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ASSESSMENT OF DROUGHT IN AGRICULTURAL REGIONS OF SLOVAKIA USING SOIL WATER DYNAMICS SIMULATION

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Assessment of agronomic drought occurrence and severity in agricultural regions of Slovakia is presented in the paper. Drought severity assessment is based on the soil water dynamics simulation by agroecological model Daisy. Daily meteorological data from the years 1961–2012 from 31 localities were used in simulations. Criteria for the drought occurrence were 1) available soil water content below 50% of available water capacity, 2) soil water content below long-term average soil water content and 3) duration of continuous drought for fifteen or more days. Standardized index of daily available soil water content was used for drought severity classification. According to the index the drought is categorized into four degrees of severity from mild to extreme drought. Cumulative sum of available soil water index was used to drought quantification throughout its duration. Normal climate period 1961–1990 was chosen as reference period to enable historical comparison of drought severity as well as climate change impacts. Extreme drought of the largest spatial extent was identified in 1990. Extreme drought occurred regionally in the southwest Slovakia in 1978 and in the southeast Slovakia in 1986, respectively.

Key words: drought, precipitation, evapotranspiration, soil water content, available soil water, Daisy model

Drought is one of the major natural events with large environmental and socio-economic impacts. With regard to the problem complexity and its several aspects general definition of drought and general method for its quantification does not exist. Drought in general influences water shortage in the soil, plants or in the atmosphere. There can be distinguished meteorological drought, agronomic drought, hydrological drought and physiological drought (Sobíšek *et al*. 1993). Agronomic drought is defined as soil water shortage in consequence of previous or prevailing meteorological drought. Its effect is gradually cumulated with extending the duration of the drought period. Start, duration and drought severity is strengthened with increasing air temperature.

Increased occurrence of extreme precipitation totals was observed on one hand and on the other hand, local or regional drought occurred more often in recent decades. According to the Fifth National Communication of the Slovak Republic on Climate Change (2009) extreme drought occurred in the years 1990 to 1994, 2000, 2002, 2003 and 2007. This fact was observed although average annual precipitation totals increased in two last decades in comparison to the normal period 1961–1990. Distribution as well as intensity of the precipitation was changed. Causality of increased drought occurrence is in increased evapotranspiration demand due to rising air temperature.

Drought impacts on land vulnerability will rise due to increasing commercial water requirements as well as climate change. Increasing number of unfavourable years for agricultural production from drought and heat waves in Europe with its economic consequences is assumed (EEA 2012).

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Drought is evaluated using various climatic indices usually calculated from empirical formulas. Climatic indices refer actual weather to the normal conditions and specify degree of drought abnormality. The most used climatic indices are % of normal, climate water balance, Humidity index according to Konček, Humidity index according to Thornthwaite, Lang's rain factor, Seljanin's hydrothermic coefficient (Sobíšek *et al*. 1993), Vysocki index, Budyko dryness index (Majerčák 2005), Aridity index (UNEP 1997), Standardised precipitation index SPI (McKee *et al*. 1993), Palmer drought severity index (Palmer 1965) and Crop moisture index CMI (Palmer 1968). Most of these indices are based only on precipitation. PDSI and CMI include simplified water balance. Choice and practical application of indices depends on user's demands.

Weakness of majority drought evaluating climatic indices is in no quantification the real water deficit due to different soil retention properties and that they do not reflect crop sensitivity to the water shortage. Time step used in the calculation can create disturbances too. Climatic indices which use annual or monthly data do not allow determine exactly the start and duration of drought.

For delimitation of drought periods is important to set the criteria. It is not sufficient to rely only on meteorological criteria when quantifying the drought in the soil. If criteria for the agronomic drought have been used it is possible to evaluate whether crop water requirements are fulfilled by the soil water storage at a given time (Tall & Kandra 2007).

Crop growth is limited by sufficient amount of the water for evapotranspiration. Thus as the most suitable for drought assessment become the methods based on the soil moisture calculation. Soil water content is one of the most dynamic soil properties. Soil water dynamics and consequently soil drought occurrence is response to the natural factors and their spatial and temporal variability, particularly weather, ground water level, topography, hydrogeological conditions, canopy, soil physical and hydrophysical characteristics. Spatial and temporal variability of the acting natural factors is reflected in the spatial and temporal variability of the soil water content which is cause why the soil moisture measurements are not realistic in appropriate extent as they are costly and time consuming. On the other hand, modelling allows obtain continual series of soil water content in the daily step.

The goal of the paper is to present methodology of drought quantification and classification providing identification of anomalies. Common procedures based on soil water balance are used. Analysis of drought occurrence in agricultural regions of Slovakia in the years 1961–2012 are presented.

MATERIAL AND METHODS

Soil moisture is the limiting factor of evapotranspration. When soil water content is sufficient actual evapotranspiration is equal to the potential evapotranspiration. When soil water content is lower than its critical value actual evapotranspiration is reduced proportionally. Soil water below wilting point is not available for plants. Available for plants is soil water in the interval between field capacity FC [mm] and wilting point WP [mm]. Amount of soil water available for the plants is called available water capacity AWC [mm]:

$$AWC = FC - WP \tag{1}$$

In agronomic practise soil water storage is usually expressed as available soil water content ASWC [mm]:

$$ASWC = SWC - WP \tag{2}$$

Or ASWC [% of AWC]:

$$ASWC = \frac{SWC - WP}{FC - WP} \cdot 100 = \frac{SWC - WP}{AWC} \cdot 100 \tag{3}$$

Soil water content SWC as well as FC and WP are calculated as weighted averages of horizons.

Equation (3) is usually used in irrigation schedules and soil moisture of 50% of AWC is in general recommendation to start irrigation of the key crops. Agronomic classification of soil water dynamics is based on the equation (3) (Benetin & Šoltész 1988).

