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ԲԱՐՁՐ ՏԵԽՆՈԼՈԳԻԱՆԵՐԻ ՏԵՂԵԿԱԳԻՐ
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Տեղեկագիրը հրատարակվում է Ակադեմիկոս Ի.Վ.Եղիազարովի ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտի, Հիդրավլիկական հետազոտությունների հայկական ազգային ասոցիացիայի, Երևանի կապի միջոցների գիտահետազոտական ինստիտուտի և Շուշիի տեխնոլոգիական համալսարանի կողմից: Հիմնադրվել է 2016թ.: Լույս է տեսնում տարեկան 4 անգամ:

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STRATEGIC MANAGEMENT OF STOCKPILED TOPSOIL GENERATED BY LARGE INFRASTRUCTURE PROJECTS: EVIDENCE FROM THE AKHURYAN RESERVOIR, ARMENIA

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Abstract

Large infrastructure projects frequently require the removal of the fertile topsoil layer during construction activities. Although this material represents a valuable natural resource, it is often treated as a temporary by-product and remains unused for long periods, resulting in quality degradation and economic losses. This study evaluates the volume, quality, and management potential of stockpiled topsoil accumulated during the construction of the Akhuryan Reservoir in Armenia.

The research combines UAV-based topographic surveying, cadastral data analysis, soil sampling, laboratory determination of humus content using the Tyurin method, and assessment of legal demand for fertile soil. The results indicate that approximately 212,532 m³ of topsoil has been accumulated within a designated storage area. Laboratory analyses revealed an average humus content of 3.54%, corresponding to high-quality agricultural soil. Comparative analysis showed a significant imbalance between the accumulated stockpile volume and the officially recorded demand for fertile soil.

The findings demonstrate that long-term storage of topsoil may lead to gradual degradation of soil quality and reduction of its agricultural value. The study proposes a strategic resource-management approach in which stockpiled topsoil generated by large infrastructure projects is considered a strategic environmental resource requiring systematic inventory, monitoring, and controlled redistribution.

The proposed approach may contribute to improved soil conservation, reduction of illegal soil extraction, and more efficient utilization of valuable land resources in Armenia and other countries facing similar challenges.

***Keywords*:** topsoil management; fertile soil; soil conservation; infrastructure projects; humus content; resource management; Akhuryan Reservoir; Armenia.

Introduction

Topsoil, the fertile upper layer of soil, is one of the most valuable natural resources within terrestrial ecosystems. Formed over thousands of years through complex physical, chemical, and biological processes, it provides the foundation for plant growth, biodiversity conservation, carbon sequestration, water regulation, and sustainable agricultural production. Unlike many other natural resources, fertile topsoil is renewed extremely slowly; therefore, its degradation or loss may result in long-term environmental, social, and economic consequences.

During recent decades, the implementation of large-scale infrastructure projects—including reservoirs, highways, industrial facilities, residential developments, mining operations, and energy infrastructure—has accelerated worldwide. Construction of such projects typically requires the removal of the fertile topsoil layer during site preparation. This material is generally stockpiled in designated storage areas for future reclamation or reuse following project completion.

Despite existing environmental regulations and engineering practices, stockpiled topsoil frequently remains unused for extended periods. Prolonged storage may lead to gradual deterioration of soil structure, reduction in biological activity, loss of active organic matter, compaction, and increased susceptibility to erosion, ultimately decreasing its agricultural and ecological value. At the same time, many regions continue to experience substantial demand for fertile soil for agricultural production, land reclamation, landscaping, and urban greening projects. This contradiction indicates that the principal challenge is not the availability of fertile soil itself, but the effectiveness of its management.

International scientific literature has devoted considerable attention to soil conservation, land degradation, and sustainable soil-resource management. However, the assessment and management of stockpiled topsoil generated by large infrastructure projects have received comparatively limited attention. Existing studies primarily focus on reclamation techniques, erosion control, and restoration practices, whereas relatively little emphasis has been placed on systematic inventory, quantitative assessment, quality preservation, demand–supply analysis, and strategic redistribution of accumulated topsoil resources. Consequently, significant methodological gaps remain regarding the integration of these aspects into a comprehensive resource-management framework.

In the Republic of Armenia, numerous large-scale water infrastructure, transportation, industrial, and urban development projects have generated substantial volumes of stockpiled topsoil. Simultaneously, both legal demand for fertile soil and cases of illegal soil extraction have been recorded, indicating deficiencies in existing management, accounting, and regulatory mechanisms. Under these conditions, accumulated topsoil should no longer be regarded merely as temporarily stored excavated material, but rather as a strategic environmental resource whose effective management can simultaneously contribute to soil conservation, sustainable agriculture, environmental protection, and more efficient utilization of national land resources.

The objective of this study is to evaluate the volume, quality characteristics, and management potential of the stockpiled topsoil accumulated during the construction of the Akhuryan Reservoir in Armenia by integrating UAV-based topographic surveying, cadastral analysis, laboratory soil testing, and demand assessment. Based on the obtained results, the study proposes a strategic management approach for stockpiled topsoil that may support sustainable resource utilization in Armenia and provide a practical framework applicable to other countries implementing large infrastructure projects.

Literature Review

Topsoil as a Strategic Natural Resource

Topsoil represents one of the fundamental components of terrestrial ecosystems, formed through long-term interactions among physical, chemical, and biological processes. Classical soil formation theory demonstrates that soil development depends on the combined influence of parent material, climate, topography, biota, and time, making fertile topsoil a slowly renewable and highly vulnerable natural resource [40]. Contemporary soil science further recognizes topsoil not only as the foundation of agricultural production but also as a provider of essential ecosystem services, including water regulation, carbon sequestration, nutrient cycling, and biodiversity conservation [35,39].

During the last decade, soil conservation has become a global priority. Assessments published by the United Nations Convention to Combat Desertification (UNCCD), the Food and Agriculture Organization (FAO), the Intergovernmental Panel on Climate Change (IPCC), and the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES) consistently identify soil degradation as one of the major threats to food security, climate resilience, and ecosystem restoration [1,10,32,33]. The loss of fertile soil or deterioration of its quality is particularly critical in countries with limited land resources, where agriculture continues to play a significant socio-economic role. Consequently, the conservation of topsoil should be regarded not only as an environmental issue but also as a strategic resource-management challenge.

Recent international policy documents increasingly recognize soil as a form of natural capital. The European Union Soil Strategy for 2030 emphasizes the importance of healthy soils for climate-change mitigation, biodiversity conservation, and food security [2]. Similar approaches are reflected in the strategic frameworks developed by FAO and the Global Soil Partnership, which highlight the necessity of sustainable soil management, systematic monitoring, and continuous assessment of soil quality [3,4,34]. These initiatives demonstrate a transition from viewing soil conservation as a purely technical issue toward considering it an integral component of national and international environmental policy.

Scientific research likewise emphasizes the need for integrated soil-health assessment. Modern studies evaluate soil quality using not only physicochemical parameters but also biological activity, soil organic carbon, microbial diversity, and ecosystem functionality [11–13]. Such an integrated perspective is particularly relevant for topsoil because it contains the highest concentrations of humus, root biomass, microorganisms, and plant nutrients that determine soil fertility and ecological performance.

Nevertheless, the majority of existing studies concentrate on agricultural soil conservation, land degradation, erosion control, and ecological restoration. Comparatively little attention has been devoted to fertile topsoil removed during the implementation of large-scale infrastructure projects. Under such conditions, topsoil enters an intermediate state: it is no longer functioning within its natural ecosystem while simultaneously remaining unused for agricultural production, ecological restoration, or landscape rehabilitation. This transitional condition creates a distinct resource-management challenge that has received limited attention in the international scientific literature.

Topsoil Management in Infrastructure and Construction Projects

The implementation of large-scale infrastructure projects is frequently accompanied by the removal of the fertile topsoil layer. During the construction of reservoirs, highways, industrial facilities, mining operations, and urban developments, topsoil is stripped from the construction site to facilitate engineering activities. International guidelines consistently recommend that fertile topsoil should be removed separately from subsoil materials, stored in designated stockpiles, and subsequently reused during land reclamation and ecological restoration [25,26,31].

Technical guidance documents addressing sustainable soil use in construction projects emphasize several key principles for topsoil preservation. These include preventing the mixing of topsoil with underlying materials, limiting stockpile height, minimizing soil compaction, and ensuring proper surface-water management during storage [25,27]. Although these recommendations provide valuable technical guidance, they primarily focus on construction practices and do not establish comprehensive long-term strategies for managing accumulated topsoil resources.

Research conducted in mining and land-reclamation contexts demonstrates that stockpiling may substantially influence the future usability of topsoil. Recent investigations have shown that prolonged storage can alter soil geochemical properties, microbial community composition, biological integrity, and restoration potential [17–23]. These findings are particularly relevant because they indicate that stockpiled topsoil should not be regarded as a stable resource whose quality remains unchanged throughout the storage period.

Despite these advances, the existing literature remains largely focused on mining and post-mining reclamation. Considerably less attention has been devoted to the accumulated topsoil generated during reservoir construction, transportation infrastructure, and urban development projects. In particular, limited research has addressed the quantitative inventory of accumulated topsoil, its legal circulation, demand assessment, and integration into long-term resource-management systems. These shortcomings become especially significant in countries where fertile soil resources are limited and where uncontrolled or illegal soil extraction creates additional environmental and governance challenges.

Therefore, the international experience in topsoil management demonstrates that while technical requirements for soil preservation are relatively well established, considerably less progress has been achieved in developing systematic approaches for inventory, valuation, monitoring, and controlled redistribution of accumulated topsoil as a strategic environmental asset. This research seeks to address this gap by examining the stockpiled topsoil generated during the construction of the Akhuryan Reservoir as a representative case of strategic topsoil resource management.

Effects of Long-Term Topsoil Stockpiling on Soil Quality

The effectiveness of topsoil conservation depends not only on the removal and storage of the fertile soil layer but also on the duration and conditions of storage. Numerous studies published in recent years have demonstrated that even when stockpiles are established in accordance with technical guidelines, prolonged storage may result in gradual deterioration of the physical, chemical, and biological properties of topsoil, thereby reducing its suitability for subsequent reuse [17–24].

Contemporary research indicates that the principal factors affecting the quality of stockpiled topsoil include storage duration, stockpile height, soil compaction, restricted aeration, and alterations in the soil moisture regime [19–23]. The combined influence of these factors reduces soil porosity, disrupts gas exchange, suppresses aerobic biological processes, and gradually decreases microbial activity. Simultaneously, changes occur in the mineralization of organic matter, accompanied by losses of active humus fractions and reduced bioavailability of essential plant nutrients [13,17,19]. These findings demonstrate that the quality of stockpiled topsoil continuously evolves during storage rather than remaining constant over time.

Particular attention has recently been devoted to changes in soil microbial communities. Fischer et al. demonstrated that increasing stockpile height significantly alters both the composition and diversity of microbial communities, directly affecting soil functionality and ecological resilience [21]. Similar conclusions were reported by Bordez et al., who observed substantial modifications in microbial diversity, enzymatic activity, and biochemical processes even after relatively short storage periods [23]. These studies suggest that evaluating topsoil quality should extend beyond conventional physicochemical analyses to include biological indicators that better reflect the functional condition of the soil ecosystem.

Structural changes within stockpiled topsoil have also been identified as an important consequence of prolonged storage. Ledesma et al. reported that extended stockpiling leads to pronounced vertical heterogeneity within soil piles, resulting in considerable differences in moisture content, soil organic carbon, nutrient availability, and microbial activity between upper and lower layers [20]. Such heterogeneity may substantially reduce the effectiveness of subsequent reclamation activities and negatively influence vegetation establishment following soil redistribution.

Similarly, Valliere et al. demonstrated that long-term stockpiling disrupts the biological integrity of topsoil even when major physicochemical properties remain relatively stable [17]. Their findings indicate that the loss of biological integrity may become one of the principal limiting factors affecting ecological restoration success. Comparable conclusions were reached by D'Agui et al., who showed that different methods used to evaluate soil biological properties exhibit varying sensitivity to storage-induced changes, emphasizing the importance of applying comprehensive assessment approaches when evaluating stockpiled topsoil quality [18].

Although considerable progress has been achieved in understanding the effects of stockpiling on soil quality, the existing literature remains strongly focused on post-mining reclamation and mine-site restoration [17–23]. Comparatively few studies have examined topsoil stockpiles generated during reservoir construction, transportation infrastructure, or other large-scale civil engineering projects. Furthermore, most available investigations concentrate on individual physical, chemical, or biological indicators rather than integrating soil quality changes with stockpile volume, storage duration, legal demand, and long-term management strategies.

Consequently, the international scientific literature provides compelling evidence that long-term topsoil stockpiling is not a neutral process. Rather, storage time itself should be regarded as an independent factor influencing soil quality and, therefore, should be explicitly considered in reclamation planning and resource management. Nevertheless, no comprehensive methodological framework has yet been proposed to integrate stockpile-induced soil quality changes with quantitative inventory, demand assessment, and strategic redistribution of accumulated topsoil resources. Addressing this methodological gap constitutes one of the principal objectives of the present study.

International Approaches to Topsoil Reuse and Resource Management

During the last two decades, international approaches to topsoil management have evolved considerably. While earlier practices primarily focused on the technical aspects of topsoil conservation and land reclamation, contemporary approaches increasingly emphasize sustainable resource utilization, circular economy principles, and the efficient management of natural capital [2–10, 27–36].

According to current international concepts, topsoil removed during the implementation of large-scale infrastructure projects should not be regarded as waste or merely as temporarily excavated material but rather as a valuable natural resource suitable for subsequent reuse. Policy frameworks and technical guidelines developed by the European Union, the Food and Agriculture Organization (FAO), the United Nations Environment Programme (UNEP), and the World Bank consistently recommend preserving fertile topsoil, preventing its degradation during storage, and returning it to productive use through ecological restoration, land reclamation, urban greening, and agricultural development whenever possible [2–10,25,26,31,34].

The scientific literature identifies several principal directions for the reuse of stockpiled topsoil, including post-mining reclamation, restoration of construction sites, landscape rehabilitation along transportation corridors, urban green infrastructure development, rehabilitation of degraded lands, and improvement of agricultural soil fertility [11–18,24,27]. Numerous studies further demonstrate that topsoil reuse not only reduces the need for extracting fertile soil from undisturbed areas but also contributes to resource conservation, ecosystem restoration, and the reduction of greenhouse gas emissions associated with land disturbance [10–16,32,33].

Recent research has increasingly highlighted the importance of systematic soil governance. The proposed European Soil Monitoring Law, together with initiatives developed within the framework of the European Union Soil Observatory (EUSO) and the EJP SOIL programme, aims to establish harmonized systems for soil monitoring, quality assessment, and long-term evaluation of soil health across Europe [5,28,29,36]. These initiatives demonstrate a gradual transition from project-specific soil management toward integrated national and regional strategies for sustainable soil governance.

Despite these advances, analysis of the international literature indicates that existing approaches remain largely focused on technical preservation measures, soil quality monitoring, and reclamation practices. Comparatively limited attention has been devoted to situations where large volumes of fertile topsoil accumulate as a consequence of infrastructure development projects and remain stockpiled for extended periods without systematic inventory, continuous quality monitoring, or coordinated redistribution mechanisms. Existing publications rarely address accumulated topsoil stockpiles as resources requiring strategic management at regional or national scales [21,25–31].

Another important limitation of current research is its predominant focus on individual projects or specific restoration sites. Most investigations evaluate the condition of topsoil removed from a particular mine, construction site, transportation project, or urban development area, whereas considerably less attention has been paid to the integrated management of accumulated topsoil originating from multiple infrastructure projects. Consequently, issues such as quantitative inventory, assessment of legal demand, controlled redistribution, economic utilization, and national coordination remain largely unexplored. As a result, accumulated topsoil continues to be treated primarily as a project-specific engineering material rather than as an integral component of national natural capital [2–10,25–36].

Therefore, the international experience demonstrates that although technical methods for topsoil preservation and reuse have been developed to a relatively high level, considerably less progress has been achieved in establishing comprehensive frameworks for the long-term management of accumulated topsoil resources. Systematic inventory, continuous quality assessment, demand analysis, and controlled redistribution remain insufficiently addressed in the existing literature. These observations suggest that topsoil generated during large-scale infrastructure projects should be regarded not merely as material intended for future reclamation but as a **strategic environmental asset** whose effective management can substantially improve the efficiency of national soil resource utilization while reducing the need for additional extraction of fertile soils from natural landscapes.

Research Gap and Conceptual Framework

A comprehensive analysis of the international scientific literature demonstrates that substantial progress has been achieved in recent years regarding soil conservation, soil health assessment, land reclamation technologies, sustainable soil management, and soil monitoring systems [1–40]. Considerable advances have been made in the development of soil quality assessment methods, technical standards for topsoil preservation, and scientific understanding of soil ecosystem services and natural capital [2–10,13–18,25–36].

Despite these achievements, the comparative review reveals several fundamental limitations that remain insufficiently addressed. First, the majority of published studies examine topsoil within the context of individual construction or restoration projects without considering accumulated topsoil generated by multiple infrastructure developments as an integrated resource system [17–24]. Consequently, existing approaches provide only project-specific assessments and do not allow evaluation of the actual scale or strategic significance of accumulated topsoil resources at regional or national levels.

A second important limitation concerns the predominant focus on the physical, chemical, and biological characteristics of topsoil, whereas considerably less attention has been devoted to the organizational, economic, and institutional dimensions of accumulated topsoil management [17–31]. In particular, issues related to systematic inventory, legal demand assessment, resource allocation, controlled redistribution, and long-term governance of accumulated topsoil remain largely absent from the existing scientific literature.

The third limitation is associated with the scale of resource management. Most international studies focus on local or project-level investigations, evaluating topsoil generated during mining operations, transportation infrastructure, or urban development projects [17–31]. Comparatively little research has examined accumulated topsoil originating from multiple infrastructure projects as interconnected strategic resources requiring coordinated management at regional or national scales.

Furthermore, current scientific approaches are primarily designed to evaluate reclamation performance or preserve soil quality during storage. To date, no comprehensive methodological framework has been proposed that simultaneously integrates quantitative inventory of accumulated topsoil, assessment of soil quality, evaluation of storage duration effects, analysis of legal demand, and strategic resource management within a unified conceptual framework [17–31].

These limitations indicate that the existing body of knowledge lacks an integrated approach capable of evaluating accumulated topsoil generated during large-scale infrastructure projects not merely as a by-product of construction activities but as a valuable long-term natural resource. This observation highlights the necessity for a new conceptual perspective based on systematic inventory, continuous quality monitoring, demand assessment, and coordinated redistribution of accumulated topsoil resources.

The present study addresses this scientific gap by proposing an integrated resource-management approach using the stockpiled topsoil generated during the construction of the Akhuryan Reservoir as a representative case study. For the first time, quantitative assessment of accumulated topsoil, laboratory soil analyses, soil quality characteristics, cadastral and spatial information, and legal demand assessment are integrated within a single analytical framework. This integrated methodology enables accumulated topsoil to be considered not as temporarily excavated construction material but as a **strategic environmental asset** whose systematic management can contribute to soil conservation, more efficient utilization of national land resources, and the achievement of sustainable development objectives.

Accordingly, this study fills an important gap in the international scientific literature by introducing the **Strategic Topsoil Resource Management (STRM) framework**, an integrated resource-management framework for the systematic inventory, quality assessment, long-term monitoring, demand analysis, and controlled redistribution of topsoil stockpiles generated during large-scale infrastructure projects. Although demonstrated using the Akhuryan Reservoir case study, the proposed framework has broader applicability and may serve as a methodological basis for sustainable topsoil resource management in other countries implementing similar infrastructure projects.

Conflict Setting

Large-scale infrastructure projects require the removal of substantial volumes of fertile topsoil during site preparation. Although environmental regulations generally require this material to be separately stripped, preserved, and reused for reclamation or land restoration, in practice accumulated topsoil frequently remains stockpiled for prolonged periods without systematic inventory, continuous quality monitoring, or coordinated management. During long-term storage, the physical, chemical, and biological properties of topsoil may gradually deteriorate, reducing its agricultural and ecological value.

At the same time, many countries continue to experience increasing demand for fertile soil for agricultural production, ecological restoration, urban greening, and rehabilitation of degraded lands. Consequently, a practical contradiction arises: while significant quantities of high-quality topsoil remain unused in storage areas, growing sectors of the economy simultaneously face shortages of fertile soil resources. This imbalance indicates that the existing challenge is not limited to soil conservation itself but extends to the absence of effective mechanisms for managing accumulated topsoil resources.

Current management practices primarily address technical aspects of topsoil stripping, storage, and reclamation within individual construction projects. However, they rarely consider accumulated topsoil as a strategic resource requiring systematic inventory, quality assessment, demand analysis, and controlled redistribution beyond the boundaries of a single project. As a result, substantial environmental, economic, and resource-efficiency opportunities remain unrealized.

The present study addresses this practical conflict by introducing the **Strategic Topsoil Resource Management (STRM)** framework, which provides an integrated approach for the systematic inventory, quality assessment, long-term monitoring, demand analysis, and controlled redistribution of accumulated topsoil generated during large-scale infrastructure projects.

Materials and Methods

The methodology developed in this study was designed to provide a comprehensive framework for the assessment and strategic management of topsoil stockpiles generated during large-scale infrastructure projects. Unlike conventional approaches, which primarily focus on soil quality assessment or individual reclamation activities, the proposed methodology integrates field investigations, unmanned aerial vehicle (UAV) surveys, digital terrain modelling, laboratory soil analyses, spatial and cadastral data evaluation, and legal demand assessment within a unified analytical framework.

The methodological structure consists of a sequence of interconnected stages that collectively enable quantitative inventory of accumulated topsoil, comprehensive evaluation of soil quality, assessment of storage-related impacts, and identification of opportunities for subsequent resource utilization. To achieve these objectives, this study develops and applies the **Strategic Topsoil Resource Management (STRM)** framework, an integrated methodological approach that considers accumulated topsoil not merely as a by-product of construction activities but as a strategic natural resource requiring systematic inventory, continuous monitoring, and science-based management. The overall research methodology is presented in **Fig. 2**, while the individual methodological stages are described in the following subsections.

Study Area

The present study was conducted within the accumulated topsoil stockpile area formed during the construction of the Akhuryan Reservoir in Shirak Province, Republic of Armenia.

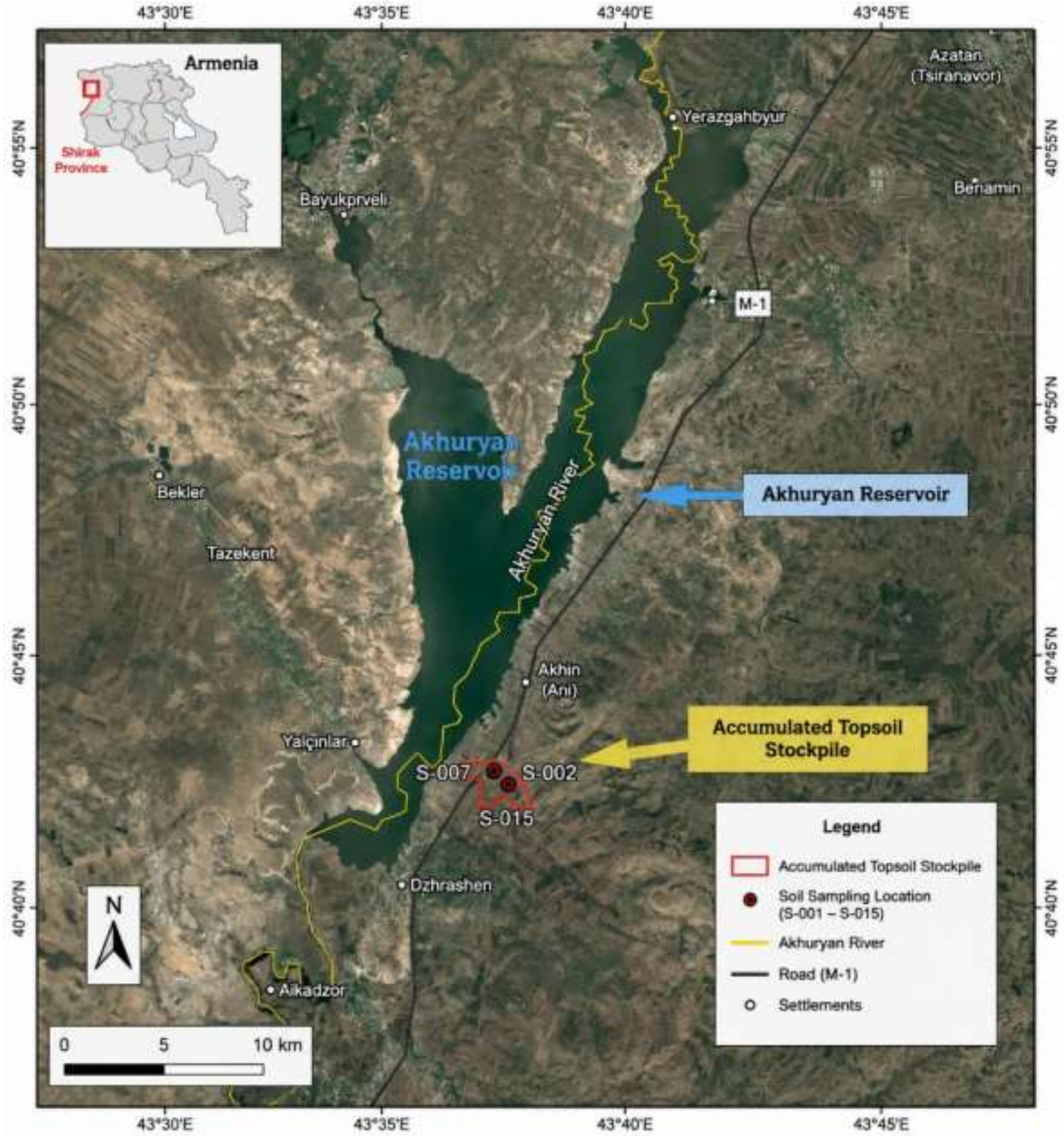

Fig. 1 Location of the Study Area and the Accumulated Topsoil Stockpile

The study area was selected as a representative case study for evaluating the accumulation, quality, and strategic management potential of topsoil generated during large-scale infrastructure projects.

Location of the Akhuryan Reservoir and the accumulated topsoil stockpile investigated in the present study. The figure illustrates the geographical position of the study area within Shirak Province, Republic of Armenia, and identifies the location of the accumulated topsoil stockpile selected for detailed field investigation and subsequent implementation of the Strategic Topsoil Resource Management (STRM) framework.

Fig. 2 Overall Research Methodology and the Strategic Topsoil Resource Management (STRM) Framework

Fig. 2 illustrates the overall methodological structure of the present study together with the integrated Strategic Topsoil Resource Management (STRM) framework. The methodology comprises five interconnected stages: (1) definition of the study area and accumulated topsoil stockpile, (2) multi-source field data acquisition, including UAV surveys, GPS observations, soil sampling, cadastral information, and field investigations, (3) integrated data processing involving digital terrain modelling, volume estimation, laboratory soil analyses, spatial analysis, soil quality assessment, and demand evaluation, (4) implementation of the Strategic Topsoil Resource Management (STRM) framework based on systematic inventory, quality assessment, long-term monitoring, demand analysis, and controlled redistribution of accumulated topsoil resources, and (5) generation of strategic outputs supporting sustainable topsoil management, environmental protection, evidence-based decision-making, and efficient resource governance.

Data Acquisition

A comprehensive data acquisition strategy was adopted to collect field, unmanned aerial vehicle (UAV), laboratory, and spatial information required for the quantitative and qualitative assessment of accumulated topsoil stockpiles. The data acquisition process included field investigations, soil sampling, high-resolution UAV imagery, geographic positioning, and the collection of cadastral and engineering documentation.

The UAV-derived imagery was used for digital terrain modelling, delineation of topsoil stockpile boundaries, and subsequent volume estimation. Field investigations also included soil sampling for laboratory analyses aimed at evaluating the principal physicochemical properties of the accumulated topsoil. In addition to primary field data, spatial, cadastral, and engineering datasets were incorporated to support the integrated analysis and implementation of the Strategic Topsoil Resource Management (STRM) framework. The integrated data acquisition strategy adopted in the present study and the relationships among the principal data sources are illustrated in Fig. 3.

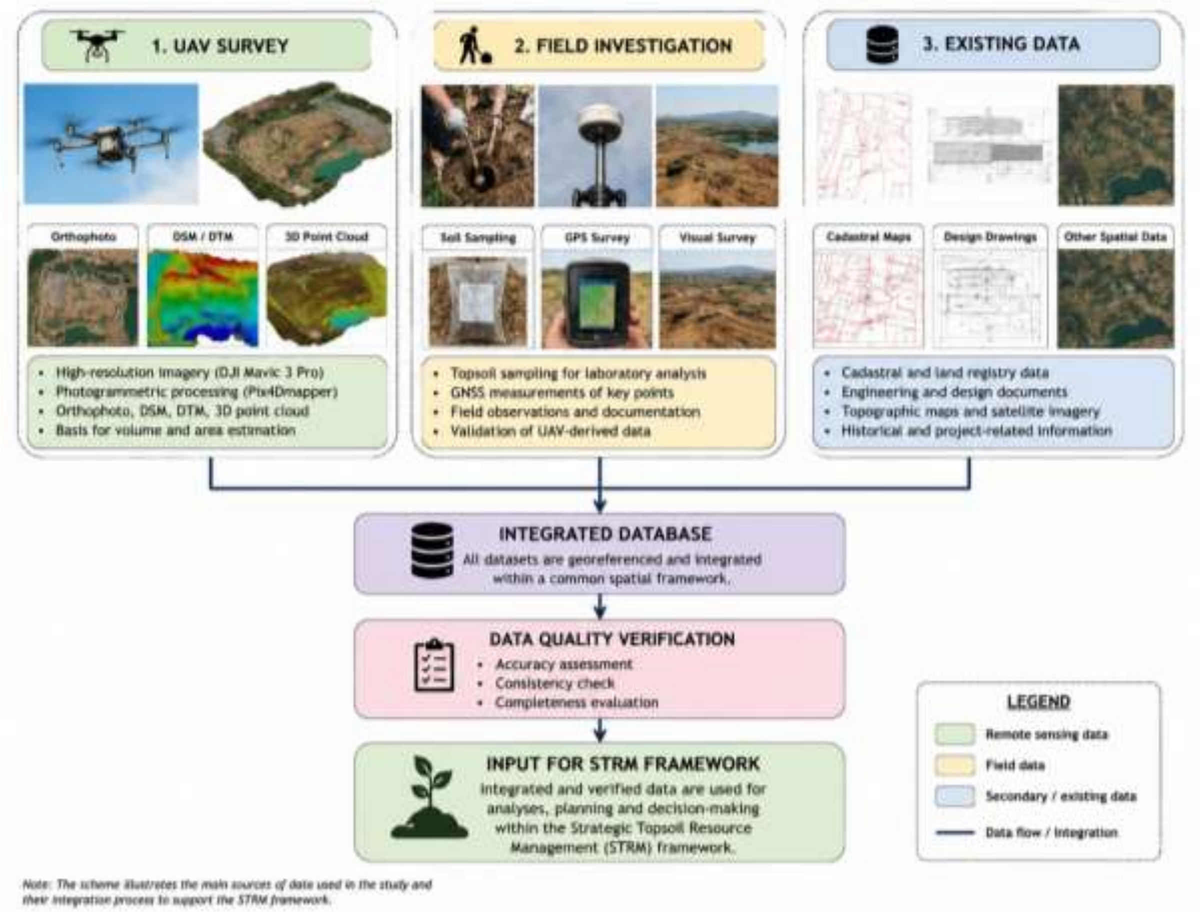

Fig. 3 Integrated Data Acquisition Scheme Applied in the Present Study

Integrated data acquisition was performed through the combined use of unmanned aerial vehicle (UAV) surveys, field investigations, and existing spatial and engineering datasets. UAV-derived products included orthophotos, digital surface models (DSM), digital terrain models (DTM), and three-dimensional spatial data. Field investigations comprised soil sampling, GPS measurements, and visual site inspections, while secondary information was obtained from cadastral maps, engineering documentation, and other spatial datasets. Following quality verification, all datasets were integrated into a common spatial database and subsequently utilized for the implementation of the Strategic Topsoil Resource Management (STRM) framework, supporting comprehensive analysis and evidence-based decision-making.

