

Engineering and technical structures of the Zhinvali hydroengineering complex and assessment of the state of their management

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Abstract

Based on theoretical and long-term field research, the article provides assessment of the management of engineering and technical structures of the Zhinvali hydroengineering complex. The methodology and quantitative assessment of the risk of loss resulting from accidents at hydraulic structures are described. The implementation of the recommendations of scientific research related to the protection of the waters of the Zhinvali reservoir will allow to extend its service life for at least another twenty years, which, subject to one-time-only investments in protection measures in the amount of 35 million GEL (1 USA Dollar - 2,90 GEL), will provide an opportunity to bring the amount of direct and indirect loss prevented to 25 million GEL per year. The calculation showed that rational management of the reservoir will allow, with an internal rate of return (IRR) of 42%, to accumulate net present value (NPV) in the amount of 87.6 million GEL over twenty additional years of operation, which in turn indicates a high efficiency of investments in the protection of reservoir waters.

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1. Introduction

One of the largest hydraulic structures in Georgia is the Zhinvali reservoir, the volume of which, with a water-surface area of 11.5 km² and a maximum depth of 75 m in front of the dam (the height of the earthen dam is 102 m.) is 520.0 million m³, including a working storage of 370.0 million m³. The reservoir is filled with mountain tributaries of the Aragvi: the White Aragvi (Mtiuleti), Gudamakari's Aragvi, Khevsureti's Aragvi, Pshavi's Aragvi (Fig. 1). Thus, the hydroengineering complex regulates the flow of rivers flowing into it and thereby protects the capital of the country - Tbilisi, from floods, the energy capacities installed on the dam provide electricity generation in the amount of 130.0 thousand kWh, at the same time, the hydroengineering complex supplies Tbilisi with drinking water (13.0 m³/sec), and the irrigated agriculture of the region - with irrigation water.

The destruction of the Zhinvali hydroengineering complex will primarily lead to the loss of the facility itself, i.e. to the loss of its value, as well as to the costs of restoration work.



Fig. 1. General view of the Zhinvali hydroengineering complex

At the same time, significant losses will occur in agricultural production, industry, power economy, housing and utilities infrastructure, and human casualties are not excluded. Losses in crop production will primarily be determined by the death of



crops that fell into the flood zone, and the washout of the fertile soil layer will require many years to restore it. If the dam of the hydroengineering complex breaks, farm animals will inevitably die, buildings and structures will be destroyed. Irreparable harm will be inflicted on housing and utilities infrastructure. It should be noted that mountain river tributaries, especially after heavy rains, carry the solid runoff eroded by them, which accumulates into the reservoir, reducing its working storage and thereby causing significant loss to the economic and communal facilities of the country. In this regard, the management of the Zhinvali hydroengineering complex should be aimed both at the effective operation of the reservoir's hydraulic structures immediately, and to a large extent at regulating the flow of the rivers feeding it, reducing solid sediments to an acceptable amount and, as a result, preserving the working storage of the reservoir for the longest possible period.

2. Literature review

The circular economy movement in sustainable economic systems is discussed in the scientific article (Andriulaitytė and Valentukeviciene, 2020). The effects of critical socio-economic factors such as economic and population growth and economic structures are analyzed. The paper is based on panel data covering 28 European countries with statistical indicators for the years 2010–2019. The circularity of economic systems derives from a systemic perspective, which includes both production and consumption, as well as issues of environmental protection. In particular, additional measures targeting behavioral consumption are needed if sustainable development is to be achieved.

The paper (Bianchi and Cordella 2022.) identifies the environmental issues of the seacoast. Structural micro-economic models of recreation demand and affordability among local residents and visitors for environmental protection, in particular management of coastal erosion processes, are evaluated. The authors of the article have discussed the coastal safety management strategy taking into account the economic indicators.

Engineering construction must be erected taking into account both the ecological and economic effect (Andriulaitytė and Valentukeviciene, 2020; Harasymiuk, 2019). The economic effectiveness of the investment depends on the material types and technology used (Nawrot, 2016) and the effective management of human resources in the construction process (Krynke, 2019). It is also important that building and engineering constructions are resistant to the effects of external factors and ensure the safety of users (Constantin and Nițescu, 2020; Zhelykh et al., 2022; Laghi et al., 2017; Chen and Zhang, 2022). For hydrological structures, safety and risks of those formed in the mountain landscapes of Georgia and calculating the material and economic damage caused by the debris flow should be assessed and the crack has to be assessed in the book by Gavardashvili (Gavardashvili, 2022).

