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УДК 332.025:330:12

АНАЛІЗ МЕТОДИЧНИХ ПІДХОДІВ ДО ФОРМУВАННЯ ТАРИФІВ НА ВОДУ ДЛЯ ЗРОШЕННЯ ТА КОМПЕНСАЦІЮ ВИТРАТ НА МЕЛІОРАТИВНУ ІНФРАСТРУКТУРУ: ДОСВІД КРАЇН-ЧЛЕНІВ ЄС

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Анотація. *Розглянуто практику країн ЄС із запровадження тарифів на воду для зрошення сільськогосподарських культур та процедур повернення коштів, витрачених на водопостачання для зрошення. Основними джерелами інформації статті стали публікації та нормативні документи України, звіти органів ЄС та World Bank, у яких проведений критичний аналіз практики ціноутворення у зрошуваному землеробстві країн ЄС за 2005–2023 рр. Проведено групування інформації про площу зрошуваних земель, рівень повернення коштів, витрачених на водопостачання, увагу приділено методичному підходу до розробки тарифів на транспортування води. Викладено тлумачення причин природного характеру, якими керувалися органи управління державами при застосуванні економічних інструментів управління зрошенням на своїх територіях. За окремими країнами із значними площами зрошуваних земель (Італія, Франція, Греція, Іспанія, Португалія та Румунія) визначено вагомі досягнення (складові) тарифоутворення та відшкодування коштів. Розкрито аспекти тарифоутворення на воду, облік води, розвиток об'єднань водокористувачів, оподаткування плати за воду. Ознаками класифікації країн було: напрями ціноутворення на воду, врахування стану водних ресурсів та меліоративних систем, різновиди тарифів, механізми ціноутворення, стан повернення коштів, витрачених на водопостачання за рахунок тарифів, вимірювання обсягів води, а також розв'язання додаткових проблем застосування економічних інструментів у зрошуваному землеробстві – інституціональні (адміністративні, правові) заходи, вплив плати за воду на економіку агросфери країни тощо. Оскільки домінуючим підходом у реалізації тарифоутворення у зрошенні країн ЄС є вимоги водної рамкової директиви, розглядався рівень досягнення показників якості виконання ВРД країнами. Встановлено, що переважна більшість світових практик формування тарифів на послуги з подачі води для зрошення, капітальних інвестицій в меліоративну інфраструктуру та її обслуговування, свідчить, що вони базуються, як на загальнодержавних інтересах, так і на зацікавленості водокористувачів і організацій, що забезпечують логістичну підтримку.*

Ключові слова: *водоподача, зрошення, тарифи, компенсація витрат, управління, системний підхід, Європейський Союз (ЄС)*

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USING THE WATER STRESS INDEX FOR TOMATO IRRIGATION CONTROL

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Abstract. *The temperature of the leaf surface of plants can be used as an indicator of the water stress of agricultural crops. Since plant temperature is affected by weather factors, it is usually expressed through the crop water stress index (CWSI). To calculate the CWSI, two input parameters must be known that relate plant temperature under and without maximum water stress to the water vapor pressure deficit. These basic equations are specific to each culture and locale. Many studies on the definition of CWSI and basic dependencies for tomatoes have been conducted abroad, such a study has not yet been conducted in Ukraine. The purpose of the research is to establish CWSI values and basic equations that are needed for the purpose of watering tomatoes in the south of Ukraine under subsurface drip irrigation. The paper presents the results of determining the theoretical and empirical water stress index of tomatoes under subsurface drip irrigation. The research results confirm that the water stress index can be used to plan the irrigation of tomatoes both independently and in combination with other methods to increase the accuracy of decision-making. An analysis of the daily dynamics of the CWSI was carried out, according to the results of which it was established that in the morning hours the water stress index on average during the observation period was almost 0, then, as the intensity of solar radiation increased, the CWSI also increased and reached its maximum value (1.08) at 20:00. The correlation coefficient between the water stress index and the intensity of solar radiation was 0.63. The relationship between irrigation rate, soil moisture, change in plant stem diameter, and CWSI was established, the correlation coefficients are –0.60, –0.55, and –0.51, respectively. Theoretical and imperial methods estimate CWSI equally, there is a high correlation between both methods (r = 0.92). It is necessary to prescribe irrigation or increase the irrigation rate according to the theoretical and empirical methods of determining CWSI, respectively, for its values of 0.3 and –2.2. The empirical method of calculating CWSIE using the resulting equations is easier to use. The CWSI values obtained for tomatoes in this study are closely correlated with the other irrigation methods.*

Key words: *water stress index, tomato, subsurface drip irrigation, plant temperature, phytomonitoring*

