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# Adaptive Water Governance Model in Azerbaijan: Integrating International Experience under Climate and Institutional Risks

**Natiq Pasha[1]* [0000-0002-5666-6835], Rashail Ismayilov[2] [0000-0002-3944-355X] and Orkhan Mikayil[3] [0009-0000-9536-2407]**
[1]Azerbaijan Technical University, Azerbaijan
[2]Water and Amelioration Scientific Research Institute, Azerbaijan State Water Resources Agency Resources Agency
[3]Aqualik LLC, Azerbaijan, om@aqualink.az
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*to whom all correspondence should be addressed: e-mail: pashanatiq@aztu.edu.az
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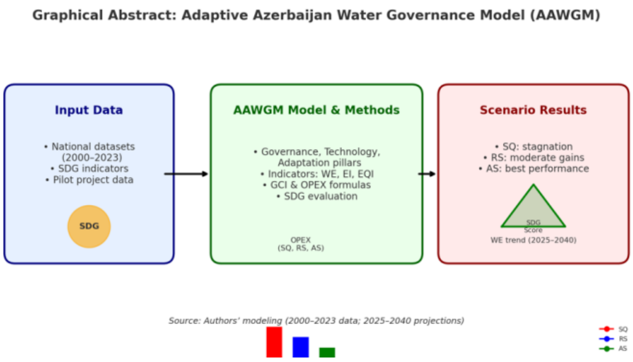
## Graphical abstract




## Abstract

Azerbaijan faces persistent water scarcity linked to climate variability, increasing demand, and dependence on transboundary inflows from the Kura and Araz rivers. These pressures highlight the need for a more coordinated and adaptable water-management system. In this study, the Adaptive Azerbaijan Water Governance Model (AAWGM) is introduced as a practical framework that draws on the governance experience of the European Union's Water Framework Directive (EU WFD) and modern water-reuse and irrigation practices. The model focuses on three priority areas: reducing agricultural water losses, upgrading outdated infrastructure, and improving ecosystem conditions. The assessment is based on indicator-driven analysis using the Governance Coordination Index (GCI), Operational Expenditures (OPEX), and SDG-related metrics. Historical data for 2000–2023 were used to calibrate and validate the model, yielding a scenario-fit accuracy of $R^2 = 0.92$ across the main indicators. Projections for 2025–2040 show that adaptive and technology-supported scenarios offer clear advantages over the Status Quo, lowering long-term operating costs while improving water-use efficiency, ecological quality, and institutional coordination. The results align with several SDGs, particularly 6, 7, 13, 15, and 17, and suggest that the AAWGM can serve as a realistic and scalable approach for countries facing similar challenges. By combining international experience with local needs and data, the model outlines a feasible pathway for strengthening water security and building resilience to climate and institutional risks in Azerbaijan.

**Keywords:** Adaptive Water Governance; EU WFD; Israel Water Innovations; Governance Coordination Index (GCI); Operational Expenditures (OPEX); SDGs (6, 7, 13, 15, 17)

## 1. Introduction

Water scarcity has become one of the central constraints to sustainable development in arid and semi-arid regions, and Azerbaijan is no exception. More than 60% of the country's renewable water resources originate outside its borders, primarily through the Kura and Araz rivers, making national water availability highly sensitive to upstream conditions (Ahmadov 2020; Abbasov R. 2020). In recent decades, shifts in precipitation patterns, declining river inflows, and higher evapotranspiration have intensified this dependence (Han *et al.* 2024). At the same time, internal pressures such as aging irrigation canals, high conveyance losses, and inefficient agricultural water use—accounting for over 70% of total withdrawals—further deepen existing shortages (Ismayilov & Suleymanov 2024; Pasha *et al.* 2023; Suleymanov 2024). A practical example of this imbalance is seen during low-flow years, when irrigation demand remains high while reduced inflows to the Mingachevir reservoir limit both downstream supply and hydropower production, creating short-term operational trade-offs for multiple sectors.

