Meteorological Drought Occurrence in Slovakia

L. Labudová and M. Turňa

Contents

Abstract Slovakia is located in the Central Europe, and its complex surface consists of mountains, valleys, but also lowlands, which are crucial for agricultural production. In the neighbouring countries, especially in Hungary and the Czech Republic, there has been paid great attention to drought occurrence for a longer time. In Slovakia, hydrological drought assessment was more often under investigation than the meteorological aspect of the drought in the past. The regionally developed methods were primarily used for its estimation, while the internationally established indicators were rarely applied. In the last years, the drought became to be discussed more frequently in the Slovak climatology, which led to the start of operational drought monitoring in Slovakia in 2015. Drought periods, which occurred in the last years and caused also yield losses in agriculture, raised the interest of the public and experts from different economic sectors in this phenomenon. The intersectoral approach seems to be the crucial way of further drought research.

This chapter aims to present two case studies, which could be the example of the linkage between climatological and hydrological approach in drought assessment on an operational level. The first case study describes the operational meteorological

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drought monitoring, which has run since 2015. The slightly modified methodology of widely known indices (SPI and SPEI) shows promising results, which can be obtained on a daily basis. It enables them to be used in intersectoral drought analysis. The example of such analysis is presented in the second case study, in which the linkage between meteorological and hydrological drought was examined. The knowledge about the causalities between these two drought types brings higher assumption for the successful design of effective integrated drought monitoring.

Keywords Hydrological drought, The Kysuca river basin, Meteorological drought, Operational monitoring, SPI

1 Introduction

Several studies focused on meteorological drought have been published in Slovakia. In the past, Šamaj and Valovič published their own newly developed methodology for the identification of drought periods in the 1970s [1]. The methodology was based on cumulative daily precipitation totals. It consisted of three criteria for drought occurrence: (a) at least 15 consecutive days with cumulative precipitation total below 1 mm, (b) at least 20 consecutive days with cumulative precipitation total below 2.5 mm or (c) at least 30 consecutive days with cumulative precipitation total below 5 mm. These criteria are stricter than well-known consecutive dry days (CDD) index, which counts the days with daily precipitation below 1 mm without considering their accumulation. According to the methodology, the regions with the highest number of drought periods were the region of Záhorie, the Danubian Lowland, the East Slovakian Lowland, the Southern Slovak Basin, the Levoča Mountains and the Podtatranská Basin (due to the precipitation shadow of surrounding mountains).

Later, more attention was paid to the research of floods and water management mitigating flood impacts in Slovakia. It was the result of great damages caused by floods, which are easier to calculate and to prove them than the damages by drought. It is the “disadvantage” of drought that its progress is very slow and not as visible as it is in the case of a flood. Additionally, it is very hard to quantify its damages in agriculture, because there can occur more negative meteorological factors influencing yields (late frosts, heat waves, hails, etc.). Especially heat waves causing the heat stress for plants can quite often accompany the drought periods.

New studies about meteorological drought have been published since the 2000s. They were the part of hydrological studies very often. Separate climatological studies on drought occurred only rarely. One of them was published by Patassiová et al. [2], who used the Palmer Drought Severity Index (PDSI). The same index was used by Litschmann and Klementová [3]. Later, the Standardized Precipitation Index (SPI) was used by Fendeková and Ženišová [4] in the hydrogeological study.

The drought is a complex problem, and it can spread through different sectors. The meteorological drought is the starting point, and its longer duration can result in the soil drought and hydrological and hydrogeological drought. Therefore, the drought research was the part of the soil, or agricultural research. For example, Skalský et al. [5] simulated the relations within the system soil-plant-atmosphere. The model WOFOST was used to assess drought impact on spring barley in the period 1997–2007. Takáč [6] used the SPI as one of the drought indicators in his study about agricultural drought in Slovakia. The newest study oriented on drought impact on yields was focused on the agriculturally most productive regions in Slovakia – the Danubian Lowland and the East Slovakian Lowland [7]. The authors used the SPI and the SPEI (Standardized Precipitation and Evapotranspiration Index) to find the relationship between drought occurrence and the yields of different crops. There was found a high significant correlation between both variables, but only in the Danubian Lowland due to complicated soil conditions in the southeast of Slovakia.

In the last years, not only the studies were the main outputs of the drought research in Slovakia. The Slovak Hydrometeorological Institute (SHMI) established its own meteorological drought monitoring in March 2015. The monitoring is based on the modified SPI and SPEI as well as on the Crop Moisture Index (CMI), and it is weekly updated. Besides the actual situation, it offers 7-day forecast of all indices based on the ECMWF data [8]. To bring more complex information for the farmers and foresters, the SHMI joined to the integrated soil drought monitoring called Intersucho in autumn 2015. This monitoring was developed by the CzechGlobe (Global Change Research Institute of the Czech Academy of Sciences), the Masaryk University and the Mendel University in Brno, Czech Republic [9]. It is based on the integrated soil model, which considers the soil parameters and simulates the soil water content in near real time.

In this chapter, two case studies are presented on operational meteorological drought monitoring and assessment, including connection to hydrological drought.