Relevance of research. Tomato (*Solanum lycopersicom* L.) is a valuable vegetable crop that is grown for its fruits. About 75 % of tomatoes are consumed fresh, and the rest is processed. The sown area in Ukraine is about 80 thous. hectares, which is 20 % of the entire area under vegetable crops [1]. In the south of Ukraine, this is the most common vegetable crop. Tomatoes belong to agricultural crops with a high level of total water consumption: 5.2–5.5 thousand m^3/ha and are sensitive to water stress [2; 3]. Accordingly, the determination of the criterion for the appointment of watering tomatoes is an important element for the operational management of the irrigation regime. Today, there are many methods of irrigation [4; 5; 6], one of the criteria for their use is the availability of the necessary tools and qualified personnel. Studies on the determination of CWSI for tomatoes [3; 7–9] and other [10–15] crops conducted abroad indicate that this index is used to assess plant water stress and manage irrigation. Such studies have not yet been conducted in Ukraine. Therefore, the need to conduct research is due to the development of a method of assigning irrigation that does not require expensive tools in order to increase the efficiency and effectiveness of managing the water regime of the soil.

Analysis of recent research and publications. One of the simple and accurate methods of watering, which does not require complex and expensive equipment, can be the water stress index (crop water stress index – CWSI), which is based on measuring plant and air temperature. Infrared thermometers [3; 10] or leaf temperature sensors [7] can be used to measure plant temperature.

The experimental [16] and theoretical [17; 18] crop water stress index (CWSI), which can be used to predict irrigation time, was developed in 1981 and has not lost its relevance today [10; 19]. When plants experience water stress, the stomata immediately close, transpiration decreases sharply, and the temperature of the leaves rises. Studies have shown a close correlation between the temperature of the plant cover and the moisture supply of plants. [9; 11; 18; 20]. To calculate the CWSI, two input parameters must be known that relate the plant temperature under and without maximum water stress to the water vapor pressure deficit. These basic equations are specific for each culture and locality [8; 9; 16; 19].

Foreign scientists have conducted many studies on determining CWSI for tomatoes [3; 7; 8; 9], cowpea [10], corn [11; 14; 15; 19], sorghum [12], winter wheat [13], pumpkins, soybean, alfalfa [16], eggplant [21; 22], watermelon [23], cotton [24], sweet pepper [25] and concluded that this index accurately assesses the water stress of agricultural crops and can be used as a criterion for irrigation.

The purpose of the study is to determine the value of the water stress index (CWSI) and the basic equations that are necessary for the purpose of watering tomatoes under subsurface drip irrigation in the conditions of the Dry Steppe of Ukraine.

Research materials and methods. The study of the water stress index of tomato plants (CWSI) was conducted in 2019 in production conditions on the lands of PE "Organic Systems". The enterprise is part of the "Agrofusion" group of companies, which specializes in growing tomatoes on drip irrigation on an area of more than 7.5 thousand hectares with further processing at its own facilities [26]. The research and production site is located on the territory of the Chaplyns′koho district of the Kherson region, Ukraine (subzone of the Dry Steppe, Google Maps location 46040' N. 33035' E.). The climate of the research area is moderately hot and very dry. The sums of temperatures above +10°C are from 3300 to 3400°C, the amount of precipitation during this period is 200–220 mm, and the hydrothermal coefficient according to G.T. Selyaninov is equal to 0.6 [27]. The soil of the research and production site is dark chestnut, low in humus (1.7–1.9%), the soil moisture content for the 0–50 cm soil layer is 25.8% of the completely dry soil (174 mm), the bulk density is 1.35 g /cm³. Water intake for irrigation was carried out from the Chaplyns′kyi Canal (Chaplynska irrigation system, feeding from the North Crimean Canal, water from the Dnipro River). In the experiment, the Melman F1 Organic early-ripening tomato hybrid for machine harvesting was used. Planting scheme 1.50×0.25 m. Irrigation pipelines of the drip irrigation system are laid at a depth of 0.25 m.

To monitor meteorological parameters, an automatic Internet weather station iMetos IMT 300 [28] from the company "Pessl Instruments" [29] was used, which was located directly at the experimental site. The weather station is equipped with sensors for air temperature, air humidity, solar radiation, wind speed, and a rain gauge. The temperature of tomato plants was measured with an LT-1z sensor, and the change in stem diameter was measured with an SD-5z sensor, which was connected to a PM-11z phytomonitor from the company "Bio-Instrument S.R.L." [30]. Sensors for monitoring the physiological state of plants were installed according to methodical instructions [31].

