Modeling and Management of Rice Water Consumption in the Danube Delta

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Abstract **– The article investigates the total water consumption of rice in the Danube Delta over six growing seasons. The study established that the average water use amounts to 9,273 m³/ha, of which more than 50% is attributed to transpiration. A comparative analysis of the Alpatyev, Blaney–Criddle, and Hargreaves methods was carried out. The Alpatyev method proved to be the most accurate (error ±1.6%), while the Blaney–Criddle method is suitable for integral assessments, and the Hargreaves method is applicable only for preliminary calculations. The obtained results can be used to optimize irrigation regimes in rice systems of southern Ukraine.**

Keywords – rice; total water consumption; evapotranspiration; water consumption coefficient; Alpatyev method; Blaney–Criddle method; Hargreaves method; Danube Delta.

I. INTRODUCTION

Rice is one of the world's leading food crops, providing nourishment for nearly half of the global population. In 1961, rice was cultivated on 115 million hectares worldwide. By 2020, the cultivation area had increased to 161 million hectares (over 40% growth) [1]. However, despite its global significance, rice is also the single largest consumer of freshwater resources. More than 75% of rice is grown under flooded conditions.

In Ukraine, rice cultivation, particularly in the southern regions and the Danube Delta, plays an important role in ensuring food security. At the same time, this sector is critically dependent on irrigation and is characterized by an exceptionally high level of water use. The efficiency of water resources management is a key prerequisite for the sustainable functioning of rice agroecosystems [2]. This issue becomes especially relevant in the context of climate change and the growing scarcity of freshwater [3; 4].

Given the substantial water requirements and limited availability of resources, it is necessary to achieve water savings at all stages of rice irrigation systems. Previous research has shown significant potential for reducing water and energy consumption in rice cultivation, as well as for improving production efficiency. For this purpose, determining water consumption norms, which include both evaporation from the soil or water surface and plant transpiration, is essential. Accurate determination of these values, and thus of total water consumption, forms the basis for establishing optimal irrigation regimes, setting water supply norms, and developing water management measures.

In scientific practice, a wide range of methods are applied to estimate evapotranspiration – from simple empirical formulas (Blaney–Criddle, Hargreaves) [5; 6], which require only minimal meteorological data, to complex equations (Penman–Monteith), which account for both energy and aerodynamic balance and are recognized as the international standard [7–9]. In addition, bioclimatic approaches are used, such as the Alpatyev method, which is based on air humidity deficit and water consumption coefficients [10]. However, the effectiveness of these methods strongly depends on regional conditions and requires further investigation.

II. STATEMENT OF THE PROBLEM

The current development of rice cultivation in Ukraine is taking place under conditions of freshwater scarcity, climate variability, and increasing environmental challenges. The Danube Delta is characterized by complex hydrogeological and hydrological conditions: shallow groundwater levels, dependence on the river's flood regime, seasonal unevenness of moisture supply, and high sensitivity to fluctuations in air temperature and humidity [3; 4].

Under such circumstances, the accurate determination of total rice water consumption becomes critically important, as it directly affects the efficiency of irrigation systems and the rational use of regional water resources [3; 4].

The aim of this study is to analyze existing approaches to determining rice water consumption norms, taking into account freshwater shortages and climate change. Thus, the urgent task is to select the most reliable and, at the same time, practically applicable method for estimating total rice water consumption under the conditions of the Danube Delta. Solving this problem will improve agricultural production efficiency, reduce environmental pressure, and ensure the stability of rice reclamation systems even under crisis conditions.

III. Solution of the Problem

The research was conducted in the central part of the Danube Delta over six growing seasons. During the experiments, the values of total rice water consumption, its components (evaporation and transpiration), as well as water consumption coefficients were determined.

The total water consumption of rice was determined using evaporimeter vessels according to the method of V.B. Zaitsev and in accordance with modern methodological recommendations [11-13]. It is equal to the value of the irrigation norm for rice and is calculated on the basis of the water balance using the formula of V.B. Zaitsev [12]:

$$M_n=(E_o+T_o-P-K)+(W+F_v+F_o)+(S_r+S_u+S_o)$$

$$M_n = (E_o + T_o - P - K) + (W + F_v + F_o) + (S_r + S_u + S_o) \quad , \qquad (1)$$

where: M_n – irrigation norm for rice, mm; E_o – evaporation from the water surface of the rice field, mm; T_o – transpiration, mm; P – precipitation, mm; K – rainfall utilization coefficient accounting for condensation (dimensionless); W – soil saturation, mm; F_v – vertical filtration, mm; F_o – horizontal runoff (lateral filtration), mm; S_r – water exchange (circulation) according to the irrigation regime, mm; S_u – unplanned water discharges, mm; S_o – water discharge at the end of the rice growing season, mm.