2 Case Study 1: Operational Meteorological Drought Monitoring

As it has already been mentioned in the Introduction, the Slovak Hydrometeorological Institute (SHMI) established its own operational meteorological drought monitoring in March 2015. In this case study, the results of the first monitoring season 2015 are presented. During this period, extremely dry conditions occurred in Slovakia, which was very well monitored by SHMI's drought monitoring. In the second part of the case study, the relationship between meteorological drought monitoring and relative soil humidity is demonstrated on the example from the monitoring season 2016.

2.1 Methods

The drought monitoring in Slovakia is primarily focused on meteorological drought. Therefore, it requires only climatologic data from the station network of the Slovak Hydrometeorological Institute (SHMI) except the Crop Moisture Index (CMI), which also requires the information about available water content (AWC) in the soil. The AWC data were provided by National Agricultural and Food Centre – Soil Science and Conservation Research Institute (NAFC – SSCRI). The climatologic data consisted of precipitation totals; maximum, minimum and average air temperature; relative air humidity; average wind speed; and sunshine duration on a daily basis. The monitoring is currently based on three indices – Standardized Precipitation Index (SPI), Standardized Precipitation and Evapotranspiration Index (SPEI) and Crop Moisture Index (CMI). During the first testing season, we also used Palmer Z-index, but it was excluded due to dissatisfying results.

The Standardized Precipitation Index was defined by McKee et al. [10] to establish the tool, which would enable the comparison of drought conditions in different climatic conditions. The precipitation totals are fitted with the gamma distribution and standardized to reach non-dimensional value. It is the worldwide used index because it requires only precipitation data in its calculation. However, its data simplicity means some disadvantage in the areas, where evaporation has an important impact on the water balance. The increasing air temperature [11] enhances the evaporation, but the SPI is not able to reflect the temperature changes in the drought assessment. Therefore, the Standardized Precipitation and Evapotranspiration Index was established by Vicente-Serrano et al. [12]. It is based on the similar principal as the SPI, but it considers simple water balance, precipitation (P) minus potential evapotranspiration (PET), instead of single precipitation. The index uses the log-logistic distribution for the data approximation. The original methodology uses the Thornthwaite's PET estimation method [13]. However, the World Meteorological Organisation and the Food and Agriculture Organisation recommend the Penman-Monteith's method [14]. Both indices can be calculated for different time steps originally defined on a monthly scale. Therefore, we had to slightly modify their methodology to get the daily operational data. In principal, all steps were preceded as they were defined by their authors. The only change is the character of the accumulation period. If the SPI is calculated on a monthly scale, the accumulated period is in average 30 days. We kept the accumulation period of 30 days, although we did not deal with monthly data, but we applied moving window on the daily data summing the daily precipitation totals or PET totals, respectively [8]. It means that the final value of the SPI (the SPEI) refers to the conditions of $n-29$ to n days, where n is a day at the end of the moving window. This principle was used for the 3-month SPI within the DROught adaPtation (DROP) project in Flanders [15], which is addressed for hydrological praxis. The 3-month time scale would be too long for agricultural purposes. Therefore, we limited the moving window to 30 days, and we applied this methodology not only on the SPI but the SPEI as well.

The Palmer's Crop Moisture Index was defined in 1968 [16], and it belongs to the group of agricultural drought indices. It takes into account week to week changes in simple water balance considering its state at the end of the previous week and soil characteristics such as available water content (AWC), which influence the soil moisture recharge. The CMI requires PET data as well. For its estimation originally used methodology by Thornthwaite is used [13].

The monitored area covered two agriculturally most important lowlands – the Danubian Lowland (DL) and the East Slovakian Lowland (ESL) in the first testing season 2015. At the moment, it covers the territory of the whole country. The monitoring is station based, and the data from 44 climatologic stations with available daily operational data access are used. The mountainous stations were excluded as the monitoring should be used primarily for agricultural purposes. The assessed period is from 1981 till the present, and the reference period for the SPI and the SPEI was fixed on 1981–2010. The historical data were homogenized for the period 1981–2014, and later data have operational character without homogenization. The monitoring is updated weekly each Monday from March to September at the official webpage of SHMI (http://www.shmu.sk/sk/?page=2161), and it consists of the assessment of the situation during the last 7 days as well as the expected changes in drought indices in the next 7 days. The forecast is based on the ECMWF model. The drought indices are visualized in figures, which are available after click on the station mark in the interactive map with figure preview. The colour of the mark represents drought intensity according to the SPEI (Fig. 1). Besides graphical visualization, we provide also text summarizing weather in the last week with an explanation, how it influenced the water balance in Slovakia and which changes are expected in the next week as well.

