Analysis of automatic control structure of transfer pipeline stations on reclamation channels

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Abstract. Hydro-reclamation system operation management comes down to the management of pumping stations and dams. Transfer pumping stations are one of the most complex, critical and energy-rich local management objects on the channels of irrigation and drainage systems. These stations are complex aggregates of hydromechanical and electrical equipment, whose optimization can be rather significant, and are important elements determining the quality of a hydro-reclamation system as a whole. The main function of the automatic control system for transfer pumping stations is providing solutions on the optimal way to compensate for mismatches arising in the system “channel-transfer pumping station” and finding the best way to compensate for these mismatches with the available means. The first problem is hydrodynamic and is solved by studying a mathematical model of the pool, coupled with a transfer pumping station. The solution of the second problem is associated with regarding the technical characteristics and condition of the equipment of the transfer pumping station and the permissible operating modes of the channel. The article discusses one of the methods for determining the mismatch in the system “channel-transfer pumping station”, which contributes to building economical and efficient control systems for transfer pumping stations.

1. Introduction

In the Russian Federation, the legislative foundation is laid in national programs for the development of land reclamation and water management. The spheres of water consumption in the agro-industrial production of Russia include water supply to settlements, agricultural enterprises, irrigation and drainage of lands, water use for fish farming and energy. The main areas of activity in Russia are water management construction, implementation of scientific and technical information in the field of both water management and land reclamation, and solution of the problem of high-quality customer service with minimal costs [1,2].

Hydro-reclamation system operation management comes down to the management of pumping stations and dams. The specificity of these structures as management objects is that they are rather complex, energy-saturated local objects, but at the same time they are also elements of a transport system [3, 4].

Currently, most of the pumping stations on the reclamation canals are ineffective. When operating in this mode, water leaks in the system may occur due to a mismatch between water supply and water consumption, as well as an increase in energy consumption.
The paper discusses the issue of increasing the efficiency of the “channel-transfer pumping station” system. Improving the efficiency of transfer pumping stations is an important task since they are the largest consumers of electricity in the world [5, 6].

The aim of the work is to select a mathematical model of the dynamic system “channel-transfer pumping station” and the algorithm for the operation of the automatic control system of a transfer pumping station. The methodological basis of the work is mathematical modeling of unsteady water movement in the canal section of the irrigation system and the measurement theory.

2. Research Methods

A pumping station with a supply channel (Figure 1), at the beginning of which there is a retaining structure, is used as a channel-transfer pumping station. With a planned water distribution, the main function of the transfer pumping station in such a system is to raise all the water entering through the canal. The water level in the canal can vary within certain limits. If no additional restrictions, for example, the requirement to stabilize the water level in a given zone are imposed on the system, then the lower limiting water level in the supply channel of the normal water level is determined by the value of the normal flow depth at a known supply of the pump station and matching it with the water flow in the channel. The upper limiting level in the area of small flows of the transfer pumping station is determined by the value of the nondepositing velocity of the water flow, and in the area of large flows is determined by the location of the emergency weir in the supply channel. The main function of the transfer pumping station is fulfilled by the automatic control system. The change in the transfer pumping station supply occurs when the water level in the controlled section of the channel reaches one of the limit values. Since the control section is usually located in the backwater area, there is no unambiguous relationship between the ordinate of the free water surface $Z$ and the flow rate $Q$. At the same time, to compensate for the mismatch that occurs in the “channel-transfer pumping station” system, it is important to know not so much the water flow in the channel as the value of the mismatch $\Delta Q$ itself. Thus, the problem can be formulated as follows: determine the mismatch $\Delta Q$ between the water flow rate in the channel and the pumping station supply using water level sensors installed in the zone of hydraulic influence of the pump station as a source of measuring information.

![Figure 1. Building arrangements of pumping station equipped with axial-flow pump](image-url)
The problem was solved based on the assumption that there is a connection between the sought value \( \Delta Q \), the ordinate of the free surface of the water in the controlled section of the channel \( Z \), and the rate of its change \( \partial x / \partial t \) in some interval. To determine the mismatch \( \Delta Q \) in the “channel-transfer pumping station” system by the known values of \( Z \), a mathematical model of this dynamic system was compiled [7-10].

3. Results and discussion

Generally, water movement in the supply channel is unsteady due to the mismatch between the water flow in the channel and the supply of the transfer pumping station, which exists almost always. We assume that its characteristics have no discontinuities and that the water surface is horizontal in any cross section. Thus, it is possible to consider the movement of water in the channel in a one-dimensional approximation.

