Original paper

CROP WATER SUFFICIENCY IN SLOVAKIA

Jozef Takáč, Blanka Ilavská

National Agricultural and Food Centre – Soil Science and Conservation Research Institute, Slovak Republic

Corresponding author: *RNDr. Jozef Takáč, PhD., National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Trenčianska 55, 821 09 Bratislava, Slovakia, e-mail: jozef.takac@nppc.sk; ORCID ID: 0000-0003-4923-4601*

Citacion: Takáč, J., Ilavská, B. (2021). Crop water sufficiency in Slovakia. In: *Pedosphere Research,* vol. 1, 2021, no. 1, pp. 20 – 39. NPPC – VÚPOP 2021. ISSN 2729–8728.

Abstract

An assessment of the trend in crop water sufficiency was made for the period 1961 – 2020. Agro-climatic indices and simulations of water balance and crop water stress with the DAISY model were used for the assessment. The coverage of crop water requirements is insufficient in the southern regions, with soil water scarcity being the main limiting factor for agricultural production, especially in the Danube Lowland. A decrease in crop water availability in the period 1991-2020 compared to the period 1961 – 1990 has been observed, mainly due to rising temperatures and thus increasing environmental evapotranspiration requirements. The highest increase in moisture demand of crops in the period 1991 – 2020 compared to the period 1961 – 1990 was recorded in the west and north of the Danube Lowland, in the case of summer crops an above-average increase in moisture demand was also recorded in Central Pohronie and East Slovakia. In the area of Bratislava and Nitra, the need for spring barley and winter wheat increased by more than 50 mm. The moisture demand for maize also increased the most in these two regions, by more than 100 mm. Within individual regions, there is spatial variability depending on soil properties and the presence of groundwater levels. The smallest average supply of available soil water in the Danube Lowland was simulated for Luvisols and Haplic Chernozems. Despite the fact that no area in Slovakia meets the conditions for designation as dry, the coverage of crop moisture needs is insufficient in the southern regions, while the lack of soil water is the main limiting factor of agricultural production, especially in the Danube Lowland.

Keywords: crop water requirements, precipitation, evapotranspiration, available water capacity, soil type, soil texture, Slovakia

INTRODUCTION

Water in the soil-crop-atmosphere system is one of the fundamental and limiting factors in crop production. Our main agricultural production areas are located in the lowlands, which are characterised by lower rainfall totals than potential evapotranspiration during the growing season. The warm lowland climate and the evaporative regime of the soils result in insufficient water supply for agricultural crops. It is natural that the role of the soil water regime has always been emphasised when assessing the impact of climate on agricultural production in the Slovak Republic.

In areas without the influence of the water table, which is a significant part of the agricultural landscape, precipitation is the only source of water supply to the root zone. According to The Sixth National Communication of the Slovak Republic on Climate Change (2013), air temperatures have been rising in recent decades, and the distribution and intensity of precipitation has also changed. A comparison of annual and seasonal mean air temperatures at different periods shows a gradual warming in all regions of Slovakia. Annual precipitation totals decreased by an average of 1.3% in Slovakia over the period 1881 – 2012, with a decrease of more than 10% in southern Slovakia. The increase in temperature, together with changes in precipitation totals and the distribution of precipitation during the year, is reflected in changes in the individual elements of the water balance.

As a result of the increase in temperatures, the onset of the growing season was 16 days earlier in the 1991 – 2016 period compared to the 1961 – 1990 period, while the end of the growing season was 10 days later, thus the main growing season lasted on average 26 days longer in the 1991 – 2016 period than in the 1961 – 1990 period (Takáč *et al.* 2017).

Evapotranspiration is an important characteristic of the natural environment and its water balance. Evapotranspiration as an important component of the water balance characterising the flow of water from the Earth's surface to the atmosphere is a useful indicator for assessing the moisture conditions of the territory in time and space. With respect to the water balance, evapotranspiration is the dominant loss component. It consists of evaporation from the soil together with transpiration from the area covered by vegetation. The limiting factor for evapotranspiration is the water supply in the soil profile. If the soil contains sufficient water, the actual evapotranspiration is equal to the potential evapotranspiration. When the soil moisture is less than its critical value, the actual evapotranspiration decreases in proportion to the decrease in soil moisture.

As a consequence of increasing temperatures, potential evapotranspiration totals and thus crop water requirements are increasing. As reported in the Sixth National Communication of the Slovak Republic on Climate Change (2013), potential evapotranspiration has increased across the country, most notably in the south, in Hurbanovo since 1951 by up to 100 mm. As a result of the warmer climate and higher potential evapotranspiration, periods of lower rainfall after 1990 were drier and longer than before.

The results of soil water simulations confirmed the trend of decreasing average soil water content and gradually increasing duration of the soil moisture period between the semiarid and arid intervals on the Žitný ostrov (Takáč 1999). For the period 1951 – 2000, the largest annual values of evapotranspiration deficit were observed in the Danube Lowland (more than 300 mm), exceeding 250 mm in the East Slovakian Lowland and 240 mm in the Záhorská Lowland and in the south-central Slovakia. Annual values of relative evapotranspiration were less than 60% in the Danube Lowland, and did not exceed 65% in the Záhorská and East Slovak Lowlands (Tomlain *et al.* 2002).

According to climate change scenarios, the soil water deficit in the Danube Lowland will increase in the growing season (Takáč 2001, Takáč *et al.* 2008). The results of the assessment of climate change impacts on agricultural production areas showed that the equilibrium climatic water balance will shift from 550 m a.s.l. to 650 m a.s.l. According to the calculated mean values, the water sufficiency of crops with a growing season in spring will improve, but the variability will increase. Conversely, the water sufficiency of crops with a growing season in the summer months will worsen (Takáč, Šiška, Lapin 2009). A significant part of the territory of Slovakia in the most agriculturally important areas (8 800 km^2) will be characterised by an average water balance deficit of more than 250 mm (Šiška & Takáč 2009). In the warm and dry climate of the Danube Lowland, production potential will be increasingly limited by decreasing water availability for crops and heat stress (Eitzinger *et al.* 2013). A trend of severe or extreme drought in summer has been confirmed for most of the monitored stations in the lowland areas (Nikolová *et al.* 2016).

The water sufficiency of crops is most often assessed by various climatic indices, usually calculated by an empirical formula. Climate indices put actual weather into a historical context, expressing deviations from normal conditions and thus quantifying the degree of abnormality of a given drought. In our context, the most commonly used climate index is the percentage of normal rainfall, expressing the ratio of current rainfall to long-term rainfall averages. Climatic indices used in our country include the climate water balance and the Konček humidity index. In recent years, other indices known from abroad have also been applied in our country, such as the Aridity Index (UNEP 1997), the Standardised Precipitation Index SPI (McKee *et al.* 1993) and the Standardised Precipitation Evapotranspiration Index SPEI (Vicente-Serrano, Lopéz-Moreno 2005) for example in the works of Takáč *et al.* (2010), Takáč (2015), Labudová *et al.* (2016) and Labudová *et al.* (2018).

Some of these indices are based on precipitation totals only, others also take into account air temperature or evapotranspiration. The disadvantage of these indices is that they do not capture the water requirement of specific crops. Indeed, the coverage of the crop water requirement is determined by a combination of climatic factors, soil factors and crop factors.

The aim of the paper is to evaluate the trend in crop water availability in the period 1961 – 2020 in the Slovak Republic using agro-climatic indices.