Research Results

Inventory and Spatial Characteristics of the Accumulated Topsoil Stockpile

The combined analysis of unmanned aerial vehicle (UAV) survey data, field investigations, and spatial datasets enabled the comprehensive inventory of the accumulated topsoil stockpile formed during the construction of the **Akhuryan Reservoir**. The inventory established the spatial extent, distribution pattern, geometric characteristics, and current condition of the accumulated topsoil stockpile. As shown in Fig. 1, the accumulated topsoil stockpile occupies a clearly delineated area that served as the principal study object for subsequent quantitative assessment, soil quality evaluation, and implementation of the Strategic Topsoil Resource Management (STRM) framework.

Quantitative Assessment of the Accumulated Topsoil Stockpile

The quantitative assessment of the accumulated topsoil stockpile was carried out using an integrated analysis of high-resolution unmanned aerial vehicle (UAV) imagery, digital terrain models (DTM), and three-dimensional spatial data. Processing of the acquired datasets enabled the determination of the geometric characteristics of the stockpile and the calculation of its principal quantitative parameters, including occupied area, total volume, relative elevation, and spatial distribution.

The application of digital terrain modelling minimized the influence of the surrounding terrain and ensured a high level of accuracy in estimating the volume of the accumulated topsoil stockpile. These results constitute the quantitative basis for determining the actual topsoil resource available within the study area and evaluating its potential for subsequent strategic management.

The accumulated topsoil stockpile occupies an area of 25,201 m² (2.52 ha) and contains 212,532 m³ of accumulated topsoil.

The principal quantitative characteristics of the accumulated topsoil stockpile are summarized in Tab. 1, while the three-dimensional spatial representation derived from digital terrain modelling is presented in Fig. 4.

Table 1.

Principal Quantitative Characteristics of the Accumulated Topsoil Stockpile

Parameter	Unit	Value
Total stockpile area	m²	25,201
Total stockpile area	ha	2.52
Total accumulated topsoil volume	m³	212,532

Three-dimensional digital terrain model illustrating the surface morphology, geometric configuration, and elevation variability of the accumulated topsoil stockpile. The model served as the basis for quantitative estimation of the stockpile area and accumulated topsoil volume.

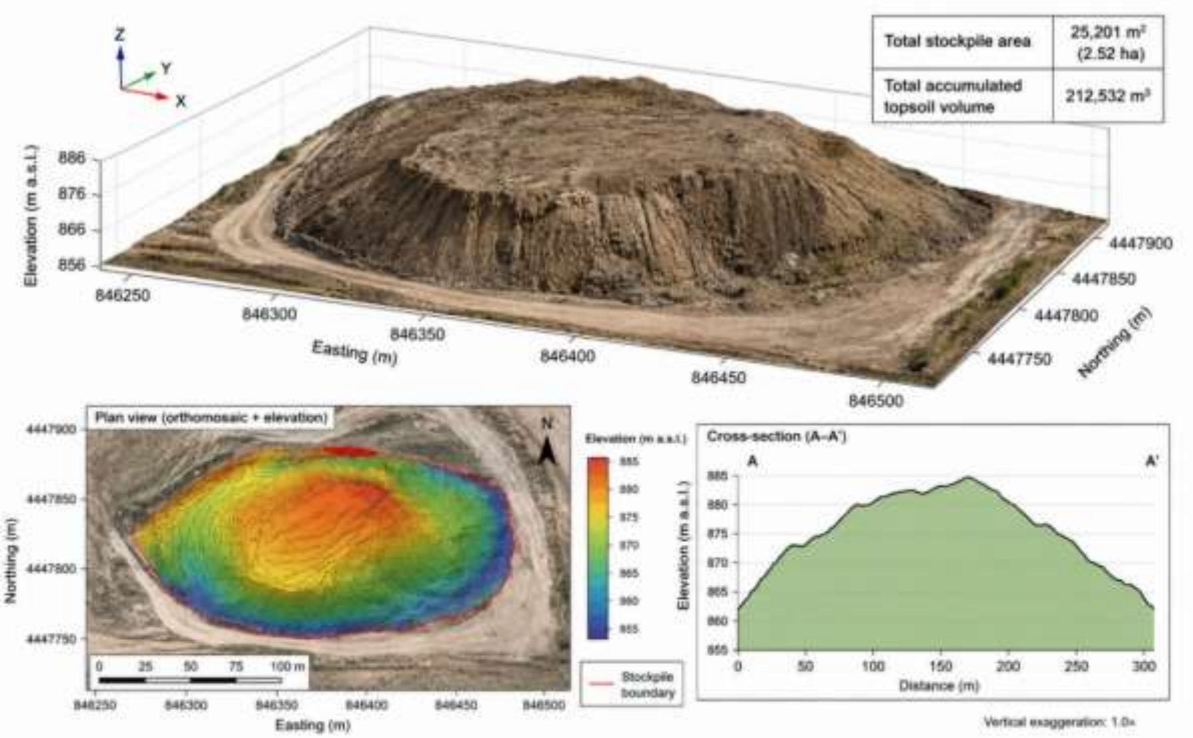

Fig. 4. Three-Dimensional Spatial Representation of the Accumulated Topsoil Stockpile

Soil Quality Assessment

The quality of the accumulated topsoil was evaluated through laboratory analysis of soil samples collected from the stockpile and from undisturbed background locations surrounding the study area. The assessment focused on the principal physicochemical properties that determine soil fertility and its suitability for future agricultural, ecological, and land restoration applications.

The laboratory analyses included determination of soil organic matter (humus), soil reaction (pH), mechanical composition, bulk density, carbonate content, and other relevant soil quality indicators. Comparative evaluation of stockpiled and background soils enabled assessment of the degree to which long-term storage affected the physical and chemical characteristics of the accumulated topsoil.

The analytical results indicate that, despite prolonged storage, the accumulated topsoil generally retained the fundamental properties required for subsequent beneficial use. Variations observed in several soil quality indicators remained within acceptable ranges and did not significantly reduce the potential suitability of the material for future reclamation, landscaping, or agricultural applications.

Table 2

Principal Soil Quality Characteristics of the Accumulated Topsoil and Background Soil

Parameter	Unit	Accumulated Topsoil	Background Soil
Number of samples	No.	12	3
Soil moisture	%	17.21	17.91
Humus content	%	3.54	4.54
Dry residue	mg/l	113.22	126.97
Soil fertility classification	–	High	High

The principal laboratory results and comparative soil quality indicators are summarized in Tab. 2**,** while the spatial distribution of the investigated sampling locations is presented in Fig. 5**.**

Comparative Analysis of Soil Quality Indicators

Comparative analysis of the laboratory results demonstrated that the accumulated topsoil generally preserved the principal physicochemical properties associated with soil fertility during long-term storage. Differences were observed between the accumulated topsoil and the undisturbed background soils; however, most of these variations remained within ranges that do not substantially limit the future utilization of the accumulated material.

The comparative evaluation of humus content, soil moisture, and other investigated soil quality indicators suggests that the observed changes primarily reflect natural physical and biochemical processes occurring during storage rather than significant degradation of the accumulated topsoil.

Interpretation of Laboratory Results

The integrated evaluation of the laboratory results indicates that, despite prolonged storage, the accumulated topsoil has largely preserved the principal properties associated with soil fertility. Although slight reductions in humus content and variations in several physicochemical indicators were observed, these changes do not indicate substantial soil degradation and remain within the range of natural variability.

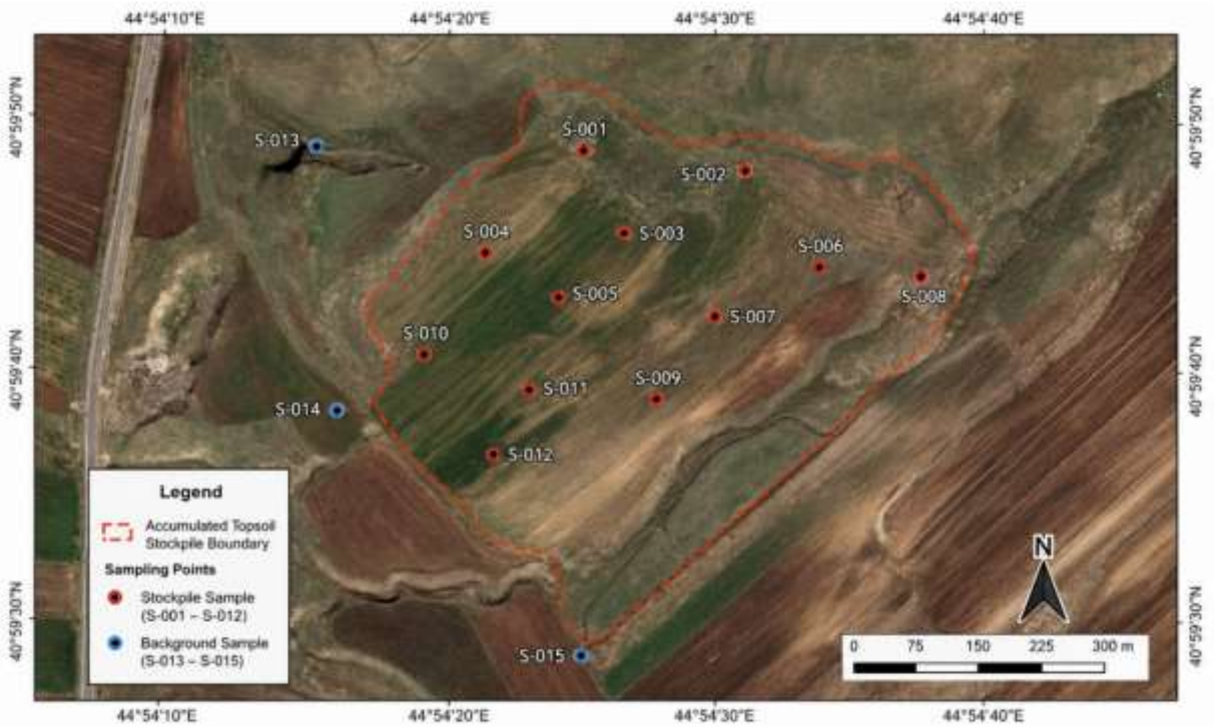

Fig. 5. Spatial Distribution of Soil Sampling Locations

Spatial distribution of soil sampling locations established for laboratory assessment of the accumulated topsoil stockpile. Twelve sampling points (S-001–S-012) were distributed throughout the stockpile to characterize its physicochemical properties, whereas three background reference samples (S-013–S-015) were collected from adjacent undisturbed soils to provide comparative baseline conditions.

Comparison with the background soils demonstrates that the accumulated topsoil continues to retain characteristics that make it suitable for subsequent beneficial utilization. The obtained results suggest that long-term stockpiling, when accompanied by appropriate storage conditions, does not necessarily result in a significant loss of soil quality or fertility.

These findings provide scientific evidence supporting the consideration of accumulated topsoil not as construction waste, but as a strategic natural resource that can be effectively utilized in land reclamation, landscape restoration, agricultural development, and other environmental management applications.

Spatial distribution of soil sampling locations established for laboratory assessment of the accumulated topsoil stockpile. Twelve sampling points (S-001–S-012) were distributed throughout the stockpile to characterize its physicochemical properties, whereas three background reference samples (S-013–S-015) were collected from adjacent undisturbed soils to provide comparative baseline conditions.

Strategic Evaluation of Accumulated Topsoil Resources

The integrated evaluation of the quantitative and qualitative results demonstrates that the accumulated topsoil investigated in the present study represents a valuable natural resource whose effective management may provide substantial environmental, economic, and social benefits. The considerable volume of accumulated topsoil together with the preservation of its principal soil fertility characteristics indicates that the material can substantially reduce the need for extracting new topsoil resources for future reclamation, landscaping, and infrastructure development projects.

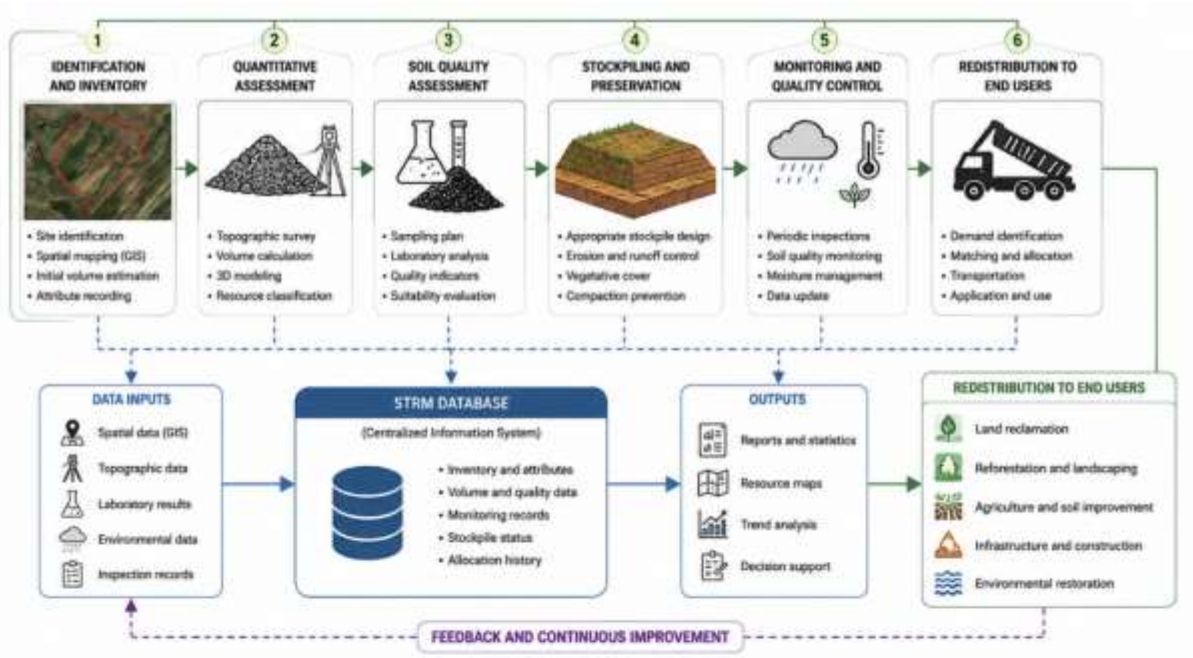

Fig. 6. Strategic Topsoil Resource Management (STRM) Framework

The framework illustrates the integrated management cycle of accumulated topsoil resources, including inventory, quantitative and qualitative assessment, preservation, monitoring, and demand-oriented redistribution to support sustainable land use and environmental restoration.

The obtained findings demonstrate that accumulated topsoil should not be regarded merely as temporarily stored material but rather as a strategic natural resource requiring long-term management. This concept is fully consistent with the proposed **Strategic Topsoil Resource Management (STRM)** framework, which emphasizes systematic inventory, continuous quality assessment, and demand-oriented redistribution of accumulated topsoil resources.

Practical Application of the STRM Framework

Strategic Topsoil Resource Management (STRM) framework developed in the present study was applied to the accumulated topsoil stockpile formed during the construction of the Akhuryan Reservoir. The application of the STRM framework enabled the integration of spatial information, quantitative assessment, laboratory analyses, and management-oriented decision-making within a unified methodological system.

Implementation of the framework provided a comprehensive inventory of the accumulated topsoil resource, quantitative estimation of its volume, evaluation of soil quality, and assessment of its potential for subsequent beneficial utilization. The integrated approach demonstrated that accumulated topsoil should be regarded not merely as material generated during construction activities but as a strategic natural resource requiring long-term management.

Application of the STRM framework further demonstrated that systematic inventory, continuous monitoring, and demand-oriented redistribution of accumulated topsoil resources can substantially improve resource utilization efficiency, reduce environmental impacts, and establish a scientifically justified system for the sustainable reuse of topsoil.

The obtained results indicate that the proposed STRM framework is applicable not only to the Akhuryan Reservoir case study but also to large-scale infrastructure, mining, transportation, and other engineering projects involving extensive earthworks and the generation of significant quantities of accumulated topsoil.

Discussion

The results of the present study demonstrate that accumulated topsoil generated during large-scale infrastructure projects should be regarded as a strategic natural resource rather than merely as temporarily stored construction material. The combined evidence obtained from quantitative assessment, laboratory soil analyses, and application of the Strategic Topsoil Resource Management (STRM) framework demonstrates that accumulated topsoil can retain its functional properties during long-term storage and can subsequently be utilized in a wide range of environmental, agricultural, and infrastructure-related applications.

Previous studies have primarily focused on topsoil stripping techniques, stockpile preservation, erosion control, or evaluation of individual soil quality parameters. In contrast, the present study proposes an integrated management framework that combines resource inventory, quantitative assessment, soil quality evaluation, continuous monitoring, demand analysis, and redistribution mechanisms within a unified Strategic Topsoil Resource Management (STRM) system.

This integrated approach enables accumulated topsoil to be considered as a form of natural capital requiring long-term management rather than as surplus construction material. Consequently, the proposed framework contributes to improved resource efficiency, reduced environmental impacts, and practical implementation of circular economy principles in large-scale engineering projects.

Advantages of the STRM Framework Compared with Existing Approaches

Most existing approaches address topsoil management as a sequence of separate activities, primarily focusing on topsoil stripping, storage, or subsequent reuse. Such approaches generally do not provide comprehensive resource inventory, long-term monitoring, or demand-oriented redistribution of accumulated topsoil resources.

In contrast, the Strategic Topsoil Resource Management (STRM) framework integrates the entire process within a unified management system. The proposed framework combines spatial inventory, quantitative assessment, soil quality evaluation, centralized database management, continuous monitoring, and end-use planning into a single decision-support framework. This integrated approach enables data-driven management decisions and promotes more efficient utilization of accumulated topsoil resources.

The principal advantage of the STRM framework lies in its transformation of the conventional perception of accumulated topsoil. Rather than considering it as temporarily stored construction material, the framework recognizes accumulated topsoil as a strategic natural resource whose value should be preserved and managed throughout its entire life cycle.

Practical Implications and Future Applications of the STRM Framework

The findings of the present study demonstrate that the proposed **Strategic Topsoil Resource Management (STRM)** framework is applicable not only to the accumulated topsoil stockpile investigated at the Akhuryan Reservoir but also to a wide range of large-scale infrastructure projects involving extensive earthworks and the generation of substantial topsoil stockpiles.

Implementation of the STRM framework enables the establishment of a centralized system for topsoil inventory and management that integrates spatial mapping, continuous quality assessment, demand evaluation, and efficient redistribution of accumulated topsoil resources among different projects. Such an approach has the potential to reduce the need for additional topsoil extraction, conserve natural soil resources, and improve the environmental sustainability of infrastructure development.

Future research should focus on digital implementation of the STRM framework, integration with Geographic Information Systems (GIS), development of national topsoil inventory databases, and the application of artificial intelligence for demand forecasting and optimized resource allocation. These developments could facilitate the establishment of next-generation topsoil management systems and promote broader implementation of circular economy principles in infrastructure development.

Conclusion

1. This study developed and applied, for the first time, the **Strategic Topsoil Resource Management (STRM)** framework for the systematic inventory, assessment, preservation, and beneficial utilization of accumulated topsoil generated during large-scale infrastructure projects.

2. Investigation of the accumulated topsoil stockpile formed during the construction of the Akhuryan Reservoir demonstrated that it occupies **25,201 m² (2.52 ha)** and contains **212,532 m³** of accumulated topsoil, indicating the formation of a substantial natural resource.

3. The integrated application of quantitative assessment, three-dimensional digital terrain modelling, and laboratory soil analyses enabled comprehensive characterization of the accumulated topsoil resource and established a reliable basis for evidence-based management.

4. Comparative soil quality assessment demonstrated that the accumulated topsoil largely preserved the principal physicochemical properties associated with soil fertility during long-term storage, confirming its suitability for future reclamation, environmental restoration, and other beneficial applications.

5. The proposed STRM framework integrates spatial inventory, quantitative assessment, soil quality evaluation, monitoring, and demand-oriented redistribution within a unified management system, representing a substantial advancement over conventional fragmented approaches.

6. The findings demonstrate that accumulated topsoil should be regarded not as a by-product of construction activities but as a strategic natural resource requiring long-term management throughout its entire life cycle.

7. The proposed STRM framework is applicable not only to reservoir construction projects but also to transportation infrastructure, mining operations, and other large-scale engineering projects, thereby supporting natural resource conservation, circular economy implementation, and environmentally sustainable infrastructure development.

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ԽՈՇՈՐ ԵՆԹԱԿԱՌՈՒՑՎԱԾՔԱՅԻՆ ԾՐԱԳՐԵՐԻ ԱՐԴՅՈՒՆՔՈՒՄ ԿՈՒՏԱԿՎԱԾ ՀՈՂԱԲՈՒՍԱԿԱՆ ՇԵՐՏԻ ՌԱԶՄԱՎԱՐԱԿԱՆ ԿԱՌԱՎԱՐՈՒՄԸ՝ ԱԽՈՒՐՅԱՆԻ ՋՐԱՄԲԱՐԻ ՕՐԻՆԱԿՈՎ

Հ.Վ. Թոքմաջյան, **Վ.Ռ. Գրիգորյան**
Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ

Խոշոր ենթակառուցվածքային ծրագրերի իրականացման ընթացքում հաճախ անհրաժեշտ է լինում հեռացնել հողի բերրի վերին շերտը: Չնայած այդ շերտը հանդիսանում է արժեքավոր բնական ռեսուրս, այն հաճախ դիտարկվում է որպես ժամանակավոր նյութ և երկար ժամանակ մնում է չօգտագործված, ինչը հանգեցնում է որակի վատթարացման և տնտեսական կորուստների: Սույն ուսումնասիրության նպատակն է գնահատել Ախուրյանի ջրամբարի կառուցման ընթացքում կուտակված հողաբուսական շերտի ծավալը, որակը և կառավարման ներուժը:

Հետազոտության շրջանակներում կիրառվել են անօդաչու թռչող սարքով իրականացված չափագրումներ, կադաստրային տվյալների վերլուծություն, հողի նմուշառում, հումուսի պարունակության լաբորատոր որոշում Տյուրինի մեթոդով, ինչպես նաև հողի պահանջարկի գնահատում: Արդյունքները ցույց են տվել, որ կուտակված հողաբուսական շերտի ծավալը կազմում է մոտ 212 532 մ³: Լաբորատոր հետազոտությունների համաձայն՝ հումուսի միջին պարունակությունը կազմել է 3.54%, ինչը համապատասխանում է բարձր որակի գյուղատնտեսական հողերին: Համեմատական վերլուծությունը բացահայտել է էական անհամապատասխանություն կուտակված պաշարների և պաշտոնապես գրանցված պահանջարկի միջև:

Հետազոտության արդյունքները ցույց են տալիս, որ հողաբուսական շերտի երկարատև պահեստավորումը կարող է հանգեցնել դրա որակի աստիճանական նվազման և գյուղատնտեսական արժեքի կորստի: Աշխատանքում առաջարկվում է ռեսուրսների ռազմավարական կառավարման մոտեցում, որի համաձայն խոշոր ենթակառուցվածքային ծրագրերի արդյունքում կուտակված հողաբուսական շերտը պետք է դիտարկվի որպես ռազմավարական բնապահպանական ռեսուրս, որը ենթակա է հաշվառման, մոնիթորինգի և վերահսկվող վերաբաշխման:

Առաջարկվող մոտեցումը կարող է նպաստել հողերի պահպանության բարելավմանը, ապօրինի հողի տեղահանման կրճատմանը և արժեքավոր հողային ռեսուրսների առավել արդյունավետ օգտագործմանը Հայաստանում և նմանատիպ խնդիրներ ունեցող այլ երկրներում:

Բանալի բառեր. հողաբուսական շերտ, սևահող, հողի պահպանություն, ենթակառուցվածքային ծրագրեր, հումուս, ռեսուրսների կառավարում, Ախուրյանի ջրամբար, Հայաստան:

СТРАТЕГИЧЕСКОЕ УПРАВЛЕНИЕ НАКОПЛЕННЫМ ПЛОДОРОДНЫМ ПОЧВЕННЫМ СЛОЕМ, ОБРАЗУЮЩИМСЯ ПРИ РЕАЛИЗАЦИИ КРУПНЫХ ИНФРАСТРУКТУРНЫХ ПРОЕКТОВ: ОПЫТ АХУРЯНСКОГО ВОДОХРАНИЛИЩА В АРМЕНИИ

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При реализации крупных инфраструктурных проектов часто возникает необходимость снятия плодородного верхнего слоя почвы. Несмотря на то, что данный слой представляет собой ценный природный ресурс, на практике он нередко рассматривается как временно изымаемый материал и длительное время остается невостребованным, что приводит к ухудшению его качественных характеристик и снижению хозяйственной ценности. Целью настоящего исследования является оценка объема, качества и потенциала управления запасами плодородного почвенного слоя, накопленного в процессе строительства Ахурянского водохранилища в Республике Армения.

В рамках исследования были использованы данные топографической съемки с применением беспилотного летательного аппарата, результаты кадастрового анализа, материалы почвенного опробования, лабораторные исследования содержания гумуса по методу Тюрина, а также сведения о существующем спросе на плодородный почвенный слой. Результаты показали, что объем накопленного почвенного материала составляет около 212 532 м³. Лабораторные исследования установили среднее содержание гумуса на уровне 3,54 %, что соответствует категории высококачественных сельскохозяйственных почв. Сравнительный анализ выявил существенный дисбаланс между объемом накопленных запасов и официально зарегистрированным спросом на плодородную почву.

Полученные результаты свидетельствуют о том, что длительное хранение плодородного почвенного слоя может приводить к постепенной деградации его свойств и снижению сельскохозяйственной ценности. В работе предлагается подход к стратегическому управлению данным ресурсом, согласно которому почвенный слой, образующийся при реализации крупных инфраструктурных проектов, должен рассматриваться как стратегический экологический ресурс, подлежащий систематическому учету, мониторингу и контролируемому перераспределению.

Предлагаемый подход может способствовать повышению эффективности охраны почв, сокращению случаев незаконного перемещения плодородного грунта и более рациональному использованию ценных земельных ресурсов как в Армении, так и в других странах, сталкивающихся с аналогичными проблемами.

***Ключевые слова*: плодородный почвенный слой; гумус; охрана почв; управление почвенными ресурсами; инфраструктурные проекты; экологические ресурсы; Ахурянское водохранилище; Армения.

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TIME CONSTRAINTS AS A RISK FACTOR IN THE DESIGN PROCESS OF WATER SUPPLY AND IRRIGATION SYSTEMS

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Abstract

The determination of design durations represents an important component of infrastructure project planning and directly influences the quality, reliability, and effectiveness of project preparation. However, concerns have increasingly emerged regarding the adequacy of design schedules specified within public procurement procedures, particularly for technically complex water infrastructure projects. This study evaluates the consistency of design durations applied in public procurement procedures for water supply and irrigation system design services in the Republic of Armenia.

The research is based on a comparative analysis of selected procurement procedures, normative design duration standards, and professionally justified design periods. In addition to direct schedule comparisons, a project complexity assessment framework was developed using technical indicators including the number of settlements served, pipeline length, water intake structures, pumping stations, regulating reservoirs, and water treatment facilities. The proposed framework was used to assess whether the design durations specified in procurement documentation were proportionate to the engineering effort required for project implementation.

The results revealed substantial discrepancies between tender-based and normative design durations. In many examined cases, design services were required to be completed within 20–30 days, whereas the corresponding normative or professionally justified durations ranged from 90 to 120 days. The observed deviations reached 75–83% in several projects. The analysis further demonstrated that projects with significantly different complexity levels were frequently assigned similar design durations, indicating that project complexity is not systematically incorporated into schedule determination.

The findings suggest that the current approach to establishing design durations does not adequately reflect the scope and complexity of engineering activities required for project preparation. The study concludes that incorporating project complexity criteria and broader application of normative duration standards could contribute to improving design quality, reducing implementation risks, and enhancing the effectiveness of public procurement procedures for water infrastructure projects.

Keywords: public procurement; design duration; project complexity; water supply systems; irrigation systems; infrastructure planning; engineering design; Armenia.

Introduction

Time is not merely an organizational resource in the engineering design process, but also a critical factor influencing the quality of design decisions and the overall performance of a project. International studies indicate that decisions made and activities undertaken during the early stages of a project have a significant impact on its subsequent development, while deficiencies at these stages may lead to cost overruns, schedule delays, and technical deviations [1,2]. At the same time, the reduction of design errors and the proper development of technical solutions are recognized as essential prerequisites for successful project implementation, since shortcomings originating during the design phase frequently result in rework, additional expenditures, and increased construction risks during later project stages [3,4].

International studies indicate that infrastructure project failures, cost overruns, and schedule delays are often attributable not only to problems arising during the construction phase, but also to inadequate assessments, design errors, and incomplete baseline data during the design and project preparation stages [5–8].

Numerous studies in the field of construction management emphasize that design errors may lead to redesign, additional work, cost increases, contractual disputes, and a decline in construction quality. As a result, the effects of deficiencies arising during the design phase often extend to subsequent stages of the project life cycle, affecting both construction performance and operational efficiency [9–12]. In this context, the time allocated for design activities should be regarded not merely as an organizational or contractual requirement, but also as an important factor influencing the quality of the design process and the development of subsequent project risks.

The design of water supply and irrigation systems is characterized by its complex and multidisciplinary engineering nature. Unlike many conventional construction projects, the design of water infrastructure involves spatially extensive linear systems, the assessment of variable topographic and hydrological conditions, the investigation of water sources, hydraulic calculations, water demand forecasting, pressure and flow distribution modeling, as well as the integrated design of pumping stations, regulating reservoirs, control facilities, and water metering systems [13–16]. In irrigation systems, additional importance is attached to the assessment of seasonal water use patterns, determination of crop water requirements, organization of water delivery regimes, accounting for water losses, and ensuring the hydraulic reliability of canals and pipelines [17–19]. The integrated solution of such multi-component engineering tasks requires adequate time resources, as each stage of the design process is based on data and calculations obtained during the preceding stages.

In recent years, GIS, EPANET, WaterGEMS, and other hydraulic modeling tools have been widely applied in the international practice of water supply and water infrastructure design, enabling engineers to evaluate network pressures, flow rates, velocities, water losses, alternative operational scenarios, and overall system reliability [20–22]. However, the effective application of these tools requires the collection of accurate baseline data, the development of network schematics, the formulation of demand scenarios, the verification of computational results, and the optimization of design solutions. Therefore, the availability of adequate time resources is an essential prerequisite not only for ensuring the completeness of design documentation, but also for supporting the reliability of hydraulic analyses and techno-economic decision-making.

In public and municipal procurement systems, the time allocated for design services is often determined not by the actual engineering and technical requirements of the design process, but rather by administrative, budgetary, or procurement-related considerations. International literature indicates that an excessive emphasis on price and the limited application of selection criteria in public procurement may negatively affect service quality, restrict professional competition, and reduce overall project performance [23–25]. For this reason, European and international procurement practices are increasingly adopting value-based procurement approaches, quality-oriented evaluation criteria, and life-cycle cost considerations, as selection based solely on the lowest initial price or short-term economic indicators does not always ensure the efficient use of public investments [23–25].

In the international literature, infrastructure project complexity is commonly regarded as a multidimensional characteristic determined by the number of technical components within a project, the degree of interconnection among these components, the diversity of engineering solutions, and the range of professional disciplines involved [30–34]. Several authors have noted that increasing project complexity is accompanied by a greater volume of design activities, increased coordination requirements, a larger number of engineering calculations, and longer design durations. Consequently, complexity assessment approaches based on the structural and technical characteristics of projects are widely applied in the evaluation of infrastructure developments [30–34].

In the design of water supply and irrigation systems, complexity is primarily determined by the configuration of the system, the number of settlements served, the extent of linear infrastructure, the presence of water intake structures, and the need to design pumping stations, regulating reservoirs, and water treatment facilities [13–22, 30-34]. Therefore, when estimating the time required for design activities, it is appropriate to consider not only project cost or financial indicators, but also the scope and interconnection of the technical components that must be developed during the design process.

Conflict Setting

Despite the extensive body of international literature addressing design errors, construction delays, cost overruns, and risks associated with infrastructure projects, relatively few studies have quantitatively evaluated the discrepancy between the actual timeframes allocated for design activities and the engineering-based durations required for their proper execution. This research gap is particularly evident in the field of water supply and irrigation systems, where the design process involves the integrated development of technical, hydraulic, geodetic, engineering-geological, and economic components.

This issue is especially relevant in countries where short implementation periods are commonly applied in public and municipal procurement of design services, while design organizations are simultaneously expected to conduct field investigations, collect baseline data, perform engineering calculations, develop design solutions, prepare cost estimates, and complete other mandatory project tasks within the same timeframe. Under such conditions, a conflict arises between the actual complexity of the design process and the time constraints imposed by procurement documentation, potentially creating additional risks for the quality of design solutions and the overall performance of infrastructure projects.