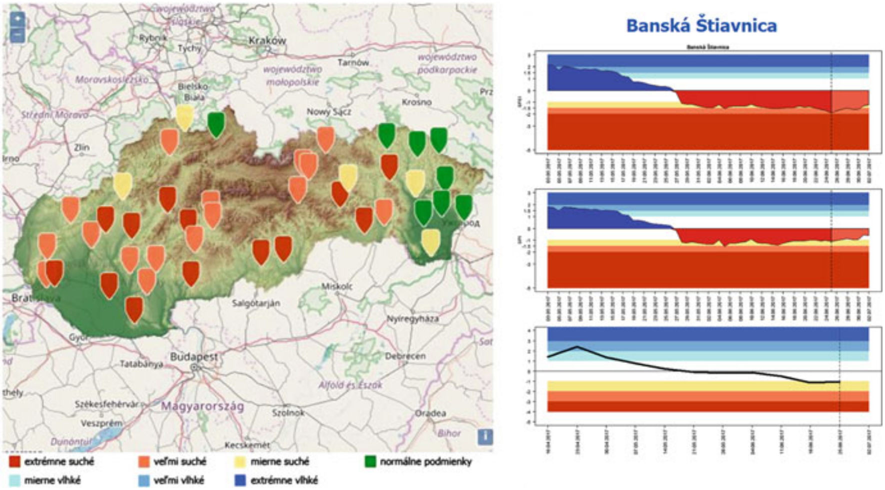

Fig. 1 The example of map graphics with figure preview on 26 June 2016. For clearer version for all stations, please visit this link (http://www.shmu.sk/sk/?dt=1498341600&page=2161)

2.2 Operational Monitoring in Praxis

2.2.1 Season 2015

As it was mentioned, the first drought monitoring season had testing character, and only two agriculturally most important lowlands were monitored. The initializing conditions were better in the Danubian Lowland (DL) than in the East Slovakian Lowland (ESL) due to drier winter conditions in the eastern part of Slovakia. A similar tendency was observed in March 2015, when the DL recorded values close to normal long-term precipitation totals, while the ESL observed only 11.8 mm in Milhostov. It resulted in the SPI values below -1 and in the south of ESL even below -1.5. The situation was getting worse at the end of the month at all monitored stations. Precipitation deficit continued in April, and the highest monthly precipitation total was observed in the southwestern part of the DL (26.1 mm), but the ESL experienced only 6.2 mm. It meant the deterioration in water balance, especially in the southeastern Slovakia. Besides the SPI and the SPEI, the CMI was also decreasing with an increasing air temperature. It reached the value -1 at the end of the month. The SPI showed even worse conditions with the values below -2. The SPEI stopped its decline closely above -2. In the DL, the indices were mostly positive and showed balanced (normal) conditions. However, they were slowly decreasing at the end of the month as well, especially in the central and southern part of the lowland.

Large regional differences also persisted in May 2015, when the DL had enough precipitation, especially in its southern locations. All three indices indicated moderate wet conditions. The month began as extremely dry according to the SPI and as very dry according to the SPEI in the ESL. The second half of the month brought the improvement of the situation, mainly after the passing of cold frontal zone on 26 and 27 May. The CMI was almost continuously decreasing as well due to rising daily air temperature, which increased the importance of evaporation in drought assessment. The CMI reached values around -1.5 in the last week of May.

The water balance in June 2015 was influenced by two main factors. The first one was a strongly deepening precipitation deficit, which was very rarely interrupted with thunderstorms connected with very intense rainfall. Such case occurred in Milhostov (ESL), where the total of 45 mm was observed. Heavy rainfall causes that surface runoff is higher than the infiltration into the soil, especially after long-lasting drought period, when the topsoil layer is quite solid. None of the used indices are able to exclude intense precipitation, which cannot finish the drought period very often. The lowest precipitation total (11.8 mm) was recorded in Somotor (southern ESL). The long-term values for June (1961–1990) are in the interval from 70 to 80 mm for these monitored stations. The second factor was high potential evapotranspiration due to very high air temperature, stable sunny weather and low relative air humidity. This factor strongly influenced the situation during whole summer and in the ESL also in September. The deviations of monthly average air temperature in summer months varied from +1.8°C up to more than +5°C. These factors caused the

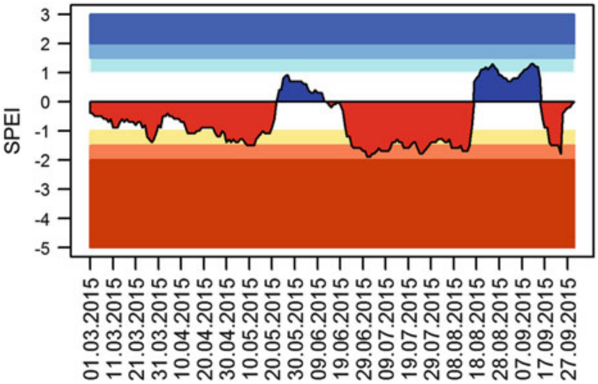

Fig. 2 The SPEI in the monitoring season 2015 in Žihárec

decrease of drought indices in both lowlands. The SPEI and the SPI were below −2 in Bratislava, Nitra, Piešťany, Žihárec (Fig. 2) and Somotor. The CMI was decreasing as well, and it reached values below −3 in Somotor and below −2 at other stations in the ESL except for the station Milhostov.

After a very dry June, even July did not bring long-desired precipitation. Moreover, the extremely high monthly average air temperature even deepened the drought. The SPI in Milhostov (ESL) decreased below −3, and both standardized indices varied around −2 in the DL. The same tendency showed the CMI as well, and all monitored stations recorded its values below −2, the stations Piešťany, Žihárec and Somotor even below −3. It has been the lowest recorded value of the CMI (−3.2) at the station Piešťany since 1961 as well as in Žihárec (CMI equal to −3.36). Comparable drought occurred in the central part of the DL only in 2012 with the minimum value equal to −3.35.

