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MATHEMATICAL MODELS AND OPTIMAL CONTROL ALGORITHMS FOR CHANNELS OF IRRIGATION SYSTEMS, TAKING INTO ACCOUNT THE DISCRETENESS OF WATER SUPPLY

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ABSTRACT

The object of research was selected section of the southern Golodnostep main canal, located in the North-East of the Republic of Uzbekistan. In recent years, scientific research has been carried out in many countries around the world, aimed at developing mathematical models and algorithms for solving problems of optimal management of water management systems, with the use of modern information systems. Methods of mathematical modeling and algorithmization of optimal control problems for systems with distributed parameters, what is considered the main channel. Optimal changes in water consumption over time and along the length of the main channel section are obtained, opening its gates allows you to increase the amount of water flow along the length of the site. During t=34,7 min. the water flow rate at the end of the main channel section reaches a value of Q=100 m³/sec and stabilization which important for canals and water gates

Keywords: optimal control, information systems, numerical methods, channels, water distribution, discrete water supply.

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INTRODUCTION

In our republic, measures are being taken to solve the problem of water delivery to consumers, which must be solved. The urgency of this problem for canals of irrigation systems is to save water resources by optimally managing the process of water delivery to consumers by providing water to a specific consumer at a set time. This problem is paid much attention to in the national economy of the republic.

Consider a section of the channel (Fig. 1, a, b) with five water intakes. The problem of water distribution taking into account the discreteness of water supply will be considered as ensuring the supply of water flow q_i for each water intake at time point T, i.e. stepwise change in water flow, with minimal fluctuation of the water level in the channel [1, 2].