Concerns over water security are not unique to Azerbaijan. Worldwide, 2.2 billion people still lack access to safely managed drinking water, and climate-related extremes affect the timing and reliability of water supplies across all regions (UN WWDR 2024). Nearly half of the global population lives in transboundary basins, where competing sectoral demands and institutional fragmentation frequently hinder coordinated decision-making (Scandizzo and Abbasov 2022; Sabbaghi 2025). These trends highlight the growing need for governance frameworks that can respond to uncertainty while balancing ecological, economic, and social objectives.

International experience offers valuable insights. The European Union's Water Framework Directive (EU WFD) demonstrates the importance of river-basin planning, ecological status assessment, and stakeholder participation in setting and achieving water management targets (Sadeghi *et al.* 2023; Abbasov and Flores 2023). Israel, although operating under very different hydrological conditions, provides another practical example: extensive wastewater reuse, precision irrigation, and real-time monitoring systems have allowed the country to maintain agricultural productivity despite chronic water scarcity (Sidorova 2025; Guliyev *et al.* 2023; Abduev *et al.* 2024). While both pathways are well documented, their combined relevance for Azerbaijan – where basin-level planning intersects with the need for technological modernization—has received limited attention in the literature (Aliyev and Zohrabbayli 2025; Penahova and Aliyeva 2024).

Existing studies in Azerbaijan have largely examined climate impacts, transboundary governance, or technology adoption in isolation (Umudov 2021; Burkhanov *et al.* 2025). However, there is still no integrated framework that brings these elements together in a single, adaptive structure. This study addresses that gap by introducing the Adaptive Azerbaijan Water Governance Model (AAWGM), which synthesizes EU WFD principles with Israeli experience in water reuse and irrigation to create a context-specific governance and technology model for Azerbaijan.

The guiding question of the research is as follows: How can an integrated governance framework that blends EU WFD principles with Israeli reuse and irrigation technologies be adapted to Azerbaijan's hydrological, socio-economic, and institutional setting to improve efficiency, resilience, and long-term sustainability under climate change?

Although developed for Azerbaijan, the AAWGM has broader relevance. Many semi-arid regions—such as parts of India, Australia, and South Africa—face similar challenges related to increasing demand, climate variability, and complex institutional structures. The model therefore offers a transferable approach for countries seeking to combine governance reforms with practical technological solutions at basin and sectoral levels.

### *1.1. Motivation, Aim, Objectives, and Scope of the Study.*

Azerbaijan's growing water stress, dependence on external inflows, and the need for coordinated sectoral decision-making create a strong motivation for developing an adaptive governance model. The aim of the study is to design and evaluate a governance and technology framework that enhances national water security under climate and institutional risks.

The specific objectives are to:

1) integrate international governance and technological practices into a unified model tailored to national conditions;
2) evaluate Azerbaijan's water system using indicator-based assessment tools; and
3) compare future scenarios to identify the most efficient and resilient pathways.

The scope of the research includes national-scale water management, agricultural and environmental indicators, and long-term scenarios for 2025–2040 based on historical data from 2000–2023.

## 2. Literature Review

### *2.1. Sustainable Water Management and Integrated Approaches*

The EU Water Framework Directive (WFD) is widely regarded as one of the most comprehensive examples of integrated water management. Francés *et al.* (2017) note that it shifted European water policy toward a basin-oriented approach that prioritizes ecological status and stakeholder involvement. Albiac *et al.* (2024) further emphasize that the directive offers a stable institutional and legal basis for balancing ecological goals with economic considerations.

Beyond its regulatory structure, the WFD operates as an adaptive governance platform. Hüesker and Moss (2015) highlight that its effectiveness largely depends on coordination across administrative levels, while Hoffmans *et al.* (2025) show that WFD-aligned monitoring systems have become essential for evaluating ecological conditions. The directive's integration with broader socio-economic strategies has also been documented. Pellegrini *et al.* (2019) and Boon *et al.* (2020) report that alignment with agriculture, energy, and urban planning has improved policy coherence and resource efficiency in member states.

