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Theoretical foundations for measuring and determining the flow rate of water delivered from reservoirs and canals to users

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ABSTRACT

An analysis of the structures of water conduits for reservoirs and irrigation canals is conducted. Existing methods for measuring and determining the flow rate during water release from such structures are analyzed, and ways to implement these methods based on modern information-measurement and telecommunication technologies are investigated. In accordance with the goals and priority directions of the National Water Strategy of the Republic of Azerbaijan, the theoretical foundations for creating operational flow rate control systems in reservoirs and irrigation canals are developed on the basis of modern measurement and information-communication technologies. A structural diagram and components of a remote flow rate control and management system for distributed water supply networks supplied by reservoirs are proposed. Hydraulic processes in the water conduit structures of reservoirs and canals are analyzed, including variants of liquid discharge from thin-walled orifices into the atmosphere and under the water level, as well as local resistances causing additional pressure losses in the reservoir outlet tunnels. For more accurate calculation of the flow rate, it is proposed to determine the total resistance coefficient of the system by identifying practical losses for each specific case.

1. Introduction

In terms of water supply, the Republic of Azerbaijan's natural conditions are characterized by a scarcity of water resources. Half of our country's 86.6 thousand km^2 area consists of plains and lowlands, which leads to significant water loss and a negative water balance in those regions. In these areas, surface evaporation is several times higher than precipitation. While the Republic's internal surface runoff is 10.0 km^3, surface evaporation is 26.6 km^3, which is 2.6 times higher. Almost the entire territory of our country lies in a moisture deficiency zone [1].

Reservoirs are water management facilities designed to collect and regulate river flows, constructed since ancient times to meet human water needs and for irrigation purposes. The first reservoir in Azerbaijan, Ganligol, with a total capacity of 0.9 million m^3, was built in 1864 in the territory of Nakhchivan. Currently, there are 153 reservoirs of various sizes across our country. The total water volume of these reservoirs amounts to 21.9 billion m^3. By regulating flood and torrent waters and generating energy, reservoirs hold great importance in the development of human activity and the country's agriculture [2].

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The area and volume of our country's main reservoirs are given in the following table.

No	Reservoir	Area, km²	Volume, km³
1.	Mingachevir Reservoir	605	15.73
2.	Shamkir Reservoir	116	2.68
3.	Yenikend Reservoir	23.2	1.58
4.	Araz Reservoir	145	1.254
5.	Sarsang Reservoir	14.2	0.565
6.	Takhtakorpu Reservoir	8.71	0.27
7.	Jeyranbatan Reservoir	13.9	0.186
8.	Agstafa Reservoir	6.3	0.12
9.	Varvara Reservoir	22.5	0.06
10.	Khanbulanchay Reservoir	24.6	0.052
11.	Khachinchay Reservoir	1.76	0.023

The majority of reservoirs in the Republic are used for irrigation. To this end, canals have been extended from the reservoirs. Irrigation canals were built for the purpose of watering arid regions. The total length of water canals across the republic is nearly 50,000 kilometers, while the total area of irrigated land is over 1.4 million hectares [3].

In accordance with the "Action Plan for Ensuring the Efficient Use of Water Resources for 2020-2022," approved by Order No. 2178 of the President of the Republic of Azerbaijan dated July 27, 2020, "On Additional Measures to Ensure the Efficient Use of Water Resources," the "National Strategy for the Efficient Use of Water Resources" (hereinafter referred to as the National Water Strategy) has been developed.

The National Water Strategy, covering the years 2024-2040, will be implemented in three stages: a short-term strategic vision through 2027, a medium-term strategic development vision through 2030, and a long-term strategic target vision through 2040.

2. Problem statement

The goals and priority directions of the National Water Strategy include priorities such as promoting the rational use of water, strengthening the protection of water basins, creating "Smart Water" systems, and others; these can be directly implemented through the creation and application of operational flow rate control systems in such utilities based on modern measurement and information-communication technologies. Let us examine these points using the example of reservoirs and irrigation canals.

The measurement and determination of the flow rate delivered to the users from both reservoirs and water canals, the collection and analysis of their data in a unified center, decision making, and the remote control of objects with feedback are among the most important challenges ahead.

3. Solution

The article aims to increase the efficiency of existing water resource use by leveraging the advantages of modern information technologies for the remote control and operational management of flow rates in distributed water supply networks supplied by reservoirs. To achieve this, the theoretical foundations for measuring and determining the flow rate delivered from reservoirs and canals to users, as well as the methods for their implementation, are investigated.

