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Assessment of meteorological and hydrological drought using drought indices: SPI and SSI in eastern Slovakia

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The current article presents a one-dimensional frequency analysis of historical drought events in the years 1972 to 2014 in the eastern part of Slovakia. Two physical drought types: meteorological and hydrological are classified by SPI – standardized precipitation index and SSI – standardized streamflow index. These indexes have the same mathematical calculation, the difference is only in the input initial monitored data collected from seven rain gauge stations and seven river stations. The most appropriate theoretical probability distribution of selected data is performed using the Kolmogorov-Smirnov test, which is done in EasyFitt program. The basic parameters of meteorological and hydrological drought are determined by the application of the RUN method. One – dimensional frequency analysis of two physical droughts is created for a purpose of estimating the probability of their occurrence in time and identifying the spatial vulnerability of this area. The main benefit of this work is the identification of the average return time of drought events. On average we can expect a moderate meteorological drought in 18.14 to 36.8 months and a hydrological drought in 26 to 60 months.

KEY WORDS: frequency analysis, SPI, SSI

Introduction

Drought is a natural phenomenon with a temporary, negative and severe deviation from the average value of precipitation during a specific time period in an area that could lead to meteorological, agricultural, hydrological and socio-economic drought (COM (2007) 414 final). Scientists distinguish two kinds of drought: physical and non-physical drought. Meteorological and hydrological and agricultural droughts are classified as physical droughts because their origin depends on natural physical processes taking place in the atmosphere and on the earth's surface. Socio-economic drought is a non-physical drought and will still occur with at least one mentioned physical drought (Blain, 2012). Hydrological drought is later than meteorological drought, and the corresponding propagation time depends on persistent precipitation deficit, the occurrence of excessive temperature, evaporation and dry winds in the territory (Van Loon, 2013). The tendency of occurrence of intense droughts is increasing due to climate change all over the world, and the territory of the European Union is no exception. During the period 1976–2006, damages by drought were around 100 billion EUR (COM (2007) 414 final). In the years 2003, 2011–2012 and 2015 EU recorded the most severe manifestations of physical droughts (Fendeková et al., 2018). From the above-mentioned factors, the need to monitor and manage the risk of drought at the international, regional and local levels is increasing. Actual drought monitoring at the regional and local levels takes place with the help of a monitoring network throughout the territory of Slovakia. This monitoring network is available on the website of the Slovak Hydrometeorological Institute.

Various methods are used for monitoring and characterization of drought, but the most used methods are indexes (Tsakiris et al., 2007). There is at least one index form each type of drought. Standardized Precipitation Index SPI (McKee et al., 1993) or Standardized Precipitation and Evapotranspiration Index SPEI (Vicente-Serrano et al., 2010) are the indexes most commonly used to identify meteorological drought. To calculate the SPEI we need monthly data on precipitation totals and temperatures, while for SPI, only precipitation data for the given area is sufficient. The computation of SPI can be performed in various time intervals, which functionally distinguish different types of physical drought, as follows: i) 1 to 3-month intervals reflect soil moisture deficit, ii) 6 to 12-month intervals reflect changes in water accumulation in surface water sources, iii) 24 to 36 months reflect changes in groundwater reserves (McKee et al., 1993). The mathematical calculation of the index can be calculated in a parametric and non-parametric way (Soľáková et al., 2013). In most cases, the non-parametric way is used because the data is usually not normally distributed. Identifying the most suitable probability distribution is possible according to the Kolmogorov-Shmirnov test (Kottegoda and Rosso, 1997), the L-moment distribution diagram (Peel et al., 2001) or the Akaike information criterion (Akaike, 1973). Some distributions such as Gamma, Generalized Gamma are zero-bounded, and if the data contains a high number of zero values, then a transformation of the cumulative probability function according to Wu et al. (2007) is necessary, so-called equiprobability transformation. In this way, we obtain a spatially and temporally stable index that can be compared with other indices from other regions (Blain, 2012).