The safety of hydrological constructions created in the mountain landscapes of Georgia and the calculation of material and economic damage caused by the flow of debris was presented in the book by GG.

The following paper (Gavardashvili and Vartanovi, 2020) describes a methodology for calculating the social-economic losses for the facilities flooded and destroyed by a tsunami-type wave in case of a possible high-rise hydraulic facility accident. The social-economic damage caused by a dam failure can be viewed as a sum of damage caused by a human, destruction of hydraulic and industrial facilities and agriculture, pond economy, forestry and communal services.

The destruction of the Zhinvali hydroengineering complex will primarily lead to the loss of the facility itself, i.e. to the loss of its value, as well as to the costs of restoration work. At the same time, significant losses will occur in agricultural production, industry, power economy, housing and utilities infrastructure, and human casualties are not excluded. Losses in crop production will primarily be determined by the death of crops that fell into the flood zone, and the washout of the fertile soil layer will require many years to restore it. If the dam of the hydroengineering complex breaks, farm animals will inevitably die, buildings and structures will be destroyed. Irreparable harm will be inflicted on housing and utilities infrastructure.

In the paper (Huang-Lachmann et al., 2018) as a result of empirical research, the authors presented the relationship between economic opportunities and climate adaptation, taking into account the population of a specific research object. The risks of climate change are discussed with the adaptation plan in mind and the economic effectiveness of incentivizing the local population and stimulating adaptation is given. In the article, a negative relationship can be identified with respect to three variables. Climate action with one group and two stakeholder groups. This paper also fails to answer such topical issues as the prediction of environmental protection in view of climate change and the attraction of investments for the implementation of ecological-economic measures at the local and international levels.

The article (Oeberghaus, 2015) presents the main characteristics of ecological economics as a trans-discipline, such as the focus on the use of people and sustainable nature, and the second – fair and efficient distribution with appropriate goals. The work focuses on the functioning of the interdependent system of nature and environment for the sustainability of human well-being, which is involved in the rest of the natural evolutionary development. A broad understanding of the interaction of social and natural capital to create sustainable environmental well-being is presented. The article (Constanza, 2020) presents the main characteristics of ecological economics as a trans-discipline, such as the focus on the use of people and sustainable nature, and the second – fair and efficient distribution with appropriate goals. The work focuses on the functioning of the interdependent system of nature and environment for the sustainability of human well-being, which is involved in the rest of the natural evolutionary development. A broad understanding of the interaction of social and natural

capital to create sustainable environmental well-being is presented. The work presents the negative side of the neglecting of some of current problems that humanity must face, such as the financial forecasting of the fight against the world pandemic, for example, Covid-19, which represents one of the current challenges for the life of the world population.

3. Object and Methods

The solution of the problem of protecting the population and territories from emergencies, reducing their consequences is possible only with the implementation of a set of measures that include an adequate assessment of the risks of their occurrence. The risk of accidents at hydraulic structures is the probable loss realized in the zone of the damaging effect of the wave of breakthrough and flooding, resulting from the destruction of the dam under the influence of various risk-forming factors. Therefore, the loss assessment is an integral part of the risk assessment, without which it is not possible to determine the value of the risk. It is recommended to determine the total loss from emergency situations on artificial water bodies by the formula:

$$Y_o = Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 + Y_8 + Y_9 + Y_{10} \quad (1)$$

Where:

Y_o – gross loss, million GEL;

Y_1 – loss to industrial facilities, million GEL;

Y_2 – loss to agricultural production, million GEL;

Y_3 – loss of transport and communication elements, million GEL;

Y_4 – loss to residential accommodation, million GEL;

Y_5 – loss to forest husbandry, million GEL;

Y_6 – expenses for the elimination of the consequences of the accident, million GEL;

Y_7 – loss to fish industry, million GEL;

Y_8 – loss caused by disruption of water supply due to the accident of water intake facilities, million GEL;

Y_9 – loss caused by damage or destruction in the flood zone of facilities where hazardous substances are obtained, processed or stored, million GEL;

Y_{10} – loss to power economy, million GEL (As of May 15, 2022, 1 US dollar is equal to 3.00 GEL).

