https://doi.org/10.33271/nvngu/2023-2/154

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PROSPECTIVE METHODS FOR DETERMINING WATER LOSSES FROM IRRIGATION SYSTEMS TO ENSURE FOOD AND WATER SECURITY OF UKRAINE

Purpose. To develop a complex system for technical diagnostics of soil hydrotechnical structures of irrigation systems for operative identification of damaged sites, reduction of nonproduction water losses, and maintaining ecological and economic efficiency of the hydroeconomic national complex in the context of water and food security.

Methodology. The result of the represented scientific study is reached by complex application of geophysical methods of the Earth's natural pulse electromagnetic field (NPEMFE) and vertical electrical sounding (VES). That allows determining qualitative indices and parameters of the damaged sites of hydrotechnical structures and water filtration paths. Mathematical methods for determining quantitative parameters of filtration losses are applied. Analytical and technoeconomic comparison of some most widely used methods with the complex of techniques proposed in the study are performed.

Findings. Field studies and analytical calculations helped determine that, depending on the design parameters of retention basins and modes of their operations, water losses are from 50 to 60 m^3/month per 1 m of the structure length. In some cases total filtration losses per month can reach up to 100 m^3 per 1 m of the length. As for the monetary equivalent, in terms of average water cost being 0.12 EUR/m^3, water loss in one standard retention basin with the conventional dimensions of 100 × 100 m is EUR 2.5 thousand per month (EUR 12.5 thousand per season).

Originality. The possibility of using a complex of geophysical methods for diagnosing technical conditions of soil dams of retention agricultural basins has been substantiated scientifically. The complex is of high informativity making it possible to determine rapidly the sites with increased filtration in the hydrotechnical objects. According to the comparison of the available models for evaluating possible filtration losses from the retention basins of irrigation systems, the parameters of estimate indicators, ensuring high reliability of the results, have been substantiated.

Practical value. Point determination of the sites with filtration water losses makes it possible to focus the repair and renewal operations on the most damaged sites that reduce considerably the time and costs along with the increase in general efficiency of the irrigation system operation.

Keywords: *water resources, water loss, regulating pool, irrigation system, complex of geophysical methods*

Introduction. Irrigation is a crucial condition for a stable and guaranteed production of agricultural products, as evidenced by centuries of experience in the use of arable land in different countries [1]. Analysis of agricultural production development shows that the greatest successes have been achieved by those countries where large-scale national programs for the creation and rational use of irrigated land have been implemented [2]. According to the research by the Institute of Water Problems and Land Reclamation of the National Academy of Sciences of Ukraine, there are more than 270.5 million hectares of irrigated land and 164.0 million hectares of drained land in the world. The main factor in the intensification of agriculture, especially in the context of global climate change, is the reclamation of irrigated land, which ensures sustainable agricultural production. Therefore, irrigated land in highly developed countries and the southern steppe of Ukraine are the main guarantor of food security [3].

According to the inventory of the State Agency of Water Resources of 2287.1 thousand acres of reclamation systems on farms that existed before, under modern economic conditions in Ukraine, only 604.2 thousand acres of irrigated land were irrigated, or 26.4 % of their total area. The main reasons for this are the unsatisfactory technical condition of on-farm reclamation networks and insufficient provision of modern sprinklers; the remaining 80 % have already met their regulatory deadlines.

The economic use of water resources, and therefore the reduction of filtration losses, are priority areas for the development of water in Ukraine. The main reason for the inefficient use and operation of irrigation systems today is the significant loss of water from the regulating pools and canals. The vast majority of these losses are associated with significant violations and unsatisfactory technical conditions of hydraulic structures of irrigated systems.

In line with the strategy [4], it should be noted that the implementation of measures aimed at restoring and developing irrigation is one of the priorities of the Association Agreement between Ukraine and the European Union, Directive 2000/60/EC of the European Parliament and of the Council of Europe of 23 October 2000 "On establishing a framework for Community action in the field of water policy". At the current level of operation, losses can exceed 35 % or more, and the world and domestic experience shows that the flow of filtration affects the strength and stability of soils of such structures and leads to accidents in more than 30 % of cases. The issue of the safety of hydraulic structures (HS) was considered in the works by authors from around the world [5–7].

