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Estimation of efficiency of use of water-lifting equipment in technological processes of agricultural production

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Abstract. The article presents the estimation of efficiency of use of water-lifting equipment in technological processes of agricultural production. It is outlined the principle of operation water-lifting equipment in technological processes of agricultural production. It is based on increasing the required pressure for the water supply network by direct repeated use of gravitational forces in the form of weight of the liquid column from natural or artificial pressure. The efficiency of the technological process is assessed by the amount of consumption of water and the speed of flow movement. These parameters (optimization criteria) depend on four main independent factors: the head height; volume of transit tanks; pipe diameter; pipe length. The optimal constructive and technological parameters of water-lifting equipment in technological processes of agricultural production are considered.

1. Introduction

One of the most important problems in the field of agricultural and industrial production is the creation of a modern water supply system. Water supply systems are complex engineering structures that provide both water supply to consumers and drainage and wastewater treatment. The use of water supply systems requires high energy costs, so the creation of systems that will promote energy conservation is necessary for the development of the industry in the country. The water supply system plays an important role in agriculture. The productivity of livestock farms depends on the water supply. To create operational water reserves, water towers are used, the filling of which requires significant energy consumption. Thus, the task of water supply systems is to expand the technological capabilities of the water supply process, increase its reliability, reduce its capital and operating costs, simplify design. Therefore, it is proposed to perform the process of increasing the pressure by gravity in the form of the weight of the liquid column of the required height. To solve it, it is proposed to implement a system of gravity water-lifting equipment that provides an automatic process of reusable pressure, which exists in the system for water supply to the consumer.

An analysis of the technical solutions of the water lift process was performed. In the research were presented the functions of water-lifting aerator technology used in these reservoirs for water quality improvement and its engineering solutions course [1]. The results showed that the technology of water-lifting aerators can effectively control the release of endogenous pollutants, remove volatile contaminants, and reduce the pollution load in reservoirs [2]. Significant

opportunities exist to reduce pumping system energy consumption through smart design, retrofitting, and operating practices [3]. The results suggest that a unit increase in the level of farm mechanization increases the demand for hired labour [4]. The authors developed techniques to incorporate differential pressure measurements in flat dilatometer and piezo-penetrometer tests to facilitate in situ measurements under water in a reservoir [5]. Also, hydraulic collecting and pipe transportation are regarded as an efficient way for exploiting submarine mineral resources [6]. The paper presents a comprehensive review of the progress that has been achieved in the past years about cavitation in valves including both mechanical heart valves and control valves [7]. The study investigates the additional installation of a pilot channel running along the canal bottom to constrict the flow width and increase the flow depth [8].

The analytical models of water lifting process in industry were investigated. The paper presents a semi-analytical model that facilitates the optimum design of small-scale hydropower systems [9]. Several practical applications in fluid mechanics have the interest to reduce energy dissipation by reducing the drag or pressure drop [10]. The paper puts forward a formula for the effect of silt sediment on the lifting force [11]. Nevertheless, site-specific factors such as differing discharge conditions, topographical boundary conditions, wastewater volume and composition should be taken into consideration by wastewater practitioners during energy benchmarking assessments [12]. Hydro informatics applies software-based artificial technology for determining these consequences accompanied to water-based approach [13]. The "waterscapes" influence on the administrative geography of the region, which were the locations where these activities took place, and the people in charge of them were integrated within the socio-economic network [14]. Water development, particularly hydropower, provides an important source of renewable energy [15]. Water Engineering Modelling and Mathematic Tools provides an informative resource for practitioners who want to learn more about different techniques and models in water engineering and their practical applications and case studies [16]. The evolution of the major achievements in water lifting devices with emphasis on the major technologies is presented and discussed [17] These technologies are the underpinning of modern achievements in water engineering [18]. The authors investigated some aspects of estimation the processes of quality management system at enterprises [19] and the mathematical modelling of the technology of processing the agricultural production [20] but the estimation of efficiency of use of water-lifting equipment in technological processes of agricultural production was not the specific subject of research.

The aim of the article is to estimate the efficiency of use of water-lifting equipment in technological processes of agricultural production.

2. Methods
Methods of physics, hydraulics, analysis and modelling were used in solving the research tasks. The study of technological parameters of the water-lifting equipment was carried out in the laboratory using the methods of mathematical statistics [21] with data processing on a PC. Experimental studies of the rise of water by water-lifting equipment were carried out on a specially designed installation.