Quantifying flow dynamics using an index: the SDI streamflow drought index was proposed by Nalbantis (2008). The SDI has a similar mathematical calculation to SPI, the monthly streamflow values are described by a lognormal distribution. The suitability of other three-dimensional statistical distributions such as lognormal, Pearson, log-logistic, Generalize Extreme Value, generalized Pareto and Weibull were studied by Vicente-Serrano et. al. (2012) in the Erbo basin in Spain and introduced the standardization of the SDI index by applying the statistical non-parametric Kolmogorov-Smirnov test or using the L-moment proportion diagram. Table 1 records the categorization of drought, which is the same for both indices: SPI and SSI and quantifies the risk of drought into classes according to severity. Such quantification of drought is issued when implementing measures in the basin or in the state (Z is a value of calculated index).

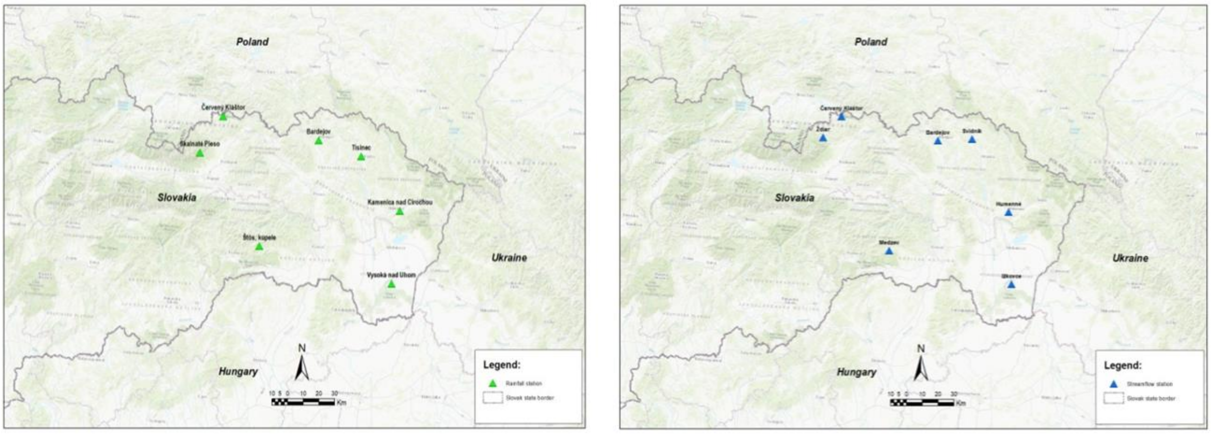
Identifying the occurrence of episodes of meteorological and hydrological drought makes the management of this event more efficient in the basin, thus ensuring the minimization of the negative impact on fauna and flora, as well as on human activities. The aim of this work was to identify episodes of moderate to extreme meteorological drought for the reference period 1972–2014 in a sub-basins: Dunajec and Poprad, Bodrog and Bodva, and also to identify the time of drought return with a 15.9% probability of occurrence.

Material and methods

The values of hydrometeorological data (values of average daily streamflows and total daily precipitation) for the selected time interval: 1971–2014 were provided for 7 river stations and 7 rain gauge stations (see Fig.1) by the Slovak Hydrometeorological Institute in Košice, only in the Ižkovce station is there a smaller time period: 1975–2014. SPI in a 12-month time frame (or SSI) is calculated using aggregated monthly precipitation totals (or monthly streamflows). Aggregation of precipitation totals (or streamflows) is performed with the help of a so-called moving window. The total precipitation value in December 2011 will have the sum of the total precipitation values from January 2010 to December 2011. And this is how we gradually obtain a statistical set of aggregated precipitation (or aggregated strreamflows), which we statistically analyze by identifying the most appropriate statistical distribution. Estimation of the most appropriate probability distribution f(x) for each month, by choosing from eight tri parameters distributions (General Extreme Value – GEV, Weibull, Lognormal,

Table 1. Categorization of drought

Index interval	Category	The probability of the event
$\boldsymbol{Z \geq 0}$	No drought	50%
$\boldsymbol{-1 \leq Z < 0}$	Mild drought	34.1%
$\boldsymbol{-1.5 \leq Z < -1}$	Moderate drought	9.2%
$\boldsymbol{-2 \leq Z < -1.5}$	Severe drought	4.4%
$\boldsymbol{Z < -2}$	Extreme drought	2.3%



a) b)

Fig. 1. Map of the location of a) rain gauge stations and b) river stations.