August brought a change for the DL, where the precipitation in the second half of the month finished drought period at all monitored stations. The SPEI showed normal to moderate wet conditions here. On the other hand, the water balance in the ESL was still worsening, and the stations recorded very dry to extremely dry conditions. The CMI reached its minimum values of the season. The station Vysoká nad Uhom recorded the value −4.40 (Fig. 3), which has been the lowest one since 1981. Similarly, the most southern station, Somotor, has not observed lower value than −4.19 before. In summary, the half of monitored stations have reached the lowest CMI since the beginning of their observation.

The last month of the monitoring season meant new drought period in the DL. The much worse situation was in the eastern part of Slovakia, where the SPEI decreased on −3.6 in Vysoká nad Uhom and other stations were approaching extreme low values as well. This long-lasting drought period was not interrupted till the end of monitoring season at the most of the ESL. The only exception was the station Milhostov. It can be concluded that the whole monitoring season was from very dry to extremely dry in the ESL as only a short interruption occurred in June.

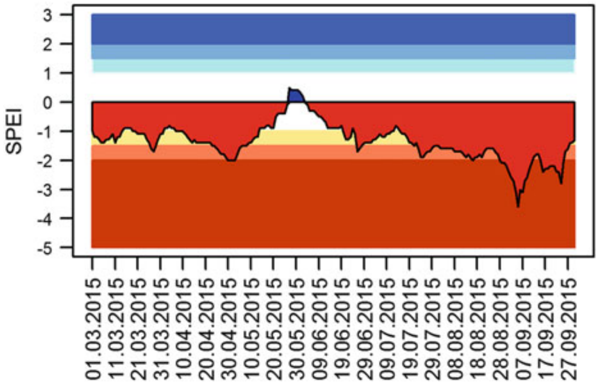

Fig. 3 The SPEI in the monitoring season 2015 in Vysoká nad Uhom

2.2.2 Operational Meteorological Drought Monitoring and Relative Soil Humidity

The SPI and the SPEI began within the range of extremely wet values at the beginning of the second season (in 2016) due to very high precipitation totals in February. They were caused by repeating circulation situation, which enabled the flow of warm and wet oceanic air masses from the south and southwest. Both indices started to increase in the middle of the month, when they crossed +1.5, and they were evidently above +2 at the end of the month. The most extreme situation occurred in the south of Western and Central Slovakia. The eastern part of the country observed wet conditions approximately 1 month earlier than the rest of the country. The exception was the Spiš region, where conditions were closer to those in the Central Slovakia. The CMI showed very similar results as the SPI. The described situation resulted in much better water balance at the beginning of the monitoring season than in the previous year.

March was poor in the precipitation, which resulted in quite a steep decrease of the SPI and SPEI. The deficit was so high that we observed worse water balance in March and in the first half of April than in the previous year at the same time in the Western and Central Slovakia. It means that the situation changed from very/extreme wet to very dry within 1 month. As the water balance in the eastern part of the country was much worse in 2015 than in other regions, this decrease meant “only” reaching the state from the previous year.

The drought development according to the SPI and the SPEI was in quite well agreement with the relative soil humidity, especially in the top 40 cm of the soil (Figs. 4 and 5), especially in the southern, lower located regions and in the northeast with the hilly land. The relative soil humidity was monitored within the project Intersucho [9].

Precipitation in April and May improved the water balance in almost all regions, except eastern Slovakia. The southeast experienced the same drought development as in the year 2015, and the situation was even worse in the Spiš region in comparison with season 2015, or a long-term mean. No change in regional

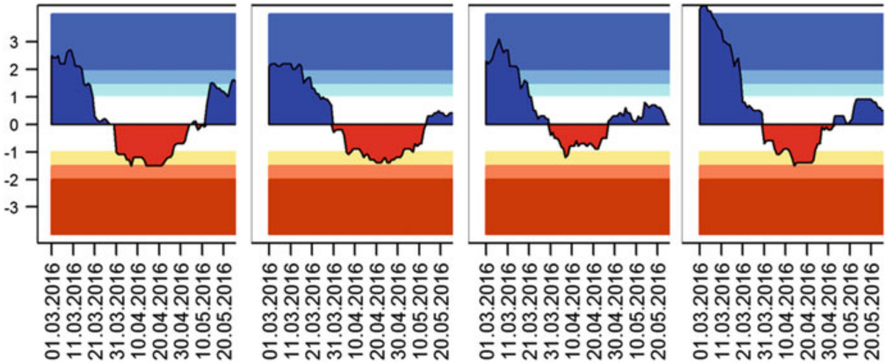

Fig. 4 The SPEI at the beginning of the monitoring season 2016 in Žihárec (1st panel), Milhostov (2nd panel), Bardejov (3rd panel) and Boľkovce (4th panel)

differentiation occurred in June, which was moderately wet in the Western Slovakia, but very dry to extremely dry in the northeast. Very good agreement was achieved between the SPEI and the relative soil humidity again. The operational SPEI caught developing drought in the topsoil layer in the northeastern Slovakia. Drought duration was not as long as in the previous year, and normal to moderate wet conditions prevailed from mid-July till the end monitoring season.

