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IMPROVING THE SYSTEM OF TECHNICAL DIAGNOSTICS AND ENVIRONMENTALLY SAFE OPERATION OF SOIL HYDRAULIC STRUCTURES ON SMALL RIVERS

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This paper reports the results of studying soil hydraulic structures (SHS) of the CC1 class of consequences on small rivers. The representativeness of the results for the domestic and world practice of further operation of such structures is ensured by the typical technical and technological approaches to the construction, materials, and conditions of their work. Dams are built of soil materials and operated over significant time periods while their standard service life has been exhausted, which increases the environmental and technical danger of their further operation. Visual surveys were conducted and the technical condition was instrumentally diagnosed by the geophysical method of the earth's natural pulsed electromagnetic field (ENPEMF); observational data were mathematically treated. The possibility of arranging areas of increased water filtration through the SHS body was substantiated, as well as watering, loosening, and suffusion; potentially dangerous zones prone to landslides, cracks, and collapse were determined. The probability of risk of an accident on dams was estimated at their cascading arrangement as a result of filtration deformations of the body and the base of the structure. Under current operating conditions, the possibility of letting the normative and excess (forced) water volumes through water discharge facilities due to precipitation or a breakthrough of the structure located upstream was estimated. The proposed approach makes it possible to manage the cascade of hydraulic structures at different stages of operation: planned, operational decision-making, forecasting. This allows diagnostic examinations to be performed in order to identify structures that require priority in raising funds for repair and restoration work or demolition (dismantling)

Keywords: hydraulic structure, soil dam, small river, geophysical research methods, filtration deformations

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1. Introduction

The dynamic growth of all sectors of the economy required the attraction of significant volumes of water resources for industries, agriculture, and utilities. This contributed to the active development of hydrotechnical construction and water management systems around the world. According to [1], there are more than half a million ponds and reservoirs. The most active accumulation of large volumes of water resources occurred in the steppe, low-water, and industrialized regions of the world. As a result, water management systems have a large number of soil hydraulic structures (SHSs) built on small and medium-sized rivers. Most such structures were erected in the last century and belong to the CC1 class of consequences [2].

It is the construction (creation) of ponds that is an extremely serious issue in terms of damming small rivers and watercourses. This leads to fragmentation of their riverbeds; decreased self-cleaning ability; deterioration of water quality; the accumulation of solid runoff; significant contamination of reservoirs with chemical compounds; environmental hazards in the use of such water resources. Without prior improvement in water quality, its use is rather limited for irrigation, fish farming, water supply, or recreation purposes [3–5].

Most small rivers have evolved from natural watercourses into cascades of artificial reservoirs. With the long-term operation of hydraulic structures over 50–70 years, one of the important issues is also the safety and reliability of these facilities. The most dangerous factor in this aspect is the cascading arrangement of dams. A slight distance between the structures along the river and different volumes of accumulated water for the most part is not designed to retain excess water in the event of an upstream facility collapse. Given this, if there is an accident at one of the dams, several cascade structures may be destroyed according to the "domino principle" [6]. The situation regarding environmentally safe operation and reliability of further work of all soil SHSs of old construction is of considerable interest to many scientists [7–9].

The relevance of this issue today is enhanced by a significant development in the world practice of the use of remote (geophysical) methods for investigating the technical condition of soil SHSs [10]. Their reliability makes it possible during operation to make urgent effective management decisions and predict the condition of the structure over time. Among the most common geophysical methods are the study of specific electrical resistance [11–13], seismic methods, etc. However, the proposed methods and procedures are quite expensive and time-consuming. This requires finding effective and inexpensive express methods. The authors of [14, 15] highlight the possibility of widespread use of modern geoinformation systems and a new equipment base. According to [16], expert assessments by specialists play an essential role in the implementation of an integrated approach in assessing the technical condition of structures and possible risks of occurrence and consequences of emergencies. The aggregate list of these factors makes it possible to improve the safety and reliability of such hydraulic structures, which predetermines the relevance of our research.

2. Literature review and problem statement

Statistics of hydrodynamic accidents on dams and levees made from soil materials [17] show that among the prevailing risk factors for emergencies are filtration deformations of SHS base and body. Additional factors are the formation of internal longitudinal and transverse cracks and the loosening of soils. However, detecting them in the initial stages of their evolution is a difficult task; they are not identified by visual examination, which requires the search for new approaches when diagnosing and operating such structures. It is noted in work [18] that the number of emergencies increases significantly after 50 years of operation. That substantiates the relevance of the issue of ensuring the safety of all soil SHSs of old construction. However, no systematic approach to assessing the technical condition and environmental risks of accidents in the management of cascades of such structures has yet been implemented. According to [6], it was also established that the structural parameters of water discharge facilities are inappropriate for letting through the maximum water volume in rain (storm) floods or spring snow melting, and they are unable to withstand the flow of water over the crest of the structure. Amplifying factors affecting the safety of operation of soil SHSs and leading to failures and hydrodynamic accidents are a long service life and a low level of engineering and technical quality of construction in the absence of proper project documentation [19]. There is an insufficiency or lack of monitoring observations and diagnostics of the technical condition of structures [9]. As a rule, this is caused by financial difficulties and the labor intensity related to such studies, as well as the limited employment of the embedded control and measuring equipment (CME). Applying remote control methods may resolve this issue.

It should be noted that in accordance with [2], SHSs are divided into 3 classes of consequences: CC3, CC2, CC1. This standard regulates "the use of technical and software means of monitoring systems for the technical condition of SHS only for structures of class CC2 and CC3". At the same time, almost 99 % of the structures that form cascades of reservoirs on small rivers belong to the CC1 class, for which neither the operating staff nor technical means of control nor the monitoring system are provided.

An additional factor in the danger of operation of such facilities is an extremely rapid trend of climate change. The authors of [20, 21] point to the redistribution of rainfall over time, that is, its total annual amount almost does not change while there is excess precipitation in a short time in the warm periods of the year. Thus, modern climate change is introducing adjustments to estimation approaches during the design and operation of SHS, which acted 50 years ago but, in fact, are still valid. Moreover, in addition to structures themselves, the projects of water discharge facilities are outdated from a technical and technological point of view. For the most part, they are partially destroyed, clogged, and unable to pass excess rainwater and floodwaters. This, in turn, leads to an increase in water level from the upper pool of the structure and increases head gradients, pore pressure, etc. The combination of such dangerous engineering-geological phenomena causes filtration deformations in the body and base of the structure and can provoke both a breakthrough (gap) of SHS and an overflow of water through the crest [22]. However, there is no effective system for diagnosing and preventing such negative phenomena for soil structures of the CC1 class. It is the prevention of the manifestation of negative natural and man-made processes that could improve the operational efficiency of these structures at different levels.