The aim of this study is to evaluate time constraints as a risk factor in the design process of water supply and irrigation systems by comparing the actual design durations specified in procurement procedures with normative or professionally justified design durations and assessing the deviations between them. The main research question addressed in this paper is the extent to which the design timeframes established in public procurement procedures correspond to the actual engineering requirements of water infrastructure design and what risks may arise under such time-constrained conditions.

Materials and Methods

The study is based on a comparative assessment of public procurement procedures conducted for the design of water supply and irrigation systems. The analysis examined projects implemented by state and municipal authorities, in which the actual design durations specified in procurement documents were compared with normative or professionally justified design durations. The research utilized procurement documentation, technical specifications, contractual requirements, and the provisions of SN RA 12-01-2022 *"Design Work Duration Standards"*, which regulates the duration of design activities in the Republic of Armenia [26].

To assess schedule deviations, the ratio between the design duration specified in the procurement documentation and the normative or professionally justified design duration was calculated for each project. This comparative assessment made it possible to determine the degree of conformity between the actual design timeframes and the real engineering requirements of the design process, as well as to identify projects characterized by elevated levels of risk.

Research Results

The analysis of public procurement procedures for water supply and irrigation system design services implemented in the Republic of Armenia revealed substantial discrepancies between the design durations specified in tender documentation and the durations justified by normative requirements or professional engineering practice. In several cases, only 20–30 days were allocated for the completion of design services, whereas the corresponding normative or professionally justified durations ranged from 90 to 120 days, depending on the scale and complexity of the project [26].

The identified discrepancies indicate that the evaluation of design schedules cannot be limited to a direct comparison between actual and normative durations. Since the engineering effort required for project implementation may vary significantly depending on project characteristics, the adequacy of design schedules should also be assessed with consideration of project technical complexity.

As the duration of the design process is directly determined by the scope and complexity of the engineering activities involved, a comparative assessment of projects requires the application of a unified design complexity criterion. Based on a review of international practice, this study proposes that project complexity should be evaluated not by the construction cost of the facility, but by the number of technical components to be developed during the design process and the degree of interconnection among them.

For the purpose of comparative project assessment, design complexity is proposed to be characterized by the following principal technical components:

1. Number of settlements served by the system;
2. Total length of transmission and distribution pipelines;
3. Presence of water intake structures;
4. Number of pumping stations;
5. Number of regulating reservoirs;
6. Presence of water treatment facilities.

These components were selected as indicators reflecting the scope and complexity of the principal engineering activities involved in the design of water supply and irrigation systems. If the design assignment includes additional engineering or technological facilities that are not covered by the above-listed components, their impact on the required design duration should be assessed separately and justified through additional calculations.

Table 1

Proposed Weighting System for Project Complexity Assessment

Complexity Component	Assigned Score	Engineering Justification
Number of settlements served	2 points per settlement	Increases field investigations, stakeholder coordination, demand assessment, and network design requirements
Pipeline length	1 point per 10 km	Increases surveying activities, hydraulic calculations, and design documentation volume
Water intake structure	5 points	Requires hydrological, hydraulic, and structural design studies
Pumping station	4 points	Requires hydraulic, structural, electrical, and mechanical design solutions
Regulating reservoir	3 points	Requires hydraulic and structural design as well as operational analysis
Water treatment facility	6 points	Represents the most technically complex component, requiring process, hydraulic, structural, electrical, and mechanical design

The weighting system presented in Table 1 was developed to provide a unified basis for the comparative assessment of project complexity. The assigned scores do not represent exact engineering labor requirements but rather reflect the relative contribution of each technical component to the overall complexity of the design process. The total project complexity score (PCS) was calculated as the sum of the scores assigned to all technical components included in a project.

$$PCS=\sum Wi$$

where: **PCS** – Project Complexity Score; $\mathbf{W_i}$ – score assigned to each technical component included in the project.

Based on the calculated PCS values, the examined projects were classified into three relative complexity categories (Tab. 2).

Table 2

Project Complexity Classification

Project Complexity Score (PCS)	Complexity Level
0–10	Low Complexity
11–20	Medium Complexity
>20	High Complexity

To provide a consistent basis for comparative assessment, the selected technical components were used as the foundation for evaluating project design complexity. This approach is not intended to determine the exact engineering effort required for each project but rather to serve as a comparative indicator of the relative complexity of different design assignments. Projects that include a larger number of interconnected technical components generally require more extensive hydraulic calculations, field investigations, development of technological solutions, engineering coordination activities, and preparation of technical documentation. Consequently, such projects require longer design periods to ensure the proper completion of all engineering tasks.

To facilitate the comparative assessment of projects with different engineering characteristics, the proposed design complexity components were subsequently used to classify the examined projects according to their relative complexity levels. This classification provided the basis for evaluating whether the design durations specified within public procurement procedures were proportionate to the engineering effort required for project implementation.

Comparative Assessment of Project Complexity

To enable the comparative assessment of projects with different technical characteristics, the selected components were used as a unified basis for evaluating design complexity. The assessment was based on the assumption that an increase in project complexity leads to a corresponding increase in the volume of engineering activities, which, in turn, requires a longer design period.

The complexity assessment considered the number of settlements served by the system, the total length of transmission and distribution pipelines, as well as the presence of major hydraulic and technological facilities included in the project. The increase in these factors results in a greater volume of field investigations, hydraulic calculations, development of technological solutions, engineering coordination activities, and preparation of design documentation.

For the purposes of comparative analysis, the examined projects were classified into three main categories:

- Low-complexity projects;
- Medium-complexity projects;

- High-complexity projects.

The classification was based on the number of technical components included in the project and the degree of interconnection among them. High-complexity projects typically involve multiple settlements, extensive pipeline systems, and various hydraulic or technological facilities, whereas low-complexity projects are generally limited to relatively simple engineering solutions.

This classification makes it possible to compare the design durations specified for different projects and to assess the extent to which they are proportional to the engineering effort required for project implementation.

The comparative assessment of the examined projects revealed substantial differences in their relative complexity levels. While some projects were limited to the design of a water supply system for a single settlement or a relatively short pipeline network, others involved multi-settlement systems, extensive transmission pipelines, water intake structures, pumping stations, regulating reservoirs, and other hydraulic facilities. Consequently, the engineering effort required for project design may vary considerably from one project to another.

However, despite the existing differences in technical complexity, the design durations specified in tender documentation were often similar or of the same order of magnitude. In several cases, high-complexity projects were assigned design periods that did not differ substantially from those established for relatively simple projects. This finding indicates that project technical complexity was not adequately considered in the determination of design schedules.

Fig. 1 and Fig. 2 present the results of the comparative assessment of design durations applied in the examined procurement procedures. The analysis demonstrates that the design periods specified in tender documentation were substantially shorter than both the normative durations and the minimum professionally justified design periods adopted in this study. In several projects, the observed deviations reached 75–83%, indicating a significant mismatch between the engineering effort required for project design and the time allocated for its completion.

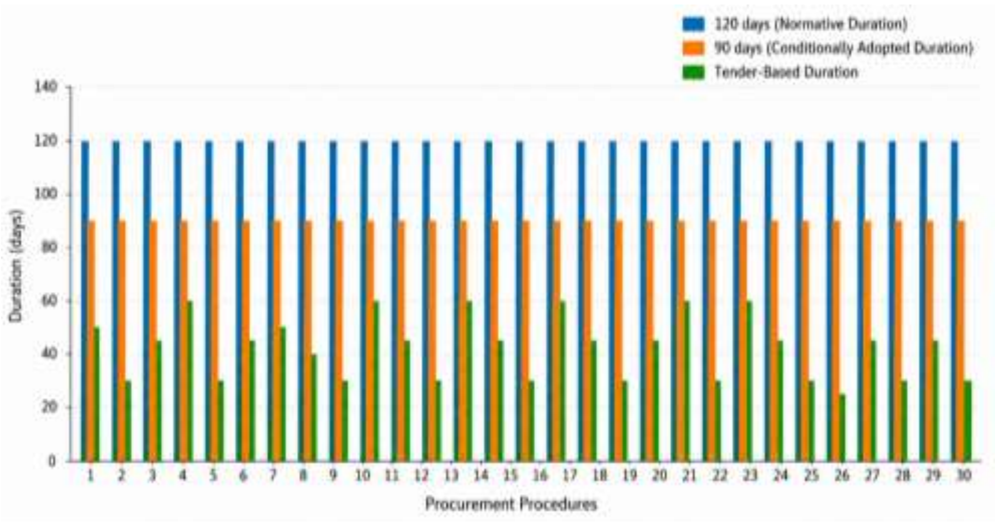

Fig. 1 Comparative Assessment of Design Durations in the Examined Procurement Procedures

Fig. 1 illustrates the design durations specified in the examined public procurement procedures compared with the minimum professionally justified design duration adopted in this study. The results demonstrate that the majority of procurement procedures allocated substantially shorter periods for design activities than those required for the proper completion of engineering investigations, calculations, and documentation. In several cases, design periods were limited to 20–30 days, despite the significantly greater effort required for project preparation.

Fig. 2 presents the percentage deviations between the design durations specified in procurement documentation and the corresponding normative or professionally justified durations. The results indicate that the observed deviations frequently exceed 50% and, in several projects, reach 75–83%. Such discrepancies suggest that the allocated design periods are often insufficient for the completion of the engineering activities required by projects of similar scale and complexity.

The largest deviations were identified in projects involving multi-settlement water supply and irrigation systems. Such projects require field investigations, geodetic surveys, hydraulic calculations, development of technological solutions, preparation of cost-estimation documentation, coordination procedures, and expert review processes, all of which demand substantial time and professional resources.

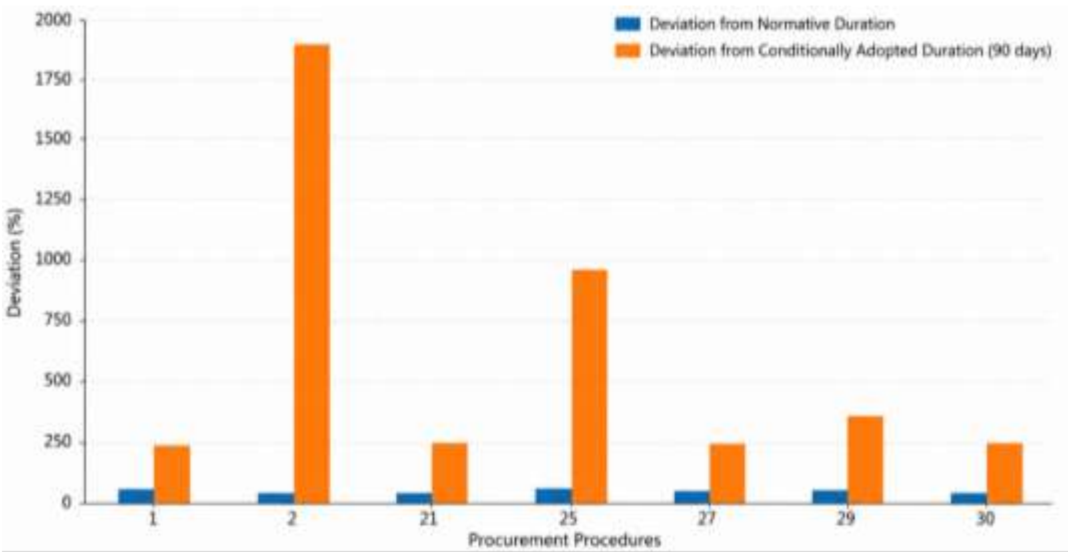

Fig. 2 Comparative Assessment of Design Duration Deviations

The results indicate that the differences between the design durations specified in tender documentation and those justified by normative requirements or professional practice represent a systemic rather than an isolated phenomenon. The findings suggest that the process of establishing design schedules does not adequately reflect project technical complexity and the engineering effort required for successful project implementation.

Discussion

The results of this study demonstrate that the design durations specified in public procurement procedures for water supply and irrigation system design services in Armenia are frequently substantially shorter than both normative requirements and professionally justified design periods. The observed deviations, which in several cases reached 75–83%, indicate that the current approach to determining design schedules does not adequately reflect the actual scope and complexity of design activities.

The findings suggest that design duration is often treated as an administrative or organizational parameter, whereas it should be directly determined by project scope and complexity. International studies on project complexity have demonstrated that complexity is one of the principal factors influencing engineering workload, planning requirements, and overall project performance [30-34]. Consequently, projects involving multiple settlements, extensive transmission pipelines, and complex hydraulic infrastructure require substantially greater design effort than relatively simple infrastructure projects.

The comparative assessment conducted in this study revealed that projects with significantly different complexity levels were frequently assigned similar design durations. This observation indicates that project complexity is not systematically incorporated into the determination of design schedules. Such an approach may create conditions in which engineering investigations, hydraulic calculations, design verification activities, and technical coordination procedures must be performed under severe time constraints.

International research has repeatedly demonstrated that deficiencies in project preparation and shortcomings during the design phase may lead to design errors, rework, quality deviations, and implementation problems during subsequent project stages [3–5, 9, 10, 12]. In construction and infrastructure projects, excessively compressed design schedules may limit opportunities for field investigations, engineering reviews, and other essential technical activities, thereby increasing technical uncertainty and the likelihood of project modifications during implementation [4, 6, 9, 10].

The results obtained in this study are also consistent with findings from the broader project management literature, according to which unrealistic planning assumptions frequently contribute to schedule-related risks, implementation difficulties, and reduced project performance [2,6, 29, 37]. Although the present study focuses specifically on design services, the identified patterns suggest that establishing design durations without adequate consideration of project complexity and engineering workload may generate similar risks in the water infrastructure sector.

From a policy perspective, the findings highlight the need for more structured and technically justified approaches to determining design durations within public procurement procedures. The incorporation of project complexity criteria into procurement planning, together with the broader application of normative duration standards, could contribute to improving the quality of design documentation and reducing implementation risks. Such measures would also be consistent with international practice, which emphasizes adequate project preparation as a prerequisite for successful infrastructure delivery [23-25].

Overall, the results suggest that improving the methodology used to determine design durations may represent an important step toward enhancing the quality, efficiency, and long-term sustainability of water infrastructure projects.

Conclusions

1. The study revealed a systemic mismatch between the design durations specified in public procurement procedures and the durations justified by normative requirements and professional engineering practice. In many cases, projects requiring extensive engineering investigations and design activities were assigned design periods significantly shorter than those considered technically reasonable.
2. The results demonstrated that project complexity is not systematically incorporated into the determination of design schedules. Projects with substantially different technical characteristics, engineering workloads, and infrastructure components were frequently assigned similar design durations, indicating the absence of a complexity-based approach to schedule determination.
3. The findings suggest that improving the methodology used to establish design durations, including the integration of project complexity criteria and wider application of normative standards, could contribute to enhancing design quality, reducing implementation risks, and improving the overall effectiveness of public procurement procedures for water infrastructure projects.

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ԺԱՄԱՆԱԿԱՅԻՆ ՍԱՀՄԱՆԱՓԱԿՈՒՄՆԵՐԸ ՈՐՊԵՍ ՋՐԱՄԱՏԱԿԱՐԱՐՄԱՆ ԵՒ ՈՌՈԳՄԱՆ ՀԱՄԱԿԱՐԳԵՐԻ ՆԱԽԱԳԾՄԱՆ ԳՈՐԾԸՆԹԱՑԻ ՌԻՍԿԱՅԻՆ ԳՈՐԾՈՆ

Է.Յու. Գալստյան

Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ

Նախագծային աշխատանքների տևողության հիմնավորված սահմանումը ենթակառուցվածքային ծրագրերի պլանավորման կարևոր բաղադրիչներից է և անմիջական ազդեցություն ունի նախագծերի նախապատրաստման որակի, հուսալիության և արդյունավետության վրա: Միաժամանակ վերջին տարիներին աճել են մտահոգությունները պետական գնումների շրջանակներում սահմանվող նախագծային ժամկետների բավարարության վերաբերյալ, հատկապես տեխնիկապես բարդ ջրային ենթակառուցվածքային նախագծերի դեպքում: Սույն հետազոտության նպատակն է գնահատել Հայաստանի Հանրապետությունում ջրամատակարարման և ոռոգման համակարգերի նախագծման ծառայությունների պետական գնումների գործընթացներում կիրառվող նախագծային ժամկետների հիմնավորվածությունը:

Հետազոտությունը հիմնված է ընտրված մրցութային ընթացակարգերի, նախագծային աշխատանքների տևողության նորմատիվների և մասնագիտական տեսանկյունից հիմնավորված նախագծային ժամկետների համեմատական վերլուծության վրա: Ժամկետների ուղղակի համեմատությունից բացի մշակվել է նախագծերի բարդության գնահատման մոտեցում, որը հիմնված է բնակավայրերի քանակի, խողովակաշարերի երկարության, ջրընդունիչ կառույցների, պոմպակայանների, կարգավորիչ ջրամբարների և ջրի մաքրման կայանների առկայության վրա: Առաջարկվող մոտեցումն օգտագործվել է գնահատելու համար, թե որքանով են մրցութային փաստաթղթերով սահմանված նախագծային ժամկետները համապատասխանում նախագծերի իրականացման համար անհրաժեշտ ինժեներական աշխատածավալին:

Արդյունքները ցույց տվեցին մրցութային և նորմատիվ նախագծային ժամկետների միջև առկա էական անհամապատասխանությունները: Ուսումնասիրված բազմաթիվ դեպքերում նախագծային աշխատանքների իրականացման համար սահմանվել են ընդամենը 20–30 օրյա ժամկետներ, մինչդեռ համապատասխան նորմատիվ կամ մասնագիտականորեն հիմնավորված տևողությունները կազմել են 90–120 օր: Առանձին նախագծերում արձանագրված շեղումները հասել են 75–83 %-ի: Վերլուծությունը նաև ցույց տվեց, որ էականորեն տարբեր բարդության մակարդակներ ունեցող նախագծերի համար հաճախ սահմանվել են նույն կամ միմյանց մոտ նախագծային ժամկետներ, ինչը վկայում է, որ նախագծերի բարդությունը համակարգված ձևով չի ներառվում ժամկետների սահմանման գործընթացում:

Ստացված արդյունքները ցույց են տալիս, որ նախագծային ժամկետների սահմանման գործող մոտեցումները բավարար չափով չեն արտացոլում նախագծերի նախապատրաստման համար անհրաժեշտ ինժեներական աշխատանքների ծավալն ու բարդությունը: Հետազոտության արդյունքները թույլ են տալիս եզրակացնել, որ նախագծերի բարդության չափանիշների ներառումը և նախագծային աշխատանքների տևողության նորմատիվների առավել լայն կիրառումը կարող են նպաստել նախագծային փաստաթղթերի որակի բարձրացմանը, ծրագրերի իրականացման ռիսկերի նվազեցմանը և ջրային ենթակառուցվածքների ոլորտում պետական գնումների արդյունավետության բարձրացմանը:

Բանալի բառեր՝ պետական գնումներ, նախագծային ժամկետ, նախագծերի բարդություն, ջրամատակարարման համակարգեր, ոռոգման համակարգեր, ենթակառուցվածքների պլանավորում, ինժեներական նախագծում, Հայաստան:

ВРЕМЕННЫЕ ОГРАНИЧЕНИЯ КАК РИСК-ФАКТОР ПРИ ПРОЕКТИРОВАНИИ СИСТЕМ ВОДОСНАБЖЕНИЯ И ОРОШЕНИЯ

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Обоснованное определение продолжительности проектных работ является важным элементом планирования инфраструктурных проектов и оказывает непосредственное влияние на качество, надежность и эффективность подготовки проектов. В последние годы все большее внимание уделяется достаточности сроков проектирования, устанавливаемых в рамках процедур государственных закупок, особенно для технически сложных объектов водохозяйственной инфраструктуры. Целью настоящего исследования является оценка обоснованности сроков проектирования, применяемых при государственных закупках услуг по проектированию систем водоснабжения и орошения в Республике Армения.

Исследование основано на сравнительном анализе отдельных процедур закупок, нормативов продолжительности проектных работ и профессионально обоснованных сроков проектирования. Помимо прямого сравнения сроков была разработана методика оценки сложности проектов, основанная на таких технических показателях, как количество обслуживаемых населенных пунктов, протяженность трубопроводов, наличие водозаборных сооружений, насосных станций, регулирующих резервуаров и водоочистных сооружений. Предложенный подход использовался для оценки соответствия сроков проектирования, установленных в закупочной документации, объему инженерных работ, необходимому для реализации проектов.

Результаты исследования выявили существенные расхождения между сроками проектирования, установленными конкурсной документацией, и нормативными либо профессионально обоснованными сроками. Во многих рассмотренных случаях на выполнение проектных работ отводилось лишь 20–30 дней, тогда как соответствующая нормативная или профессионально обоснованная продолжительность составляла от 90 до 120 дней. В ряде проектов отклонения достигали 75–83 %. Анализ также показал, что для проектов с существенно различным уровнем сложности нередко устанавливались одинаковые или близкие сроки проектирования, что свидетельствует об отсутствии систематического учета сложности проекта при определении сроков.

Полученные результаты показывают, что существующий подход к установлению сроков проектирования недостаточно отражает объем и сложность инженерных работ, необходимых для подготовки проектов. Сделан вывод о том, что включение критериев сложности проектов и более широкое применение нормативов продолжительности проектных работ могут способствовать повышению качества проектной документации, снижению рисков реализации проектов и повышению эффективности государственных закупок в сфере водохозяйственной инфраструктуры.

***Ключевые слова*:** государственные закупки; сроки проектирования; сложность проектов; системы водоснабжения; оросительные системы; инфраструктурное планирование; инженерное проектирование; Армения.

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UNIVERSAL ACCESS TO DRINKING WATER: FROM NATIONAL RESPONSIBILITY TO INTERNATIONAL SOLIDARITY

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Abstract

The Access to drinking water is increasingly recognized as one of the most important global development challenges of the twenty-first century. Although the human right to drinking water has been formally recognized by the international community, significant inequalities in drinking water accessibility continue to exist across countries and regions. Climate change, uneven distribution of freshwater resources, infrastructure limitations, financial constraints, and demographic pressures are further increasing the complexity of this challenge. This study examines the limitations of the traditional national-responsibility model for ensuring universal access to drinking water and explores the need for broader international cooperation mechanisms. Particular attention is given to the South Caucasus region and Armenia as examples of territories where long-term drinking water accessibility may be affected by environmental, infrastructural, and climatic factors. The strategic role of Lake Sevan as a potential long-term freshwater reserve is also discussed. Based on the analysis, the study proposes a new conceptual framework, the Global Drinking Water Accessibility Principle (GDWAP), which seeks to integrate national responsibility with international solidarity. The proposed principle is founded on five core pillars: sustainable water resource development, drinking water conservation and efficiency, technology transfer and knowledge sharing, international financial solidarity, and shared responsibility for universal access to drinking water. The study argues that future water policies should increasingly emphasize cooperation, long-term resource preservation, and coordinated international support mechanisms in order to improve drinking water accessibility and strengthen global water resilience.

Keywords: drinking water accessibility; water security; international solidarity; GDWAP; water governance; Lake Sevan; South Caucasus; sustainable development.

Introduction

Access to safe and sufficient drinking water is increasingly recognized as one of the most fundamental prerequisites for human well-being, public health, and sustainable development. Although water has traditionally been regarded as a natural resource and an economic good, its role extends far beyond purely economic considerations. Access to drinking water directly affects human survival, health, food security, education, economic productivity, and social stability [1,2]. The recognition of water as a fundamental human right represents one of the most significant developments in international water policy during the twenty-first century. In 2010, the United Nations General Assembly explicitly recognized the human right to safe and clean drinking water and sanitation, affirming that access to sufficient, safe, acceptable, physically accessible, and affordable water is essential for the full enjoyment of life and all human rights [3]. This position was subsequently reinforced through various international frameworks, including the Sustainable Development Goals (SDGs), particularly Goal 6, which seeks to ensure the availability and sustainable management of water and sanitation for all by 2030 [4].

Despite substantial progress in water infrastructure development, access to drinking water remains highly unequal across the world. According to recent international assessments, billions of people continue to experience periodic or permanent limitations in access to safely managed drinking water services [5]. These disparities are particularly pronounced in low-income countries, arid and semi-arid regions, small island states, and areas affected by conflict, climate change, or weak institutional capacity [6].

The growing gap between water demand and available freshwater resources has transformed drinking water from a local service-delivery issue into a matter of global concern. Climate change, population growth, urbanization, pollution, and increasing competition among water users are intensifying pressures on freshwater systems worldwide [7,8]. Consequently, ensuring universal access to drinking water can no longer be viewed solely as a national responsibility but increasingly requires international cooperation and collective action.

From this perspective, access to drinking water should be considered not only a technical or economic challenge but also an ethical, social, and global development imperative. The principle that every individual should have reliable access to sufficient drinking water regardless of geographical location or economic circumstances provides an important foundation for rethinking existing approaches to water governance and international cooperation.

Global Inequality in Access to Drinking Water

Despite the recognition of access to drinking water as a fundamental human right, the availability of safe and reliable drinking water remains highly uneven across the world. Significant disparities exist not only between developed and developing countries but also among regions within the same country. These inequalities are influenced by climatic conditions, geographical location, economic capacity, institutional effectiveness, infrastructure development, and political stability [9,10].

Sub-Saharan Africa remains one of the regions most affected by inadequate access to drinking water. Millions of people continue to rely on unimproved water sources, while rapid population growth and climate variability further increase pressure on already limited water resources [11]. Similar challenges are observed in parts of the Middle East and North Africa, where extremely low renewable water availability has led to chronic water scarcity and increasing dependence on desalination and water imports [12].

In Central Asia, growing competition among agricultural, industrial, and domestic water users has intensified concerns regarding long-term water availability. Transboundary river systems, aging infrastructure, and climate-related reductions in glacier resources are expected to increase future water stress throughout the region [13].

Small island developing states face additional challenges associated with limited freshwater resources, saltwater intrusion, and vulnerability to extreme weather events. Many such countries depend heavily on rainfall harvesting, groundwater abstraction, or costly desalination technologies to satisfy drinking water demand [14].

Recent global assessments indicate that water scarcity is no longer confined to traditionally arid regions. Climate change, population growth, urbanization, pollution, and increasing water demand are contributing to growing water stress in many parts of the world, including regions previously considered relatively water-secure [8,15].

These findings demonstrate that access to drinking water is influenced not only by natural resource availability but also by economic, technological, and institutional capacities. Consequently, the persistence of large disparities in drinking water access raises important questions regarding the adequacy of existing governance mechanisms and the distribution of responsibilities for ensuring universal access to drinking water.

Limitations of the National Responsibility Model

The prevailing approach to drinking water governance is largely based on the principle of national responsibility. Under this model, individual states are expected to develop, finance, operate, and maintain the infrastructure necessary to provide their populations with adequate drinking water services. While this approach has achieved significant successes in many countries, it also exhibits important limitations when applied to regions facing severe water scarcity, limited financial resources, or unfavorable geographical conditions [16,17].

The distribution of freshwater resources across the world is highly uneven. Some countries possess abundant renewable water resources that significantly exceed domestic demand, whereas others face chronic water deficits resulting from climatic, hydrological, and geographical constraints [18]. Consequently, the ability of governments to ensure universal access to drinking water is often influenced not only by political commitment and institutional effectiveness but also by factors beyond their direct control.

Economic disparities further complicate the situation. The construction of reservoirs, water-transfer systems, desalination facilities, treatment plants, and distribution networks often requires substantial capital investments that exceed the financial capacities of many low-income countries [19]. As a result, populations living in water-deficient regions may experience persistent limitations in access to drinking water despite the existence of internationally recognized human rights obligations.

Climate change introduces an additional layer of uncertainty. Increasing drought frequency, declining snow and glacier resources, changing precipitation patterns, and growing competition among water users are expected to intensify water stress in many regions during the coming decades [20]. Under such conditions, reliance exclusively on national resources and national financing mechanisms may prove insufficient for ensuring universal access to drinking water.

These considerations suggest that the traditional national-responsibility model, while necessary, may no longer be sufficient as the sole framework for ensuring universal access to drinking water. As water scarcity increasingly becomes a global challenge, greater international cooperation and shared responsibility mechanisms may be required to complement national efforts.

From National Responsibility to International Solidarity

The recognition of access to drinking water as a fundamental human right raises an important question regarding the distribution of responsibilities for ensuring that right. While national governments remain the primary actors responsible for providing drinking water services to their populations, the growing scale and complexity of global water challenges suggest that exclusive reliance on national efforts may no longer be sufficient in all circumstances [21,22].

The availability of drinking water is influenced by factors that frequently extend beyond national boundaries. Climate change, transboundary river systems, regional droughts, migration, economic inequalities, and technological disparities increasingly shape the capacity of countries to secure reliable water supplies for their populations [23]. Consequently, access to drinking water should not be viewed solely as a domestic policy issue but also as a matter of international concern.

The concept of international solidarity has already been applied in various fields of global development, including public health, food security, disaster response, and climate adaptation [24]. Similar principles may be relevant for addressing growing inequalities in access to drinking water. Under such an approach, countries possessing greater financial, technological, and institutional capacities could contribute to improving drinking water access in water-deficient regions through investment, technology transfer, capacity building, and infrastructure support.

Importantly, international solidarity does not imply replacing national responsibility. Rather, it represents a complementary mechanism designed to assist countries facing structural constraints that cannot be overcome solely through domestic efforts. In this context, the objective is not the redistribution of water resources themselves, but the strengthening of global capacities to ensure universal access to drinking water.

Based on the above considerations, this study proposes a new conceptual framework, termed the **Global Drinking Water Accessibility Principle (GDWAP)**, aimed at strengthening universal access to drinking water through the integration of national responsibility and international solidarity mechanisms.

Conflict Setting

Despite the international recognition of access to drinking water as a fundamental human right, hundreds of millions of people continue to experience inadequate or unreliable access to drinking water. At the same time, the natural distribution of freshwater resources, financial capacities, technological capabilities, and institutional effectiveness remain highly uneven across countries and regions. As a result, the ability to ensure universal access to drinking water is often determined not only by national efforts but also by factors beyond the control of individual states.

This situation creates a fundamental contradiction between the universal nature of the right to drinking water and the predominantly national mechanisms currently responsible for its implementation. The present study addresses this contradiction by exploring whether the traditional national-responsibility model remains sufficient under conditions of increasing global water stress and by proposing a conceptual framework based on international solidarity and shared responsibility for improving universal access to drinking water.

Research Results

Drinking Water Accessibility Challenges in the South Caucasus

The South Caucasus is characterized by significant geographical, climatic, and hydrological diversity. Although the region possesses considerable freshwater resources compared with many arid parts of the world, access to reliable drinking water remains uneven across countries and communities. The growing impacts of climate change, demographic pressures, and infrastructure limitations increasingly challenge the long-term sustainability of drinking water supply systems throughout the region.

Mountainous regions generally receive higher levels of precipitation and generate most of the surface runoff, while many lowland and densely populated areas depend on complex water-supply systems and long-distance water transfers. Consequently, the physical presence of water resources does not always guarantee reliable access to drinking water for local populations, particularly during dry periods and years characterized by hydrological extremes.