Transboundary cooperation represents another key dimension. Skoulikaris (2021) and Baranyai (2019) describe how WFD principles facilitate collaboration among countries sharing river basins, while Heldt *et al.* (2017) point out that its institutional influence extends beyond the EU. The directive's focus on ecological indicators is equally significant: Kagalou and Latinopoulos (2020) and Selek and Selek (2019) show that hydromorphological and biological parameters have strengthened ecological assessments, and Skoulikaris and Zafirakou (2019) argue that these tools support strategic adaptation under climate variability.

Collectively, the literature recognises the WFD as a global reference for integrated and adaptive governance. Baattrup-Pedersen *et al.* (2018) and Evers (2016) underscore its widespread relevance and its potential to inform policy processes outside Europe. However, despite its broad applicability, the practical adaptation of WFD principles to semi-arid and institutionally constrained environments such as Azerbaijan remains limited. This gap underscores the need for research that examines how its governance standards can be translated into contexts facing water scarcity, climate pressures, and complex institutional structures.

*2.2. Modeling Approaches in Water Management*

A key strength of the AAWGM is its emphasis on adaptive management, an approach that allows policies and operational decisions to evolve in response to environmental, institutional, and climatic changes (Pahl-Wostl *et al.* 2007). This principle supports continuous learning and adjustment by incorporating up-to-date observations, risk trends, and sectoral demands into the decision-making process (Pasha *et al.* 2025; Natiq Pasha 2024).

Within the AAWGM structure, adaptive management is implemented through several complementary mechanisms.

First, regular monitoring and evaluation rely on both field measurements and remote-sensing observations to track water availability, evapotranspiration, infrastructure performance, and cross-sectoral usage patterns (Abdelhaleem *et al.* 2021). Recent studies show that digital monitoring tools—particularly IoT-supported sensor networks and data-driven models—can enhance the reliability of real-time assessments in wastewater systems and irrigation settings, providing early warnings and improving operational decisions (Selvanarayanan *et al.* 2024; Maruthai *et al.* 2025).

Second, scenario-based planning enables the assessment of irrigation efficiency, reuse options, and governance reforms under varying climatic and socio-economic futures (Trifonov *et al.* 2017; Liao *et al.* 2021) . This approach helps to compare long-term trajectories and identify strategies that remain robust under uncertainty.

Third, institutional flexibility is central to adaptive governance. By allowing legislation and management arrangements to evolve alongside environmental and economic conditions, institutions can better respond to climate variability while aligning their objectives with SDG-related performance indicators (Liu *et al.* 2025)

Finally, public participation and stakeholder engagement support more legitimate and informed decision-making. Decision-support platforms and consultation processes help water users and communities contribute to planning, thereby improving transparency and acceptance (Bonfante *et al.* 2019).

Together, these mechanisms provide a foundation for long-term water security by strengthening efficiency, supporting reuse, and protecting ecosystem services. In parallel, operational expenditures (OPEX) are computed using official data from the Azerbaijan State Water Resources Agency (ASWRA) and the State Statistical Committee, as well as pilot project inputs from Aqualink and international benchmarks (FAO, World Bank, OECD). Although adaptive management is well described in global literature, its practical operationalization in data-scarce and institutionally constrained settings such as Azerbaijan remains limited. By linking adaptive processes with measurable indicators—such as OPEX, governance performance, and scenario evaluation—this study offers a concrete pathway for translating conceptual frameworks into applied national water-governance tools.

*2.3. International Experiences - European Union and Israel Case Studies*

At the international level, the EU Water Framework Directive (WFD) continues to serve as one of the most influential governance models for sustainable water management. Ali *et al.* (2025) highlight that basin-level planning forms the backbone of EU water policy, integrating ecological, social, and economic considerations. Rokaya *et al.* (2025) further observe that the strength of the directive lies in its ability to harmonize national policies across Member States, thereby promoting ecological resilience and economic efficiency. Abdelhaleem *et al.* (2021) add that the WFD maintains flexibility to address emerging pressures such as climate change, agriculture-related demand, and industrial expansion.