Along with the listed factors, the issue of environmental and operational safety of the further work of all SHSs is of relevance. Scientists are working on the prospects of using modern geoinformation technologies [23] and effectively ensuring the reliability of low-head SHSs [9]. However, the issues of comprehensive approaches to the management and operation of soil SHSs at their cascading arrangement remain insufficiently resolved. Given the small distance between the structures in the cascades, an accident at one of the upstream dams can provoke a gradual destruction of the structures below due to the inflow of significant volumes of water and silt. In this regard, almost all soil SHSs require repair and restoration measures and the introduction of a permanent monitoring system for their technical condition. It is impossible to perform these works simultaneously, so it is necessary to gradually apply a reasonable set of diagnostic examinations to identify structures that primarily require repair or gradual dismantling of those that do not meet the reliability criteria, etc. Assessment of the technical condition (TC) and compliance with a set of indicators of safe operation of such dams is carried out, as a rule, only visually. This makes it possible to establish only external (explicit) dangerous engineering-geological processes and structural shortcomings and violations of the parameters of structure operation. According to [17], at dams that have operating personnel, geodetic observations of precipitation and movements are carried out, as well as the position of the water level (depression curve) in a SHS body is monitored. However, such systematic research is carried out only at medium- and high-head SHSs and facilities belonging to the CC2 and CC3 classes of consequences. For diagnostic examinations of the technical condition of dams of the CC1 class for agricultural purposes, such studies are not sufficiently used or are not used at all.

An improved algorithm and components of diagnostic control over SHS are proposed in [24]. However, the issue of devising an effective system of such control for CC1 class structures remains unresolved. Thus, the actual tasks that are tackled in the current study are the following: first, it is the improvement of technical diagnostics of the state of structures of the CC1 class using geophysical methods; second, it is an attempt at developing an algorithm for the safe operation of soil hydraulic structures at their cascading arrangement on small rivers.

3. The aim and objectives of the study

The aim of this study is to improve existing approaches to the system of control and evaluation of the technical condition of hydraulic structures made from soil materials of the CC1 class of consequences. This will make it possible to improve the operational level of managing a cascade of hydraulic structures at different stages of operation: planned, operational decision-making, forecasting.

To achieve the set aim, the following tasks must be solved:

– to conduct visual evaluation and instrumental diagnostics of the technical condition of soil dams and water discharge facilities that are arranged in a cascade and assess the effectiveness of the application of the geophysical method of the Earth's natural pulsed electromagnetic field;

– to perform hydrological calculations and refine the hydraulic parameters for the operation of water discharge facilities in the case of passing storm (rain) floods;

– to establish the probability of destruction and loss of body stability in hydraulic structures and their foundations caused by filtration deformations;

– to propose an algorithm for the management and environmentally safe operation of cascades of hydraulic structures of the CC1 class on small rivers.

4. The study materials and methods

The object of our research is the processes and phenomena of a natural and man-made nature, which lead to a decrease in the level of environmentally safe operation and reliability of soil SHSs on small rivers.

The subject of the study is a cascade of hydraulic structures, which are built on one of the small rivers of the steppe zone in Ukraine – the Nyzhnya Tersa River.

This river flows in Sinelnykovsky region of Dnipropetrovsk oblast (Fig. 1). Its length is 39 km; the area of the catchment basin is 312 km^2. The river valley is mainly trapezoidal, up to 1.5–2.0 km wide, the inclination is 2 m/km. There are 61 ponds built in the Nyzhnya Tersa River basin. There are 19 reservoirs directly on the river. The densest damming with artificial reservoirs is noted along a section about 15 km long from the source of the river with a catchment area of ~105 km^2. Then the river flows in a natural channel.

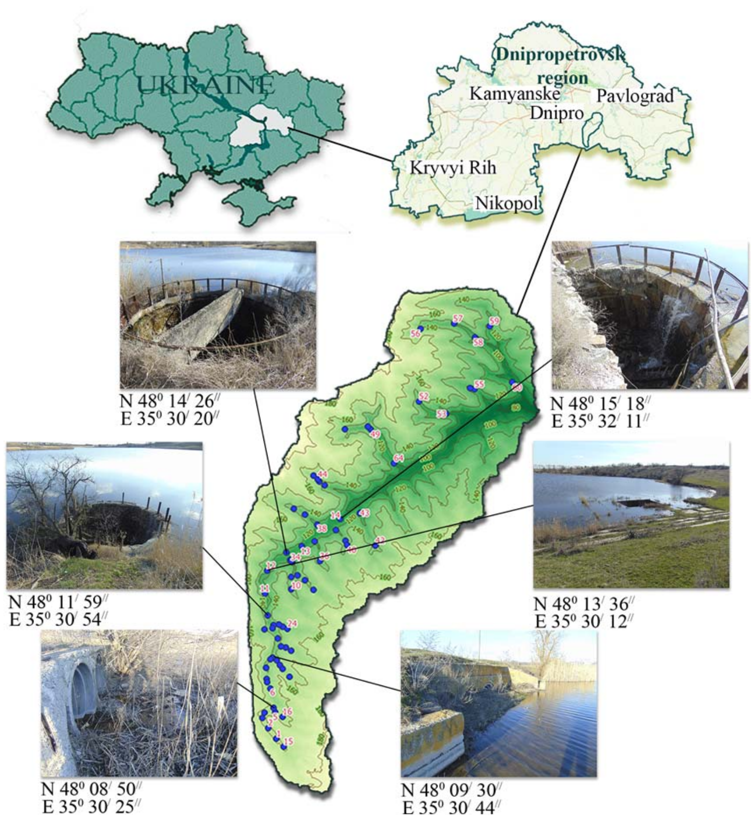


Fig. 1. Survey maps of the study area – the basin of the Nyzhnya Tersa River (points indicate reservoirs; water discharge facilities are photographed by the authors)

The soil hydraulic structures arranged in a cascade have the following technical parameters: length, ~600 m; the height of structures does not exceed 15 m; the width of the crest is 6–15 m. The area of ponds and reservoirs ranges from $1\cdot10^5$ to $1\cdot10^6$ mm^2; the average depth is 3–4 m. SHSs were built using local construction materials: loam and clay.

It should be noted that the construction of the SHS and the construction of reservoirs located downstream were carried out without proper hydrological justification due to incomplete consideration of the regulatory capacity of ponds and reservoirs located upstream.

The objects studied are similar to most dams and levees built on the rivers in the steppe zone of this country. They have common design parameters of work, operating conditions, technology, and construction techniques, made up of local soil materials, and operated for a long time (50–70 years), which testifies to the high representativeness of our studies.