To evaluate anomalies in time series standardised indices are suitable. Standardised indices express relative relation of variable deviation from the average to standard deviation of time series. In general, standardised indices are used to compare large data sets, e.g. SPI (McKee *et al*. 1993). Proposed

T a b l e 1

Degrees of drought severity based on the available soil water index ASWI

Drought degree	Extreme drought	Severe drought	Moderate drought	Mild drought	Wet
Probability interval [%]	≤ 2	2.1 to 10	10.1 to 25	25.1 to 50	≥ 50
ASWI interval [–]	≤ –1.8	–1.8 to –1.151	–1.15 to –0.721	–0.72 to 0	≥ 0

standardised available soil water index ASWI is calculated from available soil water content ASWC in daily steps according to the equation:

$$ASWI = \frac{ASWC - ASWC_{AVE}}{ASWC_{SD}} \quad (4)$$

Where $ASWC_{AVE}$ is long term average of ASWC and $ASWC_{SD}$ is standard deviation of ASWC. Similarly in case of climatic indices for $ASWC_{AVE}$ and $ASWC_{SD}$ calculation it is required 30 year duration of the time series. Normal climate period 1961–1990 was chosen as reference period to enable historical comparison of drought severity as well as climate change impacts.

Standardisation allows achieve index distribution close to the normal (Gaussian) distribution (Takáč 2012). In accordance with assessment established in climatology (Lapin *et al*. 1988) boundaries of 25 % exceeding probability for moderate drought, 10 % exceeding probability for severe drought and 2 % exceeding probability for extreme drought have been set (Figure 1). Standardisation of ASWC allows compare drought severity not only in different periods but also in different regions with various soil and climate conditions. Averages of ASWI from considered set of meteorological stations were –0.72 for moderate drought, –1.15 for severe drought and –1.81 for extreme drought, respectively. Medians of ASWI were –0.72, –1.16 and –1.80 for individual drought degrees, respectively (Takáč 2012).

Drought is related to the long term mean conditions and it is defined as long term occurrence of SWC below average value. Basic assumptions for drought are 1) the SWC is below 50% of AWC and 2) SWC is below long term average SWC at the same time. Drought duration was defined as consecutive days of negative ASWI. Exceeding probability intervals of ASWI were used for drought severity classification (Table 1). The beginning of a drought period of given degree is determined by the day when ASWI falls below threshold value and a drought continues until the threshold is exceeded again. In order to classify the drought in a particular degree the duration must be continuously at least 15 days. In the case that the relevant condition lasts more than 15 days, shorter wetter periods are not considered as the end of drought period when they lasted less than 10 % of previous drought period. These days are included in the drought period. Cumulative sum of ASWI was used to the drought quantification throughout its duration.

Drought assessment is based on the soil water dynamics simulations by agroecological model Daisy. Daisy simulates the crop production and the portion of water, nitrogen and carbon cycles that are related to the agricultural soil systems (Abraham-

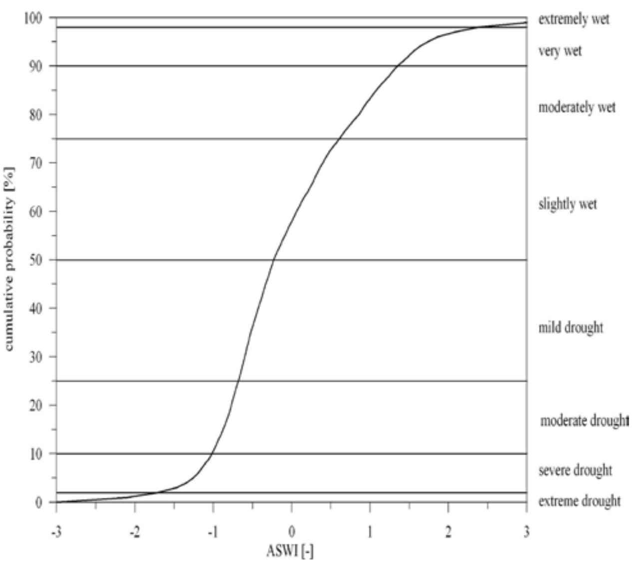

Figure 1. Cumulative probability of the ASWI in Hurbanovo in the period 1961–1990 and soil moisture classification based on the ASWI

T a b l e 2

Meteorological station position, climate subregions (LAPIN *et al.* 2002) and soil characteristics of simulated localities

Locality	Latitude N	Longitude E	Altitude a.s.l.	Climate subregion	Soil type	Soil texture	*FC* [mm]	*WP* [mm]	*AWC* [mm]
Kuchyňa	48°24′	17°09′	206	T6	Regosol	Sandy loam	230	51	179
Stupava	48°17′	17°01′	179	T4	Fluvisol	Sandy loam	244	67	177
Myjava	48°46′	17°35′	375	T6	Cambisol	Silt loam	377	168	209
Bratislava	48°10′	17°12′	131	T2	Chernozem	Silt loam	359	122	237
Hurbanovo	47°52′	18°12′	115	T1	Chernozem	Loam	340	124	216
Kráľová pri Senci	48°12′	17°28′	123	T1	Chernozem	Loam	324	108	216
Žihárec	48°04′	17°52′	111	T1	Chernozem	Silt loam	349	133	216
Jaslovské Bohunice	48°29′	17°40′	176	T2	Chernozem	Silt loam	369	147	221
Piešťany	48°37′	17°50′	165	T2	Fluvisol	Silty clay loam	377	192	185
Podhájska	48°06′	18°20′	140	T1	Chernozem	Silt loam	307	91	216
Nitra	48°19′	18°07′	173	T2	Luvisol	Silty clay loam	369	160	208
Trenčín	48°52′	18°01′	205	T4	Luvisol	Silt loam	319	122	197
Beluša	49°04′	18°19′	254	M1	Luvisol	Silt loam	346	128	218
Topoľčany	48°34′	18°09′	174	T2	Luvisol	Silty clay loam	376	165	211
Dudince	48°10′	18°52′	140	T2	Cambisol	Silty clay	395	212	183
Dolné Plachtince	48°12′	19°19′	200	T4	Luvisol	Silty clay	390	193	197
Bzovík	48°19′	19°06′	355	T4	Cambisol	Silty clay loam	363	176	187
Žiar nad Hronom	48°35′	18°52′	250	T6	Fluvisol	Loam	281	92	189
Sliač	48°39′	19°08′	313	T7	Luvisol	Silt loam	346	135	211
Lučenec	48°20′	19°44′	214	T3	Luvisol	Silt loam	387	196	191
Rimavská Sobota	48°22′	20°01′	214	T5	Luvisol	Silt loam	379	164	215
Rožňava	48°39′	20°32′	289	T7	Cambisol	Silt loam	353	139	214
Moldava nad Bodvou	48°37′	21°00′	210	T7	Fluvisol	Silt loam	324	121	213
Košice	48°40′	21°13′	230	T5	Luvisol	Silt loam	362	141	220
Somotor	48°24′	21°49′	100	T3	Fluvisol	Loam	322	113	209
Michalovce	48°45′	21°57′	112	T5	Fluvisol	Silt loam	383	163	220
Trebišov	48°40′	21°44′	104	T3	Fluvisol	Silty clay	423	194	229
Vysoká nad Uhom	48°37′	22°05′	105	T5	Fluvisol	Silt loam	394	173	221
Kamenica nad Cirochou	48°56′	22°00′	178	T7	Fluvisol	Silt loam	360	139	221
Stropkov	49°13′	21°39′	219	T7	Luvisol	Silt loam	335	113	222
Spišské Vlachy	48°57′	20°48′	396	M2	Cambisol	Silt loam	344	133	211