3 Case Study 2: Meteorological and Hydrological Drought in the Kysuca River Basin

The operational form of the SPI and SPEI described in the Case Study 1 also enables its utilization in interdisciplinary drought assessment. The Case Study 2 presents the assessment of meteorological drought as the prerequisite of a hydrological drought. The Kysuca river basin was chosen as the model area. This river basin is a quick responding river basin considering the precipitation-runoff relationship due to the flysch in the underground. Groundwater bodies are shallow, and groundwater storage is low in this type of sedimentary rock. Therefore, the flow in rivers varies according to precipitation conditions with short time shift.

3.1 Methods

3.1.1 Study Area

The Kysuca river basin is located in the northwestern part of Slovakia (Fig. 6). The surface has an upland character with a flysch as bedrock. Average air temperature in valley locations varies from 6 to 7.5°C, while surrounding mountains reach from

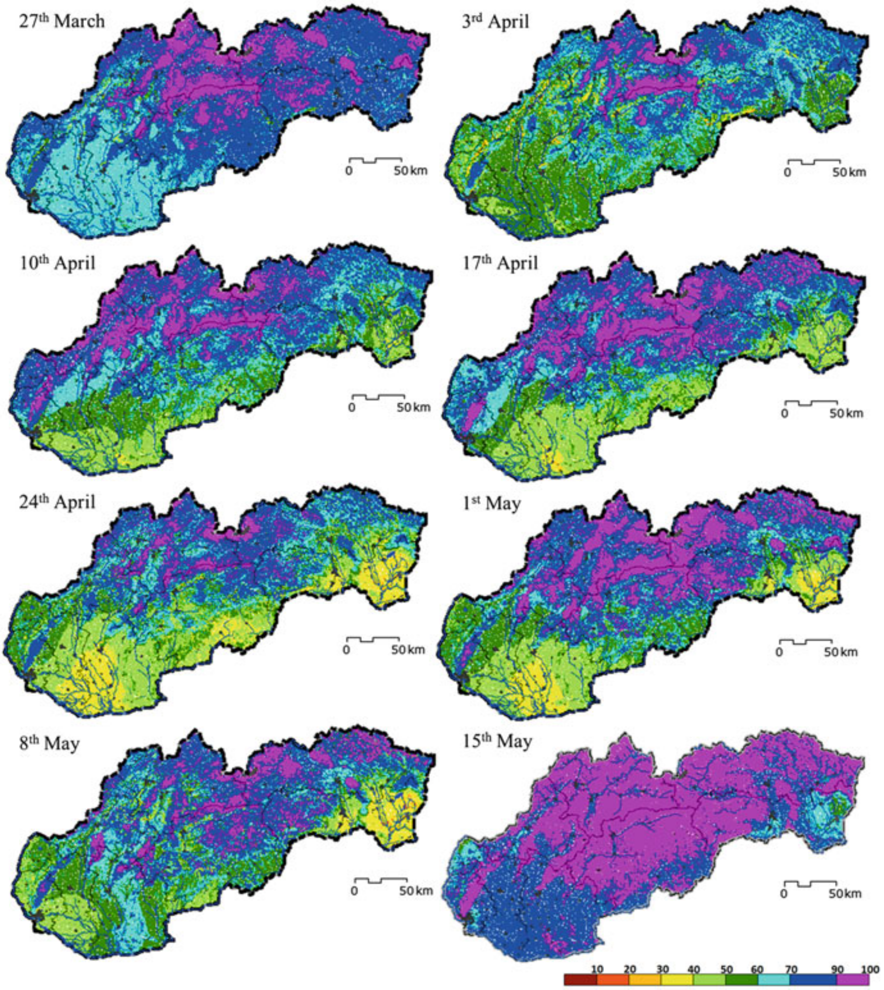

Fig. 5 Relative soil humidity in the top 40 cm of soil in Slovakia in the period 27 March to 15 May 2016 [9]

4.5 to 6°C in average. Average summer temperature reaches the values from interval 13.5 to 16.5°C. On the other hand, average winter temperature drops down to −4°C in average. Average precipitation total varies in the valleys from 950 to 1,000 mm, but the mountainous parts record from 1,000 mm up to 1,200 mm in average. The maximum precipitation falls in July; the minimum occurs in February. Average snow cover lasts in the lower parts of the basin from 80 to 90 days in average, in higher altitudes from 90 to 100 days. The snow cover occurs from 12 to 15 days in March in the most part of the river basin, but it can last up to 18 days in the highest altitudes [17].