To monitor the technical condition of the HS of all classes of consequences, calculation methods are provided by the requirements of the current standard of Ukraine (DBN V.2.4-3:2010), and for higher classes of consequences, research and experimental work of CC3 and CC2 are recommended to support the main technical solutions that determine the reliability and safety of structures. Attention to the factors influencing operational reliability is paid only for higher classes of HS consequences than CC1, in particular for hydraulic units.

For a fast and accurate diagnosis of the technical condition of the HS, it is recommended to use geophysical methods in complex exploration work [8]. At present, geophysical methods are not used in Ukraine to diagnose the technical condition of CC1 impact class structures, as their use is considered economically unprofitable and time-consuming and requires highly qualified personnel of relevant specialization. An alternative solution to the problem is the introduction of inexpensive, informative, and fast-to-use remote control methods.

Researchers [9] during engineering surveys recommended the use of a set of geophysical methods to assess the technical condition and determine the level of safety of reclamation systems and structures: an electrical exploration using electric profiling (EP); continuous seismic acoustic profiling; radar profiling along with profiles; seismic surveys by the method of seismic transmission to determine the composition and properties of peat and sapropels in the array. In the work [10], the research on the definition of places of filtration through the reinforced concrete facing of the main channel by a method of a natural electric field (NEF) is considered. However, it is planned to identify possible leakage zones of increased filtration in the structures of regulating pools using a set of geophysical methods, which include vertical electric sounding (VES), microelectric sounding (MES), electroprofiling (EP), and natural electric field method (NEF). However, the work shows significant shortcomings in the use of the above geophysical method complexes for the diagnosis of HS for water management. Significant labor costs and duration of work, high cost of work, and the need to involve highly qualified specialists in the internal processing of field data [11].

Thus, today it is an urgent practical task for the prompt and reliable diagnosis of HS irrigation systems [12]. The search for field methods to address this issue is still ongoing. An alternative to the operational determination of the technical condition of the HS may be the use of a set of geophysical methods of the Earth's natural pulsed electromagnetic field (NPEMFE) and vertical electric sounding (VES). The rationality of the proposed option will be considered in the example of the study of the technical condition of the five regulating pools.

Materials and methods. The objectives of the study are the regulating pools of irrigation systems in the Dnipropetrovsk region of the consequence class CC1. The buildings are built of local soil materials using clay and loam. Built according to standard designs and constructively made in a semi-embankment. Regulating pools have a square shape in plan and the parameters of their sides vary from 50 to 100 m; the average depth varies from 4 to 6 m. A typical structural scheme is shown in (Fig. 1).

Research methods. Commonly used methods were applied in the work: research by geophysical methods to establish filtration zones of the Earth's natural pulsed electromagnetic field (NPEMFE) and vertical electric sounding (VES); analytical and calculation – to determine the number of filtration losses of water from regulating pools. The Golden Software Surfer and IP2Win software packages were used to process the results obtained.

The NPEMFE method. The main areas of application of the NPEMFE method are assessing the stability of the stress-strain state, determining inhomogeneities in geological structure, identifying spatial patterns and depths of stress epicenters, studying and predicting dangerous geological processes and phenomena (landslides, mechanical suffusion, landslides).

