UDC 330.15
DOI: 10.15587/1729-4061.2022.268977

ASSESSMENT OF ECONOMIC EFFICIENCY INDICATORS OF ENVIRONMENTAL PROTECTION MEASURES DURING THE CONSTRUCTION OF HYDRAULIC ENGINEERING STRUCTURES

David Gurgenidze
Doctor of Academic Sciences, Professor, Rector
Georgian Technical University
Kostava str., 77, Tbilisi, Georgia, 0171
E-mail: d_gurgenidze@gtu.ge

In order to ensure the integral management of water and land resources during the implementation of environmental protection engineering measures, as well as to solve ecological problems, a macroeconomic approach directed at the final results is necessary. The traditional "narrow" economics of nature use is viewed as a single cycle of water and land resources and production waste and pollution, with insufficient attention paid to the economy itself ("black box"). For purposeful use of macroeconomics, it is necessary to build a vertical of natural productivity of each natural resource (chain), which will connect the primary natural factors with the production of final products. An effective concept of the rationalization of nature use and environmental protection against debris-flow phenomena and the matching economic mechanism of nature use in sectors and complexes can be developed and realized only after the development of the concept of development of the sector complexes and the whole economy. Regional features of the formation of the economic mechanism of nature use are important.

The assessment of economic efficiency indicators of environmental protection measures during the construction of hydraulic engineering structures is discussed. The value of efficiency obtained by environmental activities is considered by the criteria for evaluating the efficiency of the investment project, where this criterion is called net discounted income, net discounted value, or modern net income. Functional-value analysis of environmental impact during the construction of hydraulic engineering structures, including the construction of high dams, for the realization of the analytical stage, a functional model is built based on the orography of the social-ecological-economic system.

Based on theoretical and field scientific studies, the economic efficiency of the innovative debris-flow control structure has been established, the numerical value of which is equal to 16.15 USD per 1 longitudinal meter of the structure

Keywords: environmental protection, economic efficiency, hydraulic engineering structures, water and land resources, debris-flow phenomena

Received date 29.09.2022
Accepted date 07.12.2022
Published date 30.12.2022

How to Cite: *Gurgenidze, D. (2022). Assessment of economic efficiency indicators of environmental protection measures during the construction of hydraulic engineering structures. Eastern-European Journal of Enterprise Technologies, 6 (10 (120)), 6–15. doi: https://doi.org/10.15587/1729-4061.2022.268977*

1. Introduction

In case of natural disasters (floods, erosive-flood and landslide processes, snow avalanches, etc.) in modern practice, a great role is assigned to the construction of such hydrotechnical structures, the technical and economic indicators of which are characterized by high economic efficiency compared to the existing ones.

The increase in the frequency of natural disasters in the modern world has put on the agenda the construction of such modern debris-flow control structures, which are characterized by the economy of construction materials, where both secondary raw materials and local materials, such as: stone, wood, etc., are used as construction materials.

When using debris-flow control structures, taking into account the above, practice has shown us that in the construction of such hydrotechnical structures in mountain landscapes, in addition to economic indicators, great importance is attached to the reliability of these structures, which implies the multiple use of environmental protection structures in engineering practice. These two issues, such as the reliability of debris-flow control structures and the efficiency of constructions, are directly proportional to each other. The building is reliable, i.e., the building material corresponds to high strength and quality, which is also related to its cost. All this determines the economic efficiency of environmental engineering measures.

2. Literature review and problem statement

The circular economy movement in sustainable economic systems is discussed in the scientific article [1]. 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 we are going to achieve sustainable development.

The paper [2] identifies the environmental issues of the sea coast. 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.

The paper [3] discusses the socio-economic losses of the local population due to the impact of floods caused by the possible failure of high-rise dams. Mathematical modeling is used to predict the material and technical losses of the population living in the risk zones during the flood period, such as flooding of homesteads, destruction of local industrial, communal and social facilities, including human casualties. Micro- and macro-economic indicators for the restoration of the natural landscape, as well as additional investments for the implementation of environmental protection measures, are not evaluated in the work.

The monograph [4] presents the management of very relevant issues for Georgia, such as mountain landscape safety measures during natural and man-made disasters and assessment of ecological and economic damage caused by natural disasters. The assessment of the ecological and economic damage of the forest massifs burned as a result of the 2008 Georgian-Russian military action and the ways of attracting investments using them are presented. The number of areas inundated and expected human casualties as a result of the destructive wave of floods caused by the failure of high dams is discussed.

The monograph [5] provides an assessment of the economy of nature use in the former Soviet space and their shortcomings in the implementation of environmental protection measures compared to the market economy. Ecological-economic situations in the integrated management of water resources and their management on a regional scale are evaluated. The environmental conditions of mountain and foothill landscapes before the construction of the structures, after their arrangement and under operational conditions have been evaluated when using hydrotechnical structures. The analysis of socio-economic efficiency and safety of the local population in the event of an increase in the frequency of dynamic processes of natural events is discussed.

The monograph [6] discusses the dynamic processes of destruction of natural landscapes and evaluates the limits of ecological-economic damage of natural resources using reliability and risk theories. The vulnerability of the natural environment is presented according to the distribution of the function of natural events, taking into account the appropriate histogram and the theoretical curve of events. Attention is focused on the assessment of the risks of natural disasters, using which it is possible to estimate the ecological-economic damage.

In the paper [7], 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 [8] 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 can be considered as a negative side of the neglect of some of the current problems of humanity, such as the financial forecasting of the fight against the world pandemic, for example, Covid-19, which represents one of the actual challenges for the life of the world population.

The paper [9] focuses on one of the main disasters for our planet, such as – floods. The authors have mentioned that the society cannot fully protect itself from floods, because risk management during this natural disaster is a big problem, which is one of the pressing issues of the modern world. The paper discusses the issues of flood risk mitigation for the population of one of the settlements in Germany, whose population is more than 4,200 families. Flood damage can be mitigated by taking into account past damage, the latter of which provides a large effect "climate adaptation signal" in flood mitigation behavior. The paper mentions that the main role in the management of flood risks should be played by the action plans of the local governments, taking into account the relevant benefits. The paper does not pay attention to the rules of behavior of the local population in case of natural disaster – floods, which will significantly reduce the material and technical damage, including the number of human victims.