3. Principle of operation water-lifting equipment in technological processes of agricultural production
The principle of operation of equipment for lifting water (figure 1) in technological processes of agricultural production is based on increasing the required pressure for the water supply network by direct repeated use of gravitational forces in the form of weight of the liquid column from natural or artificial pressure. In this case, the natural pressure can be obtained as a result of differences in the height of the water column in waterfalls, rivers, when excess water leaks from ponds and reservoirs, and artificial pressure from any water network in which it is not enough to meet consumer needs.
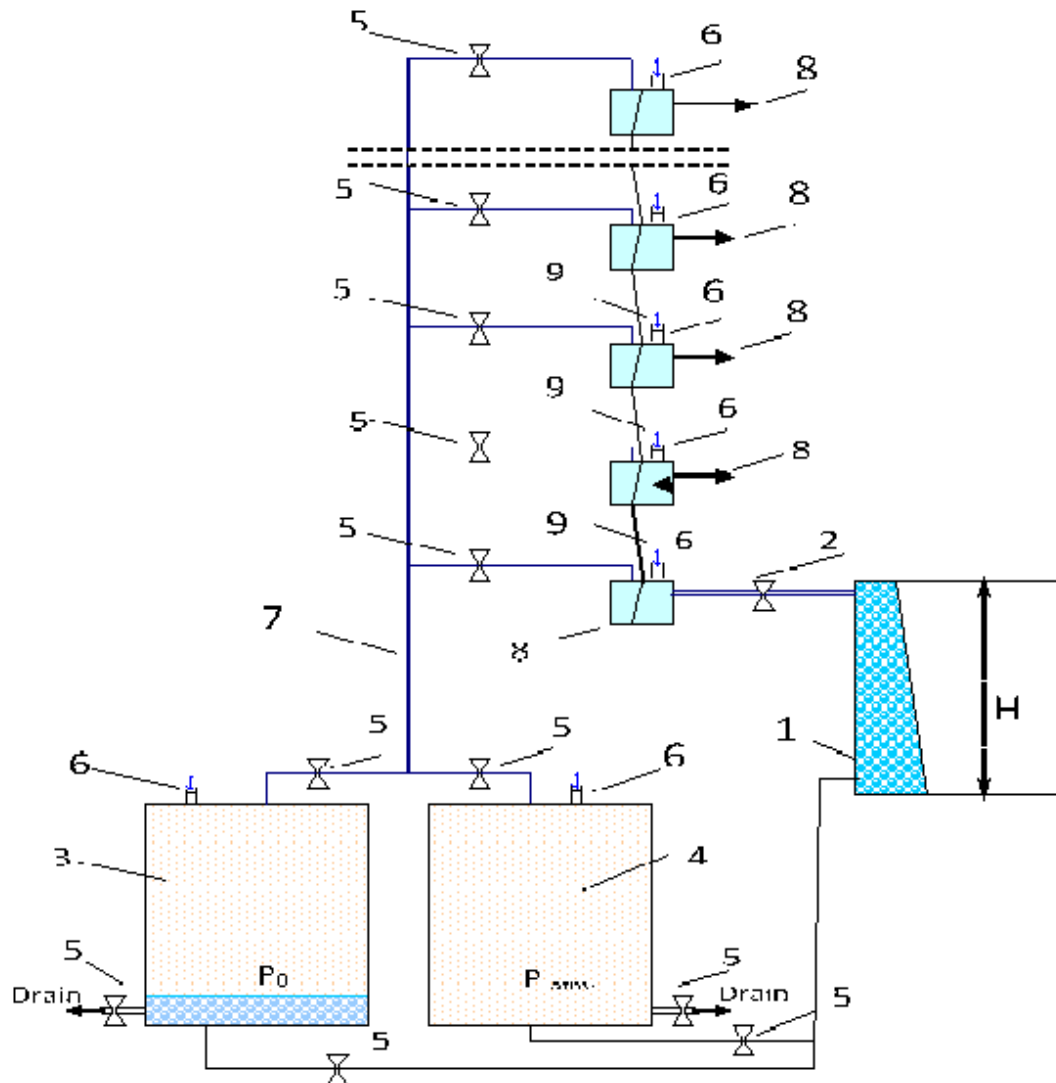
Figure 1. Water-lifting equipment in technological processes of agricultural production: 1 – pressure tank, 2 – tap for filling the transit tank, 3 – right base tank, 4 – left base tank, 5 – ball or screw tap, 6 – valve for sealing or depressurization, 7 – compression air pipe, 8 – transit tanks, 9 – pressure pipelines.

