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Total Water Consumption and Evaporation of Winter Wheat in the Irrigation Zone of Southern Ukraine

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Abstract. The most important element in the development of the irrigation regime of agricultural crops is the total water consumption or/and the amount of water that plants need during the growing season to obtain the planned crop in specific natural conditions while optimising all technological processes. The purpose of the study is to determine the features of total water consumption and average daily evaporation of winter wheat plants depending on the natural moisture supply of growing years, irrigation regimes, and groundwater level in the irrigation zone of southern Ukraine. In the course of the study, generally accepted methods were used: system approach and systems analysis, monographic, analysis and synthesis, abstract-logical, historical, field research, statistical and economic-mathematical, etc. The highest indicators of total water consumption were observed in the average weather conditions and amounted to 4,263 m^3/ha in the 2-metre layer of soil, in wet years characterised by moderate temperatures, high humidity, and a considerable number of days with precipitation, the average water consumption from this soil layer was 3,993 m^3/ha. In dry years, which were characterised by hot weather with low humidity and low precipitation, the total water consumption was the lowest and amounted to 3685 m^3/ha. The reduction of the growing season occurs in late June – early July when high air temperatures and low humidity are observed, which is the main reason for the decrease in the total water consumption of irrigated winter wheat. Analysis of data on the use of moisture from different soil layers indicates that during the autumn growing season and during the wintering of plants water reserves in the deep layers are replenished. In general, during the growing season of winter wheat, considering the winter period, the field of this crop consumes an average of 5.2 thousand m^3 of water during irrigation over 12 years. Observation of the average daily evaporation of winter wheat plants in conditions of natural and artificial irrigation indicates that it has the form of a parabola, the maximum mark of which falls on the interphase period of earing – the beginning of milky ripeness of grain

Keywords: irrigation water, average daily evaporation, groundwater level, irrigation mode

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INTRODUCTION

The most important element in shaping the irrigation regime of crops is the total water consumption or the amount of water needed by plants during the growing season to obtain the planned yield in specific natural conditions with all technological processes optimised. Total water consumption by crops is an indicator of plant needs for the entire growing season, while total evaporation relates to some of its segments. They consist of water consumption for plant transpiration, evaporation from the soil surface, and the development of biological mass. Different plant requirements for the amount of water needed for optimal growth and production processes and high yields are the result of their evolutionary development under the influence of varying climatic conditions.

Numerous studies have shown that the strongest regulatory factors of total water consumption are climatic conditions of the growing zone, weather during the growing season, biological characteristics of crop varieties and, above all, the duration of the growing season, plant moisture provision, etc. [1-3]. The loss of soil moisture for the transpiration of plants and evaporation from the soil surface during certain periods of the growing season is called total evaporation in reclamation terminology [3]. The rate of the crop total evaporation is not a constant value and varies during the growing season depending on the rate of growth and plant development, weather conditions, soil water regime, and other factors [4; 5]. As a rule, at the beginning of the growing season, the crops consume a small amount of moisture, which is mainly conditioned by evaporation from the soil surface.

In the steppe zone, the water consumption of plants depends largely on weather conditions. On non-irrigated lands, there is a constant dependence of the total water consumption reduction on wet or dry years, which is conditioned by different temperatures and precipitation during the growing season. According to scientific institutions in the Southern regions, the water consumption of rain-fed winter wheat, which is necessary for the development of a high yield, averages 70% of the optimal values, and in dry years it is 50-60% [6]. Some studies on the water consumption by irrigated winter wheat also show that it is proportionally dependent on cool and dry years [7; 8]. According to researchers, in a particular agro-climatic region where the crop grows in the optimal water regime with high agro-technical techniques, the total water consumption depends primarily on the radiation balance of the ground air and the soil surface. In very dry years, the total water consumption under irrigation is much higher than under moderate weather conditions [9].

The purpose of the study is to establish rates of water consumption by winter wheat plants depending on the conditions of natural and artificial irrigation.

