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WATER RESERVOIR LIFE EXTENSION AND METHODS SPECIFY WATER BALANCE

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Abstract

A phenomenon triggered by modern global warming is a change in the freshwater balance between the land and the ocean in favor of the latter. Centuries-old reserves of mountain glaciers, ice sheets, and groundwater are moving into the oceans. The consequences of this event are particularly severe for regions with limited water resources, where the most optimal ways of solving the problem are designing new methods to calculate water balance and water consumption, modernizing and rationalizing the existing methods, and essentially prolonging the period of operation of water reservoirs. For this purpose, this study proposes a new method that makes it possible to extend the service life of a reservoir, significantly increase the accuracy of water balance operations, and efficiently use the accumulated sediments as a natural resource. This method was made possible through the use of the results of natural experiments on small mountain reservoirs, the generalization of research data on the dynamics of silting prisms of operational reservoirs, and the use of monitoring materials of river sediment. Methods of mathematical statistics (least squares, mathematical expectation, analogy), as well as methods to calculate the basic hydrological characteristics and the water balance of the reservoir, were used to generalize the information and analyze the research data.

Keywords: water balance, silting prism, mead reservoir, Colorado River

I. Introduction

Ongoing climate fluctuations are changing the freshwater balance between the land and the ocean in favor of the latter. Centuries-old reserves of mountain glaciers, ice sheets, and groundwater are moving into the oceans. The flow of glacier-fed rivers is increasing, while the flow of the rivers with basins in areas lacking moisture is decreasing [1]. The results of monitoring the runoff of the Colorado and Rioni rivers in 1960-1990 [2-4] offer clear evidence of this fact (Fig. 1, 2).

The growing demand for regulated water and the tendency to decrease runoff has increased the importance of water reservoirs, which has led to a focus of scientists on studies related to the siltation of reservoirs and related problems [5-13].

The unfavorable trend of the spatial and temporal distribution of water resources leads to severe problems, an effective means of adaptation and solution to which is spatial and temporal regulation of river flow by reservoirs. However, besides offering numerous advantages, reservoirs also have disadvantages, including silting with sediments (sand, pebbles, gravel, etc.) and solid residues of coastal deformation, which is an irreversible process. The accumulation of these products in a reservoir forms a "silting prism," which reduces the reservoir conservation zone and causes progressing errors in the W=f(H) curve of water registration and distribution. This feature is particularly dangerous for large urban conglomerates and irrigation facilities located in regions with insufficient water supply. In the southern arid region of the United States, the Colorado River flow is used almost entirely for irrigation and municipal water supply. The waters of the Amu Darya and Syr Darya Rivers in Central Asia are distributed among users in such a way that the

Aral Sea, a lake fed by these rivers, has almost completely dried up and the region itself has become an ecological disaster zone. The main reason for this ecological disaster was the incorrect water-balance inventory of river flow and users' ignorance of the climatic decline of the flow.

