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OPTIMIZATION OF THE PARAMETERS OF DRIP IRRIGATION REGIMES FOR CROPS IN THE STEPPE OF UKRAINE

A.P. Shatkovskyi[1], Doctor of Agricultural Sciences, M.I. Romashchenko[2], Doctor of Engineering Sciences, O.V. Zhuravlov[3], Doctor of Agricultural Sciences, S.V. Riabkov[4], Doctor of Agricultural Sciences, Y.O. Cherevychnyi[5], Ph.D., O.I. Hulenko[6]

[1] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-4366-0397; e-mail: andriy-1804@ukr.net;
[2] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-9997-1346; e-mail: mi.romashchenko@gmail.com;
[3] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0001-7035-219X; e-mail: zhuravlov.olexandr@gmail.com;
[4] SE «Design and Technological Bureau» IWPRL NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0001-8219-9065; e-mail: srabkov@gmail.com;
[5] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-9959-8297; e-mail: yurecgp@gmail.com;
[6] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-1007-5677; e-mail: gulenkoai@gmail.com

Abstract. *The purpose of the research was to improve and substantiate the parameters of the drip irrigation regimes for crops in the Steppe of Ukraine. Field studies were carried out at the Kamyansko-Dniprovska experimental station (47°46' N 34°42' E), the Brylivska experimental station (46°40' N 33°12' E) and the Southern research station (46°33' N 33°59' E) from 2004 to 2021 on 11 crops. The research scheme assumed the implementation of a one-factor experiments' series with different levels of soil humidification, the control was the variant without irrigation. At the first stage, the mathematical dependencies "Soil moisture level (SML) –Number of vegetation irrigations" and "SML–Irrigation rate" were obtained for all crops. The establishment of correlations between the evapotranspiration of crops and their productivity is the result of the work. Based on this, were built the dependencies (statistical models) "Evapotranspiration – Productivity" and the most optimal options for using water were determined in terms of its costs for the formation of products for the drip irrigation of the Steppe of Ukraine. The given dependencies are reaction curves for a one-factor experiment, they consist of three areas: limiting, stationary and excessive. Correlation coefficients r=0,92–0,98 indicate a close relationship between these parameters. Established relationships "Evapotranspiration – Yield" from an agro biological point of view are not stable since there are potential opportunities for increasing yields with the same evapotranspiration. It has been established that the optimal moisture range for drip irrigation of most crops is a narrow range of soil moisture suction pressure of –9 to –15 kPa. This involves irrigation with small rates (50–75 m^3/ha) while reducing the inter-irrigation periods. Under such conditions, the ratio of actual transpiration (Tc) to potential (T_0) approaches 1 (≈ 0,83–0,87), which characterizes the water supply of plants as close to optimal.*

Keywords: *drip irrigation, soil moisture level, evapotranspiration, yield crops, mathematical dependencies*

Relevance of research The unfavorable water regime of the soil is a limiting factor in the realization of agricultural resource potential in the Steppe zone of Ukraine. Today, there are many measures aimed at minimizing the negative impact of droughts, however, as practice shows, irrigation is the most effective. During the most active development of land reclamation (1966–1990), the area of irrigated land in Ukraine was brought to 2,62 million hectares [8]. In 1990–2000 during the economic crisis in Ukraine, the actual irrigated area decreased sharply – to 0,58–0,69 million ha, which corresponds to the indicators of 1966–1968, and in 2014 – to 0,49 million ha (excluding Crimea). However, we note that this reduction refers to the so-called "large irrigation" – sprinkling. On the other hand, the area under drip irrigation increased from 4,5 thousand ha (2000) to 75,5 thousand ha (2014), of which 46,5 thousand ha were under field crops [12].