MATERIALS AND METHODS

In order to express the water sufficiency of a given crop, the reference crop evapotranspiration has been replaced by the potential evapotranspiration of a specific crop equal to the crop water requirement in the established agro-climatic indices Climatic Water Balance, Evapotranspiration Deficit and Relative Evapotranspiration. The indices were calculated for the period from sowing to harvest according to the following formulae:

Crop precipitation deficit *CPD* [mm]:

$$CPD = ET_c - R \tag{1}$$

Where *ETc* is crop water requirement [mm] and *R* is precipitation [mm],

Crop evapotranspiration deficit *CED* [mm]:

$$CED = ET_c - ET_a \tag{2}$$

Where *ETa* is actual evapotranspiration [mm],

Relative crop evapotranspiration [%]:

$$RCE = \frac{ET_a}{ET_c} \times 100 \tag{3}$$

The Penman-Monteith equation was used to calculate the reference crop evapotranspiration ET_0, as modified by FAO. The crop water requirement equal to the potential crop evapotranspiration ET_c was calculated from the reference crop evapotranspiration (Allen *et al.* 1998).

The assessment of crop water sufficiency was also based on numerical simulations with the agroecological model DAISY. DAISY is a one-dimensional agroecosystem model that simulates crop growth and development, soil water dynamics, thermal regime, organic matter balance and nitrogen dynamics in agricultural soils. The hydrological cycle simulates soil matrix and macropore water flow, infiltration, snowpack accumulation and melting, surface and subsurface runoff, evapotranspiration and interception (Hansen *et al.* 1990, Abrahamsen & Hansen 2000, Hansen 2000). The calculation of actual evapotranspiration in the DAISY model includes evaporation from interception, dew and snow cover in addition to soil evaporation and crop transpiration. In our calculations, we considered only the sum of transpiration and soil evaporation as actual evapotranspiration.

Crop parameters of the model were calibrated for Slovak conditions and verified on experimental data from field trials (Takáč 1994, Takáč & Šiška, 2011, Takáč *et al.* 2018). The reliability of the model has been demonstrated in several comparative studies (Diekkrüger *et al.* 1995, Kröbel *et al.* 2010, Palusao *et al.* 2011, Rötter *et al.* 2012, Andrade *et al.* 2021).

Table 1

Characteristics of the selected sites. W_{FC} – soil water content 0 – 100 cm at field capacity, W_{WP} – soil water content 0 – 100 cm at wilting point and *AWC* – usable soil water content 0 – 100 cm

Locality	**Soil group (WRB 2007)**	**Texture**	W_{FC} **[mm]**	W_{WP} **[mm]**	***AWC*** **[mm]**
Kuchyňa	Haplic Regosols	Sandy loam	230	51	179
Stupava	Haplic Phaeozems	Sandy loam	244	67	177
Malacky	Haplic Phaeozems	Sandy loam	264	78	186
Holíč	Haplic Phaeozems	Loamic	355	158	197
Myjava	Haplic Cambisols	Clay loam	377	168	209
Bratislava	Haplic Chernozems	Loamic	359	122	237
Hurbanovo	Haplic Chernozems	Loamic	348	124	224

Locality	Soil group (WRB 2007)	Texture	W_{FC} [mm]	W_{WP} [mm]	*AWC* [mm]
Kráľová pri Senci	Haplic Chernozems	Loamic	324	108	216
Gabčíkovo	Haplic Phaeozems	Loamic	342	125	217
Žihárec	Haplic Chernozems	Loamic	349	133	216
Jaslovské Bohunice	Haplic Chernozems	Loamic	369	147	221
Piešťany	Haplic Phaeozems	Clay loam	377	192	185
Podhájska	Haplic Chernozems	Loamic	307	91	216
Nitra	Cutanic Albic Luvisols	Clay loam	369	160	208
Mochovce	Haplic Planosols	Clay loam	403	198	205
Želiezovce	Haplic Chernozems	Clay loam	393	165	228
Trenčín	Cutanic Albic Luvisols	Loamic	319	122	197
Beluša	Cutanic Albic Luvisols	Loamic	346	128	218
Topoľčany	Cutanic Albic Luvisols	Clay loam	376	165	211
Dudince	Haplic Cambisols	Clay loam	395	212	183
Dolné Plachtince	Cutanic Albic Luvisols	Clay loam	390	193	197
Bzovík	Haplic Cambisols	Loamic	363	176	187
Žiar nad Hronom	Haplic Phaeozems	Sandy loam	281	92	189
Sliač	Cutanic Albic Luvisols	Loamic	346	135	211
Lučenec	Cutanic Albic Luvisols	Clay loam	387	196	191
Rimavská Sobota	Cutanic Albic Luvisols	Clay loam	379	164	215
Rožňava	Cutanic Albic Luvisols	Loamic	353	139	214
Moldava nad Bodvou	Haplic Fluvisols	Loamic	324	121	213
Košice	Cutanic Albic Luvisols	Loamic	362	141	220
Prešov	Cutanic Albic Luvisols	Loamic	331	118	213
Tisinec	Cutanic Albic Luvisols	Loamic	359	111	248
Somotor	Haplic Fluvisols	Sandy loam	322	113	209
Michalovce	Haplic Fluvisols	Clay loam	383	163	220
Trebišov	Haplic Fluvisols	Clay loam	423	194	229
Vysoká nad Uhom	Haplic Fluvisols	Clay loam	394	173	221
Orechová	Cutanic Albic Luvisols	Loamic	362	147	215
Kamenica nad Cirochou	Haplic Fluvisols	Loamic	350	139	211
Medzilaborce	Haplic Cambisols	Loamic	405	188	217
Stropkov	Cutanic Albic Luvisols	Loamic	335	109	218
Spišské Vlachy	Haplic Cambisols	Loamic	340	133	207

Numerical simulations with the DAISY model were performed for the period 1961 – 2020 with a series of daily values of global radiation, air temperature, humidity, wind speed and precipitation from meteorological stations representing each region. The daily meteorological data were provided by the Slovak Hydrometeorological Institute Bratislava for the purpose of identification of disadvantaged agricultural areas (Sobocká *et al.* 2010) and for the application and updating of the national system for crop yield estimation (Skalský *et al.* 2020).

Simulations were carried out in rotations involving maize, spring barley, winter wheat, sugar beet and potato crops. Simulations were carried out for representative soil profiles of selected regions (Tab. 1). Representative soil profiles were selected from the Soil survey database (Skalský & Balkovič 2002). Soil characteristics of individual soil profiles were determined by standard laboratory methods (Hraško *et al.* 1962). Soil groups were classified according to the World Reference Base (IUSS Working Group WRB 2007).

Soil water availability and thus crop water sufficiency is also influenced by soil type, soil texture and its available water capacity. To assess the influence of soil on the water balance and crop water availability, additional simulations were carried out in the Danube Lowland for three crops, namely maize, spring barley and winter wheat. The territory of the Danube Lowland was divided into four climatic regions. In each of the regions, five dominant soil types covering 99% of the agricultural land were identified (Tab. 2).

Table 2

Characteristics of Danube Lowland regions. *FC* – field capacity, *WP* – wilting point, *AWC* – available water capacity

Region / meteorological station	Soil group	*FC* [mm]	WP [mm]	AWC [mm]
Northwest *Jaslovské Bohunice*	Haplic Phaeozems	420	216	204
	Haplic Chernozems	408	171	237
	Endofluvic Chernozems	387	147	240
	Haplic Fluvisols	384	144	240
	Cutanic Albic Luvisols	408	177	231
Northeast *Nitra*	Haplic Phaeozems	432	228	204
	Haplic Chernozems	420	171	249
	Endofluvic Chernozems	372	159	213
	Haplic Fluvisols	408	159	249
	Cutanic Albic Luvisols	423	195	228
Southwest *Bratislava – airport*	Haplic Phaeozems	423	207	216
	Haplic Chernozems	396	147	249
	Endofluvic Chernozems	384	132	252
	Haplic Phaeozems	384	117	267
	Cutanic Albic Luvisols	408	213	195
Southeast *Hurbanovo*	Haplic Phaeozems	423	219	204
	Haplic Chernozems	408	168	240
	Endofluvic Chernozems	384	147	237
	Haplic Fluvisols	387	147	240
	Cutanic Albic Luvisols	429	210	219

RESULTS AND DISCUSSION

Differences in leaf anatomy, stomatal characteristics, aerodynamic properties and albedo cause the evapotranspiration of different crops to differ from each other under the same climatic conditions. These crop characteristics also change during the growing season. Of the crops evaluated, sugar beet and maize have the highest values of potential evapotranspiration, i.e. crop water requirements. Crop water requirements of the crops vary from year to year. The highest values of the water requirement of individual crops were calculated for the south-west of Slovakia. The lowest values of crop water requirements were in the north-east of Slovakia (Tab. 3).