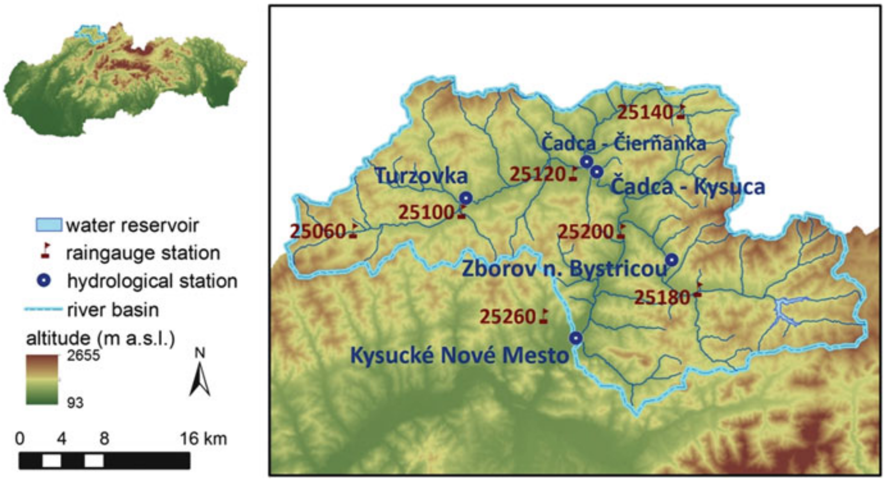

Fig. 6 Meteorological and hydrological stations in the Kysuca river basin

3.1.2 Meteorological Drought

As hydrological drought was assessed on a daily level, it was necessary to choose a daily indicator of meteorological drought. For this purpose, the operational form of the SPI and the SPEI was used. The detailed methodology was explained in the Case Study 1.

The daily station-based precipitation data were used to obtain spatial precipitation totals for each subbasin (the parts of the river basin belonging to each hydrological station) using the weighted average method. The list of rain gauge stations is in Table 1.

3.1.3 Hydrological Drought

The threshold level method is one of the most frequently used methods for the assessment of hydrological drought. Correctly chosen threshold enables to identify the beginning and the end of drought episodes as well as to compare their parameters such as deficit volume, intensity or duration. The threshold value usually varies between 70th and 95th percentile of flow duration curve (FDC), and most of the authors prefer 80th or 90th percentile ([4, 18, 19] a.o.). In this study, the threshold value was defined as the 90th percentile of the FDC. The discrete monthly threshold values were smoothed by applying a centred moving average of 30 days. The same methodology was used by Van Loon and Van Lanen [19], who created the process-based typology of hydrological drought, which was applied in this study.

Table 1 Rain gauge stations in the Kysuca river basin

ID	Station	Altitude	Latitude	Longitude
25060	Makov	574	49.373	18.486
25100	Turzovka	485	49.396	18.625
25120	Čadca	432	49.427	18.806
25140	Skalité	538	49.496	18.895
25180	Stará Bystrica	478	49.346	18.938
25200	Krásno nad Kysucou	384	49.384	18.832
25260	Nesluša	425	49.314	18.745

The dependent droughts were pooled applying the inter-event criterion of 10 days. The least duration of 10 days (a conservative value within usually used values) was used to eliminate the minor droughts in the evaluation.

3.1.4 Typology of Hydrological Drought

This typology was defined by Van Loon and Van Lanen [19]. It was based on a deep study of hydrometeorological variables in selected river basins, whereby each of them had different climatic conditions, geology and land cover. The following types were described:

- Classical rainfall deficit drought (CL)
- Rain-to-snow-season drought (RTSS)
- Wet-to-dry-season drought (WTDS)
- Cold snow season drought (CSS) with three subtypes (A, B and C)
- Warm snow season drought (WSS) with two subtypes (A and B)
- Composite drought (COM)

3.2 Linkage Between Meteorological and Hydrological Drought Occurrence

According to the SPI, the drought periods in the Kysuca river basins noted decreasing occurrence during the period 1981–2010. The same tendency was recorded in the length of the periods. The magnitude was without clear tendency, but some subbasins recorded slightly increase in the drought intensity in the last decade. It was not possible to exactly determine the months, which could be categorized as dry. However, it was possible to compare the drought occurrence in the warm (April to September) and cold half-year (October to March). In the 1980s, the number of drought periods in both half-years was equal, but the disproportionality was recorded in the next decades. The periods in warm half-year evidently prevailed (Table 2). It is in good agreement with the precipitation trend analysis. No

Table 2 Number of drought period in warm and cold half-year in the subbasins of the Kysuca river basin

Period		Kysucké N. M.	Zborov n. B.	Čadca – Čierňanka	Čadca – Kysuca	Turzovka
First decade	WH	15	14	12	15	18
	CH	16	16	14	15	16
Second decade	WH	14	15	15	16	16
	CH	8	9	7	8	9
Third decade	WH	20	15	19	20	20
	CH	14	13	13	13	14

CH cold half-year, *WH* warm half-year

significant trend was proved for the monthly precipitation totals. Nevertheless, some months experienced the changes. For example, the increase of precipitation was recorded in February, March, July and November. Average precipitation total increased about 5–11 mm/decade in February and about 6–16 mm/decade in March. The highest increase was located near the stations Stará Bystrica and Makov. The opposite tendency was noted in December.

There were only slight differences noticed in drought characteristics using the operational SPEI. The number of periods slightly increased on the contrary to the SPI. Climate conditions partially cause small differences between indices. The river basin lies in the northern, mountainous region in Slovakia, where the role of precipitation is higher than the role of potential evapotranspiration due to a lower temperature. The opposite situation could be found in the southern Slovakia, where the evapotranspiration has a key role in drought occurrence. Therefore, the importance of the increasing temperature does not lie in the changes of evapotranspiration, but it lies in the change of precipitation form as it will be explained later.

The operational SPI helped us to classify hydrological drought periods according to Van Loon and Van Lanen [19] and to identify the most frequently occurring or the most intensive drought type.