The process of operation of equipment for lifting water in the technological processes of agricultural production is as follows. Through the tap for filling the transit tank 2 with water, from the pressure tank 1, the transit tank 8 is filled with water and sealed with a sealing or depressurizing valve 6. At the same time the right base tank 3 is sealed and filled with water through a ball or screw tap 5, creating at the same time in it compressed air pressure $P_o = R_{atm.} + \gamma h$, where γ is the specific weight of water, and h is the height of the water column pressure H. Then through a ball or screw valve 5, compressed air from the right base tank 3 enters the compression air pipe 7, and then through the valve for sealing or depressurization 6 in the transit tank 8, from which water is expelled by compressed air on the pressure pipelines 9, in the transit tank 8 and fills it, and then repeats the cycle of pushing water from the transit tank 8, that is, after filling it with water, it is also sealed only by means of a valve for sealing or depressurization 6. In the next transit tanks, the process of filling and ejecting water

occurs according to the principle described above. In this case, each capacity of the water-lifting equipment starting with the second, provides at a specific level of its rise the value of water pressure $H = \gamma h$. In order to ensure the continuity of the supply of compressed air in the compression air pipe 7 of the device for raising water provides sequential and synchronous inclusion of two tanks: the right base tank 3 and the left base tank 4.

Thus, the process of increasing the pressure in equipment for lifting water of this type can be implemented not only for water supply, but also to use it to obtain sources of cheap, environmentally friendly energy by creating high-pressure hydropower plants of a wide range of capacities. Such installations can be widely used in agriculture, which, like no other industry, needs autonomous water and energy supply. The introduction of this type of installation requires full automation of the process of increasing the gravitational pressure, which eliminates the presence of human.

For experimental studies, the volumes of transit tanks equal to 1 dm, located at a height of 0.5 m, were accepted, and the choice of volumes for base tanks was made on the condition of reliable compressed air supply system for experimental studies. Experimental studies have shown that the optimum value of water flow in the pipeline corresponds to the speed of its movement is 1.2 m/s, and the time of supply of the initial volume of water to the maximum height of the system under consideration is 45 seconds. Studies have shown that taking into account all local system losses and losses along the length of the pipeline, the efficiency of the gravity water lift system is approximately 98%. During the experimental research, all the processes of sealing and depressurization of transit tanks were carried out manually, using conventional ball valves, because in the laboratory it is difficult to create a complete automation of the process of lifting water.

4. Results

The quality of the technological process is assessed by the amount of water consumption (AC) and speed of flow movement (SM). These parameters (optimization criteria) depend on four main independent factors: the head height – H, m (X_1); volume of transit tanks – V, m^3 (X_2); pipe diameter – d, m (X_3); pipe length – l, m (X_4). The above independent factors are selected as the main in this technological process by conducting preliminary experiments and their ranking according to the degree of impact on the quality of work. The levels of setting of independent variables (factors) and the range of their variation, adopted during the experiments, are given in table 1.

Table 1. Levels and range of variation factors.

Factors	Levels of variation			Interval of variation	Dimension
	-1	0	+1		
$X_1(H)$	3	6	9	3	m
$X_2(V)$	2	4	6	2	m^3
$X_3(d)$	0.02	0.04	0.06	0.02	m
$X_4(l)$	3	6	9	3	m

The plan, the average value of AC, SM was calculated. Mathematical models are obtained that adequately describe the The frequency of experiments on each of the optimization criteria was three times. For each line of technological process. The regression equations are:

- for the amount of consumption:

$$AC = 12.5 + 0.58X_1 + 5.4X_2 + 2.1X_3 - 2.6X_4 + 0.63X_1X_2 - 0.6X_1X_3 - 1.3X_1X_4 - $$
$$-2.8X_2X_3 - 1.06X_2X_4 + 1.5X_3X_4 + 2.1X_1^2 - 5.4X_2^2 - 1X_3^2 + 1.8X_4^2 \quad (1)$$

- for the speed of movement:

$$SM = 0.83 - 0.025X_1 - 0.017X_2 + 0.020X_3 - 0.011X_4 - 0.012X_1X_2 + $$
$$+0.0056X_1X_3 - 0.042X_1X_4 + 0.048X_2X_3 - 0.013X_2X_4 + 0.0097X_3X_4 + 0.12X_1^2 - \quad (2)$$
$$-0.09X_2^2 - 0.012X_3^2 + 0.014X_4^2$$

The analysis of regression equations obtained after statistical processing is usually performed with coded values of factors [21]. The study of the behaviour of optimization criteria depending on the change of independent factors will be carried out using the method of two-dimensional sections.