On average, the water requirement of spring barley, winter wheat and grain maize increased by 28 mm, 18 mm and 63 mm respectively in the period 1991 – 2000 compared to the period 1961 – 1990. The highest average increases in water requirement were found for sugar beet and potatoes, by 80 and 90 mm respectively.

The highest increase in crop water requirements in the period 1991 – 2020 compared to the period 1961 – 1990 was recorded in the west and north of the Danube Lowland, while for summer crops an above-average increase in crop water requirements was also recorded in the Central Pohronie and the East Slovak Lowland. In the Bratislava and Nitra area, the water requirement for spring barley and winter wheat increased by more than 50 mm. The water requirement for maize also increased the most in these two regions, by more than 100 mm. The gradual increase in maize water requirement can be seen in Fig. 1.

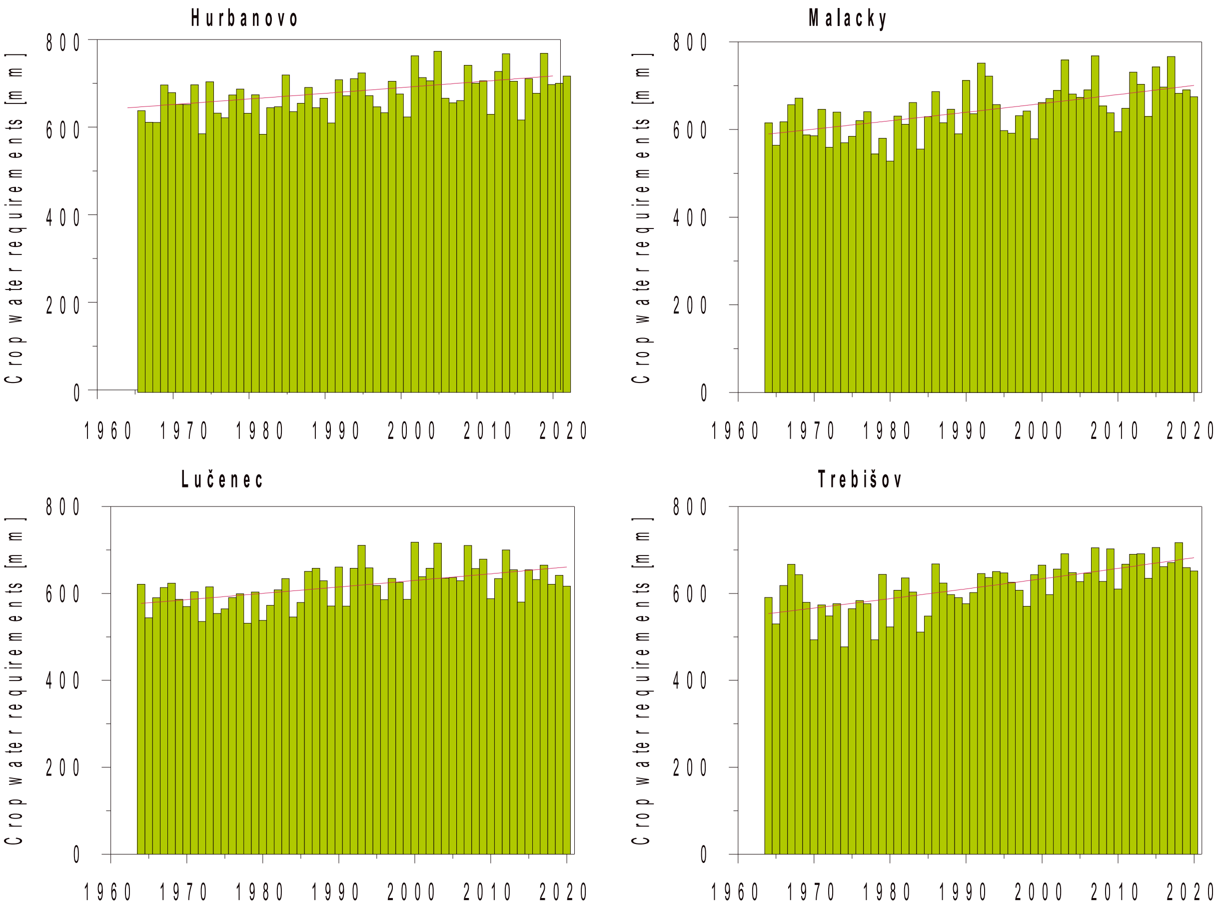

Figure 1 Maize water requirements at selected locations from 1961 to 2020

The coverage of crop water requirements varies widely from year to year, ranging from a rainfall surplus to a deficit of more than 600 mm in the case of maize in the south-west of the Danube Lowland in 2017. The lowest average deficit in crop water coverage was calculated for winter wheat and the highest for sugar beet (Tab. 4). The highest deficit for all crops was recorded in south-western Slovakia. In the period 1991 – 2020, compared to the period 1961 – 1990, the deficit increased for all crops, more so for summer crops, by an average of 50 mm. Above-average increases in the deficit were recorded in the East Slovak Lowland, in the west and north of the Danube Lowland, in the Central Pohronie and in the region of Rimavská Sobota. For summer crops, the average increase in water demand exceeded 100 mm in the south-east of the East Slovak Lowland.

The contribution of atmospheric precipitation to the water requirement of crops is highest for winter wheat and lowest for potatoes. In wheat, precipitation contributes more than 70% of the water requirement. In central and eastern Slovakia this coverage exceeds 100%, which is due to the winter rainfall. On the other hand, the water requirement of spring barley and summer crops is covered by less than 50% of the precipitation in the Danube Lowland. In the period 1991 – 2020, compared to the period 1961 – 1990, the coverage of the water requirements of crops has decreased on average by 5%, and in eastern Slovakia by more than 10%. Even the observed slight increase in rainfall totals cannot cover the increasing evapotranspiration requirements.

Insufficient coverage of crop water requirements by precipitation is reflected in the actual evapotranspiration totals. Below-average values of ET_a actual evapotranspiration for all crops were simulated for the north-west of the Záhorská Lowland, the Upper Nitra region and the south-east of the Danube Lowland, and for sugar beet and potatoes also for the north of the Danube Lowland and the Central Považie (Tab. 5). In central and eastern Slovakia, with the exception of Spiš, the simulated ET_a values were above average.

Most of the soil water during the growing season is used for crop transpiration. The remaining part of the soil water is used for evaporation, either from the soil or from snow cover, from dew and from interception. Soil evaporation contributes between 10 and 25% of the total water consumption by the crop, depending on the crop, the soil and the climatic conditions in a given year. Cereals consume 50 to 60% and maize 55 to 70% of water for transpiration. Both in absolute amounts and by percentage, the amount of water consumed for evapotranspiration decreased slightly and the proportion of water consumed for transpiration increased in the period 1991 – 2020 compared to the reference period 1961 – 1990 on all simulation profiles.

There was an increase in ET_a at most of the sites assessed. Significant decreases in ET_a in the period 1991 – 2020 compared to the period 1961 – 1990 occurred in cereals in the Záhorská Lowland, in the western Danube lowland and in the Považie region. In the south of the East Slovakian Lowland, a decrease in ET_a was detected for all crops. The same conclusions can be derived from the transpiration data (Tab.6).

A water deficit for plants occurs when water loss through transpiration exceeds water uptake by the roots. Transpiration water loss is primarily dependent on atmospheric conditions, root water uptake is dependent on soil conditions.