The theoretical and imperial water stress index (CWSI) was calculated using the formula [16–18]:

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{LBL}}{(T_c - T_a)_{UBL} - (T_c - T_a)_{LBL}}, \quad (1)$$

where $(T_c - T_a)$ – the temperature difference of the plant (T_c) and air (T_a); $(Tc\text{-}Ta)_{LBL}$ is the lower baseline, the temperature difference that is achieved under conditions when plants are well-moistened and have potential transpiration. Under these conditions, the temperature of the plant was minimal under existing environmental conditions. $(T_c - T_a)_{UBL}$ is the upper baseline, the fictitious temperature difference under the conditions if the plant were instantly dried without any changes. Under these conditions, the temperature of the plant was the maximum under existing environmental conditions.

The lower baseline was calculated using the theoretical method [3; 18], taking the resistance of the stomata equal to zero (r_c=0).

$$(T_c - T_a)_{LBL} = \frac{(R_n - G) \times r_a}{\rho_{ar} C_p \left(1 + \frac{\Delta}{\gamma}\right)} - \frac{VPD}{\gamma \left(1 + \frac{\Delta}{\gamma}\right)}, \quad (2)$$

where: r_a – aerodynamic resistance, s/m; γ – psychometric constant, kPa/°C; R_n – total radiation balance, W/m²; G – heat flow into the soil, G = 0; ρ_{ar} – air density at constant pressure, kg/m³; C_p – specific heat capacity of air at constant pressure, J/kg·°C, C_p =1013; Δ – is the slope of the pressure curve of saturated water vapor at temperature, kPa/°C; VPD – water vapor pressure deficit, kPa.

The upper baseline was calculated using the theoretical method [3; 18], assuming the resistance of the stomata to be close to infinity ($r_c \rightarrow \infty$).

$$(T_c - T_a)_{UBL} = \frac{(R_n - G) \times r_a}{\rho_{ar} C_p}. \quad (3)$$

The aerodynamic drag (r_a) needed to calculate the CWSI according to the Jackson method [18] was calculated using the formula [32]:

$$r_a = \frac{4.72 \times \left(\ln \left(\frac{z - d}{z_0} \right) \right)^2}{1 + 0.54u}, \quad (4)$$

where z – wind measurement height, m; d – the height of the offset of the zero plane, m; $d \approx 0{,}63h$; z_0 – roughness length, m; $z_0 \approx 0{,}13h$; u – wind measurement height, m; h – the height of the plant, m.

Other parameters of equations 2 and 3 were calculated according to the FAO method 56 [33]. To calculate the slope of the pressure curve of saturated water vapor (Δ), we used the average temperature of the plant and air $\left(T = \frac{T_c + T_a}{2} \right)$ according to the Jackson method [18].

The Empirical Water Stress Index (CWSI$_E$) was calculated using Equation 1, replacing the lower and upper baselines with Equations 5 and 6 [3; 7; 10; 15; 16; 19].

The lower baseline ($(T_c - T_a)_{LBL}$) was calculated using the empirical method using the formula:

$$(T_c - T_a)_{LBL} = a + b \times VPD, \quad (5)$$

where T_c – plant temperature, °C; T_a – air temperature, °C; VPD – water vapor pressure deficit, kPa; a and b – different constant coefficients for agricultural crops.

The upper base line ($(T_c - T_a)_{UBL}$) using the empirical method is calculated by the formula:

$$\begin{aligned} (T_c - T_a)_{UBL} &= a + b \times VPG = \\ &= a + b\left[e_s(T_a) - e_s(T_a + a)\right], \end{aligned} \quad (6)$$

where VPG – water vapor pressure gradient, kPa; coefficients a and b obtained from the lower baseline (5); $e_s(T_a)$ – saturated vapor pressure at air temperature Ta, kPa; $e_s(T_a + a)$ – is the saturated vapor pressure at the temperature of T_a+a, kPa.

$$e_s(T_a) = 0.6108 \times e^{\frac{17.27 \times T_a}{237.7 + T_a}},$$

$$e_s(T_a + a) = 0.6108 \times e^{\frac{17.27 \times (T_a + a)}{237.7 + (T_a + a)}}, \quad (7)$$

Research results and discussion. The water stress index was calculated for the daylight hours (2 hours after sunrise and 2 hours before sunset) [12]. Research results confirm that CWSI approaches "0" after irrigation and gradually approaches 1 as soil moisture decreases [12]. During the observation period, almost all CWSI values were in the range from 0 to 1. Deviations from this range were observed in the morning and evening, when the CWSI values were less than "0" and more than "1", respectively (Fig. 1). This result confirms research [13] on winter wheat culture conducted in northern China [13]. The results of the calculations confirm the relationship between CWSI and plant and air temperature. Thus, the correlation coefficients between CWSI and plant and air temperature were 0.71 and 0.64, respectively.

