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Hydraulic aspects of the layout of head structures during water intake from lowland rivers

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Abstract. The article discusses various types of new improved dam water intake hydroelectric systems, sedimentation facilities, sediment control devices on rivers and canals with a rational layout. The results of the analysis of studies on the use of the theory of transverse circulation and methods of artificial, active regulation of the structure of the water intake flow are presented, which has become widespread in world practice and is the main one for creating an effective design of water intake headworks for pumping stations and hydropower facilities that provide them with reliable protection from sediments. The author of the article, on the basis of numerous experimental data obtained in various countries of the world, makes a conclusion about the effectiveness and prospects of using front-type structures with more than 50% water intake. The design of water intakes of this type has been significantly improved; they can be successfully used in various conditions, including on Mountain Rivers. The author draws attention to the development of a new design of the pioneer ditch, which ensures the efficient passage of bottom sediments into the downstream of the structure, which prevents intensive silting of the reservoir basin by bottom sediments and improves the efficiency of the dam water intake.

1. Introduction

For a country located in a region with a hot climate, with a large irrigated area, guaranteed provision of water intake facilities of pumping stations, operational energy paths of hydropower facilities with the required volume of water, satisfying the need for water resources and the generation of the required capacity of hydropower facilities through the construction and reconstruction of water management and reclamation systems , is among the highest priority tasks for the national economy. In the practice of hydraulic engineering and hydropower construction, very often water intake is carried out by a dam method [1]. In cases where the household levels of the river are insufficient for the intake of water or the creation of the necessary pressure, dam water intake hydroelectric systems are installed to the power structure by gravity flow to the consumer, where the dams create a backwater level and provide a guaranteed water intake or the required demanded pressure to the structure [2–5]. The development of new and improvement of existing layout diagrams and individual design solutions for elements of water intake hydrosystem, guaranteeing the selection of design water flow rates with the least possible entrainment of riverbed sediments into the supply canals of pumping stations, becomes more urgent. The object of the study is the existing water intake waterworks in Uzbekistan. Usually, a number of structures and devices are included in the structure of dam water intake hydroelectric systems: a dam (blind and spillway or only spillway); upstream and downstream regulatory structures; washing devices; head water intake regulating structure and sedimentation tanks [6–9].

Basically, the operational services, together with a guaranteed water intake to the head structure, are faced with the task of removing clarified water and preventing siltation of the water intake area in the head structure. Many scientists have dealt with the issues of research and solution of the problem of the operation of hydroelectric facilities, which represent operational efficiency [10–14]. Many studies devoted to solving water intake problems provide recommendations for engineering solutions to combat sediment in water intake facilities built in India, the USA, Turkey, Egypt, Japan, Iran and other countries of the world [13, 15]. Despite the abundance of works devoted to solving the problem of clarified water in the head hydrotechnical and hydropower structure at the dam water intake, the issue of its effective operation has not been brought to its logical conclusion. Based on the above, the main goal of this work and the research objectives are determined. The main goal of the work is to select the most effective type of water intake structure that minimizes the flow of bottom and suspended sediments to the maximum extent, as well as reduces the intensity of siltation and inflow of reservoirs. To solve this goal, the following research objectives have been identified:

1. Consideration of various types of dam water intake hydroelectric systems used in practice by scientific research, design, construction and water management organizations in many countries of the world;

2. Generalization of the results of studies devoted to the use of the theory of transverse circulation and methods of artificial, active regulation of the flow structure to create an effective design for water intake structures of canals, providing them with reliable protection from sediments;

3. Determination of the efficiency and prospects of the use of water intake facilities and installation of the type of this structure.

2. Method

Analysis of the advantages and disadvantages of the existing water intake waterworks during operation, development of a new structural element contributing to the improvement of the operational characteristics of the water intake structure.

3. Results

As you know, water intake structures by design features belong to the following types of water intake waterworks: lateral, frontal, bottom-lattice and goby. Each type of hydrosystem has various modifications aimed at improving its design [16]. Approximate conditions for the use of various types of water intake waterworks are shown in table 1.