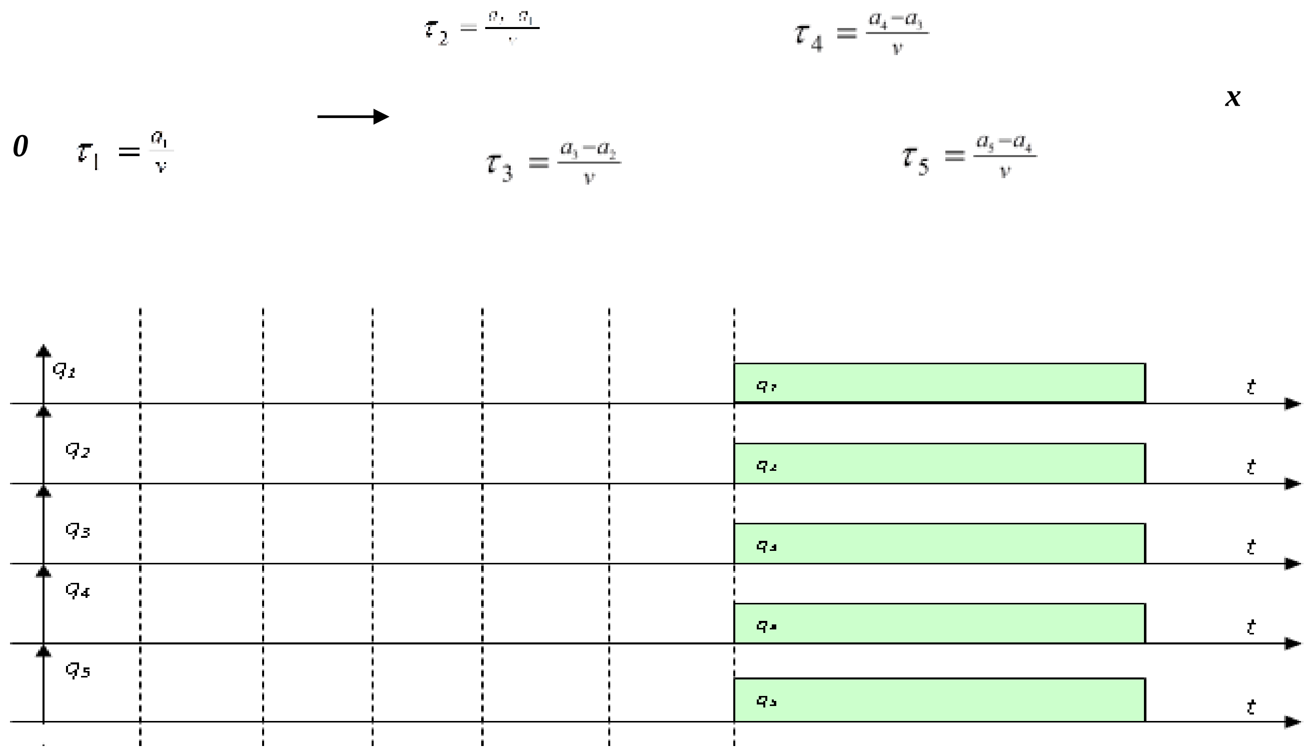

Fig. 1. Discrete water supply in the canal sections

METHODOLOGY

The direct wave model. Consider a model statement of the problems of water distribution in a given section of the channel, taking into account the discreteness of water supply, taking into account only the delay in the distribution of water flow along the length of the channel [2,3].

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The discreteness of water flow is formulated using a discrete unit function $q_i \cdot l \cdot (t-T)$.

As a mathematical model of the channel section, the one-dimensional differential equation in the form

$$\frac{\partial Q(x,t)}{\partial t} + \upsilon \frac{\partial Q(x,t)}{\partial x} = q(x,t), \qquad (1)$$

where $Q(x,t)-$ change in water flow in the channel section, $\upsilon-$ flow rate.

Initial condition:

$$Q(x,0) = Q_0(x), \qquad (2)$$

where $Q_0(x)-$ initial distribution of water flow in the channel section.

Boundary condition:

$$Q(0,t) = Q_1(t), \qquad (3)$$

where $Q_1(t)-$ change in water flow at the beginning of the channel section.

Variable definition area

$$x \geq 0, \quad t \geq 0, \quad \upsilon > 0. \qquad (4)$$

Water flows at the points of water intake of the channel section $q(x,t)$ under the conditions of discreteness of water distribution have the form

$$q(x,t) = -\sum_{i=1}^{5} q_i \, \delta(x-a_i) l(t-T). \qquad (5)$$

Equation (5) takes into account the main properties of the irrigation canal, such as the delay in water flow along the length of the canal. The change in water flow in the initial section of the channel section leads to its change in other sections of the channel section after a certain time, this is the delay. The farther the target is considered from the initial alignment, the greater the delay in water flow.

The fundamental solution to equation (1) - the Green's function has the form [4,5,6]

$$G(x,\xi,t) = l(x-\xi)\delta(\upsilon t-(x-\xi)), \qquad (6)$$

where: $\delta(x)-$ Dirac delta function

The analytical solution of equation (1) in the presence of its fundamental solution is determined as follows

$$Q(x,t) = \int_{t_0}^{t}\int_{0}^{l} G(x,\xi,t-\tau)\omega(\xi,t)\,d\xi\,d\tau, \qquad (7)$$

where $\omega(x,t)-$ standardizing function for the boundary value problem (1) - (4), which has the form [7]

$$\omega(x,t) = q(x,t) + Q_0(x,t)\delta(x,t)\delta(t) - \upsilon\delta(x)Q_1(t). \qquad (8)$$

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RESULTS

Consider the properties of the solution of equation (1). The change in water flow at the beginning of the channel section under zero initial conditions propagates with speed along the channel length. The wave front in this case does not change in length.

Kinematic wave model. The equation of the kinematic wave in the case of lateral taps is written as follows [8]

$$\frac{\partial \omega(x,t)}{\partial t}+\frac{\partial Q(x,t)}{\partial x}=q(x,t)$$
$$Q(x,t)=\omega(x,t)c(x,t)\sqrt{R(x,t)i}\,. \qquad (9)$$

Here $Q(x,t)-$ change in water flow in the channel section, υ – flow rate.

Initial conditions

$$Q(x,0)=Q_0(x),\ \ \omega(x,0)=\omega_0(x), \qquad (10)$$

where: $Q_0(x)-$ initial distribution of water flow in the channel section.

Boundary condition:

$$Q(0,t)=Q_1(t), \qquad (11)$$

where: $Q_0(x)-$ change in water flow at the beginning of the channel section.