According to the analysis of the daily dynamics of the CWSI, the tendency of this indicator to increase from 05:00 to 20:00 is followed [12; 17; 19]. Thus, after sunrise at 06:00, CWSI was close to "0" on average during the observation period, then, as the intensity of solar radiation increased, CWSI also increased and reached its maximum value (1.08) at 20:00.

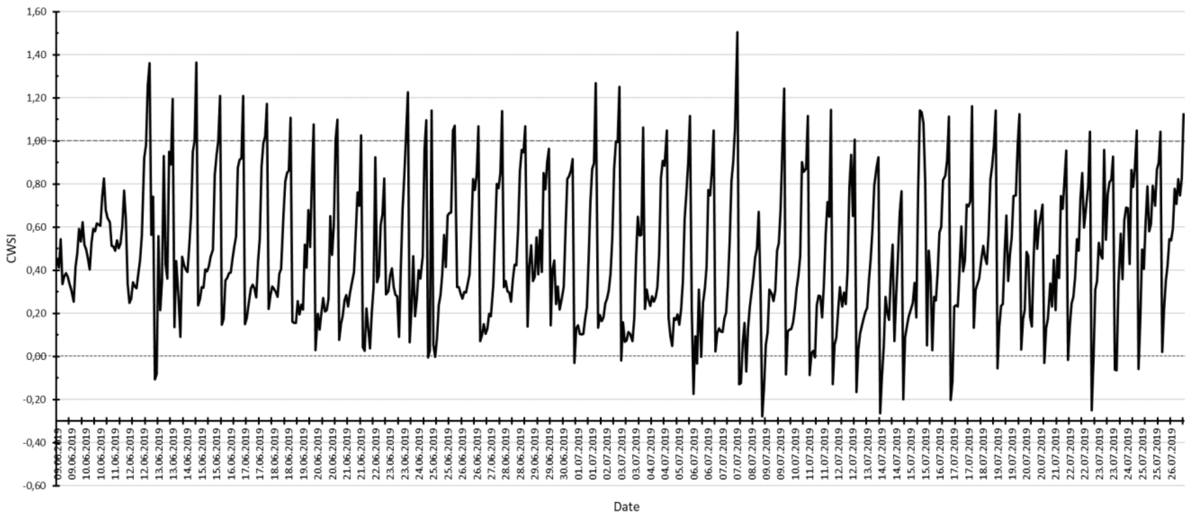

Fig. 1. Daily dynamics of the water stress index of tomato plants

The correlation coefficient between the water stress index and the intensity of solar radiation was 0,63 (Fig. 2).

For CWSI analysis, the average value of this indicator was taken at 12:00 and 13:00 [13; 16; 18]. Based on the results of calculations, it was established that the average CWSI value of tomato below 0,2 did not decrease against the background of sufficient soil moisture, which was also established by Brazilian scientists [3]. At the beginning of observations (June 10), the value of CWSI was 0.47–0.50. Then, due to precipitation, and, as a result, a decrease in the water vapor pressure deficit, the CWSI decreased to 0.28. After three waterings of 100 m^3/ha on June 14–16, the CWSI increased to 0,42, which indicates an insufficient irrigation rate. After increasing the irrigation rate from June 17 to 120 m^3/ha, the CWSI index decreased to 0,30, and later to 0,21. From June 17 to July 15, CWSI was in the range of 0.20–0.30, indicating no water stress during this period. The exception was the period from June 26 to 29, when for technical reasons the irrigation rate was reduced to 80–100 m^3/ha, and as a result, CWSI increased to 0.32–0.35.

Starting on July 15, the CWSI began to gradually rise from 0.30 to 0.50. This is due to the onset of fruit ripening, an increase in air temperature, and a deficit of water vapor pressure [9], as well as a decrease in the intensity of irrigation. Based on the results of the analysis, a relationship between the irrigation rate and CWSI was established, the correlation coefficient is –0.60. Increasing the irrigation rate reduces CWSI. It is necessary to prescribe irrigation and increase the irrigation rate for a CWSI value of 0.30 (Fig. 3).

The dependence of CWSI on soil moisture is similar to that on the irrigation rate. An increase in the rate of irrigation led to an increase in soil moisture, and as a result, CWSI decreased. Thus, at the highest soil moisture of 80–81 % MMHC (June 24 and July 1), CWSI values were the lowest and amounted to 0.18–0.20. On June 29, soil moisture decreased to 79 % MMHC and CWSI increased to 0.35. The decrease in soil moisture from July 15 to 78 % MMHC led to an increase in CWSI to 0,4. Based on the results of the study, a relationship between soil moisture and CWSI was established, the correlation coefficient is –0.55. A decrease in soil moisture by 2–3 % MMHC increased the CWSI to the threshold values (0.30) for determining the irrigation period (Fig. 4).

