Original paper

TRENDS IN THE SOIL WATER DYNAMICS IN THE PERIOD 1961 – 2020 IN AGRICULTURAL REGIONS OF SLOVAKIA

Jozef Takáč, Jaroslava Sobocká

National Agricultural and Food Centre – Soil Science and Conservation Research Institute Bratislava, 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 – 0003-3923 – 4601*

Citation: Takáč, J., Sobocká, J. (2022). Trends in the Soil Water Dynamics in the Period 1961 – 2020 in Agricultural Regions of Slovakia. *Pedosphere Research,* vol. 2, 2022, no. 2, pp. 86 – 105. NPPC – VÚPOP 2022. ISSN 2729–8728.

Abstract

An assessment of the trend in soil water dynamics in agricultural regions of Slovakia was carried out for the period 1961 – 2020. Simulations of water balance and crop water stress with the DAISY model were used for the assessment. Simulations were carried out for representative soil profiles of selected regions. Crop rotations including grain maize, spring barley, winter wheat, sugar beet and potatoes were simulated. According to the simulated values of soil water potential, in the 0 – 30 cm soil horizon thickness, according to the ecological classification of the water regime, soil moisture occurred in the arid interval almost every year on the Podunajská nížina in the southwest, and on the Východoslovenská nížina in the southeast in four out of five years. In the long term, the lowest soil water storage, expressed as percentage of available soil water capacity (ASWC), are in the west of the Záhorská nížina in the west and in the south-east of the Podunajská nížina. Changes in climatic conditions have had an impact on soil water storage. In the period 1991 – 2020 there was a slight decrease in the average soil water content in most of Slovakia compared to the period 1961 – 1990. On the contrary, an increase in soil water storage in the period 1991 – 2020 compared to the period 1961 – 1990 occurred in the south-east of the Podunajská nížina, in the Ipeľ Basin, in Spiš, and Šariš regions. The soil water deficit needed to meet the crop water requirements has increased in all southern regions except the south-east of the Podunajská nížina. The number of days with water stress can exceed 90 days in southern areas in dry years.

Keywords: soil moisture, available soil water capacity, point of decreased availability, crop water requirements, ecological classification of soil water regime

INTRODUCTION

Soil water balance is a key parameter of physical and physiological processes occurring in agro-ecological systems. The soil water regime significantly influences the productive capacity of soils and the formation of agricultural crop yields. Variations in the stock of available water in the soil are one of the causes of yield variability.

In addition to temporal variability, spatial variability is a specific characteristic of the water regime. Soil moisture is spatially heterogeneous; in addition to water uptake from atmospheric precipitation or ground water table, it is also dependent on soil properties. Under field conditions, we observe significant variability in the soil hydro-physical characteristics caused mainly by the heterogeneity of the soil cover. The main cause of spatial variability in soil water reserves and crop yields is soil water holding capacity (Cambel & Takáč 2000).

Several studies confirm the trend of increasing drought incidence in Central Europe. In the Czech Republic, a significant trend towards more intense drought episodes has been found, especially in the south-eastern part of the country (Brázdil *et al.* 2009, Trnka *et al.* 2009). Trnka *et al.* (2013) point to an increased risk of occurrence of extremely unfavourable dry years in the Czech Republic. The Sixth National Communication of the Slovak Republic on Climate Change (Ministry of the environment of the Slovak republic and the Slovak Hydrometeorological institute 2013) also states the gradual desertification of the country, especially in the south of Slovakia.

The results of the soil water dynamics simulations confirmed the trend of decreasing average soil water content and a gradual increase in the duration of the soil moisture period between the semiarid and arid intervals in the southern part of the Podunajská nížina (Takáč 1999). The trend of severe or extreme drought in summer was confirmed for most of the monitored stations in lowland areas of Slovakia (Nikolová *et al.* 2016).

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 periods decreases from south to north and from west to east. Drought severity strengthens when the drought occurred also in the previous year (Takáč 2013).

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 Podunajská nížina. In dry years, the coverage of water requirement of crops grown in summer is below 40%. As a result of climate change, water availability may fall below a critical level at which crop production will be extremely vulnerable (Takáč & Ilavská 2021).

The expected increase in temperature, together with changes in precipitation distribution and precipitation totals, will be reflected in changes in the elements of the water balance. The value of the average water content in the 0 – 100 cm horizon will gradually decrease under selected climate change scenarios (Takáč 2001). In the warm and dry climate of the Podunajská nížina, production potential will be increasingly limited by decreasing crop water availability and heat (Eitzinger *et al.* 2013). In north-eastern Austria bordering the Záhorie lowland, less water will be available in the soil in the future during the summer months in a period with a negative water balance (Herceg *et al.* 2019).

Under climate change scenarios, soil water deficits in the Podunajská nížina will worsen in the growing season (Takáč 2001, Takáč *et al.* 2008). Soil water content is expected to decrease, by up to 10% in the lowlands (Novák 1996). The moisture security of crops with a growing season in the spring months will improve according to the calculated average values, but the variability will increase. The moisture security of crops with a growing season in the summer months will deteriorate (Takáč, Šiška, Lapin 2009). A significant part of the territory of Slovakia in the most agriculturally important areas will be characterised by an average water balance deficit of more than 250 mm (Šiška & Takáč 2009).

Soil moisture modelling is considered to be one of the most appropriate methods to monitor and quantify the impact of water scarcity on agricultural production, as it allows continuous data to be obtained at a daily time step and, in combination with GIS, spatially interpreted at the necessary scale. Modelling is a key tool for assessing the impacts of climate change on agriculture, the effectiveness of adaptation measures and designing optimal strategies.

MATERIALS AND METHODS

The assessment of the soil water regime was based on numerical simulations with the agro-ecological model DAISY. The DAISY model simulates those parts of the water, carbon and nitrogen cycles that are related to agricultural soil systems. Based on management information and weather data, the DAISY model simulates crop growth, water dynamics, heat balance, organic matter balance and nitrogen dynamics in agricultural soils. The water balance sub-model consists of a surface water balance and a soil water balance. Within surface water, the processes of snowpack accumulation and melting, interception, evapotranspiration, infiltration, ponding, and surface runoff are simulated. The soil water regime is composed of water flow in the soil matrix and in the macropores. It also includes water uptake by plant roots (Hansen *et al.* 1990, Abrahamsen & Hansen 2000, Hansen 2000). Modelling of water flow in a layered soil profile including the effect of vegetation is based on the numerical solution of the Richards's equation (Richards 1931).

An important condition for the use of growth models is the verification of their reliability in reproducing real processes (Addiscot *et al.*1995). Crop modules of the DAISY model were originally calibrated for Slovak conditions within the project PHARE/EC/WAT/1 (Takáč 1994). Crop parameters of the model were optimized for Slovak conditions and validated on the basis of experimental data from field trials (Takáč 1994, Takáč & Šiška 2011, Takáč *et al.* 2018). Statistical comparison of the results of soil moisture simulations by the DAISY model with measured values showed a high level of agreement between simulated and measured values (Takáč *et al.* 2018). The reliability of the model has also been demonstrated in several comparative studies (Diekkrüger *et al.* 1995, Kröbel *et al.* 2010, Palosuo *et al.* 2011, Rötter *et al.* 2012, Andrade *et al.* 2021).

A certain degree of uncertainty in the simulations is mainly associated with the input data. Model inputs are affected by data availability, measurement errors in the observed variables, and large spatial and temporal variability. Numerical simulations with the DAISY model were performed for the period 1961 – 2020 with a series of daily data of global radiation, air temperature, humidity, wind speed and atmospheric precipitation from meteorological stations representing each region. Simulations were carried out in rotations involving grain maize, spring barley, winter wheat, sugar beet and potatoes. Simulations were carried out for representative soil profiles of the selected regions listed in the Table 1 and 2 (Takáč & Ilavská 2021).

To assess the impact of soil on the soil water dynamics, additional simulations were carried out in the Podunajská nížina for three crops, namely maize, spring barley and winter wheat. The territory of the Podunajská nížina has been divided into four climatic regions. In each of the regions, five dominant soil types covering 99% of the agricultural land were identified – Haplic Chernozems, Fluvic Chernozems, Haplic Phaeozems, Haplic Fluvisols, and Cutanic Albic Luvisols as shown in the Table 3 (Takáč & Ilavská 2021, IUSS Working group WRB 2015). A fixed groundwater level of 170 to 250 cm depth, depending on the soil type, was considered for the Fluvic Chernozems and Haplic Fluvisols.

