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Improvement of design parameters of the sediment reservoirs

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Sediment reservoirs (SR) are an important part of the irrigation systems, and their construction and operation are resource intensive. At present, such facilities are constructed on water structures mainly to deposit sediments in water by slowing down the flow rate. The design form of the SR is frequently rectangular which makes it difficult to control the sedimentation process by sediment fractions along the length of the flow. Based on the results of the theoretical analyses and field experiments, the design parameters of the SR were improved, and a computational method of sediment distribution developed. A new design of the SR, which allows separating the sediments by fractions has been proposed. In the developed SR, muddy water flows into a special reservoir that reduces the flow velocity, and the sediments are separated by fractions along the length of the cross-section, the width of which increases onwards. Large fractions are deposited by the SR itself and are removed from the facility through the sedimentation gallery. Water flowing through the regulated water-releasing gate equals 5% of the water inflowing to the SR.

KEY WORDS: sediment reservoir, sediment trap model, rate of sediment removal, irrigation

Introduction

In times of high pressure on agriculture and water resources sectors are the raising efficiency of irrigation systems and land reclamation facilities, ensuring reliable operation, modernizing and reducing operational costs highly necessary. Positive solution of these problems is closely connected with sustainable use of water resources and improvement of land reclamation (Arifjanov et al., 2019a; Arifjanov et al., 2019d).
Finding integrated solutions to the abovementioned issues requires the study and management of a sedimentation regime in streams and rivers, thus promoting the efficient use of canals, waterwork facilities, reservoirs and river networks itself. It will also provide a basis for the development of scientifically sound measures that will protect the irrigation canals from sedimentation and allows using the sediments as mineral fertilizers (Arifjanov et al., 2019d; Arifjanov et al., 2019b). Studying hydraulics of the flow and movement of sediments in the sediment-regulating structures in the rivers of Uzbekistan (sediment traps, waterwork facilities, canals and hydraulic structures in the headwater locations) will be the basis for the determination of the parameters of the hydraulic structures and provision of their optimal operation (Arifjanov et al., 2019a; Arifjanov et al., 2019d; Arifjanov et al., 2019b).
Sediment accumulation highly influence the comprehensive benefits of reservoirs and benefits gained from the water structures related to them (Liu et al., 2018; Tan et al., 2019; Moris, 2020). Therefore, sediment trapping by sediment traps has a high priority in the world because it has significant consequences for downstream structures used for irrigation, municipal water supply and hydropower purposes (Kondolf et al., 2014). Damages caused by sedimentation are:

- the sedimentation of canals and reducing their carrying capacity by 70–80%;
- accumulation of sediments at the intersection of the hydraulic structures complicates water distribution and operation;
- sediments passing through turbines and pumps damage blades, reduce functioning efficiency and their life cycle;
- accumulation of sediments in reservoirs reduces water accumulation capacity and shortens their life cycle;
- sedimentation complicates the design of water structures and increases construction costs (Kondolf et al., 2014; Arifjanov et al., 2019a; Fatxulloev and Gafarova, 2019).

The sediment trapping structures preserve hydraulic facilities, main and distribution irrigation canals from sedimentation. Volume of the sediments deposited before the canals, their composition, characteristics of the irrigation canals and hydraulic machines, and other conditions determine the strategy of coping with sedimentation. Typically, large sediments are removed from the upstream sections of the waterworks and suspended fine particles flow downstream (Arifjanov et al., 2019c; Jurík et al., 2019). The presence of large-size sediments in river water poses serious problems to the hydraulic engineering facilities and has a significant negative impact on water management in the operation of hydraulic structures and irrigation systems. Data analyses show that the volume of sediments within the large and small irrigation systems during a year is 80 mil m^3. Considerable amounts of money, labour and material are spending each year to remove these sediments from irrigation systems (Jurík et al., 2019). Therefore, the study of sediment dynamics is of great economic importance.

