Justification of technological solutions for irrigation with electrified circular sprinkler machines

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Abstract. Improving the quality of irrigation can be achieved by changing the irrigation rate in accordance with the level of moisture reserves of the field areas at the time of watering, eliminating over-watering and water erosion of soils. The purpose of the presented research was to improve the technological process of irrigation with wide-reach circular sprinkler machines, which ensures the reduction of unproductive water losses, improving the quality of irrigation. The article discusses theoretical studies of irrigation technology with circular sprinkler machines, optimized irrigation modes. Based on the conducted experimental studies, a comparative assessment of the work of sprinklers according to the standard and proposed technology, taking into account the adjustment of irrigation norms, is presented. Comparison of standard and proposed irrigation technologies with sprinkler machines showed that irrigation using the proposed technology allows saving irrigation water up to 10%.

1 Introduction

The design, production and introduction into the economic turnover of the agro-industrial complex of irrigation equipment of a new generation with higher technical and operational indicators, extensive use of automation of control systems and information technologies, is the basis for the output of irrigated agriculture to the necessary volumes of domestic food production and its competitiveness.

Increasing the technical level of sprinklers requires increasing productivity, expanding the functions of automation and control systems, improving irrigation technologies that ensure rational use of water and energy, maximum adaptation of irrigation technologies to the region of application, preservation of the fertility of irrigated soils.

Improving the quality of irrigation can be achieved by changing the irrigation rate in accordance with the level of moisture reserves of field areas at the time of watering, adapting the irrigation regime to conditions changing during the irrigation period, eliminating over-watering and water erosion of soils.

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Based on the above, the scientific problem is to ensure low-intensity irrigation, corresponding to the level of moisture reserves of the field areas at the time of their watering while maintaining the required volume of irrigation norms.

The works of many scientists are devoted to the issues of high-quality irrigation. The works of Zhuravleva L.A., Gavrilitsa A.O., Larionova A.M., Olgarenko G.V. and others are devoted to the study of surface runoff during irrigation by sprinkling, technical and technological methods of increasing the erosion-permissible irrigation norm. Most studies are based on empirical data, private research [1-4].

Improving the efficiency of using sprinkler equipment, saving irrigation water and resources were considered by Fokin B.P., Ryazantsev A.I., Zhuravleva L.A. [5-6] and other scientists.

Numerous developments and studies carried out by VNPO "Raduga" on methods and calculation models for operational planning of water use during irrigation are interesting.

The improvement of existing technologies and the development of new techniques and methods for planning and organizing irrigation with wide-coverage sprinkler equipment, the development of technical solutions that save water resources, increase erosion-permissible irrigation standards, is of fundamental importance for the development of the agro-industrial complex.

The purpose of the research is improvement of technical means and technological processes of irrigation with wide-reach sprinkler machines of circular action, ensuring reduction of unproductive water losses, improving the quality of irrigation.

2 Objective

To conduct theoretical studies of irrigation technology with circular sprinkler machines, to optimize the irrigation regime.

To carry out a comparative assessment of irrigation by sprinklers under operating conditions according to the standard and proposed technology, taking into account the adjustment of irrigation norms.

3 Research materials and methods

Modern electrified sprinkler machines have a large range of regulation of irrigation norms, driving modes and the ability to issue a given irrigation rate in different ways and according to different irrigation schemes.

The average speed of the last trolley, depending on the cycle time and the coefficient of slipping, can be determined by the formula, m / s:

$$V_{CP} = 60 \Delta S_M \beta_T / t_C \quad (1)$$

ΔS_M – machine movement step; t_D – driving time of the car; β_T – the coefficient of slipping. The time of each cycle for the machines "Kuban-LK1", "Kuban-LK1M" and "CASCADE" t_C = 100s.

At the beginning of the growing season of agricultural crops, the initial moisture reserves are determined by the formula, m^3 / ha:

$$W_0 = 100 h \gamma_P \beta_H \quad (2)$$

h – calculated soil moisture layer, mm; γ_P – soil density in the calculated layer, kg/m^3; β_H – soil moisture equal to the lowest moisture capacity, % of the dry weight of the soil. The equation of the water balance of the active layer in relation to one irrigation is determined from the expression:

$$Et = (W_0 - W_K) + M + P_{OC} + V_P - P_0, \quad (3)$$

Et – total water consumption, equal to the intensity of water consumption for a certain period of time; W_K – moisture reserves after exposure to rain (final moisture reserves), mm; *M* – irrigation rate; P_{OC} – precipitation; V_P – groundwater recharge; и P_0 – runoff and filtration losses. To simplify the R_{OC}, V_P and P_0 can be neglected.