Variable definition area

$$x\geq 0,\quad t\geq 0,\quad \upsilon>0. \qquad (12)$$

The water flow at the points of intake of the channel $q(x,t)$ in the conditions of discreteness of the distribution of water has the form [1,9]

$$q(x,t)=-\sum_{i=1}^{N}q_i\,\delta(x-a_i)l(t-T). \qquad (13)$$

Equation (9) takes into account the main properties of the irrigation canal, such as the delay and transformation of water flow along the length of the canal. In this case, the water flow rate changed in the initial section of the channel section leads to a change in water flow at other sections of the channel section after a certain time, this is called a delay, which gradually changes in time.

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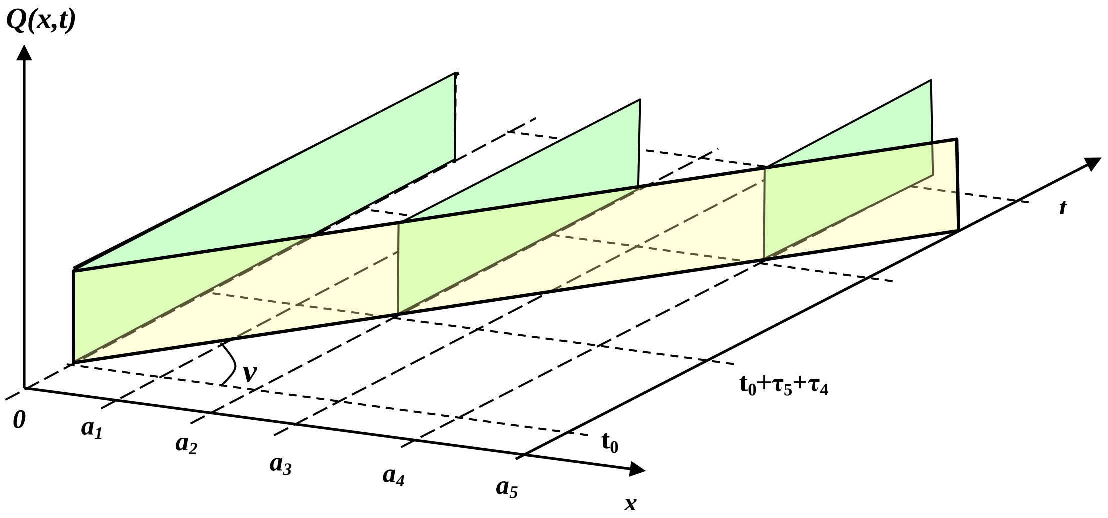

Fig. 2. The propagation of a square wave along the length of the channel

The convection-diffuse model is based on neglect of the inertial terms of the equations and has the form [10, 11]

$$\frac{\partial Q}{\partial t}+\left(\frac{\partial Q}{\partial K}\frac{\partial K}{\partial h}\right)\frac{\partial Q}{\partial x}-\frac{K^2}{2b|Q|}\frac{\partial^2 Q}{\partial x^2}=q(x,t), \qquad (14)$$

where: K – flow module.

The flow module $K(x,z)$ characterizes the magnitude of the friction forces and is determined by the following well-known formula

$$K=\omega\cdot C\sqrt{R},$$

where: R – hydraulic radius of the channel; X – wetted channel perimeter; C – Shezy coefficient.

To determine the Shezy coefficient, there is a whole series of empirical formulas. As one of them, Pavlovsky's formula can be adopted [1,12,13]

$$C=\frac{1}{n}R^{y},\ y=2{,}5\sqrt{n}-0{,}13-0{,}75\sqrt{R}\left(\sqrt{n}-0{,}1\right), \qquad (15)$$

where n – channel roughness coefficient.

Initial condition:

$$Q(x,0)=Q_0(x),\ \omega(x,0)=\omega_0(x), \qquad (16)$$

where $Q_0(x)$ – initial distribution of water flow in the channel section.

Boundary condition:

$$Q(0,t)=Q_1(t), \qquad (17)$$

where $Q_1(t)$ – change in water flow at the beginning of the channel section.