It is often not advisable to extract out all accumulated sediments of all fractions from water. In cases when sediments are completely removed, the canals will be deepened, i.e., they are deformed and will be saturated again with water and sediments. Excessive removal of sediments can also be harmful: sunlight heats the bottom of the canal, enabling plants to grow and hence, the canal capacity is reduced. Excessively de-sedimented water in mountain rivers and large reservoirs can cause soil erosion in the irrigated lands (Zhang et al., 2016; Fatxulloev and Gafarova, 2019).

The function of the sedimentation facilities like sediment traps (ST) is to deposit excessive sediments in the water courses and to transfer the remaining suspended solids within the saturation boundary to the distribution canals. Such ST are located at the head of the system or used at selected places of network with high number of distributed sediments. Their location and construction also depend on the composition of the particles and the turbidity of the flow (Lu et al., 2019; Jian et al., 2020; Yakovlev et al., 2020). On the other hand, Wang and Kondolf (2014) mentioned that in areas of high sediment yield, sustainable solutions to reservoir sedimentation must focus on passing sediment downstream, not trapping it due to the cost of building and maintaining upstream structures.

By the principle of design and operation, the sedimentation facilities are classified according to the following main criteria (Kondolf et al., 2014; Jurík et al., 2019; Moris, 2020):

- by sedimentation removal method – mechanical excavation, hydraulic flushing and mixing;
- by a mode of hydraulic flushing – periodic and continuous flushing;
- by location - structures on main canal, dispersed headwater structures, non-structural measures;
- by a number of chambers – single chamber, double chamber and multi-chamber;
- by functions of the water management system – energy production, irrigation and municipal water supply;
- by the flow mode in flow chambers – by a linear flow, a transverse circulation.

Sediment traps are installed to protect the main and distribution canals from excessive sediments. The choice of the design of these ST is technically and economically complex. It is designed within the entire complex of water intake structures. Sediments deposited in the ST inside the irrigation canal network are often mechanically removed by machinery. Nowadays, the method of hydro mechanization has become popular. Hydraulic flushing of sediments is relatively rare due to the difference in water levels in the sedimentation facilities and water courses, and due to the difficulty in generating velocities during sediment flushing.

The grain size of sediment particles tends to decrease along the water flow direction, and in the inlet part of a reservoir higher volume of sediments are deposited than in the outlet part (Bak and Dabkowski, 2013; Jing, et al., 2013). The ST inside irrigation canal networks is designed for the deposition of fine particles, which account for a large portion of the total flow (up to 70%). The saturated suspended fine sediments are typical for flat sections of the river. The Amu Darya River is an example of a water course filled with fine sediments. Fractions of less than 0.01 mm in this river flow constitute 55%, while fractions between 0.1 and 0.05 mm are on average from 26 to 27%, respectively. The number of fractions greater than 0.25 mm are less than 2%. This distribution of suspended sediment fractions is characteristic for the main and distribution irrigation canals, where large particles are deposited due to the installed sedimentation facilities at the headworks (Arifjanov et al., 2019a; Arifjanov et al., 2019d; Arifjanov et al., 2019b). Small-fraction sediments are very useful for irrigated soils as a source of mineral fertilizers (Julien, 2018) and diverting sediment-laden water onto agricultural land to permit deposition of suspended sediments can improve soil fertility (Kondolf et al., 2014).

The reservoir or sediment trap geometry or using an internal or structural barriers can maximize the hydraulic short-circuiting of sediment-laden inflows (Moris, 2020). Therefore, we present a model for periodic flushing of sediments in the reservoir and a developed method of estimating sediment distribution fractions in the proposed model. The newly proposed constant-periodic sediment flushing model depends on the protection of irrigation canals from sedimentation, and from the proper selection of the type and size of the installed sedimentation facility.

Materials and methods

Based on theoretical and field research, a new design of a constant-periodic sediment flushing reservoir was proposed. Currently, commonly used periodic sediment flushing facilities have various designs; flushing of precipitated sediments in these facilities is as follows: when one of the storage areas becomes full, large particles begin to leak into the canal, an entrance gate in the reservoir is closed, and holes beneath the gate will open. Their widths should only account for the sediment flushing capacity. The amount of water in the flushing area is reduced after opening the gate. The sediments deposited at the bottom pass to the sedimentary gallery and further downstream to the lower part of the canal (Lu et al., 2019).