A quantitative assessment of the risk of loss from an accident at the hydraulic structures of the reservoir can be carried out according to the formula:

$$R = Y_o P \quad (2)$$

Where:

Y_o - the amount of gross loss (million GEL); P - probability of loss.

Thus, the degree of risk of loss is determined according to the product probability of occurrence of this event by the amount of gross loss.

To determine the criterion for quantitative risk-based approach of short-received products, two indicators can be used:

- expected value (\bar{x}) - a possible result, which is a weighted average value of all possible results;
- mean square deviation (σ) - as a measure of the variability of the occurrence of the corresponding results.

From our point of view, the management of the Zhinvali reservoir, like any other large hydraulic structure, primarily implies proper planning and timely implementation of operating works. At the same time, the correct calculation of operating costs is the initial condition for the normal functioning of water management organizations, the maintenance of production assets in a technically sound condition, their reliable functioning, and the sustainable development of the industry.

When determining the planned (intra-company) prime cost of operation of the production assets of a hydraulic engineering facility, it makes sense to apply the following nomenclature of the main items of expenditure.

- Maintenance of the administrative-economic and engineering-technical staff of the water management organization and administrative and economic expenses.
- Maintenance of the linear operational staff.
- Cleaning of the hydro-reclamation network.
- Protective-regulating and flood prevention measures.
- Permanent repairs.
- Restoration of production assets.
- Calculation of total operating costs.

The administrative, economic and technical staff of water management organizations performs the functions of managing the organization, including all administrative and economic activities, planning and operational management of water intake and water supply, planning and organizing all types of repairs, reclamation, flood control and emergency works, compiling operational and annual reporting (Hosseinjanzadeh et al., 2015; Janin and Singh, 2003; Louck et al., 2003; Marco et al., 2012).

In order to perform the management function of a water management enterprise, a higher organization establishes managerial staff and fixed official salaries. The costs of maintaining the administrative-economic and engineering-technical staff are determined by the sum of the products of the corresponding staff units and their fixed official salaries. At the same time, administrative and economic expenses can reach 32% of the expenses of maintaining the staff.

In addition to the main staff, a number of production services can be organized under the water management organization, including the ameliorative control service, the service of operational transport and energy management, and other services. The linear staff of the ameliorative operational organization provides the instructions to its administration on water intake, water distribution and water supply, manages the work of the hydro-reclamation network of hydraulic structures, performs continuous supervision of their technical condition, organizes and controls repair works.

Approximate norms of work time expenditures for the production of works by the linear service of ameliorative systems are given in Table 1.

Table 1. Approximate norms of work time expenditures for the production of Works by the linear service of ameliorative systems

№	Unit of measurement	Composition of works	Labor costs, man/hours per year
1	2	3	4
1		Water intake from a river or reservoir	
		Regulation, measurement and accounting of discharges and horizons, maneuvering with shields, monitoring the safety of the facility, its maintenance, reporting, organization of repairs	
	structure	a) water intake structure with outlet canals discharges from 5 to 10 m ³ /sec, the working storage of the reservoir is 10-50 million m ³	2067
	structure	b) the same, but the canals discharges are up to 5 m ³ /sec, the working storage of the reservoir is up to 10 million m ³	554
	structure	c) the same, but the water intake structure is not of an engineering type	954
2		Water distribution through irrigation channels	
		Water distribution, discharges measurement, horizon monitoring, accounting, reporting, surveillance, supervision, security	
	100 km	a) irrigation channels with a flow rate from 5 to 10 m ³ /sec	5833
	100 km	b) the same, but with a flow rate of up to 5 m ³ /sec	4205
3		Regulation of discharges at water apportioning structures	
		Maneuvering with shields, security	
	structure	a) discharge costs from 5 to 10 m ³ /sec	400
	structure	b) the same up to 5 m ³ /sec	133
4		Water apportioning by inter-farm network and water supply	
	thousand hectares	Water apportioning, discharge measurement, maneuvering with shields on regulators and water outlets, horizon monitoring, accounting, reporting, supervision, security, water transfer to water users, organization of repairs	906
5		Monitoring of the condition of the flood-breaking dam	
	10 km	Bypass, inspection, security, organization of repairs	187
6		Monitoring the operation of the inter-farm collector network	
	100km	Supervision, organization of repairs and cleaning	1600
7		Monitoring of the groundwater level	
	100 points	Supervision, primary data processing, supervision of serviceability, organization of repairs	2333
8		Monitoring of hydraulic structures on flooded lands	
	100 thousand hectares of flooding		1933