The highest intensity occurred by the type WSS-B and WSS-A (Table 3). Both types recorded increasing occurrence. The WSS-B was characterized by longer average duration (ca. 30 days), but the WSS-A accumulated high deficit volumes about 9 days shorter in average. Increasing temperature in the winter season (or in its part), which was proved by trend analysis, results in the occurrence of the most intensive hydrological drought periods. Both types can be strengthened by precipitation deficit in spring. Regarding only the deficit volume, the RSST type was the second in drought type ranking after the WSS-B. On the other hand, the RSST occurrence decreases due to the higher temperature at the beginning of snow season, which has been more frequently the case recently. Moreover, its duration is short due to quite regularly occurring temperature singularity called “Christmas warming”, which causes partial snow melting subsidizing river flows. It is the same terminating factor for the CSS-A type.

Table 3 Drought types and their characteristics on the river Kysuca in Čadca in the period 1981–2010

Type	Count	*d*	*v*	*m*	1st decade	2nd decade	3rd decade
WSS-B	2	33	2,705.1	823.9	0	0	2
WSS-A	7	20.3	1,231.2	554.8	2	2	3
RTSS	1	23	1,373.8	597.3	1	0	0
CSS-C	5	23.4	972.8	431.0	1	2	2
CL	21	27.2	725.3	247.1	4	9	8
CSS-B	3	25	758.8	221.0	0	2	1

d average duration, *v* average deficit volume/1,000, *m* average intensity/100

The WSS-B type occurred only twice, in both cases at the end of the study period (1981–2010). Winter 2006/2007 was humid, but warm as well. Only several days with average daily temperature below 0°C were recorded. Under these conditions, precipitation was often in liquid form, and high discharges were observed during the whole season. Moreover, an intensive meteorological drought occurred from mid-April till mid-May (Fig. 7). It resulted in the second highest deficit volume and the third highest intensity of the hydrological drought period on the Kysuca river in Čadca. These drought parameters were even higher on the Čierňanka River. The rareness of this drought period is supported by the fact that the drought also occurred on the Bystrica River, which is anthropogenic influenced, and no drought period, except this one, has been observed since 1994.

Winter 2007/2008 had similar scenario considering air temperature. The difference was in precipitation. February and May were near normal compared to the long-term conditions, but the rest of months experienced precipitation deficit, which intensified hydrological drought (WSS-B type). This period was even more intensive than the previous one, because the deficit volume was high, but the duration was shorter.

The CL type is the most frequently occurring hydrological drought type. Therefore, the meteorological drought is the most common factor causing the hydrological drought in the Kysuca river basin. Regarding the deficit volume and the intensity, this type is not significant. It is caused by the fact that its duration is often longer than other’s types, but the flows are just below the threshold value.

The temperature is the primary factor causing hydrological drought in the Kysuca river basin in the cold half-year. However, the precipitation as the secondary factor cannot be omitted. The influence of the precipitation deficit lies more in the intensifying of drought caused by too early or too late snow melting in winter. It is also supported by the fact that the hydrological drought occurring exclusively in winter is rare and hydrological drought dominates in spring, especially in April and May.

It is interesting to consider conditions, under which the hydrological drought did not occur even though the operational SPI indicated intensive meteorological drought. The impact of meteorological drought on discharges was strongly mitigated or fully eliminated in spring by melting snow, if the winter season was cold