Table 1. Recommendations for the use of various types of water intake waterworks.

Water intake type	River sections	Supply canal configuration	Water intake coefficient, *R* not more	Recomm. water intake flow rate (m^3/s)	Comment
Side: unilateral bilateral	Foothill and flat, less often mountainous	curvilinear straightforward	0.5	no limit	At $R > 0.5$, the accumulation of entrained sediments in the headwater and periodic flushing are required.
Frontal: unilateral	Predominantly foothill	curvilinear	0.8	also	It is allowed to transfer part of the water flow (up to 30%) to the other side
Bilateral	Mainly flat, foothills are acceptable	straightforward	0.7	also	Not recommended for rivers with a lot of writhing and fin
Donno - lattice	Mountain	straightforward	0.4	< 20	Maximum design river discharge up to 300 m^3/s

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In many water intake waterworks one of the main problems is the prevention of siltation and the introduction of the headwater where the intake structure is located. Silting up of the water intake area occurs due to bottom sediments. Especially, the problem of siltation of the water intake area due to bottom sediments occurs intensively in Mountain Rivers (for example, such as Pskem). The existing dam water intake waterworks in Central Asia, based on the principle of preventing the flow of bottom sediments into water intake facilities, can be divided into three main types:

1) a water intake unit with a frontal location of the dam and a lateral location of a water intake (of the "calm backwater" type - Indian type, figure 1).

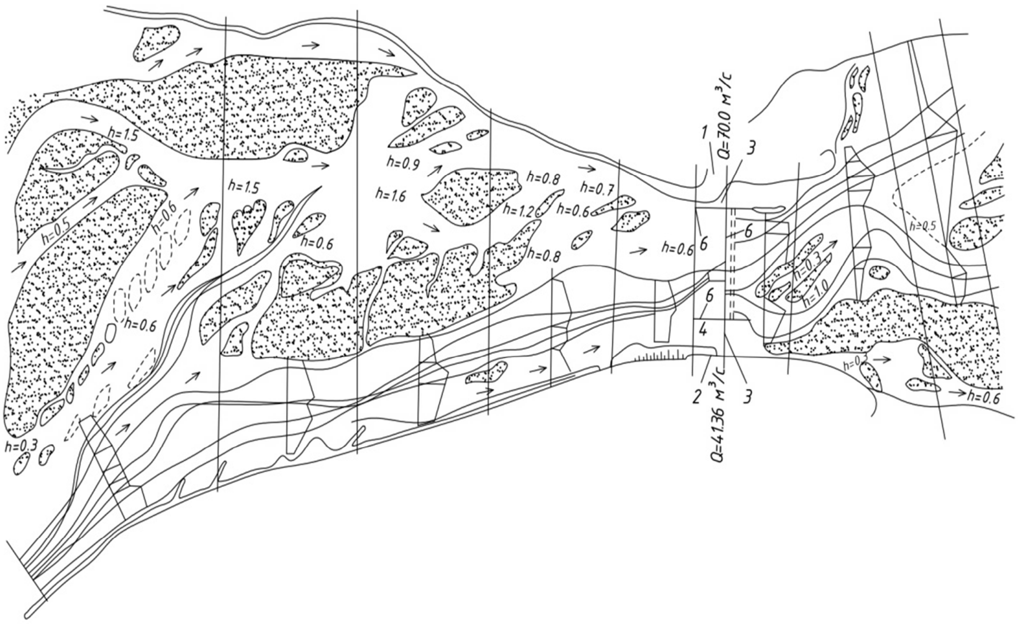

Figure 1. Water intake unit of Indian type: 1-left bank water intake; 2-right bank water intake; 3-washing sluices; 4 pockets; 5-spillway dam; 6-wall pocket.