To determine the general level of technical operation of the SHS and develop an algorithm for the management and environmentally safe operation of hydraulic structures arranged in a cascade, several methods were used. We performed visual examinations and instrumental diagnostics using the geophysical method ENPEMF [25], hydraulic calculations of parameters for water discharge facilities, and mathematical modeling of the probability of occurrence of an emergency due to filtration deformations.

The natural pulsed electromagnetic field is one of earth's natural geophysical fields and is characterized by a nonstationary state over time [26–28]. The ENPEM field propagates well in the earth's crust due to the wave nature. The energy of electromagnetic radiation (EMR) is significantly dissipated (reduced) in gas or absorbed by liquid. Since SHSs are composed of soil materials, such structures are conditionally transparent for ENPEMF. With the formation of cracks or excessive watering of the soil inside the body of the structure and its foundation, the intensity of the field decreases sharply. This pattern substantiates a decrease in the density of the pulse flow of the magnetic component of ENPEMF [25], which corresponds to the number of pulses recorded by the device over a certain measurement time interval (typically, 0.5–1.0 s). In this case, any excess of frequency-wave amplitude or ENPEMF EMR over some given level of discrimination is taken for the pulse. Thus, the magnitude of the density of the flow of pulses underlies the interpretation of the research involving ENPEMF.

Observations involving ENPEMF were carried out according to generally accepted geophysical research procedures. During the field work on the soil SHSs, their structural parameters were taken into consideration. Given the insignificant width of the crest of the structure relative to the total length, observation profiles were laid along the axis of the SHS crest. The distance between the profiles ranged from 2 to 5 m from each other, depending on the width of the structure. We measured and registered the density of the pulse flow of the ENPEMF magnetic component by the geophysical device "SIMEIZ". This device is designed at TOV "Slovyanskyy mist" (Dnipro, Ukraine). The device is equipped with the following: a module for registering electromagnetic pulses, a portable memory card for recording signals, and three highly sensitive antennas [25]. The device makes it possible to record the density of the pulse flow of magnetic and electrical components of ENPEMF in the low-frequency range of 1–50 kHz. The "SIMEIZ" equipment enables registering the value of the flow density of ENPEMF under the mode of continuous recording of the signal with a count frequency of at least 0.1 seconds. The receiver of pulsed electromagnetic signals is remote antennas. The advantage of "SIMEIZ" is a built-in frequency filter, which makes it possible in the process of observations, to "cut off" electromagnetic fields of anthropogenic origin, which are induced by the influence of power lines, underground utilities, communication systems, in particular cellular (mobile), etc.

We measured the electromagnetic pulses of ENPEMF on dams at points on profiles in increments of 2–5 m simultaneously with the use of three antennas in the low frequency range from 1 to 25 kHz. One of the antennas was vertically down. The other two antennas were directed horizontally along and across the dam at a distance of 0.2–0.4 m from the surface of the structure. Such an arrangement of the geophysical network of observations is associated with the assumption on the size of the disturbed areas. For example, the parameters of the zone of concentrated filtration flow of water through the body of a soil dam or cracks that are in the initial stages of formation may be of a small width of several meters. This substantiates the choice of the distance between the profiles and the step of the observation points on them in order to capture the area of anomalous values and the disturbed SHS zone with several profiles and points (Fig. 2).

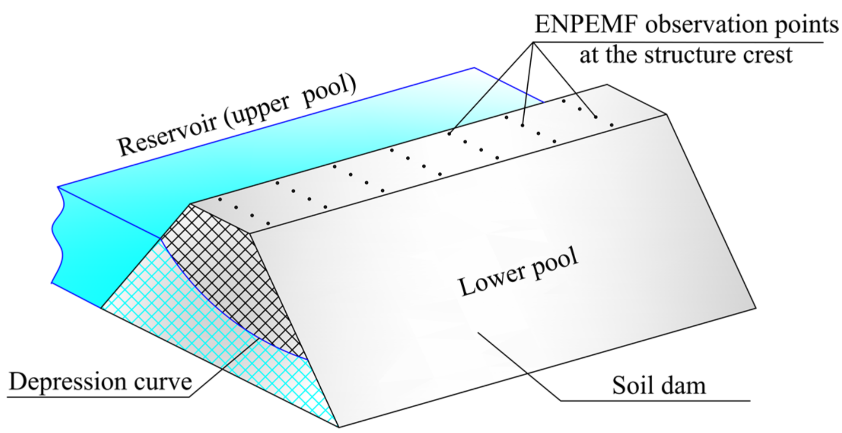


Fig. 2. Schematic showing the procedure for examining the technical condition of a soil hydraulic structure by a geophysical method: a fragment of the hydraulic structure in a reservoir with the arrangement of a network of observation points of the earth's natural pulsed electromagnetic field (ENPEMF)

Based on the results of the geophysical survey, we built the maps-diagrams of the density of the pulse flow of the ENPEMF magnetic component. We interpreted the maps built by using known criteria and signs of characteristic zones of cracking and loosening, devised for the geophysical fields of the Earth.

The assessment of the technical condition of SHS was carried out by summarizing the results of visual surveys and data on the instrumental observation of ENPEMF. The detected areas of evolution of dangerous engineering-geological processes in the body and base of the structure were referenced directly at the study object. Based on the layout (contour) of the ENPEM field, we determined places of the alternately-stressed state of the soils that the dam is composed of. This was taken into consideration when diagnosing and forecasting possible zones of landslide formation and the formation of avulsion cracks on the structures that were visually assessed as being in a satisfactory technical condition and having no clear signs of the manifestation of these processes.

According to acting standards [2], no systematic monitoring observations, technical and software means of monitoring systems are implied for the technical condition of hydraulic structures of this class (CC1) in general. The geophysical method ENPEMF is generally accepted and standardized for performing various types of engineering-geological tasks in accordance with a number of current regulatory standards. An important element confirming the reliability of research using ENPEMF is a series of well-known scientific and practical studies into the possibility of its application when diagnosing the technical condition of soil SHSs [4, 29].

The next step to solve our tasks was to determine the maximum flow rate and volume of water discharge during rain (storm) floods, which involved an empirical reduction formula in the absence of hydrometric observation materials:

$$Q_{p\%} = q_{200}\cdot\left(\frac{200}{F}\right)^{n}\cdot\lambda_{p\%}\cdot\delta_1\cdot\delta_2\cdot F, \quad (1)$$

where Q_p % is the instantaneous flow rate providing for 1 %; q_{200} is the module of maximum (instantaneous) flow rate ($m^3/s{\cdot}km^2$) with a probability of exceeding 1 %, which is reduced to the catchment area of 200 km^2; λ_p % is the conversion rate from 1 % probability of excess to the predefined probability; δ_1 is the coefficient of taking into consideration the damming of the maximum flow rate of (natural) lakes (δ_1=1.0); δ_2 is the coefficient that takes into consideration the reduction of water flow rate under the conditions of forested and wetland catchment basins (δ_2=1.0); n is the indicator of reduction in the module of estimated flow rate; F is the catchment area, km^2.