T1 warm, very dry, with mild winter; T2 warm, dry, with mild winter; T3 warm, dry, with cool winter; T4 warm, moderately dry, with mild winter; T5 warm, moderately dry, with cool winter; T6 warm, moderately humid, with mild winter; T7 warm, moderately humid, with cool winter; M1 moderately warm, moderately humid, with mild winter; M2 moderately warm, moderately humid, with cool winter; FC field capacity; WP wilting point; AWC available water capacity sen & Hansen 2000; Hansen *et al*. 1990; Hansen 2000). The hydrological processes simulated by the model include snow accumulation and melting, interception, evaporation from the canopy, infiltration, ponding, surface runoff, water movement in soil matrix and macropores. Movement of the water within unsaturated zone is based on the numeric solution of the Richards equation (Richards 1931). Reliability of the model has been demonstrated in several comparative studies (Kröbel *et al*. 2010; Palusao *et al*. 2011; Rötter *et al*. 2012). Model crop parameters were optimised and verified for Slovak condition on the basis of experimental data (Takáč & Šiška 2011).

Table 3

Mean annual simulated soil water content SWC [mm], available soil water content ASWC [mm] and available soil water content ASWC [%] in the soil profiles 0–30 cm and 0100 cm in the period 1961–1990

Locality	0–30 cm			0–100 cm		
	SWC [mm]	*ASWC* [mm]	*ASWC* [%]	*SWC* [mm]	*ASWC* [mm]	*ASWC* [%]
Kuchyňa	51	34	59	152	101	57
Stupava	52	36	64	186	119	67
Myjava	88	59	79	353	185	89
Bratislava	76	43	57	266	144	61
Hurbanovo	70	37	57	246	122	57
Kráľová pri Senci	65	37	53	227	119	55
Žihárec	82	41	62	271	138	64
Podhájska	63	33	53	207	115	53
Jaslovské Bohunice	83	43	59	290	143	65
Piešťany	91	38	62	323	131	71
Nitra	86	43	60	293	133	64
Trenčín	76	42	58	273	151	77
Beluša	89	59	87	335	207	95
Topoľčany	76	37	53	292	126	60
Dudince	97	43	68	364	152	83
Bzovík	88	42	74	342	166	89
Žiar nad Hronom	77	49	84	267	175	93
Sliač	90	58	85	337	203	95
Dolné Plachtince	96	43	64	350	158	80
Lučenec	83	47	63	323	127	66
Rimavská Sobota	82	54	68	338	174	81
Rožňava	82	56	79	333	194	91
Moldava nad Bodvou	81	56	81	313	192	90
Košice	80	48	65	301	160	73
Somotor	78	45	66	256	143	68
Michalovce	89	53	73	321	158	72
Trebišov	99	46	73	348	154	67
Vysoká nad Uhom	93	50	72	357	184	83
Kamenica nad Cirochou	95	61	84	346	207	94
Stropkov	84	59	84	323	210	94
Spišské Vlachy	86	51	78	323	190	90

Daily data of mean, maximum and minimum air temperature, air humidity, global radiation, wind speed and precipitation for the period 1961 to 2012 from 31 meteorological stations used in simulations were provided by Slovak Hydrometeorological Institute. Simulations were carried out for five field crops (winter wheat, spring barley, maize, sugar beet and potato) and permanent grassland. Each crop was simulated every year in cropping patterns in six model runs.

Simulations were performed for representative soil profiles of considered regions (Table 2). Representative soil profiles were selected from the soil database of Complex soil survey of Slovakia (Nováková & Skalský 2006; Skalský & Balkovič 2002). Soil horizons were defined by texture, bulk density,