Moisture reserve of the core before the passage of the sprinkler machine:

$$W_K = W_O - Et \quad (4)$$

where *t* – the time from the beginning of watering (the starting point of the movement of the last cart along a circle equal to the radius of watering) to the approach to the end point of watering. The final watering point depends on the chosen traffic pattern. When watering for a circle, this is the turnaround time of the machine. When watering half of the circle with reverse – the time of passage of some part of the arc of the circle. The irrigation rate is calculated according to the formula, m^3/ha:

$$M=100h\gamma_P(\beta_{HB}- \beta_{0,8HB}) \quad (5)$$

β_{HB} – humidity corresponding to the lowest moisture capacity in the calculated soil layer; $\beta_{0,8HB}$ – humidity corresponding to the pre-watering threshold of 80% HB in the active soil layer.

Consider the operation of the machine with reverse, when there is no return of the machine to the starting point after passing a full circle. Ie, the machine returns to the point φ, moving in the opposite direction, reversely, Figure 1.

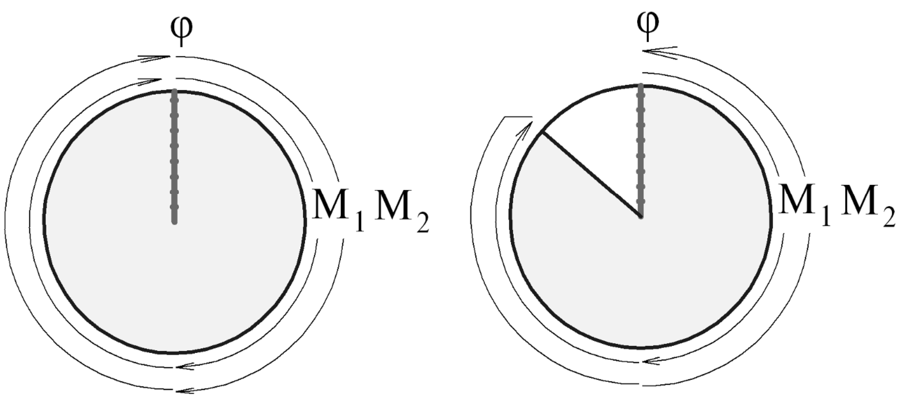

Fig. 1. Sprinkler machine Kuban-LK1M "Cascade".

In this case, watering with the same norm at the beginning of the return causes runoff and a simplified adjustment is required. We neglect fluctuations in water consumption (E, mm / day) during irrigation (t, day), and also assume the absence of precipitation during irrigation.

The condition for issuing a given irrigation rate for several passes, m^3 / ha:

$$M=M_1 (\varphi) + M_2 (\varphi) + M_3 (\varphi)...+ M_n (\varphi) \quad (6)$$

$M_1 (\varphi)$ – watering rate when the car is moving from a point φ=0 (first pass), m^3/ ha; $M_2 (\varphi)$ and $M_3 (\varphi)$ – irrigation rate for the second and third passes, m^3/ha; $M_n (\varphi)$– irrigation rate per n pass.

When driving in a straight course, day:

$$t = \frac{1}{1440K_C}\int_0^{\varphi} \frac{d\varphi}{V_{CP}(\varphi)} \quad (7)$$

where $V_{CP(\varphi)}$ – the speed of the machine, m/min; K_C – the time factor.

A layer of precipitation per pass in a circle:

$$h = \frac{120Q_M}{R_M V_{CP}} \quad (8)$$

where Q_M – machine consumption, l/s; R_M – irrigation radius equal to the length of the machine, m.

A circular sprinkler machine should ensure the issuance of irrigation norms M according to, m^3/ha:

$$M = \frac{1200Q_M}{R_M V_{CP}} \tag{9}$$

Then when passing not a full circle:

$$M_1' = 2\pi \frac{1200Q_M}{\ell_C V_{CP}} \tag{10}$$

where ℓ_C – length of the arc of the irrigation sector:

$$t = \xi \int_0^{\varphi} M_1(\varphi)\, d\varphi,\ \xi = \frac{s}{432 \cdot 10^3 K_C Q_M} \tag{11}$$

where s – the path traversed by the last cart. The maximum value of the path traveled by the trolley in one direction corresponds to the length of the arc of the circle of the trajectory of the trolley:

$$s_{MAX} = \ell = 2\pi R_M \tag{12}$$

The change in moisture reserves in the soil in front of the machine in a straight course when watering part of the circle can be represented as:

$$f_1(\varphi) = W_0 - 10E\xi \int_0^{\varphi} M_1'(\varphi) d\varphi \tag{13}$$

After the passage of the machine at time t, the moisture reserves will be determined:

$$W_1 = f_1(\varphi) + M_1'(\varphi) \tag{14}$$

If, when moving in the opposite direction in front of the machine, the moisture reserves in the soil are represented by the function $f_2(\varphi)$, then behind it they are determined from the expression:

$$W_2 = f_2(\varphi) + M_2'(\varphi) \tag{15}$$

The machine gets to the point φ repeatedly after a period of time Δt:

$$\Delta t = \xi \int_{\varphi}^{s} [M_1'(\varphi) + M_2'(\varphi)]\, d\varphi = \xi(s - \varphi)M \tag{16}$$

$$M_1'(\varphi) = 2\pi \frac{1200Q_M}{\ell_C V_{CP}(\varphi)} \left[1 - e^{10E\xi(\varphi - s)}\right] \tag{17}$$

$$M_2'(\varphi) = 2\pi \frac{1200Q_M}{\ell_C V_{CP}(\varphi)} e^{10E\xi(\varphi - s)} \tag{18}$$

Thus, by setting the path that the last cart passes, it is possible to determine the optimal value of the norm when watering in one direction and in the opposite direction. By dividing the irrigation circle into sectors, with a change of speeds, it is possible to express:

$$M_i' = 2\pi\psi \frac{1200Q_M}{\ell_C V_{CP}(\varphi)} \left[1 - \frac{1}{(1 + 10E\xi\ell_C)^{n+1-i}}\right] \tag{19}$$

where i – plot number from the beginning of the field, i=1,2…n; n – total number of partitioning sections; M_i – irrigation rate on the i site. Here $\ell_C = 2\pi R_M / n$.

The amount of precipitation, groundwater recharge, and runoff and filtration losses can be taken into account by a correction factor ψ.

We will adjust the mode of movement of the sprinkler machine from the initial section of the field to the final one, so that the irrigation rate changes by the amount of water consumption costs, taking into account the time of irrigation.

Let's say a machine with a length of L_M carries out watering with an initial irrigation rate of M, m^3 /ha. We will divide the field into four equal sectors, on each of which we will set the average values of time, watering rates and the speed of the machine. Watering time of the sector, h:

$$t_C = \frac{S_C M}{Q_M} = 0{,}5 \frac{\ell_C R_M M}{Q_M} \tag{20}$$

where t_C – watering time of the sector, h; S_C – irrigation area of the sector, ha.

When passing the first sector, the required amount of moisture W_1, m^3/ha:

$$W_1 = M + E_1 t_{C1} \tag{21}$$

where E_1 – average hourly water consumption in the first sector; t_{C1}– average watering time of the first sector, h.

Average speed of movement:

$$V_{\text{CP.C}} = \frac{\beta_{\text{T}}\ell_{\text{C}}}{60t_{\text{C}}} \tag{22}$$

Irrigation rate in the first sector:

$$M_1 = \frac{Q_{\text{M}}t_{\text{C1}}}{S_{\text{C}}} = \frac{2Q_{\text{M}}t_{\text{C1}}}{\ell_{\text{C}}R_{\text{M}}} \tag{23}$$

Watering time in the first sector:

$$t_{\text{C1}} = \frac{0{,}5\ell_{\text{C}}R_{\text{M}}M}{Q_{\text{M}} - 0{,}5\ell_{\text{C}}R_{\text{M}}\text{E}_1} \tag{24}$$

For the second sector:

$$W_2 = M + E_1t_{\text{C1}} + E_2t_{\text{C2}} \tag{25}$$

where E_2 – average hourly water consumption in the second sector, m^3/ha; t_{C2} – average watering time of the second sector, h.

$$M_2 = \frac{2Q_{\text{M}}t_{\text{C2}}}{\ell_{\text{C}}R_{\text{M}}} \tag{26}$$

Average watering time of the second sector:

$$t_{\text{C2}} = \frac{0{,}5\ell_{\text{C}}R_{\text{M}}(M + \text{E}_1t_{\text{C1}})}{Q_{\text{M}} - 0{,}5\ell_{\text{C}}R_{\text{M}}\text{E}_2} \tag{27}$$

For the third sector:

$$W_3 = M + E_1t_{\text{C1}} + E_2t_{\text{C2}} + E_3t_{\text{C3}}, \tag{28}$$

where E_3 – average hourly water consumption of the third sector, m^3/ha; t_{C3} – average watering time of the third sector, h.