Gamma, Generalized Gamma, Pearson 6, Burr, Normal) using the Kolmogorov – Smirnov test. The statistical test was done using the software: EasyFit 5.5 and Excel. The results of the statistical test at a significance level of 5% rank the probability distribution function in an Excel worksheet from the most appropriate theoretical function to the least appropriate.

Currently, the parameters of the best-fit probability distribution function are determined by the maximum likelihood method. Then we calculate the cumulative distribution function. By inverting its values in chronological time we obtain an index. Another important step is to verify whether the index values Z have a normal distribution according to the Wu et al. (2007) requirements. The identification of the beginning of a moderate drought is if Z<-1. Determining the total number of episodes and the duration. Duration is a continuous time interval during which Z is still less than -1) and the severity of individual episodes is a sum of all Z values during the continuous duration of the one drought episode. Inter-arrival time is the time that determines the period between two drought episodes or in other words, the time that elapses from the beginning of the first drought episode to the beginning of the next drought episode (Madadgar et. al, 2011).

Study area

The largest studied sub-basin, extending over the northeastern, eastern and southeastern parts of Slovakia, is the Bodrog sub-basin, where agricultural land use represents 51.2% of the total basin area of 7 272 km^2. The sub-basin of Bodrog is represented by four water meter/precipitation gauge stations, namely: Bardejov 312 m a.s.l. / Bardejov 312 m a.s.l., Svidník 216 m a.s.l. / Tisinec 192 m a.s.l., Humenné 155 m a.s.l. / Kamenica nad Cirochou 176 m a.s.l. and Ižkovce 100 m a.s.l. / Vysoka nad Uhom 230 m a.s.l. In the southern part of the studied territory there is a sub-basin of the Bodva, it is the smallest studied sub-basin with a total area of 858 km^2 and with 48.1% agricultural land use. It is characterized by a water meter station in the town of Medzev 318 m a.s.l. and approximately 12.3 km away, a precipitation gauge station in the town of Štós Kúpele 516 m a.s.l. in the northern part of the studied territory, there is a sub-basin of the Dunajec and Poprad with a total area of 1950 km^2 and with a total of 42% of the land used for agricultural purposes. This sub-basin is represented by two water meter stations and two precipitation gauge stations. There are stations in the cities: Červený Kláštor 469 m a.s.l. / Červený Kláštor 469 m a.s.l. and In Ždiar 896 m a.s.l. / Skalnaté Pleso 1778 m a.s.l.

Results and discussion

The results of the research are presented in the following. Over a 42-year time period, the total duration of long-term meteorological droughts ranged from 77 to 82 months, while in the Kamenica nad Cirochou was the most frequent occurrence of drought episodes. In January 1972 the maximum duration of the long-term meteorological drought was recorded in the north of the territory in Červený Kláštor, with a duration of up to twenty-four months. The greatest cumulative severity of the long-term meteorological drought was recorded in the south at Štós station, where rare occurrences of drought episodes are expected, but with greater duration and severity. The average inter-arrival time of a long-term meteorological drought ranges from 18.14 to 36.8 months (Table 2).

In the monitored area, the duration of long-term hydrological drought ranges from 78 to 86 months. The most frequent occurrence of the episode of a drop in the levels of surface water bodies and groundwater was recorded in the north of the territory at the Červený Kláštor station with a total of 22 drought episodes. In April, the longest twenty-five-month hydrological drought was recorded at the Medzev station, while this station is characterized as the most vulnerable station to this phenomenon during the observed period 1972–2014. The average inter-arrival time of long-term hydrological drought ranges from 23.6 to 60 months (Table 3).

Maps of the duration of meteorological drought (see Fig. 2) and hydrological drought (see Fig. 3) were created in the ArcGIS program using the spline function.