From the point of view of meeting the water requirement of crops, it is critical if the relative evapotranspiration, defined as the ET_a/ET_c ratio, falls below 50%. An average ET_a/ET_c value below 50% was calculated in the western Slovakia for sugar beet and potato (Tab. 7). In the period 1991 – 2020, a decrease in ET_a/ET_c was observed in most locations compared to the period 1961 – 1990, with only some locations in eastern Slovakia showing a slight increase of 1 – 3%.

Table 3

Average crop water requirements [mm] from sowing to harvest at selected locations for the period 1961 – 1990 and 1991 – 2020

Locality	Spring barley		Winter wheat		Maize		Sugar beet		Potatoes	
	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020
Kuchyňa	422	464	610	631	618	680	666	745	597	686
Holíč	425	444	603	614	608	665	657	743	589	686
Myjava	416	430	601	601	573	623	617	676	550	622
Bratislava	438	491	631	686	641	744	706	840	633	785
Hurbanovo	454	469	625	629	659	701	724	791	649	738
Jaslovské Bohunice	445	477	618	657	632	713	686	783	612	714
Piešťany	458	464	633	636	638	691	691	757	566	637
Nitra	437	488	601	666	632	735	693	818	620	754
Trenčín	413	447	584	612	576	664	620	721	550	655
Topoľčany	414	427	569	569	594	636	644	705	519	580
Podhájska	427	449	582	602	619	671	674	750	603	694
Želiezovce	425	441	581	589	620	660	678	737	607	684
Dudince	403	427	582	587	590	638	643	709	576	654
Dolné Plachtince	407	429	563	576	597	630	649	695	581	638
Žiar nad Hronom	381	420	544	567	529	620	571	675	506	615
Sliač	392	424	580	597	545	623	589	675	524	614
Lučenec	410	436	584	588	592	644	641	707	568	648
Rimavská Sobota	382	422	560	581	558	629	607	697	541	640
Rožňava	386	415	557	565	547	607	590	663	520	606
Moldava nad Bodvou	395	412	554	563	572	615	618	673	544	614
Košice	436	460	612	622	625	685	674	753	598	692
Tisinec	386	409	554	560	520	590	560	635	499	572
Somotor	390	432	545	576	575	645	628	716	569	659
Michalovce	379	419	533	559	557	632	604	702	541	651
Trebišov	400	435	562	584	579	652	629	718	557	659
Vysoká nad Uhom	385	420	536	555	562	626	610	695	546	644
Orechová	393	422	548	562	577	637	635	713	575	665
Kamenica nad Cirochou	393	413	567	568	544	603	587	653	523	593
Spišské Vlachy	348	386	527	548	–	–	–	–	407	448

Table 4
Average deficit in crop water requirement coverage by rainfall [mm] from sowing to harvest at selected locations for the period 1961 – 1990 and 1991 – 2020

Locality	**Spring barley**		**Winter wheat**		**Maize**		**Sugar beet**		**Potatoes**	
	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020
Kuchyňa	186	209	90	152	255	286	272	308	263	298
Holíč	207	223	144	180	285	334	306	369	291	351
Myjava	125	136	0	0	187	202	194	215	197	226
Bratislava	219	270	86	129	320	408	351	450	334	433
Hurbanovo	244	247	143	150	355	371	384	407	359	391
Jaslovské Bohunice	228	250	104	171	297	366	318	395	304	377
Piešťany	214	214	107	127	282	319	305	340	278	331
Nitra	213	260	104	177	319	401	346	427	319	408
Trenčín	182	203	80	108	248	300	265	319	248	309
Topoľčany	205	216	133	133	294	329	315	349	293	346
Podhájska	233	243	167	169	338	355	365	387	338	373
Želiezovce	232	245	170	173	345	354	373	385	343	369
Dudince	149	174	4	30	237	260	253	276	239	273
Dolné Plachtince	146	164	2	3	235	246	248	260	243	252
Žiar nad Hronom	94	149	0	0	132	203	139	215	149	225
Sliač	103	123	0	0	148	181	154	189	168	199
Lučenec	131	171	20	55	235	243	249	261	234	249
Rimavská Sobota	80	143	0	0	167	233	178	247	172	248
Rožňava	37	95	74	109	78	122	81	129	84	136
Moldava nad Bodvou	73	121	0	0	116	178	127	189	129	186
Košice	124	180	16	80	172	255	187	276	183	267
Tisinec	43	85	0	0	51	99	58	105	74	117
Somotor	115	192	12	65	185	291	203	311	199	308
Michalovce	95	151	0	0	144	225	153	237	163	247
Trebišov	136	186	44	100	203	267	216	285	207	276
Vysoká nad Uhom	93	175	0	0	148	254	157	265	168	274
Orechová	93	159	0	0	136	229	153	239	164	251
Kamenica nad Cirochou	19	96	0	0	21	96	26	98	48	119
Spišské Vlachy	16	41	0	0	–	–	–	–	12	26

Table 5

Average totals of actual evapotranspiration *ETa* [mm] from sowing to harvesting at selected sites during 1961 – 1990 and 1991 – 2020

Locality	**Spring barley**		**Winter wheat**		**Maize**		**Sugar beet**		**Potatoes**	
	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020
Kuchyňa	268	256	354	341	354	363	353	372	300	325
Holíč	238	238	327	312	338	326	306	315	264	283
Myjava	300	299	402	400	392	409	384	392	324	339
Bratislava	298	283	383	378	385	367	375	372	327	331
Hurbanovo	287	279	355	352	366	376	331	364	280	319
Jaslovské Bohunice	288	274	372	361	388	377	350	353	298	313
Piešťany	275	273	383	371	378	385	334	341	278	295
Nitra	290	285	371	371	397	393	347	357	287	306
Trenčín	268	276	359	363	356	379	335	360	285	315
Topoľčany	244	254	319	328	342	345	299	318	261	285
Podhájska	246	253	309	318	330	348	297	331	259	300
Želiezovce	241	252	304	316	337	349	288	316	244	272
Dudince	267	278	369	375	359	382	333	353	281	310
Dolné Plachtince	276	285	360	366	367	383	351	373	299	323
Žiar nad Hronom	275	308	369	393	368	421	379	421	328	365
Sliač	281	314	391	414	383	438	398	452	347	398
Lučenec	281	280	366	354	371	387	362	390	320	352
Rimavská Sobota	272	282	379	366	384	394	389	395	342	357
Rožňava	272	289	369	373	377	398	403	422	354	378
Moldava nad Bodvou	278	287	371	369	395	419	412	428	355	379
Košice	295	297	391	383	411	427	411	417	357	378
Tisinec	269	294	364	376	360	416	388	442	345	391
Somotor	274	281	355	348	379	371	390	380	337	330
Michalovce	271	303	360	383	389	426	394	430	344	378
Trebišov	257	266	348	345	373	380	341	347	294	301
Vysoká nad Uhom	277	305	364	375	396	412	400	406	348	351
Orechová	280	311	369	389	401	435	424	457	377	408
Kamenica nad Cirochou	275	298	375	388	374	424	407	441	360	388
Spišské Vlachy	237	267	338	367	–	–	–	–	304	338

Pedosphere Research, vol. 1, 2021, no. 1: 20 – 39

Table 6

Average transpiration totals T [mm] from sowing to harvesting at selected sites in the period 1961 – 1990 and 1991 – 2020