The basic climatic characteristics, i.e., annual mean air temperature and annual mean precipitation, were calculated for each site from the input meteorological data. From the model outputs, average values of evapotranspiration characteristics were calculated.

The assessment of the soil water regime was based on the calculation of the annual and seasonal integral water content in the 0 – 30 cm and 0 – 100 cm soil horizons. Agronomic criteria were used for the assessment, taking into account the plant-accessible water content expressed as % ASWC.

Table 1

Geographic location and altitude of simulated localities

Locality	**Latitude N**	**Longitude E**	**Altitude m**
Kuchyňa	48°24′	17°09′	206
Stupava	48°17′	17°01′	179
Malacky	48°27′	17°02′	165
Holíč	48°49′	17°10′	178
Myjava	48°46′	17°35′	375
Bratislava	48°10′	17°12′	131
Hurbanovo	47°52′	18°12′	115
Kráľová pri Senci	48°12′	17°28′	123
Žihárec	48°04′	17°52′	111
Jaslovské Bohunice	48°29′	17°40′	176
Piešťany	48°37′	17°50′	165
Podhájska	48°06′	18°20′	140

Locality	**Latitude N**	**Longitude E**	**Altitude m**
Nitra	48°19′	18°07′	173
Mochovce	48°16′	18°27′	212
Želiezovce	48°02′	18°38′	135
Trenčín	48°52′	18°01′	205
Beluša	49°04′	18°19′	254
Topoľčany	48°34′	18°09′	174
Dudince	48°10′	18°52′	140
Dolné Plachtince	48°12′	19°19′	200
Bzovík	48°19′	19°06′	355
Žiar nad Hronom	48°35′	18°52′	250
Sliač	48°39′	19°08′	313
Lučenec	48°20′	19°44′	214
Rimavská Sobota	48°22′	20°01′	214
Rožňava	48°39′	20°32′	289
Moldava nad Bodvou	48°37′	21°00′	210
Košice	48°40′	21°13′	230
Prešov	49°02′	21°19′	307
Somotor	48°24′	21°49′	100
Michalovce	48°45′	21°57′	112
Trebišov	48°40′	21°44′	104
Vysoká nad Uhom	48°37′	22°05′	105
Orechová	48°42′	22°14′	122
Kamenica nad Cirochou	48°56′	22°00′	178
Stropkov	49°13′	21°39′	219
Spišské Vlachy	48°57′	20°48′	396
Liptovský Hrádok	49°02′	19°44′	640
Poprad	49°04′	20°15′	693

Table 2

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 (Takáč & Ilavská 2021)

Locality	**Soil type (WRB 2015)**	**Texture**	**W_{FC} [mm]**	**W_{WP} [mm]**	**AWC [mm]**
Kuchyňa	Haplic Regosol	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

Original paper

Locality	**Soil type (WRB 2015)**	**Texture**	W_{FC} [mm]	W_{WP} [mm]	AWC [mm]
Hurbanovo	Haplic Chernozems	Loamic	348	124	224
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 Chernozem	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 Luvisosl	Loamic	319	122	197
Beluša	Cutanic Albic Luvisosl	Loamic	346	128	218
Topoľčany	Cutanic Albic Luvisol	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
Tisinec	Cutanic Albic Luvisols	Loamic	336	113	222
Kamenica nad Cirochou	Haplic Fluvisols	Loamic	350	139	211
Medzilaborce	Haplic Cambisols	Loamic	405	188	217
Stropkov	Cutanic Albic Luvisols	Loamic	335	109	218
Liptovský Hrádok	Cutanic Albic Luvisols	Loamic	331	90	241
Spišské Vlachy	Haplic Cambisols	Loamic	340	133	207
Poprad	Haplic Cambisols	Loamic	297	65	232

Table 3
Characteristics of Danubian lowland regions. *FC* – field capacity, *WP* – wilting point, *AWC* – available water capacity (Takáč & Ilavská 2021)

Region / meteorological station	Soil type (WRB 2015)	FC [mm]	WP [mm]	AWC [mm]
Northwest *Jaslovské Bohunice*	Haplic Phaeozems	420	216	204
	Haplic Chernozems	408	171	237
	Fluvic 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
	Fluvic Chernozems	372	159	213
	Haplic Fluvisols	408	159	249
	Cutanic Albic Luvisols	423	195	228
Southwest *Bratislava*	Haplic Phaeozems	423	207	216
	Haplic Chernozems	396	147	249
	Fluvic 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
	Fluvic Chernozems	384	147	237
	Haplic Fluvisols	387	147	240
	Cutanic Albic Luvisols	429	210	219

Table 4
Division of soil moisture into intervals according to the ecological classification of soil water regime (Kutílek 1978)

Interval	Soil water potential pF	Soil moisture interval
Aqatic	<1.3	Above Full water capacity *FWC*
Uvidic	1.3 – 2.4	Full water capacity *FWC* – Field capacity *FC*
Sem-iuvidic	2.4 – 3.3	Field capacity *FC* – Point of decreased availability *PDA*
Semi-arid	3.3 – 4.18	Point of decreased availability *PDA* – Wilting point *WP*
Arid	4.18 – 4.78	Wilting point *WP* – Hygroscopic coefficient H_c
Hyper-arid	> 4.78	Less than Hygroscopic coefficient H_c

The ecological classification of the soil water regime was also used to assess the soil water regime (Kutílek 1978). The criteria for the ecological classification of the water regime of soils are the degree of moisture in the soil profile, the duration of individual moisture intervals and moisture stratification. In this classification, it is customary to divide the soil profile into two layers: the top layer of the soil profile (0 – 0.3 m) and the bottom layer of the soil profile (0.3 – 1.0 m). The whole soil moisture range is divided into 6 intervals in the ecological classification according to the hydrological limits (Table 4). Considering the water requirement of the crops, when assessing the soil water regime, we considered days when soil moisture was in the semiarid and arid range as the dry season, when the crop's water requirements are not met (Takáč 1999).

RESULTS

In agricultural areas of Slovakia, according to the hydrological classification of the soil water regime, an evaporative regime with a precipitation to evapotranspiration ratio < 1 prevails (Kutílek 1978). Over the period 1991 – 2020, there was a 1 to 1.2 ˚C increase in mean annual temperature at assessed sites compared to the period 1961 – 1990. Reference evapotranspiration totals also increased as a result of the increased temperatures. At the same time, rainfall totals also increased (Table 5). Rising temperatures result in an increase in the crop water moisture requirements. 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 Podunajská nížina (Table 6).

Table 5

Mean annual air temperatures T [˚C], precipitation totals R [mm], reference evapotranspiration totals ET_0 [mm], actual evapotranspiration totals ET [mm], evapotranspiration deficit ET_0-ET [mm] and relative evapotranspiration ET/ET_0 [%] at selected meteorological stations for the period 1961 – 1990 and the period 1991 – 2020

Locality	**Period**	T	R	ET_0	ET_a	ET_0-ET	ET/ET_0
Hurbanovo	1961 – 1990	10.0	523	787	427	360	54
	1991 – 2020	11.2	570	856	456	400	53
Nitra	1961 – 1990	9.7	536	726	440	286	61
	1991 – 2020	10.7	559	793	459	434	51
Kuchyňa	1961 – 1990	9.2	642	714	423	291	59
	1991 – 2020	10.4	660	804	448	356	56
Lučenec	1961 – 1990	8.8	565	666	426	240	64
	1991 – 2020	9.8	613	725	466	259	64
Rožňava	1961 – 1990	8.3	669	598	458	140	77
	1991 – 2020	9.5	701	681	490	191	71
Michalovce	1961 – 1990	9.1	605	609	442	167	73
	1991 – 2020	10.3	652	692	494	198	71
Trebišov	1961 – 1990	8.9	547	635	406	229	64
	1991 – 2020	10.0	579	737	432	305	59

Table 6

Average values of crop water requirement of selected crops [mm] from sowing to harvesting at selected locations in the period 1961 – 1990 and in the period 1991 – 2020