2) a water intake unit using transverse circulation (Fergana type, figure 2)

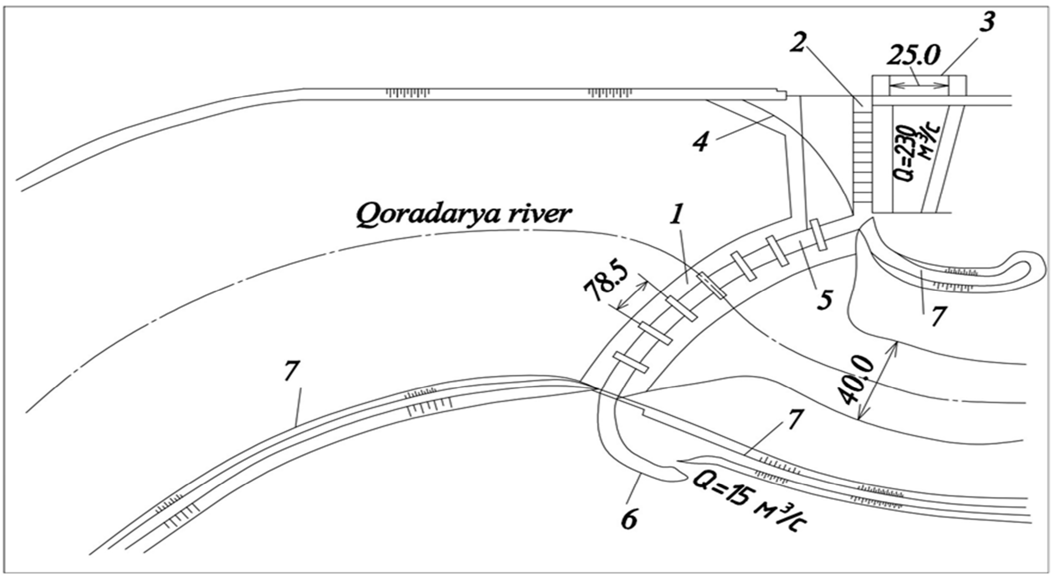

Figure 2. Fergana-type water intake node: 1-harvest dam; 2-water receiver; Canal 3; 4-curvilineary threshold water receiver; 5-duke; canal 6; 7-stringing dams.

3) a water intake unit built on the principle of vertical flow stratification (European type, figure 3)

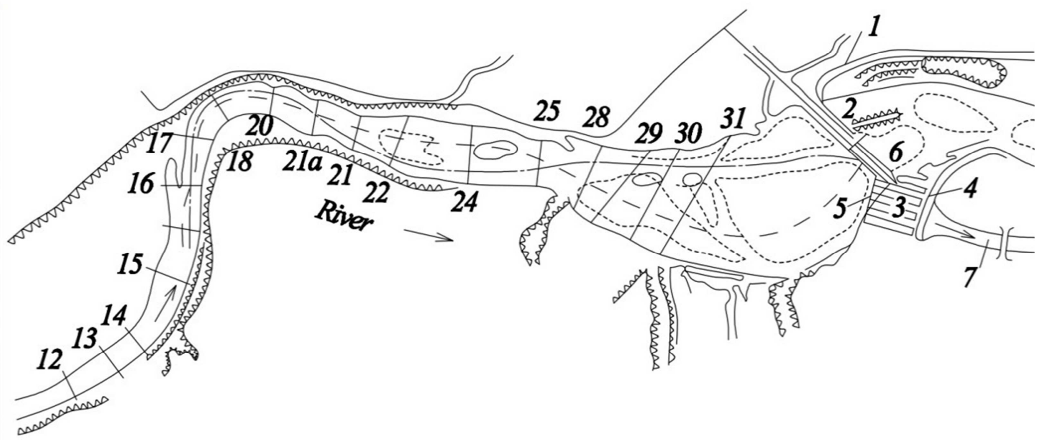

Figure 3. Water intake unit of European type: 1-foldable part of the dam; 2-blind part of the dam; 3-settling tank; 4-mud flap; 5-water intake; 6 wash galleries; 7-canal (12-31 diameters).