When substituting $X_3 = 0$ and $X_4 = 0$, the regression equations will look like:

$$AC = 12.5 + 0.58X_1 + 5.4X_2 + 0.63X_1X_2 + 2.1X_1^2 - 5.4X_2^2 \quad (3)$$

$$SM = 0.83 - 0.025X_1 - 0.017X_2 - 0.012X_1X_2 + 0.12X_1^2 - 0.09X_2^2 \quad (4)$$

- for the amount of consumption:

$$AC - 17.218 = 2.183X_1^2 - 5.493X_2^2;$$

- for the speed of movement:

$$SM - 0.8 = 0.119X_1^2 - 0.093X_2^2;$$

The two-dimensional cross section of the response surfaces is shown in figure 2. Consistently fixing the other two factors at level 0 and performing calculations similar to the above, it is obtained the regression equation in the usual form with a new combination of factors.

When substituting $X_1 = 0$ and $X_2 = 0$, the regression equations:

- for the amount of consumption:

$$AC = 12.5 + 2.1X_3 - 2.6X_4 + 1.5X_3X_4 - 1X_3^2 + 1.8X_4^2 \quad (5)$$

- for the speed of movement:

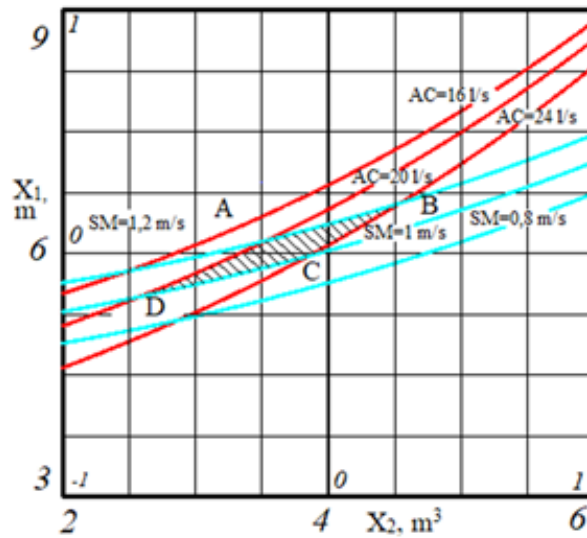$$SM = 0.83 + 0.020X_3 - 0.011X_4 - 0.0097X_3X_4 - 0.012X_3^2 + 0.014X_4^2 \quad (6)$$

In accordance:

- for the amount of consumption: $X_3 = -1.23$; $X_4 = 0.27$;
- for the speed of movement: $X_3 = -1.153$; $X_4 = 0.795$;

The regression equations in canonical form will take the form:

- for the amount of consumption:

$$AC - 11.10 = 2.0032X_3^2 - 1.153X_4^2;$$

Figure 2. Two-dimensional intersection of response surfaces at $X_3 = 0$ and $X_4 = 0$.

- for the speed of movement:

$$SM - 0.83 = 0.0179X_3^2 + 0.0805X_4^2.$$

When setting $X_2 = 0$ and $X_4 = 0$, the regression equations have the form:

- for the amount of consumption:

$$AC = 12.5 + 0.58X_1 + 2.1X_3 - 0.6X_1X_3 + 2.1X_1^2 - 1X_3^2 \tag{7}$$

- for the speed of movement:

$$SM = 0.83 - 0.025X_1 + 0.020X_3 + 0.0056X_1X_3 + 0.12X_1^2 - 0.012X_3^2 \tag{8}$$

In accordance:

- for the amount of consumption: $X_1 = -0.427$; $X_3 = -0.96$;
- for the speed of movement: $X_1 = 0.084$; $X_3 = 0.852$;

Regression equation in canonical form:

- for the amount of consumption:

$$AC - 12.5 = 2.2X_1^2 - 1.035X_3^2;$$
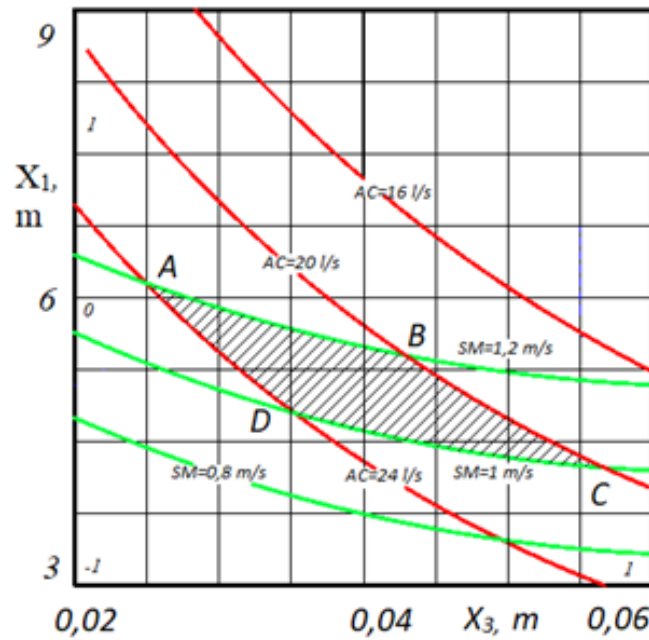
- for the speed of movement:

$$SM - 0.94 = 0.12X_1^2 - 0.0121X_3^2.$$

The two-dimensional cross section of the response surfaces is shown in figure 3.
When setting $X_1 = 0$ and $X_3 = 0$, the regression equations have the form:

- for the amount of consumption:

$$AC = 12.5 + 5.4X_2 - 2.6X_4 - 1.06X_2X_4 - 5.4X_2^2 + 1.8X_4^2 \tag{9}$$

Figure 3. Two-dimensional intersection of response surfaces at $X_2 = 0$ and $X_4 = 0$.

- for the speed of movement:

$$SM = 0.83 - 0.017X_2 - 0.011X_4 - 0.013X_2X_4 - 0.09X_2^2 + 0.014X_4^2 \qquad (10)$$

In accordance:

- for the amount of consumption: $X_2 = 0.41$; $X_4 = 0.841$;
- for the speed of movement: $X_2 = -0.121$; $X_4 = 0.336$;

Regression equation in canonical form:

- for the amount of consumption:

$$AC - 10.67 = 1.894X_2^2 - 5.51X_4^2;$$

- for the speed of movement:

$$SM - 0.709 = 0.0144X_2^2 - 0.0904X_4^2.$$

When setting $X_2 = 0$ and $X_3 = 0$, the regression equations have the form:

- for the amount of consumption:

$$AC = 12.5 + 0.58X_1 - 2.6X_4 - 1.3X_1X_4 + 2.1X_1^2 + 1.8X_4^2 \qquad (11)$$

- for the speed of movement:

$$SM = 0.83 - 0.025X_1 - 0.011X_4 - 0.042X_1X_4 + 0.12X_1^2 + 0.014X_4^2 \qquad (12)$$

In accordance:

- for the amount of consumption: $X_1 = 0.098$; $X_4 = 0.757$;

- for the speed of movement: $X_1 = 0.235$; $X_4 = 0.74$;
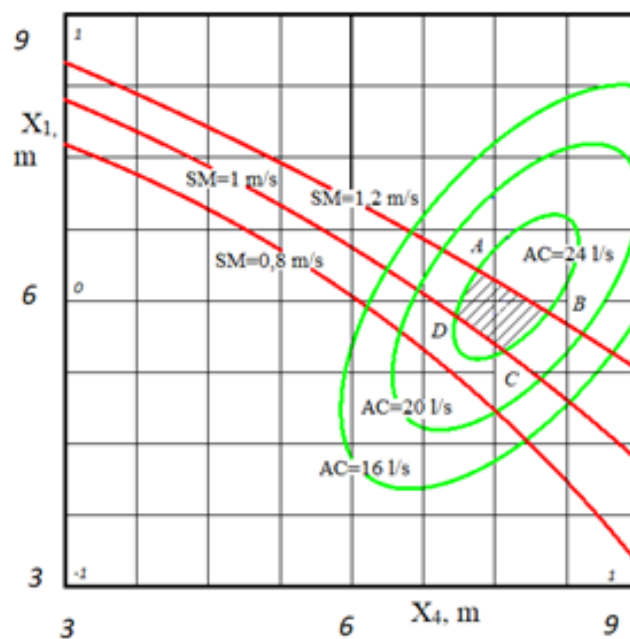
Regression equation in canonical form:

- for the amount of consumption

$$AC - 12.21 = 2.69X_1^2 + 1.32X_4^2;$$

- for the speed of movement:

$$SM - 0.87 = 0.12X_1^2 + 0.0099X_4^2.$$

The two-dimensional cross section of the response surfaces is shown in figure 4.