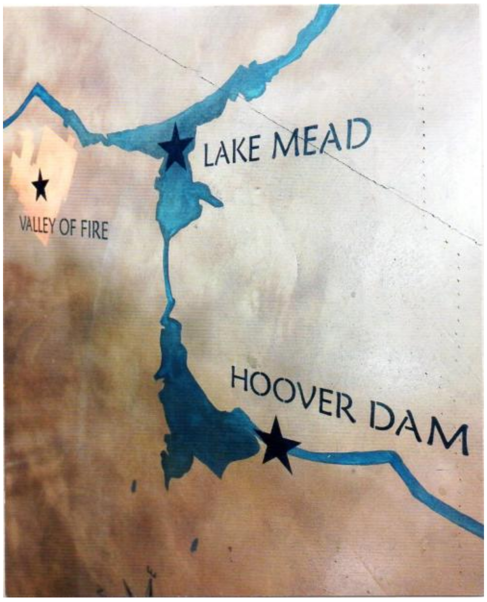

Figure 1: *Made reservoir on River Colorado*

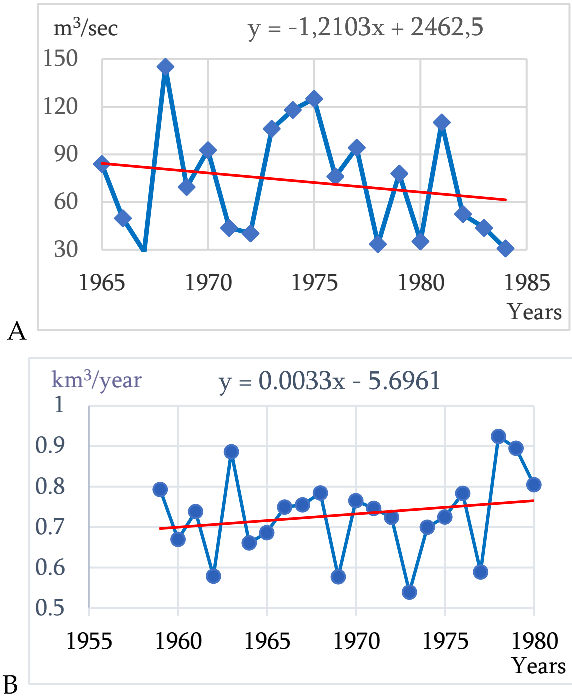

Figure 2: *The trend of multi-year flow variability of (a) the Colorado River (North America) and (b) - the Rioni (Caucasus) in terms of current climatic conditions*

The economy of many regions of the planet is limited by the lack of regulated water volumes in the reservoirs, as the volumes decrease inversely proportionally to the increase of a silting prism. This factor clearly indicates that improving reservoirs' inventory and rational use is vital in the nearest future. The lack of regulated water resources hinders economic development in in many African countries and Australia. Consequently, improving the regulation and balancing of river flow is an important task for them as well.

Accordingly, the primary purpose of this research was to conduct studies of water balance, improve the accounting of balance elements, and design and modernize the calculation formulas. The objective of the study was formulated as follows after summarizing results: assessing the reduction of a reservoir conservation zone caused by a silting prism and designing methods for periodically correcting the curve *W=f(H)* and extending the service life of the reservoir.

II. Methods

The research employed mathematical statistics methods (least squares, mathematical expectation, analogy), as well as methods to calculate the basic hydrological characteristics and the water balance of the reservoir. For this purpose, field, and natural studies were conducted on reservoirs of different regulations and types in Georgia to study the silting processes in operating reservoirs, especially when the silting prisms were in the last phase of development. The studies were also conducted on small mountain rivers, where natural experiments to study the features of silting processes are highly efficient.

III. Results and discussion

Siltation of a reservoir is an ongoing, irreversible process that reflects the accumulation process of sediment in it, specifically of material resulting from bank formation and anthropogenic activity. The deposited material forms what is known as a silting prism, a body originating at the mouths of tributaries and constantly growing in all directions. It increases most rapidly forward, to the dam, and backward, and to the mouths of the tributaries. The main feature of the prism growth rate is its permanent increase at a decreasing rate. This value is maximum in the initial phase of reservoir operation and is minimum at the end of the third phase of operation when the silting prism reaches its maximum volume. In this phase, the surface of the silting prism is plain inclined toward the dam, whose gradient and other morphometric parameters are such that any tributary can completely carry the sediment to the tailrace. In this phase, the siltation process practically stops, and the volume of the silting prism significantly (1.3-1.5 times) exceeds the size of the reservoir, fills it completely, and emerges in the estuaries above it as a “tail” of the silting prism [14, 15].

The main feature of the reservoir is the movement of the water level between the dead volume level and the normal filling level. Due to this peculiarity, during the filling and emptying phases of the reservoir, the mouths of the tributaries constantly displace and distribute the sediment within the reservoir depending on such motion. Accordingly, the river-regulating reservoir is an object functioning for a certain time (T, year), whose efficiency is maximum in the first phase of operation, and minimum in the third, when it is filled and covered with sediment and has completely lost the ability to regulate the flow.

According to the field studies, the reservoir continually losses its volume, and the multi-year regulating reservoir is reduced first to a seasonally regulating reservoir, and then to one controlling only the daily flow.