To control sediment in the layouts of the dam hydroelectric systems, the properties of the flow are used: its characteristic features with a lateral outlet from the river; natural and artificial transverse circulation in curved sections of a river or canal; reactive bottom currents excited by artificial barriers and screens; layer-by-layer water drainage and others.

Dam hydroelectric complex of the first type (Indian type), built in 1929 on the foothill section of the Zarafshan River (Pervomayskaya dam), which consists of a blind and spillway dam, two wash locks, two (left-bank and right-bank) head regulators of main canals, upstream right-bank stream-guide dam and right-bank water retention dam. This type has serious drawbacks: unregulated backed level, unstable approach of the flow to the points of water intake, ineffectiveness of washing devices with a large loss of water, significant ingress of sediment into canals and interruptions of water intake during washing. After 20 years of operation, the project proposals for the assembly of the unit did not come true. Such intakes were reconstructed.

The arrangement of water intake units of the second type (Fergana type) has proved itself well in practice and successfully protects the canals from the ingress of large bottom sediments. In such hydrosystems, transverse circulation is used, for the occurrence of which the supply canal is given a curvilinear outline in the plan, and its width is taken equal to the width of the stable canal. The intake structure is located on a concave bank. The unit includes a curvilinear supply canal; spillway dam with gates, water intake flow of various designs, head regulators. However, in structural and operational terms, units of this type have the following disadvantages: increased length of the dam due to its lateral or oblique location; non-smooth flow of water through the dam; unsatisfactory hydraulic conditions for the flow of waste flows through the dam; very poor washing conditions of the narrow and curvilinear in terms of the headwater from sediments and the introduction of the downstream by sediments. The indicated disadvantages (inherent to some extent and other types of structures) in the designed nodes of this type are easily eliminated. The water intake unit of the third type (European type), built in 1940 (Gazalkent hydroelectric complex), depends on the relative position of the water intake, bottom and waste structures, as well as on the regulation of the river canal leading to the water intake. With this arrangement of the unit, the water intake is satisfactory only under a certain operating mode of the structures (the ratio of the flow rates discharged through the dam, taken into the water intake and passed through the bottom holes). The arrangement of these types requires a significant head at the waterworks. A common disadvantage in the layout of the constructed hydroelectric complexes is the unregulated river canals and a very wide front in front of the junction (dam and water intake). On the other hand, the variable discharge regime of the river presents a great difficulty in the layout of the water intake. A certain arrangement of the unit can justify itself at certain limits of fluctuations in river flow rates, while at other flows it remains unsatisfactory.

The gradual narrowing of the supply canal with the help of a dam with a series of side discharge holes, adapts the operation of the water intake to the river regimes. In this direction, new schemes for the layout of hydraulic structures of the second type, proposed by many scientists [16, 17] make it possible to create, at all river flows, a stable frontal and concentrated river flow to the water intake, which provides a one-way water intake 4 B, with double-sided water intake (5-6) B. In the downstream, the length of the regulated canal depends on the layout of the unit and the share of water intake. It should not be less than the width of the stable canal $L_{n,b} = B$. The radii of curvature of the regulated canal are assumed to be variable. Smallest radius of curvature $R_1 = 3.5\ B$ and the greatest $R_2 = 7\ B$. The backwater curves are connected smoothly.

Under conditions of pronounced variable flow regimes in a river with water intake fluctuations from 15 - 20% during floods and up to 100% during low water periods, the most positive effect of preventing sediment into canals during water intake is achieved with the combined use of two principles - transverse circulation and stratification of the flow with canal regulation [10, 15].

Experience in the operation and design of water intakes, as well as research and development work in this area show that the application of principles using cross-circulation and stratification separately and in combination, in certain conditions, should be limited. The best results can be achieved on the foothill sections of the river with a water intake of up to 60 - 70%. With a water intake exceeding this indicator, a combination of two principles is advisable - transverse circulation and vertical stratification of the flow with canal regulation. [18, 19, 20].