Analysis of recent research and publications. The advantages of drip irrigation over other irrigation methods (sprinkling, surface irrigation) are known. In this aspect, it should be noted that due to the compliance of drip irrigation technologies with two interrelated conditions – high economic efficiency and environmental safety, it has become widely used for irrigating vegetables, fruit crops, and vineyards [1]. In recent years, the interest of Ukrainian farmers in the introduction of drip irrigation on crops such as corn, soybeans, sugar beet, sunflower, and others has increased. [3; 5]. At the same time, we state that farmers, using intensive technologies for growing field crops on drip irrigation, do not always get the desired effect. After all, drip irrigation involves changing the main components of agricultural technology: irrigation regimes, fertilization, plant protection, sowing patterns, sowing and harvesting techniques and technologies. At present, these elements have not yet been fully developed and scientifically substantiated specifically for the soil and climatic conditions of the Steppe of Ukraine.

Research materials and methods. Field studies were carried out at the Kamyansko-Dniprovska experimental station (47°46' N 34°42' E), the Brylivska experimental station (46°40' N 33°12' E) and the Southern research station (46°33' N 33°59' E) from 2004 to 2021 on 10 crops. The research scheme assumed the implementation of a one-factor experiments' series with different levels of soil humidification, the control was the variant without irrigation.

The placement of experimental sites is systematic, and replication is fourfold [14]. Tensiometric sensors installed at different depths of the soil profile and distance from the water supply point were used to determine the timing of irrigation and study evapotranspiration [10; 12]. For accounting and observations, they were used as generally accepted [2; 14], as well as improved methods [9; 11; 12].

Research results and their discussion. It has been experimentally established that, among the other factors, the level of pre-irrigation soil moisture has the greatest influence on the formation of the irrigation regime. It was recorded that with an increase in SML from -20 kPa to -15 kPa, the number of watering's and the irrigation rate, respectively, increase by 45 % or 25 pcs. and by 42 % or 900 m^3/ha (Fig. 1).

1. Objects (geography of research) and types of crops

№	The name of the scientific station	Location / soil-climatic zone	Crops / years of research
1	Kamyansko-Dniprovska experimental station	vill. Kamyanka-Dniprovska, Zaporizhzhia region, South-Central Steppe subzone, 47046' N 34042' E	carrots (2004–2006), potatoes (2006–2010), pepper, eggplant (2010–2013), sugar beet (2010–2014), corn (2012–2020), soybeans (2010–2020)
2	Brylivska experimental station	vill. Pryvitne, Oleshkivs′ky district, Kherson region, Dry Steppe, 46040' N 33012'	tomato (2009–2011), onion (2011–2013), corn (2012–2020), sugar beet (2012–2014), chickpeas (2018–2021)
3	Southern research station	vill. Velykyy Klyn, Holoprystanskyi district, Kherson region, Dry steppe 46033', N 33059' E	watermelon (2006–2008)