According to the articles, the following types of operational work are normalized under cleaning of the hydro-ameliorative network, protective and regulating and anti-flood protection works: leveling of inter-farm channels and collectors under cleaning; placement and fixing of staking signs, cleaning and destruction of vegetation along the edges and slopes of channels; works that prevent the destruction of hydraulic structures during the passage of flood discharges; works that eliminate the results of destruction after floods.

Planning of costs for the production of these works is carried out depending the following norms: leveling of inter-farm channels and collectors under cleaning; placement and fixing of staking signs – 2 man/ hours per 1 km of the channel; cleaning from mud silting - at the rate of 3 cm per year on main channels and 5 cm per year on collectors of the 1st and 2nd order; protective and regulating and flood protection works - in accordance with the statements of defects.

The approximate cost rates for permanent and restoration (overhaul) repairs of the ameliorative infrastructure are given in Table 2.

These data allow us to reliably plan the values of operating costs, to calculate their planned prime cost.

It should be noted that the accuracy of planned calculations largely depends on the effective operation of the hydrometric service of the hydroengineering complex, which distributes water among water users, monitors the accuracy of its accounting, controls the costs of sources and water intake, monitors the groundwater level.

The approximate load on the hydrometer observer is 8-10 gauging stations. With gauging stations very far from each other, observations of 5-6 gauging stations are assigned to one observer. The approximate load on one hydrometer observer for the groundwater level in wells is 8-10 points. The number of observations for the main gauging station and for stations on balance sections is 3 times a day. In winter, when non-irrigation expenditures are going through the system, the number of daily observations is reduced to one. At the closing transit dam sites and at stations that take into account drainage waters, observations are conducted all year round once a day.

Table 2. Approximate cost rates for permanent and restoration (overhaul) repairs of ameliorative infrastructure

Name of the elements of the reclamation system		Approximate service life of the structure, years	Expenses for permanent repairs as % of book value	Time interval between restoration repairs, years	Expenses of restoration Repairs as % of book value
1	2	3	4	5	6
1.	Industrial buildings				
1.1	Stone buildings	80	3.2	10	17.0
1.2	Stone buildings of cavity wall masonry	60	3.2	10	17.0
2	Hydraulic engineering structures				
2.1	Stone, concrete and reinforced concrete dikes	100	0.4	10	7.0
2.2	Earth-fill dams and dikes	100	1.0	10	4.0
2.3	Stone, concrete, wire regulating dams and cut-off walls	20	1.2	5	5.0
2.4	Stone, concrete and reinforced concrete bank protection structures	50	2.0	5	7.5
2.5	Stone, concrete and reinforced concrete water intake and sluiceway structures; settling plants; underground part of pumping stations	80	0.4	10	7.0
2.6	Earthenware duct drainage	80	0.4	10	4.0
2.7	Stone, concrete and reinforced concrete tower water intakes; gatewells and piped sluiceways; reinforced concrete cantilever extensions; offtake regulators; tube- footbridges; aquatic bridges; spillway channels; section gradients; rainwater drainages	40	0.6	5	7.5
2.8	Earthen, faced with stone, concrete and reinforced concrete inter-farm irrigation canals (main, distributary)	100	1.0	10	15.0
2.9	Farm ditches, irrigation and collector-drainage farm ditches	50	1.0	5	14.0
2.10	Stone and reinforced concrete bridges	100	1.0	10	3.0
2.11	Concrete and reinforced concrete pipes and penstocks	100	1.0	10	5.0
2.12	Stone, concrete and reinforced concrete anchored bulkheads, regulating structures	60	3.0	10	15.0
2.13	Tunnels	40	0.6	5	7.5
2.14.1	Reinforced concrete drain siphons	40	0.6	5	5.0
2.14.2	Metall drain siphons	25	0.7	5	8.0
2.15	Stone, concrete and reinforced concrete aqueducts	40	0.8	5	7.5
2.16	Stone, concrete and reinforced concrete riffles	40	0.6	5	5.0
2.17	Floodgates, regulators, outlet sluices	40	0.6	5	5.0
2.18	Stone, concrete and reinforced concrete culverts	40	1.0	5	3.0
2.19	Reinforced concrete day drifts	30	0.7	5	3.5
2.20	Regulatory shields	25	1.0	5	8.0
3.	Gauging stations	20	5.0	5	12.5
4.	Electrical appliances	30	6.0	5	15.0
5.	Inspection paths				
5.1	Asphalt-concrete	40	4.0	10	19.0
5.2	Paved with black crushed stone or black gravel	30	4.0	10	23.0
5.3	Unsurfaced	20	2.0	5	20.0