There are also single-chamber facilities connected with canals, the bottom of which is trapezoidal and attached to each other by a large base, the point of the connection is the threshold, and the bottom area is rectangular (Zhang et al., 2016; Fatxulloev and Gafarova, 2019). The disadvantage of these sedimentation facilities is the difficulty in cleaning sediment deposited in their chambers (Fatxulloev and Gafarova, 2019).

In the first case the sedimentation facility has a permanent cross-section, with no fractional deposition of sediments, and the periodic flushing mode disrupts water supply. In the second case, no sedimentation gallery exists, but fractional sedimentation is controlled.

Many years of observations of various sedimentation facilities (in Karshi, Termez, Kuyganyar, etc.) have shown that sedimentation occurs mainly at the beginning section of the facility by increasing the transverse cross-sectional surface of the flow (Arifjanov et al., 2019c; Arifjanov et al., 2019d).

However, such a process of sediment deposition along the length of the stream would cause it to lose its ability to control sedimentation by fractions. It can hence be used on irrigated areas but complicates the transport of suspended sediments containing valuable mineral fertilizers. The following design of the constructions are proposed for self- flushing of sediments and for control of fractional deposition and flushing off river sediments.

The bottom of the sediment removal reservoir (2) is trapezoidal, constructed at the angle bottom (Fig. 1), the other two parts are made horizontally, with a threshold and a vertical control gate. The size of the gate openings (4) and (5) is determined by the amount of water supplied to the canal and is intended to move the sediments into the sediment gallery (3). The vertical gate (4) is controlled by an automatic device.

The facility operates as follows: the sediments move through entry canal (1) into the sedimentation reservoir (2), where turbulent movement occurs due to trapezoidal cross-section with separation into fractions. Large fractions of suspended particles settle in the reservoir, while fine-grained sediment particles flow through outflow canal (6) into the second part of the reservoir.

During the operation of the sedimentation reservoir, once the reservoir is filled with sediments, the sediments are thrown into the gallery (3) by opening of a vertical steering gate (4).

The controlled cross-section of the gate is determined based on the water flow. Accordingly, the gate that provides an intensive removal of sediments deposited on cross-section in a vertically controlled gate into a sedimentation gallery creates a downstream flow process. Volume of water through controlled cross-section of the gate (Q) equals to 5% of water intake at the head part of the sediment reservoir (Q_1):

$$Q = 0.05 \cdot Q_1 \tag{1}$$

This allows the velocity (v) of the water to be greater than the rate of flushing out of the sediments (v_f):

$$v >> v_f \tag{2}$$

Water velocity is determined as follows:

$$v = \frac{Q}{A} \tag{3}$$

where

Q – discharge through the controlled gate [m^3 s^{-1}],
Q_1 – discharge into the reservoir [m^3 s^{-1}],
A – cross-section area of gate opening [m^2]: $A = bh$,
b – width of gate opening [m],
h – height of gate opening [m].