Locality	Spring barley		Winter wheat		Maize	
	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020	1961 – 1990	1991 – 2020
Malacky	437.3	453.0	594.0	613.3	613.0	667.5
Hurbanovo	446.8	464.3	593.7	601.3	659.1	697.1
Bratislava	442.0	491.8	591.4	647.2	650.7	744.6
Nitra	430.8	483.1	573.2	638.0	635.9	731.5
Topoľčany	413.9	424.9	568.1	569.3	594.1	636.2
Lučenec	410.1	433.8	584.0	587.3	592.3	644.7
R. Sobota	382.2	419.9	559.6	581.5	557.8	630.4
Moldava	395.2	411.5	555.9	562.7	572.4	617.6
Trebišov	399.8	432.1	562.1	582.2	579.4	651.1
Michalovce	378.8	419.2	533.3	560.2	556.7	634.8

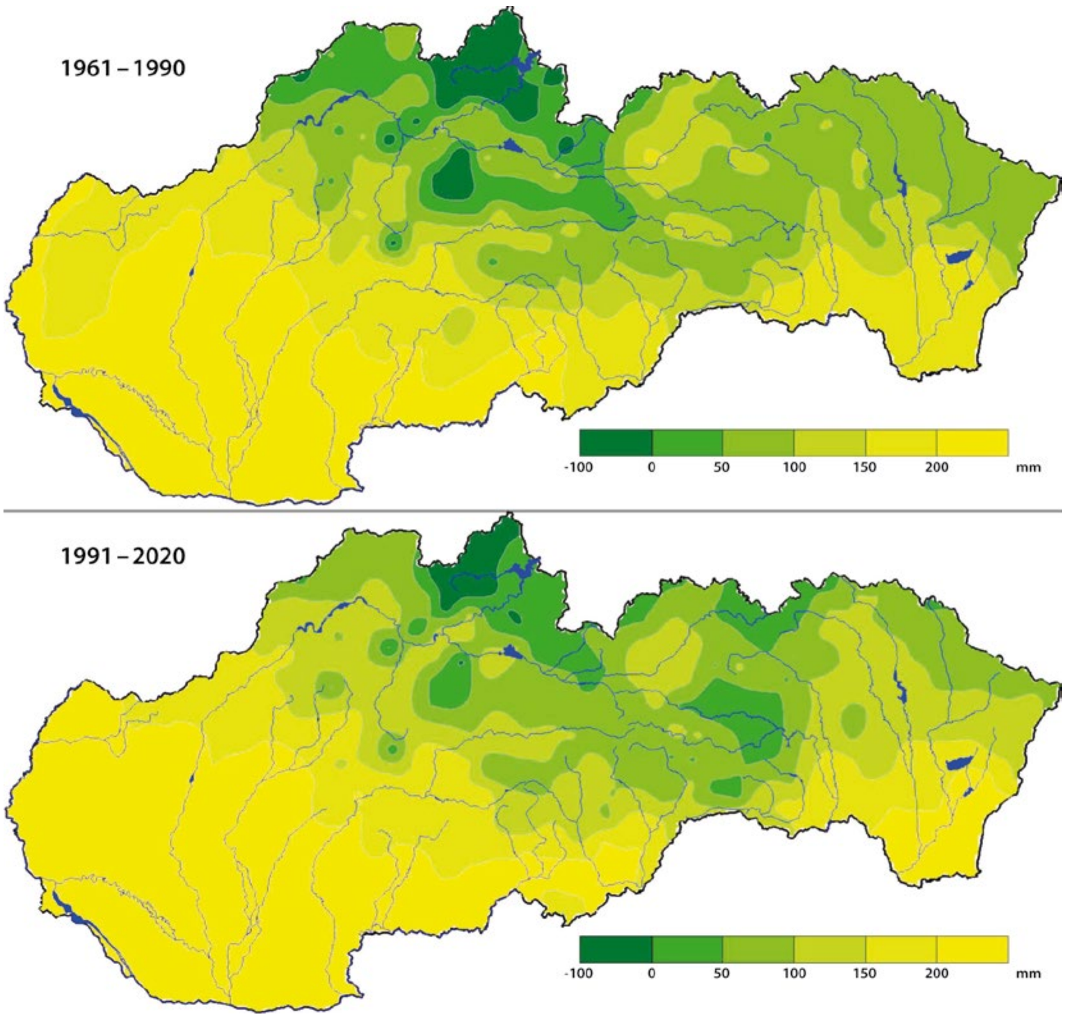


Figure 1 Mean deficit of Climate water balance (R-ET_0) in the period 1961 – 1990 and 1991 – 2020

Table 7

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 0 – 100 cm in the period 1961 – 1990 and 1991 – 2020

Locality	1961 – 1990						1991 – 2020					
	0–30 cm			0–100 cm			0–30 cm			0–100 cm		
	SWC [mm]	ASWC [mm]	ASWC [%]	SWC [mm]	ASWC [mm]	ASWC [%]	SWC [mm]	ASWC [mm]	ASWC [%]	SWC [mm]	ASWC [mm]	ASWC [%]
Kuchyňa	51	34	59	152	101	57	50	33	58	148	97	54
Stupava	52	36	64	186	119	67	51	35	62	179	112	66
Myjava	88	59	79	353	185	89	85	57	76	350	179	86
Holíč	74	28	49	275	117	59	72	27	47	265	107	54
Bratislava	76	43	57	266	144	61	72	39	51	250	128	54
Hurbanovo	70	37	57	246	122	56	72	39	59	250	126	59
Žihárec	82	41	62	271	138	64	83	43	64	276	143	66
Podhájska	63	33	53	207	115	53	65	35	56	211	124	56
Jaslovské Bohunice	83	43	59	290	143	65	80	41	56	279	131	60
Piešťany	91	38	62	323	131	71	90	38	62	320	127	69
Nitra	86	43	60	293	133	64	84	40	57	282	122	58
Trenčín	76	42	58	273	151	77	75	41	57	267	145	74
Beluša	89	59	87	335	207	95	84	54	80	317	189	87
Topoľčany	76	37	53	292	126	60	76	37	53	291	125	59
Dudince	97	43	68	364	152	83	98	45	70	367	155	85
Žiar nad Hronom	77	49	84	267	175	93	73	45	76	250	158	84
Sliač	90	58	85	337	203	95	88	56	82	330	195	92
Dolné Plachtince	96	43	64	350	158	80	99	47	69	359	166	84
Lučenec	83	47	52	323	133	58	84	48	53	324	135	58
Rimavská Sobota	82	54	68	338	174	81	81	53	67	333	169	79
Rožňava	82	56	79	333	194	91	81	54	77	326	187	87
Moldava nad Bodvou	81	56	81	313	192	90	76	52	74	296	174	82
Košice	80	48	65	301	160	73	74	43	57	280	139	63
Somotor	78	45	66	256	143	68	77	44	65	252	139	67
Michalovce	89	53	64	321	158	67	88	52	63	318	155	66
Trebišov	99	46	73	348	154	67	98	45	72	346	152	66
Vysoká nad Uhom	93	50	72	357	184	83	91	47	69	348	175	79
Kamenica nad Cirochou	95	61	84	346	207	94	94	59	82	341	202	91

As a result of increased reference evapotranspiration totals, the negative climatic water balance, characterised by the difference between precipitation totals and potential evapotranspiration totals, has been exacerbated. The deficit of climatic water balance above 200 mm in a large growing season characterized by an average daily temperature >10 °C occurred in the period 1961 – 1990 in the western part of the Záhorská nížina, in the Podunajská nížina and in the Ipeľ basin in the south-central Slovakia. In the period 1991 – 2020, the area with a climatic water balance deficit above 200 mm was extended to the entire Záhorská nížina and the Východoslovenská nížina (Fig. 1). A comparison of the average value of the water balance deficit in the period 1961 – 1990 and in the period 1991 – 2020 shows that the negative water balance widened by 10% in the main growing season. As a result of the deterioration of the climatic water balance, there was an increase in the evapotranspiration deficit and a decrease in relative evapotranspiration values during the period 1991 – 2020 compared to the period 1961 – 1990 (Table 5).