MATERIALS AND METHODS

The experimental part of the study was performed on irrigated lands of the Institute of Irrigated Farming NAAS (IIF NAAS), located on the right bank of the Dnipro, the Dnipro district of Kherson, in the Ingulets irrigation system area. The soil of the plots under study is dark chestnut, medium loamy, slightly saline based on carbonate aeolian soil, which is typical for the irrigated zone of southern Ukraine. To determine the content of relevant elements of natural soil fertility in the spring from a layer of 0-60 cm using the envelope method, samples were taken every 10 cm and sent to the agrochemical laboratory where the following parameters were determined by the current state standards of Ukraine. The content of humus in the arable layer is 2.2%, that of total nitrogen is 0.17%, mobile phosphorus and exchangeable potassium – 30 and 300 mg/kg of soil, respectively [10-12].

Experimental studies were conducted during 2009-2015 using generally accepted research methods for irrigation conditions in Southern Ukraine. In particular, general research methods (analysis, synthesis, observation, comparison, measurement, etc.), special (field, laboratory-field, laboratory, certified generally accepted scientific methods, and DSTU), mathematical-statistical and computational-comparative. To determine the indicators of total and daily water consumption, soil samples were taken every 10 cm to a depth of 2 m at the beginning and end of the growing season and during the main phases of growth and development to establish soil moisture [13; 14].

In a metre-long soil layer, the lowest moisture content (LMC) is 21.3%, wilting moisture (WM) is 9.5% of dry soil weight, texture density is 1.41 t/m^3, pH of the aqueous extract of the arable soil layer is 6.8-7.2. Groundwater lies at a depth of 15-17 m and has virtually no effect on the water-air regime of the active moisture exchange zone.

The materials of the Kherson agrometeorological station located on the territory of the experimental field were used to characterise the weather conditions in the years under study. Agricultural techniques in the experiments corresponded to the technology of growing winter wheat in the South of Ukraine, the requirements for research methods and guidelines for potatoes cultivation; mathematical processing of experimental data was conducted according to generally accepted methods [13-15].

RESULTS AND DISCUSSION

According to the long-term studies of the characteristics of water consumption of irrigated winter wheat under different weather conditions, the following results were obtained (Table 1).

***Table 1**. Total water consumption by winter wheat during the spring-summer vegetation period depending on weather conditions, m³/ha*

Years by weather conditions and their number	Soil layers			
	0-50	0-100	0-150	0-200
Wet (12 years)	3.543	3.847	3.941	3.993
Average (4 years)	3.764	4.088	4.178	4.263
Dry (6 years)	2.916	3.445	3.567	3.685
On average for 22 years	3.396	3.782	3.882	3.958
LSD_{05}, m³/ ha	150	167	168	188

The highest values of total water consumption were observed under the average weather conditions and amounted to 4,263 m³/ha in a 2-metre soil layer in wet years characterised by moderate temperatures, high humidity, and a considerable number of days with rainfall. The average water consumption from this soil layer was 3,993 m³/ha. In dry years which were characterised by hot weather, low humidity, and low rainfall, the total water consumption was the lowest and amounted to 3685 m³/ha. These data were obtained from the option in which vegetative waterings were prescribed at the optimum humidity for average loamy dark chestnut soil – 70% LMC.

Admittedly, different years with varying weather conditions (12, 4, and 6) may cause some errors in determining the total water consumption but it can not affect the results. The reason for the decrease in the total water consumption of winter wheat in dry years with optimal irrigation is a considerable shortening in the duration of spring-summer vegetation period.

It was noted that the period of spring and summer vegetation and winter wheat ripening was shortened by 8-14 days, compared to the average. The shortening of the growing season occurred in late June-early July during which there are high air temperatures and low humidity, which is the main reason for the decrease in total water consumption by irrigated winter wheat. These experimental data allow analysing the processes of moisture consumption from different soil layers in years that differ substantially in weather conditions. In all years, the main process of moisture consumption takes place in the 1st metre of the soil layer. Moisture from the 2nd metre is used more intensively (240 m³/ha) in dry years.