During the silting process, sediment constantly accumulates at the mouths of tributaries and in areas surrounding their channels. As a result, the bed rises, the water conductivity of the tributaries decreases, and the probability of catastrophic floods increases drastically. In this state, the silting prism expands in the tributaries at a distance L_i determined by the initial slope of the river (I_0) and the diameter of the largest sediment (*dm*).

The volume of water accumulated in a reservoir is measured and regulated by type *W=f(H)*, the so-called working curve, reflecting the dependence between the water level (*H*, cm) and the volume (*W*, m^3) accumulated in the reservoir. The drawback of such a dependence is that if it is not periodically corrected, an error that equals this prism value (W_0) and increases proportionately to it emerges in the operation of any hydraulic facility. This property of a prism necessitates periodic correction in the working curve according to the data of geodetic planning of the prism or results of the water-balance survey. This peculiarity of the reservoir should be considered during its design, that is, in the selection of the site and morphometric parameters, and the realization of the working curve $W=f(H)$.

Water supply in the reservoir is measured by the curve of dependence of water levels and volumes, which in practice is known as water balance or working curve $W=f(H)$. The volume of flooded water (W) depends on the water content of tributaries and the water consumption value (P), which vary from year to year and from season to season. The reservoir water balance is used, which is mathematically expressed by the following equations, to study spatial and temporal variability:

$$\Sigma G - \Sigma P = \Sigma A \pm H \quad \text{(filling phase), and}$$
$$\Sigma P - \Sigma G = \Sigma A \pm H \quad \text{(discharge phase)} \tag{1}$$

Here: G represents the components of the inflowing portion of the water balance (flow of tributaries, sediments on the water level, groundwater, etc.); P denotes the components of the outflowing portion of the water balance: water consumption for electrical power, irrigation, utilities, and evaporation; A is the change in water volume in the reservoir, which is calculated by the water working curve; and H is the balance error.

The component H in Equation 1 is a random variable called the balance accuracy index. It is a random variable as long as all balance components in Equation 1 are written with acceptable accuracy. Its value varies from years to years and seasons to seasons; that is, it is sometimes positive ($H \geq 0$), and other times negative ($H \leq 0$). The balance accuracy for any period is satisfactory if

$$\frac{\Sigma G}{H} \leq 15\% \text{ (filling phase)} \quad \text{and} \quad \frac{\Sigma P}{H} \leq 15\% \text{ (discharge phase)} \tag{2}$$

H maintains this property until new factors turn it into a constant, increasing value. A similar permanently increasing factor is the volume of a silting prism, which increases in proportion to the accumulated solid sediment. This process stops only when the volume reaches a limited and the tributaries produce stable hydrographic curves.

Accordingly, the transformation of the component H into a constant value occurs as a result of the annual accumulation of sediment of volume R_i and product in the amount of N_i formed during the deformation of the reservoir banks. Hence, in the first phase of reservoir operation, that is, after n years, it does not exceed the permissible error of water balance (2), when their volume is

$$M = \sum_i^n (Ri + Ni) \tag{3}$$

In the second phase of reservoir operation, after m years (mn) the accumulated solid material forms a prism of volume W_m. After that, the component H becomes an explicitly increasing value, and the curve $W=f(H)$ changes its position and shape (Fig. 3).

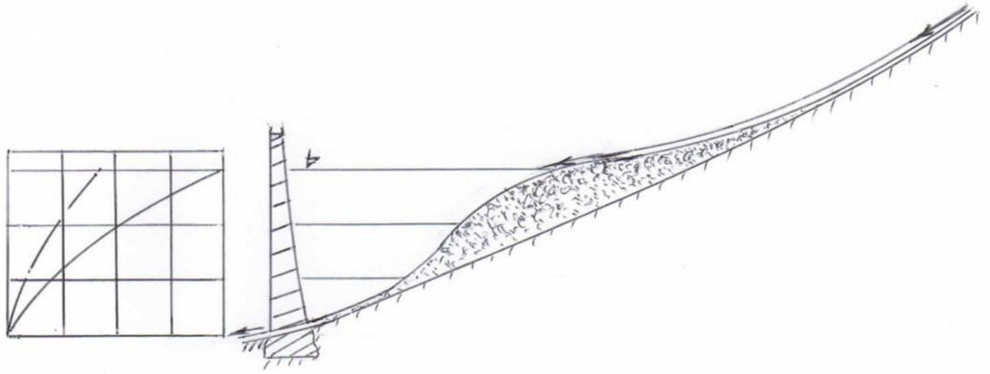

Figure 3: *Longitudinal sections of the silting prism of a reservoir in different phases of prism formation and the corresponding state of the curve W=f(H)*