The phytomonitoring method is used for operational management of tomato irrigation [4], therefore the established relationship between CWSI and the change in stem diameter confirms that the water stress index can be used to plan tomato irrigation both independently and in combination with other methods. Thus, with an increase in the diameter of the tomato stem, the CWSI decreased and vice versa. The correlation coefficient between CWSI and the change in stem diameter was –0.51 (Fig. 5).

Calculation of CWSI using the empirical method [3; 7; 10; 15; 16; 19] simplifies the use of the technique compared to the theoretical method, which requires more complex calculations. The Empirical Water Stress Index (CWSIE) was calculated using Equation 1 by changing the lower and upper baselines to Dependencies 5 and 6.

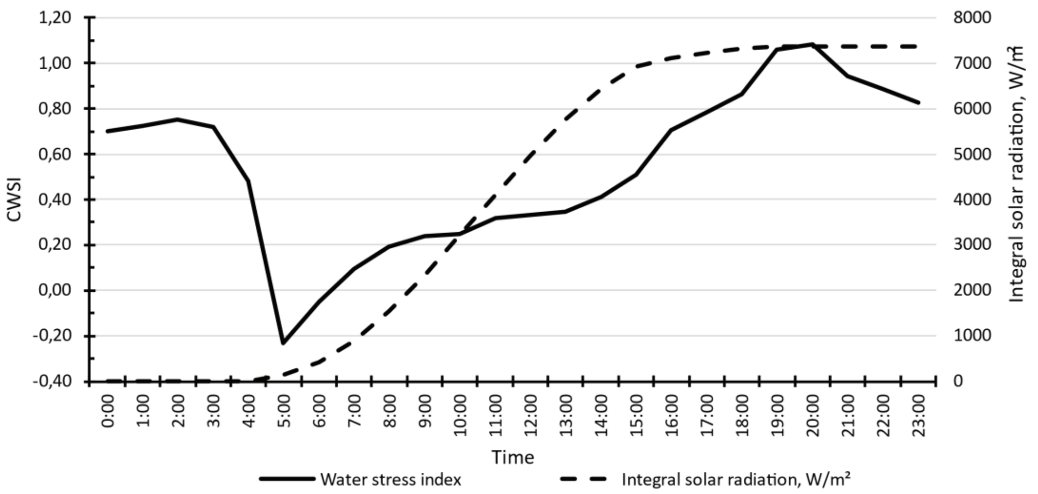

Fig. 2. Daily dynamics of tomato water stress index and solar radiation