Upon analysing the results of the long-term study on winter wheat irrigation in different regions of the Ukrainian steppe, it can be concluded that the total water consumption is influenced by moisture provision, mineral nutrition, certain agronomic techniques, and weather conditions. Therewith, attention is focused on the proportional dependence of the wheat total water consumption on the irrigation regime, which is one of the strongest regulatory factors in providing plants with moisture.

There are two major periods in winter wheat development and moisture consumption: the first one is from sprouting to vegetation stoppage in connection with the onset of winter; the second one is from the spring vegetation renewal to the grain ripening. The study established that the total evaporation of winter wheat, depending on the soil layer, is: 533-608 m³ per hectare in the period from sprouting to vegetation stoppage, 566-874 from vegetation stoppage to spring revival, 3,605-4,111 m³ per hectare from spring revival to full ripeness (Table 2).

***Table 2**. Water consumption by the winter wheat in the interphase growing periods with optimal irrigation, m³/ha (average for 12 years)*

Soil layer, cm	Period				LSD_{05}
	Sprouting-vegetation stoppage	Vegetation stoppage-spring revival	Spring revival-grain ripeness	Total moisture consumption	
0-50	608	874	3.605	5.087	122
0-100	561	779	3.931	5.271	121
0-150	533	672	4.046	5.251	125
0-200	554	566	4.111	5.231	116

Accordingly, the following pattern is observed: in the autumn and winter periods the highest water consumption takes place in the soil layers of 0-50 centimetres. This is conditioned by the fact that during these periods part of the water from the upper layers replenishes its reserves in the deeper layers.

The average amount of precipitation by periods during the studied years: sprouting-vegetation stoppage – 674 m³/ha, vegetation stoppage-spring revival – 988 m³/ha, spring revival-full grain ripeness – 1,852 m³/ha, that is, from sprouting to full grain ripeness – mm 3,524 m³/ha (Table 3).

***Table 3**. Water consumption by the winter wheat in the interphase growing periods with optimal irrigation, m³/ha (average for 2009-2020)*

Soil layer, cm	Interphase period and values							
	Sprouting-vegetation stoppage		Vegetation stoppage-spring revival		Spring revival-full grain ripeness		Total for vegetation period	
	Rainfall	Evaporation	Rainfall	Evaporation	Rainfall	Evaporation	Rainfall	Evaporation
0-50	674	608	998	874	1.852	3.605	3.524	5.087
50-100		-47		-95		326		184
100-150		-28		-107		115		-20
150-200		21		-106		65		-20

Analysis of data on moisture consumption from different soil layers shows that in the autumn vegetation period and during plant wintering water reserves in deep layers are replenished. The above can be observed from the total water consumption values which decrease from the soil layer of 0-50 cm to the layer of 0-200 cm. During the spring-summer vegetation, on the contrary, the total water consumption values in these layers increase. Such data indicate that in spring and summer the plants use water mainly from the soil layer of one metre. Therefore, all calculations concerning the total plant evaporation should be made considering the values relating to the soil layer of 0-100 cm.

A comparison of the total water consumption by a winter wheat field and the amount of precipitation during the period from sprouting to full grain ripeness allows establishing the moisture deficit, which must be compensated by irrigation. According to data on moisture consumption from a metre layer of soil, it is 1,747 m³/ha. On average over the years under study, the irrigation rate was 1,380 m³/ha.

The materials given in the table allow determining the specific weight of moisture consumed in the given periods. They show that during the wintering period the winter wheat field lost about 566 m³/ha of water (according to the values from the soil layer of 0-200 cm), and the amount of precipitation during the same period averaged 998 m³/ha over 12 years. Thus, during the winter period, the winter wheat field accumulates about 430 m³/ha of soil moisture. During the period of spring and summer growth, the disparity between water consumption (used mainly for the development of the crop) and the amount of precipitation is considerable and amounts, on average, to 1,753-2,259 m³/ha, and in most years the shortage of available moisture should be eliminated by vegetative watering.