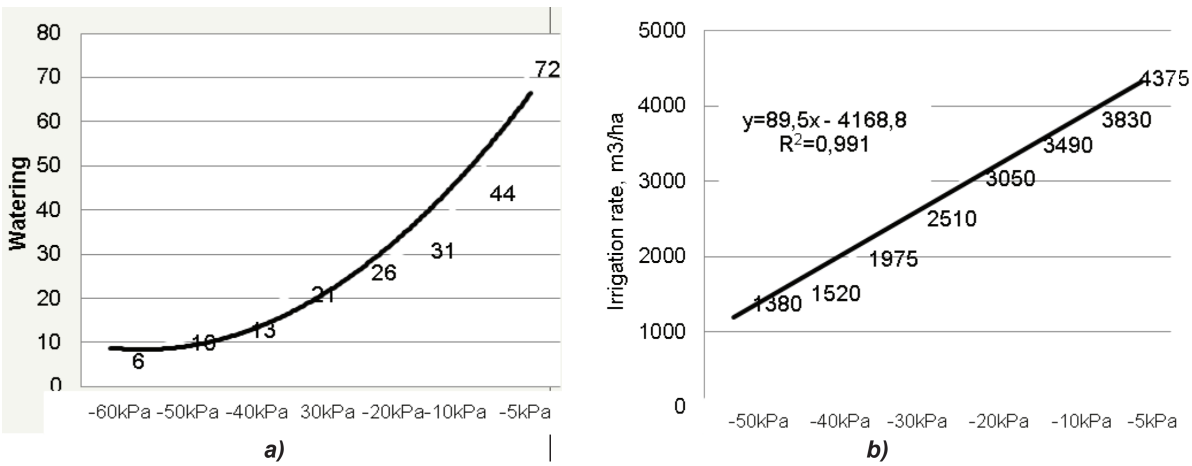

Fig. 1. Dependencies of the number of watering's (a) and irrigation rate (b) from the soil moisture level

It is known, that the irrigation regime is closely related to the meteorological parameters that directly affect physical evaporation and transpiration: the amount of precipitation, temperature and relative humidity of the air, and wind strength. The closest correlation dependence "Irrigation regime – Meteorological parameters" is established only by the "Amount of precipitation" factor.

In particular, the records state that the influence of the amount of precipitation is greater, the lower the level of moisture supply of plants: when maintaining the pre-irrigation threshold of 60% of the minimum moisture-holding soil capacity (MMHSC), the difference in the irrigation rate (or the number of watering's) between years with 50% and 75% precipitation 42%, for 70% MMHSC – 36%, 80% MMHSC – 25%, 85% MMHSC – 22%, 90% MMHSC – 17% and MMHSC – 7% (Fig. 2).

The inter-irrigation period also shortens with an increase in the temperature regime. However, such regularity can be observed only in periods of abnormal heat. For example: in August, the duration of the inter-irrigation period, while maintaining a soil moisture level of -20 kPa, is 3,5–5,5 days, depending on the crop, and in periods with abnormally high average daily air temperatures of +29–30 °C (maximum – +39,0–40,5 °C), the inter-irrigation period is shortened to 1–2 days.

As a result of research, correlations between evapotranspiration and crop yield have been established. Based on this, "Evapotranspiration-Yield" dependencies were built for drip irrigation conditions, and optimal options for water use by plants were determined from the point of view of its costs for the formation of a unit of production (Fig. 3).

These dependencies are response curves for a one-factor experiment, they consist of three

