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Mathematical Models Of Typical Elements Of Water Management Systems

Ilkhomjon Makhmudov[1] , Daniyar Jumamuratov[2] , Aybek Seytov[3] , Umidjon Sadiev[4] , Uktam Jovliev[5] , Jonibek Shonazarov[6] , Oybek Muminov[7] , Muzaffar Ruziev[8] , Muxtorbek Yusupov[9]

[1]*Doctor of technical sciences, Professor, Scientific Research Institute of Irrigation and Water Problems, Uzbekistan.*
[2]*Candidate of technical sciences, Docent, Nukus branch of Navoi State Mining Institute,*
[3]*PhD , Docent, Scientific Research Institute of Irrigation and Water Problems, Uzbekistan.*
[4]*PhD, Scientific Research Institute of Irrigation and Water Problems, Uzbekistan.*
[5]*PhD, Scientific Research Institute of Irrigation and Water Problems, Uzbekistan.*
[6]*Assistant, National Research University "TIQXMMI" Counter irrigation and agricultural technologies Institute, Department "Melioration and melioration", Uzbekistan.*
[7]*Doctorate, Department of Civil engineering construction, faculty of Construction Fergana polytechnic institute, Uzbekistan.*
[8]*Scientific Research Institute of Irrigation and Water Problems, Uzbekistan.*
[9]*Chirchik State Pedagogical Institute, Uzbekistan.*

Abstract: The article shows the results of developed mathematical models of typical elements of water management systems for the optimal management of water resources of large main canals with cascades of pumping stations and uses methods for system analysis of the process of water supply and water intake, modern methods for calculating the operating modes of pumping stations with long pipelines and calculating the operating modes of canal sections.

Keywords: mathematical model, unsteady flow of water, main canals, optimal control problems, fundamental solution, differential equations, hydrotechnical structure.

Introduction

Uzbekistan is considered as one of the largest irrigation farming countries in Central Asia. Proper use of existing water and land resources can increase crop production and yields in the agriculture sector [1]. The problem of managing a water management facility differs in that it is necessary to solve the problems of collecting information about the management object from large territories and managing its links, which are located at long distances from each other (in some cases more than a hundred kilometers). This is especially typical during managing river basin facilities. This situation necessitates the use of systems for collecting, transmitting and processing information by objects located at large distances, which consists of hardware and software.

Materials and methods

Dynamic processes in the sections of the canals, limited by barrier structures are described by a one-dimensional system of Saint-Venant equations for the unsteady movement of water in the open canals. When using canals, it is important to assess quantitative indicators of the state of reliability associated with such adverse effects as wear of canal dams under the influence of dangerous filtration currents, subsidence, and elevation of canal sections relative to the area [2].

The characteristic form of the record for the unsteady movement of water in the sections of open canals has the following matrix form [3]:

$$S\frac{\partial U}{\partial t} + \Lambda S\frac{\partial U}{\partial x} = F(U, K, t) \quad . \qquad (1)$$

where:

$$S=\begin{bmatrix}1 & -B(v+c)\\ 1 & -B(v-c)\end{bmatrix};\qquad U=\begin{bmatrix}Q\\ z\end{bmatrix};$$

$$\Lambda=\begin{bmatrix}v-c & 0\\ 0 & v+c\end{bmatrix},\qquad F=-BIv^2-g\omega\frac{Q|Q|}{K}$$

Canal section - 1:

Boundary conditions at x=0 of section – 1 [3]

$$\mathbf{Q_1(0,t)=F_0(t)=\mu_0\omega_0(t)\sqrt{2g[z_{upstream}(t)-z_{downstream}(0,t)]}} \qquad (2)$$

where: μ_0 – discharge coefficient of the hydraulic structure located at the beginning of the canal section, $\omega_0(t)$ – open hole area of shutter, $z_{upstream}(t)$ – upstream water level mark, g – acceleration of gravity, $z_{downstream}(0,t)$ – the mark of the water level at the beginning of the canal or the downstream of the hydraulic structure located at the beginning of the canal section.