The article [10] discusses the ecological-economic damage assessment of forest massifs burned as a result of military action in Georgia in August 2008 and measures to protect against soil erosion on mountain slopes.

The construction characterization of erosion control structures is discussed in the paper, but the technical-economic efficiency calculation of environmental protection structures is not highlighted.

The article [11] considers the problems of developing new approaches in the theoretical aspect of methodological support for a comprehensive assessment of the environmental friendliness of systemic natural and man-made objects based on MIPS and risk analysis. A scheme of algorithmic support for complex analysis for solving problems of environmental safety at the level of natural-technogenic complexes has been formed.

However, the article does not consider indicators of the effectiveness of the use of water and land resources, including environmental protection, particularly debris-flow control engineering measures, which are so relevant in the modern world.

In the scientific work [12], the processes of managing the cost of construction and energy projects are studied. The unreliability of the results of applying classical methods for planning their cost is revealed. The necessity of creating such cost planning methods that will take into account the specifics of these projects is substantiated. A method for planning the cost of construction and energy projects has been formed, which takes into account the change in the cost of resources over time, investment and time constraints of the project. In the scientific work, attention is mainly focused on the cost of construction-energy projects and their planning flaws. The authors have not considered and evaluated the methodology of calculating the price of the use of water and land resources and the methods of determining the cost.

In article [13], the study is aimed at developing tools to support the strategic environmental assessment of development projects of different scale territorial entities and urban ecosystems in combination with the concept of environmental impact assessment.

A tool is proposed to support the strategic environmental assessment of projects for the development of multi-scale territorial entities and urban ecosystems in combination with EIA. The applied approach makes it possible to establish a relation between the object, the ecosystem, and the territory. The authors have mainly focused on the ecological-strategic direction of environmental protection projects throughout the region. In the work, the authors have not discussed economic-ecological issues at all, and they have not particularly focused on the economic effectiveness of environmental protection measures.

3. The aim and objectives of the study

The aim of the study is to development of a method of calculate the economic effectiveness of the innovative trampoline-type debris-flow control structure.

To achieve this aim, the following objectives are accomplished:

– research of the mechanisms of economic effectiveness of the implementation of existing environmental programs under the conditions of integrated management of natural resources;

– study of the economic efficiency of the innovative debris-flow control structure.

4. Materials and methods

Field-scientific researches were carried out in the mountain landscapes, and a debris-flow prevention permeable structure built in the Telavi River gorge was selected as the basic environmental protection structure.

The main hypothesis of the research is:

– creation of an innovative construction for the effective regulation of a debris-flow-type river;

– calculation of economic indicators of innovative construction;

– clarification of the economic efficiency of the innovative debris-flow control structure in comparison with the debris-flow control structure existing in nature;

– on the basis of the experiments conducted in the hydraulic engineering laboratory, the reliable and efficient operation of the innovative debris-flow control structure has been confirmed, and in the scientific paper a detailed assessment of the innovative debris-flow control structure and its general ecological and economic indicators have been discussed.

5. Research results of a method of calculate the economic effectiveness of the innovative trampoline-type debris-flow control structure

5. 1. Researching the mechanisms of economic effectiveness of environmental programs

During the arrangement of hydraulic engineering structures, including the construction of high dams, special attention is paid to efficiency of environmental measures and its economic efficiency indicators, the reliability of which is related to the amount of investment [1–4].

At present, there are many indicators for assessing the effectiveness of investment projects. Absolute and relative efficiency criteria can be used to evaluate the effectiveness of environmental protection measures. Capital investment in environmental protection measures with absolute efficiency is determined by the following equation [5]:

$$E_p = \left[\sum_{j=1}^{n} \sum_{i=1}^{m} \left(E_{ij} - C \right) \right] / K, \tag{1}$$

where E_p is a general indicator of the efficiency of capital investment in environmental protection measures; E_{ij} – the result of environmental protection measures i, which excludes the loss on the object j; C – annual operating costs for the main funds that cause the effect; K – capital investment in environmental activities.

In order to evaluate the appropriate implementation of measures, it is possible to compare E_p with the normative coefficient of efficiency E_H=0.12. A measure will be considered economically effective only under the following conditions – $E_p \geq E_H$. Thus, the report provides established regulatory deadlines $T_H=1/E_H$ for collecting the amount. At the same time, it is possible to use the efficiency index in the natural-value form, which is called the absolute ecological efficiency index of capital investments, which is not correct.

This indicator is determined by the following equation:

$$E = \Delta B / K, \tag{2}$$

where ΔB – a reduction of harmful substances in the atmosphere, soil and water:

$$\Delta B = \sum_{j} K_j \left(B_{0j} - B_{1j} \right), \tag{3}$$

where B_{oj}–B_{1j} – the initial volume of residue of the j-ingredient; K – harmfulness coefficient of the j-ingredient.

The considered indicators do not reflect the dynamics of measures implementation, do not give an idea of the avoided losses in the public economy, do not reflect the magnitude of the effect obtained from environmental activities. The program of activities is considered as a set of measures, regardless of their sequence (order). Even the common criterion of the minimum of the given costs cannot correct the indicated shortcoming:

$$C + E_H K \to \min. \tag{4}$$

In order to compare the options of measures implemented in different periods, the discounting method can be used, based on which the criterion of relative economic effectiveness of the measures is determined:

$$\sum_{t=1}^{T} \left(K_P + K_{Dt} + C_t \right) \left(1 + E_{Hp} \right)^{-t} \to \min, \tag{5}$$

where K_p – initial capital investments in environmental protection activities; K_{Dt} – additional capital investment required for the normal operation of the environmental protection facility during the operational year t; C_t – current expenses per year for the operation and maintenance of fixed assets.