To combat sediment, the authors of this article recommend a pioneer digging device on the reservoir bowl, preferably in the old riverbed. The hydraulic parameters and geometrical dimensions of the ditch must correspond to the parameters of the canal, which provides the everyday hydrological regime of the river before the construction of the dam. The slope of the canal bottom should correspond to the domestic regime. The lining of the bottom and side walls of the pit is made with concrete lining of increased smoothness with a roughness coefficient of no more than n = 0.012-14. The pioneer pit will communicate with the reservoir bank with a slope of at least m = 3.5. The length of the pioneer dug is equal to the length of the canal from the dam to the alignment, where the violation of the river's daily routine begins. For mountain reservoirs, it can be determined from the graph plotted as a result of the analytical solution of the reservoir equation.

$$l_i = \frac{h_0}{i}\left\{\left[\eta_1 - (1-\overline{j})\Phi(\eta_1)\right] - \left[\eta_2 - (1-\overline{j})\Phi(\eta_2)\right]\right\} \tag{1}$$

here: l_i – length for each section; $\overline{j}$ – average value; η – the relative depth of their function $\Phi(\eta)$ look [21], pp.530-533; h_0 – normal depth to rivers, h_0=5; i – slope of the Pskem river bottom, i=0.0095; m – inclined; $m=3.5$.

$$\overline{j} = \frac{\alpha \cdot i \cdot \overline{C}^2 \cdot B}{g\overline{\chi}} \tag{2}$$

$\overline{B}$ – average canal width in each section

$$\overline{B} = b + 2m\overline{h} \qquad \text{[m]} \tag{3}$$

$\overline{\chi}$ – average wetted perimeter of the river in each section

$$\overline{\chi} = b + 2\overline{h}\sqrt{1+m^2} \qquad \text{[m]} \tag{4}$$

$\overline{\omega}$ – average cross-sectional area of the river in each section

$$\overline{\omega} = (b + m\overline{h})\overline{h} \qquad [\text{m}^2] \tag{5}$$

$\overline{R}$ – average hydraulic radius in each section:

$$\overline{R} = \frac{\overline{\omega}}{\overline{\chi}} \qquad \text{[m]} \tag{6}$$

Shezy coefficient:

$$C = \frac{1}{n} R^{1/6} \qquad [\mathrm{m}^{0.5}/\mathrm{s}] \qquad (7)$$

here: n - canal roughness, n = 0.02.

Then we proceed as follows. We divide the given canal into a number of sections, find out within what limits the required depths should lie. We set, in accordance with these limits, the depths h at the beginning and at the end of each selected section of the canal (one depth at the end or at the beginning of our canal is not specified for the calculation).

After that, knowing the depths at the beginning and at the end of each section, we calculate the lengths l of all sections using equation (1). All calculations are summarized in table 2.

Table 2. An example of calculating the construction of a curved free surface in the Pskem reservoir

Plot numbers	h (m)	$\bar{h}$ (m)	$\bar{B}$ (m)	$\bar{\chi}$ (m)	$\bar{\omega}$ (m)	$\bar{R}$ (m)	$\bar{C}$ ($m^{0.5}/s$)	$\bar{j}$	η	$\Phi(\eta)$	$\eta-(1-\bar{j})\Phi(\eta)$	l_i (m)
5	50	45	330	342.6	7762.5	22.6	84.1	7.25	10	0	10	1051
	40								8	0.0002	8.003	
4	40	35	260	269.8	4812.5	17.8	80.8	6.95	8	0.0002	8.002	1037
	30								6	0.0005	6.03	
3	30	25	190	197	2562.5	13.0	76.7	6.04	6	0.0005	6.03	1063
	20								4	0.002	4.01	
2	20	15	120	124.2	1012.5	8.1	70.9	5.17	4	0.002	4.008	1042
	10								2	0.025	2.10	
1	10	7.5	65	69.6	309.4	4.4	64.1	4.08	2	0.025	2.077	1638
	5								1	1.362	5.19	
											Σl_i	5831

