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IRRIGATION REQUIREMENTS AND IRRIGATION WATER USE EFFICIENCY IN SLOVAKIA IN THE PERIOD 1961−2020

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Citation: Takáč, J., Bezák, P., Sobocká, J. (2023). Irrigation requirements and irrigation water use efficiency in Slovakia in the period 1961–2020. *Pedosphere Research,* vol. **3,** 2023, no. 2, pp. 83–100. NPPC – VÚPOP 2023. ISSN 2729-8728.

Abstract

Numerical simulations by the DAISY model were performed for the period 1961–2020 with series of daily data on global radiation, air temperature, air humidity, wind speed, and atmospheric precipitation from meteorological stations representing each region in Slovakia. The simulations were run aiming to evaluate the irrigation need and irrigation water use efficiency of field crops: spring barley, winter wheat, maize, sugar beet, and potato. Also, dominant soil types were taken into consideration like Chernozem, Luvisol, Fluvisol, Mollic Fluvisol, and Phaeozem. The irrigation water use efficiency values obtained from numerical simulations are like the values obtained from the field stationary experiment. The most significant increase in the need of irrigation in the period 1991–2020 was evident in the southwest of the Danube Lowland on the upper Žitný ostrov (Rye Island). The highest increase in the moisture requirement of crops in the period 1991–2020 compared to the period 1961–1990 was recorded in the west and north of the Danube Lowland. There was a decrease in the irrigation water use efficiency for crops grown in the summer season. In the case of dense cereals, there was a reduction in the irrigation water use efficiency of mainly in the south of central Slovakia, in the Zvolenská basin, in the regions of Turiec, Šariš and Spiš. The highest average irrigation need was calculated for the area of the Danube and Záhorská Lowlands.

Keywords: water stress, irrigation needs, field crops, agroecological model DAISY

INTRODUCTION

Water in the soil-plant-atmosphere system is one of the basic and limiting factors of crop production. Supplementary irrigation is considered an effective way to alleviate or eliminate crop water stress and is even now a necessary condition for optimizing the water regime of the soil for the needs of agricultural production in the southern regions of Slovakia. The effectiveness of irrigation depends on the course of the weather, the hydro-physical properties of the soil, the availability of nutrients, the cultivated crop, and its variety, as well as the level of land management.

Supplementary irrigation significantly affects plant production. 67% of the Žitný ostrov territory permanently requires irrigation (DHI *et al.* 1995). The impact of irrigation on yield levels varied from year to year. The highest effect of irrigation on crop yields was simulated for alfalfa, the lowest for spring barley (Takáč 1996b). In 2000, with extreme temperatures during the growing season and a lack of rainfall, irrigation resulted in an increase in the yield of sugar beet tubers by 28.4%, sugar content by 41%, and raffinates by 43.9% (Bízik *et al.* 2001).

The positive effect of irrigation in the Field Stationary Experiment in Most pri Bratislave (Danube Lowland, 131 m ASL, Chernozem) was manifested mainly in crops with a growing season peaking in the summer months (maize, sugar beet). Irrigation of dense cereals was less effective, as the crops were positively affected by water reserves in the soil profile from the winter period. The production efficiency of irrigation water use by individual crops was highest in years with a small amount of atmospheric precipitation with a low amount of delivered irrigation water. Most often, the value of the production efficiency of the irrigation water uses for spring barley and winter wheat occurred in the interval of up to 1 kg/m^3 (Takáč 2008).

Agricultural production is extremely vulnerable to the impact of climate change. Changing climatic conditions also change production conditions, which can have a positive or negative impact on agricultural production.

The expected increase in temperature, along with changes in the distribution of precipitation over the growing season and precipitation totals, will be reflected in changes in individual elements of the water balance. The soil moisture deficit of individual crops will increase which will have a negative impact on the production and economy of cultivation systems of individual crops. High totals of potential evapotranspiration combined with uneven distribution of atmospheric precipitation can induce drought conditions with a much higher probability (Šiška & Takáč 2008).

It is assumed that the irrigation water need in the conditions of climate change will grow significantly. Kos (1970) for monthly time series from 10 meteorological stations in Czechoslovakia calculated that a change in temperature of +1.5 °C resulted in an average increased need of irrigation water by 20 to 35%, while a change of 4.5 °C would cause a doubling of the irrigation water need under current conditions. According to 9 alternative scenarios of climate change for Slovakia, an increase in the irrigation water need was assumed, depending on the scenario, by 17 to 332% (Takáč 1996a). At the same time, a larger scale of construction of new irrigation facilities was assumed as a compensatory measure, from 90,000 ha to 390,000 ha (Takáč & Heldi 1996). As a result of climate change, even in areas with so far only occasional occurrence of drought, its more frequent occurrence will be a limiting factor for agriculture. The increase in the need of irrigation water according to individual scenarios to the time horizon of 2075 compared to the situation in 1996 (271 million m^3) ranges between 46 million m^3 up to 900 mil. m^3 (Takáč & Zuzula 2000).

According to climate change scenarios, the lack of water in the soil in the Danube Lowland will worsen during the growing season (Takáč 2001, Takáč *et al.* 2008). DAISY model simulations found an increase in spring barley irrigation needs of approximately 3–20% depending on soil properties, region, scenarios, and time horizon. In the 2070-time horizon, the cereal irrigation season will start about 14 days earlier. On the other hand, the irrigation efficiency of spring barley and winter wheat decreases according to the scenarios. Despite this, the maximum irrigation efficiency values of spring barley in dry years increased to 4.1–4.3 kg.m^{-3} and winter wheat to 4.3 t – 4.6 kg.m^{-3} (Takáč & Šiška 2009).

According to the results of the simulations carried out by the DAISY model under the SRES A2 and B1 scenarios, by the end of the century, the annual aggregates of crop moisture requirements will gradually increase by 15% (SRES B1) and 19% (SRES A2) compared to the period 1961–1990. Due to the faster ripening of crops and the shortening of their vegetation period due to increased temperatures, the total moisture requirement of individual crops will decrease towards the end of the century. Based on the interaction of increased CO_2 concentration in the atmosphere and higher precipitation totals, it is possible to assume an increase in the production water use efficiency by spring barley and winter wheat. The results obtained for maize indicate the opposite trend. According to the calculated average values, the moisture security of crops with a growing season in the spring months will improve, however the variability will increase. Conversely, the moisture security of crops with a growing season in the summer months will deteriorate (Takáč, Šiška, Lapin 2009).