By comparing the annual costs of environmental measures with the achieved economic result, it is possible to determine the annual economic effect [6]:

$$(P-Z)\to \max. \quad (6)$$

This allows to determine the magnitude of the effect of the environmental activity, but it does not correspond to the rest of the requirements. The typical methodology developed in 1987 responds to the approach recommended in the methodology for evaluating the efficiency of the investment project. This criterion is called Net Discounted Income (NDI), Net Discounted Value (NDV), or Modern Net Income (MNI). For its calculation, the following equation is used:

$$MNI=\sum_{t=t_0}^{T}(P_t-K_t-C_t)(1+r)^{t_0-t}\to \max, \quad (7)$$

where P_t – the economic result obtained during the year; K_t – investments in environmental activities in year t; C_t – operating costs of the environmental facility per year for renovation without transfers; T – the end of the operational year; t_0 – the year of starting the operation of the environmental facility; r – discount factor.

A normative coefficient can be used as a discount factor, the value of which is obtained in accordance with the industrial methodology, by determining the economic effectiveness of costs for environmental protection (is determined temporarily E_{HP}=0.08).

Bank rate percentage is often used as a discount factor. These methods are focused on both state (government) and non-state (non-governmental) projects. Usually, the evaluation of investment effectiveness of commercial projects is discussed in the literature. The assessment of the effectiveness of the state-funded project has certain features:

1. A single discount factor is established for the project. Usually, it is determined by the minimum internal rate of return calculated for capital investment of private sector with minimum risk. In most Western European countries, the discount factor (rate) is 8–12 %.

2. Both economic and social effects are determined. If to denote the measure by i=1, n and the year of the start of its implementation by T_i^H and at the end – by T_i^K, let's obtain the option of calculating the NDI of the environmental measures program:

$$NDI=\sum_{t=t_0}^{T\Sigma}\sum_{i\in G_t}^{\Sigma}\left(\sum_j E_{ijt}-C_{it}\right)-\sum_{i\in Jt}^{\Sigma}K_{it}(1+r)^{t_0-t}\to \max, \quad (8)$$

where E_{ijt} – the result of the implementation of i-type environmental measures, expressed by the amount of avoided loss in the economic or social i-type field in t-year; C_{it} – operational measures, which are not related to the y-type measure of the t-year, without exception for renovation; K_{it} – investments of i-type events in t year; G_t – the set of events that are realized up to year t and provide a result;

$$G_t=\{i:T_i^k<t\},$$
$$J_t=\{i:T_t^k\le t\le T_i^H\}, \quad (9)$$

where J_t – the number of realization events per year.

There is another indicator along with the NDI, which is determined by the same elements. Income index – S_1.

$$S_1=\frac{\sum_{t=t_0}^{T}\left[\sum_{i\in G_t}(P_{it}-Z_{it})(1+r)^{t_0-t}\right]}{\left[\left(\sum_{i\in Jt}K_{it}\right)(1+r)^{t_0-t}\right]}\to \max. \quad (10)$$

This indicator reflects the relationship between the discounted result and the discounted capital costs and is similar to the profitability indicator but takes into account the time factor. In the case of S_1, the program does not pay off in time t.

Based on this indicator, it is possible to construct a similar criterion, which is called the efficiency index (S_2):

$$S_2=\frac{\sum_{t=t_0}^{T}\left[\sum_{i\in G_t}W_i(1+r)^{t_0-t}\right]}{\left[\left(\sum_{i\in Jt}K_{it}\right)(1+r)^{t_0-t}\right]}. \quad (11)$$

This criterion is not used as an indicator of the effectiveness of the environmental protection program (if NDC>0, S_1>1 – the program is effective, and if NDC<0, S_1<1 is ineffective). The following methods of evaluating the effectiveness of environmental protection decisions are more often used in current cost method, net profit method, profitability method, payback period method.

The methods for evaluating the effectiveness of environmental protection investments are quite simple, therefore, a more targeted option is chosen from various alternative investment projects. However, these methods do not consider the time factor, i. e. they have some disadvantages:

1) do not take into account the change of cost and profit in a certain time;

2) they offer the existence of reliable information;

3) since these methods are provided for the assessment of the investment of a specific project, in the reports, it is necessary to divide the part of the profit that is due to the investments made, which essentially complicates the calculation.

Therefore, first, it is possible to formulate the main goal of the investment project (increasing profit, reducing costs, etc.), after which let's use a suitable method that fully meets the intended goal.

The essence of the method based on the rate of profitability lies in the profitability of the given project and its comparison with the required profitability, the value of which is chosen by the investor.

It is possible to compare several options for the project. The more effective option corresponds to the maximum amount of profitability. Profitability is determined by the following expression:

$$\text{Profitability}=\frac{\text{Average Profit}}{\text{Average Capital Used}}. \quad (12)$$

Profitability expresses the degree of efficiency of capital use (the amount of net profit per 1 GEL of investments of a given environmental project). The method of evaluating the effectiveness of investments according to the payback period, which is also called the return method (i. e. Pay off, Pay back), characterizes the time after which the invested capital is returned at the expense of the profit from the realized products. The amount of profit for this period is equal to the amount of investments:

$$\text{Deadline} = \frac{\text{Investted Capital}}{\text{Average Profit}}, \text{ year.} \qquad (13)$$

In foreign practice, there is no legal (normative) meaning of the compensation period: any income eventually will compensate the investment. The issue needs to be resolved: is it acceptable for the investor to return the money within a specified deadline period. A project option is considered appropriate if the payback period is less than or equal to a predetermined period that can be determined based on experience. The disadvantage of the method is that it cannot cover the entire period of operation of the project, and it is not affected by all the charges that exist outside the scope of the payback period.

In addition, this method is focused not on the calculation of the project's usefulness, but on the determination of its liquidity. The basis for determining investments is the flow of taxes, considering the time factor.