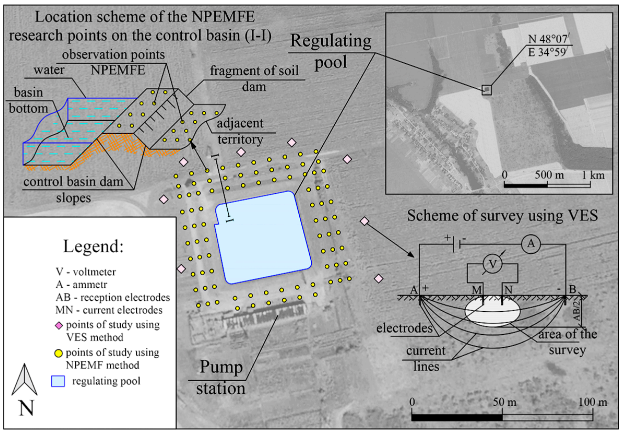

Fig. 1. The method for performing geophysical studies and structural diagram of the regulating pool (fragment of the territory obtained from the Google Earth service)

The advantage of the NPEMFE method is high productivity and low work cost. This method provides a simple and reliable control of the stress-strain state of rocks. The economic efficiency of the equipment is determined by a sharp increase in productivity due to the high speed of measurement. Unlike common methods of seismic and electrical exploration, the proposed method does not require complex preparatory operations, which reduces labor costs and labor costs by at least 5 to 8 times. The NPEMFE method allows for the recording of the destruction of rocks in the microcrack development stage by recording the characteristic pulsed electromagnetic signal. This unique feature of the method provides its high sensitivity and informativeness and allows for short-term (from several hours to several months) forecasting of catastrophic phenomena [13].

For theoretical and experimental evidence of the application of NPEMFE to identify zones of loosening and wetting in the body of canals and regulating pools of irrigation systems, the nature of the change in amplitude during the transfer of uniaxial static load to bulk soil samples was studied. Such experimental studies on the idealized model are a justification for the possibility of assessing the technical condition of canals and regulating pools of irrigation systems by NPEMFE [13].

Detection of filtration zones in the body of regulating pools can be performed using the NPEMFE method based on the selection of spatial anomalies and their interpretation. It is known that the Earth's natural pulsed electromagnetic field is one of the geoelectric fields that occur mainly during the deformation of rocks or minerals [14].

The NPEMFE examination on regulating pools was performed in the profile-plane version in two stages, when filling and empty. The last stage is performed not earlier than three weeks after emptying the pool or in the spring before filling it.

The field survey was carried out with the SIMEIZ device. The instrument allows one to determine the number of NPEMFE pulses during measurement with a relative error of ±10 % and to find the percentage of the total duration of the signal that exceeds the dynamic range to the measurement time ("scale percentage") with a relative error of ±10 %. The ready time for the device to work is no more than 5 s after inclusion. The weight of the SIMEIZ device is up to 2.5 kg, and the overall dimensions do not exceed 350 × 150 × 150 mm. The device has a built-in frequency filter, which allows the process of observations to "cut off" electromagnetic fields of man-made origin, caused by power lines, underground communications, and wireless communication systems, including cellular systems.

Graphic mode on a computer screen allows one to estimate the origin and possible source of the NPEMFE signal, and isolate and filter out electromagnetic radiation caused by external causes (atmospheric phenomena, solar activity, ultimate cosmic radiation).

The NPEMFE pulses generated by the soil or other materials are captured by three antennas and transmitted to the device. Data were written to a flash drive and then processed on a personal computer. During the analysis of field survey data, the geological and tectonic structure and hydrogeological features of the study area were taken into account.

Visualization of NPEMFE research results in the processing of field imaging materials, such as regulating pools, is usually based on pulse flux density maps using the Golden Software Surfer program.

Interpretation of chart maps is based on the standard method of geophysical data processing and the assumption that flooded areas of the sides of the pools and bottom in the NPEMFE field should correspond to areas of poorly differentiated, "blurred" field, and low pulse flux density. On the contrary, areas with high values of pulse flux density indicate a relatively normal technical condition of soils, which are located on the sides of the regulating pools.

The distance between the profiles laid on the dams of the regulating pools was up to 3 m, between the observation points on the profile 3 m, and the length of the profiles corresponded to the size of the structure studied. Topographic division of the network is not required; it is enough to link to the characteristic observation points of the GPS-navigator. Measurements were made in daylight with clear hot weather and light wind.