Boundary conditions at x=l_1 of section – 1 [4]

$$\begin{aligned}
&Q_1(l_1,t)=F_1(t)+F_2(t)+F_3(t),\\
&F_1(t)=\mu_1\omega_1(t)\sqrt{2g[z_1(l_1,t)-z_2(0,t)]},\\
&F_2(t)=\mu_2\omega_2(t)\sqrt{2g[z_1(l_1,t)-z_3(0,t)]},\\
&F_3(t)=\mu_3\omega_3(t)\sqrt{2g[z_1(l_1,t)-z_4(0,t)]},
\end{aligned} \qquad (3)$$

where: μ_i – discharge coefficient of the hydraulic structure located at the beginning of the canal section, ω_i (t) – open hole area of shutter, z_i (0,t) – – the mark of the water level at the beginning of the canal, z_i (l_i, t) – the mark of the water level at the end of the canal.

Structurally, the model of a hydraulic structure is represented by follow:

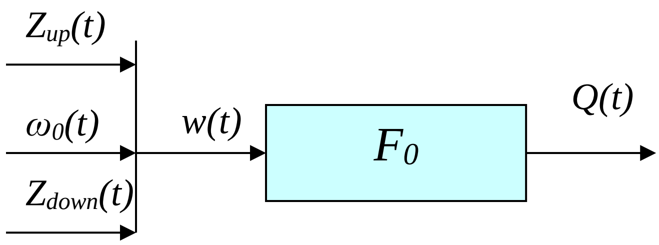


Fig.1. – Describing block of hydrotechnical structure

From the condition of conjugation of the canal sections, we use the boundary conditions for the canal sections. If the sections of the canal are interconnected by partitioning structures with a flooded outflow from under the shutter (Fig. – 2), the expressions for the boundary conditions have the following form:

As shown in [5,6], the processes taking place in the canal sections can be structurally represented as a block with distributed parameters (Fig. 2b).

where: $w_{chs}(t)$ = {$Q_0(x)$, $z_0(x)$, $u_1(t)$, $u_2(t)$, and q(x,t) }, $Q_{chs}(x,t)$ = {Q(x,t), z(x,t)} - output signals are the sequence of input signals of the block of the corresponding canal section.

$\mathscr{L}_A^{chs}$ – is an algorithmic operator of the canal section, uniquely connecting the sequence of input signals with the sequence of output signals. The algorithmic operator is a software module that determines the output signals from the given values of the input signals [7].