In the third phase, the tributaries consume most of the sediment to form their bed slope and other morphological parameters and carry an increasing amount of sediment from the reservoir to the tailrace. At the end of this phase, the reservoi's conservation zone is almost completely covered with silting prism material, and the tributaries have transported all the sediment to the tailrace. In this phase, the *H* member of the balance exceeds the reservoir conservation zone, and the working curve has the corresponding shape.

Any operation aimed at managing the accumulated water requires an appropriate monitoring system. If there is no such system provided for a reservoir, an approximate correction of the curve W=*f*(H) is possible by the average volume of solid sediment in the tributaries ($\frac{1}{n}\sum_{j}^{n} Pi$). Such information is a necessary component of the reservoir design parameters and is not difficult to obtain. The corrected, that is, the approximate value of accumulated water volume A_i, can be calculated using the following expression:

$$A_i = \sum\nolimits^{n}_{j} A - \sum\nolimits^{n}_{jPi}, \qquad i = 1,2,..n \tag{4}$$

A geodetic-bathymetric survey method is designed to avoid gross errors in water balance accounting and planning and in, related losses. With its program, a grid of reference points should be constructed, which includes a reservoir basin at the normal flooding level. The grid density depends on the morphometric and terrain peculiarities of the basin. It is advisable to conduct the survey in the season of the year when the water level is the lowest, as the land survey data are more accurate than the bathymetric data.

For the cross-sections fixed by the reference points, the cross-sections of the reservoir must be plotted with the hypsometric data taken from the design map of the reservoir basin (Fig. 5) showing the state of the terrain of the basin before flooding. Land and bathymetric surveys must be plotted in each section. The portions of each two bordering sections covered with sediment will form a geometric figure, the approximate shape of which is a prism or pyramid. The volume of such figures is calculated using well-known mathematical expressions:

$$V_i = sh \quad \text{(prism)} \tag{5}$$

Here, w_i is the volume of portions between the silting prism sections, *m³*; h is the distance between the bordering sections, m; and *s* is the area of the silted figures, m^3

$$V_j = \frac{1}{3}\left(s + \sqrt{sp} + p\right)h, \quad \text{(truncated pyramid)} \tag{6}$$

Here, V_j is the volume of the portion between the silting prism sections $\{V_j\}^{m}_{j=1}$, (in m^3), and ; *s* and *p* are the areas of the lower and upper bases of the pyramid (in m^2). The areas of silted areas with complex geometry, not resembling any known geometrical figures, can be calculated with a planimeter.

The values *Vi* and *Vj* of *n* sections of the silting prism form three information groups. One of them unites the discrete volumes of prismatic bodies (V_i). The second contains the values of pyramidal bodies (V_j), and the third contains the results of planimetry (V_f):

$$\{V_i\}^{k}_{i=1}, \ \{V_j\}^{m}_{j=1}, \text{ and } \{V_f)^{p}_{f=1}\}, \text{ where } i=1,2\ 3,\ldots k;\ j=1,2,3,\ldots m, \text{ and } k+j=n \tag{7}$$

The total volume of the silting prism is the algebraic sum of the values calculated above:

$$W = \{V_i\}^{k}_{i=1} + \{V_j\}^{m}_{j=1} + \{V_f)^{p}_{f=1}, \text{ where } k+j+f=n \tag{8}$$

According to Equation 8, $W_1 = f(H)$, *a* corrected version of the curve $W=f(H)$ will be constructed.

The frequency τ of such operations is determined by the relation of reservoir volume (*W*) to the annual volume of solid matter deposited in it (ω), that is, the frequency of curve correction is proportional to the folowung ratio.

$$\varepsilon = \frac{W}{\omega} \tag{9}$$

Generalizing the study results during the critical low-water period of Colorado reservoirs (1970-1990) for analysis and efficient recommendations is an urgent task. It is also interesting as such critical situations are numerous and their number is increasing in the arid regions of the world (Fig. 4).