The VES method refers to "quantitative" geophysical research (DBN B.2.4-1-99:2000) to identify areas of concentrated filtration. The method of vertical electric sounding allows us to investigate changes in the geological section in-depth: the value of power and resistivity of each soil layer. A four-electrode symmetric AMNB unit with supply A and B and measuring or receiving M and N electrodes was used for VES studies. Metal pins, which are driven into the ground, were used as electrodes. Steel-copper wires and cables were used for the installation of supply and receiving lines. The electrodes were located in a straight line relative to the center of the installation. During field work in the pools and canals, the size of the spacing of the supply electrodes did not exceed 60 m:

- distances AB – 3, 4, 5, 6, 9, 15, 40 m;
- the distance between the MN distances was 1 and 3 m when shooting at RP-1 VIS, RP-1 PIS, RP-2 PIS, RP-1 STIS, RP-2 STIS.

Based on the results of the measurements, the imaginary electrical resistance, which is denoted by ρ_k, is calculated and measured in Ohms · m.

As a result of a series of measurements, we get a set of values of imaginary resistance measured at known AB/2. To conveniently present the results of observations, a graph of the dependence of ρk (in Ohms · m) on AB/2 (in m) is constructed. This graph is called the sounding curve or VES curve.

To simplify processing, the vast majority of data were analyzed using a special program IPI2Win, which was developed and is designed for automatic and semi-automatic interpretation of data from various modifications of vertical electrical soundings.

The VES points were determined on the basis of NPEMFE survey data, which reduced workload and therefore labor costs.

The NPEMFE method in combination with the VES method makes it possible to significantly increase the amount of information, increase economic efficiency, and reduce labor costs during the localization of areas of latent increased filtration in the body of regulating pools of irrigation systems.

Analytical and calculation methods. In the second stage, analytical and calculation methods were used to determine the number of filtration losses of water from the regulating pools.

Three models were used to determine quantitative parameters and calculate filtration losses from the regulating pools [15]. The first model involved a method by Vedernikov V. V. Calculation is performed for the conditions of free-surface filtration flow in the homogeneous soil. In this context, specific filtration losses per 1 m of the filtration zone are defined according to formula

$$q = k_f \cdot \left(B + A \cdot h_0\right) \cdot \left(1 + \frac{h_0 + h_k}{Y}\right),$$

where k_f is the filtration coefficient of a soil dam body of the regulating pool, m/day; B is length from the slope to the point with a constant groundwater level, m; A is the coefficient considering lateral spillage of the filtration flow; h_0 is water depth in the regulating pool, m; h_k is height of the capillary rise, m; Y is depth to the waterproof layer, m.

The second calculation model is based on the recommendations of current standard of Ukraine (DBN B.2.4-1-99). The approach also makes it possible to calculate filtration water losses from the ditches of irrigation systems; in their design, they correspond to the regulating pools and have antifiltration lining.

Determine the losses of water filtration from the lined regulating pool Q_{fn}, m^3/s per 1 km, with the same thickness of the bottom lining and slopes with steady free filtration according to the following formula

$$Q_{fn} = 0.0116 \cdot \frac{k_s}{t}\left[b\left(d_c + t\right) + 2d_c\left(\frac{d_c}{2} + \frac{m \cdot t}{\sqrt{1+m^2}}\right)\right]\sqrt{1+m^2},$$

where t is thickness of the antifiltration lining, m; b is width of the regulating pools at the bottom, m; d_c is water level (depth) in the regulating pool, m; m is the coefficient of the slope laying; k_s is the average filtration coefficient of antifiltration linings taking into account the seams, taking into account the seams, m/day.

Filtration losses were also calculated according to a simplified calculation algorithm, which is easy to use, based on average parameter values, but provides reliable results. Similar calculations have already been proven in the assessment of filtration losses from the storage of mine waters from the Svistunov beam.