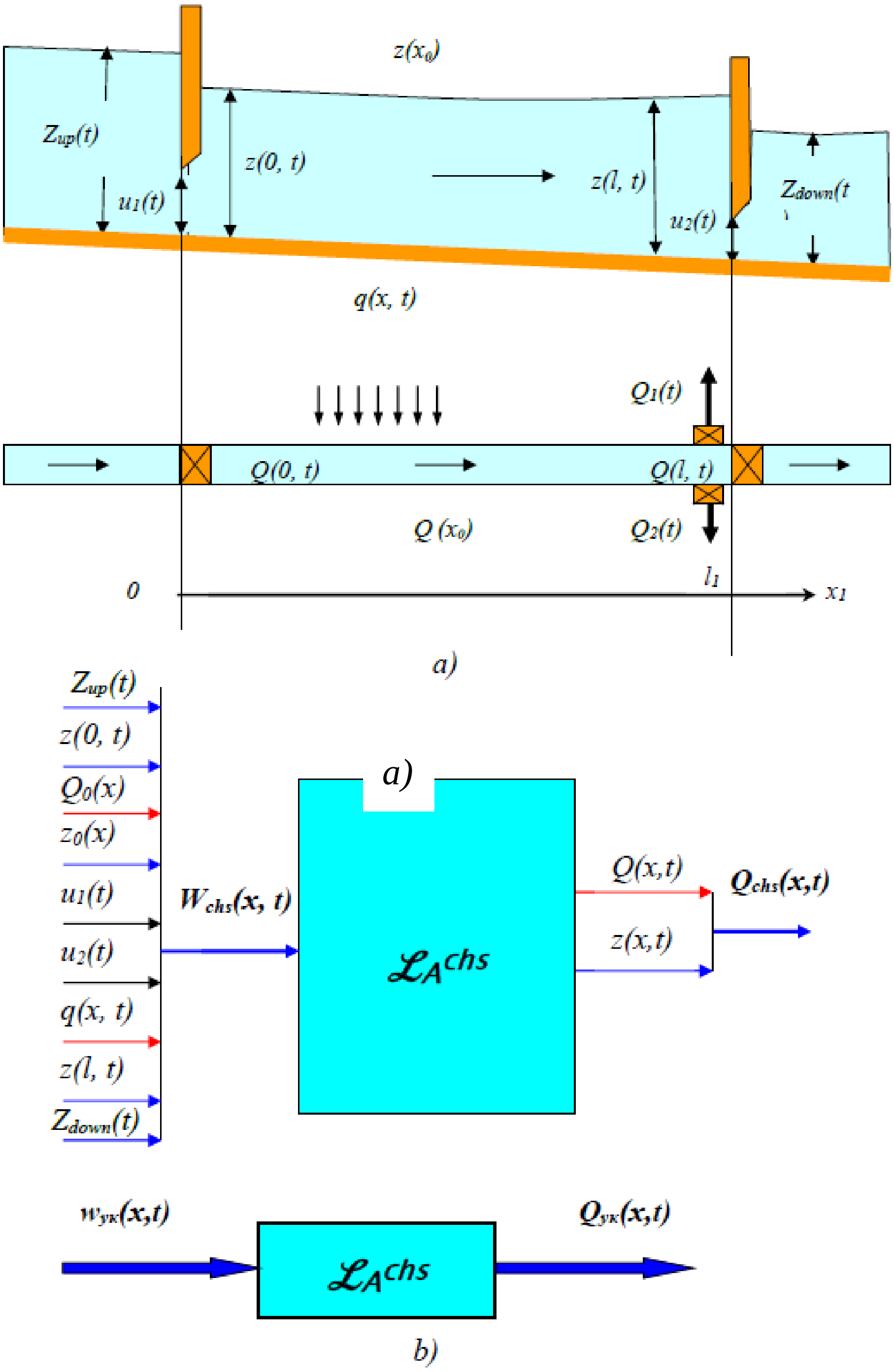


Fig.2. - Block describing, water management object - canal section

Mathematical model of a pumping station

The operating modes of the pumping station are determined algorithmically in the following sequence:

Height of lift (static pressure) - is defined as the difference between the levels of the upstream and downstream of the pumping station [8]:

$$\mathbf{H} = \mathbf{z_{up}} - \mathbf{z_{down}} \qquad (4)$$

where: $\mathbf{z_{up}}$ – upstream water level mark,

$\mathbf{z_{down}}$ - downstream water level mark.

The characteristic of pressure losses in the pipeline of the pumping station is presented in the reference catalogs in the form of functional curves depending on the flow and lifting height [9]:

$$\mathbf{\Omega_T^i} = \begin{cases} \mathbf{Q_j^i} & \mathbf{J} = \overline{\mathbf{1},\mathbf{K}};\ \ (\mathbf{i} = \overline{\mathbf{1},\mathbf{N}}),\quad \mathbf{N} \le \mathbf{M} \\ \mathbf{H_T^j} & \mathbf{J} = \overline{\mathbf{1},\mathbf{K}} \end{cases} \quad (5)$$

where: Q_j^i - argument of the pressure characteristic of the pipeline, i.e., upstream of the i-th pumping unit; K- number of points in the pressure characteristic; N- the number of operating pumping units; $H_t^j=H+\nabla H_j$ - pressure characteristic function; ∇H_j - pressure loss.

