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Optimization of Sprinkling Parameters for Improved Irrigation Quality

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Abstract—**Under conditions of water scarcity and climate change, it is crucial to align irrigation intensity with the soil's infiltration capacity. This study presents analytical modeling of the optimal sprinkling parameters (intensity and duration) taking into account the hydro-physical properties of soils, namely porosity and moisture content. Analytical equations were derived to determine the optimal irrigation duration that ensures efficient water use and prevents surface runoff formation. An example of calculations is provided for medium loamy soils under different sprinkling intensities.**

Keywords—irrigation; sprinkling; rainfall intensity; soil infiltration capacity; surface runoff; irrigation optimization.

I. INTRODUCTION

The rational use of water resources in irrigated agriculture is a key prerequisite for the sustainable development of Ukraine's agricultural sector. In the context of increasing water deficit, climate change, and soil degradation, optimizing irrigation parameters has become particularly relevant, especially considering the hydro-physical properties of soils and the hydrological conditions of the area.

Among the most widespread irrigation methods, sprinkling ensures uniform moisture distribution, the possibility of automation, and applicability to different soil types. The efficiency of this method largely depends on the structure of artificial rainfall—its intensity, droplet size, fall height, and wetting uniformity. Ignoring these parameters leads to surface runoff, soil structure destruction, decreased infiltration capacity, and irrigation-induced erosion [1, 2].

During sprinkling, water is delivered in the form of artificial rain that gradually transforms into soil moisture. The irrigation duration is determined by the irrigation application (or irrigation norm), which must restore the moisture level within the active soil layer. The sprinkler design, working pressure, and nozzle height determine the degree of jet atomization, and consequently, the average rainfall intensity.

Sprinkling intensity is a critical parameter directly influencing the rate of moisture delivery to the soil. Therefore, the quality of sprinkling depends on matching all characteristics of the artificial rainfall with the soil's hydro-physical properties—primarily its infiltration capacity.

Recent studies [3, 4] have demonstrated that both water application intensity and the kinetic energy of droplets significantly affect infiltration and erosion processes. When the critical energy flux threshold is exceeded, the soil structure becomes degraded, and water permeability decreases.

The main condition for efficient and environmentally safe sprinkling is ensuring that the artificial rainfall intensity corresponds to the soil's infiltration rate. To preserve soil structure, the recommended intensity values are 0.1–0.2 mm/min for heavy soils, 0.2–0.3 mm/min for medium soils, and 0.5–0.7 mm/min for light soils [5].

These recommendations are consistent with environmental safety standards, according to which irrigation with sprinkling machines exceeding an intensity of 0.3 mm/min is considered unacceptable [6]. However, the actual intensity of modern sprinkling machines used in southern regions often exceeds these values severalfold—for instance, the "Bauer Quadrostar" machine produces rainfall intensity up to 2.6 mm/min [1].

This significant discrepancy between technical capabilities and ecological requirements highlights the necessity of optimizing irrigation parameters and harmonizing them with the hydro-physical properties of soils.

The aim of this study is to develop an analytical model to determine the optimal sprinkling parameters that align with soil physical properties and ensure efficient water use without surface runoff formation.

II. Statement of the Problem

The research focuses on establishing relationships between sprinkling parameters and soil infiltration capacity. The main hypothesis is that for each soil type, there exists a range of irrigation intensities where the water application rate equals the infiltration rate.

The artificial rainfall intensity (ρ) was determined by

$$\rho = 60 \cdot Q/f, \text{ mm/min}, \quad (1)$$

where: Q – the water discharge, L/s; f – the effective irrigated area, m².

The maximum non-runoff irrigation application (m_{max}) was defined as

$$m_{max} = \rho \cdot t_p, \text{ mm}, \quad (2)$$

where: t_p – the irrigation duration until the appearance of puddles, min.

The infiltration rate (K) is described by [7]

$$K = K_1/t^{\alpha}, \text{ mm/min}, \quad (3)$$

where: K_1 – the infiltration rate one hour after irrigation begins; α – the attenuation exponent of the soil's infiltration capacity.