The third calculation model is as follows. Filtration water losses are calculated depending on the depth of a regulating pools and water surface area. Total losses are calculated by separate addition of filtration losses through the pool bottom, a part of dam slope structure, and sites of the damaged state of the object. To some extent, the algorithm is the application of Darcy's formula

$$Q = Q_b + Q_{s_1} + Q_{s_2};$$

$$Q_b = k_b \cdot \frac{l_b + h_b + h_k}{l_b} \cdot S_b;$$

$$Q_{m1} = k_{s_1} \cdot \frac{l_{s_1} + h_{s_1} + h_k}{l_{s_1}} \cdot S_{s_1};$$

$$Q_{s2} = k_{s_2} \cdot \frac{l_{s_2} + h_{s_2} + h_k}{l_{s_2}} \cdot S_{s_2},$$

where k_b, k_{s_1}, k_{s_2} are filtration coefficients of the bottom and slopes of a regulating pools in the damaged and undamaged states, m/day; l_b, l_{s_1}, l_{s_2} are thicknesses of the antifiltration lining on the bottom and dam slopes (with the damaged and undamaged lining), m; h_b and $h_{s_1} = h_{s_2} = h_b/2$ are average values of the water level above the bottom and along the pool slopes in the damaged and undamaged states, respectively, m; h_k is height of the capillary rise, m; S_b, S_{s_1}, S_{s_2} are areas of the water surface above the bottom, above the dam slopes in the damaged and undamaged states, m^2.

Table 1

The volumes of NPEMFE and VES work on the regulating pool irrigation system

Name HS*	Geodetic coordinates, deg.		The state of filling with water	The number of NPEMFE profiles	The total length of profiles, m	The number of NPEMFE observation points	The number of VES observation points
RP-1 Vasilevska Irrigation System (VIS)	latitude longitude	48°12′30″North 35°05′40″East	Full	21	2163	716	–
			Empty	4	340	135	2
			Total	25	2503	851	2
RP-1 Petrovska Irrigation System (PIS)	latitude longitude	48°07′47″North 35°01′43″East	Full	20	2100	878	–
			Empty	4	360	149	4
			Total	24	2460	1027	4
RP-2 Petrovska Irrigation System (PIS)	latitude longitude	48°07′26″North 34°59′35″East	Full	16	1216	460	–
			Empty	4	268	117	4
			Total	20	1484	577	4
RP-1 Soloniano-Tomakivska Irrigation System (STIS)	latitude longitude	48°05′09″North 34°44′08″East	Full	23	2300	750	–
			Empty	4	346	156	3
			Total	27	2646	906	3
RP-2 Soloniano-Tomakivska Irrigation System (STIS)	latitude longitude	48°03′46″North 34°51′00″East	Full	19	2660	1097	5
			Empty	–	–	–	–
			Total	19	2660	1097	5

Results. Five regulating pools (RP) were investigated according to the above method (Table 1). Consider the example of the RP-1 Soloniano-Tomakivska irrigation system (STIS). NPEMFE studies were carried out with an interval of one month when the pool was empty and when the pool was filled with water. In the first case, it was possible to assess the condition of the bottom of the pool, and in the second, the dynamics of water filtration through its slopes. Based on the results of surveying the flux density of the magnetic component of the Earth's pulsed electromagnetic field, maps-schemes were constructed and their interpretation was performed. The most informative data obtained from the antennas of the north-south and east-west orientation, the corresponding maps-schemes, are shown in Fig. 2.

According to the results of field surveys of the pool in the filled and unfilled states, the zones of reduced values of the flux density of the magnetic component of the NPEMFE field are distinguished. On the northern slope of two antennas, the filtration zone No. 1 at the marks of 7133-7146 m with a length of 23 m is confidently distinguished. Section No. 2, which is articulated with the western slope, is probably soaked from pipeline leaks. Because on the map obtained for the antenna located across the slope, this area is not highlighted. Filtration is probably missing.