Table 2. Identification of the basic feature of long-term meteorological drought by index SPI-12 for the period 1972–2014

	Bardejov	Tisinec	Kamenica nad Cirochou	Vysoká nad Uhom	Štós	Červený Kláštor	Skalnaté Pleso
Duration	78	**82**	81	80	80	**82**	77
Max. duration of drought episode	9 2003 V.	10 1986 XI.	12 1986 XI.	12 1992 VII.	21 1992 VII.	**24** **1972** **I.**	10 1979 X.
Severity	-117.4	-116.9	-124.2	-122.2	**-127.2**	-121.4	-119.7
Drought episodes	28	26	**29**	20	14	22	20
Average inter-arrival time	19.42	20.36	**18.14**	26.78	36.8	24.23	26.78

We created six classes of drought duration, graded from the longest duration to the shortest duration based on interpolation from the maximum duration of the drought to the minimum duration of the drought in the observed period of 1972–2014 only in Ižkovce station for hydrological drought is a period: 1976–2014.
We consider the Červený Kláštor and Tisinec stations to be among the most vulnerable areas to long-term meteorological drought for the selected period. The north and northeast of Slovakia, the surroundings of Červený Kláštor and Humenne are among the areas most vulnerable to long-term hydrological drought. More results are published in the thesis of Soľáková (2017).
Similar results were published by Fendeková at el. (2018).

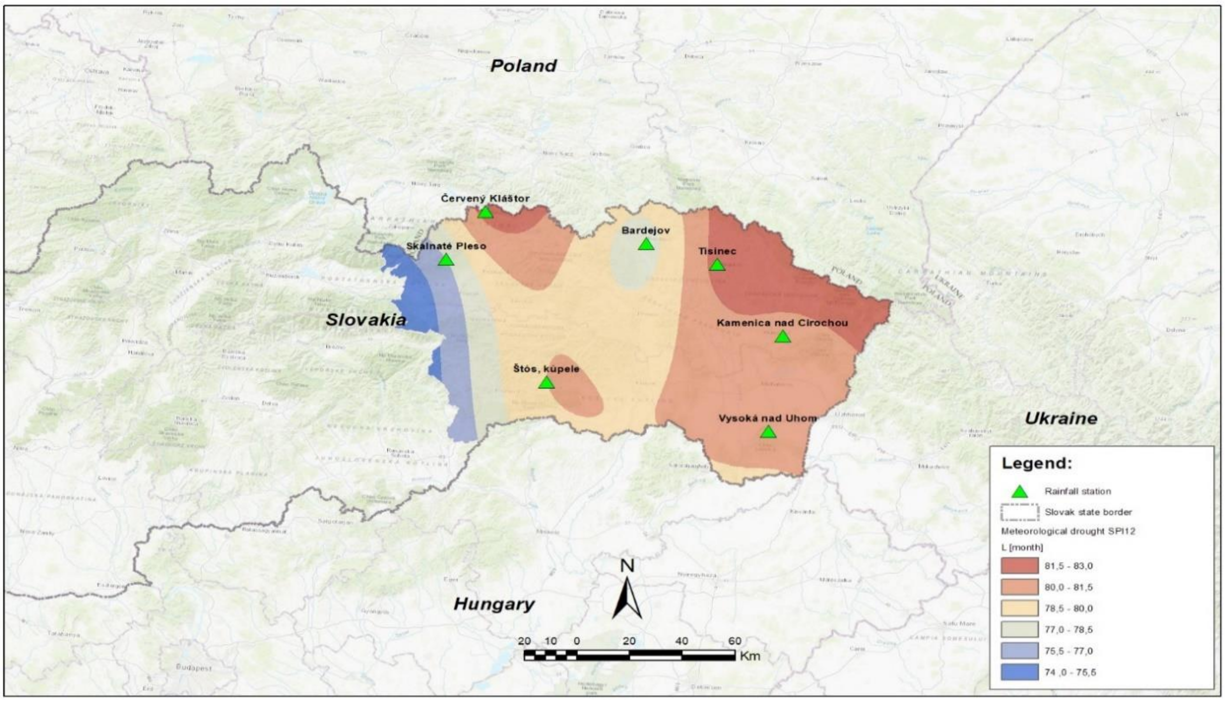


Fig. 2. Meteorological drought duration map over time period 1972–2014.