The exploitation characteristics of the pumping unit are presented as a family of curves depending on the height of the water at various angles of rotation of the impeller blades:

$$\mathbf{\Omega_e^i} = \mathbf{\Omega_{H,Q,\phi}} \cup \mathbf{\Omega_{H,\eta,\phi}},\qquad \mathbf{i} = \overline{\mathbf{1},\mathbf{N}}, \quad (6)$$

where:

$$\mathbf{\Omega_{H,Q,\phi}} = \begin{cases} \mathbf{Q_j^i} & \mathbf{i} = \overline{\mathbf{1},\mathbf{N}},\ \ (\mathbf{j} = \overline{\mathbf{1},\mathbf{K}}) \\ \mathbf{H_i} & \mathbf{i} = \overline{\mathbf{1},\mathbf{N}}, \\ \mathbf{\phi_j} & \mathbf{j} = \overline{\mathbf{1},\mathbf{K}}, \end{cases}$$

- discharge characteristic of the pumping unit

$$\mathbf{\Omega_{H,\eta,\phi}} = \begin{cases} \mathbf{\eta_j^i} & \mathbf{i} = \overline{\mathbf{1},\mathbf{N}},\ \ (\mathbf{j} = \overline{\mathbf{1},\mathbf{K}}) \\ \mathbf{H_i} & \mathbf{i} = \overline{\mathbf{1},\mathbf{N}}, \\ \mathbf{\phi_j} & \mathbf{j} = \overline{\mathbf{1},\mathbf{K}}, \end{cases}$$

- energy characteristic of the pumping unit;

φ_j - blade turning angle corresponding to the J-th curve;

η_J^i - Efficiency of the 1st pumping unit for J-th curve.

Permissible area D of operation of the pumping unit in coordinates Q-H is determined by the following external boundaries:

$$\left.\begin{aligned} D_{1\max}^{i} &= \Omega_{T}^{i\max} \cap \Omega_{H,Q,\varphi}^{i}, \\ D_{1\min}^{i} &= \Omega_{T}^{I\min} \cap \Omega_{H,Q,\varphi}^{i}, \\ D_{2\max}^{i} &= \Omega_{H,Q,\varphi\max}^{i}, \\ D_{2\min}^{i} &= \Omega_{H,Q,\varphi\min}^{i}, \end{aligned}\right\} \quad (7)$$

where: Ω_T^{max}, Ω_T^{min} – pipeline characteristic at maximum and minimum geometric lifting height; φ_{max}, φ_{min} – maximum and minimum angles of rotation of the blades of the pumping unit.

If the given values of Q and H are located inside the area D, then it is considered that the required water discharge can be provided by this unit, otherwise this mode cannot be implemented by this unit. When several units are operating, the boundaries of the allowable area are determined by summing the flow discharges within the boundaries of the areas at a constant lifting height.

Flow discharge, gauge height and efficiency operating pumping unit, i.e., the state of each operating pumping unit is characterized by a triple:

$$(z_{upstream}, z_{downstream}, \varphi),$$

where: φ_p^i – angle of rotation of the blades of the i-th operating pumping unit. Consequently, the flow discharge and efficiency of the i-th pumping unit is determined from the following expressions:

$$\Omega_p^i = (\Omega_t^i \cap \Omega_{H,Q,,\phi}) \cap \Omega_{H,Q,\eta},\quad \phi_i = \phi_i^p,\qquad \Omega_{H,Q,\phi} \subset \Omega_э^i,\ \ \Omega_{H,\eta,\phi}^i \subset \Omega_э^i \quad (8)$$

The total discharge and power consumption for the pumping station as a whole is determined as the algebraic sum of the flow discharge and capacities of the operating unit [10]:

$$\mathbf{Q}_{HC} = \sum_{\mathbf{i}\in\mathbf{N^p}} \mathbf{Q_i},\qquad \mathbf{N}_{HC} = \sum_{\mathbf{i}\in\mathbf{N^p}} \mathbf{N_i}, \quad (9)$$

where: $N_i=\Upsilon^{H}{}_iQ_i/102\eta_i$ /kW/-power of the i-th pumping unit;

Υ- volumetric weight of the pumped liquid.