The volume of rain flood runoff of estimated probability is established from the expression:

$$W_{p\%} = F\cdot h_{p\%}\cdot 10^3, \quad (2)$$

where $h_{p\%}$ is the layer of water runoff at the estimated probability, mm.

The hydraulic calculations of water discharge facilities were performed on condition that the water level from the upper pool (UP) side reaches the forced retaining horizon (FRH). The estimated damming flow rate for the range of each individual structure is determined from the formula:

$$Q_r = Q_{p\%}\cdot\left(1-\frac{W_r}{W_p}\right), \quad (3)$$

where $Q_{p\%}$ is the flow rate of estimated probability, m^3/s; W_r is the volume of damming, m^3; W_p is the volume of flooding, m^3.

The throughput of water discharge facilities is calculated for rain (storm) floods of different volumes from P=0.5 % to P=25 %. According to [2], two estimation cases for letting through the maximum flow rate are regulated: basic and verification; 5.0 % and 1. 0 % probability, respectively.

Depending on the type of water discharge facility design, we calculated its throughput from the following expressions:

$$Q = m\cdot b\cdot\sqrt{2g}\cdot H^{\frac{3}{2}}, \quad (4)$$

$$Q = \mu\cdot\omega\cdot\sqrt{2g\cdot\left(H+z_{rp}\right)}, \quad (5)$$

where μ, *m* is the water discharge facility flow rate factor (depending on the type); b is the perimeter of the inlet part of a water discharge facility, m; ω is the area of the live cross-section of the outlet pipe of a water discharge facility, m^2; H, Z_{rp} is the head, m.

We assessed the probability of an accident on the dams of the cascade due to filtration deformations of the body and base of the structure according to the procedure from [30]. A general estimation scheme is shown in Fig. 3.

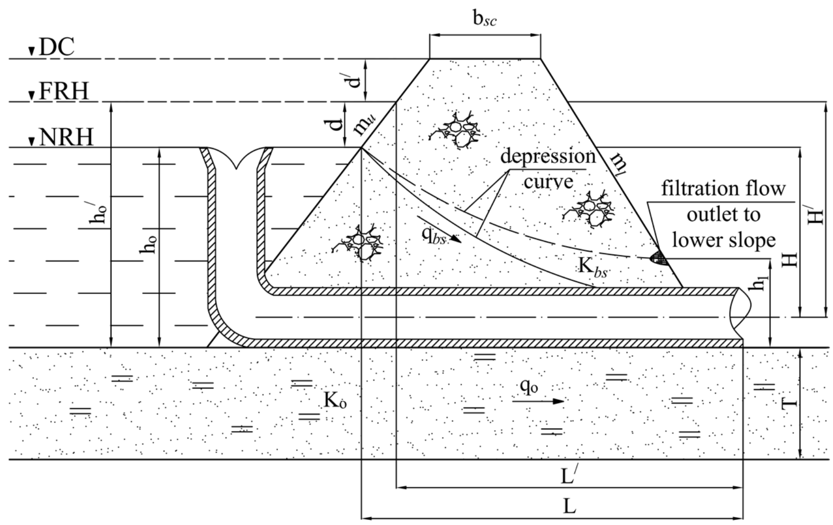


Fig. 3. Schematic showing the calculation of the probabilistic risk of an accident due to filtration deformations of the soil dam: *DC* – dam crest (hydraulic structure) of SHS; *FRH* – water level marking the forced retaining horizon; *NRH* – normal retaining horizon; H, H/ – active pressure of water on the structure; *T* – the power of the layer of water permeable base of SHS; b_{sc} – width along the structure crest; *d*, *d/* – exceeding the SHS crest above the estimated water level; q_{bs} – the amount of specific flow rate of filtration waters through the body of the soil structure; q_o – the amount of specific water flow rate in the base of the structure; h_o, h'_o the depth of water from the side of the upper pool; h_1 – the height of the depression curve output from the side of the lower slope; K_o – the coefficient of filtration of soils in the base of the dam; K_{bs} – the coefficient of filtration of soils in the body of the structure; m_u, m_l – the coefficients of arranging the upper and lower slopes, respectively

The general condition for the formation of filtration deformations of the soil of the dam body and base is as follows:

$$J_{est,m} \rangle \frac{1}{\gamma_n} J_{cr,m}, \quad (6)$$

where $J_{est,m}$ is the current average head gradient; $J_{cr,m}$ is the critical average head gradient; γ_n is the reliability factor, which is accepted in accordance with the SHS class.

We assessed the risk of destruction of the body and base of the dam due to the processes of excessive filtration by using the formula:

$$\lambda_{bs(O)} = \frac{\gamma_n}{K^{guar}_{H_{J_{est,m}}^{bs(O)}}}\cdot\lambda_n, \quad (7)$$

where γ_n is the reliability factor; λ_n is the normative risk, which is determined depending on the consequences of the structure for the main case of loads; K_H^{guar} is the guaranteed coefficient of the reliability of the body and base of the structure, respectively.

In order to introduce and implement an integrated approach to assessing the overall level of safety during the operation of SHS in a cascade, an approach based on expert assessments on different groups of indicators (categories) is proposed. These indicators characterize both the working conditions (environmental risks that may arise in the event of an emergency) and the technical condition of the structures [16]. An estimate of the level of danger of operation "R" and non-compliance of the indicators of the technical condition "TC" with the normative working conditions is proposed to be expressed as a percentage according to the following formula:

$$R(TC) = \frac{1}{N_{\max} \cdot k} \cdot \sum_{i=1}^{n} N_i \cdot 100\,\%, \quad (8)$$

where $N_{\max}$ is the maximum possible score when evaluated; k is the number of indicators by which the assessment is carried out; N_i is the estimate score of a separate i-th indicator; n is the total number of indicators (criteria) of evaluation.

Generalizing all research results makes it possible to assess the possible negative consequences of breaking through a cascade of reservoirs. In this case, the focus is on indicators of the level of technical condition of SHS and ensuring the safety of its further reliable operation, as well as possible risks and environmental consequences of the destruction of structures on the environment. A similar experience in the EU countries in improving the level of safety of operation of tail storage facilities for various purposes was adopted as a basis [31]. That approach has been improved and adapted to the working conditions of an SHS cascade on small rivers. This has made it possible to develop an algorithm for assessing and ranking structures on the principle of division into several local areas for ensuring environmentally friendly operation (Fig. 4).