Variable definition area

$$x\geq 0,\quad t\geq 0,\quad \upsilon>0. \qquad (18)$$

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Water consumption at the points of water intake of the channel section in the conditions of discreteness of water distribution

$$q(x,t)=-\sum_{i=1}^{N} q_i\,\delta(x-a_i)I(t-T). \tag{19}$$

The characteristic form of equations (1) has the form [7,14]

$$\frac{\partial Q}{\partial t}+(v\pm c)\frac{\partial Q}{\partial x}-B(v\mp c)\left[\frac{\partial z}{dt}+(v\pm c)\frac{\partial z}{\partial x}\right]=$$
$$=\left(\varphi-\frac{Q|Q|}{K^2}\right)g\omega-(v\mp c)q. \tag{20}$$

Here $\varphi=\left[i+\frac{1}{B}\left(\frac{\partial\omega}{\partial x}\right)_{h=const}\right]\left(\frac{v}{c}\right)^2.$

The initial conditions are specified as

$$z(x,0)=z_0(x),\qquad Q(x,0)=Q_0(x), \tag{21}$$

where $Q_0(x), z_0(x)-$ known features.

The boundary conditions at points $x_1=0$ and $x_2=l$ are written as follows

$$Q(0,t)=u_1(t),\ Q(l,t)=u_2(t). \tag{22}$$

Water flows at the points of water intake of the channel section, the right side of equation (1) under the conditions of discreteness of water distribution, has the form [2,15]

$$q(x,t)=-\sum_{i=1}^{N} q_i\,\delta(x-a_i)I(t-T). \tag{23}$$

In these models, there is no analytical solution of equations (9), (14) and (20) under the indicated boundary conditions, since the hydraulic parameters of the water flow is a nonlinear function that depends on the shape of the cross section of the channel section.

From the expression of the lateral water intakes (23) it is seen that consumers are provided with a discrete water supply in time in the form of a step function. With stepwise functions, to solve the problem of optimal control of water distribution, it is necessary to formulate criteria for the quality of water distribution in the channels of irrigation systems under conditions of discrete water supply to consumers and a system of restrictions.

Below, we analyze methods that use the necessary optimality conditions for the optimal distribution of water in irrigation systems under optimal water supply conditions.

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The gradient minimization method is used to approximate the solution of the problem [16.17]

$$I\ \left(u_m(t)\right)\Rightarrow min;\qquad u_m(t)\in H\ , \tag{24}$$

where H – Hilbert space, based on the construction of a minimizing sequence, which can be written in the form

$$u_{m+1}(t)=u_m(t)-\alpha_m I^{'}(u_m(t),t_0\le t\le T, m=0,1,2,...,. \tag{25}$$

where $u_0(t)$– some given initial value of the control action, α_m – positive value, I' – functional gradient, calculated by known value $u_m(t)$. If $I'(u_m(t))\neq 0$, then α_m can choose so, so that $I(u_{m+1}(t))<I(u_m(t))$.

From the condition of twice differentiability of the optimality criterion, we have

$$I(u_{m+1}(t))-I(u_m(t))=\alpha_m\left(-\|I'(u_m(t))\|^2+o(\alpha_m)\right)<0 \tag{26}$$

For all sufficiently small $\alpha_m>0$, if $I'(u_m(t))\neq 0$, then process (26) stops when the given accuracy of the problem is satisfied and, if necessary, additional studies are conducted of the behavior of the function $u_m(t)$ in the vicinity of the control to determine whether it belongs to $u_m(t)$ the optimal control or not. Since for optimal water distribution problems in irrigation systems under optimal water supply conditions, all optimality criteria are convex functions, therefore, the resulting control is close to optimal control.

There are various ways to select a value α_m. We list some of them [18.19].

1) α_m is selected from the condition

$$f_m(\alpha_m)=\inf_{\alpha_m\ge 0} f_m(\alpha_m)=f_{m*},\ f_m(\alpha_m)=I(u_m(t)-\alpha_m I^{'}(u_m(t))) \tag{27}$$

this version of the gradient method is commonly called the steepest descent method.

An exact determination of the quantity α_m from (27) is not always possible, therefore, in practice, instead of (28), it uses the condition

$$f_{m*}\le f_m(\alpha_m)=f_{m*}+\delta_m,\qquad \delta_m\ge 0,\quad \sum_{t=1}^{\infty}\delta_m\le\infty, \tag{28}$$

or

$$f_{m*}\le f_m(\alpha_m)=(1-\lambda_m)f_m(0)+\lambda_m f_{m*},\qquad 0<\lambda\le\lambda_m\le 1\ , \tag{29}$$

Quantities λ_m, δ_m here they characterize the error in fulfilling the condition (29).

2) consider $\alpha_m=\alpha>0$, then check the condition of monotony $I(u_{m+1})<I(u_m)$, and if necessary, crush the value α, achieving the fulfillment of the monotonicity condition.