From a governance standpoint, transparency, stakeholder participation, and cross-sectoral coordination are emphasized as core features. Bonfante *et al.* (2019) and Owolabi *et al.* (2020) show that these principles help ensure that management decisions are both scientifically grounded and publicly legitimate. The influence of the WFD has extended beyond Europe as well, informing policy development in regions facing similar sustainability challenges.

Israel provides a complementary case, shaped by chronic water scarcity and limited freshwater availability. Technological innovation has become central to its national water strategy. Imran and Li (2025) report that large-scale wastewater reuse now supports a significant share of agricultural production, reducing reliance on freshwater resources. Sharma *et al.* (2025) emphasize the role of desalination and efficient irrigation systems in maintaining national water security.

Institutional factors also play an important role. Clear tariff structures, efficiency incentives, and long-term investment in research and development have reinforced the country's innovation-oriented system (Helman *et al.* 2022; Riad *et al.* 2020). Advances in environmental data processing—including recent applications of optimization algorithms for improving remote-sensing analysis—further demonstrate how analytical tools can enhance technology-driven water management under scarcity (Sivasubramanian *et al.* 2025).

For Azerbaijan, both the EU and Israeli experiences offer important lessons. The WFD illustrates the value of integrated governance, basin-scale planning, and stakeholder engagement, while Israel shows how technology, institutional alignment, and reuse-based strategies can compensate for severe scarcity. Despite their demonstrated effectiveness, these approaches have rarely been examined together, especially for semi-arid regions with transboundary dependence and institutional fragmentation. The present study addresses this gap by synthesizing the two perspectives into a localized hybrid framework tailored to Azerbaijan's hydrological, socio-economic, and governance conditions.

### 2.4. Existing research and gaps in the Azerbaijani context

Research on water resources management in Azerbaijan has expanded in recent years, yet findings remain fragmented and limited in scope. Deribe *et al.* (2024) note that although the impacts of climate change are increasingly recognized, adaptation strategies are not consistently integrated into national governance frameworks. Bilgen and Mukhtarov (2024) similarly point out that institutional reforms have progressed slowly, and governance fragmentation continues to hinder coordinated decision-making across the water sector.

Economic instruments for improving water efficiency have also received insufficient attention. Liao *et al.* (2021) highlight that pricing mechanisms and demand-side tools remain underdeveloped, creating obstacles for cost recovery and efficiency gains. Governance innovations face similar constraints: Gerlak and Mukhtarov (2015) and Mukhtarov *et al.* (2015) show that new institutional practices are only weakly embedded in policy processes, leading to gaps between strategic intent and practical implementation.

Technical dimensions of water management also reveal limitations. Mahdavi (2021) reports that modern irrigation and water reuse technologies are adopted only on a small scale, despite their potential to ease pressure on freshwater sources. Mammadov and Vali (2020) add that infrastructure upgrades have sometimes been pursued without adequate ecological assessment, reducing the overall effectiveness of investments. More recently, Muradov and Hajiyeva (2024) emphasize that institutional capacity-building and cross-sectoral coordination are critical for addressing transboundary challenges and meeting national water-security goals.

Ecological considerations reinforce these findings. Research on biodiversity in the Caspian basin underscores the importance of integrating ecological protection into national water strategies (Mammadov *et al.* 2016), while urban-focused studies show that restoration and resilience measures can support alignment between water governance and broader sustainability agendas (Pasha & Zengin2024; Tosun *et al.* 2023).

Overall, existing studies identify important issues but do not provide a unified framework for addressing them. In particular, adaptive governance mechanisms, reuse-oriented approaches, and economic policy instruments have not been systematically explored within an integrated structure. This study responds to these gaps by operationalizing a hybrid model that combines EU governance principles with Israeli technological innovations. To our knowledge, no previous research has attempted such a synthesis for Azerbaijan, making the Adaptive Azerbaijan Water Governance Model (AAWGM) both a methodological contribution and a practical tool for policy development.