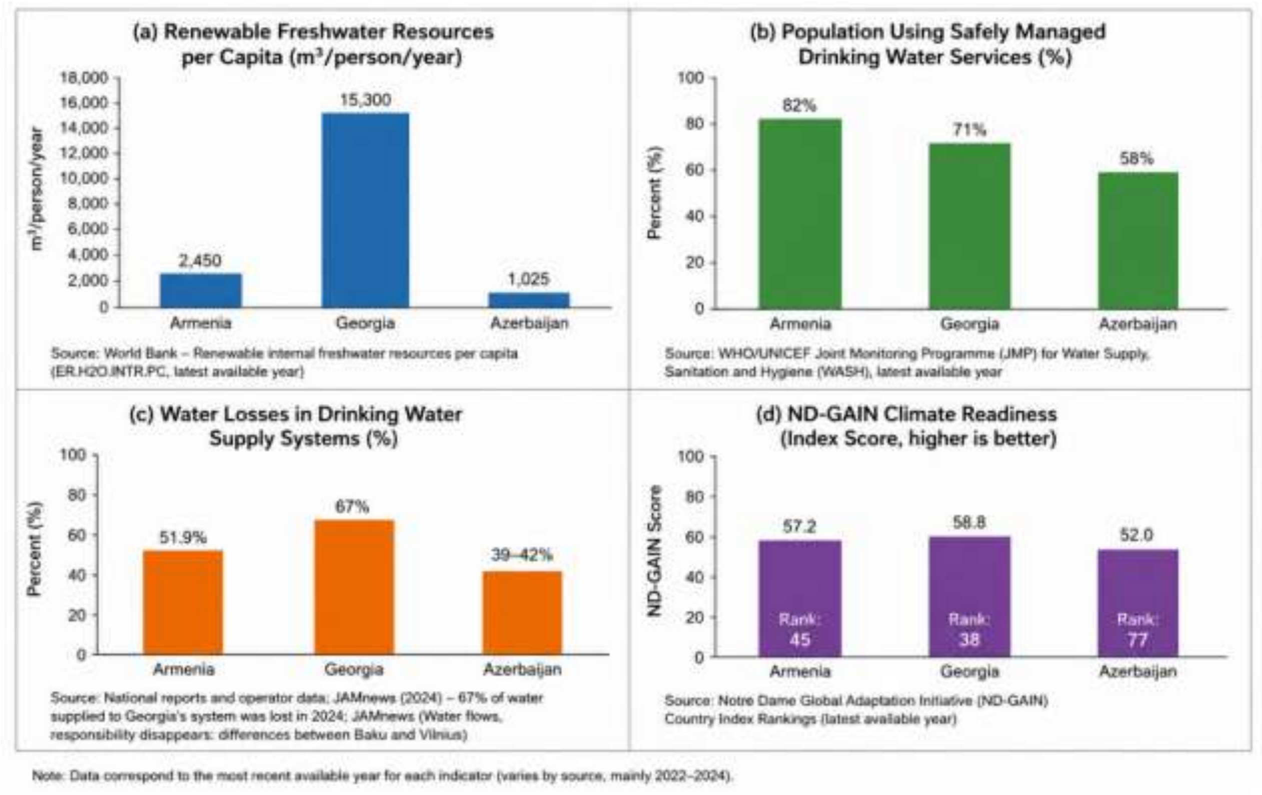

Fig 1. Comparative Indicators of Drinking Water Accessibility in the South Caucasus

Climate change is expected to become one of the most significant drivers of future drinking water challenges in the South Caucasus. Rising temperatures, changing precipitation patterns, increasing drought frequency, and the gradual reduction of snow and glacier resources may alter the hydrological regimes of many river basins. These processes are likely to increase seasonal variability in water availability and reduce the reliability of traditional drinking water sources in several parts of the region.

In addition to natural and climatic factors, the region faces significant infrastructure-related challenges. Many water-supply systems were constructed decades ago and now operate with varying degrees of physical deterioration. Water losses, insufficient investment in maintenance and modernization, and limited financial resources in certain areas reduce the overall efficiency of drinking water supply systems and increase vulnerability to future water shortages.

Another important challenge arises from the transboundary nature of many water resources within the South Caucasus. Major rivers and watersheds frequently cross national borders, creating interdependencies among countries and increasing the importance of regional cooperation in water-resource management. Under conditions of growing water demand and climate uncertainty, effective coordination among neighboring countries may become increasingly important for maintaining long-term drinking water accessibility and regional water stability.

Taken together, these factors demonstrate that future drinking water accessibility in the South Caucasus cannot be evaluated solely on the basis of available water volumes. Equal attention must be given to climate resilience, infrastructure reliability, water-management efficiency, and long-term strategic planning. Consequently, the region provides an important example of how drinking water accessibility is increasingly becoming a multidimensional challenge that requires integrated solutions extending beyond traditional water-resource assessments.

The Fig. 1 illustrates substantial differences in renewable freshwater resource availability among the South Caucasus countries. Georgia possesses significantly higher per-capita freshwater resources than Armenia and Azerbaijan, highlighting the unequal natural distribution of water resources within the region.

The comparison reveals that water availability alone does not determine drinking water accessibility. Georgia possesses the highest renewable freshwater resources per capita in the region, yet experiences the highest water losses and does not demonstrate the highest level of safely managed drinking water services. Conversely, Armenia achieves the highest drinking water accessibility despite significantly lower per-capita water resources. These findings indicate that infrastructure performance and management efficiency play a critical role in determining actual drinking water accessibility.

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Armenia as a Case of Emerging Drinking Water Accessibility Challenges

Armenia is often regarded as a country relatively rich in freshwater resources due to its extensive river network, numerous springs, groundwater reserves, and the presence of Lake Sevan, one of the largest high-mountain freshwater lakes in the world. Nevertheless, the availability of water resources at the national scale does not automatically guarantee equal and reliable access to drinking water across all regions of the country. Significant differences in geographical conditions, settlement patterns, infrastructure quality, and local water availability continue to influence drinking water accessibility in many communities.

At the same time, Armenia faces a number of challenges that may affect the long-term sustainability of drinking water supply. Population decline in some rural areas, continued migration toward urban centers, aging infrastructure, and increasing climate variability create new pressures on existing water-management systems. In addition, the unequal spatial distribution of water resources means that certain communities experience periodic difficulties in securing reliable drinking water supplies despite the country's overall water-resource potential.

Water losses within drinking water supply systems remain another important concern. Although considerable improvements have been achieved in recent decades, physical losses, leakage from aging networks, and operational inefficiencies continue to reduce the effective availability of drinking water in certain areas. Consequently, improving infrastructure performance may in some cases provide benefits comparable to the development of new water sources, while requiring significantly lower environmental impacts and financial investments.

Climate change introduces an additional dimension of uncertainty for the future of drinking water accessibility in Armenia. Rising temperatures, changes in precipitation patterns, increasing evaporation rates, and potential reductions in snow accumulation may alter the seasonal distribution of water resources. Under such conditions, ensuring long-term drinking water accessibility will increasingly depend not only on the availability of water resources but also on the capacity to store, manage, and utilize those resources efficiently and sustainably.

These circumstances highlight the importance of adopting a long-term strategic perspective toward drinking water security in Armenia. Rather than focusing exclusively on current water demand, future planning should consider the potential impacts of climate change, demographic shifts, infrastructure aging, and increasing variability in water availability. In this context, the protection and sustainable management of strategic water reserves become increasingly important components of national water policy.

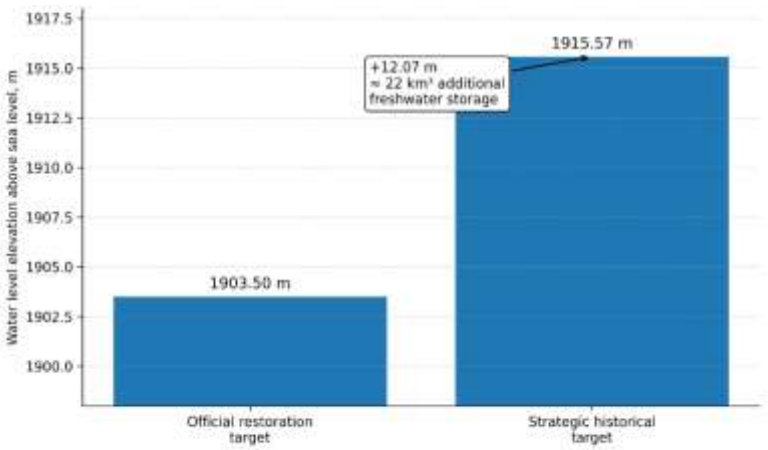
Lake Sevan as a Strategic Drinking Water Reserve for the Future

Lake Sevan occupies a unique position within the water-resource system of Armenia and the South Caucasus. As one of the largest high-mountain freshwater lakes in the world, it represents not only an important ecological and economic asset but also a strategic reserve of freshwater with potential significance for future drinking water security. In the context of increasing climate uncertainty and growing pressure on water resources, the long-term value of Lake Sevan is likely to increase substantially.

Historically, Lake Sevan has played a critical role in Armenia's water management, supporting hydropower generation, irrigation, fisheries, recreation, and ecosystem services. However, future water challenges may require a broader strategic perspective. As climate change increases the frequency of droughts and intensifies pressure on conventional water sources, the role of large freshwater storage systems is expected to become increasingly important for ensuring reliable drinking water accessibility.

From a long-term perspective, Lake Sevan may be viewed not only as a national water resource but also as a strategic freshwater reserve whose significance could extend beyond present-day economic functions. The preservation of its water quantity and quality should therefore be regarded as an investment in future water security. Water resources that are available today may become substantially more valuable under future climatic and demographic conditions, particularly in regions where alternative drinking water sources are limited or increasingly vulnerable.

Historically, the long-term restoration target for Lake Sevan has been established at 1903.5 m above sea level. However, previous scientific studies have suggested that the historical lake level of 1915.57 m above sea level should be considered as a long-term strategic objective [26].



According to these assessments, achieving this level could create approximately 22 km³ of additional freshwater storage. Such a reserve would substantially strengthen Armenia's long-term drinking-water security and significantly increase the strategic value of Lake Sevan within the South Caucasus region.

Fig. 2 Existing and Proposed Strategic Water Levels of Lake Sevan and Additional Freshwater Storage Potential

The comparison presented in Figure 2 demonstrates that the strategic importance of Lake Sevan extends beyond its current ecological and economic functions. The potential increase of approximately 22 km³ in freshwater storage highlights the considerable reserve capacity that could be available under a long-term water-security perspective. In an era characterized by increasing climate uncertainty, growing water demand, and rising pressure on conventional water sources, such large-scale freshwater reserves may acquire exceptional strategic significance. Consequently, the future management of Lake Sevan should be evaluated not only from the perspective of present-day water use but also in terms of its potential contribution to long-term drinking water accessibility and regional water resilience.

An equally important consideration is that the strategic value of Lake Sevan is determined not only by the volume of stored water but also by the possibility of preserving that resource for future generations. In a world where access to reliable drinking water is becoming increasingly uncertain, the protection of major freshwater reserves should be viewed as a long-term public investment rather than solely as a matter of current resource utilization. This perspective emphasizes the importance of balancing present-day water demands with the responsibility to maintain strategic reserves capable of supporting future societal needs.

The case of Lake Sevan illustrates a broader principle that may become increasingly relevant in the twenty-first century: water resources should be evaluated not only according to their current economic use but also according to their potential contribution to future drinking water accessibility. As uncertainty regarding future water availability increases, the strategic preservation of major freshwater reserves may become an essential component of long-term water-security planning. This perspective provides an important link between national water-management policies and the broader concept of international responsibility for ensuring universal access to drinking water. Beyond its national importance, Lake Sevan may also be considered within a broader regional context. The South Caucasus is expected to experience increasing pressure on water resources as a result of climate change, economic development, and demographic transformations. Under such conditions, large freshwater reserves acquire strategic significance that extends beyond administrative and sectoral boundaries. Consequently, the long-term protection and sustainable management of Lake Sevan should be regarded not only as a national priority but also as a contribution to regional water resilience and future drinking water accessibility.

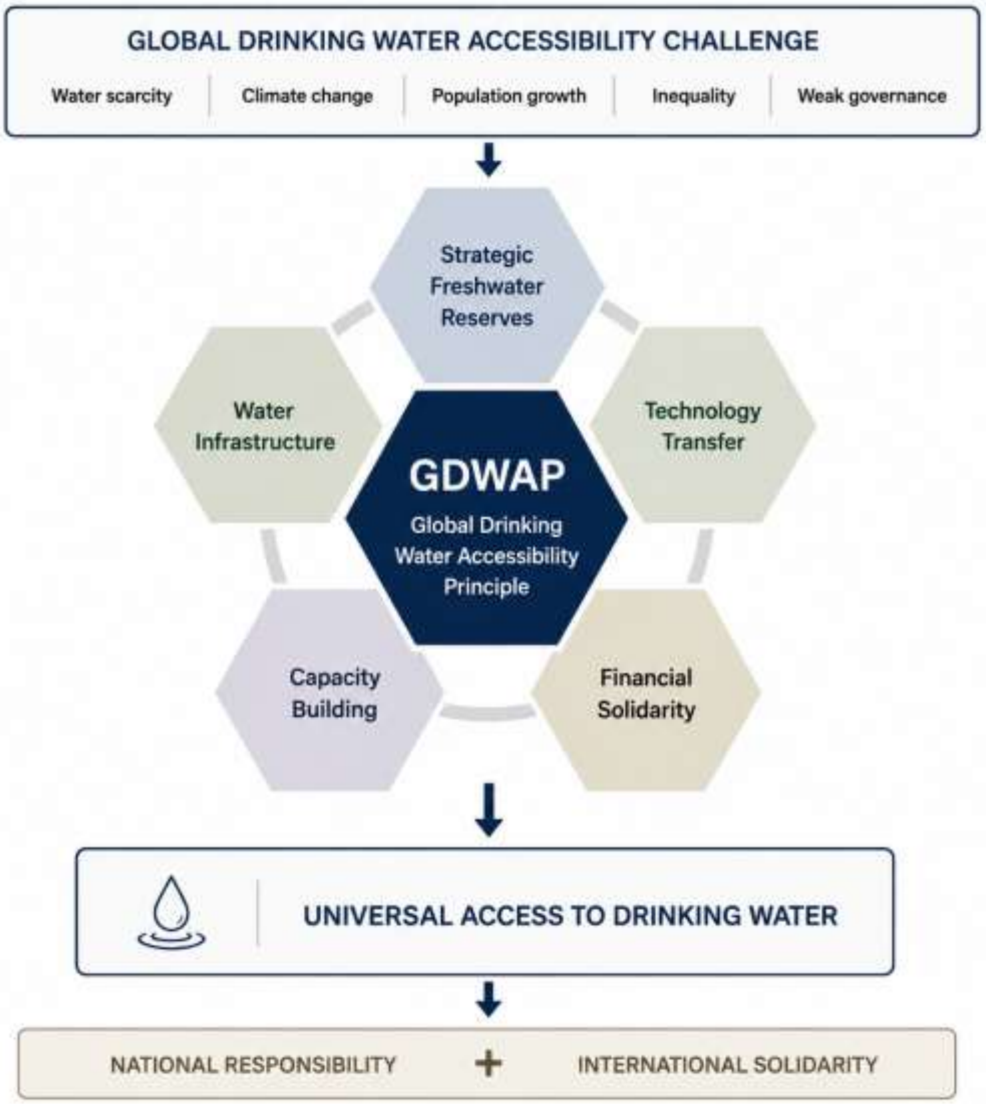


Fig. 3 Conceptual Framework of the Global Drinking Water Accessibility Principle (GDWAP)

The case of Lake Sevan illustrates a broader principle that may become increasingly relevant in the twenty-first century: water resources should be evaluated not only according to their current economic use but also according to their potential contribution to future drinking water accessibility. As uncertainty regarding future water availability increases, the strategic preservation of major freshwater reserves may become an essential component of long-term water-security planning. This perspective provides an important link between national water-management policies and the broader concept of international responsibility for ensuring universal access to drinking water. The analysis conducted in this study indicates that the growing disparity between the universal recognition of the human right to drinking water and the unequal capacity of countries to ensure that right requires a new conceptual approach. Existing governance mechanisms remain predominantly based on national responsibility, whereas many of the factors influencing drinking water availability, affordability, and reliability increasingly operate at regional and global scales.

Based on the findings presented above, this study proposes the Global Drinking Water Accessibility Principle (GDWAP) as a conceptual framework intended to complement existing national approaches. The proposed principle is founded on the premise that universal access to drinking water should be regarded not only as a national obligation but also as a shared international responsibility. Under this approach, countries retain primary responsibility for managing and developing their own water resources, while the international community contributes through cooperation, financing, technology transfer, capacity building, and support for sustainable water infrastructure development.

The proposed principle seeks to establish a balance between national sovereignty over water resources and international solidarity in ensuring universal access to drinking water. Rather than promoting the redistribution of water resources themselves, GDWAP emphasizes the redistribution of opportunities, knowledge, technologies, and financial capacities necessary to improve drinking water accessibility in water-deficient regions.

Relationship Between GDWAP and Existing International Frameworks.

The proposed Global Drinking Water Accessibility Principle (GDWAP) is intended to complement rather than replace existing international water and development frameworks. The principle is fully consistent with the human right to drinking water recognized by the United Nations, Sustainable Development Goal 6 (Clean Water and Sanitation), and ongoing international efforts aimed at improving water security and sustainable water management.

GDWAP expands these existing approaches by emphasizing the role of international solidarity in addressing persistent inequalities in drinking water accessibility. While current frameworks primarily define objectives and responsibilities, GDWAP highlights the need for enhanced cooperation, technology transfer, financial support, and capacity-building mechanisms to help achieve universal access to drinking water.

Consequently, the proposed principle should be viewed as a complementary framework that strengthens and supports existing international initiatives rather than creating a parallel governance structure.

Core Pillars of the Global Drinking Water Accessibility Principle (GDWAP)

The proposed Global Drinking Water Accessibility Principle (GDWAP) is based on five interconnected pillars intended to strengthen universal access to drinking water through cooperation between national governments, international organizations, development institutions, and the private sector.

Pillar 1 – Sustainable Water Resource Development.

Countries should promote the sustainable development of available drinking water resources, including groundwater, springs, rivers, reservoirs, rainwater harvesting systems, desalination technologies, and water reuse where appropriate.

Pillar 2 – Drinking Water Conservation and Efficiency.

Reducing physical water losses, improving operational efficiency, promoting water-saving technologies, and encouraging responsible water consumption are essential components of long-term accessibility.

Pillar 3 – Technology Transfer and Knowledge Sharing.

Access to modern water-treatment technologies, monitoring systems, digital management tools, and engineering expertise should be expanded through international cooperation mechanisms.

Pillar 4 – International Financial Solidarity.

Water-deficient regions frequently face financial constraints that limit infrastructure development. International financing mechanisms, development assistance programs, and public-private partnerships can contribute to improving drinking water accessibility.

Pillar 5 – Shared Responsibility for Universal Access.

While national governments retain primary responsibility for drinking water provision, the international community shares a collective responsibility to support efforts aimed at ensuring universal access to drinking water, particularly in regions facing structural water scarcity and limited development capacity.

Together, these pillars establish a framework that integrates local action with international cooperation and provides a foundation for improving global drinking water accessibility in a sustainable and equitable manner.

Implementation Mechanisms of GDWAP

The effectiveness of the proposed Global Drinking Water Accessibility Principle (GDWAP) depends on the establishment of practical implementation mechanisms capable of translating international solidarity into measurable improvements in drinking water accessibility. The principle is intended to complement existing national water-management systems rather than replace them. Accordingly, implementation should occur through coordinated actions at local, national, regional, and international levels.

One of the primary implementation mechanisms involves the development of sustainable water-storage infrastructure. In regions experiencing seasonal water availability, the construction of reservoirs, rainwater harvesting systems, managed aquifer recharge projects, and other storage facilities can significantly improve long-term drinking water accessibility. Water that is available during wet periods should be conserved and strategically managed to support populations during periods of scarcity.

A second mechanism concerns the reduction of water losses and the improvement of water-use efficiency. In many countries, substantial volumes of treated drinking water are lost through aging distribution systems, leakage, and inadequate management practices. Investments in modern monitoring technologies, digital water-management systems, leakage control programs, and infrastructure rehabilitation can substantially increase effective water availability without requiring the development of additional water sources.

Technology transfer represents another important implementation pathway. Advanced treatment technologies, desalination systems, smart monitoring tools, water-quality management systems, and engineering expertise are often concentrated in a relatively small number of countries. International cooperation can facilitate the transfer of such technologies and knowledge to regions facing water scarcity and limited technical capacity.

Financial cooperation constitutes a further essential component of GDWAP implementation. International financial institutions, development banks, donor organizations, climate-finance mechanisms, and public-private partnerships can support the construction of critical drinking water infrastructure in regions where national resources are insufficient. Such investments should be viewed not only as development assistance but also as contributions to global stability, public health, and sustainable development.

Finally, the implementation of GDWAP requires strengthened international cooperation and governance. Existing global initiatives related to water, climate adaptation, sustainable development, and disaster-risk reduction provide a foundation upon which more coordinated efforts to improve universal access to drinking water can be developed. In this context, international solidarity becomes a practical instrument for addressing one of the most important challenges of the twenty-first century.

Potential Benefits and Challenges of GDWAP

The proposed Global Drinking Water Accessibility Principle (GDWAP) offers several potential advantages for improving universal access to drinking water. First, it expands the traditional understanding of responsibility for drinking water provision by recognizing that global water challenges increasingly require cooperative solutions. Second, it creates opportunities for strengthening international partnerships aimed at improving water infrastructure, technological capacity, and institutional development in water-deficient regions. Third, it encourages a more efficient use of global financial and technological resources by directing support toward areas where drinking water accessibility remains critically limited.

Another important benefit of the proposed principle is its compatibility with existing international development frameworks. The objectives of GDWAP are consistent with the Sustainable Development Goals, climate adaptation strategies, public-health initiatives, and international efforts to reduce poverty and inequality. Consequently, the principle can complement rather than compete with existing global development agendas.

At the same time, several challenges should be acknowledged. Differences in national priorities, financial capacities, political interests, and governance systems may complicate the implementation of international solidarity mechanisms. In addition, questions may arise regarding the allocation of financial responsibilities, the measurement of effectiveness, and the coordination of international support programs.

Another challenge concerns the balance between national sovereignty and international cooperation. While countries retain sovereign rights over their water resources, effective implementation of GDWAP requires the recognition that universal access to drinking water represents a broader humanitarian and developmental objective extending beyond national boundaries.

Despite these challenges, the increasing global importance of drinking water accessibility suggests that the development of cooperative mechanisms may become an essential component of future water governance. In this context, GDWAP should be viewed as a conceptual framework intended to stimulate discussion and encourage the development of practical approaches for improving universal access to drinking water.

Conclusions

1. Access to drinking water has evolved from a purely technical and infrastructure-related issue into a global development challenge closely linked to public health, social stability, economic growth, and human well-being.
2. Despite the international recognition of access to drinking water as a fundamental human right, significant inequalities in drinking water accessibility persist across countries and regions due to differences in natural water availability, economic capacity, technological development, and institutional effectiveness.
3. The analysis indicates that the traditional national-responsibility model remains necessary but is increasingly insufficient as the sole mechanism for ensuring universal access to drinking water under conditions of growing water scarcity, climate change, and global interdependence.
4. The study demonstrates that many factors influencing drinking water accessibility, including climate variability, transboundary water systems, technological disparities, and financial constraints, extend beyond national boundaries and require cooperative responses.
5. To address these challenges, this study proposes the Global Drinking Water Accessibility Principle (GDWAP), a conceptual framework that combines national responsibility with international solidarity in support of universal access to drinking water.
6. The proposed principle is based on five core pillars: sustainable water resource development, drinking water conservation and efficiency, technology transfer and knowledge sharing, international financial solidarity, and shared responsibility for universal access to drinking water.
7. Future international water policies should increasingly emphasize cooperation, capacity building, sustainable infrastructure development, and coordinated financing mechanisms in order to improve drinking water accessibility and support long-term global water resilience.
8. The proposed Global Drinking Water Accessibility Principle (GDWAP) should be viewed as an initial conceptual step toward a broader framework of international water solidarity. Future research should focus on developing the theoretical foundations of water solidarity, capacity-based international responsibility, governance mechanisms, and implementation pathways capable of strengthening universal access to drinking water at the global level.

Recommendations

1. Promote recognition of universal access to drinking water as a shared international responsibility in addition to a national obligation.
2. Strengthen international financing mechanisms for drinking water infrastructure development in water-deficient regions.
3. Expand technology-transfer programs and professional capacity-building initiatives in the water sector.
4. Encourage investments in water-storage infrastructure, water-loss reduction, and efficient water-use technologies.
5. Support further research aimed at developing quantitative indicators, assessment methodologies, financing models, and practical implementation tools for the Global Drinking Water Accessibility Principle (GDWAP).

6. Promote comparative studies evaluating the role of strategic freshwater reserves, including major lakes and reservoirs, in strengthening long-term drinking water accessibility under climate-change conditions.

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ԽՄԵԼՈՒ ՋՐԻ ՀԱՄԸՆԴՀԱՆՈՒՐ ՀԱՍԱՆԵԼԻՈՒԹՅՈՒՆ. ԱԶԳԱՅԻՆ ՊԱՏԱՍԽԱՆԱՏՎՈՒԹՅՈՒՆԻՑ ԴԵՊԻ ՄԻՋԱԶԳԱՅԻՆ ՀԱՄԵՐԱՇԽՈՒԹՅՈՒՆ

Ա.Կ. Հարությունյան

Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ

Խմելու ջրի հասանելիությունը 21-րդ դարի կարևորագույն համաշխարհային զարգացման մարտահրավերներից մեկն է: Չնայած խմելու ջրի իրավունքը միջազգային մակարդակով ճանաչվել է որպես մարդու հիմնարար իրավունք, աշխարհի տարբեր երկրներում և տարածաշրջաններում շարունակում են պահպանվել խմելու ջրի հասանելիության զգալի անհավասարություններ: Կլիմայական փոփոխությունները, քաղցրահամ ջրային ռեսուրսների անհավասար բաշխվածությունը, ենթակառուցվածքային սահմանափակումները, ֆինանսական դժվարությունները և ժողովրդագրական ճնշումները լրացուցիչ բարդացնում են իրավիճակը: Սույն

հետազոտությունը վերլուծում է խմելու ջրի համընդհանուր հասանելիության ապահովման ազգային պատասխանատվության ավանդական մոդելի սահմանափակումները և ուսումնասիրում ավելի լայն միջազգային համագործակցության անհրաժեշտությունը: Առանձնահատուկ ուշադրություն է դարձվում Հարավային Կովկասին և Հայաստանին՝ որպես այնպիսի տարածաշրջանների օրինակների, որտեղ խմելու ջրի երկարաժամկետ հասանելիությունը կարող է ազդվել բնապահպանական, ենթակառուցվածքային և կլիմայական գործոններից: Քննարկվում է նաև Սևանա լճի ռազմավարական դերը որպես ապագայի քաղցրահամ ջրի կարևոր պաշար: Վերլուծության հիման վրա առաջարկվում է նոր հայեցակարգային մոտեցում՝ Խմելու ջրի համաշխարհային հասանելիության սկզբունքը (Global Drinking Water Accessibility Principle – GDWAP), որը նպատակ ունի համադրել ազգային պատասխանատվությունն ու միջազգային համերաշխությունը:

Առաջարկվող սկզբունքը հիմնված է հինգ հիմնական հենասյուների վրա՝ ջրային ռեսուրսների կայուն զարգացում, խմելու ջրի խնայող և արդյունավետ օգտագործում, տեխնոլոգիաների և գիտելիքների փոխանցում, միջազգային ֆինանսական համերաշխություն և խմելու ջրի համընդհանուր հասանելիության ապահովման համատեղ պատասխանատվություն:

Հետազոտությամբ հիմնավորում է, որ ապագա ջրային քաղաքականությունները պետք է առավել մեծ ուշադրություն դարձնեն համագործակցությանը, ռազմավարական ջրային պաշարների պահպանությանը և համակարգված միջազգային աջակցության մեխանիզմներին՝ խմելու ջրի հասանելիության բարելավման և համաշխարհային ջրային կայունության ամրապնդման նպատակով:

Բանալի բառեր՝ խմելու ջրի հասանելիություն, ջրային անվտանգություն, միջազգային համերաշխություն, GDWAP, ջրային կառավարում, Սևանա լիճ, Հարավային Կովկաս, կայուն զարգացում:

ВСЕОБЩАЯ ДОСТУПНОСТЬ ПИТЬЕВОЙ ВОДЫ: ОТ НАЦИОНАЛЬНОЙ ОТВЕТСТВЕННОСТИ К МЕЖДУНАРОДНОЙ СОЛИДАРНОСТИ

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Доступ к питьевой воде всё чаще рассматривается как один из важнейших глобальных вызовов развития XXI века. Несмотря на то, что право человека на питьевую воду официально признано международным сообществом, существенные различия в доступности питьевой воды по-прежнему сохраняются между странами и регионами. Изменение климата, неравномерное распределение пресноводных ресурсов, ограничения инфраструктуры, финансовые трудности и демографическое давление дополнительно усложняют решение данной проблемы.

В настоящем исследовании рассматриваются ограничения традиционной модели национальной ответственности за обеспечение всеобщего доступа к питьевой воде и обосновывается необходимость более широких механизмов международного сотрудничества. Особое внимание уделяется региону Южного Кавказа и Армении как примерам территорий, где долгосрочная доступность питьевой воды может оказаться под воздействием экологических, инфраструктурных и климатических факторов. Также анализируется стратегическая роль озера Севан как потенциального долгосрочного резерва пресной воды.

На основе проведённого анализа предлагается новая концептуальная модель — Принцип глобальной доступности питьевой воды (Global Drinking Water Accessibility Principle, GDWAP**),** направленная на интеграцию национальной ответственности и международной солидарности. Предлагаемый принцип основывается на пяти ключевых направлениях: устойчивое развитие водных ресурсов, сохранение и эффективное использование питьевой воды, передача технологий и обмен знаниями, международная финансовая солидарность, а также совместная ответственность за обеспечение всеобщего доступа к питьевой воде.

В исследовании утверждается, что будущая водная политика должна в большей степени ориентироваться на сотрудничество, долгосрочное сохранение водных ресурсов и координированные механизмы международной поддержки, направленные на повышение доступности питьевой воды и укрепление глобальной водной устойчивости.

***Ключевые слова*:** доступность питьевой воды; водная безопасность; международная солидарность; GDWAP; управление водными ресурсами; озеро Севан; Южный Кавказ; устойчивое развитие.

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ECONOMIC AND INSTITUTIONAL MECHANISMS FOR ENVIRONMENTAL RISK MANAGEMENT OF TAILINGS STORAGE FACILITIES

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Abstract

Tailings storage facilities (TSFs) are among the most hazardous anthropogenic structures associated with the mining industry due to their potential long-term impacts on surface water, groundwater, soil resources, ecosystems, and public health. Despite significant technological advances in the design, construction, and operation of tailings facilities, numerous environmental accidents continue to occur worldwide, demonstrating that engineering solutions alone are insufficient without effective economic and institutional management mechanisms. The objective of this study is to analyze the economic and institutional instruments used for environmental risk management of tailings storage facilities, evaluate their effectiveness, and identify opportunities for improving environmental safety. Particular attention is given to the application of the Polluter Pays Principle and the User Pays Principle, environmental charges and penalties, financial assurance mechanisms, as well as monitoring and regulatory control systems. The analysis indicates that the safe and sustainable operation of tailings facilities requires the integration of engineering, economic, and governance measures within a comprehensive risk management framework. The study concludes that strengthening financial accountability, improving environmental monitoring systems, and enhancing institutional oversight can significantly reduce environmental risks associated with tailings storage facilities and contribute to the long-term sustainability of mining activities.

***Keywords*:** tailings storage facility, environmental risk, mining industry, pollution control, Polluter Pays Principle, financial assurance, environmental monitoring, institutional governance.

Introduction

Mining is one of the strategic sectors of the global economy, providing essential raw materials for industry, energy production, construction, and high-technology development. At the same time, the extraction and processing of mineral resources generate significant quantities of waste, among which tailings and tailings storage facilities (TSFs) represent some of the most hazardous components of mining activities [1–3].

Tailings storage facilities are complex hydraulic and geotechnical systems designed for the containment of solid and semi-liquid wastes generated during mineral processing. One of their key characteristics is their ability to exert environmental impacts not only during operation but also for decades or even centuries after mine closure [3,4]. Heavy metals, sulfide compounds, and other hazardous constituents contained in tailings may migrate into the environment, causing contamination of surface water, groundwater, soils, and ecosystems [3].

Over recent decades, numerous major tailings dam failures have occurred worldwide, resulting in significant environmental, social, and economic consequences. These incidents have demonstrated that even under conditions of advanced engineering design and operational practices, tailings safety remains one of the most critical challenges facing the mining industry. International experience further indicates that risks associated with tailings facilities are determined not only by technical factors but also by the effectiveness of management systems, environmental oversight, and financial accountability mechanisms [2–4].

Water resource contamination is considered one of the most sensitive environmental issues associated with tailings storage facilities. Acid mine drainage and metal-rich effluents generated by mining activities can significantly deteriorate water quality and restrict the availability of water resources for human and ecological use [3,5]. Consequently, international environmental policy increasingly relies on economic regulatory instruments based on the Polluter Pays Principle and the User Pays Principle [5].

Economic regulatory mechanisms include pollution charges, environmental penalties, financial assurance systems, insurance instruments, and other economic incentives designed to reduce adverse environmental impacts and ensure the availability of financial resources for environmental restoration and remediation. However, the effective implementation of these instruments requires reliable monitoring systems, environmental supervision, and efficient institutional governance structures [5].