Table 8

Average number of days per year with soil water storage ASWC <50% in soil horizons 0 – 30 cm and 0 – 100 cm in the periods 1961 – 1990 and 1991 – 2020 at selected sites

Locality	**1961 – 1990**		**1991 – 2020**	
	0 – 30 cm	**0 – 100 cm**	**0 – 30 cm**	**0 – 100 cm**
Kuchyňa	165	170	163	188
Stupava	154	141	153	140
Myjava	106	49	123	64
Holíč	204	167	205	181
Bratislava	168	147	183	171
Hurbanovo	177	175	159	158
Žihárec	148	133	133	121
Podhájska	187	186	167	168
Jaslovské Bohunice	159	135	171	151
Piešťany	150	110	151	115
Nitra	157	137	168	155
Trenčín	162	89	162	99
Beluša	48	19	85	50
Topoľčany	181	155	174	153
Dudince	138	63	125	63
Žiar nad Hronom	75	39	110	79
Sliač	60	30	82	44
Dolné Plachtince	142	71	125	60
Lučenec	178	155	168	152
Rimavská Sobota	121	80	127	87
Rožňava	76	42	83	52
Moldava nad Bodvou	74	43	100	63
Košice	128	92	157	129
Somotor	130	120	136	127
Michalovce	122	106	124	112
Trebišov	115	97	118	102
Vysoká nad Uhom	108	58	128	80
Prešov	116	87	95	59

Locality	1961 – 1990		1991 – 2020	
	0 – 30 cm	0 – 100 cm	0 – 30 cm	0 – 100 cm
Tisinec	50	20	50	23
Kamenica nad Cirochou	50	20	64	35
Medzilaborce	27	5	33	2
Liptovský Hrádok	30	9	33	11
Spišské Vlachy	47	21	36	10

In the long term, the lowest soil water reserves, expressed as % of ASWC, are in the west of the Záhorská nížina and in the south-east of the Podunajská nížina. Changes in climatic conditions have had an impact on soil water reserves. In the period 1991 – 2020 there was a slight decrease in the average soil water content in most of Slovakia compared to the period 1961 – 1990 (Table 7). Significant reductions of more than 5% of the ASWC occurred in the west of the Podunajská nížina, in the central Považie, in the central Pohronie and in the Košice Basin. On the contrary, an increase in soil water reserves in the period 1991 – 2020 compared to the period 1961 – 1990 occurred in the south-east of the Podunajská nížina, in the Ipeľ Basin, in Spiš and Šariš. This slight increase of up to 5% does not represent a significant improvement in moisture conditions.

In terms of impacts on cultivated crops, the duration of a period with soil moisture in the root zone below 50 % ASWC at critical developmental stages of cultivated crops is considered critical in agricultural practice. According to numerical simulations, in the Podunajská nížina and Záhorská nížina, the soil moisture drops below 50% of the ASWC on average already in June, in the south of central and eastern Slovakia in July. In some years, this may occur as early as early spring, or may persist through autumn and winter as a result of insufficient rainfall in the autumn and winter months.

The average number of days per year with available soil water <50% of ASWC in the 0 – 30 cm and 0 – 100 cm soil horizons at selected sites for the periods 1961 – 1990 and 1991 – 2020 is shown in Table 8. The highest number of days with soil water content below 50% was recorded in the Záhorská nížina and in the southeast of the Podunajská nížina. In the period 1991 – 2020, compared to the period 1961 – 1990, the most significant increase in the number of days with soil water storage below 50% ASWC occurred in the Záhorská nížina, the west and north of the Podunajská nížina, the central Považie, the central Pohronie, the Košice basin and the eastern part of the Východoslovenská nížina. On the other hand, a significant decrease in the number of days with soil water storage below 50% ASWC occurred in the south-east of the Podunajská nížina, in the Ipelian and Lučenec basins, in Šariš and Spiš. This reduction in the number of days with soil water storage below 50% ASWC is a consequence of increased rainfall due to a change in circulation patterns, with meridional air circulation becoming more prevalent in recent years at the expense of zonal air circulation.

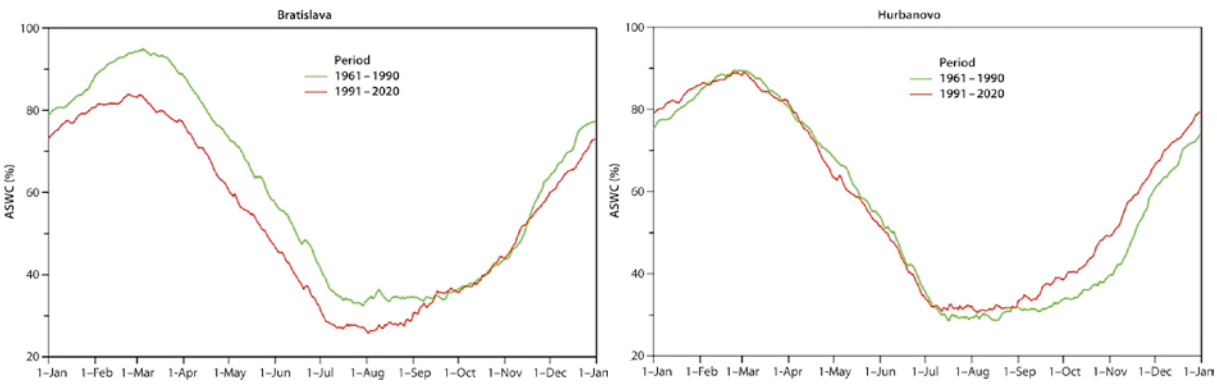


Figure 2 Average annual course of soil water storage in the periods 1961 – 1990 and 1991 – 2020 in Bratislava and Hurbanovo.

Changes in the annual pattern of rainfall were also reflected in the annual pattern of soil water storage (Figure 2). In the south-west of the Podunajská nížina (Bratislava), soil water reserves decreased by 12% in the spring, 8% in the summer, 7% in the winter and less than 1% in the autumn in the period 1991 – 2020 compared to the period 1961 – 1990. In the south-east of the Podunajská nížina (Hurbanovo), soil water reserves dropped by less than 2% in spring, while in other seasons they increased, most of all in autumn, by 7%.

Soil moisture is spatially heterogeneous; in addition to water uptake from atmospheric precipitation or groundwater, it also depends on soil properties. Depending on the texture, the soil can hold different amounts of water. The same soil water content can mean plenty of available water in one soil and not enough in another. Sandy soils have a very low value of available water capacity. Loamy soils have the highest available water capacity.

The occurrence and duration of periods with soil water storage below 50 % of ASWC varies from region to region. The fact that the water storage in the 0 – 100 cm horizon drops below 50 % of the ASWC is common in the southern regions of Slovakia and occurs almost every year. The median number of days with soil moisture below 50% ASWC in continuous periods is more than 150 days in the Podunajská nížina and Zahorská nížina. Once every 4 years in these regions, a continuous period with soil moisture less than 50 % of the ASWC reaches more than 200 days. Most of the locations in western Slovakia have maxima above 300 days in the assessed period. Available soil water storage below 50% of the ASWC occurred at the evaluated stations for an average of 90 days during 1961 – 1990 and for an average of 96 days during 1991 – 2020.