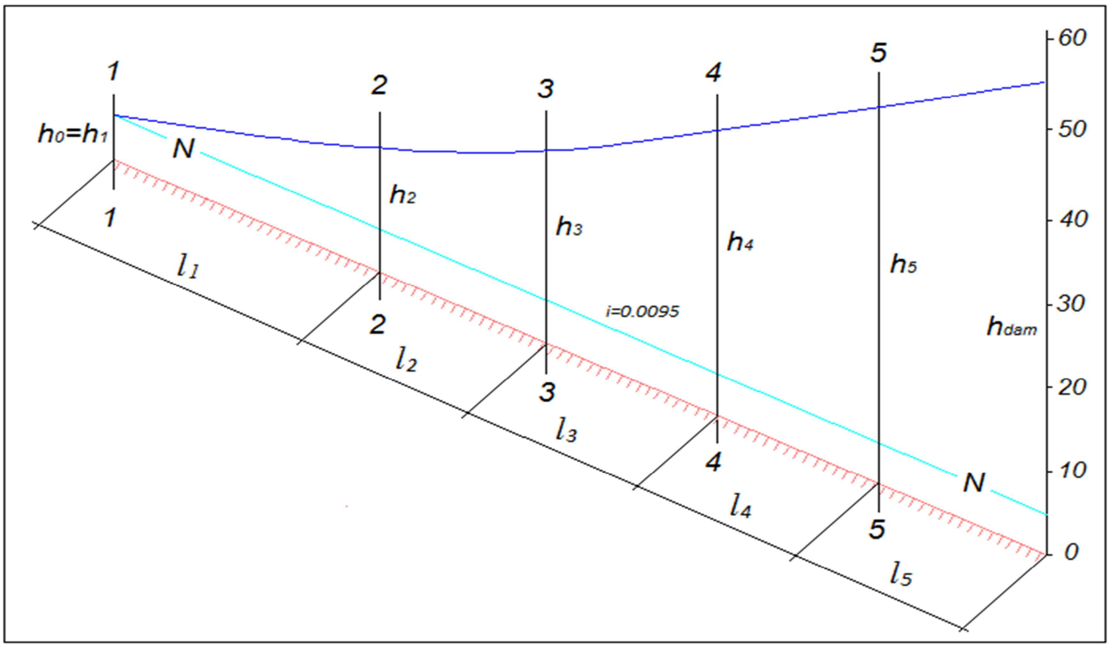

Figure 5. Graph of determination of pioneer digging in the upper reaches of reservoirs:
N-N – normal water depth; h_1, h_2, h_3, h_4, h_5 – depth of water at each section;
l_1, l_2, l_3, l_4, l_5 – section length in each section.

The proposed design allows periodic passage of bottom sediments into the downstream of the dam. Determination of the characteristic dimensions of the pit, its type (open or closed) and the study of the effect of bottom pumping on the energy absorbers of the downstream of the structure is the task of further research.

4. Conclusions

Analysis of studies related to the issue of sediment control is of undoubted interest for specialists in water management and scientific organizations. The results of the above studies allow us to draw the following conclusions:

1. The various types of dam water intake hydroelectric systems discussed above have shown that research, design, construction and water management organizations in many countries of the world have done significant work to create rational layouts of new improved structures of existing types of water intake and settling facilities, as well as sediment control devices on rivers and canals.

2. The research results presented in the reports of the IX International Congress show that the use of the theory of transverse circulation and methods of artificial, active regulation of the flow structure for the purpose of water intake has become widespread in world practice and is currently the main one for creating effective structures for water intake structures of canals that ensure their reliable protection from sediment.

3. Based on numerous experimental data obtained in various countries of the world when studying the operation of individual objects and the results of theoretical studies, it is possible to draw a conclusion about the effectiveness and prospects of using frontal-type structures with more than 50% water intake. The design of water intakes of this type has been significantly improved, they can be successfully used in various conditions, including on Mountain Rivers;

4. A new design of the pioneer ditch has been developed, which ensures efficient passage of bottom sediments into the downstream of the structure, which prevents intensive silting of the reservoir basin by bottom sediments and improves the efficiency of the dam water intake.

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