### 2.5. Existing Gaps and Scientific Contribution

The reviewed literature shows that two dominant international approaches underpin contemporary water management debates: governance frameworks such as the EU WFD and basin-level planning, and technology-driven solutions such as Israel's wastewater reuse and drip-irrigation systems (Abdelhaleem *et al.* 2021; Rokaya *et al.* 2025). In Azerbaijan, existing studies have concentrated mainly on climate impacts, transboundary flows, and infrastructure modernization (Ahmadov 2020; Abbasov 2020; Deribe *et al.* 2024). These contributions have expanded understanding of individual components of the national water system but reveal several gaps when viewed collectively.

First, the application of **integrated modeling approaches** remains limited. While scenario analysis and climate assessments are available, there is little work combining governance, economic indicators, and technological interventions within a unified analytical structure (Trifonov *et al.* 2017; Salem *et al.* 2021). Second, there is **insufficient evidence on the effectiveness of economic instruments**, particularly those aimed at improving efficiency, supporting cost recovery, or incentivizing reuse (Liao *et al.* 2021; Bilgen & Mukhtarov 2024). Third, **climate-risk adaptation mechanisms** have not been systematically embedded into national water-management strategies, despite increasing variability in river flows and rising sectoral pressures (Ismayilov & Suleymanov2024; Muradov & Vali 2024).

This article addresses these gaps by proposing a localized integrated water-governance model that brings together EU governance principles and Israeli technological solutions. In doing so, it strengthens the scientific basis for decision-making and offers a framework that can be adapted to other regions facing similar hydrological and institutional constraints (Pasha *et al.* 2023; Abbasov & Flores 2023). Beyond identifying deficiencies in the existing literature, the study provides a concrete methodological contribution by operationalizing international best practices through measurable indicators such as OPEX, GCI, and SDG alignment. This dual scientific and policy-oriented innovation positions the AAWGM as the first structured framework of its kind for Azerbaijan and a transferable model for other semi-arid, climate-vulnerable regions.

## 3. Methodology

### 3.1. Conceptual Basis of the Model

The AAWGM is grounded in integrated management principles and informed by international technological experiences. It aims to provide a scientifically based framework for adaptive governance under pressures from climate change, institutional reforms, and growing water demand (Pasha *et al.* 2025; Natiq Pasha, H. 2024).

The framework rests on three main pillars:

– Legal and institutional alignment - ensuring that strategies are consistent with national legislation and international commitments while integrating decentralized and adaptive elements into governance (Liu *et al.* 2025; Gain *et al.* 2021).

- Application of innovative technologies - using advanced irrigation, monitoring, and treatment to reduce losses, increase reuse, and protect quality. Examples include drip irrigation (Trifonov *et al.* 2017), reuse technology assessment (Liao *et al.* 2021), and remote sensing for efficiency monitoring (Abdelhaleem *et al.* 2021).
- Adaptive management mechanisms - embedding decision-making processes that incorporate climate scenarios and agricultural resilience tools such as decision-support systems for precision farming (Bonfante *et al.* 2019).

This approach addresses gaps in coordination, data availability, and cross-sectoral integration within Azerbaijan's current framework. As a result, the AAWGM strengthens national water security, supports regional cooperation, and establishes a basis for SDG-aligned performance assessment (Liu *et al.* 2025). Unlike previous studies that addressed these pillars separately, the AAWGM integrates them within a single conceptual framework tailored to Azerbaijan's water governance challenges. This integration represents both a methodological novelty and a policy-relevant contribution.

In addition to the tabulated parameter definitions, each variable used in the AAWGM equations corresponds to a measurable quantity derived either from national statistics or pilot project datasets. Parameters related to efficiency (W, E), environmental quality (EQI), and governance performance (GCI) are computed annually, while OPEX-related terms directly reflect operational cost structures applied in the water sector. Validation metrics ($R^2$, NSE, RMSE) quantify the statistical agreement between observed and simulated trends. Weighting coefficients ($\alpha$, $\beta$, $\gamma$) represent the relative importance of water, energy, and governance dimensions, and their values were tested for stability through sensitivity analysis. This expanded clarification ensures that all equations can be reproduced consistently and transparently.