Thus, the water flow and power consumption of the pumping station are determined by the following algorithmic dependencies:

$$\mathbf{Q_{ps}}(,\mathbf{t}) = \mathbf{F_q}(\mathbf{t},\ \mathbf{N_i^p}(\mathbf{t}),\ \mathbf{z_{upstream,}}(\mathbf{t}),\ \mathbf{z_{downstream,}}(\mathbf{t}))$$
$$\mathbf{N_{ps}}(,\mathbf{t}) = \mathbf{F_n}(\mathbf{t},\ \mathbf{N_i^p}(\mathbf{t}),\ \mathbf{z_{upstream,}}(\mathbf{t}),\ \mathbf{z_{downstream,}}(\mathbf{t})) \quad (10)$$

where: $N^p(t)$- many operating pumping units, $Z_{upstream}$ (t) – upstream water level mark, $Z_{downstream}(t)$ – downstream water level mark.

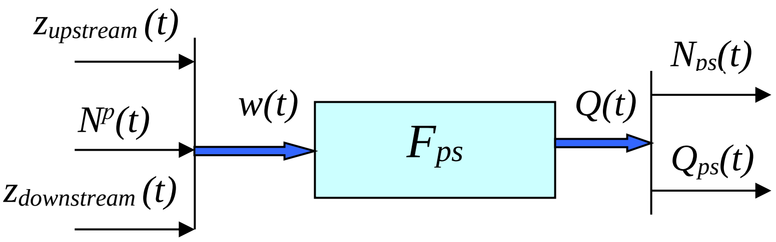


Fig.3. - Block describing the pumping station

The block describing the pumping station is shown in the figurehere: $w(t)=\{z_{upstream}(t), N^p(t)$ and $z_{downstream}(t)\}$, $Q(t) = \{N_{ps}(t), Q_{ps}(t)\}$ – sequence of input and output signals of the block of the corresponding reservoir. F_{ps} –algorithmic operator of the pumping station block [9,10,11]:

Mathematical model of the reservoir

The change in water volumes in the reservoir over time is described by the following differential equation [12,13]:

$$\frac{dW_i^R}{dt} = \sum_{j\in N^{inflow}} Q_j^{inflow} - \sum_{j\in N_1^{intake}} Q_j^{intake} - Q_i^L - Q_i^{discharge},$$

$$W_i^R(0) = W_0^R, \qquad W^R = F_w(H^R), S^R = F_s(H^R), \qquad t \in [0, T] \qquad (11)$$

где W_i^R – reservoir water volume at a time t; Q_j^{inflow} and Q_j^{intake} – water discharge rate of the j-th inflow and water intake from the reservoir; Q^L – intensity of water loss in the reservoir; $Q^{discharge}$ – discharge of water from the reservoir; S^R – reservoir surface area, $F_w(H^R)$ - volumetric characteristic of the reservoir, $F_s(H^R)$ – areal characteristic of the reservoir.