The general structural diagram of the remote control and management system for the flow rate in distributed water supply networks supplied by a reservoir is proposed as shown in Fig. 1, using modern measurement methods and devices, control units, and radio-linked information-communication technologies. These devices, consisting of microprocessor-based flow rate measuring sensors, actuators, and microcontroller-based intelligent control units, serve as the primary interface for both local control and communication with the central system.

The system consists of branch control and management units (BCMU) installed on each branch diverted from the water supply network to a consumer, intelligent devices capable of transmitting real-time data from the Reservoir Control and Management Dispatch Center (RCDC) to the Network Central Control and Management Point (NCCMP) via GSM communication in "ONLINE" mode, and the algorithms that implement their mathematical support.

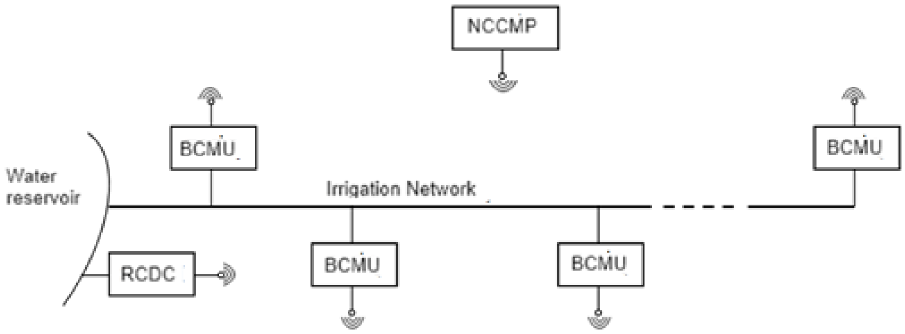

Fig. 1. Structural diagram of the remote flow rate control and management system for distributed water supply networks supplied by a reservoir.

NCCMP – Network Central Control and Management Point; RDC – Reservoir Dispatch Center; BCMU – Branch Control and Management Unit.

The following scientific and technical issues are resolved in the system:

- Development of algorithms for calculating the current flow rate of water released from the reservoir into its outlet tunnel based on the gate opening area;
- Development of algorithms that account for the impact of local resistances on pressure loss in the reservoir outlet tunnel;
- Development of measurement and calculation algorithms for the current flow rate of water released from the reservoir outlet tunnel into the water supply network;
- Development of algorithms for calculating the water flow rate released to each consumer at the branching nodes of the water supply network based on their gate opening area (Q (t)) and determining the integral (cumulative) water flow rates for various periods;
- Regular transmission of data to the NCCMP in "ONLINE" mode;
- Determination of water losses in the network through the development and implementation of balance control algorithms.

Analysis of the structures of reservoirs, irrigation canals, and their water conduits shows that the number and design of gates vary; however, gates with rectangular orifices are predominant (Fig. 2). It should be noted that in reservoirs, it is usually necessary to use a hydraulic system for the management of water conduits. However, this is not required for canal water conduits, where the hydraulic system is replaced by a screw-operated slide gate. Thus, in order to determine the flow rate of water transferred from reservoirs and canals to the canal and each user respectively, it is necessary to accurately measure and control the gate opening height a.

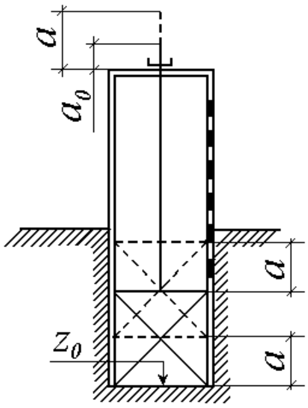

Fig. 2. Construction of water conduits in reservoirs and irrigation canals. a – gate opening height, z_0 – level of the gate sill (bottom).

Hydraulic processes occurring in the water conduit structures of reservoirs and canals have been examined in several works [4, pp. 208-211; 5, pp. 24-27], including variants of liquid discharge from thin-walled orifices both into the atmosphere and under the water level.

Let us examine the analysis of these variants for the purpose of creating and applying operational flow rate control systems based on modern measurement and information-communication technologies.