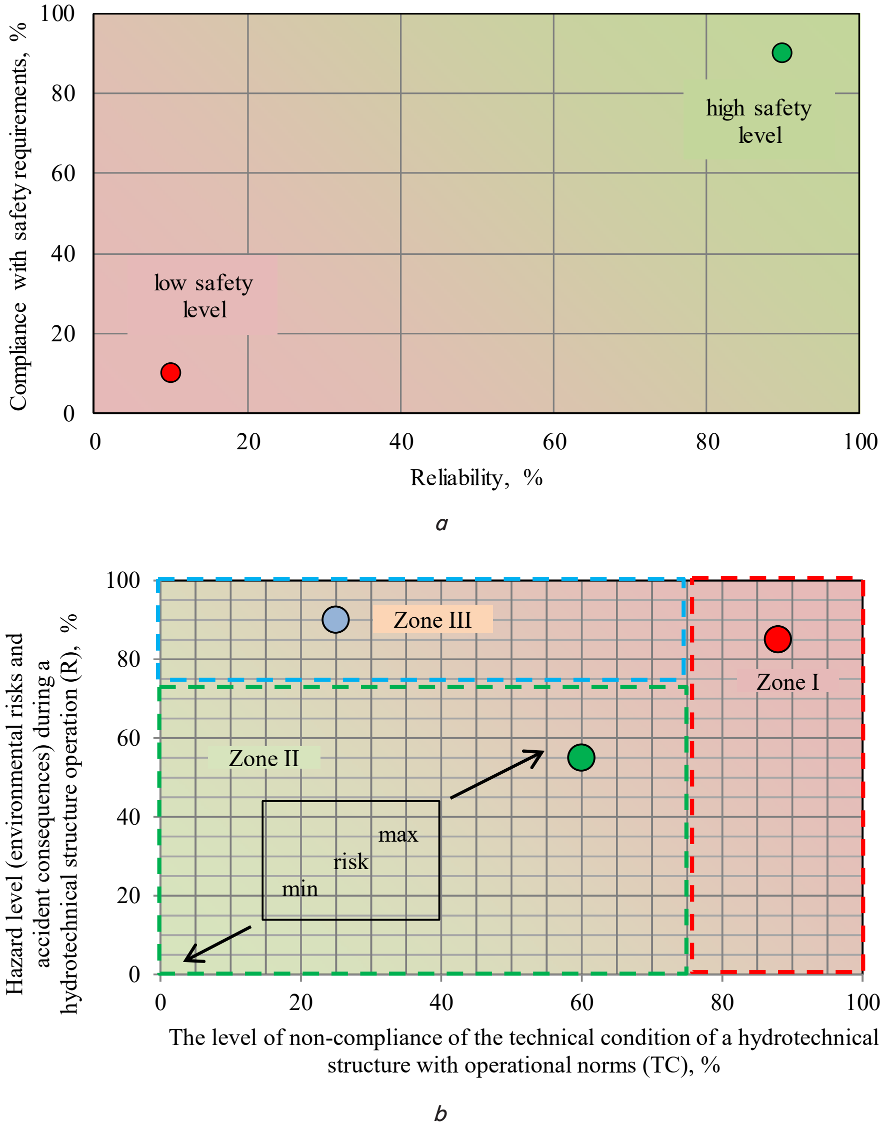


Fig. 4. Diagrams of the visual representation of results from assessing the operational safety of a hydrotechnical structure when managing a cascade of hydraulic structures: *a* – the experience of the European Union [30]; *b* – our developed algorithm

In this case, "zone I" corresponds to a dangerous level, and "zone II" corresponds to satisfactory operational conditions. Conditional "zone III" satisfies the indicators of the level of technical operation of SHS but requires considerable attention to monitoring the technical condition of the structure. This is justified by a high level of danger and possible negative environmental consequences in the event of a break or accident at the dam.

5. Results of studying the management and environmentally safe operation of soil hydraulic structures

5. 1. Results of the visual and instrumental assessment of the technical condition of hydraulic structures

Our results of the assessment of the level of technical operation of soil SHSs are represented by the example of one of the studied dams. Diagnostic visual examinations and field studies were carried out at the structure using the ENPEMF method according to the above methodology. Based on the measurements, a map-diagram of the density of the pulse flow of the magnetic component of ENPEMF was constructed (Fig. 5).

According to the results of visual surveys, a section of subsidence of the dam body in the central part was found, as well as a zone of the concentrated filtration flow through the body of the structure on its right side (Fig. 5, *a*). Following the interpretation of the map-diagram and its analysis based on the results of geophysical research, additional shortcomings of the technical condition were established. In the body of the soil SHS, in addition to visually diagnosed disturbed areas, local zones of water filtration through the body of the structure and water saturation of soils were found (Fig. 5, *b*, positions 3 and 4). Geophysical studies involving ENPEMF recorded the area of watering and wash-out of part of the dam crest (Fig. 5, *b*, position 5), which is confirmed by the release of the filtration flow of water from the side of the lower pool (Fig. 5, *a*, photograph on the right).

Thus, the overall results of our survey at all the facilities studied have shown that most structures are in poor technical condition. In addition to the disturbed parts that are visually diagnosed, all hydraulic structures additionally, according to instrumental observations, demonstrate areas of concentrated filtration and landslide zones. Given that there are not only ponds and reservoirs downstream of each of the reservoirs but settlements as well, cascading destruction of SHS may be associated with significant environmental risks, negative consequences, and losses of socio-economic nature.

5. 2. Hydraulic calculation of the water discharge facilities throughput

To pass excess water flows in rain (storm) floods or spring snow melting, SHSs are equipped with discharge devices. Because the project documentation is absent or partially lost, it was established according to the results of our visual survey that most water discharge facilities were made in the form of overflow reinforced concrete pipes or mine wells. Drainage devices have a number of structural and technical shortcomings. They are partially destroyed, there are no garbage-containing grilles, they are littered with fragments of reinforced concrete structural elements and wood, silt, etc.