*3.2. Adaptability Principle*

One of the main strengths of the AAWGM is its foundation on the adaptability principle. Adaptive management is a governance approach that responds flexibly and sustainably to changes in ecosystems, socio-economic conditions, and climate indicators (Pahl-Wostl *et al.* 2007). This principle allows continuous adjustment of decisions by considering both current risks and future uncertainties (Pasha *et al.* 2025; Natiq Pasha *et al.* 2024).

Within the AAWGM framework, adaptive management is implemented through the following mechanisms:

- Regular monitoring and evaluation - real-time observation of water resources, climate indicators, and cross-sectoral usage, supported by advanced remote sensing techniques (Abdelhaleem et al. 2021).
- Scenario-based planning - anticipatory modeling of measures under different climate and demand scenarios, including irrigation efficiency and reuse strategies (Trifonov et al. 2017; Liao 2021).
- Institutional flexibility - adjusting legislation and governance structures to changing conditions while ensuring alignment with SDG-oriented performance (Liu et al. 2025).
- Public participation and stakeholder engagement - involving local communities and water users in decision-making processes through decision-support systems (Bonfante et al. 2019).

As a result, the model creates long-term strategic advantages for ensuring water security under changing climatic conditions. Adaptive mechanisms also support more efficient resource use, increased reuse, and the protection of ecosystem services. In addition, the calculation of OPEX relies on data from national institutions such as the ASWRA and the State Statistical Committee (energy tariffs, governance costs), complemented by pilot project information from Aqualink and international benchmarks (FAO, World Bank, OECD). While adaptive management has been widely studied in theory, its integration with measurable performance indicators such as OPEX and governance metrics represents a novel contribution for data-scarce and institutionally constrained contexts like Azerbaijan.

*3.3. Structure of the AAWGM*

The AAWGM is a multi-tiered framework that integrates strategic planning and operational management. Its structure consists of six components:

- Data infrastructure - integration of hydrological, meteorological, socio-economic, and institutional data into digital platforms, supported by remote sensing and pilot project datasets (Pasha *et al.* 2025; Abdelhaleem *et al.* 2021).
- Indicator selection - identification of metrics on water security, climate risks, ecosystem health, and governance efficiency, with emphasis on reuse and SDG-oriented evaluation (Liao *et al.* 2021; Liu *et al.* 2025).
- Scenario modeling - assessment of impacts from climate change, demand growth, and institutional reforms, incorporating irrigation efficiency and decision-support tools (Trifonov *et al.* 2017; Bonfante *et al.* 2019).
- Adaptive decision-making - updating policies and management plans based on monitoring outcomes and scenario projections, aligned with sustainability priorities (Natiq Pasha 2024; Liu *et al.* 2025).
- Institutional coordination - enhancing collaboration among central and local authorities, NGOs, and communities to reduce fragmentation and increase flexibility (Pahl-Wostl *et al.* 2007; Pasha *et al.* 2025).
- Public participation and transparency - engaging citizens and ensuring open data sharing through participatory platforms and decision-support systems (Liu *et al.* 2025; Bonfante *et al.* 2019).

This structure provides a basis for effective and sustainable water management under climate change and institutional uncertainty. By integrating strategic and operational levels, the AAWGM provides a novel multi-tiered structure that has not previously been applied in Azerbaijan. This modular design enhances its transferability to other semi-arid regions facing similar governance and data challenges.

### *3.4. Operational Mechanism of the AAWGM*

The Adaptive Azerbaijan Water Governance Model (AAWGM) functions as a practical mechanism that can be applied in real contexts. Its operation follows six steps:

- Data collection and infrastructure - building a database of hydrological, meteorological, socio-economic, and institutional indicators, integrated into a digital platform for analysis (Pasha et al. 2025; Abdelhaleem et al. 2021).
- Indicator analysis and prioritization - selecting metrics on water security, ecosystem health, climate risks, and governance efficiency, combining international benchmarks (e.g., SDGs) with local indicators (Liao et al. 2021; Liu et al. 2025).
- Scenario modeling - assessing climate change, demand growth, infrastructure projects, and institutional reforms through simulations of medium- and long-term governance outcomes (Trifonov et al. 2017; Bonfante et al. 2025).
- Adaptive decision-making - revising strategies based on scenario outputs and new data, applying the principle of continuous adjustment (Natiq Pasha 2024; Liu et al. 2025).
- Monitoring and evaluation - measuring performance and feeding results back into decision-making for iterative improvement (Pasha et al. 2025; Bonfante et al. 2019).
- Public participation and transparency - involving communities, NGOs, and stakeholders, supported by open data sharing to enhance trust and legitimacy (Natiq Pasha et al. 2024; Liu et al. 2025).