Liquid discharge from an orifice in the wall of a thin-walled tank into the atmosphere (Fig. 3.a) and under the water level (Fig. 3.b) is examined. Here, P_o is the pressure at the free surface of the liquid in the tank, S_o is the cross-sectional area of the orifice, S_j is the cross-section of the jet at distance l_o from the tank wall, and H is the distance from the free surface of the liquid to the center of gravity of the orifice, in other words, the immersion depth of the center of gravity of the orifice below the liquid level. Under the condition of neglecting the drop of the jet under the influence of gravity at distance l_o, the distance between the center of gravity of the jet's cross-section in plane 2–2 and the free surface of the liquid is H. Observations show that after the liquid jet exits the thin-walled orifice, it contracts slightly in plane 2–2 at a close distance to the tank wall; that is, the cross-sectional area of the jet S_j is smaller than the cross-sectional area of the orifice S_o. This is due to the effect of inertial forces arising from the change in direction of the liquid particles' velocities as they approach the orifice. Plane 1–1 passes through the free surface of the liquid, and plane 2–2 passes through the contracted section of the jet's cross-section.

The ratio of the compressed cross-sectional area of the jet to the cross-sectional area of the orifice is called the jet contraction coefficient:

$$\varepsilon = \frac{S_j}{S_o}; \tag{1}$$

To find the flow rate of the liquid flowing from the tank and the average velocity in the contracted cross-section of the jet, the Bernoulli equation was applied to sections 1-1 and 2-2; as a result, the following expression was obtained for the average velocity in the contracted cross-section of the jet:

$$v_0 = \varphi\sqrt{2gH}. \tag{2}$$

Here, $\varphi -$ velocity coefficient, dependent on the hydraulic resistance coefficient ξ, which accounts for the pressure loss between sections 1-1 and 2-2, expressed by the following formula:

$$\varphi = \sqrt{\frac{1}{1+\xi}} \tag{3}$$

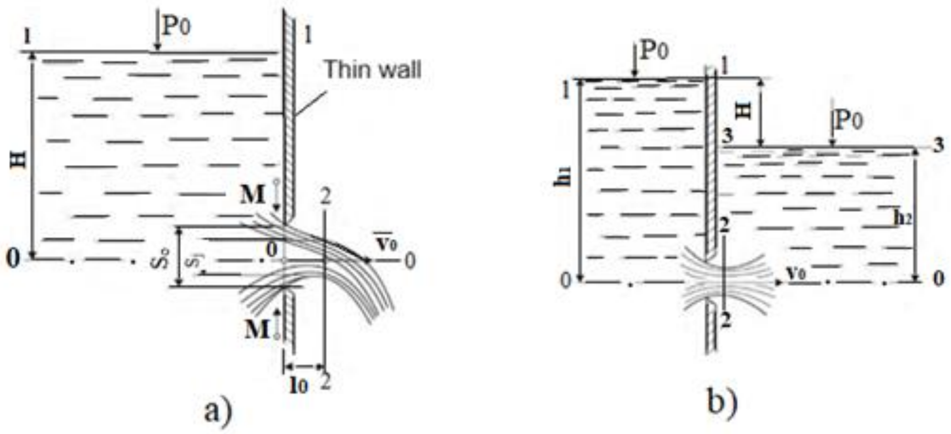

Fig. 3. Liquid discharge from an orifice in the wall of a thin-walled tank: a) into the atmosphere and b) under the water level

Once the average velocity in the contracted cross-section of the jet is known, the following expression is obtained for the flow rate of the liquid flowing from the tank:

$$Q = S_o \varphi \varepsilon \sqrt{2gH}. \tag{4}$$

Here, $\varphi\varepsilon = \mu$ is the discharge coefficient.

As seen from the expressions, all these flow coefficients are interrelated. All flow coefficients vary depending on the value of the Reynolds number.

Graphs of the relationship between the flow coefficients ε, φ, μ and the Reynolds number (Re) for the case of perfect jet contraction (Fig. 4) were proposed by A.D. Altshul and are provided in relevant handbooks [6, p. 49].

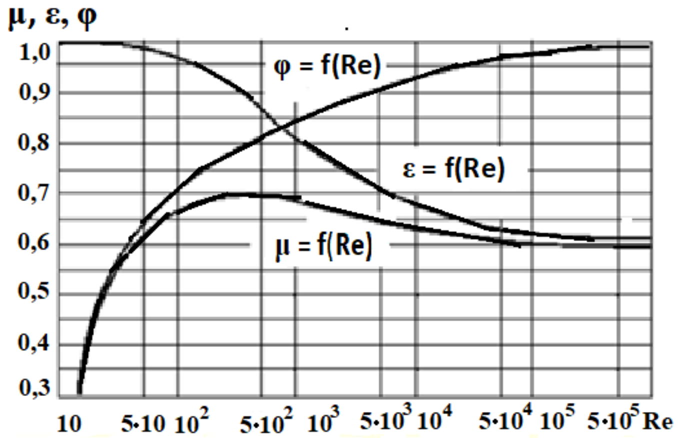

Fig. 4. Graphs of the relationship between the flow coefficients ε, φ, μ and Re

As seen, as the Reynolds number increases up to 10^5, the velocity coefficient φ also increases. With further increases in the number, the values of can be considered constant and φ = 0.97. (As the Reynolds number increases, the contraction coefficient decreases. When the Reynolds number is , the coefficient is practically accepted as constant, and for the case of perfect contraction, this value is taken within the interval of ε ≈ 0,61 ÷ 0,64).