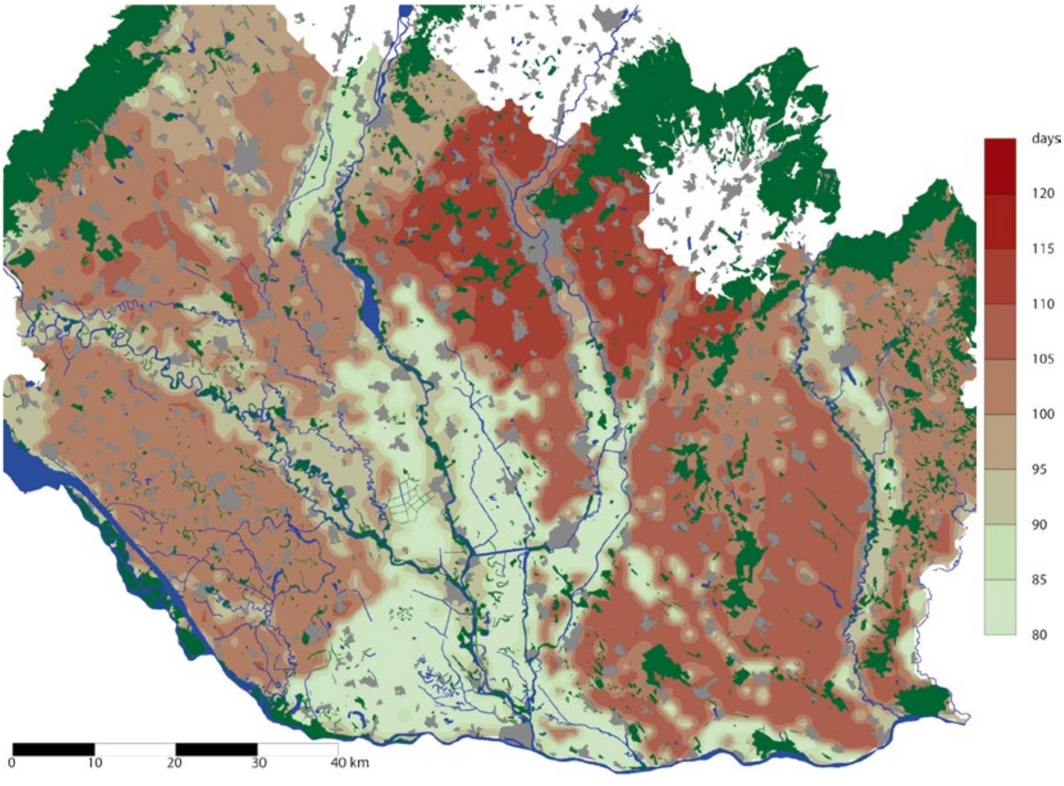


Figure 3 Mean number of days with ASWC below 50% in the soil horizon 0 – 100 cm under maize in Podunajská nížina

Spatial variation in this characteristic also occurs within regions, depending on soil properties and the presence of groundwater table. As can be seen in Figure 3, the number of days with soil moisture less than 50% ASWC varies over a wide range, from an average of 75 days to more than 120 days. The smallest number of days with soil moisture below 50% ASWC in the Podunajská nížina was calculated for the areas with the presence of the water table on the lower Žitný ostrov Island and in the vicinity of watercourses. The highest number of days with usable soil water supply in the Podunajská nížina was simulated for Luvisols and Haplic Chernozems, the lowest for Phaozems. With the exception of the South-eastern part of lowland, the number of days with soil water storage below 50 % of the ASWC increased by an average of 2 to 17 days, depending on crop and soil type, in the 1991 – 2020 period compared to the 1961 – 1990 period.

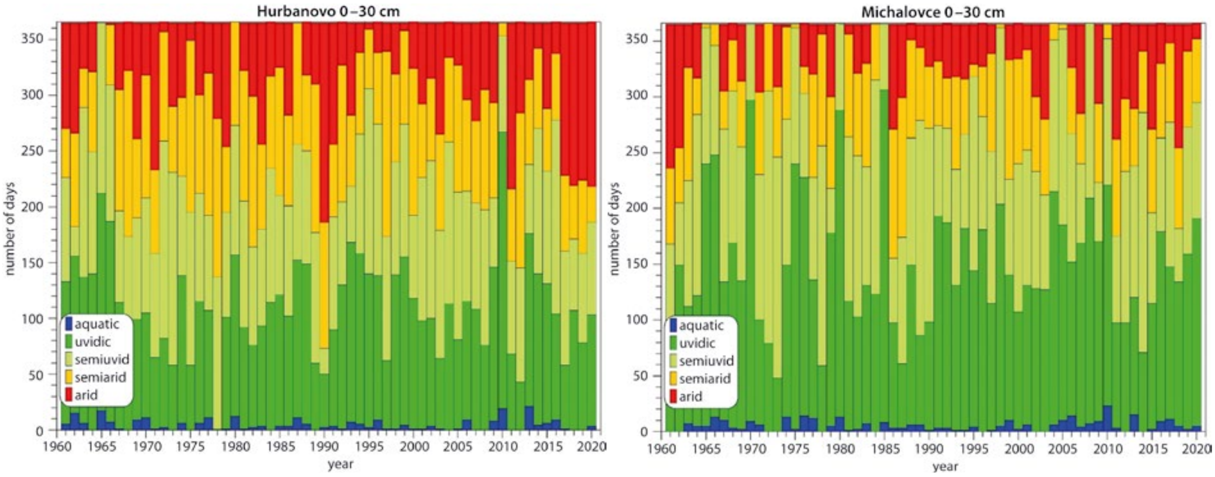


Figure 4 Number of days with different degrees of soil profile moisture according to the ecological classification of soil water regime in the 0 – 30 cm horizon in Hurbanovo and Michalovce in the period 1961 – 2020

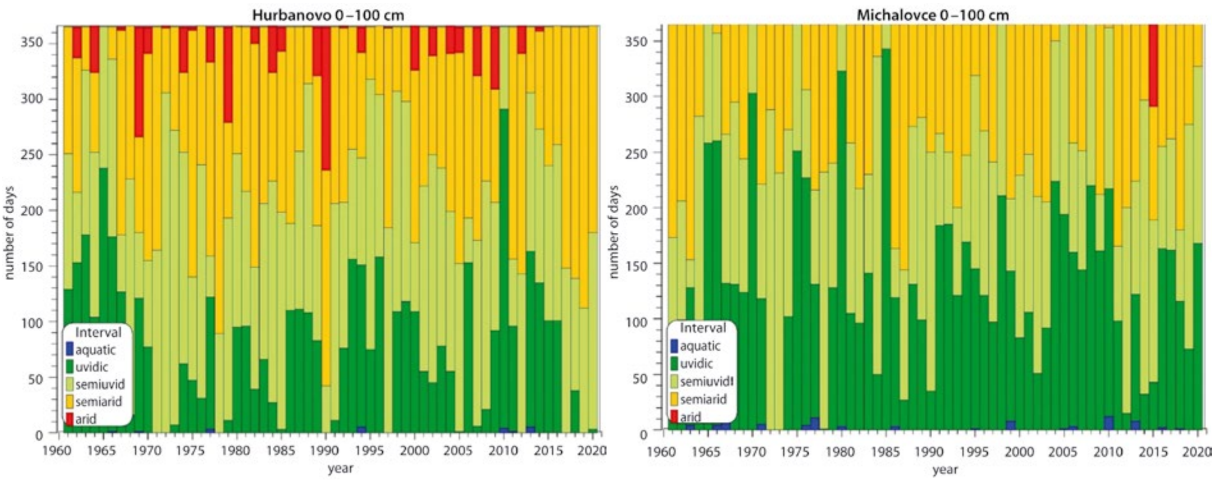


Figure 5 Number of days with different degrees of soil profile moisture according to the ecological classification of soil water regime in the 0 – 100 cm horizon in Hurbanovo and Michalovce in the period 1961 – 2020

In addition to spatial variability, soil water storage shows considerable temporal variability. Soil water content fluctuates significantly from year to year. The highest average annual soil water storage in the whole territory of Slovakia was recorded in 1965 and 2010. On the other hand, the smallest average annual available soil water supply was simulated over the entire area in 1973, 1990, 2012, and 2017. The years 1978 and 1989 were also exceptionally dry in the western part of Slovakia.

According to the simulated values of soil water potential, in the 0 – 30 cm soil horizon, according to the ecological classification of the water regime (Kutílek, 1978), soil moisture occurred in the arid interval almost every year in Hurbanovo on the Podunajská nížina, and in Michalovce on the Východoslovenská nížina in four out of five years (Fig. 4). In the 0 – 100 cm soil horizon in Hurbanovo, soil moisture occurred in the arid interval in two of the three years, in Michalovce only 74 days in 2015 (Fig. 5).

In both Hurbanovo and Michalovce, uvidic interval (average 108 days in Hurbanovo, 146 days in Michalovce) and semiuvidic interval (average 108 days in Hurbanovo, 118 days in Michalovce) were dominated in the 0 – 30 cm soil horizon. Similarly, in the 0 – 100 cm soil horizon in Michalovce were dominated the uvidic (133 days) and semiuvidic (128 days) soil moisture interval. In Hurbanovo, in the 0 – 100 cm soil horizon was dominated by the subuvidic (141 days) and semiarid (130 days) soil moisture intervals.

The driest year in Hurbanovo was 1990, when soil moisture in the arid interval in the 0 – 30 cm horizon lasted 179 days and in the 0 – 100 horizon 129 days. According to this criterion, the driest years in Michalovce were 2018 and 2011, when the soil moisture in the arid interval in the 0 – 30 cm horizon was 111 and 103 days, respectively.