3) sometimes α_m determines from conditions

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$$0 < \varepsilon_0 \le \alpha_m \le 2/(L + 2\varepsilon), \qquad (30)$$

where L – Lipschitz constant $\varepsilon, \varepsilon_m$ – positive numbers, which are the parameters of the method.

4) possible choice α_m from the condition

$$I(u_m) - I(u_m - \alpha_m I'(u_m)) \ge \varepsilon \alpha_m \left\| I'(u_m) \right\|^2, \qquad \varepsilon < 0, \qquad (31)$$

to determine this α_m, they usually ask $\alpha_m = \alpha$ and then crush it until the inequality written out is fulfilled.

5) a priori assignment of α_m from the conditions

$$\alpha_m > 0, \quad m = 0,1,2,...., \quad \sum_{m=0}^{\infty} \alpha_m = 0, \quad \sum_{m=0}^{\infty} \alpha_m^2 < \infty \qquad (32)$$

For example, you can take $\alpha_m = c(k+1)^{-b}, c = const > 0, \frac{1}{2} < b < 1$. Such a choice α_m is simple to implement, but does not guarantee the conditions for the fulfillment of monotony and converges slowly.

6) in cases where the value is known in advance $I_* = \inf I(u_m) > -\infty$, can take

$$\alpha_m = I(u_m(t)) - I'_* / \left\| I'(u_m(t)) \right\|^2, \qquad (33)$$

In practice, for iterative methods, iterations continue until a condition is satisfied, i.e. criterion for ending an account. Here it is possible to use such criteria for ending the account as $\left\| u_m(t) - u_{m+1}(t) \right\| \le \varepsilon, \quad \left| I(u_m(t)) - I(u_{m+1}(t)) \right| \le \delta, u, u \left\| I'(u_m(t)) \right\| \le \gamma,$

(34)

where ε, δ u γ – given numbers. Sometimes the number of iterations is specified.

The gradient projection method is used to approximate solution of problem (1), (2) and (3) in the case of imposing restrictions on the control functions, i.e. [20]

$$u_m(t) \in U, \qquad (35)$$

where U – convex closed set from Hilbert space U.

The minimizing sequence of solving the optimization problem based on the gradient projection method is constructed according to the rule

$$u_{m+1}(t) = P_U\left(u_m(t) - \alpha_m I'(u_m(t))\right), t_0 \le t \le T, m = 0,1,2,.... \qquad (36)$$

where P_U – operator of design in the field of management.

The projection $u_m(t)$ onto the set U is defined as follows

$$\left\| u_m(t) - \omega_m(t) \right\| = \inf \left\| u_m(t) - \upsilon_m(t) \right\| \qquad (37)$$

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Expression (37) means that if the calculated control value belongs to the set U, then the calculated control value is accepted. If the calculated control value leaves does not belong to the set, then close values of the set U are taken. This method is convenient when there is a formula for projecting control onto many constraints U [21].

If

$$U=\{u_m(t);\ u_{min}\le u_m(t)\le u_{max}\}, \tag{38}$$

then the design operator is defined as follows

$$u_{m+1}(t)=\begin{cases}u_{min} & npu\ u_m(t)-\alpha_m I'(u_m(t))<u_{min},\\ u_m(t)-\alpha_m I'(u_m(t)) & npu\ u_{min}\le u_m(t)-\alpha_m I'(u_m(t))\le u_{max},\\ u_{max} & npu\ u_m(t)-\alpha_m I'(u_m(t))>u_{max}.\end{cases} \tag{39}$$

If the given accuracy of the problem is satisfied and, if necessary, additional studies are carried out on the behavior of the function in the vicinity of the control $u_m(t)$ to determine whether it will belong to $u_m(t)$ the optimal control.