On the other hand, to further refine the discharge coefficient μ, for values of the Reynolds number greater than ten thousand, another formula by A.D. Altshul can also be used:

$$\mu = 0{,}592 + \frac{5{,}5}{\sqrt{Re}} \tag{5}$$

It should be noted that flow coefficients have been studied for years and confirmed by practical results; they are provided in handbooks for various approximate hydraulic calculation cases. For instance, for cases of water flowing through circular and other shaped orifices with a diameter of d $> 1\ cm$, it is recommended to take these coefficients as follows [6, p. 49]:

– jet contraction coefficient - $\varepsilon = 0.61 - 0.63$;
– velocity coefficient - $\varphi = 0.97 - 0.98$;
– discharge coefficient - $\mu = 0.60 - 0.62$;
– resistance coefficient - $\xi = 0.04 - 0.06$.

In the case of liquid discharge from a thin-walled orifice under another level (Fig. 3.b), this level must be taken into account.

In the case of submerged discharge from an orifice, the calculation formulas are the same as those for discharge into the atmosphere. However, in expressions (2) and (4), head H is the difference between the hydrostatic heads on both sides $\mathrm{H} = \mathrm{h}_1 - \mathrm{h}_2$, and the discharge coefficient μ differs from the case of discharge into the atmosphere [7, p. 68].

At the same time, when determining the flow rate of water released from reservoirs to the user, local resistances can arise in addition to friction resistance, depending on the construction of the outlet tunnel. Specifically, local resistances occur as a result of abrupt changes in the flow’s normal configuration, cross-section, and direction within the outlet tunnel, which causes additional pressure loss. The pressure loss in local hydraulic resistances usually constitutes a significant portion of the system’s pressure loss and is calculated using the following formula:

$$h_y = \xi \frac{v_1^2}{2g} \tag{6}$$

Here, v_1 is the average velocity in the section of the tunnel where the local resistance is located, and ξ is the local resistance coefficient.

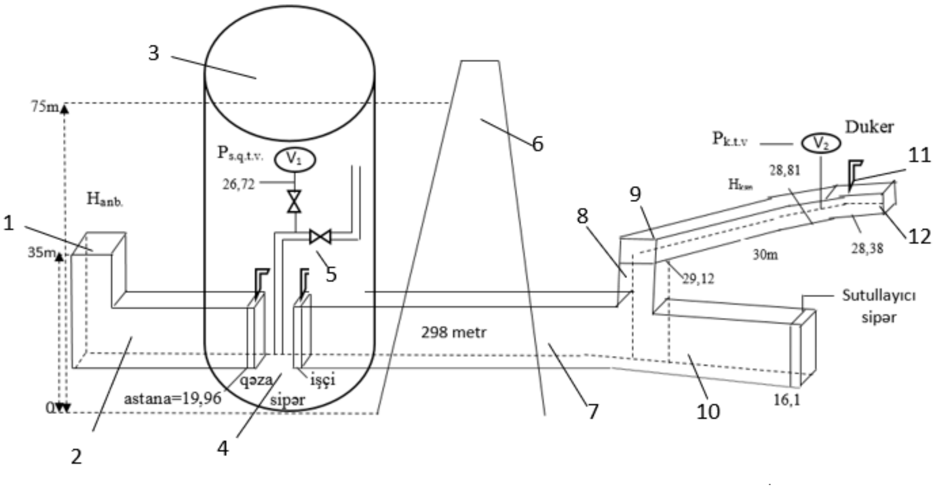

Fig. 5. Water delivery scheme from the Khanbulanchay reservoir

1 – intake tower, 2 – inlet tunnel, 3 – gate tower, 4 – gates, 5 – air vent valve, 6 – earthen dam of the reservoir, 7 – water conduit tunnel, 8 – canal tower, 9 – outlet canal, 10 – spillway tunnel, 11 – inverted siphon gates, 12 – inverted siphon