In the Republic of Armenia, mining constitutes an important sector of the national economy, and several large tailings storage facilities are currently in operation. Therefore, the implementation of effective environmental risk management systems for tailings facilities is essential for both environmental protection and the sustainable development of the mining sector. In this context, economic and institutional mechanisms capable of preventing, mitigating, and controlling tailings-related environmental risks acquire particular significance.

Literature Review

The safe management of tailings storage facilities has become one of the most important and widely studied topics in the mining sector during recent decades. Most research has focused on structural safety, causes of failures, environmental impacts, and risk management approaches associated with tailings facilities [3, 13–15, 19, 20].

Studies on the environmental impacts of tailings facilities indicate that mineral processing residues may contain heavy metals, sulfide compounds, and other hazardous substances capable of exerting long-term effects on surface water, groundwater, soils, and ecosystems [3,15]. Research conducted by Golik and co-authors demonstrated that the environmental influence of tailings facilities often extends far beyond their immediate boundaries due to the migration of contaminants through aquatic environments [3].

The investigation of tailings dam failures and their consequences occupies a prominent place in international scientific literature. Studies by Rico and co-authors revealed that tailings dam failures are primarily associated with design deficiencies, hydrological factors, operational violations, and management shortcomings [13,14]. Similar conclusions were reached by Lin and co-authors, who analyzed tailings dam failures across different regions of the world and found that, in addition to technical causes, governance and regulatory deficiencies play a significant role in accident occurrence [19]. The study conducted by Lyu and co-authors further confirmed that tailings dam failures are generally caused by multiple interacting factors, including engineering, organizational, and management-related components [25].

Particular attention has been devoted in recent years to the Mariana (Fundão) and Brumadinho tailings dam disasters in Brazil, which are considered among the largest technological and environmental disasters in the history of the mining industry [16–18]. Investigations of these events demonstrated that even the application of advanced engineering solutions cannot guarantee environmental safety in the absence of effective governance systems, monitoring mechanisms, and accountability frameworks [16–18].

Research aimed at improving the technical safety of tailings facilities has emphasized the application of innovative materials and technologies. Avanesyan demonstrated that the use of polymer-mineral materials can improve the protective characteristics of tailings facilities, reduce filtration losses, and enhance operational reliability [2]. Nevertheless, several authors have emphasized that technical solutions alone cannot completely eliminate environmental risks unless they are accompanied by effective economic and institutional management systems [6,15,20].

International standards and guidelines play a significant role in contemporary tailings management practices. The Global Industry Standard on Tailings Management (GISTM) represents the most comprehensive international framework for tailings governance, emphasizing risk assessment, transparency, stakeholder engagement, accountability, and long-term responsibility throughout the entire life cycle of tailings facilities [6]. Similarly, the guidelines developed by UNECE and ICMM highlight the importance of safety culture, continuous monitoring, emergency preparedness, and preventive risk management measures [8,21]. The literature concerning economic regulatory mechanisms is largely based on the Polluter Pays Principle and the User Pays Principle [10,11]. OECD documents identify these principles as fundamental economic instruments of environmental governance aimed at internalizing environmental costs within production processes and natural resource utilization activities [10,11]. Studies conducted by Tokmajyan, Markosyan, and Simonyan demonstrated that environmental charges, penalties, and other economic instruments can function effectively only when supported by reliable monitoring and enforcement systems [5].

Recent years have also witnessed increasing attention toward financial accountability and financial assurance mechanisms. Studies conducted by the World Bank and the International Institute for Sustainable Development (IISD) indicate that environmental insurance, reclamation funds, financial guarantees, and closure assurance instruments constitute essential components of modern tailings governance. These mechanisms help ensure the availability of sufficient financial resources for mine closure, land reclamation, environmental remediation, and long-term post-closure management activities [22–24].

The literature review demonstrates that the majority of existing studies focus either on the technical safety of tailings facilities or on the assessment of their environmental impacts. Comparatively few studies examine economic and institutional mechanisms for environmental risk management as an integrated system. In particular, limited attention has been devoted to the interconnected assessment of financial accountability, environmental charges, monitoring systems, regulatory oversight, and governance effectiveness within a unified conceptual framework.

Consequently, there remains a significant need for an integrated approach that combines engineering safety, economic regulation, financial responsibility, and institutional governance within a single environmental risk management framework for tailings storage facilities.

Addressing this scientific gap constitutes the primary objective of the present study.

Conflict Setting

Despite substantial investments in engineering safety improvements, environmental incidents associated with tailings facilities continue to occur worldwide, indicating that technical measures alone are insufficient for ensuring long-term environmental protection. As mining activities continue to expand, environmental risks associated with tailings storage facilities are also increasing. Numerous cases of water, soil, and ecosystem contamination continue to be reported in different countries despite advances in tailings design, construction, and operational technologies.

At the same time, international literature remains primarily focused on engineering and geotechnical aspects of tailings safety, whereas comparatively limited attention has been devoted to economic and institutional mechanisms of environmental risk management. Existing governance systems often fail to provide adequate prevention of environmental impacts, effective compensation for environmental damage, and reliable long-term monitoring of tailings-related risks.

Consequently, a contradiction emerges between the continuous improvement of technical safety measures and the persistent occurrence of environmental impacts associated with tailings storage facilities. This contradiction highlights the need for a more comprehensive approach that integrates engineering solutions with economic regulatory instruments, financial responsibility mechanisms, and institutional governance frameworks.

The objective of this study is to investigate the economic and institutional mechanisms for environmental risk management of tailings storage facilities, analyze international experience in their application, and identify opportunities for improving environmental safety within the context of mining activities.

Research Results

Economic Instruments for Environmental Risk Management of Tailings Storage Facilities

The analysis of international experience demonstrates that economic instruments constitute one of the principal mechanisms for reducing environmental risks associated with tailings storage facilities. Unlike purely technical measures, economic instruments influence the behavior of mining operators by creating financial incentives for pollution prevention, environmental protection, and long-term responsibility.

Among the most widely applied economic mechanisms are environmental charges, pollution fees, environmental taxes, financial assurance systems, reclamation funds, environmental insurance schemes, and compensation mechanisms. These instruments are generally based on the Polluter Pays Principle (PPP) and the User Pays Principle (UPP), which seek to internalize environmental costs into mining activities and ensure that environmental damage is not transferred to society.

The Polluter Pays Principle requires mining operators to bear financial responsibility for environmental impacts resulting from their activities. In the context of tailings management, this principle is implemented through environmental charges, penalties for regulatory violations, compensation payments, and mandatory remediation obligations. International experience indicates that properly designed pollution charges encourage companies to invest in safer technologies and environmental protection measures, thereby reducing the probability of environmental accidents.

The User Pays Principle complements the Polluter Pays Principle by ensuring that the costs associated with the use of natural resources are incorporated into operational expenditures. This mechanism contributes to more efficient resource utilization and supports the generation of financial resources necessary for environmental monitoring, reclamation, and post-closure management activities.

A growing number of countries have introduced financial assurance mechanisms requiring mining companies to provide financial guarantees prior to project implementation. These guarantees may take the form of reclamation bonds, trust funds, bank guarantees, environmental insurance, or other financial instruments. Their primary objective is to ensure the availability of sufficient financial resources for mine closure, rehabilitation, and environmental restoration regardless of the future financial condition of the mining operator.

The analysis indicates that economic instruments are most effective when implemented as part of an integrated environmental governance framework. Pollution charges alone are often insufficient to prevent environmental damage unless accompanied by effective monitoring systems, transparent reporting procedures, regulatory enforcement, and institutional accountability mechanisms. Consequently, economic instruments should be considered not as independent tools but as components of a broader environmental risk management system.

Institutional Mechanisms for Environmental Risk Management of Tailings Storage Facilities

Institutional governance mechanisms play a crucial role in ensuring the environmental safety of tailings storage facilities. International experience demonstrates that even the most comprehensive systems of environmental charges and financial responsibility cannot effectively manage tailings-related risks in the absence of reliable governance, monitoring, and regulatory oversight mechanisms.

The institutional governance framework encompasses the activities of regulatory authorities, environmental monitoring systems, inspection and enforcement mechanisms, emergency preparedness programs, as well as instruments that ensure stakeholder participation and transparency. The integrated functioning of these components enables not only the response to environmental problems after they occur but also the prevention of potential risks at an early stage.

Environmental monitoring represents one of the most important institutional instruments in tailings management. Monitoring systems are designed to continuously assess the structural condition of tailings facilities, water quality, groundwater levels, soil contamination, and other environmental indicators. Modern international standards increasingly require real-time data collection and analysis, enabling the early detection of hazardous trends and the prevention of potential accidents.

Regulatory oversight constitutes another fundamental element of institutional governance. Government authorities are responsible for supervising the design, construction, operation, and closure of tailings storage facilities. International studies indicate that a significant proportion of tailings-related incidents are associated not only with technical deficiencies but also with inadequate regulatory control, weak enforcement, and insufficient compliance with environmental requirements. Consequently, the effectiveness of regulatory oversight directly influences the level of environmental risk.

In recent years, increasing attention has been devoted to stakeholder participation and transparency. International organizations and professional associations emphasize that information regarding tailings management should be accessible to local communities, non-governmental organizations, and other interested stakeholders. Enhanced transparency contributes to stronger public oversight, increased trust, and earlier identification of potential environmental risks.

Particular importance is also attached to the management of mine closure and post-closure periods. Numerous studies have demonstrated that environmental risks associated with tailings facilities often persist long after mining activities have ceased. For this reason, contemporary institutional approaches require long-term monitoring programs, clearly defined post-closure responsibilities, and organizational mechanisms capable of ensuring environmental protection for decades following mine closure.

The analysis indicates that the effectiveness of institutional mechanisms largely determines the overall success of environmental risk management in tailings storage facilities. Even facilities characterized by advanced engineering design and adequate financial resources may become sources of environmental hazards if effective monitoring, regulatory oversight, accountability, and stakeholder engagement mechanisms are absent. Therefore, institutional governance systems should be regarded as a fundamental component of environmental safety and sustainable tailings management.

Integrated Framework for Environmental Risk Management of Tailings Storage Facilities

The analysis of international experience indicates that neither economic instruments nor institutional mechanisms alone are sufficient to ensure an adequate level of environmental safety in tailings storage facilities. Economic instruments provide financial incentives for environmental protection and responsibility, while institutional mechanisms establish the governance structures necessary for monitoring, enforcement, and accountability.

Consequently, effective environmental risk management requires the integration of these mechanisms into a unified framework.

The proposed integrated framework is based on four interconnected pillars: economic responsibility, financial assurance, institutional governance, and environmental monitoring. The interaction among these pillars creates a comprehensive system capable of preventing environmental impacts, minimizing risks, and ensuring long-term environmental protection throughout the entire life cycle of a tailings storage facility.

The first pillar, economic responsibility, is founded on the Polluter Pays Principle and the User Pays Principle. Through environmental charges, penalties, compensation payments, and resource-use fees, mining operators are encouraged to reduce environmental impacts and invest in safer technologies and management practices.

The second pillar consists of financial assurance mechanisms designed to guarantee the availability of financial resources for mine closure, reclamation, environmental remediation, and post-closure monitoring. Financial guarantees, environmental insurance, reclamation bonds, and dedicated rehabilitation funds reduce the risk of transferring environmental liabilities to governments or local communities.

The third pillar is institutional governance, which includes regulatory oversight, compliance control, emergency preparedness, stakeholder engagement, and transparency mechanisms. Effective governance ensures that environmental requirements are properly implemented and continuously monitored throughout project development and operation.

The fourth pillar is environmental monitoring. Continuous monitoring of water quality, groundwater conditions, soil contamination, structural stability, and ecological indicators enables the early detection of environmental threats and supports timely corrective actions. Modern digital monitoring technologies further enhance the effectiveness of risk management systems by providing real-time information for decision-making.

The proposed framework emphasizes that environmental safety cannot be achieved through isolated measures. Instead, sustainable tailings management requires the simultaneous application of economic incentives, financial guarantees, institutional oversight, and environmental monitoring. The integration of these components strengthens environmental governance, reduces the probability of environmental accidents, and improves the long-term sustainability of mining activities.

The results of the analysis suggest that the implementation of integrated environmental risk management frameworks can significantly improve the environmental performance of tailings storage facilities and contribute to achieving higher standards of environmental protection and sustainable resource development.

A tailings facility operator should not be treated only as an ordinary taxpayer. In addition to standard tax obligations, the operator should finance the environmental costs required to prevent, monitor, control, and remediate both current and future risks generated by tailings storage activities. In this context, environmental responsibility should be understood not as a single payment or penalty, but as a structured system of financial obligations covering monitoring, insurance, reclamation, emergency response, and damage compensation.

Based on the analysis conducted in this study, a conceptual environmental responsibility model for tailings storage facility operators is proposed (Fig.). Unlike the conventional approach, which primarily relies on taxes, royalties, and permit fees, the proposed model extends financial responsibility to include environmental monitoring, environmental insurance, emergency preparedness, reclamation activities, post-closure management, and environmental damage compensation. This approach seeks to ensure that both current and future environmental costs associated with tailings storage facilities are borne by the operator rather than transferred to society or future generations.

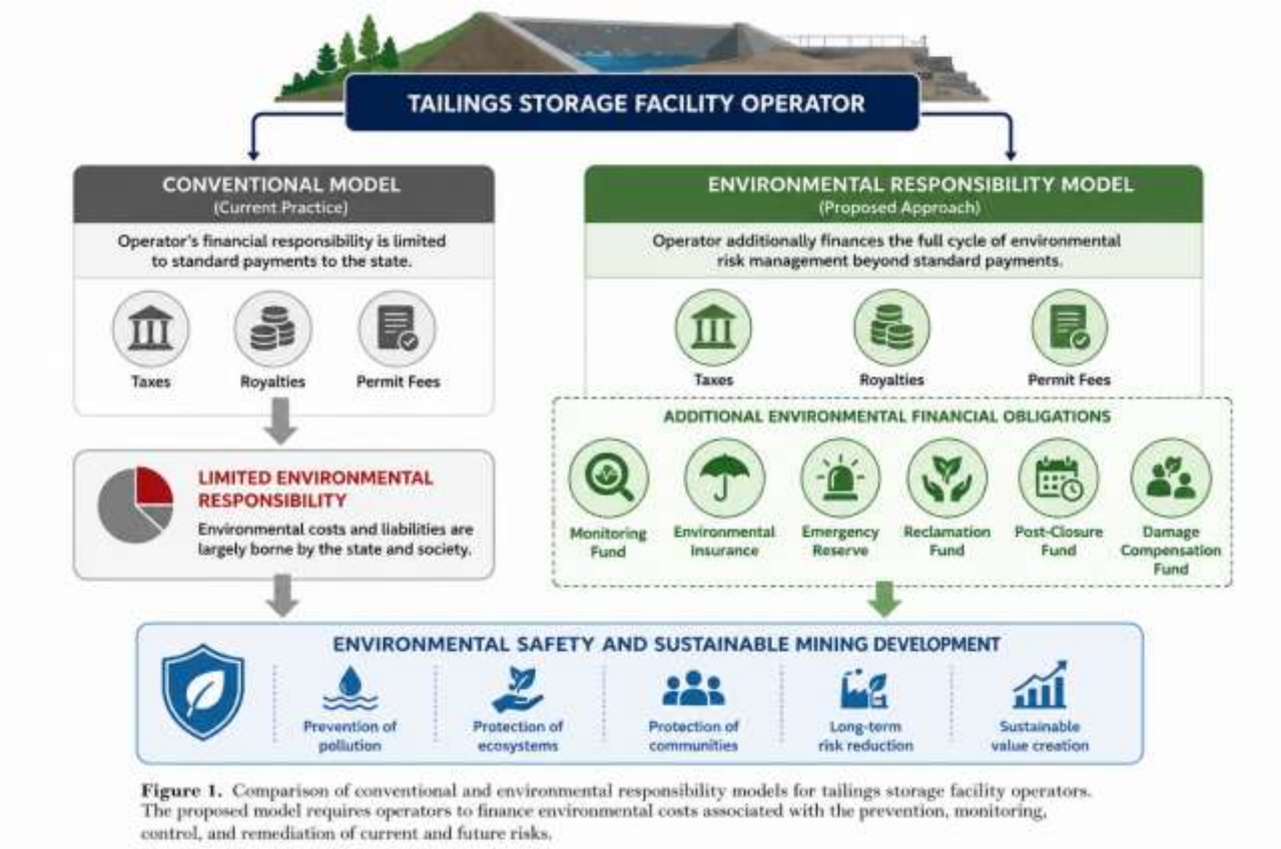

Fig. Comparison of Conventional and Environmental Responsibility Models for Tailings Storage Facility Operators

The proposed environmental responsibility model extends the financial obligations of tailings storage facility operators beyond conventional taxes, royalties, and permit fees. In addition to standard payments, operators are required to finance environmental monitoring, environmental insurance, emergency preparedness, reclamation activities, post-closure management, and environmental damage compensation. This approach aims to ensure that the costs associated with the prevention, control, monitoring, and remediation of current and future environmental risks are borne by the operator rather than transferred to society or future generations.

Conclusions

This study investigated the economic and institutional mechanisms for environmental risk management of tailings storage facilities, analyzed international experience in their application, and evaluated opportunities for improving environmental safety within the context of mining activities.

The results demonstrate that the environmental safety of tailings storage facilities cannot be ensured solely through engineering and technical measures. Despite significant advances in tailings design, construction, and operational technologies over recent decades, environmental incidents and major failures continue to occur worldwide, resulting in contamination of water resources, soils, and ecosystems.

The literature review revealed that environmental risks associated with tailings facilities are determined not only by technical factors but also by governance effectiveness, regulatory oversight, financial accountability, and institutional performance. International experience from major tailings disasters indicates that deficiencies in management and supervision frequently constitute key contributing factors to environmental accidents.

The study confirms that the Polluter Pays Principle and the User Pays Principle represent important economic instruments for environmental risk management in the mining sector. Environmental charges, penalties, compensation mechanisms, and financial assurance instruments can encourage more responsible environmental behavior and contribute to risk reduction.

At the same time, the effectiveness of economic instruments largely depends on the quality of institutional governance. Effective monitoring systems, regulatory oversight, transparency, stakeholder participation, and accountability mechanisms are essential prerequisites for ensuring environmental safety and reducing long-term environmental risks.

One of the principal outcomes of the study is the development of an integrated environmental risk management framework and a conceptual environmental responsibility model for tailings storage facility operators (Fig.). The proposed framework consists of four interconnected components: economic responsibility, financial assurance, institutional governance, and environmental monitoring. This approach enables tailings management to be viewed as a unified system and enhances the overall effectiveness of environmental risk management.

Based on the findings of the study, the following recommendations are proposed:

1. Strengthen the implementation of the Polluter Pays Principle within tailings management systems.
2. Expand the application of financial assurance mechanisms and environmental insurance instruments in mining projects.
3. Improve environmental monitoring systems through the adoption of modern digital technologies and real-time data collection methods.
4. Enhance regulatory oversight and environmental auditing procedures.
5. Promote greater participation of local communities and civil society organizations in environmental decision-making processes.
6. Develop long-term strategies for mine closure and post-closure management of tailings facilities.
7. Implement integrated environmental risk management systems that combine technical, economic, and institutional measures.

Overall, the study demonstrates that improving the environmental safety of tailings storage facilities requires a comprehensive and multi-dimensional approach in which engineering solutions, economic responsibility, and institutional governance operate as mutually reinforcing components of a unified environmental management system.

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ՊՈՉԱՄԲԱՐՆԵՐԻ ԲՆԱՊԱՀՊԱՆԱԿԱՆ ՌԻՍԿԵՐԻ ԿԱՌԱՎԱՐՄԱՆ ՏՆՏԵՍԱԿԱՆ և ԻՆՍՏԻՏՈՒՑԻՈՆԱԼ ՄԵԽԱՆԻԶՄՆԵՐԸ

Վ.Ռ. Գրիգորյան
Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ

Պոչամբարները հանքարդյունաբերության առավել վտանգավոր տեխնածին օբյեկտներից են, որոնք կարող են երկարաժամկետ ազդեցություն ունենալ մակերևութային և ստորերկրյա ջրերի, հողային ռեսուրսների, էկոհամակարգերի և բնակչության առողջության վրա: Չնայած վերջին տասնամյակներում պոչամբարների նախագծման և շահագործման ոլորտում գրանցված տեխնոլոգիական առաջընթացին, բազմաթիվ բնապահպանական վթարներ շարունակում են արձանագրվել աշխարհի տարբեր երկրներում՝ վկայելով, որ տեխնիկական լուծումները բավարար չեն առանց արդյունավետ տնտեսական և ինստիտուցիոնալ կառավարման մեխանիզմների: Հետազոտության նպատակն է վերլուծել պոչամբարների բնապահպանական ռիսկերի կառավարման տնտեսական և ինստիտուցիոնալ գործիքները, գնահատել դրանց կիրառման արդյունավետությունը և բացահայտել բնապահպանական անվտանգության բարձրացման հնարավոր ուղղությունները: Աշխատանքում ուսումնասիրվել են «աղտոտողը վճարում է» և «օգտագործողը վճարում է» սկզբունքները, բնապահպանական վճարների և տուգանքների համակարգերը, ֆինանսական երաշխիքների կիրառումը, ինչպես նաև մոնիթորինգի և վերահսկողության ինստիտուցիոնալ մեխանիզմները: Վերլուծության արդյունքները ցույց են տալիս, որ պոչամբարների անվտանգ շահագործումը պահանջում է ինժեներական, տնտեսական և կառավարման միջոցառումների համակցված կիրառում: Հիմնավորվում է, որ ֆինանսական պատասխանատվության, շարունակական մոնիթորինգի և արդյունավետ վերահսկողության համակարգերի զարգացումը կարող է էականորեն նվազեցնել պոչամբարների հետ կապված բնապահպանական ռիսկերը:

Բանալի բառեր. պոչամբար, բնապահպանական ռիսկ, հանքարդյունաբերություն, աղտոտման վերահսկում, աղտոտողը վճարում է, ֆինանսական երաշխիքներ, մոնիթորինգ:

V.R. Grigoryan
ECONOMIC AND INSTITUTIONAL MECHANISMS FOR ENVIRONMENTAL RISK MANAGEMENT OF TAILINGS STORAGE FACILITIES

ЭКОНОМИЧЕСКИЕ И ИНСТИТУЦИОНАЛЬНЫЕ МЕХАНИЗМЫ УПРАВЛЕНИЯ ЭКОЛОГИЧЕСКИМИ РИСКАМИ ХВОСТОХРАНИЛИЩ

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Хвостохранилища относятся к числу наиболее опасных техногенных объектов горнодобывающей промышленности, способных оказывать долговременное воздействие на поверхностные и подземные воды, почвенные ресурсы, экосистемы и здоровье населения. Несмотря на значительный технологический прогресс в области проектирования и эксплуатации хвостохранилищ, во многих странах мира продолжают фиксироваться экологические аварии, свидетельствующие о том, что технических решений недостаточно без эффективных экономических и институциональных механизмов управления. Целью исследования является анализ экономических и институциональных инструментов управления экологическими рисками хвостохранилищ, оценка их эффективности и выявление направлений повышения экологической безопасности. В работе рассмотрены принципы «загрязнитель платит» и «пользователь платит», системы экологических платежей и штрафов, механизмы финансовых гарантий, а также институциональные инструменты мониторинга и экологического контроля. Результаты исследования показывают, что безопасная эксплуатация хвостохранилищ требует комплексного применения инженерных, экономических и управленческих мер. Обосновано, что развитие систем финансовой ответственности, непрерывного мониторинга и эффективного экологического надзора способно существенно снизить экологические риски, связанные с эксплуатацией хвостохранилищ.

***Ключевые слова*:** хвостохранилище, экологический риск, горнодобывающая промышленность, контроль загрязнения, принцип «загрязнитель платит», финансовые гарантии, мониторинг.

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STRATEGIC MANAGEMENT OF DRINKING WATER RESOURCES IN ARMENIA: BALANCING CLIMATE CHANGE, BOTTLED WATER PRODUCTION, AND LONG-TERM WATER SECURITY

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Abstract

Armenia possesses substantial drinking water resources, including high-quality groundwater, springs, and mineral water reserves, which constitute an important component of the country's environmental, economic, and strategic assets. At the same time, increasing bottled water production, climate change, growing water demand, and the need to ensure long-term water security are creating new challenges for the sustainable management of these resources. Although Armenia is generally considered a water-rich country, the long-term availability of drinking water cannot be assessed solely on the basis of current resource abundance. Strategic management requires the integration of climatic, environmental, economic, and institutional factors that influence both water availability and resource sustainability.

This study presents a comprehensive assessment of Armenia's drinking water resources and evaluates the interactions between climate change, bottled water production, and long-term water security. The analysis is based on official statistical data, hydrological information, climate indicators, and institutional documents describing water resource management and bottled water production trends. The study examines recent changes in water abstraction, production dynamics, resource utilization, and the potential impacts of climate variability on drinking water resources.

Based on the identified challenges, the paper proposes an integrated strategic management framework aimed at balancing economic development with long-term resource conservation. The framework emphasizes sustainable groundwater management, climate adaptation, protection of drinking water sources, improved monitoring systems, efficient allocation of water resources, and evidence-based decision-making. The proposed approach demonstrates that effective drinking water resource management should move beyond traditional resource accounting and incorporate long-term resilience, ecosystem protection, and adaptive governance.

The findings contribute to the development of sustainable water resource management policies and provide practical recommendations for balancing bottled water production with the preservation of Armenia's strategic drinking water resources under changing climatic conditions.

***Keywords*:** drinking water resources; strategic water management; bottled water production; climate change; groundwater; water security; sustainable resource management; Armenia.

Introduction

Freshwater resources are among the most valuable strategic assets for ensuring sustainable development, protecting public health, supporting economic growth, and maintaining ecosystem integrity. Although approximately 71% of the Earth's surface is covered by water, less than 1% of global water resources is readily available as accessible freshwater for human use. Rapid population growth, urbanization, industrial expansion, agricultural intensification, and climate change are increasing pressure on freshwater resources worldwide, making their sustainable management one of the most important global environmental challenges of the twenty-first century.

Access to safe drinking water is internationally recognized as a fundamental human right and constitutes a key component of the 2030 Agenda for Sustainable Development, particularly Sustainable Development Goal 6, which calls for universal and equitable access to safe and affordable drinking water. Nevertheless, ensuring long-term drinking water security extends beyond guaranteeing present-day access. It also requires protecting water sources, maintaining groundwater recharge, adapting to climate change, improving governance, and balancing environmental, economic, and social interests over extended planning horizons.

During the last decade, scientific attention has increasingly shifted from conventional water resource development toward integrated strategic water resource management. This transition reflects the growing recognition that countries possessing relatively abundant freshwater resources are not immune to water-related risks. Climate variability, changing precipitation regimes, increasing evaporation, groundwater depletion, pollution, and competing water demands may gradually reduce the reliability of drinking water supplies even where current resource availability appears sufficient. Consequently, modern water management strategies increasingly emphasize long-term resilience, adaptive governance, and sustainable resource management rather than the continuous expansion of water abstraction.

Armenia is among the countries endowed with substantial high-quality drinking water resources, primarily supplied by groundwater aquifers, mountain springs, and mineral water sources. These resources form the foundation of the country's drinking water supply system and support a steadily expanding bottled water industry that contributes significantly to national economic development and export growth. However, increasing water demand, climate-induced hydrological changes, and the continued expansion of bottled water production are creating new challenges for the long-term sustainability and strategic management of these valuable resources.

Although numerous scientific studies have addressed Armenia's drinking water resources, most have focused on individual aspects such as hydrogeological conditions, water quality, water balance, water supply systems, or statistical assessments of bottled water production. Comparatively few studies have comprehensively examined the interrelationships among climate change, drinking water resource utilization, the expansion of bottled water production, and long-term water security within a unified strategic management perspective. Consequently, there is a clear need for an integrated strategic approach to the management of Armenia's drinking water resources that extends beyond conventional resource assessment and incorporates long-term resource conservation, climate resilience, sustainable economic development, and the safeguarding of water security.

Global Approaches to Drinking Water Resource Management

The management of drinking water resources has evolved considerably over the past several decades in response to growing environmental, socio-economic, and climatic challenges. Traditionally, water management policies primarily focused on expanding water supply through the construction of reservoirs, groundwater abstraction systems, inter-basin water transfers, and centralized distribution infrastructure. This engineering-oriented approach was largely driven by the objective of meeting increasing water demand and supporting economic development. However, the accelerating impacts of climate change, rapid urbanization, population growth, environmental degradation, and increasing competition among water users have demonstrated that expanding water supply alone is insufficient to ensure long-term drinking water security [1,5,7].

These challenges have led to a gradual transition from conventional water resource development toward integrated and strategic management approaches. One of the most influential concepts introduced during this transition is Integrated Water Resources Management (IWRM), which promotes the coordinated management of water, land, and related natural resources to maximize economic and social benefits while preserving ecosystem sustainability. Since its introduction by the Global Water Partnership, the IWRM framework has become one of the fundamental principles guiding national water policies and international water governance. Complementary governance frameworks developed by the Organisation for Economic Co-operation and Development have further emphasized transparency, institutional coordination, stakeholder participation, accountability, and evidence-based decision-making as essential elements of effective water governance [7–10].

In recent years, scientific and policy attention has increasingly shifted toward the broader concept of water security, which extends beyond ensuring adequate water quantity and quality. Contemporary approaches recognize that long-term drinking water security depends on the resilience of water resources to climate change, the sustainability of groundwater recharge, ecosystem protection, effective governance, adaptive management, and the capacity of institutions to respond to emerging environmental risks. This transition is reflected in the United Nations World Water Development Reports and the Sustainable Development Goal 6 framework, which advocate integrated management strategies capable of balancing environmental sustainability, economic development, and social equity while strengthening resilience to climate-related pressures [1–6,12–14].

Despite the substantial progress achieved in strategic water resource management during the past two decades, existing international approaches primarily focus on integrated governance, water-use efficiency, climate adaptation, and ecosystem protection at the general water-resource level. Comparatively less attention has been devoted to the strategic management of drinking water resources as a distinct category of national natural assets, particularly in countries possessing abundant high-quality groundwater reserves and rapidly expanding bottled water industries. Furthermore, limited emphasis has been placed on balancing long-term drinking water security with the increasing economic utilization of potable water resources. These knowledge gaps indicate the need for more specialized strategic management approaches capable of integrating climate resilience, groundwater sustainability, economic development, and long-term protection of drinking water resources within a unified management framework.

Despite the significant progress achieved in strategic water resource management, increasing scientific attention is now focused on understanding how climate change influences the long-term sustainability of drinking water resources, thereby necessitating a more detailed examination of climate-related impacts on water availability and security.

Climate Change and Drinking Water Resources

Climate change has emerged as one of the most significant challenges affecting the sustainability of drinking water resources worldwide. Rising air temperatures, changing precipitation patterns, increasing evapotranspiration, more frequent droughts, and the growing occurrence of extreme hydrological events are altering the natural processes that regulate water availability and groundwater recharge. These changes directly influence both the quantity and quality of drinking water resources and increase uncertainty regarding their long-term availability [1–6,12–14].

Numerous studies have demonstrated that groundwater systems, traditionally considered more resilient than surface water resources, are also becoming increasingly vulnerable to climate variability. Reduced recharge rates, prolonged dry periods, changing snow accumulation and snowmelt dynamics, and increasing abstraction pressures may gradually diminish groundwater reserves and alter spring discharge regimes. Since groundwater constitutes the principal source of drinking water in many countries, including Armenia, these processes have become a major concern for long-term water resource planning and sustainable management [3,11–14].

Beyond physical impacts on water availability, climate change also affects drinking water quality through increased sediment transport, higher concentrations of dissolved pollutants, changing hydrochemical conditions, and greater risks of contamination during extreme hydrological events. Consequently, ensuring drinking water security increasingly requires integrated monitoring systems capable of simultaneously evaluating hydrological, hydrogeological, climatic, and water-quality indicators rather than relying on individual environmental parameters [1–6,12–14].

Recent international research emphasizes that adaptation to climate change should become an integral component of strategic drinking water resource management. Modern adaptation measures include the protection of groundwater recharge areas, enhancement of monitoring systems, improvement of water-use efficiency, diversification of drinking water sources, development of climate-resilient infrastructure, and the incorporation of climate projections into long-term water resource planning. These approaches contribute not only to reducing climate-related risks but also to strengthening the resilience and sustainability of national drinking water systems [1–6,9,12–14].