Analyses using drought indices indicate a significant increase in the incidence of drought in Central Europe as well (Trnka *et al.* 2015). Meteorological drought in summer is usually linked to anticyclonic situations with high temperatures and thus high evapotranspiration. The occurrence of drought in the territory of Slovakia, analyzed with the help of climatic and agroclimatic indices, determined two very dry regions in which the water deficit exceeds 250 mm. They are the Danube Lowland and the East Slovak Lowland, i.e. the two most productive agricultural regions of Slovakia (Šiška & Takáč 2009).

In the Lowland areas of Slovakia, a trend of severe or extreme drought in the summer was confirmed for most of the monitored stations (Nikolová, Nejedlík, Lapin 2016). In the last two decades, the regional extent of drought has increased in the territory of the Slovak Republic. The most vulnerable areas to drought are the Záhorská and Danube Lowlands (Takáč 2015). From a comparison of the average value of the climatic water balance in the period 1961–1990 and in the period 1991–2016, it was found that the negative water balance deepened by 10% in the main growing season (Takáč, Bezák, Ilavská 2017). In all southern regions of Slovakia, except for the southeast of the Danube Lowland, a decrease in the coverage of the moisture needs of crops was recorded in the period 1991–2020 compared to the period 1961–1990 (Takáč & Sobocká 2022).

The aim of this contribution is to evaluate the irrigation need and production efficiency of irrigation of field crops in Slovakia in the period 1961–2020, based on numerical simulations with the agroecological model DAISY.

MATERIALS AND METHODS

The assessment of irrigation requirements and irrigation water use efficiency was based on numerical simulations by the agroecological model DAISY. DAISY is a one-dimensional agro-ecosystem model that simulates crop growth, water regime, heat regime, organic matter balance and nitrogen dynamics in agricultural soils based on management information and weather data. The water balance sub-model consists of the surface water balance and the soil water balance. Within the framework of the surface water, the modelled processes are the accumulation and melting of the snow cover, interception, evaporation from the vegetation, infiltration, flooding, and surface runoff. The soil water regime is composed of water flow in the soil matrix and in the macropores. Modelling of water flow in a stratified soil profile including the effect of vegetation is based on the numerical solution of the Richards equation. The DAISY model enables the construction of complex management scenarios (Hansen *et al*. 1990, Abrahamsen & Hansen 2000). Crop parameters of the DAISY model were optimized and verified for our conditions based on experimental data (Takáč 1994, Takáč & Šiška 2011, Takáč *et al*. 2018).

Numerical simulations by the DAISY model were performed for the period 1961–2020 with series of daily data on global radiation, air temperature, air humidity, wind speed and atmospheric precipitation from meteorological stations representing each region in Slovakia. The simulations were run alternately involving spring barley, winter wheat, grain maize, sugar beet, and potato. These simulations were performed on representative soil profiles of the selected regions listed in Table 1. The basic characteristics of the soil profiles in the evaluated locations are listed in Table 2.

The crop irrigation need was simulated by the model in automatic mode when the soil water supply in the root zone drops below the point of decreased availability. An irrigation dose of 30 mm was applied. The minimum interval between two irrigation doses was limited to 7 days.

In order to assess the influence of soil properties on the irrigation regime, additional simulations were carried out on the territory of the Danube Lowland for the period 1961–2020 for three crops, namely maize, spring barley and winter wheat. The territory of the Danube Lowland was divided into four climatic regions: Bratislava, Hurbanovo, Nitra, and Jaslovské Bohunice. In each of the regions, five dominant soil types were identified, covering 99% of agricultural land (IUSS Working Group WRB 2015): Chernozem, Luvisol, Fluvisol, Mollic Fluvisol, and Phaeozem. In the case of Fluvisols, Phaeozems, and Mollic Fluvisols a fixed groundwater level at a depth of 170 to 250 cm was determined depending on the soil type.

In the Rišňovce location (Nitrianska hills, 178 m ASL, Chernozem), simulations were carried out to assess the effect of fertilization, irrigation, and soil properties on the yields of five crops: spring barley, winter wheat, maize for grain, rapeseed, and alfalfa. The simulations were performed for the period of 1961–2020 on five soil pits of different granular composition – 2 pits of loamy Luvisol, one pit each on Luvisol sandy and loamy-sandy soil, and one pit on sandy-loamy Chernozem. Various doses of fertilization were applied, including automatic fertilization when the nitrogen supply in the soil profile fell below the critical threshold.

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Table 1
Geographical coordinates and altitude of the evaluated locations

Locality	Latitude	Longitude	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
Nitra	48°19′	18°07′	173
Mochovce	48°16′	18°27′	212
Želiezovce	48°02′	18°38′	135
Turčianske Teplice	48°52′	18°51′	502
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
Medzilaborce	49°15′	21°55′	308
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′	695

Table 2
Basic characteristics of soil profiles of selected locations.

Locality	**Soil Type (WRB 2015)**	**Soil texture**	***FC* [mm]**	***WP* [mm]**	***AWC* [mm]**
Kuchyňa	Regosol	Sandy loam	230	51	179
Stupava	Phaeozem	Sandy loam	244	67	177
Malacky	Phaeozem	Sandy loam	264	78	186
Holíč	Phaeozem	Loamy	355	158	197
Myjava	Cambisol	Clayey loam	377	168	209
Bratislava	Chernozem	Loamy	359	122	237
Hurbanovo	Chernozem	Loamy	348	124	224
Kráľová pri Senci	Chernozem	Loamy	324	108	216
Gabčíkovo	Phaeozem	Loamy	342	125	217
Žihárec	Chernozem	Loamy	349	133	216
Jaslovské Bohunice	Chernozem	Loamy	369	147	221
Piešťany	Phaeozem	Clayey loam	377	192	185
Podhájska	Chernozem	Loamy	307	91	216
Nitra	Luvisol	Clayey loam	369	160	208
Mochovce	Planosol	Clayey loam	403	198	205
Želiezovce	Chernozem	Clayey loam	393	165	228
Turčianske Teplice	Luvisol	Clayey loam	358	187	171
Trenčín	Luvisol	Loamy	319	122	197
Beluša	Luvisol	Loamy	346	128	218
Topoľčany	Luvisol	Clayey loam	376	165	211
Dudince	Cambisol	Clayey loam	395	212	183
Dolné Plachtince	Luvisol	Clayey loam	390	193	197
Bzovík	Cambisol	Loamy	363	176	187
Žiar nad Hronom	Fluvisol	Sandy loam	281	92	189
Sliač	Luvisol	Loamy	346	135	211
Lučenec	Luvisol	Clayey loam	387	196	191
Rimavská Sobota	Luvisol	Clayey loam	379	164	215
Rožňava	Cambisol	Loamy	353	139	214
Moldava nad Bodvou	Fluvisol	Loamy	324	121	213
Košice	Luvisol	Loamy	362	141	220
Prešov	Luvisol	Loamy	331	118	213
Somotor	Fluvisol	Sandy-loam	322	113	209
Michalovce	Fluvisol	Clayey loam	383	163	220
Trebišov	Fluvisol	Clayey	423	194	229
Vysoká nad Uhom	Fluvisol	Clayey loam	394	173	221
Orechová	Luvisol	Loamy	362	147	215
Kamenica n/Cirochou	Fluvisol	Loamy	350	139	211
Medzilaborce	Cambisol	Loamy	405	188	217
Stropkov	Luvisol	Loamy	335	109	218
Spišské Vlachy	Cambisol	Loamy	340	133	207
Liptovský Hrádok	Cambisol	Loamy	331	98	233
Poprad	Cambisol	Sandy loam	297	65	232