For the direct wave model, we apply the gradient projection method.

$$u^{m+1}(x,t)=\begin{cases}u_{min} & npu\ u^m(x,t)-\alpha_m(\lambda)_0^m<u_{min},\\ u^m(x,t)-\alpha_m(\lambda)_0^m & npu\ u_{min}\le u^m(x,t)-\alpha_m(\lambda)_0^m\le u_{max},\\ u_{max} & npu\ u^m(x,t)-\alpha_m(\lambda)_0^m>u_{max}.\end{cases} \tag{40}$$

$$\delta v_1^{m+1}(t)=\begin{cases}v_{1min} & npu\ \delta v_1^m(t)-\alpha_m\lambda(0,t)^m<v_{1min},\\ \delta v_1^m(t)-\alpha_m\lambda(0,t)^m & npu\ u_{min}\le\delta v_1^m(t)-\alpha_m\lambda(0,t)^m\le v_{1max},\\ v_{1max} & npu\ \delta v_1^m(t)-\alpha_m\lambda(0,t)^m>v_{1max}.\end{cases} \tag{41}$$

Here $\lambda(x,t)$ – the conjugate variable determined by the solution of the conjugate boundary value problem for the kinematic wave model.

DISCUSSION

It should be noted that the boundary value problem for the main variables for the simplified model is solved in direct time, and the boundary value problem for conjugate variables in the opposite. These boundary value problems are solved by numerical methods, for example, finite-difference or finite elements [6,7]. With a good choice of the initial condition and initial controls, the proposed algorithm quickly converges. The initial controls are selected from the solution of the optimal water distribution problem under optimal water supply between consumers obtained using simplified models of unsteady water movement in the canal sections [1], and

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the initial conditions are determined from the solution of the steady water movement in the canal sections.

The optimal distribution of water in irrigation systems under optimal water supply conditions is formulated as the problem of optimal control of systems with distributed parameters [4, 11].

The optimal control of unsteady water movement in the channels of irrigation systems was tested on the example of the section of the South Golodnostepsky main canal (SGMC), which is located in the Syrdarya and Jizzakh regions in the north-east of the Republic of Uzbekistan

The hydraulic and morphometric parameters of the SGMC section are as follows: water consumption in the channel section Q_0=101 m^3/c; depth of water flow in this section of the channel H_0=5,05 m; gravitational constant g=9,8 m/c^2; Shezy coefficient y=1/6; channel length l=17,7 km; channel bottom slope i =0,00006; the width of the water flow at the bottom of the living section of the channel B_0=39,4 m; water flow rate υ_0 =0,85 m^2/c; efficiency E=0,9.

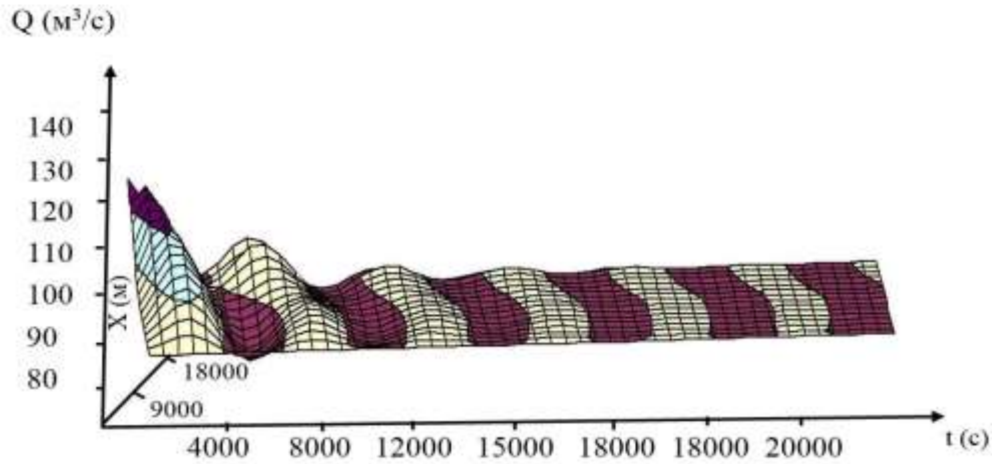

Fig. 3. Change in water flow over time and along the length of the main canal section.

It can be seen from the figure that, after the gates are opened, the increased flow rate at the beginning of the channel section allows increasing the water consumption along the length of the specified section of the main channel. During t = 20 823 c (34.7 min.), the water flow at the end of the section increases to Q = 100 m^3 /c and stabilizes.

CONCLUSION

The results of numerical experiments show that the water flow at the end of the channel section is stabilized, which is necessary for the water intake from the channel located there.

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Comparison of the results of numerical experiments and field studies conducted in this section of the main canal shows that the water level parameters in them differ slightly, their error is no more than 3-5%, this is of great importance in the national economy.

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