T a b l e 4

Sum of ASWI in five driest periods on the selected sites

Locality	1		2		3		4		5	
	year	ΣASWI	year	ΣASWI	year	ΣASWI	year	ΣASWI	year	ΣASWI
Kuchyňa	1990	–695.6	1997	–339.3	1974	–264.8	2012	–263.2	1978	–257.7
Stupava	1990	–758.4	1974	–248.2	1978	–235.8	1983	–232.9	2012	–220.8
Myjava	1991	–177.0	2003	–168.9	2000	–168.3	1989	–145.9	1992	–138.1
Bratislava	1990	–585.7	1978	–365.7	1998	–338.2	1977	–279.3	2003	–278.2
Hurbanovo	1978	–603.1	1990	–569.2	2012	–285.0	1983	–198.0	2003	–171.8
Kráľová pri Senci	1990	–766.0	1978	–588.1	2012	–230.6	1983	–228.0	1991	–197.3
Žihárec	1990	–732.1	2012	–339.7	1978	–258.3	2011	–219.7	1968	–210.5
Jaslovské Bohunice	1990	–868.6	1978	–293.2	1991	–225.6	1997	–217.5	1998	–215.0
Piešťany	1989	–353.0	1978	–268.5	1983	–224.4	1990	–190.7	1971	–178.3
Podhájska	1990	–539.0	1978	–315.1	1971	–295.3	1983	–254.2	2012	–183.1
Nitra	1990	–684.2	2012	–273.7	1978	–230.8	2006	–218.1	1971	–203.1
Trenčín	1989	–396.6	1997	–344.0	1996	–294.5	1990	–238.5	1973	200.0
Beluša	2003	–315.9	2011	–285.8	2012	–282.6	2000	–266.1	1983	–221.4
Topoľčany	1990	–697.6	1971	–290.2	1978	–273.0	1983	–268.4	2012	–202.0
Dudince	1990	–202.2	1997	–132.7	2000	–130.9	1962	–129.0	1983	–126.6
Dolné Plachtince	1986	–191.9	2011	–177.9	1990	–167.1	2000	–148.0	1983	–142.5
Bzovík	1990	–233.8	2000	–183.0	1993	–178.7	1982	–125.1	2007	–123.0
Žiar nad Hronom	2000	–265.8	1993	–241.5	2012	–227.4	2003	–199.5	2009	–195.7
Sliač	2012	–252.5	2000	–251.0	1993	–198.1	1983	–185.7	1973	–153.8
Lučenec	2002	–564.7	1989	–403.0	1988	–283.0	2012	–268.1	1983	–230.8
Rimavská Sobota	2012	–248.2	1963	–203.3	2000	–200.8	1986	–194.5	1993	–193.7
Rožňava	1986	–260.0	1982	–232.5	2012	–213.5	2003	–213.1	1993	–212.3
Moldava nad Bodvou	1986	–358.2	2011	–295.4	1993	–280.8	1964	–217.6	1968	–211.3
Košice	1973	–361.0	2002	–365.2	1986	–342.2	2012	–292.1	1993	–234.4
Somotor	1990	–301.4	1986	–295.4	2002	–245.5	1962	–234.9	1964	–234.4
Michalovce	1986	–420.9	1963	–292.5	1961	–283.6	2011	–231.8	1987	–215.0
Trebišov	1986	–359.4	1999	–184.1	1973	–165.4	1993	–153.0	2009	–152.0
Vysoká nad Uhom	1986	–374.2	2011	–234.9	1961	–231.9	1962	–188.3	2009	–163.4
Kamenica nad Cirochou	1961	–360.8	2003	–215.5	1962	–195.1	1964	–124.0	2007	–122.5
Stropkov	1961	–351.9	2003	–221.1	1962	–178.1	1964	–175.8	2011	–157.0
Spišské Vlachy	1961	–412.8	1962	–277.8	1964	–160.3	1993	–156.1	1967	–141.9

retention curve parameters, saturated hydraulic conductivity, humus content and C / N ratio.

RESULTS AND DISCUSSION

Crop yields crucially depend on weather. Yield variability is significantly affected by soil water dynamics in growing period as well as outside of growing period. Consequence is given to the winter water supply. It is optimal if sufficient snow cover was formed during the winter and snow melts slowly in early spring. Distribution of the precipitation during the growing season plays important role too.

Soil water content shows natural annual cycle. Maximum soil water storage is at the end of the winter and minimum occurs in the summer months. For impacts of drought on crop growth, the drought duration, intensity and time of occurrence in terms of the crop development stage is crucial. In the case of extreme drought the impacts on yields may be severe.

Wet period with SWC above 50% of AWC dominates during the winter months. Drought of different intensity with SWC below 50% of AWC occurs almost every year in the summer months. Drought starts usually at first in southwest Slovakia later in central and eastern Slovakia. SWC falls below 50% of AWC in the western lowlands on average during June and in the south of central and eastern Slovakia in July (Figure 2). Drought severity and duration are different in each year. This can occur in early spring in some years or drought may persist from autumn and winter due to the lack of precipitation. In some years, the persistent winter drought continues over the next year. If soil water storage has not been refilled during the winter months the impacts of low summer precipitation are strengthened and almost complete drying of soil profile occurs.

Soil moisture is spatially heterogeneous. Soil water storage depends not only on refilling from precipitation and ground water table but it also depends on soil retention properties. The soil can retain different amounts of water in dependence on soil texture. The same quantity of water may represent sufficiency in one soil but deficiency in the other. Sandy soils have very little available water capacity. Loamy soils have the highest available water capacity. The time necessary for the formation of soil water deficit is different in dependence on soil retention capacity and thus the time when meteorological drought proceeds to the agronomic drought is different in dependence on soil retention capacity.

Effect of soil properties on available quantity of water for crops is obvious from the comparison of different way of expressing average SWC (Table 3). Although average precipitation totals in Kuchyňa are higher than in Hurbanovo average ASWC on loamy chernozem in Hurbanovo is higher than average ASWC on sandy loam regosol in Kuchyňa. The same amount of SWC in Spišské Vlachy and Stropkov signifies different ASWC. The same amount of ASWC [mm] in Stupava and Kráľová pri Senci signifies different ASWC expressed in percentage. Different texture of soil horizons in Kuchyňa and

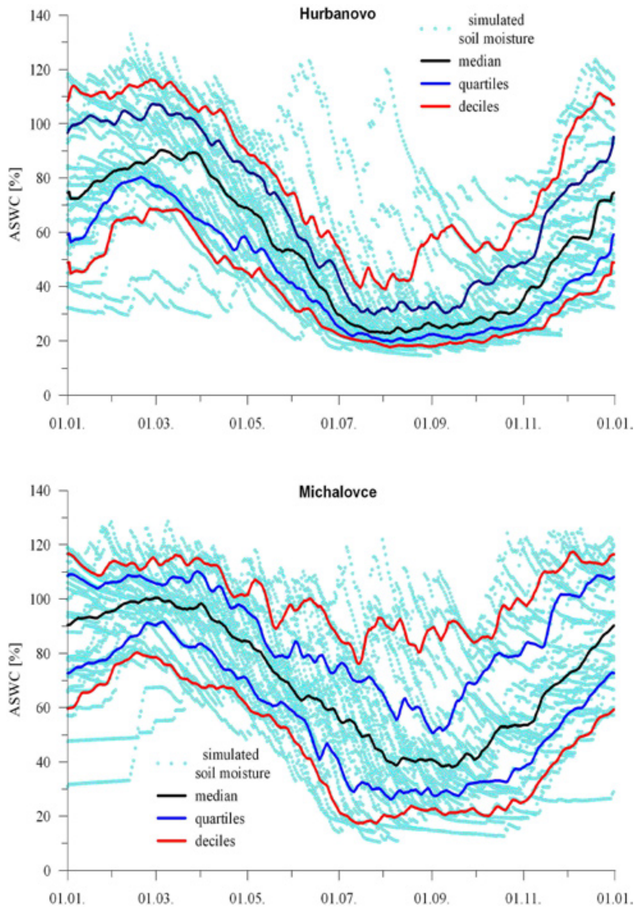

Figure 2. Annual cycle of soil water content [% of AWC] in the soil horizon 0–100 cm in the period 1961–1990 in Hurbanovo and Michalovce