In general, during the winter wheat vegetation period (considering the winter period), the irrigated field of this crop consumes an average of about 5.2 thousand m³ of water over 12 years, which necessitates a careful approach to irrigation in the Southern Steppe.

A similar analysis is made for the 22-year period (1999-2020). The data obtained show that during the period from sprouting to spring vegetation revival, the field of winter wheat consumes, on average, 1,175 m³/ha of water from the 2-metre soil layer, and the total water consumption during the spring-summer vegetation period is 3,734 m³/ha. Thus, on the average, a field of winter wheat in the south of Ukraine at the optimal irrigation regime requires about 4,900 m³/ha of water for a high yield (6.0-6.5 t/ha and more), a great part of it is supplied by moisture-storing and vegetative watering.

Monitoring of the average daily evaporation of winter wheat plants at natural and artificial watering shows that it has the form of a parabola, its maximum value coincides with the interphase period of earing – the beginning of milky ripeness and averages 59.3 m³/ha over 12 years under the optimal irrigation regime and 35.2 m³/ha without irrigation (Table 4).

***Table 4**. Average daily evaporation of irrigated winter wheat during the spring-summer growing season, m³/ha (average for 12 years)*

Interphase period	Average daily evaporation	
	No watering	Optimal irrigation regime
Spring growth renewal – stem elongation	20.3	23.5
Stem elongation – earing	30.9	42.4
Earing – grain milky ripeness start	35.2	59.3
Grain milky ripeness start – grain full ripeness	13.1	30.5

Immediately after plant revival and before the phase of stem elongation and from milky and to full ripeness, the average daily evaporation is minor and averages 23.5-30.5 m³/ha under irrigation conditions and 20.3-13.1 m³/ha with no irrigation, respectively. Based on long-term observations of the dynamics of moisture consumption by winter wheat plants from a metre-long soil layer under the optimal irrigation regime, the total and average daily evaporation of winter wheat over the decades of spring-summer vegetation was calculated. These data were systematised in accordance with different weather conditions and specific evaporation rates were determined (Table 5).

Table 5. *Total (E) and average daily (Ē) evaporation of winter wheat under different weather conditions, m³/ha*

Month	10-day period	Wet (6 years of monitoring)		Average (5 years of monitoring)		Wet (4 years of monitoring)	
		E	Ē	E	Ē	E	Ē
March	2	–	–	180	18.0	200	20.0
	3	227	20.6	239	21.7	263	23.9
April	1	230	23.0	214	21.4	315	31.5
	2	312	31.2	276	27.6	276	27.6
	3	370	37.0	328	32.8	351	35.1
May	1	363	36.3	340	34.0	445	44.5
	2	365	36.5	352	35.2	51.2	51.2
	3	484	44.0	549	49.9	495	45.0
June	1	510	51.0	560	56.0	420	42.0
	2	390	39.0	344	34.4	322	32.2
	3	335	33.5	236	23.6	335	33.5
July	1	276	27.6	241	24.1	327	32.7
	2	316	31.6	257	25.7	–	–

These data allow tracing the dynamics of moisture absorption by winter wheat under optimal moisture conditions during the spring-summer growing season, considering weather differences. The data show that in dry years the maximum water consumption by winter wheat plants is observed in the second ten-day period of May, and in wet and medium years it shifts to the first ten-day period of June. In addition, these data help to establish the beginning and the end of the winter wheat growing season, depending on the weather conditions of the spring and summer vegetation period. Most importantly, these data can be used for setting the timing and rates of vegetative irrigation.

One of the urgent problems of irrigated farming is that groundwaters can lie on different levels, sometimes exceeding 3 m. They have a considerable impact not only on soil-forming processes but also affect plant water regimes. In this regard, a series of field experiments to establish the average daily evaporation of crops in areas with close levels of low-mineralised groundwater were conducted (Fig. 1).