The territorial environmental protection program is formed with a set of measures, the implementation of which gives us the opportunity to achieve the set goal of stability or improvement of the ecological situation in the considered cities, districts or regions. The analysis in practice, formed by a state and regional environmental protection measures, shows that the measures are chosen not by a special method, but by considering individual sectors and inter-sectoral complexes (in separate industrial enterprises with different branches in the field of communication, in social security, etc.). At the same time, attention is not paid to the fact that the goal of the environmental protection program is divided into separate sub-objectives (e. g., pollution of a separate area of the environment – in the air atmosphere, in the water environment, etc.). This leads to the fact that the set of measures does not meet all sub-objectives, and their realization does not allow the achievement of the set goal. In addition, in the process of forming a complex of measures, attention is not paid to the volume of investments, the results of their implementation, which are expected when the measures are implemented, show their natural form – reduction of loss from harmful substances, termination of wastewater pollution, etc. These results do not guarantee consistency between different measures [7, 8].

Functional-cost analysis (FCA), which includes the formulation of target requirements and designed solutions, is a more comprehensive complex approach to problem solving. The FCA method has gained worldwide recognition. It was developed in the 40^s of the 20th century as an economic analysis of constructive and technological decisions. In the 1960s, FCA began to be used on a fairly large scale in machine-building and tool-equipment enterprises. In the 1970s and 1980s, laboratories and centers for using FCA were created, new FCA methods were developed, and computers were used for their implementation.

The creation of FCA and its use in various fields led to the reduction of all kinds of costs. It is impossible to use one of the many methods of FCA for a systematic examination of the costs of a specific and complex object, such as a territorial environmental protection program, since when using PCA, special methods need to be developed for this or that facility (object), although the essence of PCA remains the same at the methodological level. The enterprise should be divided into constituent parts, their functions should be separated, and the importance of functions and its constituent parts should be evaluated.

Four stages are distinguished during the realization of the FCA: informative, analytical, creative and research. Usually, the informational stage includes collecting, preparing and systematizing data about the facility (object).

Environmental protection program can be considered as a complex system which should be the object of analysis and design. It would be correct to try to transfer the methods of FCA to the process of formation of measures for environmental protection.

It is advisable to form measures based on alternative options for environmental protection projects (Fig. 1). It corresponds to the research stage of FCA [9].

Fig. 1 shows the scheme of measures ensuring the realization of the final goals. For example, the objective O1.1 provides two measures (activities), and the objective O1.2 – one, while one measure of the objective O1.1 has three alternative options: $m^1_{1,1,1}, m^2_{1,1,1}, m^3_{1,1,1}$; the second has two alternative options: $m^1_{1,1,2}$ and $m^2_{1,1,2}$. Objectives M.2.1 and M.2.2 do not have alternative options for measures.

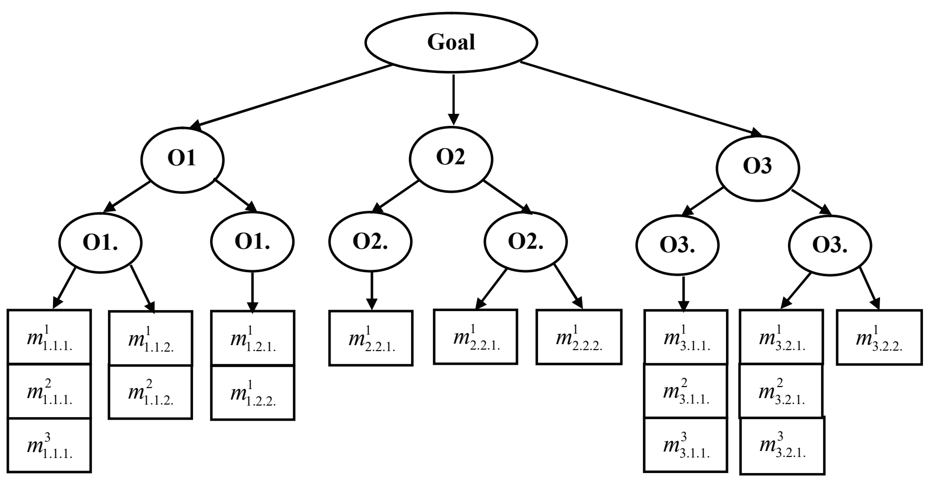

Fig. 1. Alternative options for the target tree

Solutions among the FCA alternatives are selected in the following way: Either decisions are made from many alternatives by one or more criteria, or an economic-mathematical model is used to form the best set of decisions through selection from alternative options. Both approaches have the right to coexist, but the second one is more thorough, since all additional decisions are considered when solving the optimization task [10].

In case of choosing measures of the environmental program, it is necessary to select a more comprehensive approach, therefore, in the first case, it is most appropriate to rely on the information about measures: $\overline{\omega}_i$ – assessment of the importance of events; ρ_t – assessment of the prospects of events; K_t – amount of expenses during the realization of measures.

Choosing the best measures from alternative options requires a maximum integrated assessment of measures:

$$\eta_i = \lambda_1\omega_i + \lambda_2\rho_i + \lambda_3 K_i, \tag{14}$$

where λ_1, λ_2, λ_3 are indicators of coefficient evaluation, which are obtained based on the expertise (λ_{1t}+λ_2+λ_3=1).

When choosing the measures of the environmental program based on the optimization approach, for each final goal, which has alternative options for the measure, it is possible to draw up an economic-mathematical model:

$$\sum_{i=1}^{n_j} K_i X_i \to \min,$$

$$\sum_{i=1}^{n_j} \omega_i X_i \geq 1,$$

$$\sum_{i=1}^{n_j} X_i = 1, I = 1, L_j,$$

$$X_i = \begin{Bmatrix} 0 & \\ 1, & i = 1, n_j \end{Bmatrix}, \tag{15}$$

where n_j – the number of measures that provide the j-th final goal, including the alternative; L_j – the number of alternative options of measures for the j-th goal; J_{ij} – many alternative i-variants of measures for j-objective.