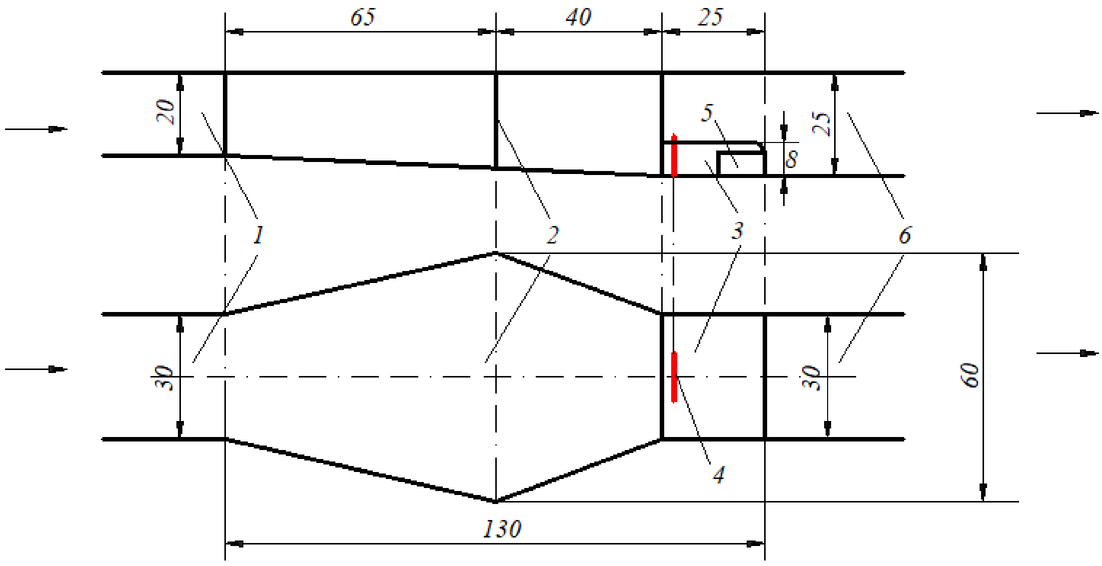

Fig. 1. One-chamber scheme of periodic sediment flushing facility; 1 – entry canal, 2 – sediment reservoir, 3 – flushing gallery, 4 – gate into the sediment gallery, 5 – sediment passing canal to irrigated area, 6 – outflow canal.

The value of the flushing velocity (v_f) shall be determined based on the recommendations provided in the "Construction Standards and Regulations" (Building Norms and Regulations, KMK 2.06.03-97). By controlling (opening or closing) the vertical gate, it is possible to achieve the regime required to remove the accumulated sediments.
Base on the research conducted in a newly developed sediment reservoir, a mathematical model of sediment distribution along the length of the stream was developed. Based on this model, the formula for calculating the sediments along the stream flow is:

$$S = S_0\left(\frac{A_0}{A}\right) exp\left\{-\frac{\alpha}{Q^2}\int_0^x \sin\alpha A^2\,dx\right\} \tag{4}$$

where
S – suspended sediments at the entrance to gallery [kg m^{-3}],
S_0 – suspended sediments at the entrance to reservoir [kg m^{-3}],
A_0 – corresponding cross-sectional area at the entrance to reservoir [m^2],
α – parameter characterizing sediments in a stream [-], which can be determined:

$$\alpha = \frac{3g(\rho_t-\rho)}{2\rho_t}\left(\frac{d_0}{d_i}\right)^3 \tag{5}$$

where
ρ_t – solid particle density [kg m^{-3}],
ρ – fluid density [kg m^{-3}],
d_i – diameter of the sediment particles [m],
g – acceleration of free fall [m s^{-2}],
d_0 – characteristic diameter of the sediment moving at a rate equal to the flow velocity [m].

The advantage of the proposed equation (4) is that the distribution of sediments along the flow length in the equation (4) depends on the variation of the flow hydraulic elements. This allows for a more detailed description of the process.
The abovementioned equation (4) can be calculated by dividing the turbidity distribution in the arbitrary cross-section with a function of river (reservoir) length. In particular cases, changes along the length of the river cross-section (A_x) can be estimated as follows:

$$A_x = A_0 + 2\tan\beta HL \tag{6}$$

where
A_x – cross-section change [m^2],
β – angular value of the river slope relative to horizontal level [-],
H – average depth of flow [m],
L – length of river or reservoir [m].

To calculate the distribution of sediments along the flow length in the extending cross-section, the expression (6) is placed into the equation (4) and integrate to obtain the following:

$$S = S_0\left(\frac{A_0}{A}\right) exp\left\{-\frac{\alpha(A^3-A_0^3)}{2Q^2\tan\beta H}i\right\} \tag{7}$$

where
i – slope of the riverbed [-].