The infiltrated water layer (W) after irrigation time t is determined by

$$W = K_1 \cdot t^{1-\alpha}/(1-\alpha), \text{ mm}. \quad (4)$$

In simplified form, the average infiltration rate for the first unit of time is

$$K_0 = K_1/t^{1-\alpha}, \text{ mm/min}, \quad (5)$$

and the infiltrated water layer is

$$W = K_0 \cdot t^{1-\alpha}, \text{ mm}. \quad (6)$$

For equilibrium between water application and infiltration, the following criterion applies

$$\rho \cdot t = K_0 \cdot t^{1-\alpha}, \quad (7)$$

from which the optimal irrigation duration is derived

$$t_{opt} = (K_0/\rho)^{1/\alpha}, \text{ min}. \quad (8)$$

The parameters K_1 and α must be determined experimentally. For loamy soils of the Krasnoznamyanka irrigation system, the indices K_1 and α were found to depend on soil porosity, expressed as

$$K_1 = 8.2 - 0.12 \cdot A, \text{ mm/min}, \quad (9)$$

where: A – the soil porosity, %.

The attenuation exponent α depends on the soil moisture content, varying from 0.8 near the wilting point to 0.3 at the field capacity. This relationship can be approximated as:

$$\alpha = 0.3 + 0.5 \cdot (\beta_{ex} - \beta_{wp})/(\beta_{fc} - \beta_{wp}) \quad (10)$$

where: β_{ex}, β_{wp}, β_{fc} – the initial moisture, wilting point, and field capacity, %, respectively.

The derived equations make it possible to incorporate soil physical properties into modeling irrigation intensity and duration, ensuring closer alignment between water application and its infiltration capacity. Figure 1 shows a graph for determining the maximum non-runoff irrigation application as a function of soil infiltration capacity.

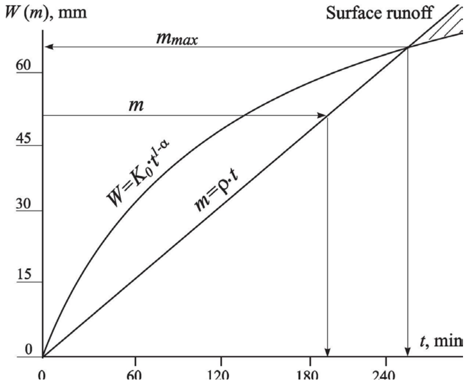

Figure 1. Graph for determining the maximum non-runoff irrigation application as a function of soil infiltration capacity

III. Solution of the Problem

Based on the proposed model, graphical dependencies between the applied water layer ($m=\rho \cdot t$) and the infiltrated moisture layer ($W=K_0 \cdot t^{1-\alpha}$) were constructed.

Calculations were performed for medium loam with parameters K_1=2.8 mm/min and α=0.5 for three artificial rainfall intensities: ρ=0.1, 0.2 and 0.3 mm/min (Fig. 2).

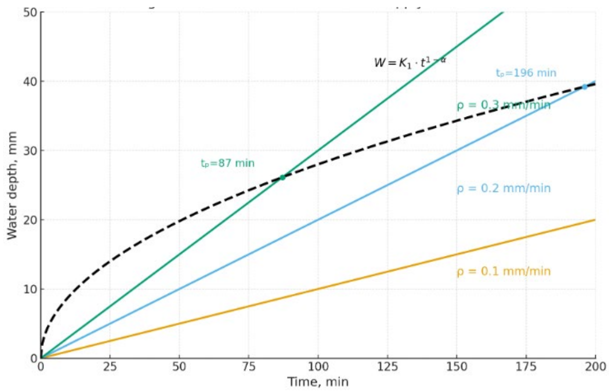

Figure 2. Relationship between the applied water layer and infiltrated moisture for medium loam (K_1 = 2.8 mm/min; α = 0.5)

The graph shows that as rainfall intensity increases, the time until surface runoff appears decreases, and the maximum irrigation application decreases accordingly.