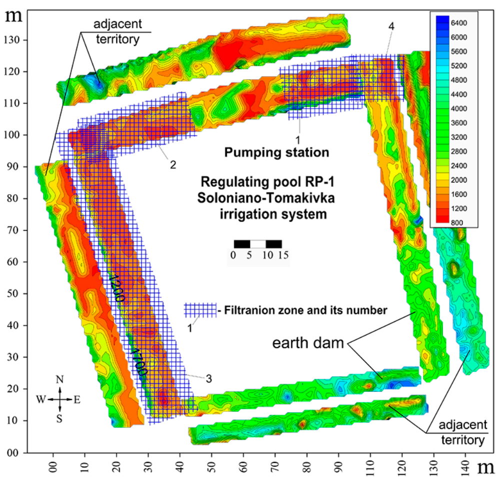

Fig. 2. Map-scheme of the flux density of the magnetic component of the pulsed electromagnetic field of the Earth of the regulating pool RP-1 STIS according to horizontal antennas

On the western slope, flooding is observed due to the flow of the underwater pipe. This is evidenced by the vertical electrical sounding at point number 1, at a depth of 4.5 m there is a very large value of electrical resistivity 399 · 10^4 Ohm · m. This corresponds to the resistance of crystalline rocks or asbestos-cement pipes. Flooding is not recorded in the NPEMFE field from the outside of the slope, there is no filtration from the regulating pool. The southern slope is in satisfactory condition. The zones of reduced values are not fixed. Vertical electrical sounding showed that the resistivity at point number 3 corresponds to poorly watered loams. And the waterproof layer is at a depth of 11 m.

On the eastern slope, the filtration area is fixed on the marks along the Y-axis 1112–1125 m, whose length is 13 m. Spatially, it is confined to the junction of the eastern and northern slopes. There are defects in the waterproofing of the pool (Fig. 2). Judging by the drawing of the NPEMFE field, the bottom of the pool is in satisfactory condition. The length of the filtration sections is 36 m.

It should be noted that in the RP-1, Soloniano-Tomakivska irrigation system (STIS) regulating pool is near the village. The second stage of the study of Malosacharin was not performed because the water from the IS of RP did not dissolve.

The VES work was carried out in a point version on all regulating pools within the selected according to the NPEMFE data of the filtration zones through the slopes of the dams. A total of 36 points were worked out. This remote method refers to the "quantitative" ones. The survey results were obtained from the depths of groundwater in the areas adjacent to the regulating pools of irrigation systems.

In the first regulated pools surveyed in the profile, there were 3 points in the wind farm, which were located on the slope of the dam and two at the foot of the slopes after 20 m, the second 20 m from it perpendicular to the dam. The third is 40 m from the dam of the regulating pool to obtain stable groundwater level values.

Table 2

Comparative characteristics of water losses for filtration per month in the facilities studied by three calculation methods

Object name	Depth of filling of the pool, h_0, m	The total volume of regulating pools, m^3	Length of disturbed areas, L, m	Filtration losses, m^3/month according to Vedernikov V. V.	Filtration losses, m^3/month according to DBN	Filtration losses, m^3/month according to the application of the Darcy formula
RP-1 STIS	3.7	19,500	36	4569	4389	4196
RP-2 PIS	3	9600	53	4555	4411	4452
RP-1 VIS	4	10,000	62	8129	8111	8184
RP-1 PIS	3.7	15,400	73	8963	8900	8508
RP-2 STIS	4	53,800	131	17,711	17,959	17,292

Based on the results of the field and analytical studies conducted above for all regulating pools, their technical conditions were identified as unsatisfactory. Loss of filtration of them causes increased groundwater in areas adjacent to buildings and can lead to further flooding.

Filtration losses are calculated using three methods; the results of these calculations are presented in Table 2.

The calculations show that, depending on the technical condition of the regulating pool, as well as the chosen method of calculation, these losses per month can be between 15 and 30 % of the volume of water pumped into the pool.