Locality	**Spring barley**		**Winter wheat**		**Maize**		**Sugar beet**		**Potatoes**	
	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020
Kuchyňa	170	161	221	207	252	264	213	231	151	177
Holíč	143	144	191	180	237	229	168	172	118	134
Myjava	176	176	262	260	262	285	208	220	143	164
Bratislava	197	188	245	234	276	268	230	230	175	186
Hurbanovo	197	186	224	217	270	282	200	230	143	179
Jaslovské Bohunice	184	173	233	216	281	276	204	207	145	161
Piešťany	179	179	242	230	281	289	200	206	136	156
Nitra	193	189	235	228	296	296	211	218	143	161
Trenčín	165	170	219	224	253	273	192	210	136	161
Topoľčany	155	161	192	199	247	249	169	182	124	144
Podhájska	169	171	195	197	246	260	183	208	141	173
Želiezovce	164	171	188	194	252	261	172	194	123	145
Dudince	167	175	234	238	256	279	188	207	133	160
Dolné Plachtince	172	177	228	228	263	276	203	222	147	170
Žiar nad Hronom	161	193	229	253	255	305	219	259	162	202
Sliač	164	192	245	265	263	315	229	280	174	223
Lučenec	172	173	230	217	256	276	199	234	154	192
Rimavská Sobota	160	168	239	227	260	279	216	229	165	189
Rožňava	156	171	223	228	256	278	231	252	172	206
Moldava nad Bodvou	168	181	231	235	278	306	248	274	184	224
Košice	186	191	248	244	293	315	249	267	187	225
Tisinec	155	174	222	237	242	289	217	265	169	210
Somotor	169	177	221	216	267	263	236	231	174	181
Michalovce	167	195	228	247	277	312	240	273	181	220
Trebišov	164	175	221	215	275	285	205	217	149	166
Vysoká nad Uhom	168	191	230	240	278	299	238	247	176	190
Orechová	175	198	234	253	288	321	265	294	212	245
Kamenica nad Cirochou	155	177	219	239	251	296	231	265	176	208
Spišské Vlachy	131	153	188	206	–	–	–	–	135	163

Table 7

Average relative crop evapotranspiration ET_a/ET_c [%] from sowing to harvesting at selected sites in the period 1961 – 1990 and 1991 – 2020

Locality	**Spring barley**		**Winter wheat**		**Maize**		**Sugar beet**		**Potatoes**	
	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020
Kuchyňa	61	56	58	55	57	54	53	50	50	48
Holíč	56	54	54	51	56	49	47	43	45	42
Myjava	72	70	67	67	68	66	62	58	59	55
Bratislava	68	59	61	56	60	50	53	45	52	43
Hurbanovo	63	60	57	56	56	54	47	46	44	43
Jaslovské Bohunice	65	58	60	55	61	53	51	46	49	44
Piešťany	60	59	60	59	59	56	49	45	46	43
Nitra	67	59	62	56	63	54	51	44	46	41
Trenčín	65	62	62	59	62	57	55	50	52	48
Topoľčany	60	59	58	56	58	55	47	45	45	44
Podhájska	58	57	53	53	53	52	45	44	44	43
Želiezovce	58	57	54	52	55	53	43	43	40	40
Dudince	66	65	64	64	61	60	52	50	49	48
Dolné Plachtince	68	67	64	64	62	61	54	54	52	51
Žiar nad Hronom	72	73	68	69	69	68	67	63	65	60
Sliač	72	74	67	69	70	70	67	67	66	65
Lučenec	69	65	63	61	63	61	57	56	57	55
Rimavská Sobota	71	67	68	63	69	63	64	57	64	56
Rožňava	70	70	66	66	69	66	68	64	68	63
Moldava nad Bodvou	70	69	66	66	69	68	67	63	65	62
Košice	67	65	64	62	66	63	61	56	60	55
Tisinec	69	71	66	67	69	70	69	69	69	68
Somotor	70	65	65	61	66	58	62	54	61	51
Michalovce	71	72	67	68	70	68	65	62	64	59
Trebišov	64	62	62	59	65	59	55	49	54	46
Vysoká nad Uhom	72	72	68	68	70	66	66	59	65	55
Orechová	71	73	67	69	69	68	67	64	66	62
Kamenica nad Cirochou	70	72	66	68	69	70	69	68	69	66
Spišské Vlachy	66	69	64	67	–	–	–	–	66	66

Table 8

Variance range of ET_a/ET_c [%] of selected crops at selected sites in the period 1961 – 1990 and 1991 – 2020

Locality	**Spring barley**		**Winter wheat**		**Maize**		**Sugar beet**		**Potatoes**	
	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020
Kuchyňa	37	50	34	44	36	52	35	49	34	49
Holíč	40	48	38	39	42	50	38	42	37	40
Myjava	15	21	18	27	20	35	25	37	29	39
Bratislava	32	54	34	45	37	55	39	53	42	52
Hurbanovo	43	49	39	44	42	50	43	47	35	47
Jaslovské Bohunice	40	47	37	42	43	43	41	45	42	43
Piešťany	30	45	23	38	26	42	31	40	32	40
Nitra	40	43	40	45	39	42	42	42	42	37
Trenčín	32	45	32	37	36	37	38	34	35	37
Topoľčany	42	43	39	38	33	43	35	42	38	43
Podhájska	45	45	42	38	39	41	26	39	34	41
Želiezovce	50	47	47	49	45	45	39	44	37	42
Dudince	28	30	34	35	31	35	41	35	39	39
Dolné Plachtince	27	31	30	34	28	35	36	38	33	37
Žiar nad Hronom	20	21	23	24	13	23	21	29	18	34
Sliač	21	19	25	17	15	21	22	27	18	30
Lučenec	31	45	31	46	28	41	30	43	30	42
Rimavská Sobota	23	40	25	42	24	44	23	49	22	53
Rožňava	22	25	21	21	22	22	21	26	20	30
Moldava nad Bodvou	20	39	23	34	15	37	17	32	19	27
Košice	33	39	28	40	17	34	25	35	26	33
Tisinec	19	16	19	17	20	18	18	15	16	16
Somotor	29	41	31	39	26	46	36	43	29	43
Michalovce	24	19	21	22	15	30	20	34	20	36
Trebišov	27	36	32	40	22	43	30	35	33	37
Vysoká nad Uhom	23	21	17	23	13	31	19	39	25	40
Orechová	25	19	19	18	15	33	22	34	19	35
Kamenica nad Cirochou	23	16	21	15	20	22	18	26	20	31
Spišské Vlachy	22	16	25	18					28	18

Table 9

Average number of days with water stress of selected crops at selected sites in the period 1961 – 1990 and 1991 – 2020

Locality	**Spring barley**		**Winter wheat**		**Maize**		**Sugar beet**		**Potatoes**	
	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020
Kuchyňa	12	20	19	25	23	29	29	35	23	30
Holíč	17	22	27	31	25	37	41	52	30	42
Myjava	1	5	2	5	8	13	18	26	17	25
Bratislava	7	18	16	26	24	37	35	49	25	43
Hurbanovo	11	17	24	24	32	32	46	47	34	41
Jaslovské Bohunice	10	19	19	27	22	34	36	47	27	39
Piešťany	12	16	19	20	21	27	37	44	28	37
Nitra	8	18	18	26	20	34	38	51	30	44
Trenčín	9	13	13	18	17	26	27	36	21	30
Topoľčany	13	16	23	21	26	31	41	47	30	40
Podhájska	15	19	28	26	33	33	44	46	31	37
Želiezovce	16	17	30	27	32	33	48	50	37	44
Dudince	7	10	10	12	19	21	37	39	28	33
Dolné Plachtince	3	8	10	11	22	20	35	32	26	29
Žiar nad Hronom	0	1	0	2	3	9	8	17	6	16
Sliač	0	1	1	2	3	4	8	10	6	9
Lučenec	4	10	11	17	21	21	30	33	20	23
Rimavská Sobota	2	7	3	10	9	16	21	29	13	23
Rožňava	1	2	2	3	4	7	7	11	4	9
Moldava nad Bodvou	1	2	2	4	3	5	7	11	6	9
Košice	4	9	7	14	10	16	17	26	11	19
Tisinec	0	0	0	0	0	1	2	2	1	3
Somotor	4	10	5	16	13	26	23	34	16	30
Michalovce	1	2	1	4	4	9	14	19	9	18
Trebišov	7	12	10	18	13	22	28	37	20	31
Vysoká nad Uhom	0	3	1	6	4	13	15	25	10	25
Orechová	0	1	1	3	3	9	10	15	6	15
Kamenica nad Cirochou	0	0	0	1	0	2	3	6	2	7
Spišské Vlachy	2	1	1	1	–	–	–	–	3	2

The minimum recorded values of ET_a/ET_c in the period 1961 – 1990 were 23% for potatoes in Holíč and Želiezovce, 25% for sugar beet in Hurbanovo, 28% for maize in Holíč and Želiezovce, 29% and 31% for winter wheat and spring barley in Želiezovce, respectively. In the period 1991 – 2020, the minimum ET_a/ET_c values found in Bratislava were 18% for potatoes, 21% for maize and sugar beet, and 24% for spring barley. For winter wheat, a minimum ET_a/ET_c value of 25% was calculated in Želiezovce for this period. The maximum ET_a/ET_c values were 80% in both periods.