Figure 4: *The water level of Mead Reservoir (Lake) in 2023*

The Colorado River flow (Table 1) is regulated by three large and several small reservoirs (Table 2). These reservoirs supply irrigation and municipal water to the states of California, Arizona, and Nevada, as well as the cities of Las Vegas, Los Angeles, and San Diego [7]. These cities consume ~1.0 km^3 of water per year, while the states are much heavier and more extensive (21.6 km^3) consumers of irrigation water. The average volume of annual sediment of this river is ~145 million tons. With water flooding in the reservoir starting in the spring of 1935, the volume of the silting prism produced in the reservoir is expected to have reached 12.6 billion tons by 2020.

Consequently, due to siltation, the reservoir had already lost 34% of its volume by 2020, most of which (80-85%) was useful volume. During this period, the volume of the Mead Reservoir decreased to 23 km^3. If, based on this information, the curve W=f(H) of the reservoir were not corrected periodically, the measurement and consumption of the accumulated flow would be recorded with incremental errors, the size of which has reached ~12.6 km^3 at present. These studies show that when the silting prism ignores the permanent reduction of useful water volume and this process develops against the background of flow reduction caused by current climate change (Fig. 1), the water balance of the regulated flow and water consumption proceeds with ever-increasing errors.

Table 1: *Colorado River Basin Water Balance*

Basin area, thous. km^2	Atmospheric precipitation, P		Runoff, Q		Evaporation, E		Balance mismatch H=P-Q-E		Runoff coefficient $k=\frac{Q}{P}$
	mm	km^3	mm	km^3	mm	km^3	mm	km^3	
635	377	239	$\frac{36}{0.24}$	$\frac{23}{0.15}$	$\frac{258}{294}$	$\frac{164}{187}$	83	22	0.10 0.0

Numerator: flow balance before the construction of the reservoirs;
Denominator: flow balance during the operation of the reservoirs

Table 2: *Morphometry of Colorado River reservoirs*

Water reservoir	Start filling, year	Normal inflow level, m asl	Morphometry						
			Volume W, km^3	Area F, km^2	Depth, m	Length, m	Regu-lation	Usage
Powel, Australia	1964	1174	33.3 25.7*	658	179.5	300	Multiyear	Flood; Irrigation; Communal supply; Energy sector; Navigation.
Mead, US	1935	368.7	36.8 33.5*	640	162	185	Multiyear	Flood; Irrigation; Communal supply; Energy sector.
Mohave, USA	1951	214	0.25	10.7	197	74.1	Annual	Irrigation; Energy sector; Communal supply.

(* Useful water volume)

It is impossible to prevent the process of silting of reservoirs, especially of those regulating river flows. However, it is possible to considerably increase their service life. For this purpose, a system of sediment collection quarries should be provided in the area of displacement of the curve of reservoir flooding and in the mouths of tributaries.

The sediment collection system captures most and the largest fractions of sediment during floods and flash floods. Sediments from these quarries can be used for construction, to fill degraded coastal beaches, to increase the service life of reservoirs, and for other purposes. The operation of such quarries will greatly reduce the heavy burden on nature caused by the extraction of inert material (sand, pebbles, and gravel).

IV. Conclusions

- Permanently decreasing flow regulation capacity of reservoirs is inevitable due to the growth of the silting prism and modern climate warming.
- The operations using the $W = f(H)$ curve, if the curve is not periodically corrected according to the silting prism size, contain increasing errors, which is particularly problematic in arid regions with great water consumption.
- In case of a shortage of regulated water resources, the accuracy of water balance and water consumption operations in the reservoirs must be improved significantly.
- The proposed method is the first attempt to increase the safety of the population in the mouths of tributaries, reduce the pressure on nature caused by sediment removal from river beds, and increase the volume and reliability of inert material supply.
- Water consumption problems in the near future make it urgent to extend the lives of reservoirs and launch sediment collection quarries.

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