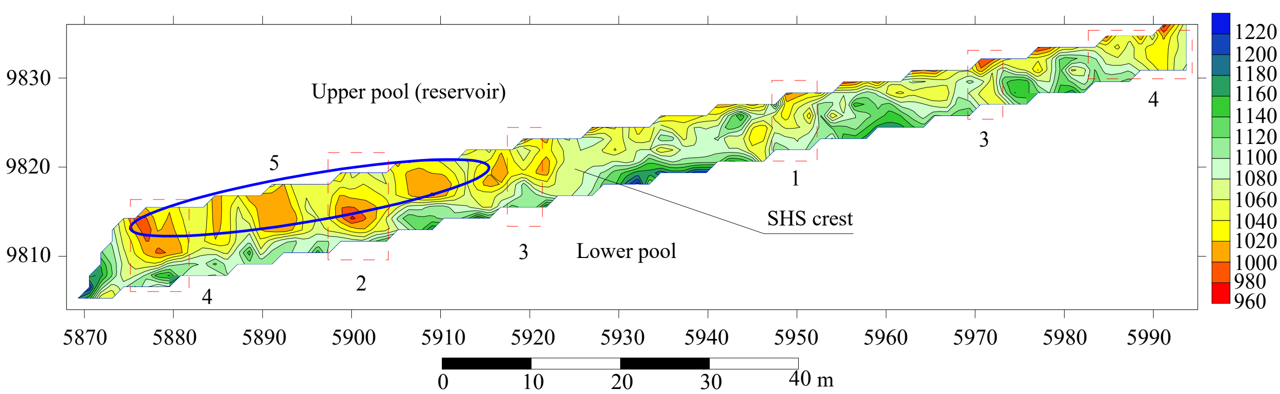
The results of hydrological calculations of dammed water flow rate in the range of the studied hydraulic structures are given in Table 1.

Table 1

Calculation of dammed flow rate $P_{1\,\%}$-probability at water discharge facilities in the cascade of hydraulic structures on the Nyzhnya Tersa River

Water discharge facility No.	Parameters and indicators of hydrological calculations			
	$Q_{1\,\%}$, m^3/s	Wr, ×10^6 m^3	Wp, ×10^6. m^3	Qr, m^3/s
1	38.20	2.286	3.26	11.41
2	35.02	0.035	2.44	34.51
3	34.27	0.570	2.27	25.68
4	31.96	0.065	1.80	30.81
5	31.48	0.350	1.71	25.04
6	28.33	0.115	1.20	25.62
7	24.56	0.143	0.75	19.86
8	17.72	0.074	0.25	12.52

a



b

Fig. 5. An example of studying a water facility: *a* – satellite image of the reservoir and an exit zone for the filtration flow of water through the body of a hydraulic structure;
b – map-diagram of the density of pulse flow of the magnetic component of ENPEMF

Note: a conditional coordinate system in meters is applied; X-axis – direction to the east; Y-axis – orientation to the north; the color scale on the right shows the gradation of the density of the pulse flow of the magnetic component of the earth's natural pulsed electromagnetic field; rectangles show areas of avulsion disturbances and loosening of the soil; the blue line marks the area of water saturation and the crest wash-out

We estimated the hydraulic parameters and throughput of water discharge facilities (Table 2) for the main and verification cases.

Table 2

Determining parameters for the throughput of water discharge facilities in the cascade of hydraulic structures on the Nyzhnya Tersa River

SHS No. in a cascade	SHS class of consequences	Water volume W, $\times 10^6$. m^3	The catchment area F, ha	Normative indicators of probability P, %, exceeding the estimated maximum water flow rate according to the main (test) estimation cases	Theoretical (6) and actual (7) flow rate of water discharge facilities Q, m^3/s (probability P, %)		Correspondence of calculated parameters to normative values
1	CC1	0.993	8150	5.0 (1.0)	8.3	7.0 (2.0)	+
2	CC1	0.594	6320	5.0 (1.0)	14.2	12.7 (10.0)	–
3	CC2-2	1.050	5680	3.0 (0.5)	45.0	45.0 (0.5)	+
4	CC1	0.120	4340	5.0 (1.0)	7.0	7.0 (15.0)	–
5	CC1	0.534	4280	5.0 (1.0)	6.8	5.6 (8.0)	–
6	CC1	0.165	3010	5.0 (1.0)	1.1	1.1 (20.0)	–
7	CC1	0.187	2270	5.0 (1.0)	5.8	3.1 (10.0)	–
8	CC1	0.184	1870	5.0 (1.0)	2.8	2.3 (7.0)	–

The calculations determine the non-compliance with the regulatory requirements for the passage of maximum flow rate and volumes of flood (rain) waters of the predefined probability, which are regulated by the current state standard [2]. It has been established that the unsatisfactory technical condition of water discharge facilities significantly reduces the hydraulic parameters of their throughput. When passing floods with high probability, there is a potential danger of the water level reaching the mark of the crest of structures with subsequent overflow. In the case of the formation of a gap in the body of the dam, the volumes of water accumulated in the upper reservoirs suddenly reach the below ponds that significantly complicates the throughput capacity of the water discharge facilities. Under such working conditions, the probability of overflying water through the crest of soil dams, followed by their destruction, increases.

5. 3. Calculating the probabilistic risk of an accident due to filtration deformations of the body and base of dams

Based on the established operational shortcomings of the structure of water discharge facilities and their hydraulic parameters, we estimated the probabilistic risk of an accident due to filtration deformations of the body and base of dams. Such calculations were carried out on the marks of the normal retaining horizon, forced retaining horizon, and the crest of the structure (Table 3) to the overflow of water through it, which, for soil SHSs, is almost irrevocably destructive.

Table 3

Evaluating the parameters of filtration deformations and the likely risk of an accident in SHS cascade at different water levels (at the marks of NRH/FRH/crest of the hydraulic structure)*