Explanations: *FC* – field capacity in the soil horizon 0–100 cm, *WP* – wilting point in the soil horizon 0–100 cm, *AWC* – available water capacity in the soil horizon 0–100 cm

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The irrigation water use efficiency *IWUE* [kg dry matter/mm] was calculated from the results of the simulations as the ratio of the difference in the yield of the irrigated and rainfed crop and the supplied irrigation water according to the formula:

$$IWUE = \frac{Yirr - Yrf}{W}$$

where *Yirr* is the yield of the irrigated crop [kg dry weight/ha], *Yrf* is the rainfed yield of the non-irrigated crop [kg dry weight/ha] and *W* is the amount of supplied irrigation water [mm/ha].

RESULTS AND DISCUSSION

In terms of the hydrological classification of the soil water regime, the evaporative regime prevails in the agricultural land of Slovakia. As a result of rising temperatures, there is an increase in the moisture requirement of crops. The highest increase in the moisture requirement of crops in the period 1991–2020 compared to the period 1961–1990 was recorded in the west and north of the Danube Lowland. On the other hand, in the period 1991–2020, compared to the period 1961–1990, there was a slight decrease in the average water supply in the soil in most of Slovakia (Takáč & Ilavská 2021).

The share of atmospheric precipitation covering the crop moisture requirements is the highest for winter wheat and the lowest for potatoes. Rainfall covers more than 70% of wheat's moisture needs. In central and eastern Slovakia, this coverage exceeds 100%, which is due to the reserve of winter precipitation. On the other hand, the moisture needs of spring barley and summer crops are covered by precipitation to less than 50% in the Danube Lowland.

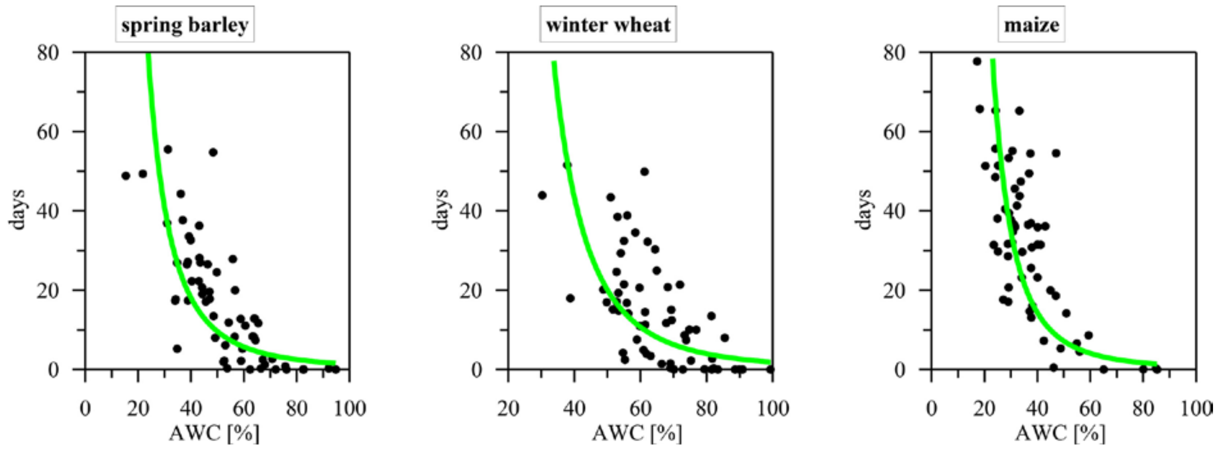
From the point of view of the impacts on the cultivated crops, the duration of the period with soil moisture in the root zone below 50% *AWC* in the critical development phases of the cultivated crops is decisive. In irrigation practice, a value of 50% *AWC* is recommended for the beginning of field crop irrigation. The so-called differentiated irrigation regimes, in which the start of crop irrigation in different phenological phases was determined at a different *AWC* value (Takáč 2015).

The fact that the water supply in the 0–100 cm soil horizon drops below 50% of the *AWC* is common in the southern regions of Slovakia and occurs almost every year. According to mathematical simulations, in the Danube and Záhorská Lowlands, the soil moisture drops below 50% *AWC* as early as during June. In some years, this condition can occur already at the beginning of spring, or it can persist during autumn and winter because of insufficient precipitation totals in the autumn and winter months. Within individual regions, there is spatial variability in the water reserves in the soil, depending on the soil properties of and the presence of the groundwater level. The average number of days with a reserve of usable water in the soil below 50% during the maize growing season ranges from 75 to 120 days in the Danube Lowland. The smallest number of days with soil moisture below 50% *AWC* on the Danube Lowland was calculated for areas with the presence of an underground water level on the lower Žitný ostrov (Rye Island) and near watercourses.

In the period 1991–2020, compared to the period 1961–1990, the most significant increase in the number of days with a water supply in the soil below 50% occurred in the Záhorská Lowland, the west and north of the Danube Lowland, the central Považie, the central Pohronie, the Košice basin and the eastern parts of the East Slovak Lowland. On the other hand, a significant decrease in the number of days with a water supply in the soil below 50% *AWC* occurred in the southeast of the Danube Lowland, in the Ipeľská and Lučenecká basins, on Šariš and Spiš regions (Takáč & Sobocká 2022).

The lack of water in the soil will manifest itself in water stress, which has an adverse effect on crop yields. As the water supply in the soil decreases, the number of days with water stress increases (Graph 1).

Growing demands on the moisture needs of crops due to rising temperatures and lack of water in the soil manifests itself in water stress, which has an adverse effect on crop yields. The number of days with water stress has an increasing trend (Table 3). Crops suffer the most from water stress in the Danube Plain, the Záhorská Lowland and the south of the East Slovak Lowland, while crops with a growing season in the summer months are more affected by water stress.