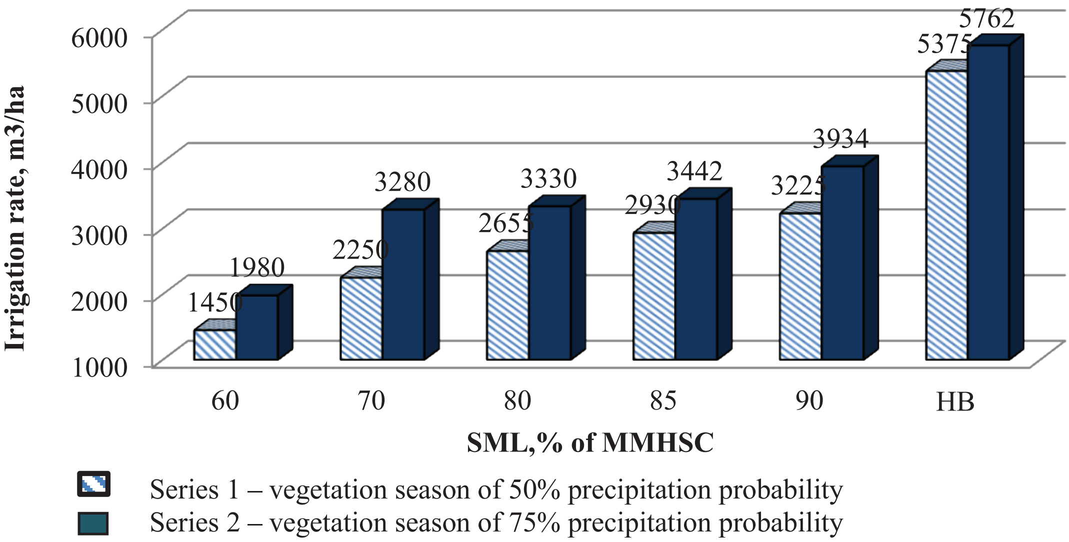

Fig. 2. Dependence of the irrigation rate on the availability of precipitation

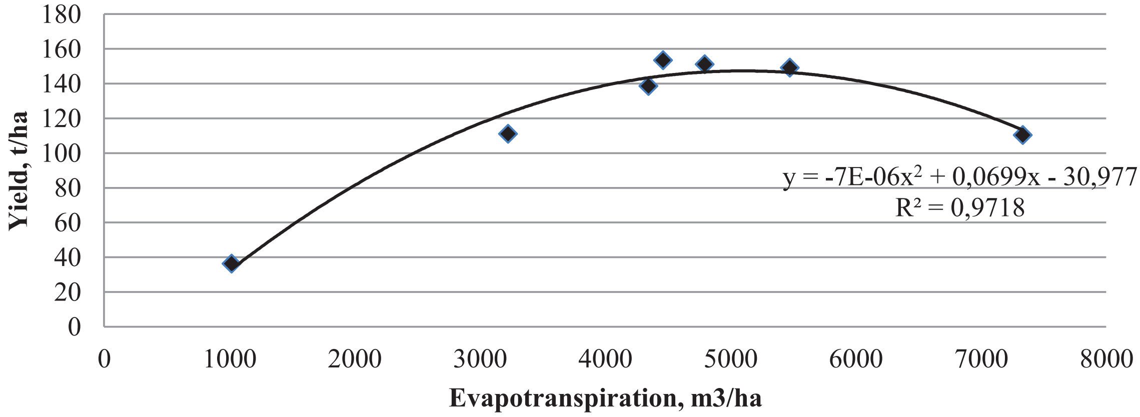

Fig. 3. Dependence of "Evapotranspiration-Yield" under drip irrigation (on the example of tomatoes)

areas: limiting, optimal, and inhibitory (excessive). The coefficient of determination R^2 = 0,81–0,98 indicates a close relationship between these values. It has been established that the limiting area of the curve corresponds to the experimental options for RPWG from -50 to -35 kPa and the variant without irrigation (control), the optimal area – from –35 to –10 kPa and the inhibitory area (excess area) – from –10 to 0 kPa. Established dependencies "Evapotranspiration-Yield", from an agro biological point of view, are not stable, since there are opportunities to increase yields with the same plant's evapotranspiration. Therefore, the task of future research on the study of plant's evapotranspiration processes is to reduce unproductive water consumption (for physical evaporation, runoff into the lower soil horizons) while simultaneously increasing crop yields.

Generalized experimental data on irrigation regimes prove that for most crops the lowest critical limit of soil moisture is -25… -30 kPa (Table 2).

The optimal moisture range for light and medium loams for tilled crops is a fairly narrow interval from -15 to -9 kPa, which provides for irrigation with relatively small rates while reducing the inter-irrigation periods. According to analytical calculations, with such a narrow range, the ratio of actual transpiration (T) to potential (T_0) approaches 1 (≈0,83–0,87), which characterizes the moisture supply of plants as close to optimal [6]. The results obtained are a refinement of the previously stated conclusions [7], that noted that the optimal lower limit of moistening of hard loamy soil is 75–80 % of MMHSC, medium and light loam – 65–70 % of MMHSC and sandy loam – 65 % from MMHSC and data confirmation [4].

It is natural that the maintenance of high humidity conditions the growth of both physical evaporation and transpiration. This, in turn, increases irrigation rates (Table 3), which are 3,3–4,1 thousand m³/ha for vegetables, and 3,8–5,4 thousand m³/ha for other field crops. Based on these data, the thesis about the "economy of irrigation water with drip irrigation" was clarified: with practically the same irrigation rates, with drip irrigation, a 1,5–3,5 times higher yield is formed, which gives reason to talk exclusively about the saving of specific water consumption for the formation of a crop unit.

