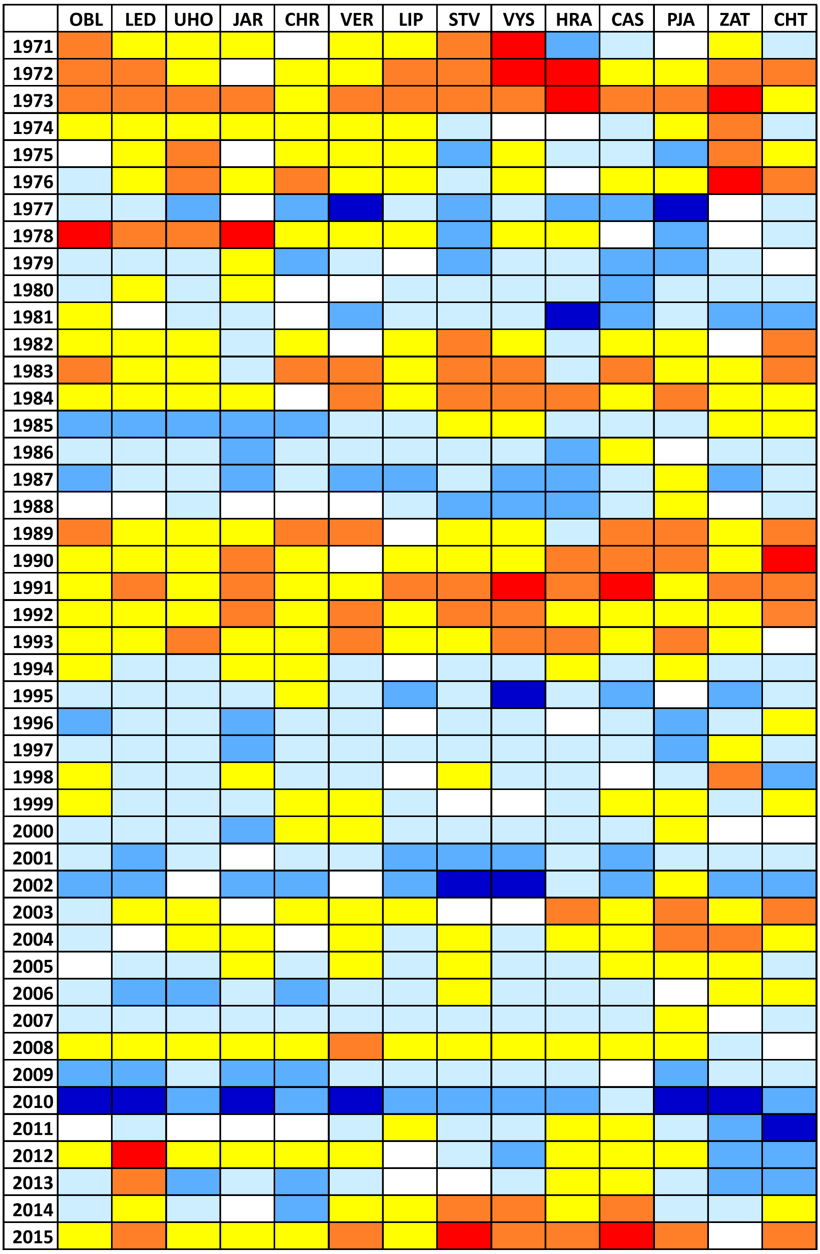

Fig. 3. Annual values of the EDI index at all localities during 1971–2015.