Despite considerable progress in understanding climate-related impacts on water resources, most existing studies primarily assess the physical consequences of climate change on hydrological systems. Comparatively limited attention has been devoted to evaluating how climate change interacts with the expanding economic utilization of drinking water resources, particularly bottled water production, and how these combined pressures influence long-term strategic management and national water security. This issue is particularly relevant for countries where drinking water resources represent both an essential public resource and a growing economic asset.

Bottled Water Production, Groundwater Sustainability, and Research Progress in Armenia

The global bottled water industry has experienced remarkable growth during the past two decades, driven by increasing consumer demand for safe drinking water, urbanization, changing lifestyles, and concerns regarding the quality of public water supplies. In many countries, bottled water production has become an important economic sector, contributing to employment, regional development, and export revenues. However, this rapid expansion has also intensified scientific discussions regarding the long-term sustainability of groundwater abstraction, protection of drinking water sources, and the need to balance economic development with the conservation of strategic water resources [1–6].

Groundwater represents the principal source of bottled drinking water in most producing countries. Although groundwater generally provides high-quality drinking water with relatively limited treatment requirements, excessive abstraction may gradually exceed natural recharge rates, resulting in declining groundwater levels, reduced spring discharge, ecosystem degradation, and increasing vulnerability to climate variability. Consequently, international studies increasingly emphasize that bottled water production should be managed within the broader framework of sustainable groundwater management and long-term water security rather than solely through economic considerations [3,5,9,11–14].

Armenia possesses abundant high-quality groundwater resources and numerous natural springs, creating favorable conditions for the development of bottled drinking water and mineral water production. During recent decades, this sector has become an important component of the national economy and has strengthened its position in international markets. At the same time, the sustainable utilization of these resources has become an increasingly important issue as climate change, growing water demand, and expanding economic activities continue to increase pressure on strategic drinking water reserves.

Among the studies devoted to Armenia's drinking water resources, the work of Markosyan et al. (2018) represents one of the first comprehensive assessments integrating information on national drinking water resources with the country's bottled water production and export potential [15]. The study demonstrated the significant availability of high-quality drinking water resources in Armenia and highlighted their economic importance as a strategic natural asset. It also emphasized the country's considerable opportunities for expanding bottled water exports based on its favorable hydrogeological conditions.

Since the publication of that study, however, substantial changes have occurred. New statistical data, advances in scientific understanding of climate change, evolving international approaches to water security, growing bottled water production, and increasing attention to sustainable groundwater management have considerably altered the context within which Armenia's drinking water resources should be evaluated. These developments indicate that previous assessments require further expansion toward integrated strategic management approaches capable of simultaneously addressing climate resilience, groundwater sustainability, economic development, and long-term drinking water security.

Conflict Setting

Despite the significant progress achieved in drinking water resource management during recent decades, an important scientific contradiction remains unresolved. On the one hand, countries possessing abundant high-quality drinking water resources are generally considered to have a favorable long-term water security outlook. On the other hand, climate change, increasing groundwater abstraction, expanding bottled water production, and growing socio-economic demand are progressively altering the conditions under which these resources are utilized and conserved. Consequently, resource abundance alone can no longer be regarded as a sufficient indicator of long-term drinking water security.

This contradiction is particularly evident in Armenia. The country possesses substantial reserves of high-quality groundwater and spring water, while bottled water production has become an increasingly important economic sector. Simultaneously, climate change, changing hydrological conditions, and increasing pressure on groundwater resources introduce new uncertainties regarding the long-term sustainability of drinking water resources. These interacting processes require a management approach that extends beyond conventional resource inventories and production statistics.

The analysis of the available scientific literature indicates that existing studies generally examine hydrogeological conditions, water quality, climate impacts, groundwater utilization, or bottled water production as separate research topics. Comparatively few studies have attempted to integrate these components within a unified strategic management framework capable of simultaneously evaluating climate resilience, groundwater sustainability, economic development, and long-term drinking water security.

Accordingly, there is a need to develop a comprehensive strategic management approach that considers drinking water resources not only as environmental assets but also as strategic national resources requiring long-term protection, adaptive management, and evidence-based policy development.

The objective of this study is to comprehensively assess the current status and development trends of Armenia's drinking water resources, evaluate the potential impacts of climate change and bottled water production, and develop an integrated strategic management framework that supports balanced decision-making between economic development, conservation of drinking water resources, and long-term water security. The proposed framework represents the principal scientific contribution of this study and is intended to provide methodological support for strategic drinking water resource management in Armenia and in other countries facing similar environmental and socio-economic challenges.

Materials and Methods

Study Area

The Republic of Armenia was selected as the study area because of its considerable reserves of high-quality drinking water resources, extensive groundwater systems, numerous mountain springs, and well-developed bottled water industry. These characteristics make Armenia an appropriate case for evaluating the interactions among climate change, drinking water resource utilization, economic development, and long-term water security. Particular attention was given to groundwater resources, which constitute the principal source of drinking water for both public supply and bottled water production.

Data Sources

The study was based on the integration of multiple data sources, including official statistical publications of the Statistical Committee of the Republic of Armenia (ArmStat), reports of the Ministry of Environment, national water cadastre information, hydrogeological and climatic datasets, and international publications issued by UNESCO, UN-Water, the World Meteorological Organization (WMO), the Intergovernmental Panel on Climate Change (IPCC), the Organisation for Economic Co-operation and Development (OECD), and the World Bank. Data covering the period 2018–2025 were used to evaluate recent developments in drinking water resources, bottled water production, groundwater utilization, and climate-related indicators.

Research Methodology

The research employed an integrated methodological approach combining literature review, statistical analysis, comparative assessment, trend analysis, hydrogeological evaluation, climate assessment, and policy analysis. Temporal trends in drinking water resource utilization and bottled water production were analyzed using official statistical data. Climate-related influences were evaluated through the assessment of temperature and precipitation trends together with internationally recognized climate reports. Comparative analysis was applied to identify relationships among climate change, groundwater sustainability, bottled water production, and long-term drinking water security. The results of these analyses were synthesized to identify the principal strategic challenges affecting drinking water resource management in Armenia.

Development of the Strategic Drinking Water Resource Management Framework

Based on the identified scientific gaps, literature review, statistical evaluation, climate assessment, and policy analysis, a Strategic Drinking Water Resource Management Framework (SDWRMF) was developed. The framework integrates four interrelated components: (i) assessment of drinking water resource availability and sustainability; (ii) evaluation of climate-related pressures and groundwater resilience; (iii) assessment of economic utilization, including bottled water production; and (iv) strategic management and policy decision-making. The proposed framework provides a systematic methodology for evaluating drinking water resources as strategic national assets while simultaneously considering environmental sustainability, economic development, and long-term water security. The practical application and validation of the framework are presented in the subsequent Results and Discussion section.

Research Results

Drinking Water Resources of Armenia

Armenia possesses substantial high-quality drinking water resources that constitute one of the country's most valuable strategic natural assets. Drinking water is supplied predominantly from groundwater aquifers and natural springs, which are characterized by favorable hydrogeological conditions and generally high water quality. These resources satisfy the majority of the country's public drinking water demand while simultaneously supporting the production of bottled drinking and mineral water. Owing to their strategic importance for public health, socio-economic development, and environmental sustainability, the long-term protection and rational management of these resources have become fundamental priorities of national water policy. Consequently, the assessment of drinking water resources should extend beyond conventional quantitative inventories and incorporate considerations of sustainability, resilience, and long-term water security.

The hydrogeological structure of Armenia plays a decisive role in the formation and long-term availability of drinking water resources. The country's mountainous terrain, complex geological setting, and diverse aquifer systems provide favorable conditions for the accumulation, natural filtration, and continuous recharge of groundwater. As a result, groundwater constitutes the primary source of drinking water for most settlements and represents the principal resource supporting bottled water production. Compared with surface water resources, groundwater generally exhibits greater stability in both quantity and quality, making it particularly valuable under conditions of increasing climatic variability. Nevertheless, the sustainability of groundwater resources depends on maintaining a balance between natural recharge and water abstraction, emphasizing the importance of continuous monitoring and scientifically based resource management.

Table 1

General Characteristics of Armenia's Water Resources

Indicator	Value	Unit
Average annual river runoff	7.2–7.7	billion m³/year
Renewable internal freshwater resources	6.85–7.0	billion m³/year
Number of rivers	~9,480	—
Number of reservoirs	74	—
Total reservoir storage capacity	0.988	billion m³
Lake Sevan water volume	~38.0	billion m³
Official strategic national water reserve	39.3	billion m³

Note: The value of **39.3 billion m³** is adopted in this study as the official indicator of Armenia's strategic national water reserve in accordance with the Law of the Republic of Armenia *"On the National Water Program of the Republic of Armenia"* (Law No. HO-232-N, adopted on 27 November 2006). This value represents the legally recognized strategic water reserve ensuring the country's long-term water and environmental security. Values such as **45.5 billion m³**, occasionally reported in the literature, refer to the gross national water resource potential and are therefore not used as the official strategic water reserve indicator in the present study.

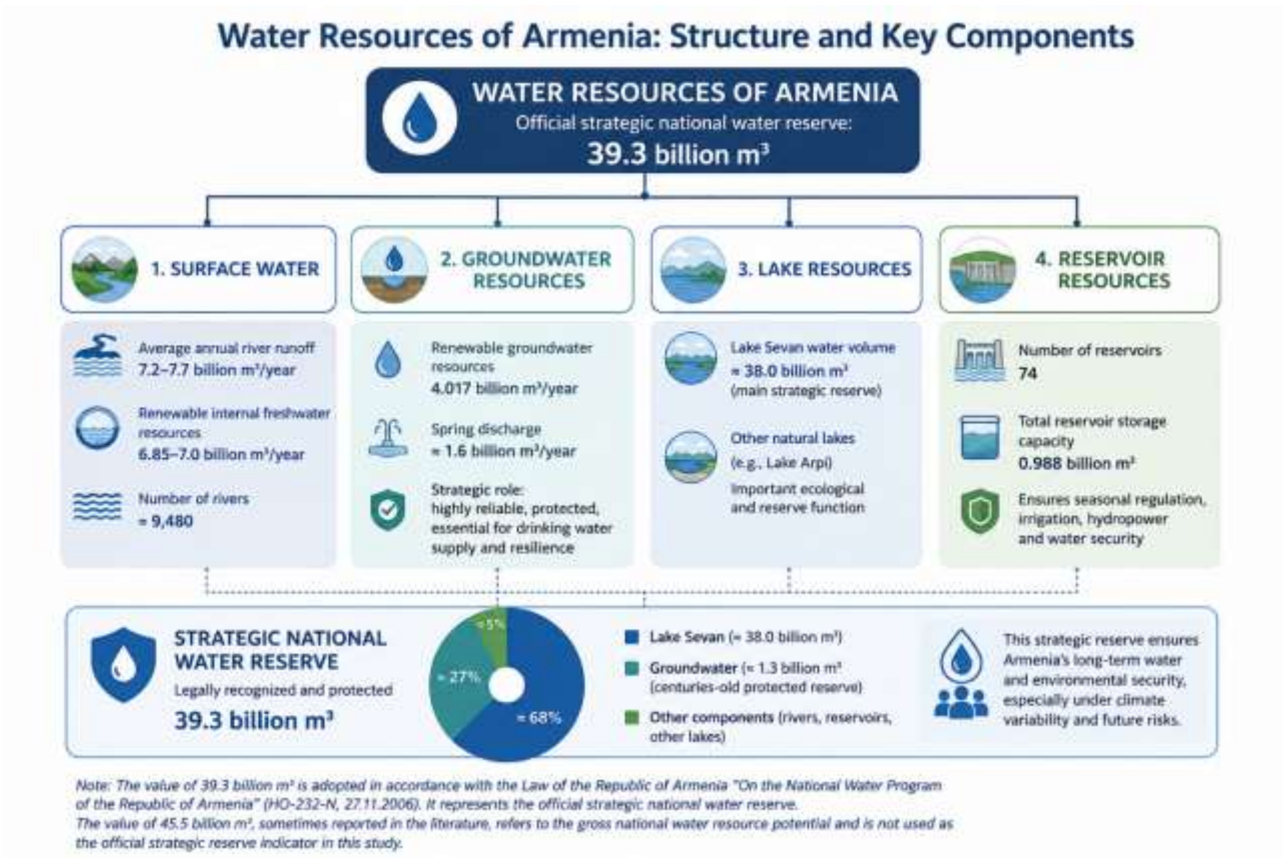

Fig. 1 General Structure of Armenia's Water Resources

Fig. 1 illustrates the general structure of Armenia's water resources, including surface water, groundwater, lake resources, and reservoirs, together with their principal quantitative characteristics. The figure highlights the central role of Lake Sevan and groundwater resources in ensuring the country's long-term water security and provides the conceptual basis for the subsequent assessment of strategic drinking water resources using the Strategic Drinking Water Resource Management Framework (SDWRMF).

The analysis of Armenia's water resources demonstrates that the country possesses considerable freshwater potential, forming a strong basis for long-term water security. As summarized in Tab.1 and illustrated in Fig.1, Armenia's water resources comprise surface waters, groundwater, lake resources, and reservoirs, which together constitute an integrated national water system. Surface water resources are represented by an average annual river runoff of approximately 7.2–7.7 billion m³ and an extensive hydrographic network of nearly 9,480 rivers. Lake Sevan, with an estimated water volume of approximately 38 billion m³, constitutes the country's principal strategic freshwater reserve, while the existing network of 74 reservoirs provides a total storage capacity of approximately 0.988 billion m³, contributing to seasonal flow regulation and water supply reliability. According to the National Water Program of the Republic of Armenia, the officially recognized strategic national water reserve amounts to 39.3 billion m³, representing the legally protected long-term freshwater reserve that underpins the country's water and environmental security.

Table 2

Characteristics of Armenia's Strategic Groundwater Resources

Indicator	Value	Unit
Total renewable groundwater resources	4.017	billion m³/year
Spring discharge	1.595	billion m³/year
Drainage discharge	1.419	billion m³/year
Deep groundwater discharge	1.003	billion m³/year
Potential exploitable groundwater resources	>3.0	billion m³/year
Officially approved exploitable groundwater reserves	1.215	billion m³/year
Drinking water supplied from groundwater	96	%
Official strategic groundwater reserve	1.3	billion m³
Principal strategic hydrogeological basin	Ararat Artesian Basin	—
Contribution of the Ararat Artesian Basin to national groundwater resources	45–50	%

Note: Renewable groundwater resources represent the annually replenished groundwater potential of the country. Potential exploitable groundwater resources (>3.0 billion m³/year) refer to the estimated maximum volume that could theoretically be abstracted under favorable hydrogeological and engineering conditions without causing irreversible depletion. In contrast, the officially approved exploitable groundwater reserves (1.215 billion m³/year) represent the legally verified and technically proven portion of groundwater resources approved for sustainable use through the state hydrogeological assessment system. In accordance with the objectives of this study, both indicators are presented because they characterize different dimensions of Armenia's strategic groundwater potential and its currently approved sustainable utilization capacity.

Fig. 2 presents the structure of Armenia's renewable groundwater resources and their role in national drinking water supply. The figure illustrates the distribution of renewable groundwater into spring, drainage, and deep groundwater flow components, together with the relationship between renewable resources, potential exploitable resources, officially approved exploitable groundwater reserves, and the strategic groundwater reserve. It also highlights the dominant contribution of the Ararat Artesian Basin to the country's groundwater resources and the fundamental role of groundwater in providing centralized drinking water supply.

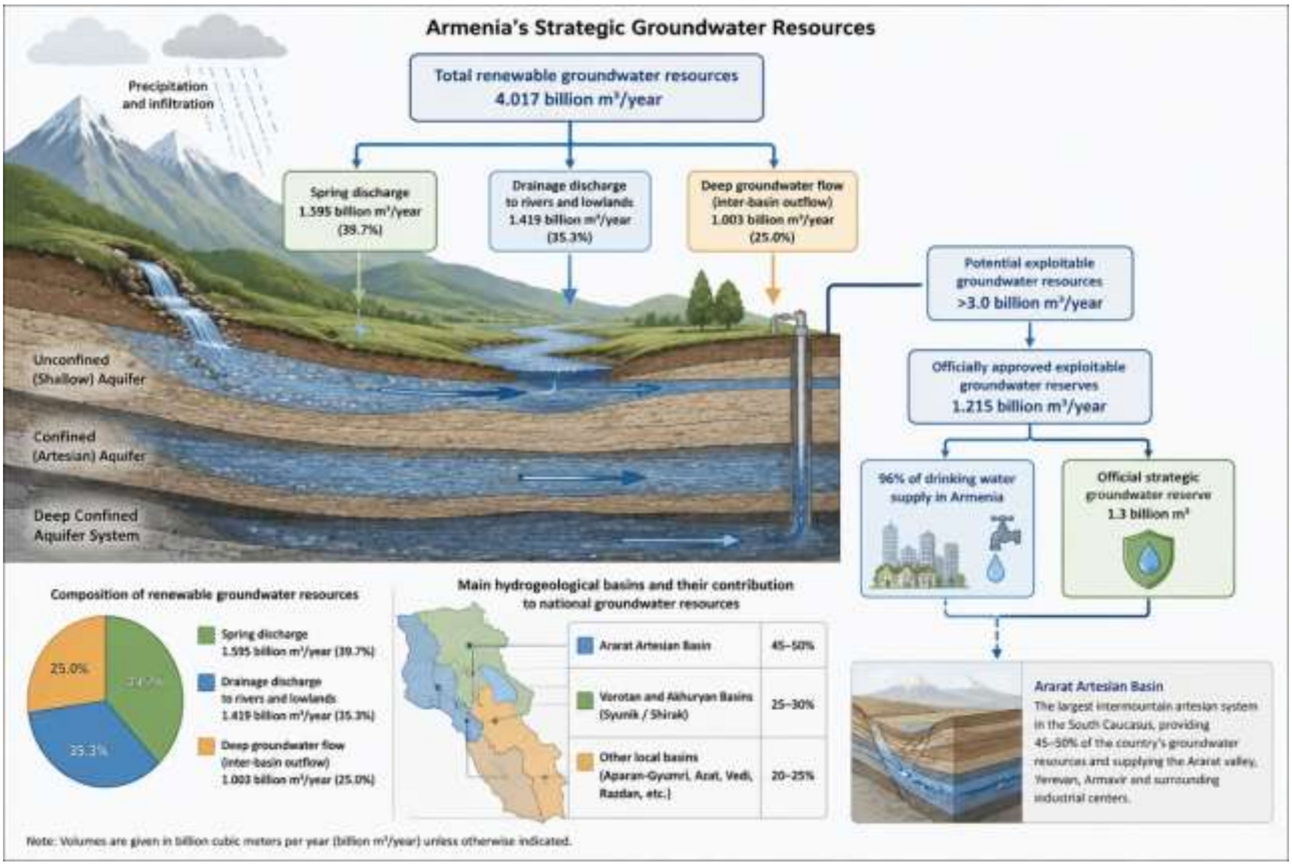

Fig. 2 Structure and Utilization of Armenia's Strategic Groundwater Resources

The characteristics of Armenia's strategic groundwater resources are presented in Table 2 and illustrated in Figure 2. The country possesses approximately 4.017 billion m³/year of renewable groundwater resources, which are replenished through natural hydrological processes and constitute the principal source of drinking water. Renewable groundwater consists of three major components: spring discharge (1.595 billion m³/year), drainage discharge (1.419 billion m³/year), and deep groundwater flow (1.003 billion m³/year), indicating a well-balanced hydrogeological system. Although the country's potential exploitable groundwater resources exceed 3.0 billion m³/year, the officially approved exploitable groundwater reserves amount to 1.215 billion m³/year, reflecting the volume that has been hydrogeologically verified and authorized for environmentally sustainable abstraction. Groundwater supplies approximately 96% of Armenia's centralized drinking water, highlighting its critical importance for national water security. Furthermore, the officially recognized strategic groundwater reserve of 1.3 billion m³, together with the dominant contribution of the Ararat Artesian Basin, demonstrates the strategic significance of groundwater resources for ensuring long-term drinking water security under increasing climatic and socio-economic pressures.

Table 3

Climate Change Indicators Affecting Drinking Water Resources in Armenia (2018–2025)

Year	Mean Annual Temperature (°C)	Temperature Anomaly (°C)	Annual Precipitation (mm)	Precipitation Relative to Climate Normal (%)
2018	9.1	+1.5	480–520	80–87
2019	8.5	+0.7	480–520	80–87
2020	9.0	+1.2	480–520	80–87
2021	8.9	+1.1	550	92
2022	8.2	+0.3	570	96
2023	9.02	+1.2	510	86
2024	8.87	+1.0	740.98	125
2025*	8.9–9.0	~+1.0	~490**	82–84

Preliminary estimates based on official hydrometeorological observations.

Climate normal (1991–2020): Mean annual precipitation: 592 mm. Temperature anomalies are calculated relative to the official climatic normal (1991–2020).

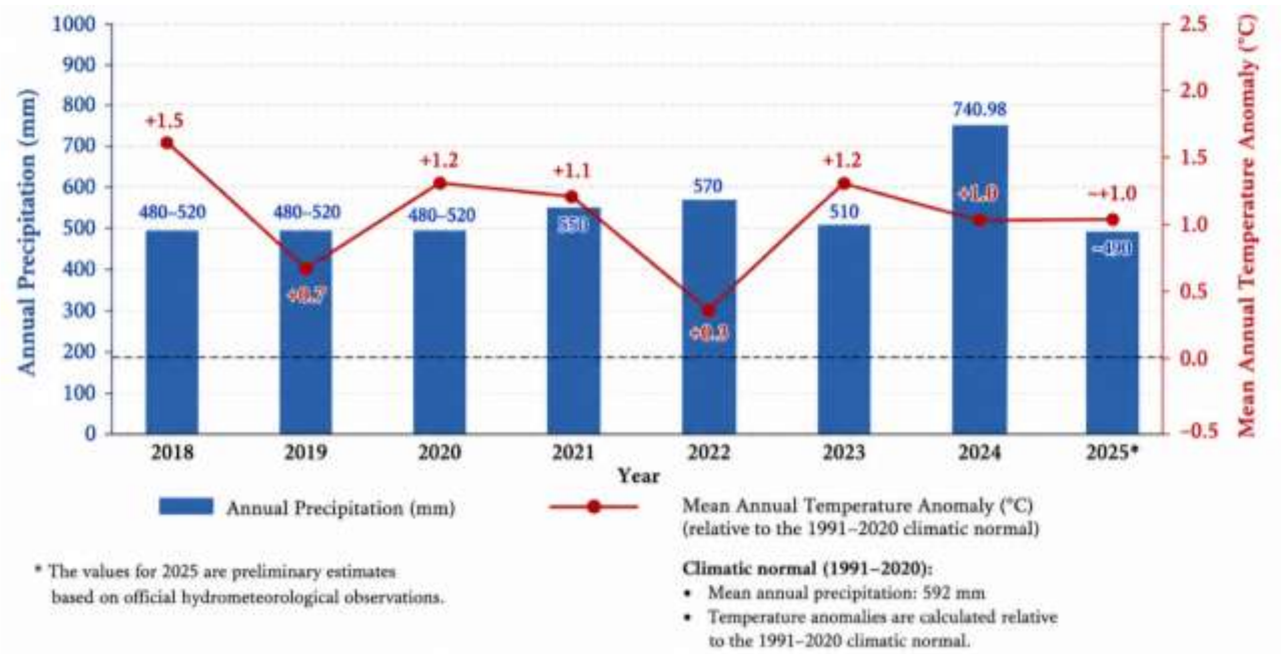

Fig. 3. Trends in Mean Annual Temperature Anomalies and Annual Precipitation in Armenia (2018–2025)

The Fig. 3 illustrates the temporal variation of two principal climatic indicators affecting drinking water resources in Armenia during 2018–2025. Annual precipitation is presented as bars, while mean annual temperature anomalies relative to the 1991–2020 climatic normal are shown as a line. The combined presentation highlights the persistent warming trend together with pronounced interannual precipitation variability, emphasizing the increasing climatic uncertainty influencing the long-term sustainability of drinking water resources.

Climate data presented in Table 3 and Figure 3 demonstrate a clear warming trend and increasing climatic variability in Armenia during the period 2018–2025. Mean annual air temperature remained consistently above the climatic normal throughout the study period, with positive anomalies ranging from +0.3°C to +1.5°C, confirming the ongoing warming observed across the country. At the same time, annual precipitation exhibited pronounced interannual variability, ranging from prolonged drought conditions during 2018–2020 and again in 2025 to exceptionally wet conditions in 2024. Such fluctuations indicate increasing climatic instability rather than a simple linear change in precipitation patterns.

These climatic changes have direct implications for the long-term sustainability of drinking water resources. Reduced snow accumulation, earlier snowmelt, and increasing evapotranspiration decrease groundwater recharge, while declining spring discharge and increasing dependence on groundwater abstraction place additional pressure on strategic drinking water reserves. According to national assessments, climate change has already contributed to measurable reductions in the discharge of mountain springs and has intensified pressure on the Ararat Artesian Basin. Climate projections indicate that by 2050, renewable groundwater resources may decline by approximately 8–10%, emphasizing the necessity of integrating climate adaptation measures into the strategic management of drinking water resources.

Table 4

Bottled Water Production and Groundwater Utilization in Armenia (2018–2025)

Indicator	Value	Unit
Bottled drinking and natural mineral water production (2024–2025)	145–155	million liters/year
Groundwater abstraction for bottled water production	0.145–0.155	million m^3/year
Share of officially approved exploitable groundwater reserves	~0.013	%
Bottled water export (2024)	30.9	million liters
Planned annual export growth	5–8	%
Principal export markets	Russia, USA, UAE, Kazakhstan, Ukraine	—
Main strategic groundwater pressure identified at the national level	Aquaculture and agricultural irrigation	—
Strategic environmental requirement for the bottled water industry	Continuous hydrogeological monitoring of mineral water sources	—

Note: Current official assessments indicate that bottled water production utilizes only a very small fraction of Armenia's officially approved exploitable groundwater reserves and therefore does not presently constitute a significant threat to national strategic drinking water resources. Nevertheless, continued industry expansion, combined with climate change and increasing groundwater demand, underscores the importance of preventive strategic groundwater management and continuous hydrogeological monitoring.

Fig. 4 illustrates the relative position of bottled water production within the overall structure of groundwater utilization in Armenia. The figure demonstrates that, although the bottled water industry has experienced continuous production and export growth, its current groundwater abstraction represents only a negligible proportion of the officially approved exploitable groundwater reserves. In contrast, aquaculture and agricultural irrigation constitute the principal anthropogenic pressures on groundwater resources. Nevertheless, considering projected climate change, increasing water demand, and the expected expansion of bottled water production, preventive strategic management and continuous hydrogeological monitoring remain essential to ensure the long-term sustainability of Armenia's strategic drinking water resources.

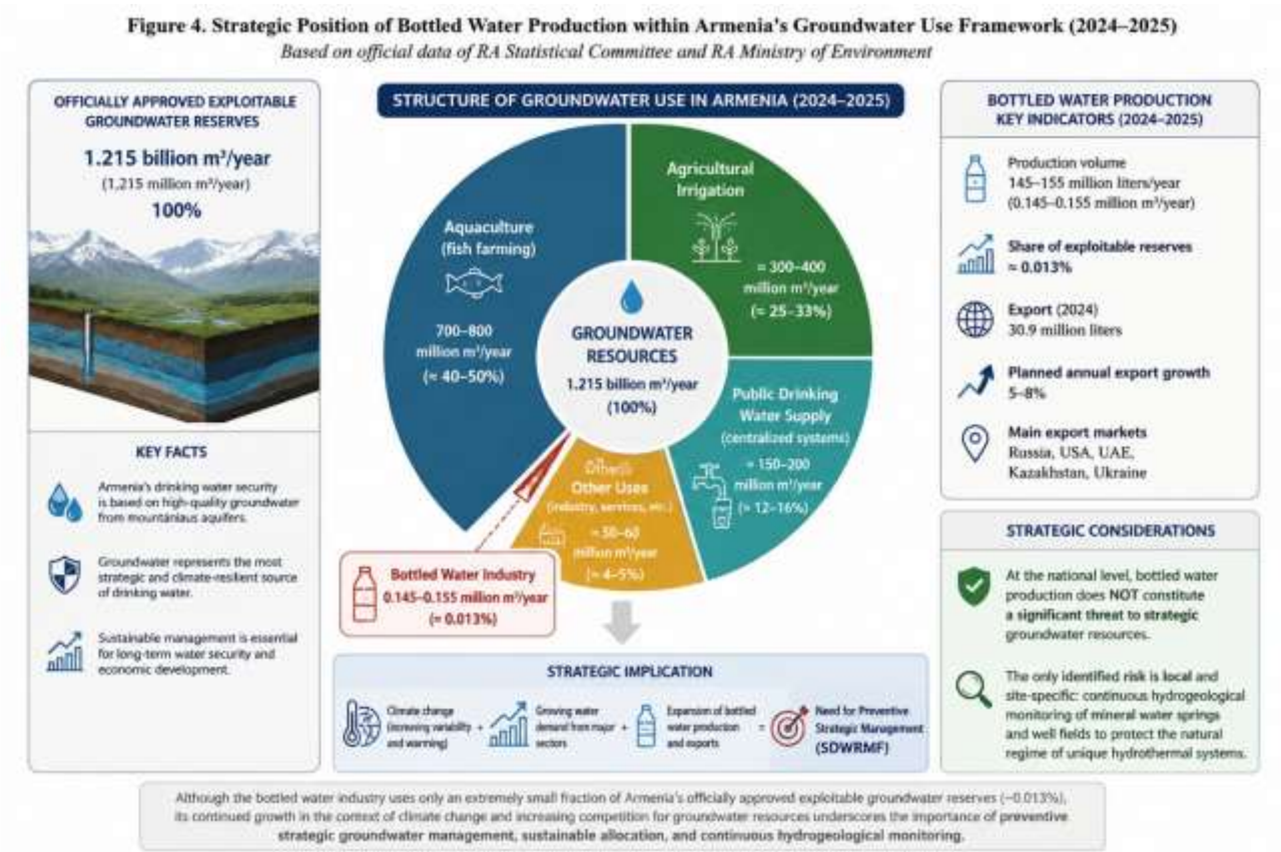

Fig. 4 Groundwater Utilization Structure and the Position of Bottled Water Production within Armenia's Strategic Water Resources Management Framework

The results presented in the preceding sections demonstrate that Armenia currently possesses sufficient strategic drinking water resources to ensure long-term national water security. However, the analysis also reveals that future sustainability cannot be evaluated solely on the basis of resource availability. Climate change is gradually reducing groundwater recharge, increasing climatic variability and uncertainty, while socio-economic development is expected to increase future water demand. At the same time, the bottled water industry continues to expand and contributes to economic growth and export development, although its current groundwater abstraction remains negligible in comparison with the officially approved exploitable groundwater reserves.

These findings indicate that strategic drinking water management should move beyond the traditional assessment of available water resources toward an integrated preventive management approach capable of simultaneously considering natural resource availability, climate-related risks, economic utilization, environmental sustainability, and long-term national water security. To address these challenges, this study proposes the Strategic Drinking Water Resource Management Framework (SDWRMF) as an integrated decision-support framework for balancing resource conservation, economic development, and sustainable groundwater utilization under changing climatic conditions.

The Strategic Drinking Water Resource Management Framework (SDWRMF) is designed to support long-term decision-making by integrating the principal factors affecting drinking water resource sustainability into a unified management system. Unlike conventional approaches that primarily focus on the availability of water resources, the proposed framework simultaneously considers the quantity and quality of drinking water resources, climate-related pressures, groundwater utilization, economic development, environmental protection, and institutional governance. This integrated perspective enables strategic decisions to be based not only on current resource availability but also on future risks and sustainability objectives, thereby strengthening the resilience of national drinking water resource management.

Fig. 5 Strategic Drinking Water Resource Management Framework (SDWRMF)

Fig. 5 presents the Strategic Drinking Water Resource Management Framework (SDWRMF) proposed in this study. The framework integrates five interrelated management dimensions: drinking water resources, climate change and associated risks, groundwater utilization, economic use and development, and institutional governance. These components are linked through an integrated assessment and decision-support process that enables comprehensive evaluation of resource conditions, climate-related pressures, groundwater sustainability, economic development, and governance effectiveness. The framework supports adaptive and preventive decision-making aimed at balancing resource conservation, sustainable economic development, and the long-term security of Armenia's strategic drinking water resources under changing climatic conditions.