Differentiation of the moisture level by development stages of plants confirmed the existence of critical periods in the life of plants, during which even a slight decrease in soil moisture beyond the optimal range leads to significant yield losses. It has been established that plants experience the highest sensitivity to a decrease in available moisture in the soil during the period of formation of fruiting organs or the period preceding it (Table 3).

The result is the hypothesis's confirmation [13] that states that biennial plants (onion, carrots, sugar beet) in the first year of life do not have a clearly defined critical period regarding moisture availability. At the same time, even in the first year of life, when we grow these crops to obtain productive organs, we note their unequal resistance to the reduction of soil moisture in different phases of development. For example, for carrots and sugar beets, such a "sensitive", but not critical period – Is the intensive growth of root crops.

Studies have confirmed the patterns of evapotranspiration formation: the minimum amount of moisture consumed by plants at the beginning of the growing season gradually increases with the development of their above-ground mass and decreases again by the end of the growing season. Peak parameters of plant evapotranspiration were recorded in the hottest periods; calendar-wise, they usually

2. Generalized parameters of drip irrigation regimes for field crops (heavy/medium loam soil)

Crop	Preirrigation soil humidity, -kPa	Waterings	Irrigation rate, m³/ha	Evapo-transpiration, m³/ha	Evapo-transpiration coefficient, m³/t	Yield, t/ha
Tomato	25–20–30	40	3450	4950	32.7	151.9
Pepper	25–20	42	3655	5020	74.9	67.0
Eggplant	20	53	4085	5330	112.7	47.3
Watermelon	27	15	1200	2600	48.4	45.4
Carrots	25–30	22	3280	5075	72.6	69.8
Onion	15	42	3340	4280	74.7	57.3
Potato	25	17	1250	2300	84.9	27.1
Corn	20	29	4400	6500	357.1	18.2
Soy	20	31	5400	6900	1112.9	6.22
Sugar beet	23	23	3840	5400	44.5	121.4
Chickpeas	25	26	4800	6860	1410	4.90

3. Critical periods for moisture supply of field crops with drip irrigation

Crop	A critical phase or growth stages of plants
Tomato	budding – flowering
Pepper	flowering – development of fruits
Eggplant	flowering – development of fruits
Watermelon	flowering – development of fruits
Potato	budding – flowering
Corn	10 days before throwing out the panicle – flowering – 10 days after flowering
Soy	budding – flowering

corresponded to the 2nd-3rd decade of July – the 1st – 2nd decade of August. The maximum indicators of daily evapotranspiration are fixed at the level of 9–12 mm in the conditions of the Steppe of Dry Ukraine and 8–11 mm in the conditions of the Steppe of Southern Ukraine. Design institutions should be guided by such parameters when designing drip irrigation systems in these soil-climatic zones.

Conclusions. The obtained dependencies "Evapotranspiration-Yield" for drip irrigation are response curves for a single-factor experiment, which have the form of an asymmetric parabola, described by a quadratic equation. The coefficient of determination R^2 = 0,81–0,98 indicates a close relationship between evapotranspiration and productivity parameters. It has been established that the optimal range of moistening of light and medium loams for field crops is a narrow interval from -9 kPa to -15 kPa, which provides for irrigation with lower rates while simultaneously shortening the periods between watering. Therefore, the ratio of actual transpiration (T) to potential transpiration (T_0) is close to 1 (≈0,83–0,87), which characterizes the moisture supply of plants as close to optimal. The existence of critical periods in the life of plants regarding moisture supply was confirmed, at the same time, it was established that in the first year of life, two-year plants (onion, carrots, sugar beet) do not have a clearly defined critical period regarding moisture supply. It was established that the maximum daily evapotranspiration rates of field crops under drip irrigation in the conditions of the Steppe of Dry Ukraine are 9–12 mm, and the Steppe of Southern Ukraine is 8–11 mm.