The average range of variation in ET_a/ET_c was about 30% in the period 1961 – 1990, and 4% (winter wheat) to 10% (maize) higher in the period 1991 – 2020 (Tab. 8). The maximum value of the variation range of ET_a/ET_c in the period 1961 – 1990 was recorded in Želiezovce, in the period 1991 – 2020 in Bratislava.

The lack of water in the soil and the increasing water requirements of crops due to rising temperatures will result in water stress, which has an adverse effect on crop yields. In general, the number of days with water stress had an increasing trend (Tab. 9). Crops suffer the most from water stress in the Danube Lowland, the Záhorská Lowland and the south of the East Slovak Lowland. The highest increase in the number of days with water stress in the period 1991 – 2020 compared to the period 1961 – 1990 was recorded in the north-west of the Záhorská Lowland, in the west and north of the Danube Lowland and in the south of the East-Slovak Lowland. Crops with a growing season in the summer months are more affected by water stress. Peaks in the average number of days with water stress in the period 1991 – 2020 for all crops were calculated for the north-west of the Záhorská Lowland, while in the period 1961 – 1990 they occurred in the south-east of the Danube Lowland.

In addition to climatic conditions, soil conditions also affect the water requirement of crops, although to a much lesser extent than climatic factors (Tab. 10). Soil and its water retention capacity are the main cause of spatial variability in soil water reserves and crop yields. Depending on the grain composition, soils can hold different amounts of water.

Table 10

Average deficit of crop water requirement coverage by precipitation [mm] on different soils of the Danube Lowland in the periods 1961 – 1990 and 1991 – 2020

Soil group	**Spring Barley**		**Winter Wheat**		**Maize**	
	1961 – 1990	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**
Haplic Phaeozems	241	280	188	228	354	411
Haplic Chernozems	246	276	197	222	358	404
Endofluvic Chernozems	241	289	175	237	356	425
Haplic Fluvisols	241	285	182	233	355	418
Luvisols	237	281	186	233	346	413

The influence of soil properties is least pronounced in spring barley, where, due to the shorter growing season, the average difference in deficit between soils in the Danube Lowland in the period 1961 – 1990 was less than 10 mm. In the case of winter wheat, the maximum difference between Haplic Chernozem and Fluvic Chernozem was 22 mm, and in the case of maize between Luvisol and Haplic Chernozem 12 mm.

In the period 1991 – 2020, the deficit widened by more than 40 mm on average for cereals and by more than 60 mm for summer crops compared to the period 1961 – 1990. The difference between soil types was on average 13 mm for spring barley, 15 mm for winter wheat and 21 mm for maize in the period 1991 – 2020. The average water requirement coverage of spring barley, winter wheat and maize decreased by 3 – 5%, 3 – 8% and 2 – 4%, respectively, in the Danube Lowland in the period 1991 – 2020 compared to the period 1961 – 1990.

Differences in soil water holding capacity will also be reflected in plant water uptake, manifested in reduced transpiration and increased crop water stress. The lowest mean values of relative evapotranspiration of the evaluated crops in the period 1961 – 1990 were calculated on Haplic Chernozems and Luvisol, below 60% in the case of maize (Tab. 11). The highest number of days with water stress was simulated just on Haplic Chernozems and Luvisol, the lowest on Endofluvic Chernozems and Haplic Fluvisol (Tab. 12).

Table 11
Average relative evapotranspiration of selected crops ET_a/ET_c [%] from sowing to harvesting on different soils of the Danube Lowland in the period 1961 – 1990 and 1991 – 2020

Soil group	**Spring Barley**		**Winter Wheat**		**Maize**	
	1961 – 1990	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**
Haplic Phaeozems	68	65	70	70	69	65
Haplic Chernozems	60	55	63	62	56	53
Endofluvic Chernozems	65	59	67	65	64	58
Haplic Fluvisols	70	66	70	70	68	64
Luvisols	61	54	63	61	57	52

Table 12
Average number of days with water stress of selected crops on different soils of the Danube Lowland in the period 1961 – 1990 and 1991 – 2020

Soil group	**Spring Barley**		**Winter Wheat**		**Maize**	
	1961 – 1990	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**
Haplic Phaeozems	4	9	3	5	7	12
Haplic Chernozems	13	20	13	16	29	32
Endofluvic Chernozems	8	15	6	11	16	24
Haplic Fluvisols	4	8	3	6	9	15
Luvisols	12	20	12	17	28	33

In the period 1991 – 2020, the average values of relative evapotranspiration of spring barley and maize on individual soils of the Danube Lowland decreased by 3 – 7% and 3 – 6%, respectively. In the case of winter wheat, the decrease was smaller, only up to 2% on Luvisol and Haplic Phaeozem. The same trends can be observed from the outputs of the number of days with water stress.

These differences are due to the different amount of available water in the soil as a result of the different retention capacities of the different soils. In terms of impacts on the crops grown, the duration of the period with soil moisture in the root zone below 50% of the *AWC* at the critical development stages of the crops grown is crucial. According to mathematical simulations, in the Danube and Záhorská lowlands, the soil moisture drops below 50% of the *AWC* on average as early as June, and in the south of central and eastern Slovakia in July. In some years, this situation may occur as early as the beginning of spring, or may persist during autumn and winter as a result of insufficient rainfall in the autumn and winter months.

The occurrence and duration of periods with soil water storage below 50% of the *AWC* varies from region to region. The fact that the 0 – 100 cm horizon water content falls below 50% of the *AWC* is common in the southern regions of Slovakia and occurs almost every year. Of the 40 sites assessed, the median number of days with soil moisture below 50% of the *AWC* in continuous periods is more than 150 days in the Danube and Záhorská lowlands. Once every 4 years in these regions, a continuous period with soil moisture below 50% of the AWC reaches more than 200 days. Most of the stations in western Slovakia have peaks above 300 days in the assessed period.

Available soil water storage below 50% of the *AWC* occurred at the 40 stations evaluated for an average of 90 days in the period 1961 – 1990 and an average of 96 days in the period 1991 – 2020. In addition to spatial variability, soil moisture shows considerable temporal variability. Soil water content varies significantly from year to year. The variation in the available water in the soil is one of the causes of variability in yields. Apart from 1990 and 2012, a continuous dry period with soil moisture less than 50 % of the *AWC* for more than 200 days occurred in the Danube Lowland in 1989, 2003, 2011, 1983, 1977 and 1971 and in the Záhorská Lowland in 2003, 1983, 1989, 1973, 2000 and 1977. In the Eastern Slovakian Lowland, the dry season with soil moisture less than 50 % of the *AWC* lasted more than 200 days only in 1986. 1993 was also a very dry year in terms of the duration of the dry season in eastern Slovakia.