SHS No. in a cascade	Specific filtration flow of water through the body of the dam q_{bs}, m^2/s	Specific flow rate of filtration flow at the base of the dam q_o, m^2/s	Total specific filtration water flow rate q, m^2/s	The average head gradient in the body of the structure $J_{est,bs}$	The average head gradient in the base of the structure $J_{est,o}$	Critical head gradient $J_{cr,m}$	Maximum local head gradient when reaching the day surface J_{est}	Risk of destruction of the body of the hydraulic structure λ_{bs}, $\times 10^{-3}$	Risk of destruction of the base of the hydraulic structure λ_o, $\times 10^{-3}$	Overall risk of dam destruction λ, $\times 10^{-3}$	Regulatory risk of destruction ** λ_n, $\times 10^{-3}$
1	0.392	0.138	1.063	0.226	0.153	0.8	1.060	1.942	1.297	3.240	6
	0.535	0.155	1.380	0.265	0.172	0.8	1.184	2.247	1.461	3.708	
	0.779	0.179	1.917	0.329	0.199	0.8	1.372	2.791	1.689	4.481	
2	0.540	0.138	1.358	0.220	0.154	0.8	1.040	1.892	1.302	3.193	6
	0.805	0.160	1.931	0.270	0.178	0.8	1.199	2.288	1.512	3.800	
	1.006	0.176	2.363	0.308	0.195	0.8	1.312	2.610	1.658	4.268	
3	0.577	0.110	1.376	0.170	0.121	0.8	0.798	1.460	1.026	2.485	3
	0.928	0.127	2.111	0.211	0.141	0.8	0.931	1.791	1.199	2.991	
	1.729	0.159	3.775	0.293	0.176	0.8	1.153	2.483	1.494	3.977	
4	0.347	0.125	0.948	0.196	0.140	0.8	0.953	1.687	1.180	2.867	6
	0.598	0.154	1.505	0.259	0.171	0.8	1.166	2.200	1.454	3.654	
	0.830	0.175	2.012	0.313	0.195	0.8	1.325	2.650	1.653	4.303	
5	0.767	0.160	1.857	0.268	0.177	0.8	1.195	2.298	1.491	3.791	6
	0.988	0.173	2.323	0.303	0.193	0.8	1.298	2.568	1.633	4.201	
	1.131	0.184	2.630	0.329	0.204	0.8	1.371	2.789	1.729	4.518	
6	0.395	0.152	1.098	0.268	0.170	0.8	1.196	2.302	1.433	3.734	6
	0.492	0.164	1.313	0.298	0.183	0.8	1.285	2.530	1.549	4.079	
	0.521	0.170	1.382	0.314	0.188	0.8	1.331	2.667	1.597	4.264	
7	0.394	0.141	1.072	0.234	0.156	0.8	1.084	2.005	1.322	3.328	6
	0.522	0.156	1.356	0.269	0.174	0.8	1.197	2.284	1.472	3.756	
	0.642	0.174	1.633	0.319	0.193	0.8	1.344	2.706	1.639	4.345	
8	0.250	0.121	0.744	0.191	0.134	0.8	0.933	1.641	1.134	2.776	6
	0.343	0.137	0.960	0.225	0.152	0.8	1.054	1.911	1.290	3.201	
	0.366	0.145	1.022	0.245	0.161	0.8	1.120	2.078	1.366	3.444	

*Note: for each SHS in a cascade, the first value is calculations for NRH; the second value – FRH; third value – indicators at the mark of the crest of the structure; ** – regulatory risk of an accident in accordance with [2]*

Further comparison of our results is given in Table 4.

It is established that the overall risk (probability) of an accident does not exceed the normative value (except for the case of an increase in the water level to the level of the crest at the third structure). At the same time, there is a significant increase in the overall risk of a dam body crashing at the water level at the dam crest mark relative to the normal retaining horizon, which, in percentage terms, ranges from 15 to 60 %.

Table 4

Comparison of the calculated parameters of the risk of an accident at SHS due to filtration deformations at different levels of water in the upper pool

SHS No. in a cascade	Overall risk of destruction at the mark NRH, $\lambda \cdot 10^{-3}$	Overall risk of destruction at the mark FRH, $\lambda \cdot 10^{-3}$	Overall risk of destruction at water level at the dam crest mark, $\lambda \cdot 10^{-3}$	Increased overall risk of destruction at FRH relative to NRH, %	Increasing the overall risk of destruction of the SHS body at water level at the crest of the structure relative to NRH, %
1	3.240	3.708	4.481	14.4 % ↑	38.2 %↑
2	3.193	3.800	4.268	19.0 % ↑	33.6 %↑
3	2.485	2.991	3.977	20.3 % ↑	60.0 %↑
4	2.867	3.654	4.303	27.4 % ↑	50.0 %↑
5	3.791	4.201	4.518	10.8 % ↑	19.2 %↑
6	3.734	4.079	4.264	9.2 % ↑	14.2 %↑
7	3.328	3.756	4.345	12.8 % ↑	30.5 %↑
8	2.776	3.201	3.444	15.3 % ↑	24.0 %↑

Thus, our study's results point to the need for a systematic approach to assessing both the technical condition of SHSs and determining the level of their environmentally safe operation, which requires the introduction of new approaches.

5. 4. Developing an algorithm for the management and environmentally safe operation of dams in a cascading arrangement

Our results of assessing the technical condition and level of operation of the examined facilities underlie the proposed algorithm for the management and environmentally safe operation of dams in a cascading arrangement, which is shown in Fig. 6.

The proposed scheme summarizes the list of the main components of both diagnostic control and the system algorithm for step-by-step safety, namely:

– the need to update passport data on the reservoir and SHS of class CC1 at the current level of operation;

– the technical condition of SHS – visual and instrumental studies on the use of geophysical methods are recommended to be carried out not only at the initiative of the balance holder but also during periods of "high waters";

– hydrological calculations are justified in connection with changes in climatic conditions, relevant features of the formation of maximum runoff and the influence of man-made and natural factors on the operation of hydraulic structures;

– the criterial indicators for assessing the reliability of SHS operation are an integral part of the qualitative and quantitative generalization of the technical condition of the structure;

– based on the previous stages of evaluation, it is possible to establish the level of safe operation of such SHSs in a cascade arrangement, taking into consideration many criteria and expert assessments;

– forecasting changes in the technical condition and the ability to make informed management decisions as a result of research is an integral part of ensuring a high level of technical operation for balance-keeping organizations.