From the economic point of view, it is most expedient to use the complex of the Earth's natural pulsed electromagnetic field (NPEMFE) and vertical electric sounding (VES) in comparison with the proposed complex of geophysical methods by electric profiling (EP), natural field (NF) and microelectric sounding (MES) (Table 3).

Table 3

Comparative characteristics of the estimated cost of studies on the technical condition of regulating pools by different sets of geophysical methods

Comparative complexes	The name of the geophysical method	The number of staff units	Cost of works, euros
1	VES	3	800
	NPEMFE	2	
2	EP	5,75	1200
	NF	6	
	MES	3	

Discussion. Since the *20th* century, earthen dams and other structures have been massively built for hydro technical and reclamation purposes. However, the high permeability of soils and their poor gradation are often the cause of the development of mechanical suffusion and other phenomena that lead to the destruction of dams.

Information on the possibility of using a set of NPEMFE and VES geophysical methods to assess the technical condition of regulating pools is not available in the available literature. Therefore, to date, the results of the study were compared with those available at other hydraulic structures, such as soil dams and canals [16].

As a result of comparing the characteristics of the estimated cost of studies on the technical condition of regulating pools by different sets of geophysical methods, namely, the complex of the natural pulsed electromagnetic field of the Earth (NPEMFE) and vertical electric sounding (VES) with a set of geophysical methods of electric profiling (EP), natural field (NP) and micro probing (MP), the economic feasibility of implementing the first complex was revealed. The cost of performing a set of geophysical methods to determine the technical condition of one typical regulating pool was 800 and $ 1,300, respectively.

It should be noted that researchers [17, 18] argue that at present, geophysical methods can be considered good ways to perform the tasks of monitoring existing dams in a non-intrusive and much faster and cheaper way than traditional geotechnical methods. With their help, it is possible to detect anomalies in the body of the dam or its foundation at an early stage and carry out prompt repair work [19]. Such variations may indicate an increase in the filtration flow, an increase in the size of cracks, the formation of voids, caverns, and other manifestations of instability [20]. Depending on how any investigation is conducted and on the target anomaly, electrical methods such as electrical profiling, electrical tomography (ET), and self-potential (SP) methods have been recognized as water-sensitive technologies and are used to investigate the spatial distribution of the wetted area and possible leaks.

The effectiveness of the application of geophysical methods for studying the technical condition of soil dams is evidenced by the works. The results of our research have expanded the scope of application by adding regulating pools to it. It should be noted that researchers [16] also use specialized software packages IPI2WIN and Surfer during interpretation. Unlike other commercial software applications that are costly to government departments when analyzing geophysical data, partial curve matching and one-dimensional (1-D) computer iteration methods have been used to interpret VES curves and pseudo-transverse resistivity profiles due to their simplicity and cost-effectiveness.

Conclusions. The prerequisite for ensuring food and water security of Ukraine in the post-war period is the implementation of the concept of sustainable water supply, reduction of water losses and related energy costs. They are also the largest components of the financial costs of water management. There are still ways to improve the methods for monitoring the operation of regulating pools of irrigation systems. These scientific and practical searches include a reliable operational assessment of the technical condition of hydraulic structures and the determination of the water consumption for filtration with the subsequent possibility of operational information on the management of water resources. This is due to the specifics of the operation of water supply systems in rural areas, which is characterized by a significant length and dependence of cost dynamics on the growing season. Our team proposed a method to identify areas of water loss for filtration, in particular those that are not visually apparent, and an algorithm to calculate the quantitative indicators of these losses.

The use of a set of electrical reconnaissance methods for diagnosing the technical condition of hydraulic structures allows you to quickly and timely identify: places of defects and corrosion damage to the lining of regulating pools, and places of possible filtration losses. According to the results of studies on the technical condition of the five control basins, the application of a set of methods of the Earth's natural pulsed electromagnetic field and vertical electric sounding can be adapted to local conditions, to the specifics of design solutions for hydraulic structures, and financial resources of water management.