The choice of measures determines the result of the decision of this task, which ensures the minimum costs of the total satisfaction of the j-th goal. If the majority of measures do not allow to ensure the full satisfaction of the corresponding goal, then the given task will not have a solution (meaning). In order to solve the problem, it is necessary to weaken the first constraint:

$$\sum_{i=1}^{n} \omega_i X_i \geq \varepsilon_j, \tag{16}$$

where ε_j – a sufficient value to satisfy the j-th goal (ε_j>0).

Satisfying a collection of measures in this way may require too much investment. In such a case, it is necessary to highlight the most important ones from the complete set of measures. The limit of the allocation is determined either by the amount of transfer of financial means, or by the degree of realization of the goal (or its individual sub-objectives).

Let's consider the selection of measures' options in the program from a wider range in such a way that the costs of their realization are minimal. This task is found in special literature. Its solution lies in the minimization of costs for the realization of measures, etc. Before that, it is necessary to solve the problem:

$$\sum_{i=1}^{n_j} Z_i U_i \to \min,$$

$$\sum_{i=1}^{n_j} e_{ij} U_i \geq E_j, j = 1, n,$$

$$X_i = \begin{Bmatrix} 0 & \\ 1, & i = 1, m \end{Bmatrix}, \tag{17}$$

where i – a number of an alternative measure (i=1, m); Z_t – the amount of expenditure for the implementation of i-measures; U_i – searchable target variable with the following value: if U_t=1 – i event is included in the program, if U_t=0 – i event has been postponed. ε_{ij} – improvement of the j indicators at the expense of the realization of the i measure; E_j – value of improvement of j-index that should be achieved.

In some cases, it is possible to use the reverse model when selecting measures:

$$\sum_{i=1}^{n_j} e_i U_i \to \max,$$

$$\sum_{i=1}^{n_j} Z_i U_i \leq \Phi, \tag{18}$$

$$X_i = \begin{Bmatrix} 0 & \\ 1, & i = 1, m \end{Bmatrix},$$

where Φ – the volume of investments allocated for the implementation of the environmental protection program.

The use of these models is justified, for example, to select the necessary one from the options of technological processes or to control atmospheric pollution. To solve this task, it is necessary to use the hierarchical representation of criteria in the form of a tree, the last peaks of which are specific indicators. In this case, it is determined by:

$$x_i = \sum_{i \in J_j} a_{ij} X_j, \tag{19}$$

where j_j – the set of i-th criteria that produces the j-th criterion; a_{ij} – the constant of the influence of the j-th criterion on the i-th criterion; x_t and x_j – the value of the i and j criteria.

In order to find the optimal set of measures that provide the value of x_i^* – criteria $\left(i \in J^{k^*}\right)$ it is necessary to solve the problem:

$$\sum_{i=1}^{m} Z_i U_i \to \min,$$

$$x_j = x_j^0 + \sum_{i=1}^{m} d_{ij} U_i, \quad i \in J^k, \tag{20}$$

$$x_i = \sum_{j \in k+1} a_{ij} x_j, \quad i \in J^k, \quad k = k^*, \quad k-1,$$

where x_j^0 – the base value of the j-index; j^k – the set of final values at level k (at the top of the tree).

To solve the inverse problem, it is necessary to change the "face" of the model:

$$\min\left\{\alpha_j\left(x_j - x_j^0\right)/x_j^0\right\} \to \max, \; i \in J^k,$$

$$x_j = \sum_{j \in J^{k+1}} a_{ij} x_j, \quad i \in J^k, \quad k = k^*, k-1, \tag{21}$$

$$\sum_{i=1}^{m} Z_i U_i \leq F,$$

where α_j – the meaning (priority) of the j-th criterion: $\sum_{i \in J^{k^*}} \alpha_j = 1$; F – the amount of investment allocated for the realization of the project. Relative magnitude of improvement of maximum criteria $\left(x_j - x_j^0\right)/x_j^0$ in the proposed model. Since in general cases the number of improved criteria is more than one, then it is necessary to solve the multi-criteria problem by improving all criteria $i \in J^{k^*}$ simultaneously. To do this, it is purposefully possible to use the maximum criteria, which realizes the Chebyshevsky principle of equal concession:

$$\min\left\{a_j\left(x_j - x_j^0\right)\Big/x_j^0\right\} \to \max, \qquad (22)$$

$$i \in J^k.$$

Since the $i \in J^{k^*}$ criteria can have different values, it is possible to consider the value of the criteria (priority) with the help of the a_j – coefficient. The value of the criteria is determined through expertise. When determining the importance of criteria, it is necessary to consider the role of each in the overall criterion. For this it is necessary to use the PERT method. The value of an individual criterion should be evaluated according to the individual branch of the criterion tree.

Based on the performed calculation, it is easy to determine the value of k^* level criteria, which is included in the objective function of the multi-criteria task formed above:

$$\alpha_i = \prod_{j \in L_i} v_j, i \in J^k, \qquad (23)$$

where L_j – the set of criteria between the i-th criterion and the common criterion. The direct and indirect tasks of forming a set of measures of the territorial environmental protection program given above belong to the class of discrete mathematical programming tasks with objective variables. A random search method can be used to solve these types of problems.

For such a specific object of analysis as measures of the protection program, it is necessary to perform the following important activities:

1) revealing and forming the functions of the object, both as a whole and its constituent parts;

2) allocating high-cost zones, revealing functional reserves;

3) building a functional model;

4) evaluation of function value;

5) confronting the tasks of finding options for the realization of functional models with the necessary quality assurance and functionally acceptable costs.

Basic, auxiliary and useless functions are distinguished in FCA methods. Using the analysis of the environmental protection program, the function of the measures can be determined based on the analysis of the socio-ecological-economic model of the region's functioning. It was mentioned above that the implementation of a systematic investigation of the functioning of the region is effective using the oriented graphs that are based on the modelling. In order to reveal the functions of measures, it is necessary to connect orientation graphs with contours. Then the functions will be formed according to the contours of this graph. Let's note that one measure can be associated with several contours (Fig. 2).