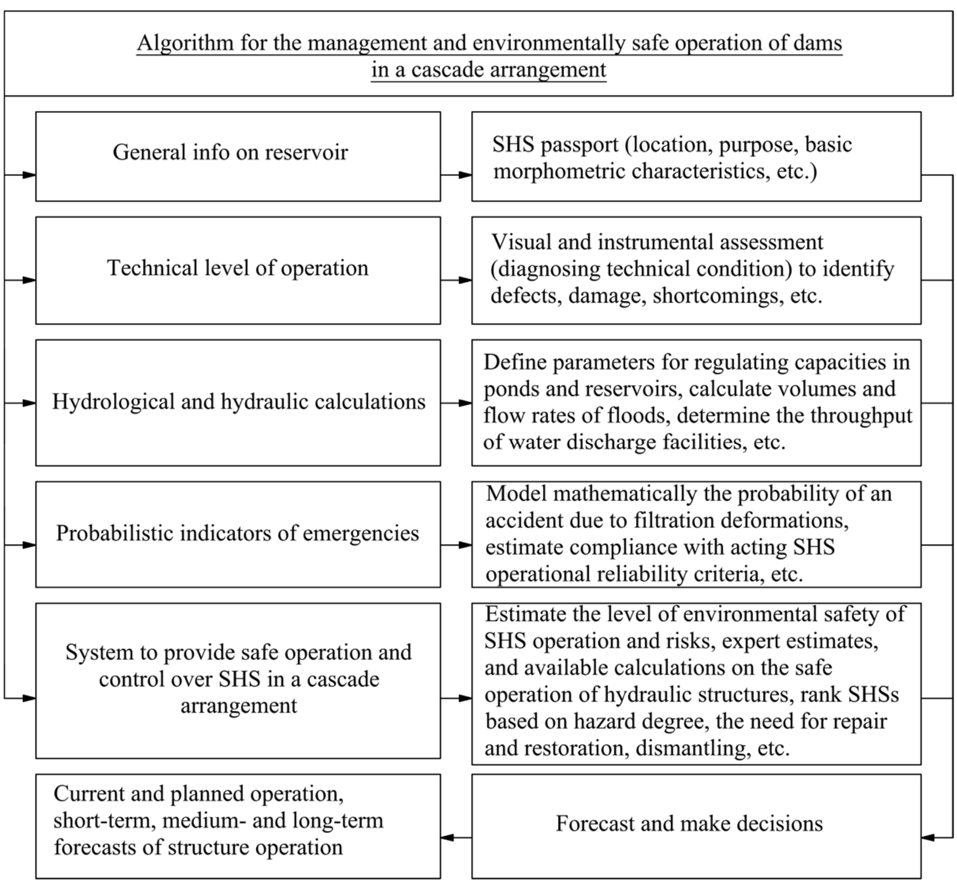


Fig. 6. Flowchart of the proposed algorithm for the management and environmentally safe operation of hydraulic structures of class CC1 in cascades

The implementation of the proposed algorithm for categorizing the structures according to the level of their technical condition and the danger of operation is illustrated by the example of an SHS cascade on the Nyzhnya Tersa River. It was established that among the studied objects, three are in the zone of potential risk of an accident. The technical condition and operational safety of seven dams is downgraded. Two SHSs meet safety requirements but require increased attention during operation due to the high level of negative socio-environmental consequences in the case of a breakthrough. Our results provide an opportunity to assess the probable cumulative effect during the destruction of one or more dams. In this case, each subsequent SHS would accept the volume of water arriving from the upstream reservoirs. The total volume of water from rain (storm) floods with the addition of the volume accumulated in reservoirs that can be discharged is ~17.5×106 m^3. The zone of potential danger of flooding the territory and deterioration of sanitary and hygienic conditions of water use may include 9 settlements with more than 2.5 thousand inhabitants.

The proposed algorithm in practical implementation makes it possible to take medium- and long-term forecast decisions on the planned improvement of the technical condition of SHSs or their gradual elimination.

6. Discussion of results of assessing the technical condition and environmentally safe operation of hydraulic structures in a cascading arrangement

It is worth noting that most facilities were built more than 50–70 years ago in an economic way without proper design documentation (alternatively, the documents were lost over time) based on the old standards and engineering approaches. Thus, the need for an integrated approach to assessing the level of technical condition of the cascades of soil hydraulic structures of the CC1 class, which form ponds and reservoirs on small rivers, requires the development of an effective operating algorithm. To this end, it is proposed to compile technical passports of reservoirs and dams on them, to conduct hydrological and hydraulic (engineering) calculations. As well as define parameters for changing the water level in ponds and reservoirs and the conditions for the safe technical and environmental operation of hydraulic structures in the case of a significant amount of precipitation and possible destruction of the structure located upstream. The proposed measures could become the basis for implementing a system of constant monitoring of the technical condition of SHS in order to assess (forecast) its impact on the environment.

Our study and calculations based on the example of a representative object of research are the basis for determining the further level of environmentally safe operation of structures. The probability of a significant increase in the water level from the upper pool side in the case of heavy rains or a breakthrough of SHS upstream of the river has been established. Such data are the basis for assessing the probability of an emergency due to filtration deformations of the body and base of the structure. The comparison of calculated cases of the probability of SHS destruction due to filtration deformations reveals that, in general, the overall risk does not exceed the regulatory one. At the same time, there is a significant increase in the overall risk of a dam body crashing at the water level at the dam crest mark relative to the normal retaining horizon, which, in percentage terms, ranges from 15 to 60 %.

The advantages of our study include the implemented example of the use during diagnostic examinations of not only known (classical) methods of technical diagnostics but also the application of the remote geophysical method ENPEMF. The combination of methods makes it possible to identify areas of concentrated water filtration through the body of SHS, watering zones, and the stressed-strained state of the soil. Additionally, the initial stages of avulsion crack formation are diagnosed, which cannot be established visually, according to geodetic observations, or by embedding control and measuring equipment.

Effective management of cascades of hydraulic structures of the CC1 class under current operating conditions requires further improvement of the technical diagnostics system and the algorithm for their environmentally safe operation. In particular, a significant step is the need for systematic compilation of passports for water bodies. It is mandatory to include in such documentation the operational indicators and parameters for SHS and water discharge facilities. These indicators can include those reported in our work providing for the sequence and fullness of such information, based on the proposed algorithm. They should include hydrological, hydraulic, and probabilistic indicators of the occurrence of an accident due to filtration deformations. This makes it possible to take effective planning and operational decisions, as well as predict changes in the technical condition of structures over time. The results of diagnostic surveys and the parameters of engineering calculations provide an opportunity to establish the level of priority of receipt of funds for ongoing repair and restoration works and major reconstruction of water management facilities. This improves the operational and environmental safety of SHS performance. In other cases, given the inexpediency of SHS further operation, its gradual elimination is proposed.

7. Conclusions

1. Our visual examinations and diagnostics of the technical condition of SHS using the geophysical method of the Earth's natural pulsed electromagnetic field prove the effectiveness of a set of such studies. In particular, it becomes possible to identify potential areas of concentrated water filtration through the body of SHS, watering zones, and the stressed-strained state of the soil, the initial stages of suffusion formation, avulsion cracks, etc., which do not have a visual manifestation. Such hidden zones of the initial evolution of negative engineering-geological processes occur in all the studied structures and account for about 50 % of the total number of violations of the technical condition.

2. Based on the hydrological calculations and the determined hydraulic parameters for water discharge facilities, their inability was established, in the vast majority, to pass the maximum flow rate of rain (storm) floods. Under regulatory conditions for 5 % and 1 % probabilities for basic and verification cases, respectively, the current parameters of operation of water discharge facilities meet the conditions for probabilities of 10 % to 2 % in general. That could lead to an increase in the water level to the marks of SHS crest and the overflow of water through the dam.

3. Under the current operating conditions, our calculation of the probabilistic risk of a hydrodynamic accident due to filtration deformations indicates a significant increase in

its level, from 14 % to 60 %, which, in some cases, exceeds the regulatory indicators.

4. Based on the generalization of existing experience in the operation of soil hydraulic structures, modern approaches to assessing the technical condition and subsequent environmentally safe operation of soil SHS on small rivers have been proposed. The implementation of the proposed approach provides an opportunity to control the cascades of hydraulic structures of the CC1 class at different stages of operation. This improves the operational and environmental safety of SHS.

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