Drinking Water Resources

The first component of the Strategic Drinking Water Resource Management Framework (SDWRMF) is based on the comprehensive assessment of drinking water resources. It encompasses not only the quantitative evaluation of available water resources but also the assessment of their quality, natural recharge capacity, strategic importance, and long-term sustainability. Particular attention is given to the interrelationship between surface water and groundwater resources, the protection of strategic water reserves, continuous monitoring of drinking water quality, and the maintenance of sustainable abstraction limits. This component forms the foundation of the SDWRMF, as all subsequent management decisions should be based on an objective assessment of the current condition of the country's drinking water resources and their capacity to ensure long-term water security.

Climate Change and Risk Assessment

The second component of the Strategic Drinking Water Resource Management Framework (SDWRMF) focuses on the assessment of climate change and its implications for the long-term sustainability of drinking water resources. This component evaluates trends in air temperature, precipitation, drought frequency, extreme hydrological events, and their influence on groundwater recharge, spring discharge, and drinking water availability. It also incorporates climate projections, vulnerability assessment, and scenario analysis to identify potential future risks affecting strategic water resources. By integrating climate-related information into the decision-making process, the framework supports adaptive management strategies that enhance the resilience of drinking water resources under changing environmental conditions and reduce the long-term risks associated with climate uncertainty.

Sustainable Groundwater Utilization

The third component of the Strategic Drinking Water Resource Management Framework (SDWRMF) focuses on ensuring the sustainable utilization of groundwater resources, which constitute the principal source of drinking water in Armenia. This component emphasizes maintaining a balance between groundwater abstraction and natural recharge while preserving groundwater quality and the long-term functionality of aquifer systems. It includes continuous hydrogeological monitoring, assessment of groundwater abstraction rates, protection of strategic groundwater reserves, regulation of groundwater use by different economic sectors, and prevention of localized overexploitation. Particular attention is given to preserving the hydrogeological stability of strategically important groundwater basins, especially the Ararat Artesian Basin, through science-based management, regular monitoring, and adaptive regulatory measures. This component ensures that groundwater utilization remains environmentally sustainable while supporting national drinking water security and socio-economic development.

Economic Development and Bottled Water Production

The fourth component of the Strategic Drinking Water Resource Management Framework (SDWRMF) addresses the relationship between economic development and the sustainable utilization of drinking water resources. The framework recognizes bottled drinking and natural mineral water production as an important contributor to national economic growth, employment, and export development. At the same time, it emphasizes that economic activities relying on strategic groundwater resources should be managed within scientifically justified and environmentally sustainable limits. This component promotes the integration of economic planning with groundwater resource protection through regular assessment of groundwater abstraction, continuous hydrogeological monitoring, environmental impact evaluation, and adaptive management mechanisms. Such an approach ensures that economic development can continue without compromising the long-term sustainability and strategic security of Armenia's drinking water resources.

Institutional Governance and Decision Support

The fifth component of the Strategic Drinking Water Resource Management Framework (SDWRMF) focuses on institutional governance and evidence-based decision support. It provides the organizational and regulatory foundation necessary for implementing integrated drinking water resource management at the national level. This component promotes coordination among governmental institutions, scientific organizations, water utilities, environmental authorities, and other stakeholders involved in water resource management. It also emphasizes continuous data collection, monitoring, information exchange, and periodic reassessment of management decisions based on updated scientific evidence and changing environmental conditions. By integrating reliable scientific information with adaptive governance mechanisms, this component enhances the effectiveness, transparency, and long-term resilience of strategic drinking water resource management while supporting informed policy development and sustainable decision-making.

Expected Benefits of Implementing the Strategic Drinking Water Resource Management Framework (SDWRMF)

The implementation of the Strategic Drinking Water Resource Management Framework (SDWRMF) is expected to strengthen the long-term sustainability, resilience, and efficiency of drinking water resource management in Armenia. By integrating hydrological, climatic, environmental, economic, and institutional information into a unified decision-support framework, SDWRMF enables a comprehensive assessment of both current conditions and future risks.

The proposed framework supports early identification of emerging threats to strategic drinking water resources, improves coordination among responsible institutions, promotes evidence-based policy development, and facilitates adaptive management under changing climatic and socio-economic conditions. Furthermore, SDWRMF provides a balanced approach that simultaneously supports groundwater conservation, sustainable economic development, and the protection of national drinking water security.

Beyond its application in Armenia, the conceptual structure of SDWRMF may also serve as a transferable decision-support framework for other countries facing similar challenges related to climate change, increasing groundwater demand, and the need to balance economic development with the long-term protection of strategic drinking water resources.

Discussion

Principal Scientific Findings

The present study demonstrates that Armenia possesses substantial strategic drinking water resources, primarily supplied by high-quality groundwater, which currently provide approximately 96% of the country's centralized drinking water supply. The assessment confirmed that the existing groundwater resources and officially approved exploitable reserves remain sufficient to support both domestic water supply and the continuing development of the bottled water industry. Nevertheless, the analysis indicates that the long-term sustainability of these resources cannot be evaluated solely on the basis of their current availability.

The results further demonstrate that climate change has become one of the principal long-term drivers influencing the sustainability of drinking water resources in Armenia. Persistent positive temperature anomalies, increasing climatic variability, changes in precipitation patterns, and projected reductions in groundwater recharge collectively increase uncertainty regarding future drinking water availability. These findings support the growing international consensus that strategic water management should increasingly focus on resilience and adaptive capacity rather than solely on resource abundance.

The study also demonstrates that the current scale of bottled drinking and mineral water production does not constitute a significant pressure on Armenia's strategic groundwater resources. According to the available official data, groundwater abstraction for bottled water production represents only a negligible proportion of the officially approved exploitable groundwater reserves. The principal anthropogenic pressures continue to originate from other sectors, particularly aquaculture and agricultural irrigation. However, the combination of climate change, increasing groundwater demand, and the expected long-term expansion of water-dependent economic activities justifies the adoption of preventive strategic management approaches.

The principal scientific contribution of this research is the development of the Strategic Drinking Water Resource Management Framework (SDWRMF), which integrates hydrological, climatic, environmental, economic, and institutional factors within a unified decision-support framework. Unlike conventional approaches that evaluate these factors separately, SDWRMF provides an integrated methodology for balancing drinking water resource conservation, sustainable economic development, and long-term national water security under changing climatic conditions.

Comparison with Previous Studies

Previous studies on Armenia's drinking water resources have primarily focused on individual aspects of water resource management, including hydrogeological characteristics, groundwater resources, drinking water quality, water supply systems, climate change impacts, or bottled water production. These studies have made important contributions to understanding the country's water resources and have provided valuable scientific and technical information for sectoral planning and resource management.

The findings of the present study are generally consistent with previous research regarding the strategic importance of groundwater resources, the increasing influence of climate change, and the growing economic significance of bottled water production. However, unlike earlier studies, which have largely examined these issues independently, the present research integrates them within a single strategic management perspective.

The principal distinction of the proposed Strategic Drinking Water Resource Management Framework (SDWRMF) lies in its ability to simultaneously consider resource availability, groundwater sustainability, climate-related risks, economic utilization, environmental protection, and institutional governance within a unified decision-support framework. This integrated approach provides a broader basis for strategic planning and policy development than conventional resource assessment methodologies.

Furthermore, although the framework was developed using Armenia as a case study, its conceptual structure is sufficiently flexible to be adapted for application in other countries facing similar challenges associated with climate change, increasing groundwater demand, and the need to balance economic development with long-term drinking water security.

Practical Implications of the Strategic Drinking Water Resource Management Framework (SDWRMF)

The proposed Strategic Drinking Water Resource Management Framework (SDWRMF) has important practical implications for the sustainable management of drinking water resources in Armenia. By integrating hydrological, climatic, environmental, economic, and institutional information into a unified decision-support framework, SDWRMF provides a systematic basis for strategic planning and evidence-based policy development.

The framework can support governmental institutions in evaluating alternative management scenarios, identifying emerging risks, prioritizing investments, and developing adaptive measures aimed at protecting strategic drinking water resources. It also facilitates coordination among institutions responsible for water management, environmental protection, climate adaptation, and economic development, thereby improving the overall effectiveness of water governance.

From an operational perspective, SDWRMF may be applied as a planning and assessment tool for groundwater monitoring programs, abstraction licensing, climate adaptation strategies, and long-term water resource planning. Its flexible conceptual structure allows periodic updating as new scientific information, monitoring data, and policy priorities become available, ensuring that management decisions remain responsive to changing environmental and socio-economic conditions.

The practical implementation of SDWRMF therefore represents not only a scientific contribution but also a potential management instrument for strengthening national drinking water security and supporting sustainable development under increasing climatic uncertainty.

Study Limitations and Future Research

Although the proposed Strategic Drinking Water Resource Management Framework (SDWRMF) provides an integrated approach to strategic drinking water resource management, several limitations should be acknowledged. First, the framework was developed using Armenia as the primary case study, and its application in other geographical and institutional settings will require adaptation to local hydrological, climatic, and governance conditions. Second, the present study is based primarily on officially available statistical, hydrological, and environmental data, which may be refined as new monitoring results and updated national databases become available.

Future research should focus on the practical implementation and validation of SDWRMF through detailed regional case studies, quantitative performance indicators, and scenario-based modelling under different climate and socio-economic development pathways. Additional research may also investigate the integration of remote sensing, geographic information systems, artificial intelligence, and real-time monitoring technologies into the framework to further improve decision support and adaptive water resource management.

Despite these limitations, the proposed framework establishes a comprehensive scientific foundation for strategic drinking water resource management and provides a flexible basis for future methodological development and international application.

Conclusions

1. The present study confirms that Armenia possesses substantial strategic drinking water resources, with groundwater constituting the principal source of the country's centralized drinking water supply. The current resource base remains sufficient to support both domestic water demand and the continued development of the bottled water industry.
2. Climate change represents one of the most significant long-term challenges for the sustainable management of Armenia's drinking water resources. Persistent warming, increasing climatic variability, and projected reductions in groundwater recharge highlight the necessity of integrating climate adaptation into strategic water resource management.
3. The analysis demonstrates that bottled drinking and natural mineral water production currently utilizes only a negligible proportion of the officially approved exploitable groundwater reserves. At present, the principal anthropogenic pressures on groundwater resources originate primarily from aquaculture and agricultural irrigation rather than from the bottled water industry.
4. The findings indicate that the long-term sustainability of strategic drinking water resources should be evaluated through an integrated perspective that simultaneously considers hydrological, climatic, environmental, economic, and institutional factors instead of relying solely on resource availability.
5. The Strategic Drinking Water Resource Management Framework (SDWRMF) proposed in this study provides an integrated decision-support framework capable of balancing drinking water resource conservation, sustainable groundwater utilization, economic development, and long-term national water security under changing climatic conditions.
6. The proposed framework offers practical opportunities for improving strategic planning, adaptive management, institutional coordination, and evidence-based policy development related to drinking water resource management in Armenia.
7. Although developed using Armenia as a case study, the conceptual structure of SDWRMF may also be adapted for application in other countries facing similar challenges associated with climate change, increasing groundwater demand, and the long-term protection of strategic drinking water resources.

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STRATEGIC MANAGEMENT OF DRINKING WATER RESOURCES IN ARMENIA: BALANCING CLIMATE CHANGE, BOTTLED WATER PRODUCTION, AND LONG-TERM WATER SECURITY

ՀԱՅԱՍՏԱՆԻ ԽՄԵԼՈՒ ՋՐԱՅԻՆ ՌԵՍՈՒՐՍՆԵՐԻ ՌԱԶՄԱՎԱՐԱԿԱՆ ԿԱՌԱՎԱՐՈՒՄԸ. ՀԱՎԱՍԱՐԱԿՇՌԵԼՈՎ ԿԼԻՄԱՅԱԿԱՆ ՓՈՓՈԽՈՒԹՅՈՒՆՆԵՐԸ, ՇՇԱԼՑՎԱԾ ՋՐԻ ԱՐՏԱԴՐՈՒԹՅՈՒՆԸ և ԵՐԿԱՐԱԺԱՄԿԵՏ ՋՐԱՅԻՆ ԱՆՎՏԱՆԳՈՒԹՅՈՒՆԸ

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Հայաստանը հարուստ է բարձրորակ խմելու ջրային ռեսուրսներով, ներառյալ ստորերկրյա ջրերը, աղբյուրները և հանքային ջրերը, որոնք հանդիսանում են երկրի բնապահպանական, տնտեսական և ռազմավարական կարևորագույն բնական պաշարներից մեկը: Միաժամանակ շշալցված ջրի արտադրության աճը, կլիմայական փոփոխությունները, ջրի պահանջարկի ավելացումը և երկարաժամկետ ջրային անվտանգության ապահովման անհրաժեշտությունը ձևավորում են նոր մարտահրավերներ այդ ռեսուրսների կայուն կառավարման համար: Չնայած Հայաստանը համարվում է համեմատաբար ջրառատ երկիր, խմելու ջրային ռեսուրսների երկարաժամկետ ապահովվածությունը չի կարող գնահատվել միայն դրանց առկա քանակական պաշարների հիման վրա: Ռազմավարական կառավարումը պահանջում է կլիմայական, բնապահպանական, տնտեսական և ինստիտուցիոնալ գործոնների համակցված գնահատում, որոնք ազդում են ինչպես ջրային ռեսուրսների հասանելիության, այնպես էլ դրանց կայունության վրա:

Սույն հետազոտությունը ներկայացնում է Հայաստանի խմելու ջրային ռեսուրսների համալիր գնահատում՝ վերլուծելով կլիմայական փոփոխությունների, շշալցված ջրի արտադրության և երկարաժամկետ ջրային անվտանգության միջև առկա փոխազդեցությունները: Վերլուծությունը հիմնված է պաշտոնական վիճակագրական տվյալների, հիդրոլոգիական տեղեկատվության, կլիմայական ցուցանիշների և ջրային ռեսուրսների կառավարման ու շշալցված ջրի արտադրության ոլորտը կարգավորող փաստաթղթերի ուսումնասիրության վրա: Հոդվածում գնահատվում են ջրառի, շշալցված ջրի արտադրության, ջրային ռեսուրսների օգտագործման դինամիկան և կլիմայական փոփոխությունների հնարավոր ազդեցությունները խմելու ջրի պաշարների վրա:

Բացահայտված հիմնախնդիրների հիման վրա առաջարկվում է խմելու ջրային ռեսուրսների ռազմավարական կառավարման ինտեգրված շրջանակ, որի նպատակն է ապահովել տնտեսական զարգացման և ջրային ռեսուրսների երկարաժամկետ պահպանության միջև հավասարակշռություն: Առաջարկվող մոտեցումը հիմնված է ստորերկրյա ջրերի կայուն կառավարման, կլիմայական փոփոխություններին հարմարվողականության, խմելու ջրի աղբյուրների պահպանության, մոնիթորինգի համակարգերի կատարելագործման, ջրային ռեսուրսների արդյունավետ բաշխման և գիտականորեն հիմնավորված որոշումների ընդունման սկզբունքների վրա: Հետազոտության արդյունքները կարող են նպաստել Հայաստանի ջրային քաղաքականության կատարելագործմանը և երկարաժամկետ ջրային անվտանգության ապահովմանն ուղղված ռազմավարությունների մշակմանը:

Բանալի բառեր՝ խմելու ջրային ռեսուրսներ, ռազմավարական կառավարում, շշալցված ջրի արտադրություն, կլիմայական փոփոխություններ, ստորերկրյա ջրեր, ջրային անվտանգություն, կայուն զարգացում, Հայաստան:

СТРАТЕГИЧЕСКОЕ УПРАВЛЕНИЕ РЕСУРСАМИ ПИТЬЕВОЙ ВОДЫ АРМЕНИИ: БАЛАНС МЕЖДУ ИЗМЕНЕНИЕМ КЛИМАТА, ПРОИЗВОДСТВОМ БУТИЛИРОВАННОЙ ВОДЫ И ДОЛГОСРОЧНОЙ ВОДНОЙ БЕЗОПАСНОСТЬЮ

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Армения располагает значительными запасами высококачественных ресурсов питьевой воды, включая подземные воды, родники и минеральные воды, которые являются одним из важнейших природных, экологических, экономических и стратегических ресурсов страны. Вместе с тем рост производства бутилированной воды, изменение климата, увеличение потребности в водных ресурсах и необходимость обеспечения долгосрочной водной безопасности формируют новые вызовы для устойчивого управления этими ресурсами. Несмотря на то что Армения традиционно считается страной, богатой водными ресурсами, долгосрочная обеспеченность питьевой водой не может оцениваться исключительно по объему существующих запасов. Стратегическое управление требует комплексного учета климатических, экологических, экономических и институциональных факторов, влияющих как на доступность, так и на устойчивость водных ресурсов.

В настоящем исследовании представлена комплексная оценка ресурсов питьевой воды Армении с анализом взаимосвязей между изменением климата, производством бутилированной воды и долгосрочной водной безопасностью. Исследование основано на официальных статистических данных, гидрологической информации, климатических показателях и нормативно-институциональных материалах, характеризующих управление водными ресурсами и развитие производства бутилированной воды. Выполнен анализ динамики водозабора, производства бутилированной воды, использования водных ресурсов, а также потенциального воздействия климатических изменений на ресурсы питьевой воды.

На основе выявленных проблем предложена интегрированная система стратегического управления ресурсами питьевой воды, направленная на обеспечение баланса между экономическим развитием и долгосрочным сохранением водных ресурсов. Предлагаемый подход основан на принципах устойчивого управления подземными водами, адаптации к изменению климата, охраны источников питьевой воды, совершенствования систем мониторинга, эффективного распределения водных ресурсов и принятия научно обоснованных управленческих решений. Полученные результаты могут способствовать совершенствованию водной политики Армении и разработке долгосрочных стратегий обеспечения водной безопасности.

***Ключевые слова*:** ресурсы питьевой воды, стратегическое управление, производство бутилированной воды, изменение климата, подземные воды, водная безопасность, устойчивое управление, Армения.

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PROJECT COMPLEXITY AND DESIGN SERVICE PRICING IN PUBLIC PROCUREMENT OF WATER INFRASTRUCTURE PROJECTS

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Abstract

The pricing of engineering design services represents an important component of infrastructure project preparation and directly influences the ability of design organizations to perform the investigations, calculations, and technical activities required for the development of reliable project documentation. However, in public procurement procedures, design service prices may be determined without systematic consideration of project technical complexity and the actual scope of engineering work.

This study evaluates the adequacy of design service pricing in public procurement procedures for water supply and irrigation infrastructure projects in the Republic of Armenia. The research is based on a comparative analysis of selected procurement procedures, project characteristics, contract prices, and estimated design costs derived from applicable pricing approaches. Project technical complexity is assessed using the Project Complexity Score (PCS), which integrates the principal engineering components of water infrastructure projects, including the number of settlements served, pipeline length, water intake structures, pumping stations, regulating reservoirs, and water treatment facilities.

The analysis compares project complexity levels with the design prices established in procurement procedures and examines whether increases in technical complexity are accompanied by corresponding increases in the financial resources allocated for design activities. To support the comparative assessment, a Design Price Adequacy Ratio (DPAR) is introduced as the ratio between the contracted design price and the estimated justified design price.

The results reveal substantial inconsistencies between project technical complexity and design service pricing. Projects with considerably different engineering workloads may receive similar levels of design financing, while in several cases the contracted design prices are significantly lower than the estimated values required for adequate project preparation. These findings indicate that project complexity and engineering workload are not systematically incorporated into the determination of design service prices.

The study concludes that integrating project complexity criteria and quantitative price adequacy indicators into public procurement planning could improve the transparency and technical justification of design service pricing, reduce the risks associated with underfunded design activities, and contribute to improving the quality and effectiveness of water infrastructure project preparation.

Keywords**:** public procurement; design service pricing; project complexity; Project Complexity Score; Design Price Adequacy Ratio; water supply systems; irrigation systems; engineering design.

Introduction

The preparation of reliable engineering design documentation is a critical stage in the development of infrastructure projects. Decisions made during the design phase influence project feasibility, construction cost, implementation schedules, operational reliability, and long-term infrastructure performance. Deficiencies originating during project preparation and design may subsequently lead to design modifications, rework, construction delays, cost overruns, quality deviations, and additional expenditures during project implementation [1–6]. Therefore, the effectiveness of infrastructure investment depends not only on the financial resources allocated for construction but also on the adequacy of resources provided for engineering investigations, technical analysis, and design activities before construction begins. Engineering design services represent a knowledge-intensive professional activity involving the integration of field investigations, engineering calculations, analysis of alternatives, development and verification of technical solutions, preparation of cost estimates, interdisciplinary coordination, and production of design documentation. The scope and intensity of these activities vary substantially depending on project size, technical configuration, the number and diversity of infrastructure components, environmental conditions, technological requirements, and the degree of interconnection among individual project systems [7–10]. Consequently, the resources required for engineering design should reflect the actual engineering workload and technical complexity of the project rather than being determined solely by the financial scale of the planned construction.

Water supply and irrigation infrastructure projects are particularly relevant in this context because their design frequently combines spatially extensive linear networks with hydraulic structures, mechanical and electrical equipment, and technological facilities. Engineering activities may include topographic and engineering-geological investigations, assessment of water sources, hydrological studies, water demand analysis, hydraulic modeling, pipeline design, and the development of water intake structures, pumping stations, regulating reservoirs, water treatment facilities, automation systems, and cost-estimation documentation [11–16]. The integrated development of these components requires the participation of specialists from several engineering disciplines and sufficient professional, organizational, and financial resources.

Public procurement procedures are intended to promote competition, transparency, equal treatment of economic operators, and efficient use of public resources. However, the economic efficiency of procurement cannot be evaluated solely through reductions in initial contract prices. Procurement approaches dominated by price competition may result in contract values that do not adequately reflect the actual scope, complexity, and professional effort required for engineering services [17–20]. This issue is particularly important for intellectual and professional services, where service quality depends strongly on specialist competence, labor input, data quality, technical analysis, and interdisciplinary coordination.

International research has demonstrated that procurement strategies and tender evaluation methods may significantly affect project performance. Excessive emphasis on the lowest initial price can encourage aggressive bidding and increase the risk that contractors or consultants operate under financial constraints inconsistent with the actual requirements of the assignment [17–22]. Although competitive pricing is an essential element of public procurement, insufficient financial resources for engineering design may restrict field investigations, reduce the depth of technical analyses, limit the assessment of alternative solutions, and decrease the resources available for design verification and coordination. Such limitations may subsequently contribute to design deficiencies, rework, project modifications, cost growth, and implementation difficulties [1–6, 21–24].

The determination of appropriate prices for engineering design services is complicated by the substantial differences among infrastructure projects. Projects with similar construction costs may require considerably different volumes of engineering work, whereas projects with different financial scales may involve comparable levels of technical effort. Construction cost alone therefore cannot provide a sufficient basis for evaluating the resources required for engineering design. Project complexity is a multidimensional characteristic associated with the number of technical components, their interdependencies, technological diversity, organizational interfaces, uncertainty, and the range of professional disciplines involved [7–10]. These characteristics directly affect the volume of investigations, engineering calculations, coordination activities, technical verification, and documentation required during the design process.

In water supply and irrigation projects, technical complexity may be influenced by the number of settlements served, total pipeline length, water intake structures, pumping stations, regulating reservoirs, water treatment facilities, and other hydraulic and technological components. An increase in the number and interconnection of such components generally increases the engineering workload required for project preparation. Nevertheless, procurement prices for design services are not always established using transparent quantitative criteria that explicitly reflect these differences in technical complexity and engineering effort.

Existing studies on public procurement primarily focus on competition, tender evaluation methods, procurement efficiency, construction costs, schedule performance, cost overruns, and the consequences of lowest-price selection [17–22, 25–27]. Research on project complexity, meanwhile, has developed conceptual and multidimensional approaches for understanding the influence of technical, organizational, and environmental characteristics on project management and performance [7–10]. However, considerably less attention has been given to the quantitative relationship between the technical complexity of infrastructure projects and the financial resources allocated for engineering design services, particularly in the water infrastructure sector.

This research addresses this gap by evaluating the relationship between project technical complexity and design service pricing in public procurement procedures for water supply and irrigation infrastructure projects in the Republic of Armenia. To provide a quantitative basis for comparative assessment, the study applies a Project Complexity Score (PCS) based on the principal technical components of water infrastructure projects. The obtained complexity scores are compared with contracted and estimated design prices to determine whether increasing project complexity is accompanied by a corresponding increase in the financial resources allocated for engineering design activities.

In addition, the study introduces the Design Price Adequacy Ratio (DPAR), defined as the relationship between the contracted design price and the estimated justified design price. The indicator is intended to support the identification of potential underpricing, overpricing, and disproportionality in the financing of engineering design services and to provide a quantitative basis for comparing procurement procedures involving projects with different technical characteristics.

The aim of the study is to determine whether the prices established for engineering design services adequately reflect the technical complexity and engineering workload of water supply and irrigation infrastructure projects and to identify potential inconsistencies in existing pricing practices. The results are expected to contribute to the development of more transparent, technically justified, and complexity-sensitive approaches to the pricing and procurement of engineering design services.

Literature Review

The scientific literature relevant to the pricing of engineering design services can be divided into several interconnected research directions: the consequences of deficiencies during project preparation and design, the multidimensional nature of project complexity, the technical characteristics of water infrastructure design, and the influence of procurement mechanisms and price-based competition on project performance. Although these research areas have developed largely independently, their integration provides an important theoretical basis for examining whether the financial resources allocated for engineering design services correspond to the technical complexity and engineering workload of infrastructure projects.

A substantial body of research has demonstrated that deficiencies originating during the design stage may significantly affect subsequent project implementation. Design errors, incomplete documentation, insufficient coordination, and inadequate technical analysis may contribute to rework, cost growth, delays, quality deviations, and additional expenditures during construction [1–6]. These findings indicate that engineering design should not be considered merely as a preliminary administrative stage of infrastructure development. Rather, it represents a critical professional process whose quality depends on the availability of sufficient technical, organizational, and financial resources.

Research on rework and design deficiencies has also shown that the consequences of inadequate project preparation may extend beyond direct correction costs. Design changes and errors can generate additional coordination requirements, disrupt construction processes, increase uncertainty, and affect overall project performance [1–6, 23, 24]. From the perspective of engineering service pricing, these findings are particularly relevant because insufficient resources allocated during the design stage may reduce the ability of design organizations to perform comprehensive investigations, evaluate alternatives, verify technical solutions, and coordinate the work of different engineering disciplines.

A second important research direction concerns the concept of project complexity. Project complexity has been described as a multidimensional characteristic that cannot be adequately represented by project size or construction cost alone. Baccarini conceptualized project complexity in terms of differentiation and interdependency among project elements [7], while subsequent studies expanded this understanding by incorporating technical, organizational, and environmental dimensions [8–10]. These approaches demonstrate that the resources required for project preparation and implementation depend not only on the financial scale of the project but also on the number of components, their interrelationships, technological diversity, organizational interfaces, uncertainty, and the range of professional disciplines involved.

The literature on project complexity therefore provides an important theoretical basis for evaluating engineering design services. As technical components and their interdependencies increase, the need for investigations, calculations, modeling, coordination, verification, and documentation also increases. However, most existing complexity frameworks have been developed primarily for project management, organizational analysis, and assessment of implementation risks [7–10]. Considerably less attention has been given to the direct quantitative relationship between project complexity and the financial resources required for engineering design activities.

Water supply and irrigation infrastructure projects provide a particularly relevant context for examining this relationship. The design of such projects may involve hydraulic modeling, optimization of water distribution systems, assessment of irrigation performance, design of pipelines and hydraulic facilities, and coordination of multiple interconnected technical components [11–16]. The literature demonstrates the increasing analytical and computational requirements associated with the design and optimization of water infrastructure systems. However, these studies primarily focus on technical performance, hydraulic optimization, system reliability, and operational efficiency rather than on the pricing and financial adequacy of professional engineering design services.

Another major research direction concerns public procurement and the mechanisms used for selecting contractors and professional service providers. Existing studies have examined tender evaluation methods, the role of price and non-price criteria, competition among bidders, and the influence of procurement strategies on project outcomes [17–22]. This literature demonstrates that the selection mechanism applied in procurement procedures may influence bidder behavior, contract prices, and subsequent project performance.

Particular attention has been given to procurement approaches dominated by the lowest initial price. Competitive bidding may contribute to the efficient use of public resources, but excessive price competition can also create incentives for aggressive bidding and contract prices that may not correspond to the actual requirements of the assignment [17–22]. For engineering design services, this issue is especially important because the final quality of the service depends strongly on specialist labor, professional expertise, investigation activities, technical analysis, interdisciplinary coordination, and design verification.

Studies addressing construction performance, cost overruns, and project implementation risks further demonstrate that decisions made during procurement and project preparation can have long-term consequences [23–27]. However, much of this literature focuses on construction contracts, large infrastructure projects, and implementation-stage performance. Professional engineering services are often considered indirectly, despite their critical role in determining the technical quality and reliability of project documentation.

The reviewed literature therefore reveals an important research gap. Existing studies provide substantial evidence regarding the consequences of design deficiencies, the multidimensional nature of project complexity, the technical requirements of water infrastructure design, and the influence of procurement and price competition on project performance. Nevertheless, these research directions have rarely been integrated into a quantitative framework for evaluating whether the prices established for engineering design services are proportionate to project technical complexity and engineering workload.

In particular, limited attention has been given to the development of measurable indicators that enable the comparison of project complexity with contracted design prices and justified design costs. The absence of such indicators restricts the ability of contracting authorities, researchers, and engineering organizations to identify potential underpricing, overpricing, or disproportionality in the financing of engineering design services.

Accordingly, the present study integrates two analytical dimensions that have generally been examined separately in previous research: the technical complexity of infrastructure projects and the financial adequacy of engineering design service pricing. The Project Complexity Score (PCS) is applied to provide a quantitative representation of the principal technical components affecting engineering workload, while the Design Price Adequacy Ratio (DPAR) is introduced to evaluate the relationship between contracted design prices and estimated justified design prices. The integration of these indicators provides the conceptual basis for the subsequent formulation of the research problem and methodological framework.

Conflict Setting

The pricing of engineering design services in public procurement involves a fundamental conflict between the objective of achieving cost efficiency through competitive procurement and the need to allocate sufficient financial resources for the proper preparation of technically complex infrastructure projects. Contracting authorities seek to obtain engineering services under economically advantageous conditions, whereas design organizations must perform the full scope of investigations, calculations, technical analyses, coordination activities, and documentation required to produce reliable design solutions.

This conflict becomes particularly significant when the financial resources allocated for engineering design are determined without explicit consideration of project technical complexity and engineering workload. Water supply and irrigation infrastructure projects may differ substantially in the number of settlements served, pipeline length, number and type of water intake structures, pumping stations, regulating reservoirs, treatment facilities, and other hydraulic and technological components. Consequently, projects included within the same general procurement category may require substantially different levels of professional effort, specialist participation, investigation activities, engineering calculations, and interdisciplinary coordination.

However, the pricing of engineering design services may not adequately reflect these differences. Projects characterized by substantially different technical configurations and engineering workloads may receive comparable levels of design financing. Conversely, projects with similar levels of technical complexity may be assigned considerably different contract prices. Such inconsistencies indicate that the relationship between project complexity and design service pricing requires systematic quantitative assessment.

A further methodological problem concerns the determination of a justified reference price for engineering design services. The contracted price resulting from a competitive procurement procedure represents the market outcome of bidding but does not necessarily indicate the financial resources objectively required for the adequate performance of the design assignment. At the same time, construction cost alone cannot serve as a sufficient indicator of engineering workload because projects with similar construction costs may differ substantially in technical complexity and design requirements.

Therefore, the assessment of design price adequacy requires two interconnected analytical dimensions. The first is the quantitative characterization of project technical complexity. The second is the comparison of the contracted design price with an estimated justified design price determined using a consistent and transparent calculation approach. The integration of these dimensions makes it possible to examine whether increasing project complexity is accompanied by a proportional increase in design financing and to identify cases of potential underpricing, overpricing, or disproportionality.

In this study, project technical complexity is evaluated using the Project Complexity Score (PCS), which integrates the principal technical components affecting engineering workload in water supply and irrigation infrastructure projects. The financial adequacy of design service pricing is evaluated using the Design Price Adequacy Ratio (DPAR), defined as the ratio of the contracted design price to the estimated justified design price.

Accordingly, the central research problem addressed in this study is the potential mismatch between the technical complexity of water supply and irrigation infrastructure projects and the financial resources allocated for engineering design services through public procurement procedures.