Trebišov is reflected in lower ASWC [%] of entire soil profile compared to the topsoil. There exist horizons below topsoil with lower AWC compared to AWC of the topsoil in these localities.

The highest average annual SWC was calculated throughout Slovakia in the years 1965 and 2010 (Figure 3). The lowest average annual SWC was simulated on the majority of localities in the year 1990. Average annual SWC was extremely low in the southwest also in the year 1978. Cause of the extremely low SWC in the years 1978 and 1990 is not only low precipitation in the summer months but also insufficient precipitation in the preceding winter period when soil water storage was not filled up as it was usual in the other years. Similar situation was also in the year 2012 when precipitation below average was recorded from the summer of the year 2011 to the autumn of the year 2012.

Occurrence and duration of the period with SWC below 50% of AWC is different in the individual regions. Such period occurs in the west Slovakian lowlands almost every year. Median of continuous period with SWC below 50% of AWC is more than 50 days on the majority of evaluated sites. Median of continuous dry period is 166 days in Kuchyňa, 168 days in Hurbanovo and 169 days in Podhájska and Kráľová pri Senci (Figure 4). On these sites is one of four years SWC below 50% of AWC more than 200 days. Average number of days with SWC below 50% of AWC from 31 sites

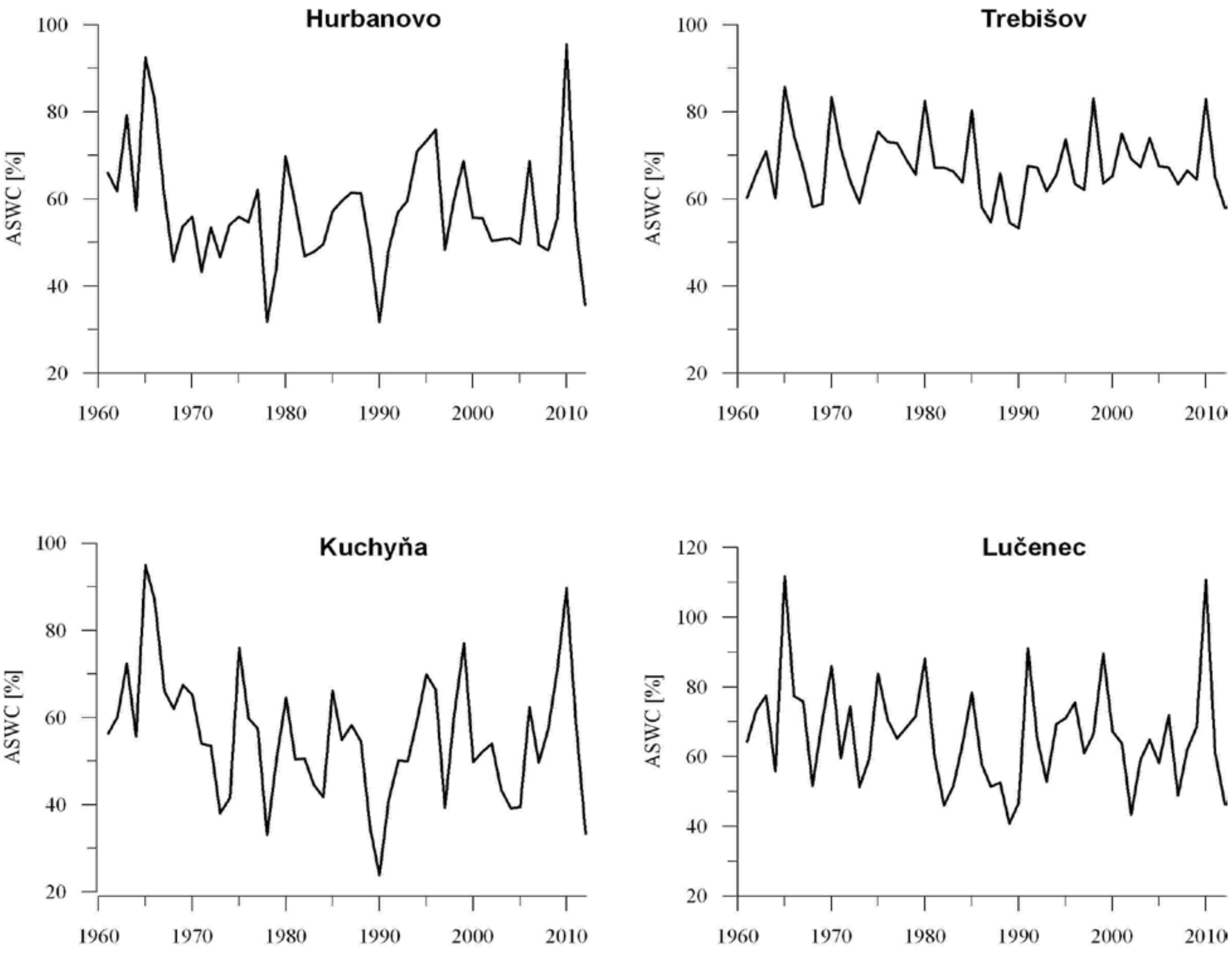

Figure 3. Mean annual soil water content SWC [% of AWC] in selected sites in the period 1961–2012

was 90 days in the period 1961–1990 and 96 days in the period 1991–2012.