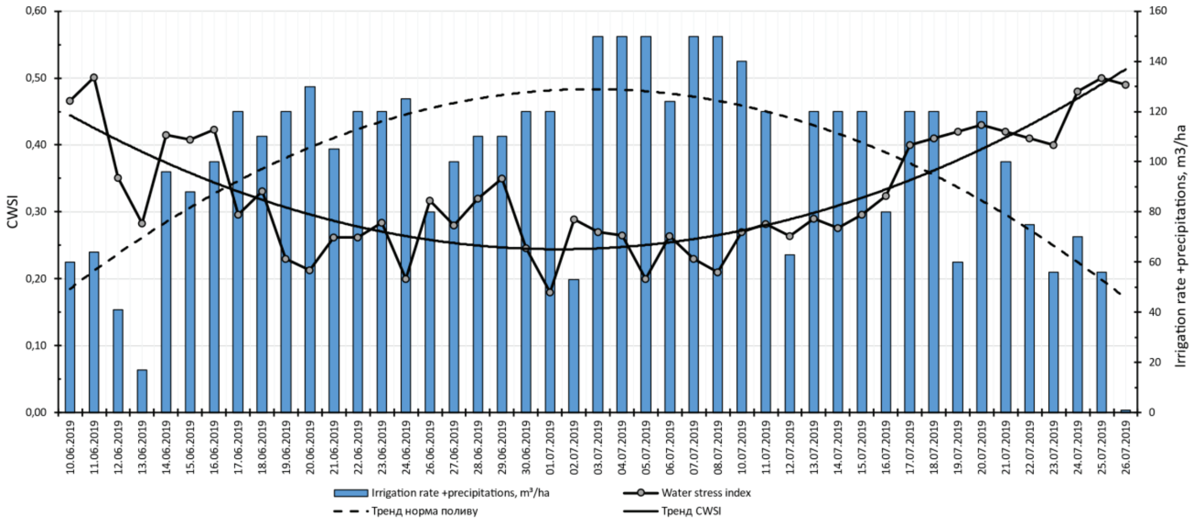

Fig. 3. Dependence between tomato irrigation rate and CWSI

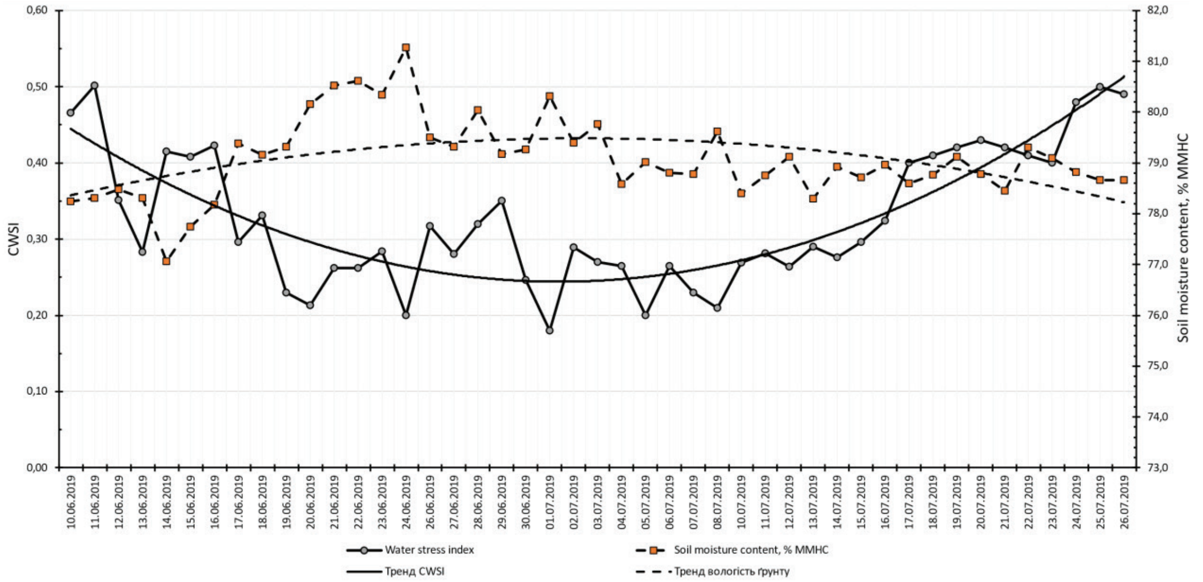

Fig. 4. The relationship between soil moisture and CWSI of tomatoes

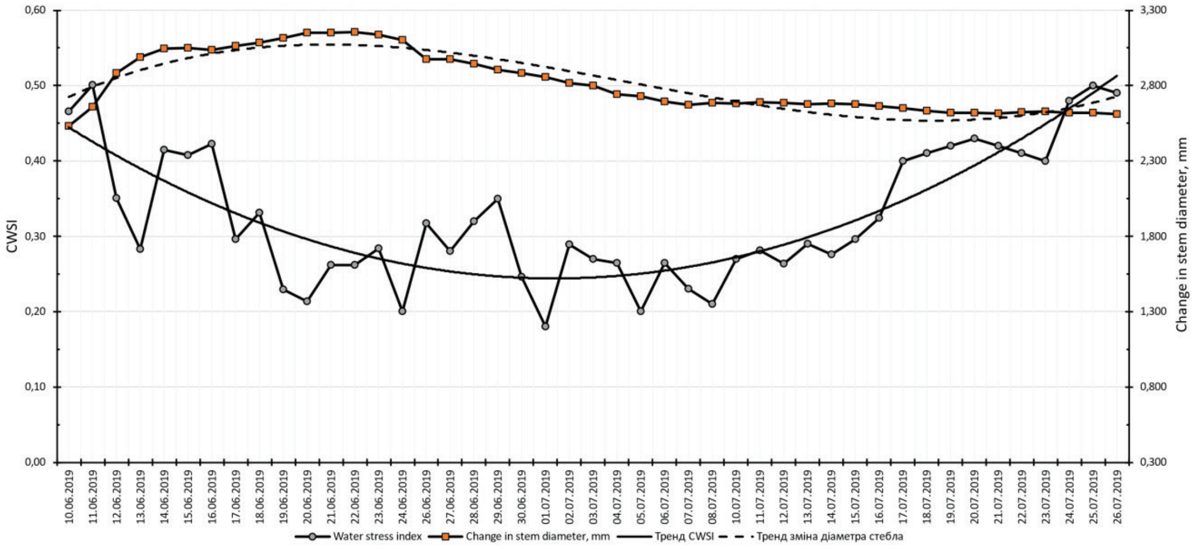

Fig. 5. The relationship between the change in stem diameter and CWSI of tomatoes

To obtain the equation of the lower baseline $(T_r - T_a)_{LBL}$, we used the data obtained according to dependence 2. Based on the results of the calculations, we obtained the basic equations for determining the CWSI of tomatoes:

$$\left(T_c - T_a\right)_{LBL} = -0.842 - 2.591 \times VPD, \quad (8)$$

$$\left(T_c - T_a\right)_{UBL} = -0.842 - 2.591 \times VPG. \quad (9)$$

According to the obtained equation 8, it was established that with a water vapor pressure deficit of 0,1 to 4,2 kPa, the temperature difference between the plant and the air was from 1.2 to –6.30°C (Fig. 6).