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ОПТИМІЗАЦІЯ ПАРАМЕТРІВ РЕЖИМІВ КРАПЛИННОГО ЗРОШЕННЯ СІЛЬСЬКОГОСПОДАРСЬКИХ КУЛЬТУР В СТЕПУ УКРАЇНИ

А. П. Шатковський[1], докт. с.-г. наук, М.І. Ромащенко[2], докт. техн. наук, О.В. Журавльов[3], докт. с.-г. наук, С.В. Рябков[4], докт. с.-г. наук, Ю.О. Черевичний[5], канд. с.-г. наук, О.І. Гуленко[6]

[1] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна; https://orcid.org/0000-0002-4366-0397; e-mail: andriy-1804@ukr.net;
[2] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна; https://orcid.org/0000-0002-9997-1346; e-mail: mi.romashchenko@gmail.com
[3] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна; https://orcid.org/0000-0001-7035-219X; e-mail: zhuravlov_olexandr@ukr.net
[4] ДП «Проектно-технологічне бюро» ІВПіМ НААН, Київ, 03022, Україна; https://orcid.org/0000-0001-8219-9065; e-mail: srabkov@gmail.com
[5] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна; https://orcid.org/0000-0002-9959-8297; e-mail: yurecgp@gmail.com
[6] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна; https://orcid.org/0000-0002-1007-5677; gulenkoai@gmail.com

Анотація. *Метою досліджень було удосконалення та обґрунтування параметрів режими краплинного зрошення сільськогосподарських культур в Степу України. Польові дослідження проводили на Кам’янсько-Дніпровської дослідній станції ІВПіМ (47046' пн.ш. 34042' сх.д.), Брилівському опорного пункту ІВПіМ (46°40′ пн.ш. 33°12′ сх.д.) та Південній дослідній станції ІВПіМ (46°33′ пн.ш. 33°59′ сх.д.) у період з 2004 по 2020 роки на 10 сільськогосподарських культурах. Схема досліджень передбачала реалізацію серії однофакторних дослідів з різними рівнями зволоження ґрунту, контрольним був варіант без зрошення. На першому етапі нами отримали математичні залежності «Рівень зволоження ґрунту – Кількість вегетаційних поливів» та «Рівень зволоження ґрунту – Зрошувальна норма» для всіх культур. Режим краплинного зрошення також знаходився у зв’язку з метеорологічними параметрами, які безпосередньо впливали на фізичне випаровування та інтенсивність транспірації. Найбільш тісну кореляційну залежність «Режим краплинного зрошення – Метеорологічні параметри» було встановлено за фактором «Кількість опадів». Результатом роботи є встановлення кореляційних зв’язків між евапотранспірацією сільськогосподарських культур та їх урожайністю. На основі цього для краплинного зрошення Степу України побудовано залежності (статистичні моделі) «Евапотранспірація – Урожайність» та визначено найбільш оптимальні варіанти використання води з точки зору її витрат на формування продукції. Наведені залежності є кривими реакції на однофакторний дослід, вони складаються із трьох областей: лімітуючої, стаціонарної та інгібуючої. Коефіцієнти кореляції r = 0,92 – 0,98 свідчать про тісний зв’язок між цими параметрами. Встановлені залежності «Евапотранспірація – Урожайність» з агробіологічної точки зору не є стійкими, тому що існують потенційні можливості підвищення врожайності за однакової евапотранспірації. Встановлено, що оптимальним діапазоном зволоження за краплинного зрошення більшості сільськогосподарських культур є вузький інтервал всмоктуючого тиску ґрунтової вологи -15 до -9 kPa. Це передбачає проведення поливів невеликими нормами (50-75 м³/га) за одночасного скорочення міжполивних періодів. За таких умов співвідношення фактичної транспірації (Тс) до потенційно можливої (T_0) наближається до 1 (≈ 0,83–0,87), що характеризує вологозабезпечення рослин як близьке до оптимального.*

Ключові слова: *краплинне зрошення, рівень вологості ґрунту, випаровування, урожайність сільськогосподарських культур, математичні залежності*