At the same time, it should be borne in mind that hydraulic structures wear out during the operational period, while their cost decreases in comparison with the initial cost. In order to determine and account for the actual (market) value of hydraulic structures, an inventory of the reclamation system is carried out. In this regard, a continuous inventory of reclamation systems is carried out every 5-10 years. A continuous inventory of reclamation systems provides for accounting of the main

structures and equipment, as well as all auxiliary devices, buildings, structures, equipment and inventory.

A continuous inventory of reclamation systems provides for accounting of the main structures and equipment, as well as all auxiliary devices, buildings, structures, equipment and inventory. The purpose of a continuous inventory of reclamation systems is to establish the inventory value of structures

(Huang-Lachmann J., Hannemann M., Guenther E, 2018, Nawrot, J., 2016).

The inventory value of the system is determined based on its initial construction cost, the cost of restoration works (overhaul repairs) and the degree of wear and tear according to the formula:

$$I = X + Z + Kt \quad (3)$$

Where:

X – initial cost of funds (million GEL);

Z – the costs of overhaul repairs carried out from the moment of commissioning of the facility to the moment of the current inventory (million GEL);

K – annual wear and tear (depreciation) (million GEL);

t – the actual age of the structure (years).

Data on the inventory value of reclamation funds are entered into technical passports, which are compiled for each hydraulic structure (except small ones), reservoir, pumping station and other inter-farm structures, civil buildings (except gatehouses, temporary shelters, sheds, warehouses, etc.)

Passport lists are made for small hydraulic structures, dubs, pumping units of intrafarm purposes, gatehouses, temporary buildings, gauging stations, wells, etc.

The technical passport of the system must contain the following data: name, location, type, category, year of construction, other information about the system; general data, as well as design indicators of the size, type and materials of the structure; annually entered variable information about the repair works carried out during the past year, about the condition and percentage of the shelf life of the structure; information about construction and inventory cost of the facility.

Schematic drawings of structures, longitudinal and transverse profiles of channels, photographs are attached to technical passports. Information about the technical condition and cost of the certification object is given for each element of the structure (headwall, wall, fastening, etc.). The technical passport of the hydroengineering complex contains tables of water balance (water intake, its consumption, energy efficiency ratio) and land fund (availability of irrigated land, their use, reasons for not using land with an irrigation network).

Cadastral records of the changes that have occurred, the main indicators for hydraulic structures and reclaimed lands are annually entered into the passports of reclamation systems. The cadastral records indicate the dates of the work performed, their volumes and costs. Cadastral records on the reclamation condition of the serviced lands, on the groundwater regime and on the measures taken to improve the condition of reclaimed lands are of particular importance. When certifying irrigation systems, an irrigation map of the system must be drawn up. All channels and structures should be plotted on the irrigation map, the scheme of the organization of the operational service, the distribution of operational sites, service communication lines, operational roads, special observation points should be shown. The map should show the location of operational buildings, the location of storage facilities. All changes that occur on the system as a result of repair works, remodeling and reconstruction of reclamation systems and

structures, all additionally constructed structures and devices are plotted on the map (Gavardashvili and Vartanovi, 2020).