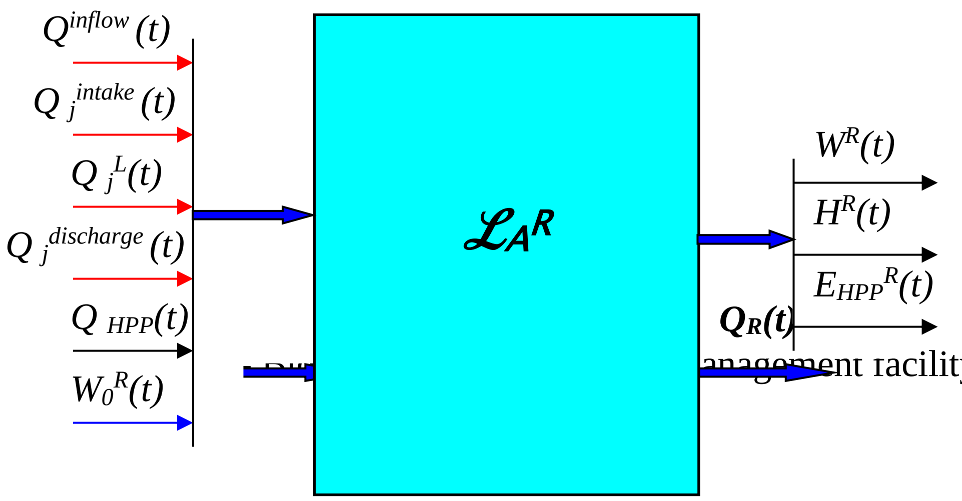
Many reservoirs are designed for complex purposes, which include hydroelectric power plants. For such reservoirs, descriptions of energy regimes are required in the model

The generation of electricity by a hydroelectric power plant is described by the following expression [14]:

$$E_{HPP}^R = 9{,}81\eta \int_0^t \Delta H^R(\tau) Q_{HPP}(\tau) d\tau \qquad (12)$$

where: $\Delta H(t)$ – pressure change over the time, $Q_{HPP}(t)$ –water discharge flowing through the turbines of a hydroelectric power plant, η - HPP turbine efficiency.

In that way, by knowing $Q_j^{inflow}(t)$, $Q_j^{intake}(t)$, $Q^L(t)$, $Q^{discharge}(t)$, $Q_{HPP}(t)$ and W_0^R - solving equation (1), and by expression (2) we can determine $W^R(t)$, $H^R(t)$ and $E_{HPP}^R(t)$ and structurally present it as a block (Fig.4)



where: $W_R(t)=\{Q_j^{inflow}(t), Q_j^{intake}(t), Q^L(t), Q^{discharge}(t), Q_{HPP}(t)$ and $W_0^R\}$, $Q_R(t) = \{W^R(t), H^R(t)$ and $E_{HPP}^R(t)\}$ – the sequence of input and output signals of the block of the corresponding reservoir.

$\mathscr{L}_A^R$- an algorithmic operator that uniquely links the sequence of input signals with the sequence of output signals.

Mathematical model of a gauging station in the sections of the canal and rivers

The gauging station on sections of rivers and canals are built to unambiguously determine the water discharge according to the measured values of the water level on them. There is a special calibration characteristic of the gauging station where there is a dependence in the form of a graph or table, determined on the basis of field measurements of water discharge at various level values.

Mathematically, this dependence is written as [15]:

$$Q = f(H), \tag{13}$$

где Q – water discharge, H water level.

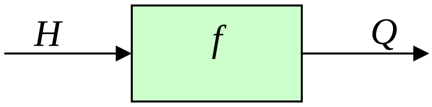


Fig.5. - Block describing the gauging station in the area of rivers and canals

Results and Discussion

The main results of the article are:

- Mathematical models and algorithms have been developed for modeling processes in automatic water distribution control systems at typical water management facilities (hydrotechnical structures, hydroelectric facilities and reservoirs)
- Recommendations have been developed for choosing a control scheme for typical water management facilities based on modeling processes in automatic control systems for typical water management facilities.

Conclusion

In this article, typical elements of water management systems are selected, mathematical models, algorithms and software modules for modeling typical elements of water management systems for automation, collection and processing of data objects are developed.

The developed algorithms can be applied in the design and operation of automation systems, data collection and processing.

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