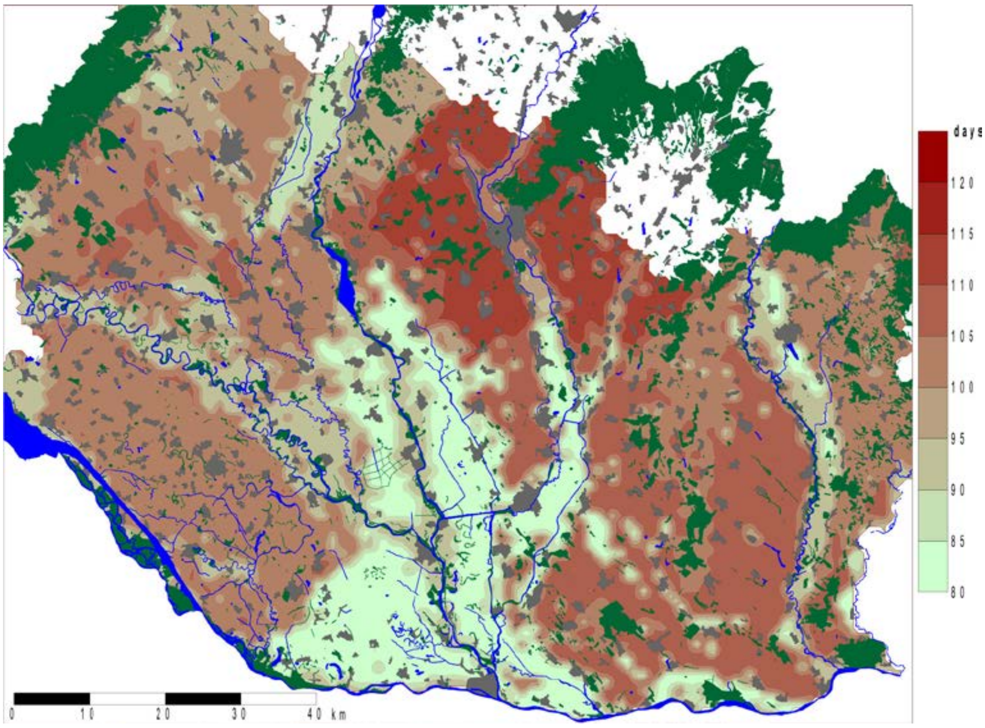

Figure 2 Average number of days with soil water content less than 50% of *AWC* in the Danube Lowland

Spatial variation in this characteristic also occurs within regions, depending on soil properties and the presence of groundwater levels. The average number of days with available water in the soil during the maize growing season below 50% ranges from 75 to 120 days in the Danube Lowland (Figure 2). The lowest number of days with soil moisture below 50% of the *AWC* in the Danube Lowland was calculated for areas with the presence of groundwater table on the lower Žitný ostrov and near watercourses. The lowest average available soil water in the Danube Lowland was simulated for l

Luvisol and Haplic Chernozems, the highest for Endofluvic Chernozems and Fluvisols. With the exception of the south-eastern part of the lowland, the number of days with soil water storage below 50 % of the *AWC* increased by an average of 2 to 17 days in the period 1991 – 2020 compared to the period 1961 – 1990, depending on the crop and soil type.

CONCLUSION

Although no area in Slovakia qualifies as arid, crop water requirements are insufficient in the southern regions, with soil water scarcity being the main limiting factor for agricultural production, particularly in the Danube Lowland. In dry years, the coverage of water requirement of crops grown in summer is below 40%.

According to model calculations using general atmospheric circulation scenarios, soil moisture was already predicted to decrease between April and October in the 1990s, with the greatest decrease in soil moisture expected between July and September. Trends observed in recent decades confirm these assumptions. As a result of climate change, water availability may fall below a critical level at which crop production will be extremely vulnerable. In view of these facts, it will be necessary to prepare adaptation measures at local, regional and national level.

ACKNOWLEDGEMENT

This work was supported by Ministry of agriculture and rural development of the Slovak Republic under Grant No. RPVV-VÚPOP 2 „Management of farming on agricultural soil with regard to its sustainability" and supported by the Slovak Agency for Research and Development No. APVV-15-0406.

REFERENCES

Abrahamsen, P., Hansen, S. (2000). DAISY: An Open Soil, Crop, Atmosphere System Model. In *Environmental Modelling & Software*, vol. **15**, 2000, No. **3**, P. 313 – 330. ISSN 1364-8152.

Andrade, E.P., Bonmati, A., Esteller, L.J., Montemayor, E., Vallejo, A.A. (2021). Performance and environmental accounting of nutrient cycling models to estimate nitrogen emissions in agriculture and their sensitivity in life cycle assessment. *The International Journal of Life Cycle Assessment (*2021) 26:371–387. https://doi.org/10.1007/s11367-021-01867-4.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. (1998). Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. *FAO Irrigation and Drainage Paper* **56**. FAO, Rome. ISBN 92 – 5-104219 – 5.

Diekkrüger, B., Söndgerath, D., Kersebaum, K.C., McVoy, C.W. (1995). Validity of Agroecosystem Models: a Comparison of Results of Different Models Applied to the Same Data Set. In *Ecol. Model.*, **81**, 3 – 29, https://doi.org/10.1016/0304 – 3800(94)00157-D.

Eitzinger, J., Trnka, M., Semerádová, D., Thaler, S., Svobodová, E., Hlavinka, P., Šiška, B., Takáč, J., Malatinská, L., Nováková, M., Dubrovský M. & Žalud, Z. (2013). Regional climate change impacts on agricultural crop production in Central and Eastern Europe – hotspots, regional differences and common trends. *Journal of Agricultural Science*. Vol.: **151** (6), pp. 782 – 812. DOI: https://doi.org/10.1017/S0021859612000767.

Hansen, S. (2000). *DAISY, a Flexible Soil – Plant – Atmosphere System Model.* Equation Section 1. Copenhagen: The Royal Veterinary and Agricultural University, 2000, p. 1–47. ISBN 87-503-8790-1.

Hansen, S., Jensen, H.E., Nielsen, N.E., SVENDSEN, H. (1990). DAISY – A Soil Plant System Model. Danish Simulation Model for Transformation and Transport of Energy and Matter in the Soil-Plant-Atmosphere System. Copenhagen: National Agency for Environmental Protection, 1990. 272 p. ISBN 87-503-8790-1.

Hraško, J. *et al.* (1962). *Rozbory pôd.* Slovenské vydavateľstvo pôdohospodárskej literatúry, Bratislava, ISBN 64- 028-62, s. 342.

IUSS Working Group WRB. (2007). World Reference Base for Soil Resources 2006, 2007. *World Soil Resources Report* No. **103**. FAO, Rome. ISBN 9.2-5-105511-4.

Kröbel, R., Sun, Q., Ingwersen, J., Chen, X., Zhang, F., Müller, T., Römheld, V. (2010). Modelling water dynamics with DNDC and DAISY in a soil of the North China Plain: A comparative study. In *Environmental Modelling & Software*, vol. **25**, pp. 583–601. DOI: 10.1016/j.envsoft.2009.09.003.

Labudová, L., Labuda, M., Takáč, J. (2016). Comparison of SPI and SPEI applicability for drought impact assessment on crop production in the Danubian Lowland and the East Slovakian Lowland. *Theoretical and Applied Climatology*, p. 491 – 506. DOI: 10.1007/s00704-016-1870-2.

Labudová, L., Turňa, M., Polčák, N. (2018). Sucho v roku 2017 v kontexte vývoja suchých období od roku 1981 na Slovensku (Drought in 2017 in the context of the development of dry seasons since 1981 in Slovakia). *Meteorologický časopis*, **21**, 2018, 13 – 21.

McKee, T.B., Doesken, N.J., Kleist, J. (1993). The Relationship of Drought Frequency and Duration to Time Scales. In Proceedings of the 8th Conference on Applied Climatology, January 17 – 22, American Meteorological Society, Anaheim CA, USA. pp. 179–184.

Ministry of the Environment of the Slovak Republic and the Slovak Hydrometeorological Institute (2013). *The Sixth National Communication of the Slovak Republic on Climate Change under United Nations Framework Convention on Climate Change and Kyoto Protocol.* Bratislava. 136 pp.