Alternating wet and dry periods differs from the annual cycle according to the average monthly ASWI. Relatively dry and wet periods often last for more than one year (Figure 5). The longest recorded period of below-average soil moisture at most sites was around 2 years. The longest period was recorded in the Záhorská lowland and lasted from October 1988 to December 1991, i.e. 39 months.

According to the sum of ASWI the year 1990 was identified as the driest year on 12 from 31 sites mainly in the western Slovakia (Table 4). The driest year in southeast Slovakia was the year 1986 and in the northeast Slovakia the year 1961. The second driest year in the western Slovakia was the year 1978. The year 1983 was found mostly as the fourth or fifth driest year in western and central Slovakia. The year 2012 was in the majority of cases the third driest year but the driest year in Rimavská Sobota and Sliač. Severe drought that occurred in other years had only local importance. These results correspond with the order of years according to the average annual SWC (see above).

Continuous drought persisted more than 400 days in period 1989–1990, the longest in Kráľová pri Senci – 593 days (Table 5). The lowest ΣASWI was calculated in Jaslovské Bohunice (–868.6). Extreme drought in western Slovakia in the year 1990 was preceded by moderate to severe drought in the year 1989. Drought of 1989 continued steadily until 1990 in Záhorská lowland and in the southwest of Danubian Lowland while elsewhere it was interrupted for varying lengths of time. In some sites the drought in the previous year 1989 was more severe than the drought in the year 1990 (Myjava, Piešťany and Lučenec). For instance in Lučenec severe drought occurred already in the year 1988. Severe and extreme drought continued also in the year 1989 till April 1990. Moderate

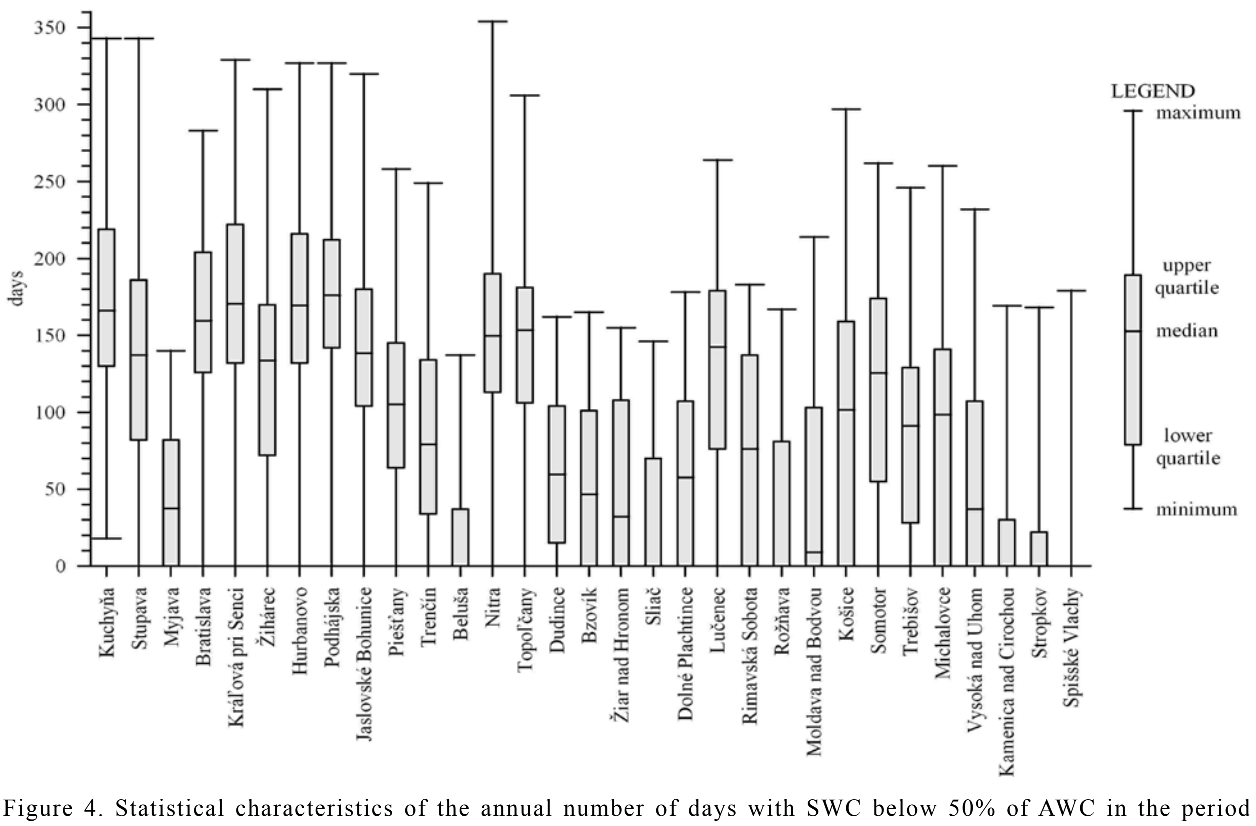

Figure 4. Statistical characteristics of the annual number of days with SWC below 50% of AWC in the period 1961–2012

drought followed from the end of June to the end of October 1990 (Figure 6).

In western Slovakia was extremely dry also the year 1978 that was preceded by moderate and severe drought in the year 1977. Severe and extreme drought continued in the southern part of Danubian Lowland also in the year 1979. Continuous drought persisted more than 200 days in this region, in Hurbanovo and Kráľová pri Senci it was almost 600 days. The lowest ΣASWI was calculated in Hurbanovo (–603.1). Neither in the southern part of central Slovakia nor in the eastern Slovakia the drought was present in the year 1978. For instance there were only 47 days of mild and moderate drought in Lučenec and 39 days of mild drought in Michalovce in the year 1978. In this part of Slovakia were the years 1977 and 1979 drier than the year 1978.

Continuous drought in East Slovakian Lowland lasted more than 200 days only in the year 1986. The lowest ΣASWI was calculated in Michalovce (–420.9).