Graph 1 Relationship between the usable water supply in the soil [% AWC] and the simulated number of days with water stress in selected crops on Chernozem in the Hurbanovo location (spring barley, winter wheat, maize)

Once every 10 years in the Danube and Záhorska Lowlands, the number of days with water stress for spring barley is more than 30 days, for winter wheat more than 40 days, for maize more than 50 days, for sugar beet more than 70 days and for potatoes more than 60 days. In the East Slovak Lowland, it is more than 20 days for spring barley, more than 40 days for winter wheat and maize, and more than 50 days for sugar beet and potatoes. In dry years, for crops grown in summer, the number of days with water stress exceeded 90.

The average number of days with water stress increased in the period 1991–2020 compared to the period 1961–1990. 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 northwest of the Záhorská Lowland, in the west and northeast of the Danube Lowland and in the south of the East Slovak Lowland. On the upper Žitný ostrov, the average increase in the number of days with water stress was 13 days for maize, 14 days for sugar beet and up to 18 days for potatoes.

The maxima of the average number of days with water stress in the period 1991–2020 were calculated for all crops in the northwest of the Záhorská Lowland, while in the period 1961–1990 the maxima occurred in the southeast of the Danube Lowland of Slovakia. In the northern regions of Slovakia, water stress occurred only exceptionally, approximately once every 5 to 10 years, while the maximum simulated duration of more than 20 days occurred only once every 60 years.

Supplementary irrigation serves to eliminate or at least alleviate water stress. As the number of days with water stress increases, so does the need for crop irrigation (Graph 2). The highest average irrigation need was calculated for the area of the Danube and Záhorská Lowlands (Table 4). According to the performed simulations, in the period 1991–2020, compared to the period 1961–1990, the need for irrigation increased in all regions of Slovakia, except for Šariš and Spiš regions. The most significant increase in the need for irrigation occurred in the southwest of the Danube Lowland on the upper Žitný ostrov.

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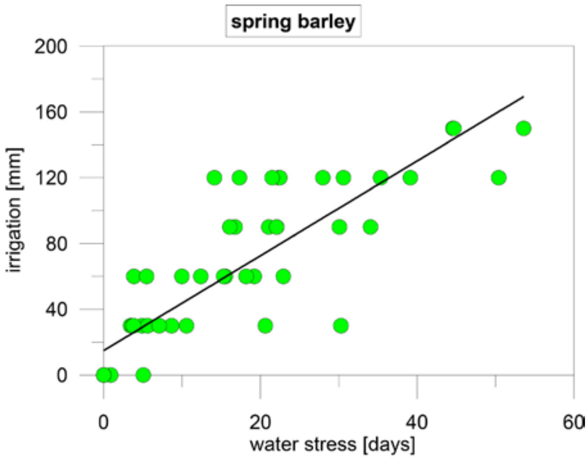
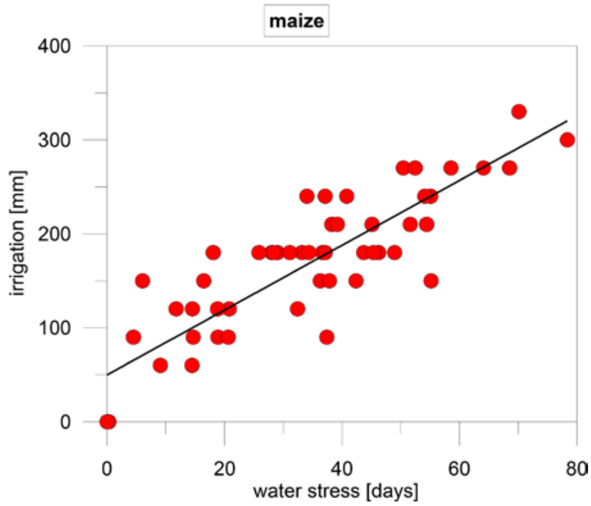
Table 3
Average number of days with water stress of non-irrigated crops at selected locations

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
Stupava	9	18	16	24	18	25	30	37	24	31
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	38	25	50	25	43
Hurbanovo	11	17	24	24	32	32	46	47	34	41
Kráľová pri Senci	12	14	22	22	26	27	41	41	28	36
Gabčíkovo	5	10	11	14	18	22	30	33	23	30
Žihárec	5	8	11	12	17	19	29	30	21	27
Jaslovské Bohunice	10	19	19	27	22	34	36	47	27	39
Piešťany	12	16	19	20	21	27	37	44	28	37
Podhájska	15	19	28	26	33	33	44	46	31	37
Nitra	8	18	18	26	20	34	38	51	30	44
Mochovce	13	18	26	28	28	33	49	52	36	43
Želiezovce	16	17	30	27	32	33	48	50	37	44
Turčianske Teplice	1	2	1	2	2	5	4	12	4	11
Trenčín	9	13	13	18	17	26	27	36	21	30
Beluša	0	0	0	1	0	3	3	9	3	9
Topoľčany	13	16	23	21	26	31	41	47	30	40
Dudince	7	10	10	12	19	21	37	39	28	33
Dolné Plachtince	3	8	10	11	22	20	35	32	26	29
Bzovík	1	2	6	7	12	15	24	25	18	23
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
Prešov	3	2	5	3	7	1	14	5	9	4
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 n/Cirochou	0	0	0	1	0	2	3	6	2	7
Medzilaborce	0	0	0	0					2	3
Stropkov	0	0	0	0	0	1	2	2	1	3
Spišské Vlachy	2	1	1	1					3	2
Liptovský Hrádok	0	0	0	0					0	1
Poprad	3	2	3	1					5	5





Graph 2 Dependence between the number of days with water stress and the irrigation need of spring barley and maize for grain in Hurbanovo

In addition to spatial variability, irrigation demand also shows considerable temporal variability. On the one hand, there are years without the need for irrigation, on the other hand, there were years with an extremely high need for irrigation. While in the years 1965 and 2010, with extraordinary rainfall totals, irrigation was not needed in the entire territory of Slovakia, in other years there were significant regional differences in the irrigation need. Maximum amounts of irrigation water of 120–150 mm for dense cereals were simulated across the entire area in 1993, 2012 and 2017. Regionally, high amounts of irrigation water were also calculated in other years, e.g., in 1998 on the Danube Lowland and the south of central Slovakia, in 2007 on the Záhorská Lowland and in the west of the Danube Lowland. For crops grown in the summer months, the highest irrigation needs were simulated in 1990, 2015 and 2017.

The basic statistical characteristic of the irrigation requirements of spring barley and maize for grain at selected locations in the periods 1961–1990 and 1991–2020 are shown in the Graph 3. On the Danube and Záhorská Lowlands, 5 irrigation doses of 30 mm each were needed in one of the ten years for dense cereals and 7 or more irrigation doses for crops grown in the summer months, while in the period 1991–2020 these high numbers of irrigation were doses simulated in only one out of four years. On the contrary, in one of the four years, no or only one irrigation dose was simulated for dense cereals.