The following surface runoff onset moments were obtained:

for ρ=0.1 mm/min – t_k=784 min, m_{max} = 78.4 mm;

for ρ=0.2 mm/min – t_k=196 min, m_{max} = 39.2 mm;

for ρ=0.3 mm/min – t_k=87 min, m_{max} = 26.1 mm.

These dependencies demonstrate that as rainfall intensity increases, the equilibrium between application and infiltration is reached faster—approximately inversely proportional to the square of intensity.

The obtained results can be used for selecting sprinkler machine parameters, configuring automatic irrigation systems, and developing environmentally safe water use regulations.

IV. Conclusion

1. An analytical model was developed to match artificial rainfall intensity with soil infiltration capacity, allowing determination of optimal irrigation duration and application considering soil hydro-physical properties.

2. It was established that optimal irrigation duration is governed by the relationship between water application intensity and soil parameters. Increasing rain intensity shortens irrigation duration but decreases infiltration efficiency.

3. For medium loamy soils, the following results were obtained:

at 0.3 mm/min: t = 87 min, m_{max} = 26.1 mm;

at 0.2 mm/min: t = 196 min, m_{max} = 39.2 mm;

at 0.1 mm/min: surface runoff was not observed at standard irrigation application/norms.

4. The proposed approach can be applied to: selecting operational modes of sprinkling machines; calculating parameters for automated irrigation systems with adaptive control; improving standards for environmentally safe water use.

5. The obtained results form the basis for further development of optimization systems for sprinkling regimes that account for climatic factors, soil type, and root-zone moisture content.

References

[1] L. M. Bulaienko, Features of Sprinkling Use in the South of Ukraine. Kherson: Zroshuvane Zemlerobstvo. Collection of Scientific Works, vol. 61, pp. 88–90, 2014. [in Ukrainian: Л. М. Булаєнко, «Особливості використання дощування в умовах Півдня України» Зрошуване землеробство. Збірник наукових праць, Вип. 61, с. 88–90, 2014.] Available: http://izpr.ks.ua/archive/2014/61/32.pdf

[2] S. M. Kozishkurt and M. Ye. Kozishkurt, Advantages, Disadvantages and Ways to Improve Irrigation Efficiency. Rivne: Visnyk UDUVHP, vol. 1, no. 25, pp. 51–61, 2004. [in Ukrainian: С. М. Козішкурт, М. Є. Козішкурт, «Переваги, недоліки та шляхи підвищення ефективності дощування земель» Вісник УДУВГП, т. 1, № 25, с. 51–61, 2004.]

[3] L. Chen, Y. Wang, Z. Huang, and T. Liu, "Influence of raindrop impact angle on soil crust formation," Agricultural Water Management, vol. 290, art. 108514, 2023.

[4] X. Zhang, R. Li, and H. Yang, "Critical factors affecting soil runoff and erosion under sprinkler irrigation," Agricultural Water Management, vol. 287, art. 108299, 2023.

[5] Lower Dnipro Basin Water Resources Management, Basseinove upravlinnia vodnykh resursiv nyzhnoho Dnipra. [in Ukrainian: Басейнове управління водних ресурсів нижнього Дніпра.] Available: https://buvrnd.gov.ua/materialy-624.htm?ps=3

[6] Cabinet of Ministers of Ukraine, On Environmental Safety Standards for Irrigation and Drainage. Resolution No. 766, September 2, 2020. [in Ukrainian: Кабінет Міністрів України, «Про затвердження екологічних нормативів зрошення та осушення» Постанова № 766, 2 вересня 2020 р.]

[7] A. N. Kostyakov, Fundamentals of Melioration. Moscow: Selkhozizdat, 1960, pp. 85–87. [in Russian: А. Н. Костяков, Основы мелиорации. М.: Сельхозиздат, 1960, с. 85–87.]