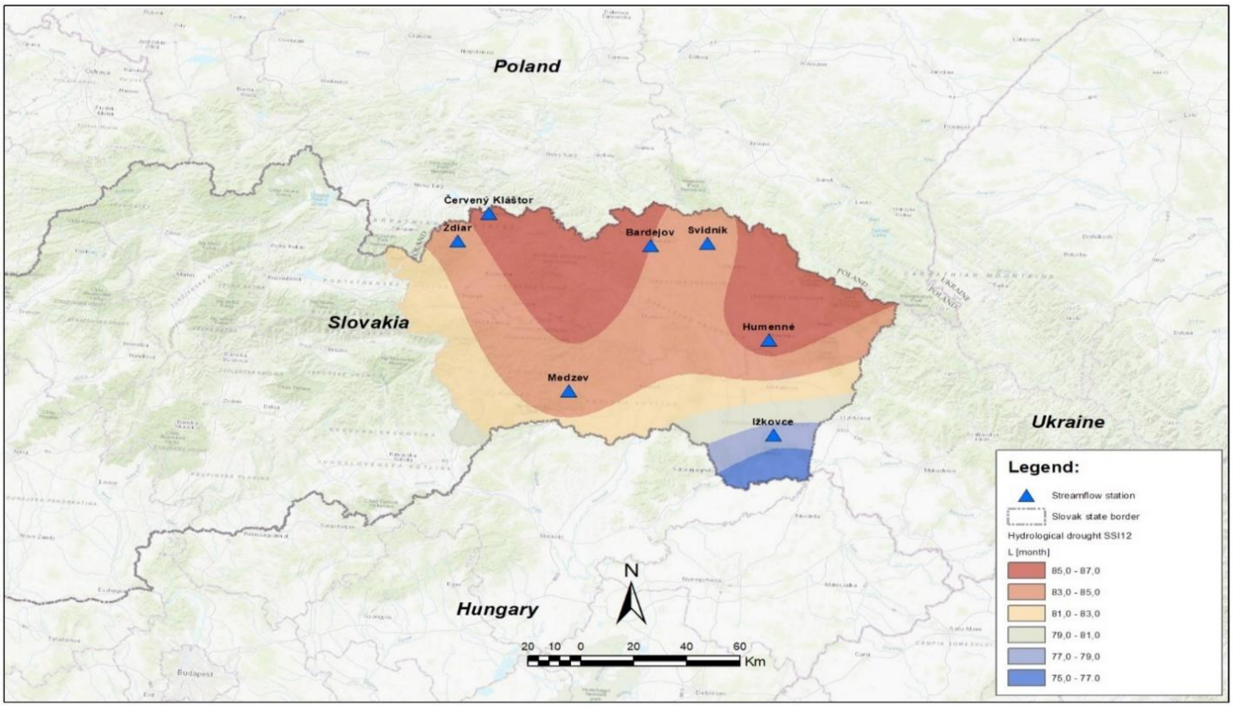


Fig. 3. Hydrological drought duration map over time period 1972–2014, for Ižkovce period: 1976–2014.

Table 3. Identification of the basic feature of long-term hydrological drought by index SSI-12 for the period 1972–2014 and for Ižkovce station from 1976 to 2014.

	Bardejov	Svidnik	Humenné	Ižkovce	Medzev	Červený Kláštor	Ždiar
Duration	85	84	**86**	78	84	**86**	84
Max. duration of drought episode	15 1972 I.	13 1984 II.	12 1986 XII.	13 2003 II.	**25** **2002** **IV.**	13 1993 V.	17 1986 VIII.
Severity	-127.6	-125.9	-127.3	-116.6	**-130.1**	-122.2	-119.9
Drought episodes	17	18	15	11	9	**22**	20
Average inter-arrival time	31.6	29.82	33.67	36.1	60	**23.6**	26

Conclusion

The primary cause of physical droughts is precipitation deficits in the basin, which, due to long-term effects, cause deficits in the levels of surface water bodies and the levels of underground bodies. The long-term persistence of these deficits in the basin leads to significant economic, social and environmental damage. The main task was the identification of long-term meteorological and hydrological drought for the time interval of 1971-2014 in three sub-basins located in eastern Slovakia. Events of long-term meteorological drought were recorded more often than events of hydrological drought, thus confirming the fact that occurrences of long-term deficit of surface water levels are largely compensated by underground water reserves in those sub-basins. The identification of the average inter-arrival time of drought tor each station contributes to the timely prediction and warning of these phenomena, as well as to their better management. In the future Slovakia could be vulnerable to a moderate meteorological drought approximately in 20 to 30 months and to a hydrological drought in 20 to 60 months. Future research in the drought risk assessment is inevitable especially due to climate change impacts.

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