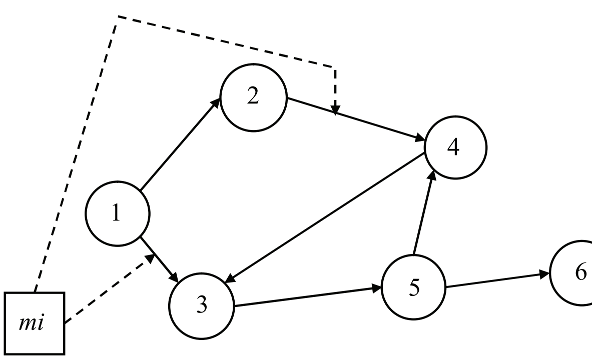

Fig. 2. Impact of measures on multiple contours

In order to assess the development of the socio-ecological-economic system, it is necessary that the goals belonging to one of the levels of the structural-objective model should exist in the form of peaks of orientation graphs. As a result, it is possible to highlight the impacts of primary contaminants on these peaks and provide a link between structural-objective and functional models [11].

The full effect of the impact of the j-th factor on the l-th factor, which is one of the goals of the social-ecological-economic system, is calculated by the following equation:

$$T_{(jl)} = \left\{\left(\sum_{t=1}^{R} E^t_{jl} \prod_{s=1}^{S} 1 - L_s\right) \Big/ \prod_{s=1}^{S} 1 - L_s\right\}^*, \qquad (24)$$

where $E^t_{(jl)}$ – the separable effect of r open path from j to l; L_s – reverse effect of s-ring providing relevant feedback; R – number of open paths from j to l; S – number of s-rings providing relevant feedback; $\{\}^*$ – operator that indicates that firstly the numerator and denominator are multiplied, then the terms equal to the derivatives of the effects are removed, and only then the division is performed.

If to determine the full effect of the influence of the factor $T^I_{(jl)}$ before and after the realization of the measure $T^0_{(jl)}$, then the change in the effect will be:

$$\Delta T_{(il)} = T^I_{jl} - T^0_{jl}. \qquad (25)$$

In order discuss the change of factor in detail, $T_{(iI)}$ can be expressed as a function of contour coefficients:

$$T_{(jl)} = f\left(a_m, m = 1, M\right).$$

The change of the effect due to the impact on the contour of the measure can be determined by the following equation:

$$b_m = \frac{dT_{(jl)}}{da_m}, \qquad (26)$$

where b_m – the magnitude of the change in coefficient m.

The sum of the effect change according to individual arcs is equal to the total effect change:

$$\Delta T_{(jl)} = \sum_{m=1}^{M} b_m \frac{dT_{ij}}{da_m}. \qquad (27)$$

As a result, based on directed graph analysis, it is possible to construct the functional model shown in Fig. 3.

This model has two levels: level of objectives and level of measures. The contours from the j-measure move towards the goal if $\Delta T_{(jI)}=0$. In Fig. 3, part of the contours is marked with "+" sign, the other part is marked with "–" sign. This is since based on $\Delta T_{(jI)}$ wit is possible to identify beneficial (improvement of the values of the system indicators, which helps to achieve the goal – sign "+") and harmful (deterioration of the values of the system indicators, which prevents the achievement of the goal – sign "–") actions.

The structural-functional model provides a comprehensive evaluation of each measure, evaluation of their blocks, directed to the structural goal. According to the structural model, the completeness of the achievement of the structural goal is evaluated directly, according to the functional model – the beneficial and harmful effects of the measures and their blocks. At the stage of the analysis of the systematic investigation of the measures of the program, it is necessary to analyze the costs necessary for the implementation of the measures and determine their compliance with the expected result.

The method of comparing the costs of functions with the point estimate of the value of the function is based on the fact that the value of the function is considered to be the normalized condition for the allocation of costs. When using the systematic analysis of the event, it is possible to modify this method and call it the method of comparing the cost of the measure with the result assessment. The result of the measures can be evaluated according to the indicators of the proportionality of the measures. In addition, when formulating the method, the word *function* disappears, and to the extent that a complex of measures is considered, the method can be called *complex-value analysis*. For its realization, it is possible to use the structural-value scheme and priority assessments on the goal tree (Fig. 4).

Complex-value analysis can be performed for any level of the hierarchical level of the Goals' Tree, starting from the first level. For this, it is possible to construct a diagram - "costs-results" (Fig. 5).

If to find the dependence of costs on the result, then in the case when this dependence is less than 1, there is a degree of reliability and it is not necessary to specify measures and costs, and if the dependence is greater than 1, then the source of information should be specified, the set of measures should be improved.

5. 2. Calculation of the economic efficiency of the innovative Debris-flow control structure

Regional features of the formation of the economic mechanism of nature use are important. The principle issue of the economic mechanism can be formulated as follows: orientation to the rationalization of nature use and environmental protection, expansion of the scale of use of natural resources in the economy (type of economic mechanism with compensatory, soft restrictions) or stabilization and reduction of the scale of use of nature (rigid and stimulating type mechanisms). This dilemma may not even be formulated in such an obvious way, and it turns out to be the result of choosing economic or social goals outside the ecological context.

The second formulated principle logically follows from the above – it is impossible to create a local economic mechanism for the use of nature, which will operate in the first stage of the vertical (chain) of "nature-products" and separate from the regulatory mechanisms of the processes of natural resources protection.

The mechanism of nature use should become part of the general mechanism regulating individual measures on the environmental vertical and should be focused on the final result. Taking into account all of the above, the implementation of environmental protection measures and the evaluation of its effectiveness are functionally related to the complex evaluation of the economic-ecological mechanism.

As an illustration, let's consider a practical example: in order to protect the city of Telavi (East Georgia) from debris-flow, three debris-flow control barrages were built in the bed of the Telavi river gorge, the cost of one longitudinal meter of which was 863 USD (Fig. 6).

If to regulate the debris-flow in the bed of the Telavi river gorge with an innovative debris-flow control construction of the arch-step trampoline type, the construction material of which is used secondary raw materials (for example, scrapped metal rails), then the cost of one longitudinal meter is 175 USD (Fig. 7).