Results

Based on the research results, the model of a flexible cross-section of the sedimentation reservoir was constructed in the laboratory (Fig. 1 and Fig. 2). The model of the sedimentation reservoir is divided into 4 sections (A, B, C, D) along the length. The distribution of sediment fractions was observed at each cross-sectional site (Fig. 3), and changes of the flow depth were measured (Table 1).
Depend on the above-developed equation (7), calculations were performed for different sediment particles and turbidity levels on the proposed model in the laboratory conditions and applied for the conditions of real sedimentation reservoir. The calculation results for the laboratory model are presented in the Table 1 and for the real reservoir in the Table 2. The calculation presented in the Table 2 are based on the field research made in Fergana valley and was calculated for the parameters of the water intake system of the Sokh canal which is tributary of Great Fergana canal. The rate of sediment removal of particle sizes from 0.01 mm to 0.005 mm vary between 80–97% of the fractions in the total sedimentation in both situations and obtained the ability to keep most fractions in the range of 0.5–0.1 mm in the sediment reservoir. It is possible to see that less than 0.50 percent of this sediment comes out from sediment reservoir. With increasing the tgβ angle of the proposed sediment reservoir model, the process of fractional distribution of suspended sediments in the flow structure will be possible. Based on this, it will be possible to allow the sediments to remain large fractions of suspended sediments larger than 0.1 mm and smaller than 0.01 mm through the structure. The main purpose of avoiding small fractions without holding them in the sediment reservoir was found the presence of microelements in their composition, which can increase soil fertility. The obtained results indicate that it is possible to achieve the desired sediment treatment mode by considering the parameters of flow and river sediments.
Water flow rate in the model was calculated based on the measurement by Thomson weir. The sediment movement and flow rates were calculated in each selected flow section over time. The sediment distribution in the selected flow sections is variable (Fig. 2 and Fig. 3), and the sediments in the flow section A did not settle considerably because of the high flow velocity. The minimum flow velocity is in the flow section C. Due to the changing cross-section in the flow section D the water velocity increases, and the sediments are flushed into the flushing gallery resulting in increased efficiency of flushing of the sediments into a sediment accumulating section. The variability of the cross-section of sediment accumulating section causes sort

Table 1. Sediment distribution in the sedimentation reservoir model

d_i [mm]	d_0 [mm]	d_i/d_0	Q [cm^3 s^{-1}]	b [cm]	I	H [cm]	L [cm]	$tg\beta$	S_0 [kg m^{-3}]	S [kg m^{-3}]	rate of sediment removal
0.01	0.005	2.0	78.0	31.0	0.0001	1.2	180	0.1	2	1.96	0.97
0.01	0.005	2.0	78.0	31.0	0.0001	1.2	180	0.12	2	1.90	0.89
0.01	0.005	2.0	78.0	31.0	0.0001	1.2	180	0.15	2	1.60	0.80
0.5	0.1	5.0	78.0	31.0	0.0001	1.2	180	0.15	2	1.01	0.51
0.5	0.1	5.0	78.0	31.0	0.0001	1.2	180	0.12	2	0.997	0.50
0.5	0.1	5.0	78.0	31.0	0.0001	1.2	180	0.15	2	0.64	0.32

Table 2. Sediment distribution in the real sedimentation reservoir

d_i [mm]	d_0 [mm]	d_i/d_0	Q [m^3 s^{-1}]	b [m]	I	H [m]	L [m]	$tg\beta$	S_0 [kg m^{-3}]	S [kg m^{-3}]	rate of sediment removal
0.01	0.005	2.0	30.0	200.0	0.0001	2.0	400.0	0.1	4.0	3.80	0.95
0.01	0.005	2.0	30.0	200.0	0.0001	2.0	400.0	0.12	4.0	3.18	0.80
0.01	0.005	2.0	30.0	200.0	0.0001	2.0	400.0	0.15	4.0	2.92	0.73
0.5	0.1	5.0	30.0	200.0	0.0001	2.0	400.0	0.1	4.0	2.01	0.50
0.5	0.1	5.0	30.0	200.0	0.0001	2.0	400.0	0.12	4.0	1.80	0.45
0.5	0.1	5.0	30.0	200.0	0.0001	2.0	400.0	0.15	4.0	1.55	0.39