It is possible to use the obtained equation of the lower baseline $(T_p - T_a)_{LBL}$ [10; 14; 34] to determine the irrigation of tomatoes. To do this, it is necessary to measure the temperature, the relative humidity of the air, and the temperature of the plant. Then, by substituting the water vapor pressure deficit (VPD) in equation 8, calculate the permissible temperature difference $(T_c - T_a)_{LBL}$. In order to determine the time of watering, it is necessary to compare the temperature difference between the plant and the air $(T_c - T)$, measured in the field, with the permissible value $(T_c - T_a)_{LBL}$, in this case, three conditions are met:

1. If the value of $(T_c - Ta)$ is less than $(T_c - T_a)_{LBL}$ – watering is not required.
2. If the value of $(T_c - T_a)$ is greater than $(T_c - T_a)_{LBL}$ – irrigation is missed, it is necessary to urgently prescribe irrigation.
3. If the value of $(T_c - T_a)$ is approximately equal to $(T_c - T_a)_{LBL}$ – it is time for watering.

The values obtained by CWSI calculations using the theoretical method are greater than the empirical ones [3; 9; 21]. But regardless of this, there is a close correlation between both methods (r = 0.92), which indicates the possibility of using these methods for the operational planning of watering tomatoes. The empirical method of calculating the $CWSI_E$ using the resulting equations 8 and 9 is preferred because of its simplicity. It is necessary to prescribe irrigation or increase the irrigation rate using the empirical method of determining $CWSI_E$ when the value is –2.2 (Fig. 7).

Conclusions. The research results confirmed that the water stress index (CWSI) can be used for the operational management of tomato irrigation. The correlation coefficients between CWSI and plant and air temperature were 0.71 and 0.64, respectively.

In the morning hours, CWSI was close to “0”, then, as the intensity of solar radiation increased, CWSI also increased and reached its maximum value (1.08) at 20:00. The correlation coefficient between the water stress index and the intensity of solar radiation was 0.63.

The relationship between irrigation rate, soil moisture, and CWSI of tomatoes was established – the correlation coefficient was –0.60 and –0.55, respectively. Increasing the irrigation rate reduced CWSI. It is necessary to prescribe irrigation or increase the irrigation rate for a theoretical CWSI value of 0.30.

The relationship between CWSI and the change in stem diameter was established: as tomato stem diameter increased, CWSI decreased, and vice versa. The correlation coefficient between CWSI and stem diameter change was –0.51.

Theoretical and empirical methods estimate the CWSI equally, and there is a high correlation between these methods (r = 0.92). The empirical method of calculating CWSIE using the resulting equations 8 and 9 is recommended due to its ease of application. It is necessary to prescribe irrigation or increase the irrigation rate using the empirical method of determining CWSIE when a value of –2.2 is reached.