If to calculate the economic effect using equation (1), then the annual economic effect is:

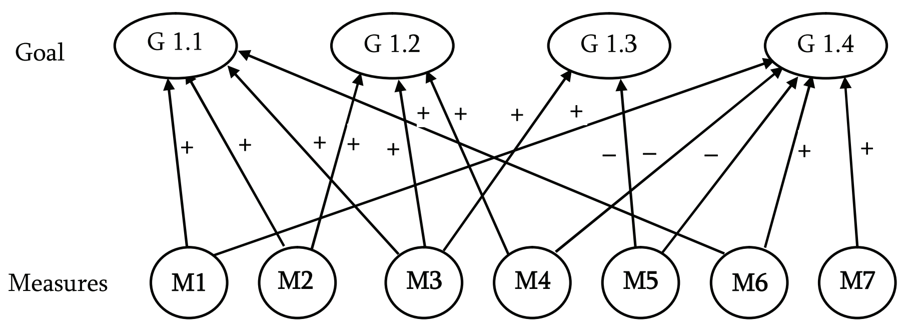

Fig. 3. Functional model of goal realization based on measures

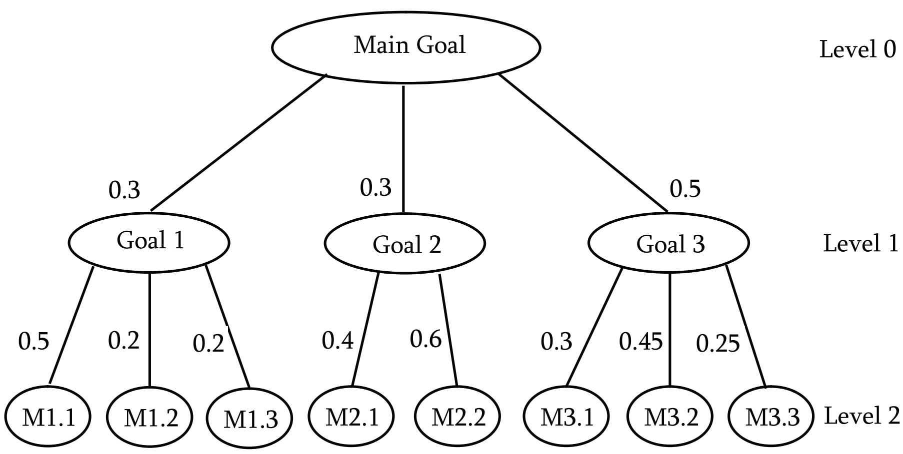

Fig. 4. A Tree of goals

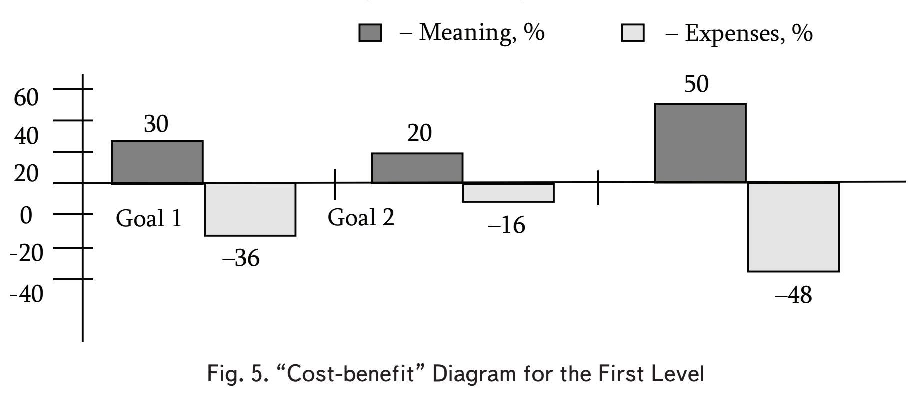

Fig. 5. "Cost-benefit" Diagram for the First Level

$$E_p=\left[\sum_{j=1}^{n}\sum_{i=1}^{m}\left(E_{ij}-C\right)\right]/K=$$
$$=\ 863-175\ \ /42.6=16.15\$.$$

Fig. 6. Debris-flow control structure in the bed of Telavi river gorge

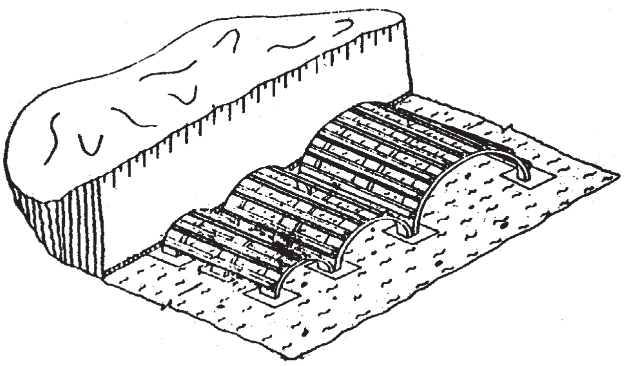

Fig. 7. General view of the innovative debris-flow control structure

Thus, the obtained result allows to recommend the presented innovative flood protection structure for its use in practice.

6. Discussion of the research results of the economic effectiveness of environmental protection hydraulic engineering structures

Scientific studies have shown that the trend of climate change in Georgia has significantly increased the probability of occurrence of natural disasters in mountain landscapes. In order to reduce the damage caused by natural disasters (e.g. debris-flow, floods, avalanches, etc.) the creation of innovative and reliable environmental protection hydraulic engineering structures was on the agenda. The engineering structure presented in Fig. 7 [4] is an innovative construction, the reliability of which has been confirmed on the basis of experiments (modeling) conducted in the hydraulic engineering laboratory.