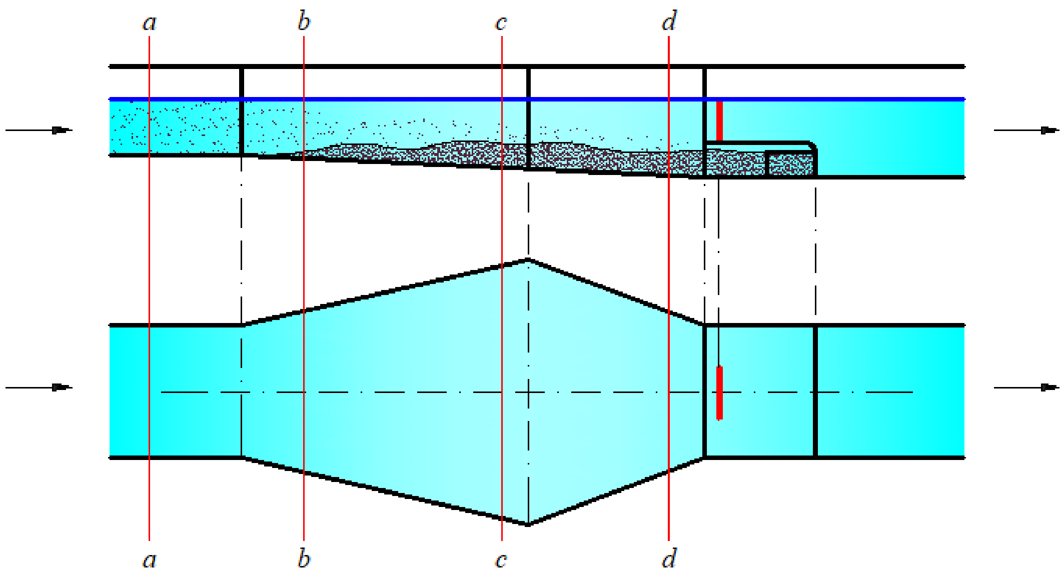

Fig. 2. Laboratory model of the sediment reservoir in lateral view (above) and top view (below).

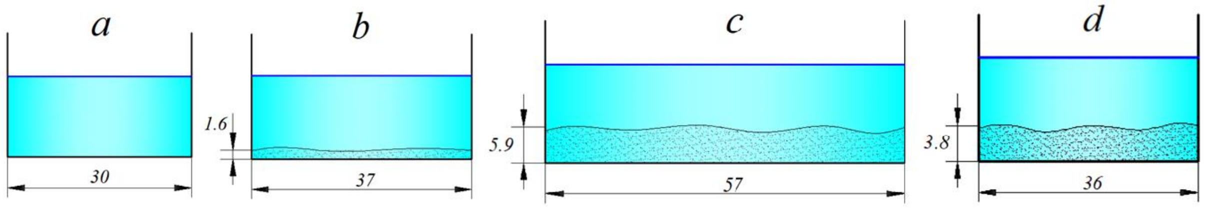

Fig. 3. Distribution of sediments by cross-sections.

of sediments by diameter. This allows the small sediments to flow out of the reservoir.

Conclusion

Theoretical and laboratory research results allowed improving the constructive parameters of the sediment management structures in rivers. The new design of the sediment reservoirs, which allows separation of river sediments into fractions has been developed. River sediments can be separated by the sediment tank of the new design into fractions, and small fractional particles can be transferred into irrigation fields.

The mathematical model describing the sediment distribution in the developed sediment tank model was improved and a computational method developed. A distinctive feature of this model is the description of the sediment distribution in the stream depending on sediment fractions. Based on the developed calculation method it is possible to predict sedimentation process by considering the uneven flow characteristics in the sediment reservoirs constructed in the irrigation canals. The turbidity distribution for the sediments of different fractions is carried out in fractional order, and the total turbidity is calculated by summing the total sediment volume corresponding to the sediment fractions.

Obtained results allow to conclude that constructing sediment reservoir of variable cross-section allows separating the sedimentation by their fractions. The proposed calculations can be used in any hydraulic facility, reservoirs included, where water purify from river sediments is needed. It is recommended to be used considering the hydraulic and hydrological parameters of the canal under consideration.

The proposed design of the sedimentation reservoir has been recognized by the Intellectual Property Agency as a useful model № FAP 00927 (Arifjanov et al., 2014).

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