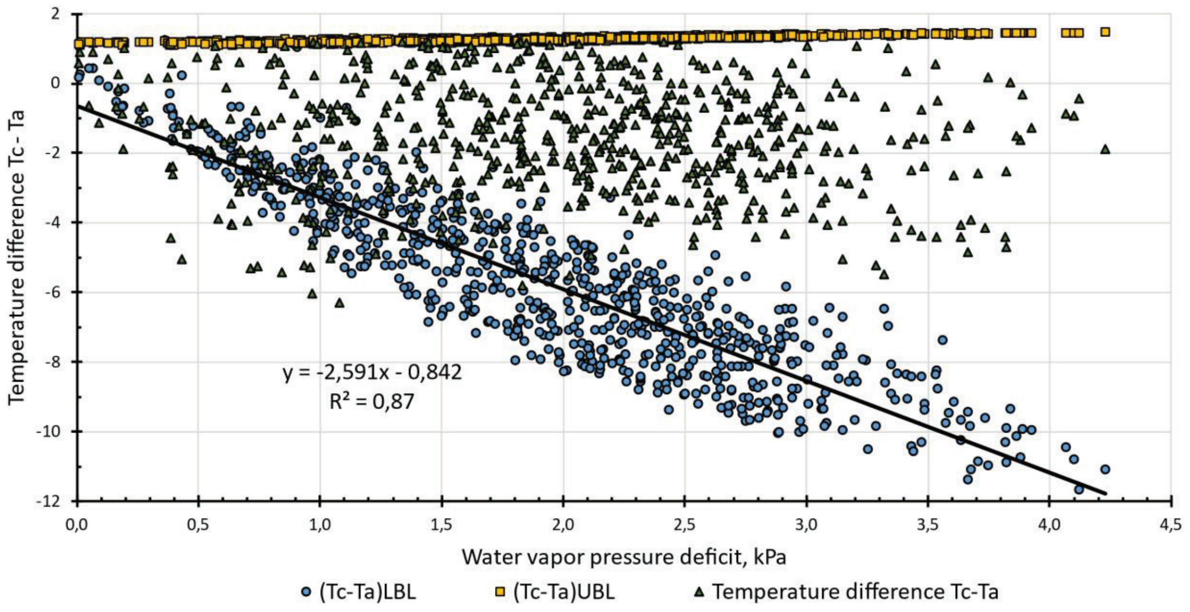

Fig. 6. Temperature difference between tomato plants and air depending on the deficit of water vapor pressure

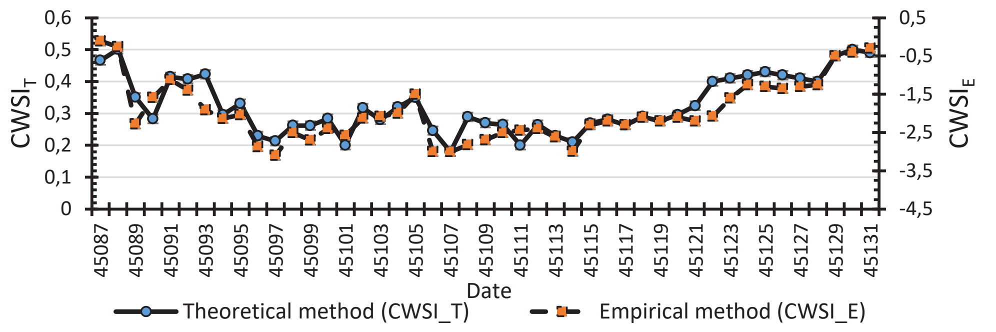

Fig. 7. Dynamics of the theoretical ($CWSI_T$) and empirical ($CWSI_E$) tomato water stress index

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ВИКОРИСТАННЯ ІНДЕКСУ ВОДНОГО СТРЕСУ ДЛЯ КОНТРОЛЮ ЗРОШЕННЯ ТОМАТІВ

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Анотація. *Температура листової поверхні рослин може бути використана в якості показника водного стресу сільськогосподарських культур. Оскільки на температуру рослин впливають погодні чинники, її, зазвичай, виражають через індекс водного стресу (crop water stress index – CWSI). Для розрахунку CWSI необхідно знати два вхідних параметра, які пов'язують температуру рослин в умовах максимального водного стресу та без нього з дефіцитом тиску водяної пари. Ці базові рівняння специфічні для кожної культури та місцевості. Багато досліджень із визначення CWSI та базових залежностей для томатів проведено за кордоном, в Україні таке дослідження ще не проводили. Мета дослідження – встановити значення CWSI та базові рівняння, які потрібні для призначення поливів томатів на півдні України за підґрунтового краплинного зрошення. У роботі наведено результати визначення теоретичного та емпіричного індексу водного стресу томатів за підґрунтового краплинного зрошення. Результати досліджень підтверджують, що індекс водного стресу можливо використовувати для планування поливів томатів як самостійно, так і в комплексі з іншими методами для підвищення точності прийняття рішення. Проведено аналіз добової динаміки CWSI, за результатом якого встановлено, що у вранішні години індекс водного стресу в середньому за період спостережень дорівнював майже 0, потім, за мірою підвищення інтенсивності сонячної радіації, CWSI також зростав і максимального свого значення (1,08) досягав о 20:00. Коефіцієнт кореляції між індексом водного стресу та інтенсивністю сонячної радіації становив 0,63. Встановлено зв'язок між нормою поливу, вологістю ґрунту, зміною діаметра стебла рослин та CWSI, коефіцієнти кореляції дорівнюють –0,60, –0,55 та –0,51 відповідно. Теоретичний та імперичний методи однаково оцінюють CWSI, між обома методами існує висока кореляційна залежність (r = 0,92). Призначати полив або збільшувати норму поливу за теоретичного та емпіричного методів визначення CWSI відповідно необхідно за його значення 0,3 та –2,2. Емпіричний метод розрахунку CWSIE із використанням отриманих рівнянь є більш простим у використанні. Значення CWSI, отримані для томатів, в цьому дослідженні тісно корелюють з іншими методами призначення поливів.*

Ключові слова: *індекс водного стресу, томат, підґрунтове краплинне зрошення, температура рослини, фітомоніторинг*