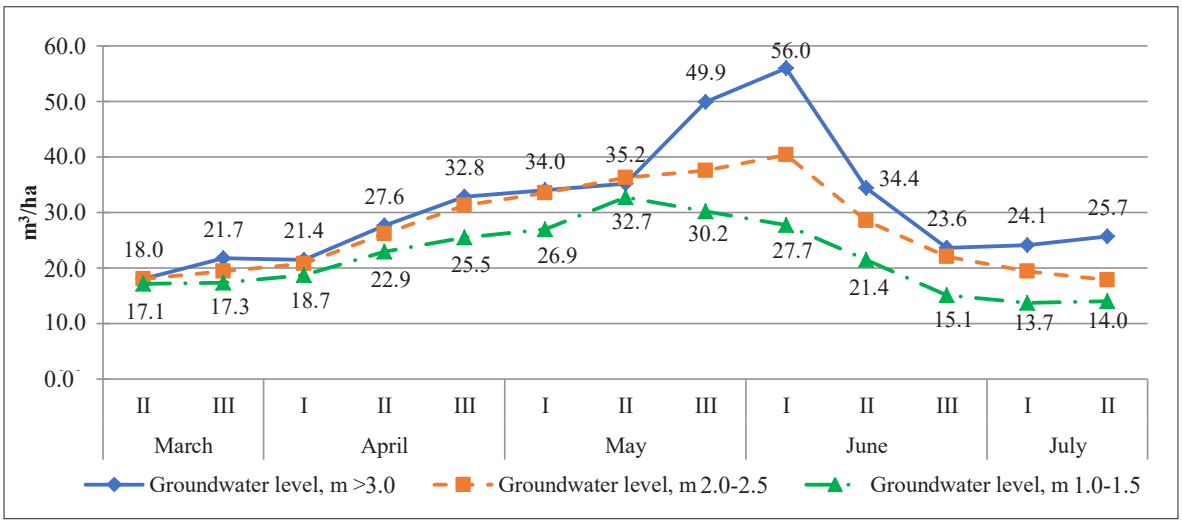

Figure 1. *Average daily evaporation of winter wheat depending on the groundwater level, m³/ha*

It has been established that the average daily values of crop evaporation at a groundwater level of more than 3 m and not more than 2 m are almost the same from the second decade of March to the second decade of May and range from 18.0 to 36.3 m^3/ha. From the 3rd ten-day period of May to the 2nd ten-day period of June, the average daily evaporation of winter wheat at a level deeper than 3 metres increases considerably compared to other levels and reaches its maximum (49.9-56.0 m^3/ha), in the 3rd ten-day period of May – 1st ten-day period of June at the level of 2-2.5 m, the average daily evaporation of plants does not exceed 37.5-40.4 m^3/ha. The average daily evaporation of plants at groundwater levels not deeper than 1.5-1 m is completely different. Due to the use of moisture directly from the water level, it decreases substantially and reaches its maximum in the 2nd ten-day period of May – 32.7 m^3/ha, which is almost 2 times lower compared to the groundwater occurrence deeper than 3 m.

The results obtained correlate with the materials obtained by researchers in different natural and climatic zones; thus, according to research at the Kansas Research Station (USA), over 3 years of observations, the average daily evaporation of winter wheat was: autumn (after sowing, October) – 17.5 m^3/ha, winter (November – February) – 7.5 m^3/ha, to tillering (March – April) – 22.4, from tillering to tubing (May 1-15) – 40.0, from tubing to flowering (May 15-28) – 62.2, from flowering to milky ripeness (May 28 – June 6) – 87.0, from milky to waxy ripeness (June 6-13) – 75.0 and from wax to full maturity (June 13-28) – 37.4 m^3/ha [16].

Similar results were obtained at the Volga Research Institute of Irrigated Agriculture. According to studies under the optimal irrigation regime (water-charging irrigation and vegetation at a soil moisture content of 80% HB), the total and average daily evaporation for the interphase periods was: seedlings – the beginning of steady cooling – 606 and 16.9 m^3/ha, the beginning of spring regrowth tubing – 620 and 21 m^3/ha, tubing – earing – 1063 and 52.9 m^3/ha, earing – milky ripeness of grain – 1605 and 65.2 m^3/ha, dairy – full ripeness of grain – 798 and 35.9 m^3/ha, respectively [17].