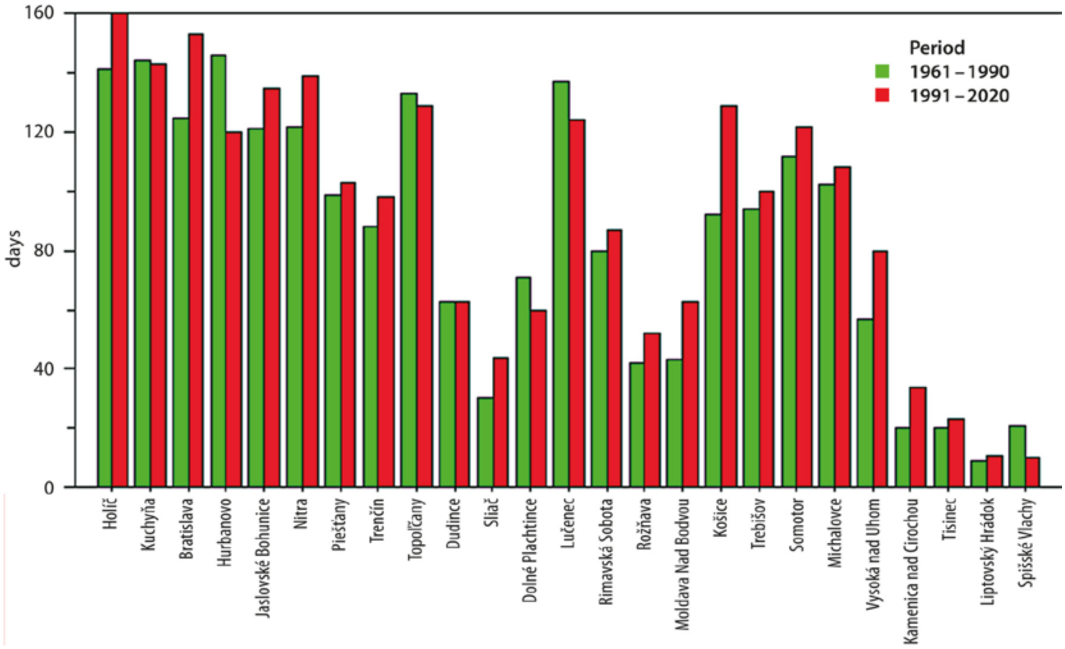


Figure 6 Number of days with soil moisture in the arid and semiarid interval between 1961 – 1990 and 1991 – 2020 at selected sites.

In terms of the annual course, the semiuvidic and uvidic interval predominates in the winter, and the semiarid and arid interval predominates in the summer half of the year. The number of days when the soil water supply occurs in the semiarid and arid interval, i.e., below the point of decreased availability, was the highest in the period 1961 – 1990 in the Záhorská nížina and in the south-east of the Podunajská nížina, i.e., more than 140 days (Fig. 6). In the period 1991 – 2020, the highest number of days with soil moisture in the semiarid and arid interval occurred in the west of the Záhorská nížina and in the southwest of the Podunajská nížina, i.e., more than 150 days.

As can be seen in Figure 6, trends vary from region to region. The greatest increase in the number of days with soil moisture in the semiarid and arid interval in the period 1991 – 2020 compared to the period 1961 – 1990 occurred in the west of the Záhorská nížina (19 days), the southwest of the Podunajská nížina (28 days), the north of the Podunajská nížina (14 – 17 days), the Košice basin (20 – 37 days), and the east of the Východoslovenská nížina (23 days). On the contrary, a decrease in the number of days with soil moisture in the semiarid and arid interval in the period 1991 – 2020 compared to the period 1961 – 1990 occurred in the southeast of the Danube Basin (26 days), in the Ipeľ Basin (11 days), in the Lučenec Basin (13 days), and in the Spiš Basin (11 days).

Original paper

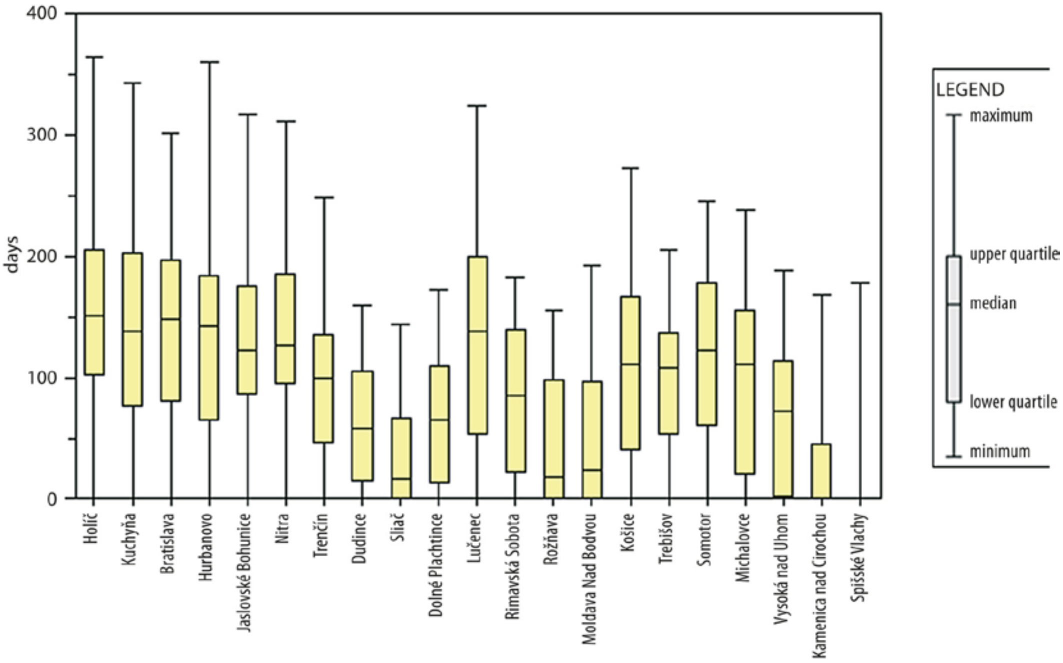


Figure 7 Statistical characteristics of the number of days with soil moisture in the arid and semiarid interval in the period 1961 – 1990 and 1991 – 2020 at selected sites.

The number of days with soil water supply at the point of decreased availability varies from year to year (Figure 7). In 1965 there was not a single day with soil moisture in the semiarid and arid interval in any region, in 2010 such a day occurred with soil moisture in the semiarid interval only 13 days in Bratislava and 5 days in Trebišov and Michalovce.

Peaks of 300 days or more below the point of decreased availability occurred in the Záhorská nížina, the Podunajská nížina and the Lučenec basin. In Holíč, in the western part of the Záhorská nížina, the soil water supply was below the point of decreased availability for the whole year in 1978 and 327 days in 1990. In Hurbanovo, in the south-east of the Podunajská nížina, the highest maximum values of the number of days with soil water supply below the point of decreased availability were recorded in 1978 and 1990, i.e., 361 days and 315 days, respectively. Of the regions assessed, the lowest incidence of days with soil water supply below the point of decreased availability was recorded in the Spiš region, where there were 6 years of drought in the 1960s, the highest being in 1961, with 179 days. In recent decades, this phenomenon has occurred less frequently in the Spiš region, once or twice per decade. The median value is equal to 0 and the upper quartile value is close to 0.

As the length of the period of low rainfall increases, so do the impacts on water availability for crops. Meeting the water requirements of crops is limited by the water supply in the soil. As the stock of available water in the soil decreases, the coverage of crop water needs also decreases (Figure 8). If soil water reserves are not replenished sufficiently in winter, the effects of low rainfall in the summer months are amplified and the soil profile is almost completely drained. The reason for the low soil water storage in 1978 in western Slovakia and in 1990 and 2012 throughout the territory was not only the low rainfall in the summer months, but also the insufficient rainfall in the preceding winter period, as a result of which the soil water storage was not replenished in most of the territory in the way it is usually replenished in other years.