Works on certification of reclamation systems, including cadastral records are made at the beginning of each year, as well as during the economic year to the extent that the repair works, remodeling and reconstruction of reclamation systems, construction of new structures and devices are carried out. The time spent on the production of works related to certification is approximately 15-20 working days, including the insertion of permanent information in passports - 10-15 days. The approximate rate of working time spent on the production of annual works on certification of reclamation systems is 320 man/hours (the specified rate can be adjusted in specific production conditions).

It should be noted that the management of the Zhinvali hydroengineering complex should be aimed both at the effective operation of the reservoir's hydraulic structures immediately, and at the antimud slide protection facilities and snow-protective (avalanche protective) structures, at regulating the flow of rivers feeding it, to reducing solid sediments to an acceptable amounts and, as a result, preserving the working storage of the reservoir for the longest possible period. At the same time, the economic efficiency of the calculation should be based on the methodologically correct principles of determining ecological, economic and social loss, in particular, on the principles of its duality: the division of loss into direct and indirect. At the same time, the amount of direct loss is correlated with the level of the working storage of the reservoir, the smaller the working storage, the greater the loss of both drinking water supply in Tbilisi and electricity generation. As for indirect loss, its value is directly related to an increase in the level of morbidity of the population, which causes deterioration of health and reduction in active life expectancy; decrease in the possibilities of irrigated agriculture, decrease in the recreational opportunities of the region, etc. (Harasymiuik, 2019, Krynke, 2019).

Protection of the waters of the working storage of the Zhinvali reservoir will extend its service life for at least another twenty years, which, subject to one-time only investments in protective measures in the amount of 35 million GEL, will provide an opportunity to bring the amount of direct and indirect loss prevented up to 25 million GEL per year.

The calculation of the economic efficiency of reservoir management is carried out according to the formulas (Gavardashvili G., Vartanovi M., 2020):

$$NPV = \sum_{k=1}^n \frac{P_k}{(1+r)^k} - \sum_{j=1}^m \frac{IC_j}{(1+i)^j} \quad (4)$$

$$\sum_{k=0}^n \frac{CF_k}{(1+IRR)^k} = 0 \quad (5)$$

Where:

NPV – Net Present Value, million GEL;

IRR – internal rate of return, %;

P_k – annual amount of loss prevented, million GEL;

IC_j – investments in environmental protection measures, million GEL;
 r – discount factor; - projected average inflation rate.

The calculation showed that the rational management of the reservoir will allow for twenty additional years of operation to accumulate, at an internal rate of return (IRR) of 42%, Net Present Value (NPV) in the amount of 87.6 million GEL, which in turn indicates a high efficiency of investments in the protection of reservoir waters.

5. Summary and conclusion

In the article, based on the analysis of the results of expedition-field works, the current state of the Zhinvali hydroengineering complex is assessed. The conducted field expert studies both in the body of the Zhinvali earthen dam and in its main structures, including at riffles, on the drainage system in the tail races, on the reinforced concrete tunnel intended for drinking water supply in Tbilisi, on the Bodorma reservoir and at other main structures allowed, taking into account the corresponding risk of accidents, to assess the reliability of the structures.

Approximate norms regulating the value and order of carrying out permanent and overhaul repairs of the reclamation and energy infrastructure of the hydroengineering complex are proposed. To assess the management of the Zhinvali reservoir, its economic efficiency was calculated.

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Zhinvali 水利工程综合体的工程技术结构及其管理状况评估

關鍵詞

水工建筑物
 日瓦里水库
 管理
 投资
 风险

摘要

基于理论和长期的现场研究，本文对 Zhinvali 水利工程综合体的工程技术结构管理进行了评估。描述了水工建筑物事故造成损失风险的方法和定量评估。实施与 Zhinvali 水库水域保护相关的科学研究建议，将使其使用寿命至少再延长 20 年，只需一次性投资保护措施，金额为 3500 万 GEL (1 美元 - 2.90 GEL) 将提供一个机会，使每年避免的直接和间接损失达到 2500 万 GEL。计算表明，水库的合理管理将使内部收益率 (IRR) 为 42%，在额外 20 年的运营中积累 8760 万 GEL 的净现值 (NPV)，这反过来又表明在水库水域保护方面的投资效率很高。