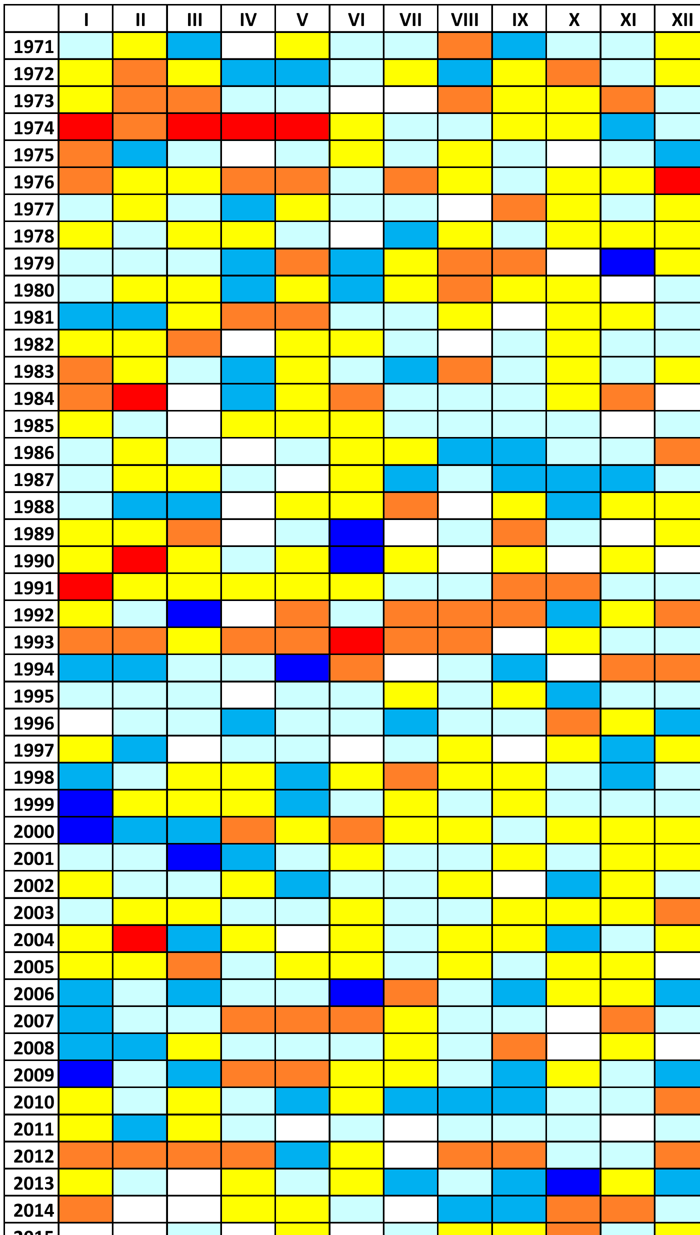

Fig. 4. Ten-day values of the EDI index within the growing season during 1971–2015.

Table 2. Trend analysis of EDI index values at all localities (** P < 0.01, * P < 0.05).

Locality	Altitude (m)	P-value	Trend – MK test
Brno-Chrlice	211	0.035*	positive
Čáslav-Filipov	247	0.181	–
Hradec nad Svitavou	489	0.386	–
Chrastava	434	0.073	–
Jaroměřice	462	0.146	–
Lednice	167	0.049*	positive
Lípa	515	0.027*	positive
Pusté Jakartice	322	0.648	–
Staňkov	417	0.977	–
Uherský Ostroh	208	0.005**	positive
Věrovany	219	0.553	–
Vysoká	561	0.010**	positive
Znojmo-Oblekovice	233	0.004**	positive
Žatec	250	0.003**	positive

performed the analysis of various characteristics describing the extremity of the precipitation regime and found that there has been no decrease in the total amount of rainfall, but rather a shift toward greater unevenness of its distribution over time. *Spinoni et al. (2014)* investigated the causes and mechanisms of drought emergence in different parts of Europe and came to the realization that Central Europe has seen an increase in the unevenness of the precipitation distribution in combination with air temperature increase. *Briffa et al. (2009)* reported in their analyses that the observed increase in temperature has the main influence on the trend of drier summer conditions. Although there was an increase in extreme precipitation totals, local or regional drought occurred more frequently in recent decades. It is caused by increased demands on evapotranspiration due to increasing air temperature (*Takáč, 2013*). *Podhrázská et al. (2013)* and *Středová et al. (2013b)* recorded in their results an increase in potential evapotranspiration and thus higher predisposition of intensive agricultural areas in Southern and Central Moravia and Central Bohemia to drought in the period 1961–2010 compared to the average values in the period 1901–1950.

4. Conclusion

The dry years (with EDI index value < 0) – in order from the driest year – were the years 1973, 1991, 1972, 2015, 1990, 1984, 1993 and 1992. The years with the most favourable precipitation conditions (with EDI index value > 0) were – in the order from the wettest year – the years 2010, 2002, 1977, 1995, 1987 and 2001. The considerable variability of precipitation conditions was observed in growing season from 61st to 180th day of the year. However, four growing seasons (1973, 1974, 1976 and 1993) were evaluated as dry and three growing seasons (1987, 2006 and 2010) were assessed as wet. Seven localities had a statistically significant increasing linear trend (P < 0.01, P < 0.05), and it can be expected a slight increase in precipitation in a substantial part of the territory in the Czech Republic. However, this probably does not suggest that the territory will be saturated with precipitation at an optimal level for growing agricultural crops due to significant annual fluctuations in the distribution of rainfall over time and area and due to the increase of evapotranspiration demands during the growing season.

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