Median of ΣASWI and lower quartile from 31 sites in the reference period 1961–1990 were –49 and –105, respectively. Median of ΣASWI and lower quartile decreased in the period 1991–2012 to –75 and –133, respectively. According to the average of ΣASWI from 31 sites equal to –240 the year 1990 was the driest one. The ΣASWI in the year 1990 was less than –100 in 21 sites, of which less than –200 in 14 sites and less than –300 in 10 sites.

From the assessment of the drought occurrence and duration according to ΣASWI it is evident that in the last decades the extreme drought occurs also in the regions in which drought has occurred in the

Table 5

Drought characteristics in the year 1990

Locality	Rank	Start date	End date	Continuous drought		Of which [days]		
				[days]	Σ ASWI [–]	Moderate drought	Severe drought	Extreme drought
Kuchyňa	1	10.5.1989	9.12.1990	579	–695.6	404	239	139
Stupava	1	24.5.1989	9.12.1990	565	–758.4	442	220	151
Bratislava	1	13.9.1989	17.11.1990	431	–585.7	376	225	147
Hurbanovo	2	17.9.1989	28.10.1990	433	–569.2	345	205	155
Kráľová pri Senci	1	12.4.1989	25.11.1990	593	–766.0	489	297	157
Žihárec	1	15.6.1989	18.11.1990	522	–732.1	436	258	166
Podhájska	1	23.9.1989	28.10.1990	401	–539.0	370	218	130
Nitra	1	18.9.1989	17.11.1990	426	–684.2	380	260	156
Jasl. Bohunice	1	13.4.1989	16.11.1990	583	–868.6	503	350	197
Piešťany	4	19.5.1990	28.10.1990	163	–190.7	140	112	54
Trenčín	4	21.5.1990	23.9.1990	126	–238.5	109	57	35
Topoľčany	1	12.5.1989	28.10.1990	535	–697.6	426	233	142
Dudince	1	20.5.1990	28.10.1990	162	–202.2	162	107	0
D. Plachtince	3	16.6.1990	28.10.1990	135	–167.1	135	41	0
Bzovík	1	17.5.1990	28.10.1990	165	–233.8	165	107	22
Lučenec	23	22.6.1990	28.10.1990	129	–109.6	67	0	0
Rimavská Sobota	27	21.7.1990	7.10.1990	79	–67.0	54	0	0
Michalovce	30	16.7.1990	6.10.1990	83	–50.3	35	0	0
Trebišov	11	21.7.1990	28.10.1990	100	–82.6	71	0	0
Somotor	1	23.3.1990	2.11.1990	225	–301.4	220	103	53

previous decades only rarely. Five driest periods occurred in Myjava from the year 1989 and in Žiar nad Hronom from the year 1993. Four driest periods occurred in Beluša from the year 2000 (Table 4). Regional extent of drought increased in the last two decades. While in the period 1961–1990 ΣASWI < –100 was on average annually at 9 sites, in the period 1991–2012 it was already on average annually at 12 sites. ΣASWI < –100 in 20 and more sites occurred in the years 1983, 1990, 2000, 2003, 2007, 2011 and 2012, thus mainly after 1990. Drought of ΣASWI < –100 had the largest spatial extension in the years 2003, 2000 and 2012 when occurred at 28, 27 and 28 sites, respectively thus again in the recent