Table 4

Average crop irrigation requirements [mm] at selected locations 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	40	56	73	89	110	141	134	174	134	183
Stupava	38	65	55	89	102	135	146	195	136	188
Holíč	74	77	98	107	119	159	206	278	188	257
Myjava	20	37	12	34	72	99	112	153	107	149
Bratislava	42	77	67	109	139	206	185	287	170	284
Hurbanovo	53	65	88	104	154	168	220	248	212	256
Žihárec	26	37	42	55	101	114	145	175	148	183
Jaslovské Bohunice	89	108	110	135	176	216	230	294	202	271
Piešťany	76	77	88	89	144	170	198	242	182	232

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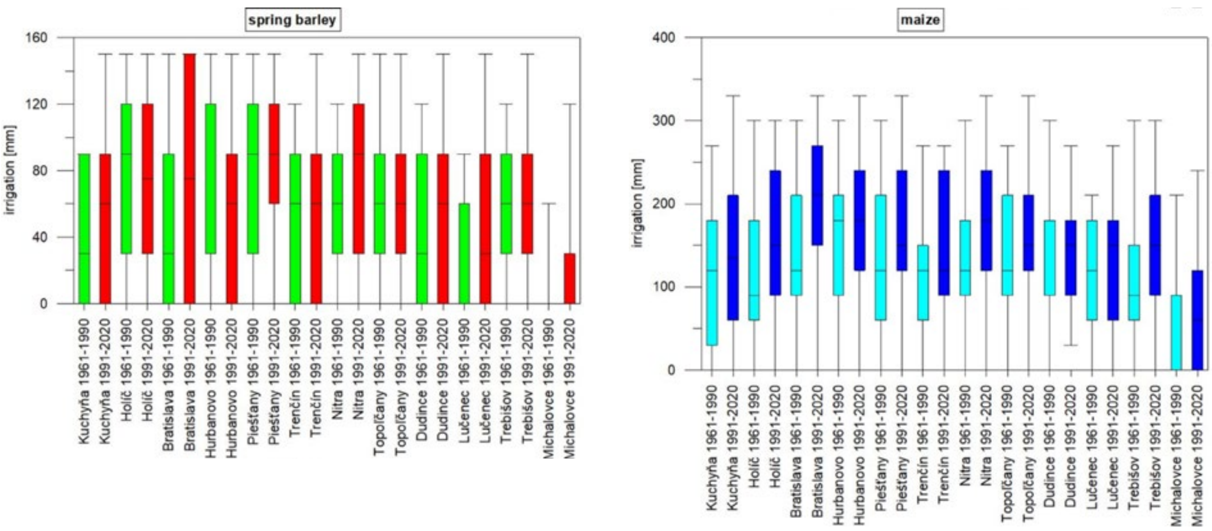
Locality	Spring barley		Winter wheat		Maize		Sugar beet		Potatoes	
	1961-1990	1991-2020	1961-1990	1991-2020	1961-1990	1991-2020	1961-1990	1991-2020	1961-1990	1991-2020
Podhájska	68	70	96	104	158	174	210	237	182	226
Nitra	52	78	65	108	122	178	187	278	187	275
Mochovce	66	73	85	102	148	177	221	271	200	259
Želiezovce	67	76	95	97	155	164	224	246	218	264
Turčianske Teplice	10	22	9	23	20	50	35	80	34	77
Trenčín	44	56	53	70	108	142	145	205	131	184
Beluša	1	9	0	9	12	38	25	66	29	65
Topoľčany	61	65	80	81	133	157	199	243	169	224
Dudince	44	55	50	60	116	134	169	202	168	204
Dolné Plachtince	36	46	46	54	119	126	158	170	158	183
Bzovík	30	35	29	40	86	100	119	151	120	150
Žiar nad Hronom	2	12	2	14	28	62	48	102	48	102
Sliač	5	10	6	13	32	47	56	79	42	75
Lučenec	20	46	38	63	104	126	144	161	122	154
Rimavská Sobota	11	38	12	39	67	102	92	151	82	137
Rožňava	6	13	6	22	29	47	36	64	32	63
Moldava nad Bodvou	2	14	5	17	25	36	44	72	44	72
Košice	22	48	36	66	67	95	86	138	78	128
Prešov	14	11	23	17	49	21	64	39	60	38
Somotor	17	41	23	55	68	137	100	185	103	182
Michalovce	8	19	9	23	37	76	65	125	64	132
Trebišov	53	70	55	83	92	138	155	213	124	203
Vysoká nad Uhom	13	28	15	31	40	97	66	152	79	157
Orechová	5	10	8	14	30	68	49	107	48	106
Kamenica n/ Cirochou	0	8	1	10	1	38	7	55	19	65
Spišské Vlachy	11	8	8	6					27	21

In addition to climatic conditions, soil conditions also affect crop irrigation requirements, although to a much lesser extent than climatic factors. Knowledge of the spatial variability of soils is essential for modelling of water movement in soil as well as for irrigation management and planning. Soil and its retention capacity are the main cause of spatial variability in soil water stocks and crop yields. Depending on the soil texture, the soil can contain different amounts of water. Of the 5 soil types on the Danube Lowland, the highest irrigation need was simulated on Chernozems and Luvisols, the lowest one for dense cereals on Fluvisols and for maize on Chernozems (Takáč 2023).



Graph 3 Basic statistical characteristics of the irrigation requirements of spring barley and maize at selected locations in the period 1961–1990 and 1991–2020