The main research question is formulated as follows: To what extent do the prices established for engineering design services in public procurement procedures reflect the technical complexity and engineering workload of water supply and irrigation infrastructure projects?

To answer this question, the study addresses three interconnected research questions:

1. Is there a statistically identifiable relationship between project technical complexity, expressed through the Project Complexity Score (PCS), and the contracted price of engineering design services?
2. To what extent do contracted design prices differ from estimated justified design prices for projects with different levels of technical complexity?
3. Can the Design Price Adequacy Ratio (DPAR) provide a consistent quantitative basis for identifying potential underpricing, adequate pricing, and overpricing of engineering design services?

The analysis of these questions provides the basis for evaluating whether existing design service pricing practices adequately account for differences in project technical complexity and for developing a more transparent and technically justified approach to the financial assessment of engineering design services.

Materials and Methods

Research Design and Data Selection

The study was designed as a quantitative comparative assessment of engineering design service pricing in public procurement procedures for water supply and irrigation infrastructure projects in the Republic of Armenia. The analytical framework was developed to examine whether differences in project technical complexity are reflected in the financial resources allocated for engineering design activities.

The empirical dataset consisted of selected public procurement procedures for engineering design services related to water supply and irrigation infrastructure projects. The unit of analysis was an individual procurement contract for the preparation of engineering design documentation. Projects were selected to ensure sufficient variation in technical characteristics, engineering workload, and contracted design prices.

The selection criteria required that each procurement procedure contain sufficient technical and financial information to identify the principal infrastructure components included in the design assignment and to determine the initial estimated procurement price and the final contracted design price. Projects for which the available procurement documentation did not provide sufficient information for consistent technical characterization or price comparison were excluded from the analysis.

For each selected project, data were collected on the type and scope of infrastructure, number of settlements served, total pipeline length, number of water intake structures, pumping stations, regulating reservoirs, water treatment facilities, and other major hydraulic and technological components. Financial data included the initial estimated procurement price and the final contracted price of the engineering design services.

To ensure comparability among projects with different technical configurations and financial scales, the analysis was conducted in four consecutive stages. First, the technical characteristics and financial data of the selected projects were compiled and standardized. Second, project technical complexity was quantified using the Project Complexity Score (PCS).

Third, contracted design prices were compared with estimated justified design prices, and the Design Price Adequacy Ratio (DPAR) was calculated. Finally, statistical relationships between project complexity and design service prices were examined, and the obtained results were interpreted through comparative analysis of projects with different complexity levels.

The methodological framework was therefore structured to evaluate two interconnected dimensions of engineering design service pricing: whether higher project complexity is associated with higher contracted design prices and whether the financial resources allocated through procurement procedures are proportionate to the estimated justified cost of the engineering design activities required.

Research Results

Financial Characteristics of the Selected Procurement Procedures

The empirical analysis included 30 public procurement procedures for engineering design services related to water supply, irrigation, and associated infrastructure projects in the Republic of Armenia. The analyzed procedures covered projects with substantially different construction costs and corresponding design price scales, providing an appropriate empirical basis for evaluating variations in the financial resources allocated for engineering design activities.

The construction costs of the analyzed projects ranged from approximately AMD 8.10 million to AMD 800.00 million. Depending on the construction cost category, the estimated justified design prices were calculated using design price rates ranging from 2–3% to 6–7%. The comparison revealed substantial variation between the estimated justified design price ranges and the prices established in the procurement procedures.

The results demonstrate that the analyzed procurement procedures cannot be characterized by a uniform relationship between construction cost and design service pricing. While some procurement prices were within or close to the estimated justified price ranges, a considerable number of cases were characterized by substantial underpricing. Several procedures showed particularly large discrepancies, with procurement prices representing only a fraction of the estimated minimum design price.

Tab. 1 presents the complete financial dataset used as the initial empirical basis for the subsequent analysis of project complexity and design price adequacy.

Project Complexity Assessment Using the Project Complexity Score (PCS)

To evaluate differences in the engineering workload associated with water supply and irrigation infrastructure projects, project technical complexity was quantified using the Project Complexity Score (PCS). The indicator was developed to transform the principal technical characteristics of the analyzed projects into a comparable quantitative measure of engineering complexity.

The PCS framework includes six technical components that directly influence the volume of investigations, engineering calculations, hydraulic analysis, interdisciplinary coordination, and design documentation required during project preparation: the number of settlements served, total pipeline length, number of water intake structures, pumping stations, regulating reservoirs, and water treatment facilities.

Table 1

Financial Characteristics of the Analyzed Procurement Procedures

Project	Construction Cost (AMD million)	Applicable Design Rate (%)	Estimated Justified Design Price (AMD million)	Procurement Price (AMD million)
P1	565.00	2–3	11.30–16.95	3.50
P2	800.00	2–3	16–20	12.75
P3	23.69	6–7	1.42–1.66	1.056
P4	66.00	6–7	3.96–4.62	4.40
P5	257.94	3–4	7.74–10.32	18.00
P6	51.78	6–7	3.11–3.62	2.20
P7	47.14	6–7	2.83–3.30	3.00
P8	37.40	6–7	2.24–2.62	3.10
P9	25.00	6–7	1.50–1.75	0.50
P10	13.20	6–7	0.79–0.92	0.80
P11	27.50	6–7	1.65–1.93	2.00
P12	20.60	6–7	1.24–1.44	1.20
P13	55.00	6–7	3.30–3.85	1.80
P14	8.10	6–7	0.54–0.63	0.90
P15	81.40	6–7	4.88–5.70	4.00
P16	12.21	6–7	0.73–0.85	0.40
P17	33.00	6–7	1.98–2.31	8.00
P18	≈18–22	6–7	1.08–1.54	0.25
P19	8.80	6–7	0.53–0.62	0.60
P20	24.45	6–7	1.47–1.71	1.50
P21	214.50	4–5	8.58–10.73	9.30
P22	20.90	6–7	1.25–1.46	1.344
P23	157.30	4–5	6.29–7.87	2.90
P24	9.60	6–7	0.58–0.67	0.60
P25	209.00	4–5	8.36–10.45	5.60
P26	230.00	4–5	9.20–11.50	2.00
P27	250.80	3–4	7.52–10.03	2.34
P28	≈28–35	6–7	1.68–2.45	1.64
P29	209.00	4–5	8.36–10.45	9.225
P30	223.27	4–5	8.93–11.16	10.55

Source: Authors' calculations based on public procurement documentation.

Because the selected technical components differ in measurement units and potential ranges, their raw values cannot be directly aggregated. Therefore, each component was transformed into a standardized component score using predefined ordinal scoring intervals. The scoring intervals were established to represent increasing levels of engineering workload associated with each technical characteristic.

The Project Complexity Score was calculated as:

$$PCS = w_1 S + w_2 L + w_3 I + w_4 P + w_5 R + w_6 T$$

where: **S** is the standardized score for the number of settlements served; **L** is the standardized score for total pipeline length; **I** is the standardized score for the number of water intake structures; **P** is the standardized score for the number of pumping stations; **R** is the standardized score for the number of regulating reservoirs; **T** is the standardized score for the number of water treatment facilities; and $\mathbf{w_1}$–$\mathbf{w_6}$ are the weighting coefficients assigned to the respective technical components.

The weighting coefficients were introduced because the selected technical components do not contribute equally to engineering workload. Pipeline length primarily affects the volume of surveying, hydraulic calculations, longitudinal profiles, and preparation of linear infrastructure documentation. Water intake structures, pumping stations, regulating reservoirs, and treatment facilities require additional structural, hydraulic, mechanical, electrical, technological, and automation design activities. The number of settlements served increases the spatial distribution of the project and the requirements for network coordination, demand assessment, and integration of individual system components.

For the present comparative assessment, the following weighting structure was applied:

Table 2

Weighting Coefficients Used for the Calculation of the Project Complexity Score (PCS)

Technical Component	Symbol	Weight
Number of settlements served	S	0.15
Total pipeline length	L	0.20
Water intake structures	I	0.15
Pumping stations	P	0.15
Regulating reservoirs	R	0.15
Water treatment facilities	T	0.20
Total		**1.00**

Each technical component was evaluated on a five-point ordinal scale ranging from 1 to 5. A score of 1 represents projects with a limited technical scope, while a score of 5 represents projects characterized by a large number or substantial scale of technical components and, consequently, greater engineering workload.

Table 3

Scoring Criteria for the Technical Components of the Project Complexity Score (PCS)

Score	Settlements Served	Pipeline Length (km)	Water Intakes	Pumping Stations	Regulating Reservoirs	Treatment Facilities
1	1	≤5	0	0	0–1	0
2	2–3	>5–15	1	1	2–3	1
3	4–6	>15–30	2	2	4–6	2
4	7–10	>30–50	3	3	7–10	3
5	>10	>50	≥4	≥4	>10	≥4

The resulting PCS values range theoretically from 1.00 to 5.00. For interpretation and comparative analysis, the projects were classified into four complexity levels.

Table 4

Classification of Projects According to the Project Complexity Score (PCS)

PCS Range	Complexity Level
1.00–1.99	Low complexity
2.00–2.99	Moderate complexity
3.00–3.99	High complexity
4.00–5.00	Very high complexity

The proposed PCS framework provides a consistent quantitative basis for comparing projects with different technical configurations. Rather than using construction cost as a proxy for engineering complexity, the indicator directly incorporates the principal infrastructure components that determine the scope of engineering investigations, calculations, coordination activities, and preparation of design documentation.

The calculated PCS values were subsequently compared with the procurement prices and estimated justified design prices presented in Table 1. This comparison was used to examine whether higher project complexity was accompanied by a corresponding increase in design financing and to identify potential inconsistencies between engineering workload and the financial resources allocated for project preparation.

Project Complexity Results

The application of the proposed PCS framework requires the technical characteristics of each analyzed project to be converted into standardized component scores according to the criteria presented in Table 3. The weighted component scores are then aggregated to obtain the final PCS value for each project.

However, the financial dataset presented in Table 1 does not by itself contain sufficient technical information for calculating PCS values for all 30 projects. Therefore, the PCS-based analysis was limited to those procurement procedures for which the available documentation provided complete and comparable information on the technical components included in the PCS framework.

Based on the completeness of the available technical documentation, projects with sufficient information on the number of settlements served, pipeline length, water intake structures, pumping stations, regulating reservoirs, and treatment facilities were selected for the PCS-based assessment. For each selected project, the original technical characteristics were converted into standardized scores using the criteria presented in Table 3, after which the weighted PCS value was calculated according to the adopted weighting coefficients.

The calculated component scores and the resulting PCS values for the selected projects are presented in Table 5. The table provides the quantitative basis for comparing project technical complexity with the corresponding design service prices and for the subsequent calculation of the Design Price Adequacy Ratio (DPAR).

Due to the absence of complete and comparable technical component data for all 30 procurement procedures, the subsequent price adequacy assessment was based primarily on the financial dataset presented in Table 1, while the PCS framework was used as a methodological basis for interpreting project complexity differences.

Design Price Adequacy Assessment

To quantitatively evaluate the adequacy of design service pricing, the procurement prices presented in Table 1 were compared with the estimated justified design prices. Since the justified design price was expressed as a range, the midpoint of the corresponding interval was used as the reference value for comparative calculations.

The Design Price Adequacy Ratio (DPAR) was calculated as:

$$DPAR = \frac{CP}{JPR}$$

where **CP** is the procurement price of the engineering design services and **JDP** is the estimated justified design price represented by the midpoint of the corresponding justified price interval.

Table 5

Design Price Adequacy Ratio (DPAR) for the Analyzed Procurement Procedures

Project	JDP Midpoint (AMD million)	Procurement Price (AMD million)	DPAR	Interpretation
P1	14.125	3.50	0.25	Underpricing
P2	18.000	12.75	0.71	Underpricing
P3	1.540	1.056	0.69	Underpricing
P4	4.290	4.40	1.03	Relatively adequate
P5	9.030	18.00	1.99	Overpricing
P6	3.365	2.20	0.65	Underpricing
P7	3.065	3.00	0.98	Relatively adequate
P8	2.430	3.10	1.28	Overpricing
P9	1.625	0.50	0.31	Underpricing
P10	0.855	0.80	0.94	Relatively adequate
P11	1.790	2.00	1.12	Relatively adequate
P12	1.340	1.20	0.90	Relatively adequate
P13	3.575	1.80	0.50	Underpricing
P14	0.585	0.90	1.54	Overpricing
P15	5.290	4.00	0.76	Relatively adequate
P16	0.790	0.40	0.51	Underpricing
P17	2.145	8.00	3.73	Overpricing
P18	1.310	0.25	0.19	Underpricing
P19	0.575	0.60	1.04	Relatively adequate
P20	1.590	1.50	0.94	Relatively adequate
P21	9.655	9.30	0.96	Relatively adequate
P22	1.355	1.344	0.99	Relatively adequate
P23	7.080	2.90	0.41	Underpricing
P24	0.625	0.60	0.96	Relatively adequate
P25	9.405	5.60	0.60	Underpricing
P26	10.350	2.00	0.19	Underpricing
P27	8.775	2.34	0.27	Underpricing
P28	2.065	1.64	0.79	Relatively adequate
P29	9.405	9.225	0.98	Relatively adequate
P30	10.045	10.55	1.05	Relatively adequate

Source: Authors' calculations based on the financial data presented in Table 1.

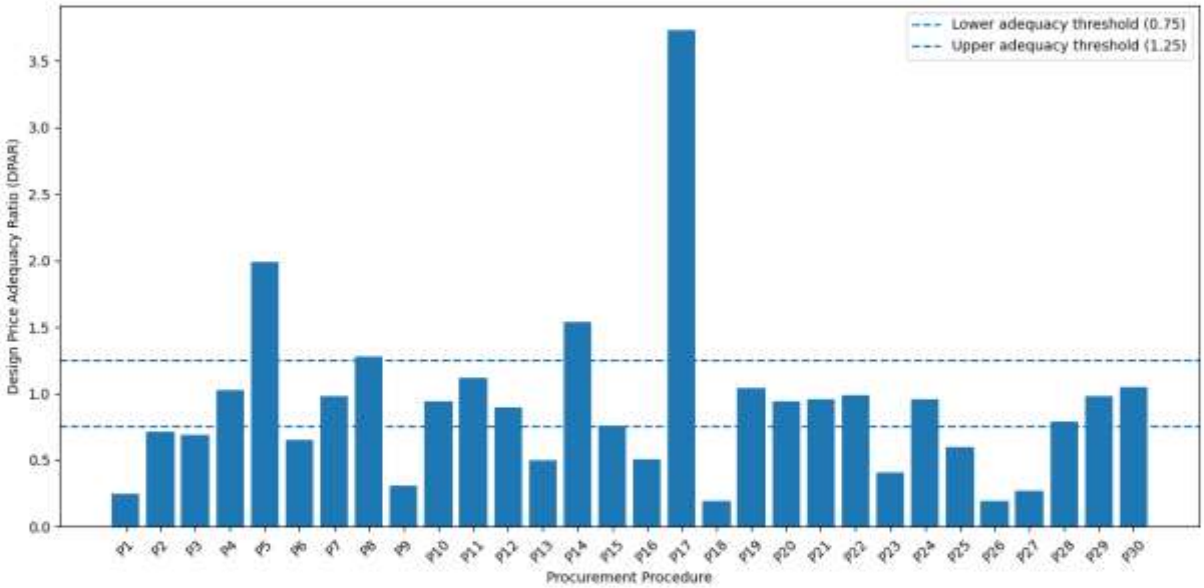

Fig. 1. Distribution of the Design Price Adequacy Ratio (DPAR) across the Analyzed Procurement Procedures

The distribution of DPAR values across the analyzed procurement procedures is presented in Fig. 1. The figure visually demonstrates substantial differences between procurement prices and estimated justified design prices. While a considerable number of procedures fall within the relatively adequate pricing range ($0.75 \leq DPAR \leq 1.25$), several cases are located substantially below or above the adopted adequacy thresholds. Particularly pronounced deviations are observed for P17 on the upper side and for P18 and P26 on the lower side. The simultaneous presence of substantial underpricing and overpricing provides additional evidence of inconsistencies in the existing pricing practices for engineering design services.

For interpretation purposes, DPAR values below 1.00 indicate that the procurement price is lower than the estimated justified design price, while values above 1.00 indicate that the procurement price exceeds the estimated justified reference value. In this study, DPAR values below 0.75 were interpreted as underpricing, values from 0.75 to 1.25 as relatively adequate pricing, and values above 1.25 as overpricing.

The DPAR results reveal substantial variation in the adequacy of design service pricing across the analyzed procurement procedures. Of the 30 cases, 12 were classified as underpriced, 14 as relatively adequate, and 4 as overpriced. Thus, 40% of the analyzed procedures were characterized by design prices below the adopted adequacy threshold, while only 46.7% fell within the relatively adequate pricing range. The remaining 13.3% exceeded the upper adequacy threshold. These results indicate that design service pricing practices are highly heterogeneous and that a considerable proportion of procurement procedures do not provide financial resources proportionate to the estimated justified design price.

The calculated DPAR values ranged from 0.19 to 3.73, indicating substantial differences in the relationship between procurement prices and estimated justified design prices. The lowest DPAR values were observed for P18 and P26 (0.19), followed by P1 (0.25) and P27 (0.27), demonstrating cases in which the procurement price represented only a small fraction of the estimated justified design price. Conversely, P17 showed the highest DPAR value (3.73), followed by P5 (1.99) and P14 (1.54), indicating substantial overpricing relative to the adopted reference value. The simultaneous presence of pronounced underpricing and overpricing suggests the absence of a consistent pricing mechanism capable of maintaining proportionality between procurement prices and estimated engineering design requirements.

The distribution of DPAR values further demonstrates that deviations from the estimated justified design prices were not limited to isolated procurement procedures. Underpricing was observed across projects with different construction costs and design price scales, indicating that inadequate design financing cannot be attributed exclusively to a particular project size category. Similarly, relatively adequate and overpriced cases were distributed across different financial groups. This pattern suggests that the observed pricing inconsistencies are systemic rather than associated solely with the financial scale of individual infrastructure projects.

Overall, the DPAR analysis demonstrates that the existing procurement pricing practices do not consistently ensure proportionality between the financial resources allocated for engineering design services and the estimated justified design prices. The results support the need for more transparent and quantitatively grounded pricing approaches that can reduce extreme deviations and improve the financial adequacy of engineering design contracts.

The identified variation in DPAR values raises an important question regarding the factors responsible for the observed pricing inconsistencies. Since projects with different construction costs exhibited underpricing, relatively adequate pricing, and overpricing, construction cost alone does not appear to provide a sufficient basis for determining appropriate design service prices. The obtained results therefore require further interpretation in relation to project technical complexity, procurement pricing practices, and the potential consequences of inadequate design financing.

Discussion

The results demonstrate that the pricing of engineering design services cannot be adequately explained by construction cost alone. The coexistence of substantial underpricing, relatively adequate pricing, and overpricing across projects of different financial scales indicates that the current pricing approach does not consistently reflect the actual engineering workload required for project preparation. This finding is particularly important for water supply and irrigation infrastructure projects, where the volume of engineering investigations, hydraulic calculations, technical solutions, and interdisciplinary coordination depends strongly on project configuration and technical complexity.

The DPAR distribution also indicates that the observed pricing inconsistencies cannot be interpreted simply as a general tendency toward underpricing. Although underpriced procedures constituted a substantial share of the analyzed cases, several projects were characterized by procurement prices considerably exceeding the estimated justified reference values. This bidirectional variation suggests that the principal problem lies not only in insufficient financing but also in the absence of a consistent and transparent mechanism for determining design service prices. A pricing system that produces both pronounced underpricing and overpricing may lead to inefficient allocation of public resources and reduce the predictability of engineering service procurement.

The results further indicate that construction cost-based pricing approaches should be complemented by explicit consideration of project technical complexity. Projects with similar construction costs may differ substantially in the number and type of infrastructure components, spatial extent, hydraulic configuration, and interdisciplinary design requirements. Consequently, the engineering workload associated with project preparation may vary even when projects belong to the same financial category. The PCS framework proposed in this study provides a methodological basis for incorporating these differences into the assessment of design service pricing and for moving toward more complexity-sensitive procurement practices.

The financial adequacy of engineering design contracts may also have implications for the quality of project preparation. When procurement prices are substantially lower than the estimated justified design prices, design organizations may face constraints in allocating sufficient resources to field investigations, engineering calculations, alternative analysis, technical verification, and interdisciplinary coordination. Conversely, procurement prices considerably exceeding justified reference values may indicate inefficient allocation of public funds. Therefore, improving design service pricing requires a balanced approach that seeks to ensure sufficient financing for technically adequate project preparation while simultaneously preventing unjustified expenditure of public resources.

The proposed combination of DPAR and PCS also has practical implications for public procurement decision-making. DPAR enables the identification of substantial deviations between procurement prices and estimated justified design prices, whereas PCS provides a structured basis for considering differences in project technical complexity. Used together, these indicators can support a more transparent preliminary assessment of whether the financial resources allocated for engineering design services are broadly consistent with the characteristics of the project. However, they should be regarded as decision-support tools rather than substitutes for detailed cost estimation and professional engineering judgment.

The findings of this study are consistent with previous research emphasizing that procurement decisions based predominantly on price may not adequately reflect the requirements of professional engineering services [17–22]. At the same time, the results extend the existing literature by demonstrating that the problem is not limited to lowest-price selection alone. The substantial dispersion of DPAR values indicates broader inconsistencies in the relationship between procurement prices and estimated justified design costs. This finding supports the need to complement conventional procurement criteria with quantitative indicators capable of evaluating price adequacy and project-specific engineering complexity.

The study has several limitations that should be considered when interpreting the results. The analysis was based on a limited dataset of public procurement procedures and on estimated justified design price ranges derived from the adopted pricing approach. In addition, complete and comparable technical data required for calculating PCS values were not available for all analyzed projects, which limited the empirical integration of project complexity and price adequacy. Future research should therefore expand the procurement dataset, apply the PCS framework to projects with complete technical characteristics, and examine the statistical relationship between project complexity, design service prices, and subsequent project implementation outcomes.

Overall, the findings demonstrate that improving the procurement of engineering design services requires moving from predominantly cost-based pricing toward a more differentiated approach that considers both financial adequacy and project-specific technical complexity. The combined use of DPAR and PCS provides a methodological basis for identifying pricing inconsistencies and supporting more transparent and technically justified procurement decisions. Although further empirical validation is required, the proposed framework offers a practical direction for improving the allocation of financial resources for engineering design services in water supply and irrigation infrastructure projects.

Conclusions

1. The analysis demonstrated substantial inconsistencies between the procurement prices of engineering design services and the estimated justified design prices for water supply and irrigation infrastructure projects. Only 46.7% of the analyzed procedures were classified as relatively adequate, while 40.0% were characterized by underpricing and 13.3% by overpricing.
2. The calculated DPAR values ranged from 0.19 to 3.73, revealing substantial dispersion in the relationship between procurement prices and estimated justified design prices. The simultaneous occurrence of pronounced underpricing and overpricing indicates that the identified problem cannot be explained solely by a general tendency toward insufficient financing of engineering design services.
3. The distribution of DPAR values across projects with different construction costs demonstrates that pricing inconsistencies are not confined to a particular financial scale of infrastructure projects. Construction cost alone therefore does not provide a sufficient basis for determining financially adequate prices for engineering design services.
4. The results support the need to complement construction cost-based pricing approaches with explicit consideration of project-specific technical complexity. The proposed PCS framework provides a structured methodological basis for representing differences in engineering workload associated with the number, scale, and configuration of the principal technical components of water infrastructure projects.
5. The combined application of DPAR and PCS provides a methodological framework for evaluating engineering design service pricing from two complementary perspectives: financial adequacy and project technical complexity. These indicators may support more transparent and technically justified procurement decisions but should be used as decision-support tools rather than substitutes for detailed cost estimation and professional engineering judgment.
6. Substantial underpricing of engineering design services may restrict the resources available for field investigations, engineering calculations, alternative analysis, technical verification, and interdisciplinary coordination, thereby increasing risks related to the quality of project preparation. Conversely, substantial overpricing may lead to inefficient allocation of public financial resources.
7. The findings demonstrate the need for a more transparent, differentiated, and quantitatively grounded mechanism for determining the prices of engineering design services in public procurement procedures. Such a mechanism should seek to ensure proportionality between the technical characteristics of infrastructure projects, the engineering workload required for project preparation, and the financial resources allocated for design activities.
8. Further research should expand the empirical procurement dataset, apply the PCS framework to projects with complete and comparable technical characteristics, and

statistically examine the relationships between project complexity, design service pricing, and subsequent project implementation outcomes. Such analysis would allow further validation and refinement of the proposed methodological framework.

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PROJECT COMPLEXITY AND DESIGN SERVICE PRICING IN PUBLIC PROCUREMENT OF WATER INFRASTRUCTURE PROJECTS

ՆԱԽԱԳԾԵՐԻ ԲԱՐԴՈՒԹՅՈՒՆԸ և ՆԱԽԱԳԾԱՅԻՆ ԾԱՌԱՅՈՒԹՅՈՒՆՆԵՐԻ ԳՆԱԳՈՅԱՑՈՒՄԸ ՋՐԱՅԻՆ ԵՆԹԱԿԱՌՈՒՑՎԱԾՔՆԵՐԻ ՊԵՏԱԿԱՆ ԳՆՈՒՄՆԵՐՈՒՄ

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Ինժեներական նախագծային ծառայությունների գնագոյացումը ենթակառուցվածքային նախագծերի նախապատրաստման կարևոր բաղադրիչ է և անմիջականորեն ազդում է նախագծային կազմակերպությունների՝ հուսալի նախագծային փաստաթղթերի մշակման համար անհրաժեշտ հետազննությունները, հաշվարկները և տեխնիկական աշխատանքներն իրականացնելու հնարավորության վրա: Սակայն պետական գնումների ընթացակարգերում նախագծային ծառայությունների արժեքները կարող են սահմանվել առանց նախագծերի տեխնիկական բարդության և ինժեներական աշխատանքների իրական ծավալի համակարգված հաշվառման:

Սույն հետազոտության նպատակն է գնահատել Հայաստանի Հանրապետությունում ջրամատակարարման և ոռոգման ենթակառուցվածքների նախագծերի պետական գնումների ընթացակարգերում նախագծային ծառայությունների գնագոյացման համարժեքությունը: Հետազոտությունը հիմնված է ընտրված գնման ընթացակարգերի, նախագծերի բնութագրերի, պայմանագրային արժեքների և կիրառվող գնագոյացման մոտեցումների հիման վրա որոշված նախագծային հաշվարկային արժեքների համեմատական վերլուծության վրա: Նախագծերի տեխնիկական բարդությունը գնահատվում է Project Complexity Score (PCS) ցուցանիշի միջոցով, որը ներառում է ջրային ենթակառուցվածքների նախագծերի հիմնական ինժեներական բաղադրիչները՝ սպասարկվող բնակավայրերի թիվը, խողովակաշարերի երկարությունը, ջրընդունիչ կառուցվածքները, պոմպակայանները, կարգավորիչ ջրամբարները և ջրի մաքրման կառույցները:

Վերլուծության ընթացքում համեմատվում են նախագծերի բարդության մակարդակները և գնման ընթացակարգերով սահմանված նախագծային ծառայությունների արժեքները՝ գնահատելու համար, թե արդյոք տեխնիկական բարդության աճն ուղեկցվում է նախագծային աշխատանքների իրականացման համար հատկացվող ֆինանսական միջոցների համապատասխան աճով: Համեմատական գնահատումն իրականացնելու նպատակով առաջարկվում է Design Price Adequacy Ratio (DPAR) ցուցանիշը՝ որպես նախագծային ծառայությունների պայմանագրային արժեքի և հիմնավորված հաշվարկային արժեքի հարաբերակցություն:

Արդյունքները ցույց են տալիս նախագծերի տեխնիկական բարդության և նախագծային ծառայությունների գնագոյացման միջև էական անհամապատասխանություններ: Ինժեներական աշխատանքների ծավալով զգալիորեն տարբերվող նախագծերի համար կարող են սահմանվել նախագծային ֆինանսավորման համադրելի մակարդակներ, մինչդեռ մի շարք դեպքերում պայմանագրային արժեքները զգալիորեն ցածր են նախագծերի պատշաճ նախապատրաստման համար անհրաժեշտ հաշվարկային արժեքներից: Ստացված արդյունքները վկայում են, որ նախագծերի բարդությունը և ինժեներական աշխատանքների ծավալը համակարգված կերպով չեն ներառվում նախագծային ծառայությունների արժեքների որոշման գործընթացում:

Հետազոտությունը եզրակացնում է, որ նախագծերի բարդության չափանիշների և գնային համարժեքության քանակական ցուցանիշների ներառումը պետական գնումների պլանավորման գործընթացում կարող է բարձրացնել նախագծային ծառայությունների գնագոյացման թափանցիկությունն ու տեխնիկական հիմնավորվածությունը, նվազեցնել թերֆինանսավորված նախագծային աշխատանքների հետ կապված ռիսկերը և նպաստել ջրային ենթակառուցվածքների նախագծերի նախապատրաստման որակի ու արդյունավետության բարձրացմանը:

Բանալի բառեր՝ պետական գնումներ, նախագծային ծառայությունների գնագոյացում, նախագծերի բարդություն, Project Complexity Score (PCS), Design Price Adequacy Ratio (DPAR), ջրամատակարարման համակարգեր, ոռոգման համակարգեր, ինժեներական նախագծում:

СЛОЖНОСТЬ ПРОЕКТОВ И ЦЕНООБРАЗОВАНИЕ ПРОЕКТНЫХ УСЛУГ В ГОСУДАРСТВЕННЫХ ЗАКУПКАХ ПРОЕКТОВ ВОДНОЙ ИНФРАСТРУКТУРЫ

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Ценообразование инженерно-проектных услуг является важным компонентом подготовки инфраструктурных проектов и непосредственно влияет на способность проектных организаций выполнять изыскания, расчёты и технические работы, необходимые для разработки надёжной проектной документации. Однако в процедурах государственных закупок стоимость проектных услуг может определяться без систематического учёта технической сложности проектов и фактического объёма инженерных работ.

Целью настоящего исследования является оценка адекватности ценообразования проектных услуг в процедурах государственных закупок проектов инфраструктуры водоснабжения и орошения в Республике Армения. Исследование основано на сравнительном анализе выбранных процедур закупок, характеристик проектов, договорных цен и расчётной стоимости проектных работ, определённой на основе применяемых подходов к ценообразованию. Техническая сложность проектов оценивается с использованием показателя Project Complexity Score (PCS), который учитывает основные инженерные компоненты проектов водной инфраструктуры, включая количество обслуживаемых населённых пунктов, протяжённость трубопроводов, водозаборные сооружения, насосные станции, регулирующие резервуары и сооружения водоподготовки.

В ходе анализа сопоставляются уровни сложности проектов и стоимость проектных услуг, установленная в процедурах закупок, с целью определения того, сопровождается ли увеличение технической сложности соответствующим увеличением финансовых ресурсов, выделяемых на выполнение проектных работ. Для проведения сравнительной оценки предлагается показатель Design Price Adequacy Ratio (DPAR), определяемый как отношение договорной стоимости проектных услуг к расчётной обоснованной стоимости проектирования.

H.V. Tokmajyan, A.Kh. Markosyan, E.Yu.. Galstyan

PROJECT COMPLEXITY AND DESIGN SERVICE PRICING IN PUBLIC PROCUREMENT OF WATER INFRASTRUCTURE PROJECTS

Результаты исследования выявляют существенные несоответствия между технической сложностью проектов и ценообразованием проектных услуг. Проекты, значительно различающиеся по объёму и сложности инженерных работ, могут получать сопоставимые объёмы финансирования проектирования, тогда как в ряде случаев договорная стоимость проектных услуг значительно ниже расчётных значений, необходимых для надлежащей подготовки проектов. Полученные результаты свидетельствуют о том, что техническая сложность проектов и объём инженерных работ систематически не учитываются при определении стоимости проектных услуг.

В исследовании делается вывод о том, что включение критериев сложности проектов и количественных показателей адекватности стоимости в процесс планирования государственных закупок может повысить прозрачность и техническую обоснованность ценообразования проектных услуг, снизить риски, связанные с недостаточным финансированием проектных работ, и способствовать повышению качества и эффективности подготовки проектов водной инфраструктуры.

***Ключевые слова*:** государственные закупки; ценообразование проектных услуг; сложность проектов; Project Complexity Score (PCS); Design Price Adequacy Ratio (DPAR); системы водоснабжения; оросительные системы; инженерное проектирование.

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