To compare the experimental data, the effectiveness of theoretical methods for determining total water consumption – Alpatyev, Blaney–Criddle, and Hargreaves – was evaluated in order to establish the most reliable and practically applicable approach for the conditions of the Danube Delta.

The study established that the average total rice water consumption is 9,273 m³/ha per growing season, ranging from 8,994 to 9,468 m³/ha. The values of transpiration and evaporation were determined for different growth stages. At the initial stage (emergence–tillering), evaporation prevailed in the water balance structure (120–140 mm). Later, with an increase in leaf surface area, transpiration intensified, and in the stem elongation–panicle initiation phase it exceeded evaporation by 43–48%. Overall, the share of transpiration in total water consumption ranged from 50.6% to 56.6%, whereas evaporation dominated during the early growth stages.

The water consumption coefficient, which characterizes the irrigation water expenditure per unit of yield, ranged from 188 to 216 m³/100 kg, averaging 200.6 m³/100 kg.

The analysis of experimental results revealed a strong correlation between water consumption and regional climatic parameters. In particular, a high correlation was found between total water consumption and air humidity deficit (r = 0.85), as well as between total water consumption and radiation balance (r = 0.96). These relationships allow for more accurate determination of irrigation norms, hydromodules, and water supply requirements in designed systems, as well as improvements in planned water use on existing systems in the southern Danube region.

The analysis of theoretical methods for determining rice water consumption in the Danube Delta showed the following:

- The Blaney–Criddle method is based on mean monthly air temperature and relative day length; however, it does not always adequately reflect regional conditions [5];

- The Hargreaves method relies on temperature amplitude and radiation balance and is mainly applied for preliminary calculations or in the absence of meteorological data. Although widely used internationally, it yields significant errors under Danube Delta conditions, as it does not account for air humidity deficit and flooding specifics [6];

- The Alpatyev method, based on a bioclimatic approach, accounts for air humidity deficit and the agrobiological characteristics of rice, making it better adapted to the conditions of the Danube Delta [10];

- The Penman–Monteith method, regarded as the international standard for determining reference evapotranspiration, could not be applied due to the absence of necessary meteorological data [7–9]. Its application requires a complete dataset, including wind speed at 2 m height, daily solar radiation, saturation deficit, and psychrometric parameters. On the experimental plots of the Danube Delta, such information was not systematically collected, which made the use of this method impossible.

A comparative analysis of the methods revealed substantial differences in their accuracy and practical applicability (Fig. 1).

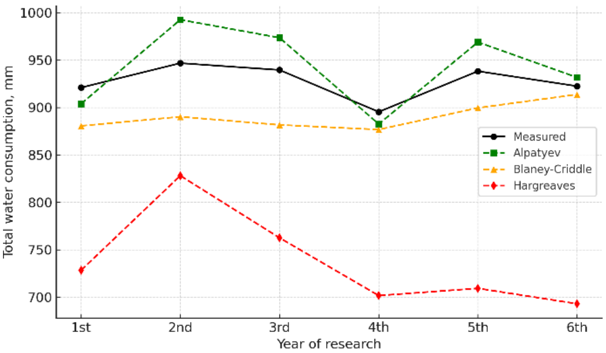

Figure 1. Comparison of measured and calculated values of total rice water consumption in the Danube Delta (six growing seasons)

The Alpatyev method proved to be the most reliable, providing the smallest deviation from actual data (±1.6%) and adequately accounting for both the regional climatic conditions and the biological characteristics of the crop. The Blaney–Criddle formula demonstrated satisfactory accuracy only at the level of integral estimates for the entire growing season (average deviation about 4%), whereas the Hargreaves method showed the largest errors (approximately 20%), which limits its application to preliminary calculations only.

Thus, under production conditions in the Danube Delta, the Alpatyev method is the most appropriate for use. The empirical formulas of Blaney–Criddle and Hargreaves may serve as auxiliary tools, while the heat balance method should be applied as a control reference.

IV. CONCLUSION

1. The average total rice water consumption in the Danube Delta amounts to 9,273 m³/ha, of which more than half is attributed to transpiration.

2. A strong correlation was established between water consumption and air humidity deficit ($r = 0.85$) as well as radiation balance ($r = 0.96$), which allows for more accurate determination of irrigation norms.

3. The most reliable method was found to be the Alpatyev method (error ±1.6%), while the Blaney–Criddle formula is suitable for integral assessments (≈4%), and the Hargreaves method shows significant errors (up to 20%).

4. For the conditions of the Danube Delta, it is recommended to use the Alpatyev method as the main approach, while the Blaney–Criddle and Hargreaves methods may serve as auxiliary tools.

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