The use of the proposed set of geophysical methods allows timely repair and restoration work to be carried out at the sites identified during diagnosis, which reduces the economic costs of the reconstruction of hydraulic structures.

The introduction of a set of geophysical methods NPEMFE and VES as one of the instrumental monitoring methods provides an opportunity to improve the organization of operation and, if necessary, repair and restoration work. This will help prevent accidents and extend the life of hydraulic structures for water management.

According to field research and analytical calculations, it is established that depending on the design parameters of regulatory structures and their modes of operation, filtration water losses range from 50 to 60 m^3/month per 1 m of construction length, filtration water losses reach 100 m^3/month per 1 item of their length. In monetary terms, with an average water cost of 0.12 euros/m^3, water losses in one typical regulating pool with a conditional size of 100 × 100 m are 2.5 thousand euros/month.

Recommendations. For operative diagnosis of a technical condition and timely detection of sites of loss of water on a filtration from regulating pools of irrigation systems at initial stages the following is recommended:

1. A combination of fast and low-cost geophysical methods of the Earth's natural pulsed electromagnetic field and vertical electric sounding.

2. Use of the method of a quantitative assessment of water losses for filtration, taking into account the design parameters of the objects and the identified violations of their technical condition.

Acknowledgments. *We are grateful for the Czech Development Cooperation's support, which allowed us to start this scientific cooperation, and to Doctor of Technical Sciences, Professor D. V. Rudakov.*

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Перспективні методи визначення втрат води зі зрошувальних систем для забезпечення продовольчої та водної безпеки України

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Мета. Розробка комплексної системи технічної діагностики ґрунтових гідротехнічних споруд зрошувальних систем для оперативного визначення порушених ділянок, зменшення непродуктивних втрат води й забезпечення еколого-економічної ефективності водогосподарського комплексу країни в контексті водної та продовольчої безпеки.

Методика. Результат представленого наукового дослідження досягається шляхом комплексного застосування геофізичних методів природного імпульсного електромагнітного поля Землі (ПІЕМПЗ) і вертикального електричного зондування (ВЕЗ). Це дозволяє визначити якісні показники й параметри порушених ділянок конструкції гідротехнічних споруд і шляхи фільтрації води. Застосовані математичні методи визначення кількісних параметрів фільтраційних втрат. Виконані аналітичні й техніко-економічні порівняння деяких найбільш застосованих методів із запропонованим у дослідженні комплексом.

Результати. За натурними дослідженнями та аналітичними розрахунками встановлено, що, залежно від проектних параметрів регулюючих басейнів і режимів їх експлуатації, втрати води становлять від 50 до 60 $м^3$/місяць на 1 м довжини споруди. У деяких випадках загальні фільтраційні втрати за місяць можуть досягати 100 $м^3$ на 1 м довжини. У грошовому еквіваленті за середньої вартості води 0,12 євро/$м^3$ втрати води в одному типовому регулюючому басейні умовним розміром 100 × 100 м становлять 2,5 тис. євро/місяць (12,5 тис. євро/сезон).

Наукова новизна. Науково обґрунтована можливість застосування комплексу геофізичних методів для діагностики технічного стану ґрунтових дамб регулюючих сільськогосподарських басейнів. Даний комплекс має високу інформативність і дозволяє оперативно встановлювати ділянки підвищеної фільтрації в конструкції гідротехнічної споруди. За проведеним порівнянням існуючих моделей оцінки фільтраційних втрат води з регулюючих басейнів зрошувальних систем обґрунтовані параметри розрахункових показників, що забезпечують вищу достовірність результатів.

Практична значимість. Точкове визначення ділянок фільтраційних втрат води дозволяє зосередити ремонтно-відновлювальні роботи на найбільш порушених ділянках, що значно скорочує час і витрати, а також підвищує загальний рівень ефективності експлуатації зрошувальної системи.

Ключові слова: *водні ресурси, втрати води, регулюючий басейн, зрошувальні системи, комплекс геофізичних методів*

The manuscript was submitted 16.11.22.