Usually, the local resistance coefficient ξ is more accurate when determined through experimentation. For this purpose, specialized graphs, tables, and reference materials are compiled. However, this is a very extensive task, and in some cases, conducting experiments faces major obstacles; nevertheless, for certain specific cases known in the literature [4, pp. 197-210], it is possible to determine ξ theoretically. Examples include pressure loss in suddenly and gradually expanding flows, pressure loss in flow contraction, etc. Therefore, by analyzing the reservoir outlet tunnel (Fig. 5) from this perspective, specifically by representing it as a system of consecutively connected, previously studied sections, it would not be difficult, given the modern stage of development in information and microprocessor technologies, to calculate the total local resistance coefficient as the algebraic sum of the local resistance coefficients of its individual parts. **In a suddenly expanding flow, the pressure loss** is equal to the velocity head resulting from the difference in velocities. In literature, this is known as the Borda-Carnot theorem. According to the continuity equation, $v_1 S_1 = v_2 S_2$; therefore, if we write $v_2 = \frac{v_1 S_1}{S_2}$, we obtain the following expression for the local pressure loss:

$$h_y = \xi \frac{v_1^2}{2g} \tag{7}$$

$$\xi = (1 - \frac{S_1}{S_2}) \tag{8}$$

Therefore, the local resistance coefficient in a pipe with a suddenly expanding cross-section depends on the diameters of the narrow and wide sections. If $S_2 >> S_1$, then by assuming $v_2 \approx 0$, we get $S = 1$; i.e.,

$$h_y = v_1^2 / 2g \tag{9}$$

The gradually expanding section of a flow is called a diffuser. In a diffuser, the velocity of the liquid flow decreases while the pressure increases; as a result, kinetic energy is converted into pressure energy. The velocity of the liquid layer near the wall becomes so small that its kinetic energy cannot overcome the pressure increase and comes to a halt, or even moves in the opposite direction. This backflow causes the main flow to separate from the wall and leads to the eddy formation. If we determine the local pressure loss for a diffuser, we obtain the following expression:

$$h_y = \xi \frac{v_1^2}{2g} \tag{10}$$

Local resistance in flow contraction. Here, provided the ratio of the cross-sectional areas remains constant, the energy loss is lower compared to the case of sudden expansion. Energy loss in a liquid flow through a suddenly contracting section occurs due to the onset of friction and the formation of vortices at the inlet of the narrow part of the flow. As a result, the cross-section of the flow in the contracting part decreases, and the space remaining between the wall and the flow fills with eddies. Pressure loss occurs during the subsequent expansion of the flow. By making the transition to the narrow structure smooth, the pressure loss at the entry point can be reduced.

Total resistance coefficient of the system. Normally, there are points in hydraulic structures where a large number of local resistances are connected. In such cases, the total pressure loss will consist of the algebraic sum of the pressure losses spent on overcoming friction along the length of the structure and the pressure losses arising from local resistances [4, p. 207].

We can write the total pressure loss as follows:

$$H = \xi_s \frac{v_1^2}{2g}, \tag{11}$$

where ξ_s is the total resistance coefficient of the system, expressing the sum of friction and local resistances of individual sections as follows:

$$\xi_s = \sum_{j=1}^{k} \lambda_j \frac{L_j}{d_j} (\frac{S_1}{S_j})^2 + \sum_{i=1}^{n} \xi_1 (\frac{S_1}{S_i})^2 \tag{12}$$

Here, λ_j, d_j, S_j are the resistance coefficient spent on friction over individual lengths $L_{j,}$, the diameter, and the cross-sectional area, respectively:

4. Conclusion

1. Analysis of the variants of liquid discharge from thin-walled orifices into the atmosphere and under the water level shows that they can play a foundational role in determining the flow rate for most water conduits of reservoirs and canals. This, in turn, presents an important task: the precise measurement of parameters H, h_1, h_2 included in the above expressions, and both the precise measurement and operational management of S_o, as well as gathering this data into a single center for operational processing during mode changes. In other words, there is a need for the creation of modern SCADA systems. To this end, the measurement and control variants of the level and S_o parameters must be analyzed.

2. Analysis of the structures of reservoirs, irrigation canals, and their water conduits shows that while the number and design of gates vary, gates with rectangular orifices are predominant. This, in turn, requires an individual approach to improving metrological and operational parameters by taking into account local resistances when designing the measurement system for each specific case.

3. For gates with rectangular orifices, the measurement and control of the opening height a, the selection of industrial instruments, and the development and implementation of methods to minimize installation errors must be performed.

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