Table 5

Average irrigation water use efficiency [kg dry matter/mm] at selected locations 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	12.1	21.4	23.4	26.1	18.0	15.7	29.2	27.6	34.9	29.8
Stupava	15.3	19.4	33.1	31.2	18.3	16.0	28.9	26.5	37.0	31.0
Holíč	16.9	24.9	30.5	36.2	17.3	26.0	27.9	27.8	35.9	30.1
Myjava	15.3	8.6	20.5	19.7	17.4	13.6	20.6	25.0	30.7	30.8
Bratislava	17.0	21.5	35.2	30.0	22.8	18.9	29.8	25.5	28.7	26.8
Hurbanovo	8.6	16.7	21.2	26.2	23.0	17.7	32.2	28.5	36.0	27.6
Žihárec	14.1	17.6	33.9	34.4	19.3	18.1	30.9	24.9	27.5	23.8
Jaslovské Bohunice	8.4	12.1	15.8	21.9	9.8	15.3	23.0	22.0	25.8	24.5
Piešťany	10.3	9.2	19.5	19.6	9.7	15.4	26.5	27.3	35.7	30.2
Podhájska	17.0	20.0	40.8	32.6	25.5	19.4	33.7	30.3	37.4	28.7
Nitra	11.3	12.1	24.4	27.4	16.0	17.9	30.3	27.2	34.8	30.5
Mochovce	11.7	15.8	37.8	31.7	22.9	19.5	34.8	28.4	40.1	31.3
Želiezovce	15.4	20.1	38.5	45.3	25.6	22.7	33.5	28.5	36.4	28.7
Turčianske Teplice	18.4	4.6	25.2	17.7	10.1	13.7	19.4	25.6	23.9	25.7
Trenčín	15.9	23.8	31.1	36.3	14.9	18.8	26.9	27.4	35.8	31.3
Beluša	21.9	16.8		8.6	16.9	16.0	17.7	23.3	26.2	26.1
Topoľčany	15.7	22.0	33.2	43.1	21.1	22.1	32.0	31.3	39.1	31.8
Dudince	9.7	9.0	27.9	9.1	24.2	22.4	31.2	28.4	36.4	31.8
Dolné Plachtince	8.1	7.2	16.8	8.1	22.0	15.3	31.6	27.8	34.0	28.8
Bzovík	12.6	6.9	24.0	20.9	18.2	15.4	29.9	25.2	34.9	28.1
Žiar nad Hronom	5.0	8.0	25.7	30.0	16.2	15.2	21.9	25.4	31.0	28.6
Sliač	20.7	12.5	22.0	14.0	21.1	20.0	21.4	20.6	31.3	23.0

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
Lučenec	25.0	15.0	28.5	23.5	23.3	18.8	34.7	29.2	35.2	26.0
Rimavská Sobota	17.1	16.6	42.4	33.7	21.6	20.4	29.4	28.9	29.7	25.9
Rožňava	4.2	7.0	29.2	20.1	15.0	18.5	20.6	24.1	21.7	20.1
Moldava nad Bodvou	-	2.5	31.3	14.9	15.7	13.1	22.7	23.4	24.8	19.9
Košice	8.6	12.2	20.8	26.2	16.0	21.6	23.5	29.0	30.2	24.7
Prešov	28.8	2.6	33.5	18.5	11.9	9.3	27.3	21.3	32.3	22.0
Somotor	10.2	23.8	31.7	38.4	31.0	24.2	26.1	28.4	28.8	27.4
Michalovce	3.9	8.2	30.7	17.5	11.4	18.0	24.2	23.6	19.9	22.9
Trebišov	2.3	11.4	16.5	17.5	13.0	18.5	26.0	26.2	31.2	28.0
Vysoká nad Uhom	1.2	9.7	3.4	27.5	15.0	17.4	25.0	25.3	24.9	28.2
Orechová	2.3	9.0	0	18.2	16.0	15.9	25.4	23.3	25.3	21.9
Kamenica n/Cirochou	-	3.8	3.1	2.1	2.9	9.8	17.7	17.3	35.3	18.9
Spišské Vlachy	18.1	8.0	15.3	7.3					27.0	22.5

The average irrigation water use efficiency at selected locations in the period 1961–1990 and 1991–2020 is shown in the Tab. 5. In the period 1991–2020, compared to the period 1961–1990, there was a decrease in irrigation water use efficiency for crops grown in the summer season. In the case of dense cereals, there was a reduction in the irrigation water use efficiency of mainly in the south of central Slovakia, in the Zvolenská basin, in the regions of Turiec, Šariš and Spiš. In approximately half of the evaluated locations, there was an increase in the irrigation water use efficiency of dense cereals.

The effectiveness of irrigation depends on the course of the weather (distribution of precipitation, air temperature and evapotranspiration), hydro-physical soil properties, availability of nutrients, the cultivated crop, and its variety, as well as the level of land management and is also influenced by the timing of the irrigation dose.

The irrigation water use efficiency also depends on the amount of supplied water and the irrigation regime. With a smaller amount of supplied irrigation water, the irrigation efficiency is higher (Tab. 6). A large amount of irrigation water may not produce a larger crop. Excess irrigation can lead to reduced yields. Sun *et al.* (2006) found, based on three-year field trial results with winter wheat, that the water use efficiency decreases as the amount of supplied irrigation water increases. According to the model results of water-limited crops of winter wheat (Takáč 1999), in some years one irrigation dose was sufficient for a comparable increase in yield than several irrigation doses, the timing of the application of the irrigation dose was decisive.

The irrigation water use efficiency depends on the growth phase of the crop, when the irrigation dose was applied. The crop reacts differently to water stress in individual growth phases. This is also confirmed by the results of the simulations in the Tab. 6, when irrigation production efficiency was highest under minimized irrigation. The minimum interval between two irrigation doses with full irrigation was limited to 7 days. The reduced irrigation regime was limited by an interval between irrigation doses of 10 days for dense cereals and 14 days for maize. With the minimized irrigation regime, irrigation was applied at the time of heading, or at the beginning of milk maturity, depending on the water content in the soil. Similar values of irrigation water use efficiency as for the Hurbanovo area were also obtained for other locations of the Danube Lowland.

Nutrient deficiency can also cause crop depression. This is also confirmed by the results obtained from a stationary field experiment with different fertilizing variants at the Stationary Field Experiment in Most pri Bratislave (Bízik 1999), where the production efficiency of spring barley and winter wheat irrigation was in 47% of cases, or 22% of cases was negative, it means that irrigation led to a decrease in yields

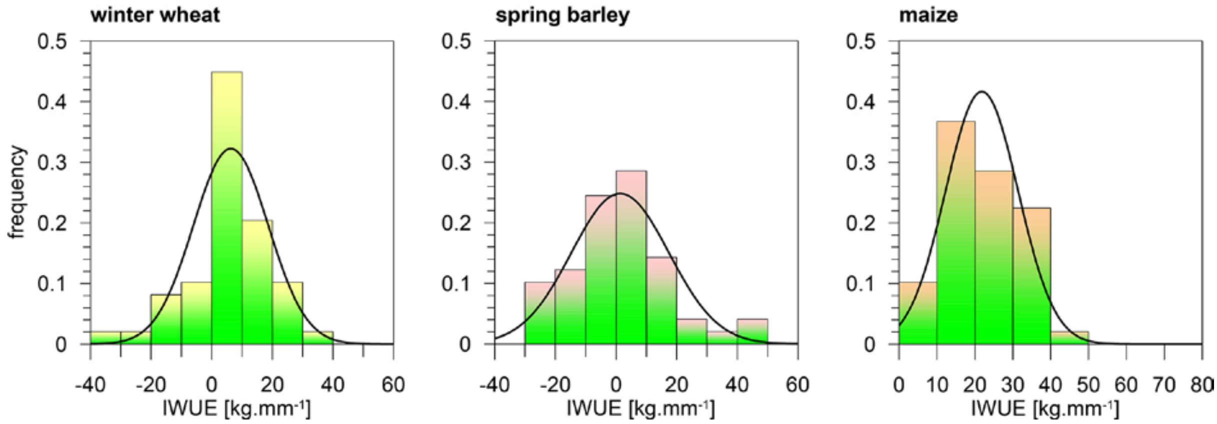
(Takáč 2008). Negative values of irrigation water use efficiency occasionally occurred even in the case of optimally fertilized variants. In the case of maize and sugar beet, the negative values of the irrigation water use efficiency in the stationary field trial did not occur even in the case of unfertilized variants or insufficiently fertilized variants.