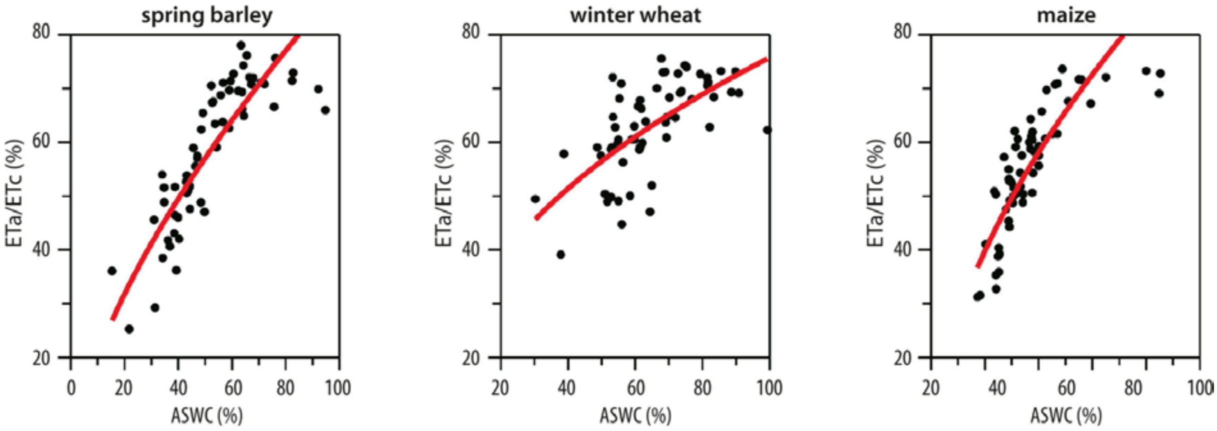


Figure 8 Relationship between available soil water content [% ASWC] and water requirement of selected crops at Hurbanovo

Table 9

Average values of water requirement coverage of selected crops [%] at selected locations in the period 1961 – 1990 and in the period 1991 – 2020

Locality	**Spring barley**		**Winter wheat**		**Maize**	
	1961 – 1990	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**
Holíč	56	54	54	51	56	49
Hurbanovo	44	44	65	67	44	44
Bratislava	48	40	75	62	47	41
Jasl. Bohunice	65	58	61	55	61	53
Nitra	48	41	71	62	48	41
Topoľčany	52	50	70	66	53	48
Dudince	66	65	64	64	61	60
Lučenec	68	62	81	82	63	61
R. Sobota	79	67	67	62	68	62
Moldava	81	72	96	94	81	72
Trebišov	66	57	79	75	66	59
Michalovce	76	62	96	92	76	64

In all southern regions of Slovakia, with the exception of the south-eastern part of the Podunajská nížina, a decrease in the coverage of the crop water moisture requirement was recorded (Table 9), with the greatest decrease observed in the south-western part of the Podunajská nížina. Even the observed slight increase in precipitation (Table 5) cannot meet the increasing evapotranspiration requirements. In dry years, the water requirement of summer crops such as maize and sugar beet is below 30%.

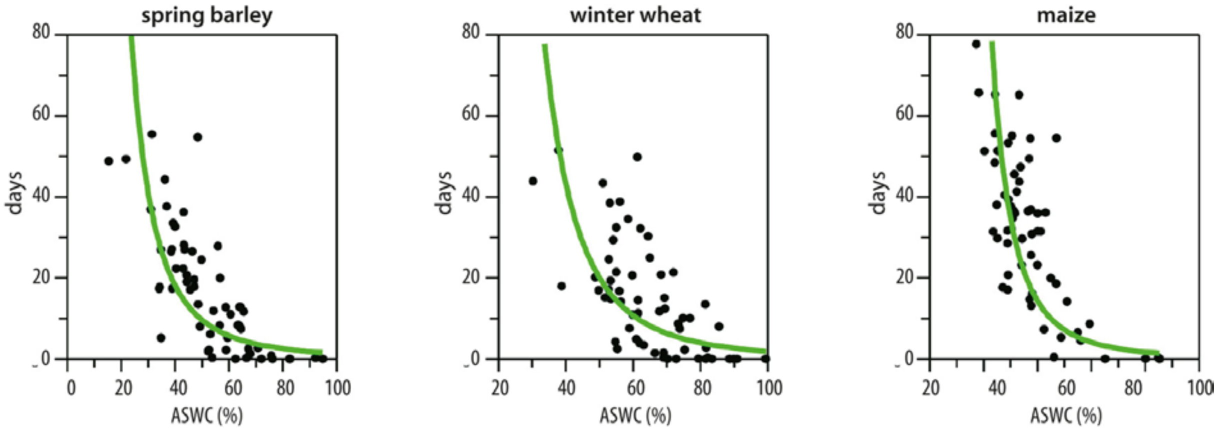


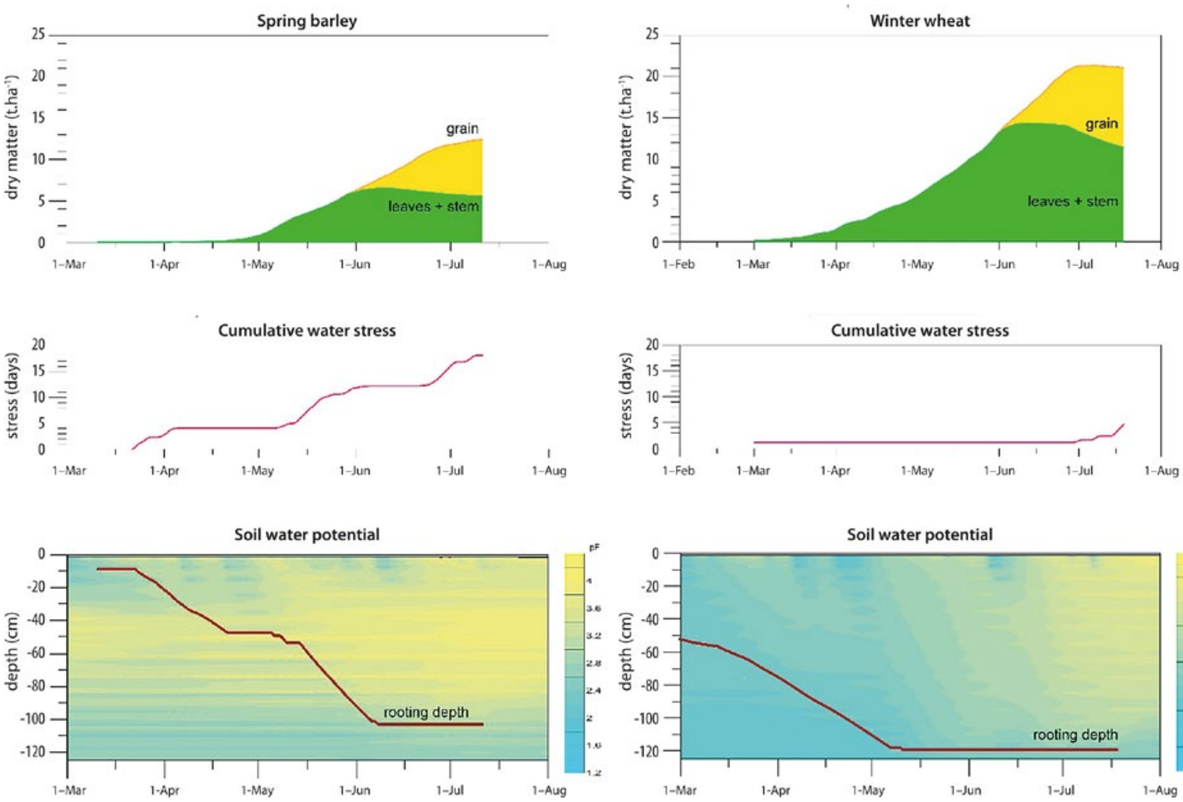
Figure 9 Relationship between available soil water content [% ASWC] and simulated number of days with water stress for selected crops on Chernozem in Hurbanovo

Table 10
Average number of days with water stress for selected crops at selected sites during 1961 – 1990 and 1991 – 2020

Locality	**Spring barley**		**Winter wheat**		**Maize**	
	1961 – 1990	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**	**1961 – 1990**	**1991 – 2020**
Holíč	17	22	27	31	25	37
Hurbanovo	11	16	24	24	32	32
Bratislava	7	18	16	26	24	37
Jasl. Bohunice	10	19	19	27	22	34
Nitra	8	18	18	26	20	34
Topoľčany	13	16	23	21	26	31
Dudince	7	10	10	12	19	21
Lučenec	4	10	11	17	21	22
R. Sobota	2	7	3	10	9	16
Moldava	1	2	2	4	3	5
Trebišov	7	12	10	18	13	22
Michalovce	1	2	1	4	4	9

When soil moisture drops below the point of decreased availability, crops are subjected to water stress (Figure 9). The average number of days with water stress increased in the period 1991 – 2020 compared to the period 1961 – 1990, but remained at the same level or slightly decreased in the south-east of the Podunajská nížina for winter wheat and summer crops (Table 20). In dry years for crops grown in summer, the number of days with water stress exceeded 90. In terms of impacts on crop growth and yield formation, it is important at which growing stage water stress occurs.