On the basis of field-experimental scientific investigations carried out on the flood control structure built in the bed of the Telavi river gorge (Fig. 6), it was established that in the case of movement with catastrophic parameters of the flood, the failure of the structure's nodes is common, which significantly reduces the reliability of the hydraulic engineering structure. It is for this purpose that an innovative trampoline-type anti-flooding structure was developed at the above mentioned scientific-research institute (Fig. 7). In order to develop a recommendation for the use of this structure in practice, it was necessary to determine the economic efficiency of the construction, which was calculated by us using equation (28). During the period of the conducted studies, which were related to the evaluation of the economic efficiency of the innovative hydraulic engineering structure, there were difficulties related to the evaluation of the design data and cost accounting documents of the flood control structure built in the bed of the Telavi river gorge (Fig. 6), which economic indicators were calculated in 1970 in Soviet period's currency – rubles.

A feature of the proposed study is the calculation of the technical and economic efficiency of an innovative flood control structure, which, compared with the existing methodology, is due to the innovativeness of the design.

As for the limitations of the study, the construction material of environmental protection structures, which can be secondary raw materials (including scrap metal rails or ropes) or local building material – e.g., lime, or stonean cause it. The inflation of the national currency in the country should be also be taken into account, which will make the budget for the construction of environmental measures more expensive.

It should be also be noted that the world practice of planning and implementation of environmental engineering measures has made it clear that the complete solution of the fight against natural disasters with engineering-ecological measures is a priority of those countries that have a sustainable economy and a big-budget.

Climate change has led to an increase in the risks of natural disasters, which requires accurate forecasting and the development of effective and reliable constructions of engineering structures, which is also related to the effective management of environmental-economic issues.

Considering all of the above, in order to manage effectively the issue in the future, a regional solution of environmental measures is recommended, where several countries will be involved in the project, taking into account the percentage share with the appropriate budget.

7. Conclusions

1. After studying and analysing the theoretical and practical environmental programs, a methodology was developed, using which the mechanisms of economic efficiency of environmental programs under the conditions of integrated management of natural resources were evaluated.

2. Using the economic indicators of the base structure selected in nature, the economic efficiency of the innovative debris-flow control structure is established, the numerical index of which is 16.15 USD per one longitudinal meter of the structure.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing	Data availability
The study was performed without financial support.	Data will be made available on reasonable request.

References

1. Bianchi, M., Cordella, M. (2023). Does circular economy mitigate the extraction of natural resources? Empirical evidence based on analysis of 28 European economies over the past decade. Ecological Economics, 203, 107607. doi: https://doi.org/10.1016/j.ecolecon.2022.107607
2. Landry, C. E., Shonkwiler, J. S., Whitehead, J. C. (2020). Economic Values of Coastal Erosion Management: Joint Estimation of Use and Existence Values with recreation demand and contingent valuation data. Journal of Environmental Economics and Management, 103, 102364. doi: https://doi.org/10.1016/j.jeem.2020.102364
3. Gavardashvili, G., Vartanov, M. (2020). Methods to calculate the social-economic damage caused by floods. Development of Management and Entrepreneurship Methods on Transport (ONMU), 3 (72), 5–11. doi: https://doi.org/10.31375/2226-1915-2020-3-5-11
4. Gavardashvilii, G. (2011). Measures for the safety of mountain landscapes during natural and technogenic disasters. Tbilisi. Available at: https://dspace.nplg.gov.ge/bitstream/1234/34390/1/BunebriviTeknologiebisKatastrofebi.pdf
5. Gurgenidze, D., Gavardashvilii, G. (2022). Fundamentals of the ecological-economic theory of integrated natural resource management. Tbilisi. Available at: https://dspace.nplg.gov.ge/bitstream/1234/389089/1/BunebriviResursebisIntegrirebuliMartvisEkologiurEkonomikuriTeoriisSafudzvlebi.pdf
6. Gurgenidze, D., Gavardashvili, G., Aliyev, V., Ujma, A. (2020). Dam Break and Flash Flood Prediction Case Study: Zhinvali Dam, Georgia. Abstracts of The Second Eurasian RISK-2020 Conference and Symposium. doi: https://doi.org/10.21467/abstracts.93.55
7. Huang-Lachmann, J.-T., Hannemann, M., Guenther, E. (2018). Identifying Links between Economic Opportunities and Climate Change Adaptation: Empirical Evidence of 63 Cities. Ecological Economics, 145, 231–243. https://doi.org/10.1016/j.ecolecon.2017.09.001
8. Costanza, R. (2020). Ecological economics in 2049: Getting beyond the argument culture to the world we all want. Ecological Economics, 168, 106484. doi: https://doi.org/10.1016/j.ecolecon.2019.106484
9. Osberghaus, D. (2015). The determinants of private flood mitigation measures in Germany – Evidence from a nationwide survey. Ecological Economics, 110, 36–50. doi: https://doi.org/10.1016/j.ecolecon.2014.12.010
10. Gavardashvilii, G., Vartanov, M. (2009). Assessment of conomical and ecological damage to forests burned as a result of war took place in Georgia (August, 2008) and preventive measures against soil erosion on mountainous slopes. Collected Papers No. 64 of Water Management Institute. Tbilisi, 48–59. Available at: https://dspace.nplg.gov.ge/bitstream/1234/237227/1/Samecniero_Shromata_Krebuli_2009_N64.pdf
11. Kozulia, T., Emelyanova, D., Kozulia, M. (2014). Complex ecological estimation of natural and manmade complexes which basis on MIPS- and risk analysis. Eastern-European Journal of Enterprise Technologies, 3 (10 (69)), 8–13. doi: https://doi.org/10.15587/1729-4061.2014.24624
12. Babaev, V., Sukhonos, M., Starostina, A., Beletsky, I. (2016). Improving the processes of cost management in the construction and energy projects. Eastern-European Journal of Enterprise Technologies, 4 (3 (82)), 10–14. doi: https://doi.org/10.15587/1729-4061.2016.75515
13. Boyko, T., Dzhygyrey, I., Abramova, A. (2017). Using the assessment method of environmental risk of a project in strategic territorial planning. Eastern-European Journal of Enterprise Technologies, 3 (10 (87)), 10–17. doi: https://doi.org/10.15587/1729-4061.2017.101848