On average, for 5 years under study at the Rostov Regional Research and Reclamation Station, the total and average daily evaporation during the growing season was: sowing – the beginning of tillering – 390 and 17.0 m^3/ha, autumn tillering – 560 and 20.0 m^3/ha, spring tillering – 805 and 35.0 m^3/ha, tube output – 1350 and 45.0 m^3/ha, earing – grain development 585 and 45.0 m^3/ha, milky ripeness – 760 and 40.0 m^3/ha, wax ripeness – 350 and 23.0 m^3/ha [18].

CONCLUSIONS

In general, the field of winter wheat during irrigation consumes an average of about 5.2 thousand m^3 of water for vegetation, considering the winter period. Analysis of data on the use of moisture from different soil layers indicates that during the autumn growing season and during the wintering of plants water reserves in the deep layers are replenished. During the spring and summer vegetation, on the contrary, the total water consumption in these layers increases. Such data indicate that in spring and summer the plants use water mainly from a metre layer of soil. Therefore, in all calculations, it is better to consider the indicators in the soil layer of 0-100 cm for the total evaporation of plants.

A comparison of the total water consumption of the winter wheat field and the amount of precipitation for the period from germination to full ripeness of the grain indicates the moisture deficit, which must be compensated by vegetative irrigation. According to data on moisture consumption from a metre layer of soil, it is 1,747 m^3/ha. On average over the years under study, the irrigation rate was 1,380 m^3/ha.

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Сумарне водоспоживання та випаровування озимої пшениці в зоні зрошення півдня України

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Анотація. Найважливішим елементом при формуванні режиму зрошення сільськогосподарських культур є сумарне водоспоживання або/та кількість води, яка необхідна рослинам протягом вегетаційного періоду для отримання запланованого врожаю в конкретних природних умовах при оптимізації всіх технологічних процесів. Метою досліджень є визначення особливостей сумарного водоспоживання та середньодобового випаровування рослин пшениці озимої залежно від природньої вологозабезпеченості років вирощування, режимів зрошення та рівня ґрунтових вод у зоні зрошення півдня України. У ході дослідження використовувалися загальноприйняті методи: системного підходу та системного аналізу, монографічний, аналізу і синтезу, абстрактно-логічний, історичний, методи польових досліджень, статистичні та економіко-математичні методи тощо. Найвищі показники сумарного водоспоживання спостерігалися у середні за погодними умовами роки і становили у 2-метровому шарі ґрунту 4263 м^3/га, у вологі роки, які характеризувалися помірними температурами, високою вологістю повітря і значною кількістю днів з опадами, середній показник водоспоживання з цього шару ґрунту дорівнював 3993 м^3/га. У посушливі роки, які відрізнялися спекотливою погодою з низькою вологістю повітря і невеликою кількістю опадів, сумарне водоспоживання було найменшим і склало 3685 м^3/га. Скорочення вегетаційного періоду відбувається наприкінці червня – на початку липня, коли спостерігаються високі температури повітря і низька його вологість, що і є основною причиною зменшення показників сумарного водоспоживання зрошуваної пшениці озимої. Аналіз даних використання вологи з різних шарів ґрунту свідчить про те, що в осінній період вегетації, а також під час зимівлі рослин, проходить поповнення запасів води у глибоких шарах. Загалом за вегетацію пшениці озимої, враховуючи і зимовий період, поле цієї культури при зрошенні витрачає в середньому за 12 років близько 5,2 тисяч кубічних метрів води. Спостереження за показниками середньодобового випаровування рослин пшениці озимої в умовах природного та штучного зволоження свідчить про те, що воно має форму параболи, максимальна позначка якої припадає на міжфазний період колосіння – початок молочної стиглості зерна

Ключові слова: поливна вода, середньодобове випаровування, рівень підґрунтових вод, режим зрошення