Table 6
Median irrigation water delivered and irrigation water use efficiency [kg/dry matter/m^3] on Chernozem in the Hurbanovo area

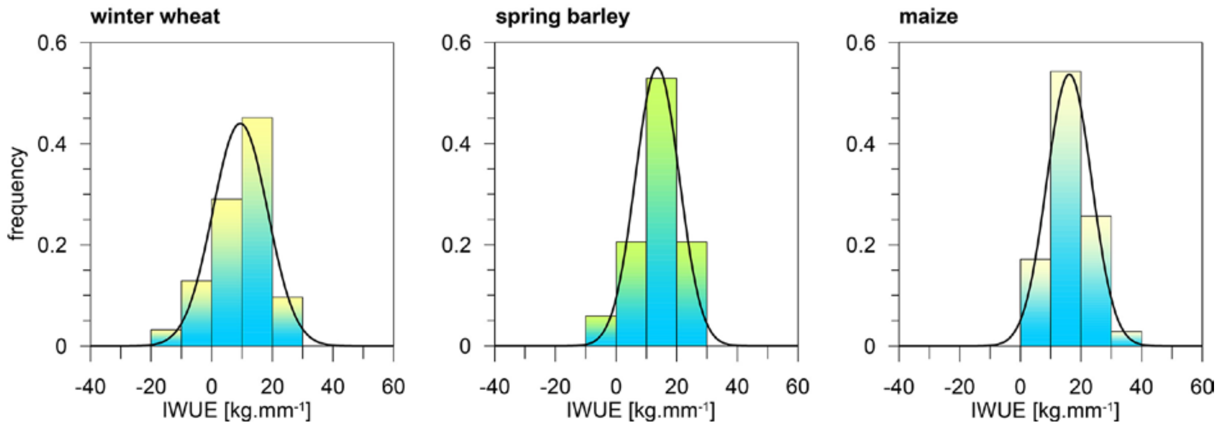
	Spring barley		**Winter wheat**		**Maize**	
	Irrigation dose [mm]	*IWUE* **[kg dry matter/ mm]**	**Irrigation dose [mm]**	*IWUE* **[kg dry matter/ mm]**	**Irrigation dose [mm]**	*IWUE* **[kg dry matter/ mm]**
Full	60	14.7	90	17.6	210	19.8
Reduced	45	15.9	60	30.0	90	24.3
Minimized	30	17.3	30	36.5	60	25.2

The irrigation water use efficiency was highest in years with a small amount of atmospheric precipitation, while a relatively small amount of irrigation water was delivered. The maximum values of the irrigation water use efficiency from a field stationary experiment were calculated for winter wheat 42 kg dry matter/mm in 1989, for spring barley 43 kg dry matter/mm in 1983, for maize 45 kg dry matter/ha in 1990 and for sugar beet 43 kg dry matter/mm in 2006. The irrigation water use efficiency in the field stationary experiment most often occurred in the interval 0–10 kg/mm. The smallest average irrigation water use efficiency was calculated for spring barley, the highest for maize. Histograms of the irrigation water use efficiency from a stationary field trial in Most pri Bratislave and according to simulations by the DAISY model are shown in Graphs 4, 5 and 6.

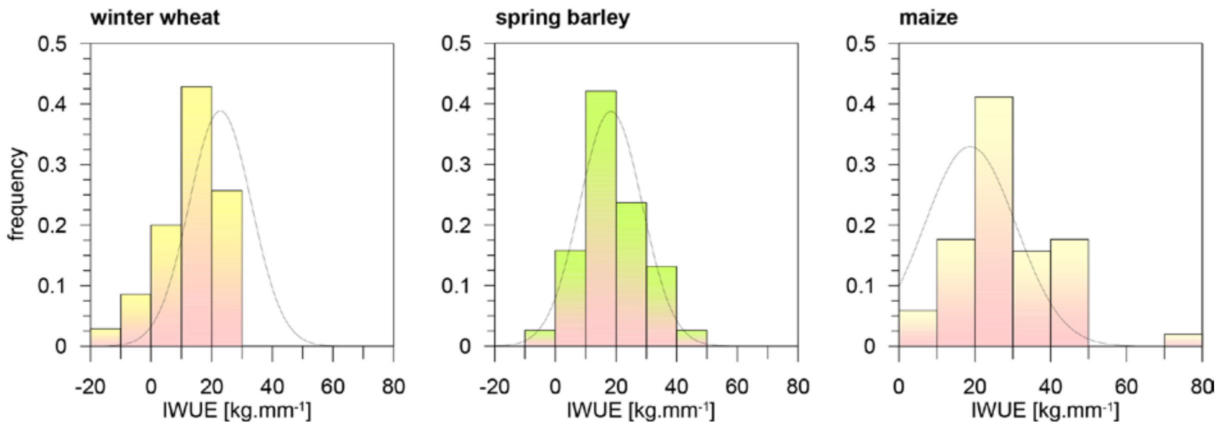
The irrigation water use efficiency values obtained from numerical simulations are similar to the values obtained from the field stationary experiment. Most often, the irrigation water use efficiency according to simulations in the area of upper Žitný ostrov for all crops was in the range from 10 to 20 kg/mm. In contrast to the field stationary experiment, the lowest irrigation water use efficiency was calculated for winter wheat according to the simulation results.



Graph 4 Irrigation water use efficiency of winter wheat, spring barley and maize for grain in a stationary field trial in Most pri Bratislave



Graph 5 Irrigation water use efficiency of winter wheat, spring barley and maize for grain on Chernozem in the area of upper Žitný ostrov with optimal fertilization according to simulations by the DAISY model



Graph 6 Irrigation water use efficiency of winter wheat, spring barley and maize for grain on loamy Luvisol in Rišňovce when fertilizing in automatic mode according to simulations by the DAISY model

In the Rišňovce locality, the highest values of irrigation water use efficiency were calculated on loamy Luvisol with automatic fertilization. The average value of irrigation water use efficiency for the period 1961–2020 reached 22.3 kg/mm for winter wheat, 17.9 kg/mm for spring barley and 18.8 kg/mm of delivered irrigation water for maize. As in the case of the field stationary experiment and simulations for the area of the upper Žitný ostrov in the case of Rišňovce the irrigation of dense cereals in some years led to a decrease in economic yields.