The continuity equation and the dynamic equation for slowly varying motion (Saint-Venant’s equation) presented in differential form are as follows [11]:

\[
\frac{\partial Q}{\partial t} + q = 0 \quad (1)
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial vQ}{\partial x} = - gw \left( \frac{\partial Z}{\partial x} + \frac{Q}{R C^2} \right), \quad (2)
\]

where \( x \) is cross-sectional coordinate, \( kg \); \( Z \) is ordinate of free water surface, m; \( t \) is time, s; \( Q \) is water consumption, \( m^3/s \); \( w \) is cross-sectional area of flow, \( m^2 \); \( B \) is free flow surface width, m; \( V = Q/w \) is average flow velocity, m/s; \( q \) is inflow per unit length of the channel directed to the normal of axis \( x \), \( m^3/s \); \( K \) is \( wC \) - transport capacity of the section, \( C \) is Chezy coefficient, \( R \) is hydraulic radius, m; \( g \) is gravitational acceleration, \( m/s^2 \).

Let us also denote the flow depth:

\[
h (x, t) = Z (x, t) - Z_0(x), \quad (3)
\]

where \( Z_0(x) \) is channel bottom ordinate.

We assume that \( w (x, h), B (x, h) = , q (x, h, t), K (x, h), (x) \) are the given functions.

The sought-for functions are the ordinate of the free water surface \( Z (x, t) \), the rate of its change and consumption \( Q (x, t) \).

The equations are hyperbolic partial differential equations; the system of equations on the plane \( (x, t) \) has two characteristic directions [5]:

\[
= V \pm C, \quad (4)
\]

where \( C \) is is small disturbance propagation speed, m/s.

These equations can be reduced to the following form:

\[
\frac{\partial Q}{\partial t} + (V \mp C) \frac{\partial Q}{\partial x} = B (V \pm C) \left[ \frac{\partial Z}{\partial t} + (V \pm C) \frac{\partial Q}{\partial x} \right] = F_1,2 \quad (5)
\]

where

\[
F_1,2 = V^2 (-B \frac{\partial Z_0}{\partial x} + \frac{\partial w}{\partial x} | h = \text{const} ) - gw \frac{Q|Q|}{R C^2} - g (V \mp C). \quad (5)
\]

Calculation of unsteady water flow in a channel is reduced to solving equation (4) with initial and boundary conditions, as well as matching condition in places of concentrated inflow, a sharp change in cross-section, or at hydraulic structures.

The initial conditions are given in the following form:

\[
Z (x, 0) = ; Q (x, 0) = (x). \quad (6)
\]

The boundary condition is set by one of the following dependencies:

\[
Z = Z (t), \quad Q = Q (t), \quad Q = Q (Z) \quad (7)
\]

While only flow regimes \( |V| < C \) are considered, then only one boundary condition is specified in each section. For points along the length of the channel, in which there are discontinuities in the
geometry, concentrated inflow and similar factors, the conjugation conditions apart from the boundary ones for two adjacent sections are noted.

Pairing conditions nth and (n + 1)th sectors can be presented as follows:

\[ Z_m (x_m, t) = (x_m, t) \]  
\[ Q_m (x_m, t) = Q_{m+1} (x_m, t) - Q_{m+1/2}(t) - \Omega_m + \frac{1}{2} \frac{\partial Z}{\partial t}, \]  

where \( Q_{m+1} \) is сосредоточенный приток, given function of \( t \); \( \Omega_m + \frac{1}{2} \frac{\partial Z}{\partial t} \) is inflow stipulated by additional capacity at the border of the sites.

If it is necessary to take into account the influence of local resistances, the pairing conditions are as follows:

\[ Z_m (x_m, t) = (x_m, t) \]  
\[ Q_m (x_m, t) = (x_m, t) + Q_m Q_m , \]

where \( (x_m, t) \) is given function of \( t \). Equations (4)…(11) specifically describe the problem of unsteady water flow in a channel.

Having approximated relations (4) ... (11) using an implicit scheme, it is possible to obtain a determined system of algebraic equations for the unknown variables \( n = 0, 1, 2, \ldots, N \).

To solve the problem of determining the mismatch between the flow rate of water in the channel and the supply of the transfer pumping station, the dependence \( Z = Z () \) is of particular interest.

The pumping in most cases changes discretely, by alteration of the composition of the constituent units. Consequently, the mismatch \( \Delta Q \) in the general case is determined with an excess using the family of curves \( Z = Z () \).

Taking into account the above, the determination of the mismatches that have arisen in the “channel-transfer pumping station” system is carried out using an algorithm, the block diagram of which is shown in Figure 2.

**Figure 2.** Block diagram of the algorithm for determining the mismatch in the “channel-transfer pumping station” system

4. Conclusion

1. The presented method and algorithm for determining the mismatch in the “channel-transfer pumping station” system allows synthesizing an effective control system for the pumping station,
which operates on the basis of data received from the water level sensor installed in the zone of hydraulic influence of the transfer pumping station.

2. The considered concept of a self-regulating irrigation system and its methodology enables the following:
   - to dramatically reduce water losses from canals due to better coordination of water supply and water consumption,
   - to increase the economic efficiency of systems by improving design technology based on mathematical modeling.

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