In addition to climatic and soil conditions, the effects of drought on crop growth and yield depend on the crop itself. The effects of drought on yields can vary from year to year for different crops. As can be seen in the Figure 10, while the roots of winter wheat sown in autumn draw water from greater depths in the spring and the crop does not suffer from water stress, in the case of spring barley, water stress starts shortly after emergence. Differences in spring soil water content were influenced both by the lack of winter rainfall and by the pre-crop. Between September 1989 and March 1990, only 132 mm of precipitation fell, which was less than 50% of normal. In the case of spring barley, the pre-crop was maize, which drained more water from the soil profile in the previous year than spring barley, which was the pre-crop before winter wheat.



Figures 10 Development of spring barley and winter wheat on Cutanic Albic Luvisols at Nitra in 1990

CONCLUSION

The assessment of soil water regime with emphasis on the occurrence and duration of drought in the period 1961 – 2020 was based on simulations of soil water regime by the agro-ecological model DAISY at selected sites in agricultural regions of Slovakia. Although no area in Slovakia is classified as arid, the coverage of the crop water requirements is insufficient in the southern regions, especially in the Podunajská nížina. According to the simulated values of soil water potential, in the 0 – 30 cm soil horizon, according to the ecological classification of the water regime, soil moisture occurred in the arid interval almost every year in Hurbanovo on the Podunajská nížina, and in Michalovce on the East Slovak Lowland in four out of five years.

The greatest increase in the number of days with soil moisture in the semiarid and arid interval in the period 1991 – 2020 compared to the period 1961 – 1990 occurred in the west of the Záhorská nížina, the southwest of the Podunajská nížina, the north of the Podunajská nížina, the Košice basin and the east of the Východoslovenská nížina. On the contrary, a decrease in the number of days with soil moisture in the semiarid and arid interval in the period 1991 – 2020 compared to the period 1961 – 1990 occurred in the south-east of the Podunajská nížina, in the Ipeľ Basin, the Lučenec Basin and in Spiš.

In all southern regions of Slovakia, except for the south-east of the Podunajská nížina, a decrease in the coverage of the crop water requirements was recorded. In dry years, the crop water requirements grown in summer is below 30% and the number of days with water stress can exceed 90.

ACKNOWLEDGEMENT

This publication is the result of the project implementation: „Scientific support of climate change adaptation in agriculture and mitigation of soil degradation" (ITMS2014+ 313011W580) supported by the Integrated Infrastructure Operational Programme funded by the ERDF.

Original paper

REFERENCES

Abrahamsen, P., Hansen, S. (2000). DAISY. An Open Soil, Crop, Atmosphere System Model. *Environmental Modelling & Software,* Vol. **15(3):** 313–330. ISSN 1364-8152.

Addiscot, T., Smith, J., Bradbury, N. (1995). Critical Evaluation of Models and Their Parameters. *Journal Environmental Quality*, Vol. **34:** 803–807.

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*, Vol. **26:** 371–387. https://doi.org/10.1007/s11367-021-01867-4

Brázdil, R., Trnka, M., Dobrovolný, P., Chromá, K., Hlavinka, P., Žalud, Z. (2009). Variability of Droughts in Czech Republic, 1881 – 2006. *Theor. Appl. Climatol.,* Vol. **97:** 297–315.

Cambel, B., Takáč, J. (2000). Priestorová diferenciácia hydrofyzikálnych vlastností pôd na príklade modelového územia Šaľa. VI. Zjazd Slov. spol. pre poľnohospodárske, lesnícke, potravinárske a veterinárne vedy pri SAV. Zborník prednášok. Sekcia pedologická. Zvolen 6. – 7. 9. 2000. VÚPOP, Bratislava, s. 29–34, ISBN 80-85361-78-7

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. *Ecol. Model.*, Vol. **81:** 3–29.

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):** 782–812

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.

Herceg, A., Nolz, R., Kalitz, P., Gribowszki, Z. (2019). Predicting impacts of climate change on evapotranspiration and soil moisture for a site with subhumid climate. *J. Hydrol. Hydromech.,* Vol. **67(4):** 384–392. DOI: 10.2478/johh-2019-0017.

IUSS Working Group WRB. (2015). World reference base for soil resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. *World Soil Resources Report* No. **106.** FAO Rome.

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. *Environmental Modelling & Software,* Vol. **25:** 583–601. DOI: 10.1016/j.envsoft.2009.09.003.

Kutílek, M. 1978. *Vodohospodářská pedologie*. Praha: SNTL/ALFA, 1978, 296 s.

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*, Vol. **33(2):** 119–135.

Novák, V. (1996). *Vplyv očakávaných klimatických zmien na bilanciu vody v pôde a produkciu biomasy na Slovensku: Projekt Country Study SR*. Bratislava: SHMÚ, ÚH SAV, 1996.

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. In European journal of agronomy, Vol. **35(3):** 103–114. DOI: 10.1016/J.EJA.2011.05.001.

Richards, L.A. (1931). Capillary Conduction of Liquids through Porous Media *Physics*, Vol. **1(5):** 318–333.

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:** 23–36. ISSN 0378-4290.

Šiška, B., Takáč, J. (2009). Drought Analyse of Agricultural Regions as Influenced by Climatic Conditions in the Slovak Republic. Időjárás, Vol. **113(1–2):** 135–143. ISSN 0324-6329.

Takáč, J. (1994). Verifikácia modelu DAISY – Simulovanie úrod obilnín. *Vedecké práce VÚZH,* Vol. **21:** 95–104.

Takáč, J. (1999). Trendy vývoja vodného režimu pôd v modelových podmienkach Žitného ostrova. *Vedecké práce VÚVH*, Vol. **24:** 195–208. VÚZH Bratislava,

Takáč, J. (2001). Dôsledky zmeny klímy na bilanciu vody v poľnohospodárskej krajine. NKP SR, 2001, zv. **10:** 16–26.

Takáč, J. (2013). Assessment of Drought in Agricultural Regions of Slovakia Using Soil Water Dynamics Simulation. *Agriculture (Poľnohospodárstvo*), Vol. **59(2):** 74–87. DOI: 10.2478/agri-2013 -0007.

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:** 1623–1626, ISSN 0133-3720.

Takáč, J., Šiška, B. (2011). Kalibrácia a validácia modelu DAISY pre podmienky Slovenska. *Vedecké práce VUPOP*, Vol. 33: 161–172. ISBN 978-80-89128-91-4.

Takáč, J., Šiška, B., Lapin, M. (2009). Dôsledky zmeny klímy na vlahovú zabezpečenosť poľných plodín podľa scenárov SRES A2 a B1. *Vedecké práce VÚPOP*, Vol. **31:** 87 – 200, ISBN 978-80-89128-59-4.

Takáč, J., Kotorová, D., Makovníková, J., Kováč, L. (2018). Validácia modelu DAISY v podmienkach Východoslovenskej nížiny. *Vedecké práce VÚPOP*, Vol. **40:** 100–113, Výskumný ústav pôdoznalectva a ochrany pôdy Bratislava. ISBN 978-80-8163-030-9.

Takáč, J., Ilavská, B. (2021). Crop water sufficiency in Slovakia. *Pedosphere Research*, Vol. **1(1):** 20–39. NPPC – VÚPOP 2021. ISSN 2729-8728.

Trnka, M., Dubrovský, M., Svoboda, M., Semerádová, D., Hayes, M., Žalud, Z., Wilhite, D. (2009). Developing a Regional Drought Climatology for the Czech Republic. *Int. J. Climatol.,* Vol. **29:** 863–883.

Trnka, M., Kersebaum, K.C., Eitzinger, J., Hayes, M., Hlavinka, P., Svoboda, M., Dubrovský, M., Semerádová, D., Wardlow, B., Pokorný, E., Možný, M., Wilhite, D., Žalud, Z. (2013). Consequences of Climate Change for the Soil Climate in Central Europe and the Central Plains of the United States. *Climate Change,* Vol. **120(1 – 2):** 405 – 418.