Irrigation efficiency is also influenced by soil properties. According to the results of simulations with five soil types on the Danube Plain, irrigation proved to be the most effective on Chernozems and Luvisols, especially in the southwest of the Danube Lowland. Irrigation on Phaeozems was the least effective. From the evaluated crops, maize irrigation proved to be the most effective, when the average irrigation efficiency on Chernozems and Luvisols in the southeast of the Danube Lowland in the period 1961–1990 exceeded 20 kg/mm (Fig. 1).

In the period 1991–2020, compared to the period 1961–1990, the irrigation water use efficiency increased on average for the entire territory of the Danube Lowland for spring barley, however, for winter wheat and maize it remained unchanged, while the decrease in the production irrigation efficiency for wheat and maize was calculated mainly for the southeast Lowlands (Fig. 2).

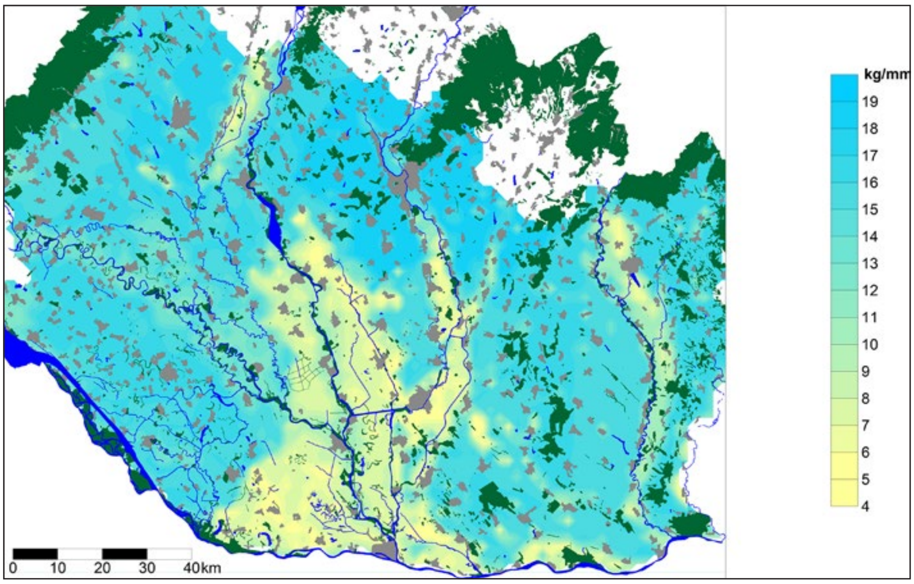


Figure 1 Average irrigation water use efficiency of maize in the Danube Lowland in the period 1991–2020

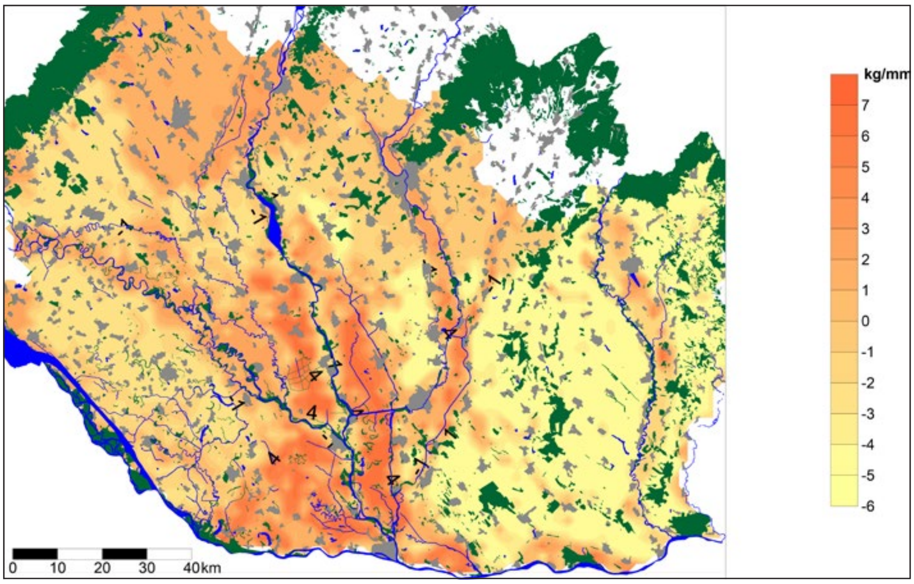


Figure 2 Average difference in irrigation water use efficiency of maize in the Danube Lowland between the periods 1961–1990 and 1991–2020

Based on the analysis of results from field experiments and simulations with the DAISY model, it can be concluded that the positive effect of irrigation was manifested mainly in crops with a growing season peaking in the summer months (maize, sugar beet, potatoes). Irrigation of dense cereals was less effective, often leading to a reduction in yields.

Because the need for irrigation and its effectiveness are influenced by several factors, namely climate (air temperature, precipitation, evapotranspiration), soil properties and agricultural technology (mainly fertilization, irrigation regime), optimization of the irrigation regime is necessary.

Rational water management on irrigated areas is an agronomically, technically, and organizationally demanding process that requires sufficient information. In the past, several decision support tools were therefore developed, the so-called irrigation dispatching (Brežný 1973, Takáč & Senko 1989, Heldi & Čislák 1997, Takáč 2007).

CONCLUSION

The highest average irrigation requirements in Slovakia were calculated for the area of the Danube and Záhorská Lowlands. According to the performed simulations, in the period 1991–2020, compared to the period 1961–1990, the need for irrigation increased in all regions of Slovakia, except for Šariš and Spiš regions. The most significant increase in the need for irrigation occurred in the southwest of the Danube Lowland on the upper Žitný ostrov.

Precipitation totals, or the amount of water supplied to the system is not the only decisive factor determining the efficiency of water use by crops. Other factors are the way and timing of irrigation, soil properties, distribution of precipitation during the growing season, crop requirements for water and nutrients and their interactions. The irrigation water use efficiency was highest in years with a small amount of atmospheric precipitation with a small amount of delivered irrigation water. Irrigation on Chernozems and Luvisols proved to be the most effective.

Because the production and economic effect of irrigation of winter wheat and spring barley is lower compared to crops grown in summer, their irrigation is currently mainly on lighter and/or shallow soils, where the water accessible to the crops falls below a critical level the border earlier and more often.

ACKNOWLEDGEMENT

This contribution was created thanks to the support of the Operational Program Integrated Infrastructure for the project: Sustainable systems of intelligent farming considering the challenges of the future 313011W112, co-financed from the resources of the European Regional Development Fund.

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