At the same time, the irrigation rate:

$$M_3 = \frac{2Q_{\text{M}}t_{\text{C3}}}{\ell_{\text{C}}R_{\text{M}}} \tag{29}$$

Average watering time of the third sector:

$$t_{\text{C3}} = \frac{0{,}5\ell_{\text{C}}R_{\text{M}}(\text{M} + \text{E}_1t_{\text{C1}} + \text{E}_2t_{\text{C2}})}{Q_{\text{M}} - 0{,}5\ell_{\text{C}}R_{\text{M}}\text{E}_3} \tag{30}$$

Accordingly, for the fourth sector:

$$W_4 = M + E_1t_{\text{C1}} + E_2t_{\text{C2}} + E_3t_{\text{C3}} + E_4t_{\text{C4}} \tag{31}$$

where E_4 – average hourly water consumption of the fourth sector, m^3/ha; t_{C4} – average watering time of the fourth sector, h.

Irrigation rate:

$$M_4 = \frac{2Q_{\text{M}}t_{\text{C4}}}{\ell_{\text{C}}R_{\text{M}}} \tag{32}$$

Average watering time of the fourth sector:

$$t_{\text{C4}} = \frac{0{,}5\ell_{\text{C}}R_{\text{M}}(\text{M} + \text{E}_1t_{\text{C1}} + \text{E}_2t_{\text{C2}} + \text{E}_3t_{\text{C3}})}{Q_{\text{M}} - 0{,}5\ell_{\text{C}}R_{\text{M}}\text{E}_4} \tag{33}$$

The parameters of subsequent watering are determined in the same way.

Experimental studies were carried out on electrified circular sprinkler machines "Kuban-LK1", "Kuban-LK1M" (Cascade) and "CASCADE".

4 Results

Experimental studies were carried out on neighboring irrigation sites. The irrigation rate with standard irrigation technology was 400 m^3/ha. The irrigation season was divided into decades, during which precipitation, humidity and the issued irrigation norm were noted. Soil moisture (up to 0.8 m) practically does not differ from the soil moisture watered by standard technology.

The irrigation rate according to the standard technology was introduced for 4 irrigation of 400 m^3/ha. The irrigation norm for optimized supply in 2021 was 1,570 m^3/ha and 1,490 m3/ha, which is 30 and 110 m^3/ha less, respectively, Table 1.

Table 2 also shows the influence of the phase of plant development on the amount of runoff. With an increase in protective properties during the growth of the plant, the sufficient watering rate increases. The most gentle watering regime is required at the beginning of the irrigation period.

Table 1. Comparative data on irrigation rate according to standard technology and optimized water supply per 1ha machine.

Parameter	2021 year		2022 year	
	Standard	Optimization	Standard	Optimization
Irrigation rate, m3/ha	1600	1570	1600	1490
Economy, m3/ha	0	30	0	110

Table 2. Irrigation characteristics.

Soil type	DM brand	Effective irrigation rate, m^3/ha	Sufficient irrigation rate, m3/ha	The amount of runoff, m3/ha under the last span	Note
Chernozem ordinary	"Kuban-LK1"	305 400 510	530 540 535	0 0 0	
Dark chestnut loam	"Kuban-LK1M" (CASCADE)	300 405 495	535 540 550	0 0 0	"Kuban-LK1M" (CASCADE)
	"Kuban-LK1M" (CASCADE)	300 405 500	380 385 390	0 20 110	soil not protected by plants

The developed technology was implemented on sprinkler machines "Kuban-LK1M" and "CASCADE" installed on irrigated fields in LLC "Nashe Delo" (Krasny Yar village, Engels district, Saratov region) and in NPO "Volga region" (Stepnoye village, Engels district, Saratov region), Figure 2.

Fig. 2. Sprinkler machine Kuban-LK1M "Cascade".

5 Results

Existing irrigation technologies with wide-reach circular sprinkler machines have a disadvantage due to the fact that watering with a constant rate does not always correspond to the value of the required moisture in various sectors of the irrigated field, which leads to overspending of irrigation water, increased runoff and soil erosion. Based on the analysis of the effectiveness of the use of circular sprinkler machines, the parameters of the irrigation process were justified, ensuring a reduction in surface runoff and unproductive water losses.

Comparison of standard and proposed irrigation technologies with sprinklers showed that irrigation using the proposed technology allows saving irrigation water up to 10 %.

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