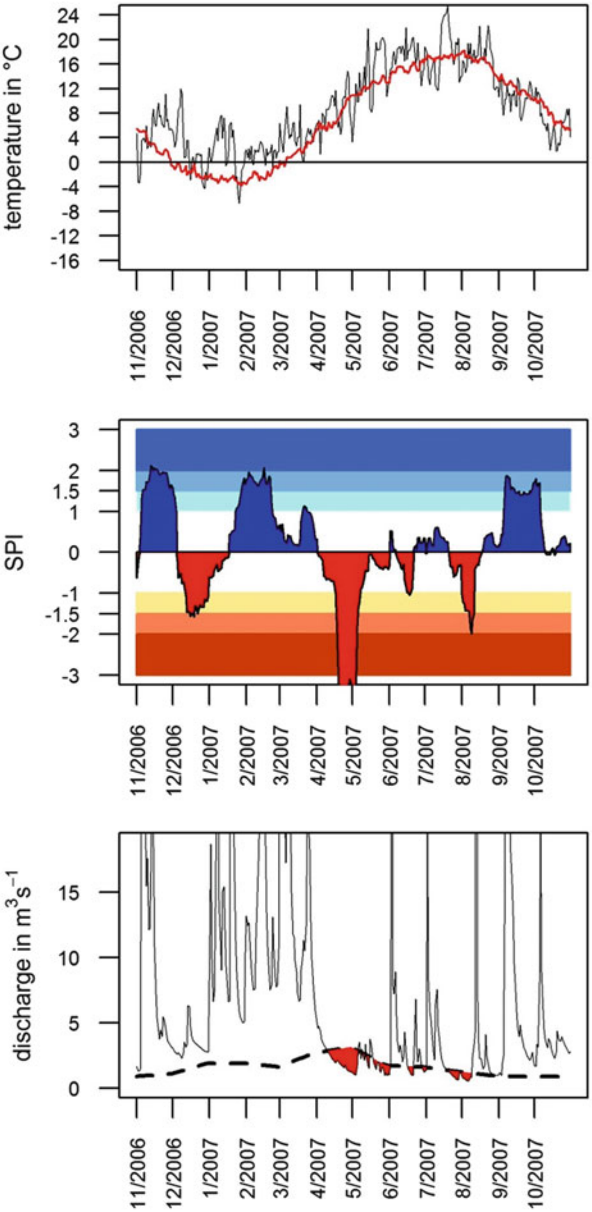

Fig. 7 Warm snow season drought (subtype B) on the Kysuca river in Čadca in the hydrological year 2007 (average daily air temperature, upper panel; operational SPI, middle panel; discharges, lower panel). Red line represented long-term average daily temperature and the dashed line represented threshold Q_{90}

and rich in precipitation and high snow cover was accumulated. Then spring precipitation deficit was less important than precipitation and temperature conditions in the snow season. For example, such case was noted in the hydrological year 1982.

Warm winter or earlier snow melting does not have to necessarily lead to hydrological drought if the operational SPI reaches positive values in April. Then naturally high discharges are not the result of snow melting, but the result of precipitation recorded in spring, e.g. such conditions were observed in the hydrological years 1983, 1990, 1994 a.o.

Meteorological drought in late summer or in autumn did not result in hydrological drought, if a natural precipitation maximum occurred from late June to mid-July as usual. This precipitation maximum improves the initiation discharges in the river and its tributaries before the meteorological drought occurring later (e.g. hydrological years 1987, 1997 a.o.).

The results of hydrological drought classification are slightly different for the Bystrica River behind the Nová Bystrica dam. The main reason has been almost no drought occurrence since 1994. Therefore, the final average parameters of drought periods were mainly based only on the earlier period. Despite that fact, the most intensive hydrological droughts were caused by warm snow seasons (both WSS-A and WSS-B). These periods were the only droughts occurring in the last decade on the anthropogenic influenced part of the river. Considering the whole study period, the most often occurring drought type was the CL type, but which was not at all observed in the last decade. It shows that water management can avoid the hydrological drought, which is primarily caused by precipitation deficit. On the other hand, the drought periods caused by changing temperature conditions in snow season point on the importance of temperature observation regarding the forecasting of hydrological drought.

4 Summary and Conclusion

The experience of the last years raised the attention of researchers and the general public in the topic of drought and its impacts in Slovakia. The need to monitor its development in near real time led to the launching of the operational meteorological drought monitoring by the Slovak Hydrometeorological Institute. The indicators used for the monitoring obtain a daily overview of changing water balance. The first two monitoring seasons brought sufficient results describing the development of meteorological drought in Slovakia in detail.

The advantage of modified SPI and SPEI, which are used for the monitoring, lies in the possibility to compare them to the indicators used in other research disciplines such as hydrology or soil science. The promising results were obtained by the comparison of the operational indices to the relative soil humidity. Therefore, the meteorological drought monitoring could be a good tool for early warning even on the sites, where the measurement or modelling of soil humidity is problematic due to the lack of measured data. Moreover, the recorded correlation between the SPI/SPEI results and crop yields in the Danubian Lowland supports the applicability of both indices for agricultural purposes. Their operational form enables to monitor drought on a daily basis during different phenological phases.

The application of the modified SPI helped to identify different hydrological drought types. On the other hand, the analysis pointed to the fact that precipitation deficit is not the only cause of the drought occurrence. The air temperature in snow season is sometimes more important than precipitation deficit in the river basin.

To avoid damages caused by drought, it is necessary to design integrated drought monitoring as the important part of early warning system. The meteorological conditions are the starting point of drought spreading within the hydrological cycle. Therefore, well-designed meteorological drought monitoring, bringing sufficient information in near real time, is an assumption for the effective early warning system.

5 Recommendations

Recently, drought research has been accelerated, and many studies have been published. Most of them is focused only on one sector: climatology, hydrology or agriculture. In the future, the emphasis should be put on interdisciplinary approach leading to integrated drought monitoring. Such monitoring would bring relevant information for all interested groups and would be sufficient basis for effective early warning system. Integrated drought early warning system is another necessary output of future research for mitigating drought impact in the changing climate.

Current drought monitoring methods have still had several weaknesses. The influence of snow cover on hydrological drought occurrence is very important, especially in spring season, when the snow cover is melting and increases discharges. Changing snow conditions due to the climate change result in hydrological drought occurrence after weak snow season. Therefore, it is important to implement monitoring of snow cover into hydrological drought monitoring according to regional dependencies between these two phenomena.

The weakness of meteorological drought monitoring is the absence of method, which could separate intense precipitation as the result of convection. Such precipitation has often only local effect, and most of them form only surface runoff. The established drought indices such as the SPI, SPEI or CMI do not consider low efficiency of intensive precipitation for soil moisture improvement or vegetation condition. Their values increase often above 0 value after such event, but dry conditions persist in the landscape, e.g. in the form of low soil humidity. For integrated drought monitoring, it will be important to establish a method, which could eliminate impact of intensive precipitation on the estimation of drought indices.

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