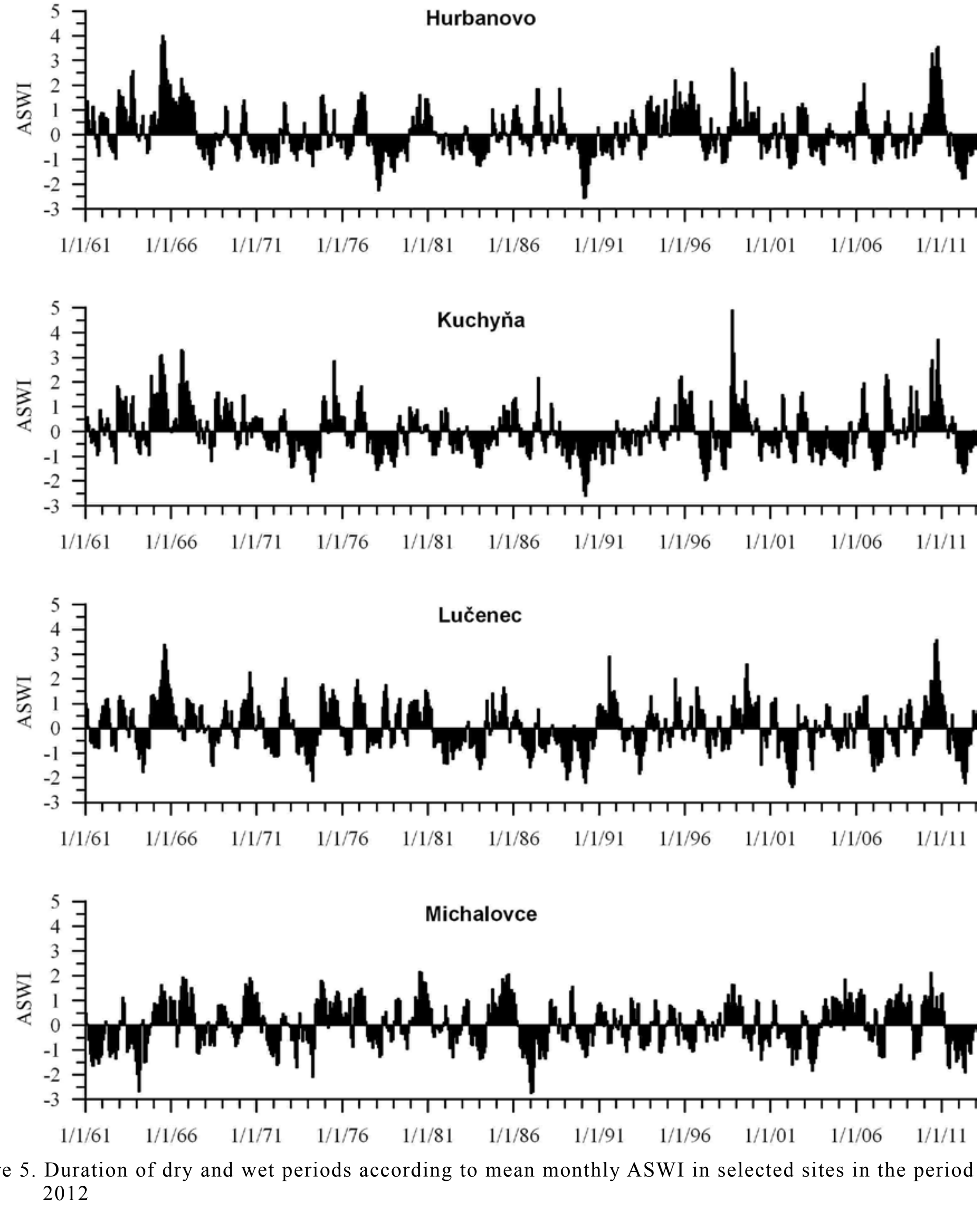

Figure 5. Duration of dry and wet periods according to mean monthly ASWI in selected sites in the period 1961–2012

years. Drought of ΣASWI < –100 had the largest spatial extension in the year 2012 when this value was reached even at 16 sites.

As regards the climate indices the driest year according to the Aridity index was the year 2003 in western Slovakia and the year 1961 in eastern Slovakia. The driest years according to the percent of normal as well as SPI were the years 2003, 1971 and 1989 in western Slovakia and the year 1961 in eastern Slovakia. The years 2003, 2011 and 1986 were driest according to the climate water balance (Takáč *et al*. 2012). According to ΣASWI of the above years the year 2003 was the driest one only in Beluša and second driest year in four sites. The years 1961 and 1986 were the driest years in 3 sites and in 6 sites in eastern Slovakia, respectively. The year 1989 was the driest years in 2 sites in the middle part of Váh river basin.

Tall and Gomboš (2011) carried out evaluation of the drought in Milhostov in East Slovakian Lowland using several climatic indices. The driest years were the years 1961, 1967 and 1993 according to Lang's rain factor and Seljanin's hydrothermic coefficient, the years 1967, 1961 and 1993 according to Vysocki index, the years 1967, 1961 and 2003 according to the climate water balance, the years 2007, 1986 and 1996 according to the evapotranspiration deficit and the years 2007, 1968 and 1969 according to the PDSI. As shown usage of various indices gives different results. From all these years only the year 1986 was calculated among three driest years in this site according to ΣASWI.

When climatic indices are used entire precipitation totals are included in calculation. There is not considered surface runoff in the case of inefficient heavy rainfall. Models simulate surface runoff and in addition they include water losses due to interception, evaporation from the canopy, ponding, percolation from macropores and soil matrix. These processes play an important role in the soil water balance. Therefore simulation results give more precise information on water availability for crops and drought occurrence.

CONCLUSION

Prolonged continuous dry periods occur regularly in the lowlands. Duration of the continuous dry periods is shorter in the foothill areas and basins. Generally occurrence and duration of dry peri-

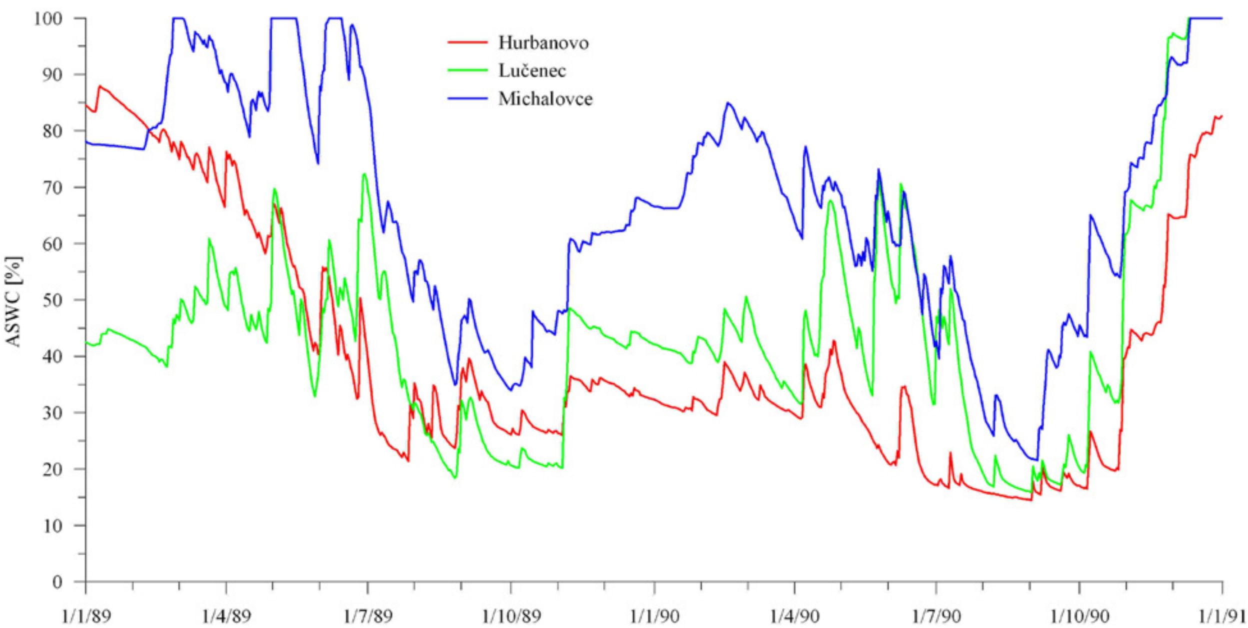

Figure 6. Daily soil water content SWC [% of AWC] in selected sites in the period 1989–1990

ods decreases from south to north and from west to east. This zoning is partially interrupted due to the different soil retention capacity in evaluated sites. Alternating wet and dry periods differs from the annual cycle. Drought severity strengthens when the drought occurred also in the previous year.

The procedure used allows classify the long-term drought throughout the duration of its effects. It is applicable to assess the current situation in real time. The introduction of the reference period allows expression of the drought severity in historical context. Linking climate database, soil database and GIS enables use this procedure to build an information system of drought. For the assessment of the long term trends is necessary to use the longest time series.

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