Nikolová, N., Nejedlík, P., Lapin, M. (2016). Temporal Variability and Spatial Distribution of Drought Events in the Lowlands of Slovakia. *Geofizika*, **33**, 2, 119 – 135, DOI: 10.15233/gfz.2016.33.10.

Palosuo, T., Kersebaum, K.C., Angulo, C., Hlavinka, P., Moriondo, M., Olesen, J.E., Patil, R.H., Ruget, F., Rumbaur, Ch., Takáč, J., Trnka, M., Bindi, M., Caldag, B., Ewert, F., Ferrise, R., MirscheL, W., Saylan, L., Šiška, B., Rötter, R. (2011). Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models. *European journal of agronomy*, vol. 35, no. **3**, pp. 103–114. DOI: 10.1016/J.EJA.2011.05.001.

Rötter, R., Palosuo, T., Kersebaum, K.C., Angulo, C., Bindi, M., Ewert, F., Ferrise, R., Hlavinka, P., Moriondo, M., Nendel, C., Olesen, J.E., Patil, R.H., Ruget, F., Takáč, J., Trnka, M. (2012). Simulation of spring barley yield in different climatic zones of Northern and Central Europe: A comparison of nine crop models. *Field Crops Research*, vol. **13**, pp. 23–36. ISSN 0378-4290.

Skalský, R., Balkovič, J. (2002). Digital Database of Selected Soil Profiles of Complex Soil Survey of Slovakia (KPP-DB). *Vedecké práce Výskumného ústavu pôdoznalectva a ochrany pôdy,* **25,** Bratislava: VÚPOP, p. 129–140, ISBN 80-89128-07-6.

Skalský, R., Fulmeková, Z., Kusý, D., Sviček, M. (2020). *Odhad úrody a produkcie kukurice na zrno, cukrovej repy technickej, slnečnice ročnej a zemiakov k 20.09.2020* (Estimate of harvest and production of grain, maize, sugar beet, annual sunflower and potatoes to 20.09.2020). Priebežná správa k riešeniu úlohy v rámci kontraktu s MPRV SR, Bratislava: NPPC – VÚPOP, 39 s.

Sobocká, J., Skalský, R., Balkovič, J., Takáč, J., Nováková, M. (2010). *Nové metodické postupy pre navrhované spoločné pôdne a klimatické kritériá, ktoré možno použiť pre klasifikáciu znevýhodnených poľnohospodárskych území na úrovni Európskej únie.* (New methodological procedures for the proposed common soil and climatic criteria that can be used for the classification of less-favoured agricultural areas at European Union level. Guideline). Metodická príručka pre LFA. VÚPOP, Bratislava, 23 s.

Šiška, B., Takáč, J. (2009). Drought Analyse of Agricultural Regions as Influenced by Climatic Conditions in the Slovak Republic. *Időjárás*, vol. **113**, no. 1–2, p. 135–143. ISSN 0324-6329. Available on: /Users/Admin/Downloads/95934faaa6b90d449c4fe5693ed79fe7-113-1- 2-13-siska.pdf.

Takáč, J. (1994). Verifikácia modelu DAISY – simulovanie úrod obilnín (DAISY model verification – cereal harvest simulation). *Vedecké práce V*ýskumného ústavu závlahového hospodárstva, **21**, VÚZH Bratislava, s. 95 – 104.

Takáč, J. (1999). Trends In Soil Water Regime In Model Conditions Of Žitný Ostrov. *Scientific Papers of the Research Institute of Irrigation,* Bratislava, No. **24**, VÚZH Bratislava: 189 – 201.

Takáč, J. (2001). Dôsledky zmeny klímy na bilanciu vody v poľnohospodárskej krajine (Consequences of climate change on the water balance in the agricultural country). *Národný klimatický program SR 10/01*, SHMÚ, Bratislava, s. 16 – 26. ISBN 80-88907-24-1.

Takáč, J. (2015). *Sucho v poľnohospodárskej krajine* (Drought in agricultural land.) NPPC-VÚPOP, Bratislava. 69 s. ISBN 978-80-8163-012-5.

Takáč, J., Bárek, V., Halaj, P., Igaz, D., Jurík, Ľ. (2008). Possible Impact of Climate Change on Soil Water Content in Danubian Lowland. *Cereal Research Communications, Vol.* **36**, 2008, pp. 1623 – 1626. ISSN 0133-3720.

Takáč, J., Bezák, P., Ilavská, B. (2017). Zhodnotenie zmien klimatických indikátorov v období 1961 – 1990 A 1991 – 2016 pre potreby aktualizácie agroklimatických regiónov (Evaluation of changes in climate indicators in the period 1961 – 1990 and 1991 – 2016 for the needs of updating agro-climatic regions). *Vedecké práce Výskumného ústavu pôdoznalectva a ochrany pôdy*, **39**, Bratislava. 104 – 125. ISBN 978-80-8163-022-4.

Takáč, J., Nováková, M., Skalský, R., Sobocká, J. (2010). Identifikácia sucha na Slovensku s použitím klimatických kritérií (Drought identification in Slovakia using climatic criteria). *Vedecké práce Výs-*

kumného ústavu pôdoznalectva a ochrany pôdy, **32**, Bratislava. ISBN 978-80-89128-82-2. 88 – 100.

Takáč, J., Skalský, R., Dodok, R., Kusý, D. (2017). Bilancia využiteľnej vody v pôde v regióne Podunajskej nížiny v období 1961 – 2015 (Balance of usable water in the soil in the Danubian Lowland region in the period 1961 – 2015). *Vedecké práce Výskumného ústavu pôdoznalectva a ochrany pôdy*, **39**, Bratislava. 126 – 141. ISBN 978- 80-8163-022-4.

Takáč, J., Šiška, B., Lapin, M. (2009). Dôsledky zmeny klímy na vlahovú zabezpečenosť poľných plodín podľa scenárov SRES A2 a B1 (Consequences of climate change on the moisture security of field crops according to SRES A2 and B1 scenarios). *Vedecké práce Výskumného ústavu pôdoznalectva a ochrany pôdy*, **31**, Bratislava. ISBN 978-80-89128-59-4. 187 – 200.

Takáč, J., Šiška, B. (2011). Kalibrácia a validácia modelu DAISY pre podmienky Slovenska (Calibration and validation of the DAISY model for the conditions of Slovakia). *Vedecké práce Výskumného ústavu pôdoznalectva a ochrany pôdy*, **33**, Bratislava. 161 – 172. ISBN 978-80-89128-91-4.

Takáč, J., Kotorová, D., Makovníková, J., Kováč, L. (2018). Validácia modelu DAISY v podmienkach Východoslovenskej nížiny (Validation of the DAISY model in the conditions of the East Slovakian lowland). *Vedecké práce Výskumného ústavu pôdoznalectva a ochrany pôdy,* **40**, Výskumný ústav pôdoznalectva a ochrany pôdy Bratislava, p. 100 – 113. ISBN 978-80-8163-030-9.

Tomlain, J., Špánik, F., Valšíková, M. (2002). Priemerné a extrémne úhrny potenciálnej a aktuálnej evapotranspirácie na území Slovenska za obdobie 1951 až 2000 (Average and extreme sums of potential and current evapotranspiration in Slovakia in the period 1951 to 2000). Štúdia XIX, roč. XVI. SBkS SAV, SPU v Nitre. Bratislava, Nitra.

UNEP (1997). *World Atlas of Desertification.* 2. ed. ISBN 0 340 69166 2, 182 pp. Available on: https://wedocs.unep.org/20.500.11822/30300.

Vicente-Serrano, S.M., Lopéz-Moreno, J.I. (2005). Hydrological response to different time scales of climatological drought: an evaluation of the standardized precipitation index in a mountainous Mediterranean basin. *Hydrol Earth Syst Sci,* **9**: 523–533.

Received: November 25, 2021
Accepted: December 17, 2021
Published online: January 2022