Figure 4. Two-dimensional cross-section of the response surfaces at $X_2 = 0$ and $X_3 = 0$.

When setting $X_1 = 0$ and $X_4 = 0$, the regression equations have the form:

- for the amount of consumption:

$$AC = 12.5 + 5.4X_2 + 2.1X_3 - 2.8X_2X_3 - 5.4X_2^2 - 1X_3^2 \tag{13}$$

- for the speed of movement:

$$SM = 0.83 - 0.017X_2 + 0.020X_3 + 0.048X_2X_3 - 0.09X_2^2 - 0.012X_3^2 \tag{14}$$

In accordance:

- for the amount of consumption: $X_2 = 1.225$; $X_3 = -2.71$;
- for the speed of movement: $X_2 = 0.273$; $X_3 = 1.38$;

Regression equation in canonical form:

- for the amount of consumption:

$$AC - 12.86 = -0.58X_2^2 - 5.89X_3^2;$$

- for the speed of movement:

$$SM - 0.78 = -0.0052X_2^2 - 0.0968X_3^2.$$

After the analysis of two-dimensional surfaces of section (figures 2–4) it is possible to make the following statements. With the value of the existing pressure equal to $5.5 - 6.5$ m and the volume of transit tanks equal to $3 - 4.5$ m^3, the amount of consumption of water will be in the range of $20 - 24$ l/s, and the speed of flow movement will be $1 - 1.2$ m/s (figure is limited by ABCD points, figure 2). The diameter of the pipeline will be 0.04 m, the length of the pipeline will be 6 m. Moreover, with increasing pressure increases the amount of flow, the speed also increases. And if increases the volume of transit tanks, the speed of movement begins to increase, but the amount of consumption decreases. At the existing pressure equal to $4.5 - 6$ m and the diameter of the pipeline, which is $0.025 - 0.055$ m, the amount of consumption of water will be within $20 - 24$ l/s, the speed of flow movement will be 1.2 m/s. The volume of transit tanks will be 4 m^3, with a pipeline length of 6 m (figure ABCD, figure 3). Moreover, increasing the diameter of the pipeline, the flow rate increases, and the speed begins to decline.

At the level of the existing pressure within $6 - 6.5$ m and length of the pipeline equal $7 - 8$ m, the amount of consumption of water will be 24 l/s, at speed of flow movement within $1 - 1.2$ m/s (figure ABCD, figure 4). Moreover, the diameter of the pipeline will be 0.04 m, with the volume of transit tanks equal to 4 m. But with increasing length of the pipeline, the flow rate and speed decrease.

The optimal constructive and technological parameters of water-lifting equipment can be considered as follows: the head height $X_1 = 5...6.5$ m; volume of transit tanks $X_2 = 4...4.5$ m^3; diameter of the pipeline $X_3 = 0.04...0.05$ m; the length of the pipeline $X_4 = 6...7$ m. The optimization criteria are in the range: the amount of consumption of water $AC = 20 - 24$ l/s; the speed of flow movement $SM = 1 - 1.2$ m/s.

5. Conclusion

A review of literature sources on the use of systems and equipment for water supply showed that the known technical solutions for raising water in water bodies usually have low efficiency and require energy consumption during operation. Also, they are not always technological in addressing the issues of increasing the pressure in the water supply network and maintaining it at the level necessary for the consumer. Thus, there is a need to address the issue of improving the quality of water supply to consumers, reducing energy consumption in the operation of the water supply system and maintaining the required pressure in the water supply network by designing water-lifting equipment in technological processes of agricultural production.It was found that the main optimization criteria for assessing the quality of the technological process were: the amount of consumption of water $AC = 20 - 24$ l/s and the speed of flow movement $SM = 1 - 1.2$ m/s.

On the basis of theoretical and experimental studies it is established that these optimization criteria depend on four main independent factors: the head height – H, m; volume of transit tanks – V, m; pipe diameter – d, m; pipe length – l, m. Also, the most favourable constructive and technological parameters of the water-lifting equipment are established, namely: head height $X_1 = 5...6.5$ m; volume of transit tanks $X_2 = 4...4.5$ m^3; diameter of the pipeline $X_3 = 0.04...0.05$ m; the length of the pipeline $X_4 = 6...7$ m.

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