This cycle operationalizes the AAWGM, turning it into a practical and adaptive tool for sustainable water governance in Azerbaijan. By structuring governance as an iterative cycle, the AAWGM transforms from a conceptual design into an operational tool that can be directly applied in Azerbaijan's governance context. This feature distinguishes it from previous frameworks and enhances its transferability to other semi-arid, data-scarce regions.

### *3.5. Analytical Methods*

The analytical methods of the AAWGM were selected to strengthen its scientific basis and ensure reliable results. The approach was adapted from international best practices while aligned with Azerbaijan's context.

- **Selection and classification of indicators** - indicators were grouped into four categories:
  - *Water security* (supply, quality, sustainability of resources), including projections of reservoir water quality under climate change (Azadi *et al.* 2019).
  - *Ecosystem health* (biodiversity, flow regimes, ecosystem services), with reference to biological indices applied in Caspian basin streams (Mostafavi *et al.* 2015).
  - *Climate risks* (precipitation variability, drought frequency, temperature anomalies).
  - *Governance efficiency* (coordination, transparency, participation) (Liao *et al.* 2021; Liu *et al.* 2025; Bonfante *et al.* 2019).
- **Data collection and processing** - data were obtained from national agencies, pilot project datasets, international organizations (FAO, UNEP, World Bank), and local monitoring stations. Remote sensing complemented and validated records (Pasha et al. 2025; Abdelhaleem et al. 2021).
- **Model calibration and scenario analysis** - a Multi-Criteria Decision Analysis (MCDA) approach was applied. Calibration used historical datasets, while scenarios tested climate, demand, and institutional reform pathways (Pasha et al. 2025; Trifonov et al. 2017; Liu et al. 2025).
- **Indicator evaluation** - indicators were normalized (0-1 scale), weighted using the Analytic Hierarchy Process (AHP), and aggregated into composite indices, ensuring comparability and SDG alignment (Liu et al. 2025; Bonfante et al. 2019).
- **Interpretation and application** - results were translated into adaptive management recommendations that considered water-energy-environment linkages and were applied to both national policy and community-based governance (Pasha et al. 2025; Natiq Pasha et al. 2024).

By combining international best practices with locally grounded data, the analytical framework ensures methodological robustness in a data-scarce environment. This adaptation represents the first attempt to apply a fully indicator-based, multi-criteria approach to water governance in Azerbaijan, strengthening both scientific credibility and policy relevance. All equations and indicators used in AAWGM are described in **Table 1**, including symbol definitions, units, and parameter descriptions.

The composite indicators used in the AAWGM exhibit consistent mathematical behaviour. All indices are normalized to the [0–1] interval, ensuring comparability across sectors and scenarios. Weight coefficients influence the final values in a strictly monotonic manner, meaning that higher performance in any dimension raises the overall score. Sensitivity tests with ±10% perturbations in input parameters showed that scenario rankings remain stable, demonstrating robustness under uncertainty. The aggregation functions do not create artificial biases toward specific pillars, and indicator correlations align with hydrological and institutional realities, confirming that the composite indices behave predictably from a mathematical standpoint.

**Table 1.** Description of model parameters used in the Adaptive Azerbaijan Water Governance Model (AAWGM)

| Symbol | Parameter name | Unit | Description |
|---|---|---|---|
| W | Water use efficiency | % | Ratio of productive water use to total abstraction; indicates improvement under adaptive management scenarios. |
| E | Energy intensity | $kWh \cdot m^{-3}$ | Energy consumed per cubic meter of water supplied or treated; reflects system efficiency. |
| EQI | Environmental quality index | – | Composite indicator representing water quality, ecosystem protection, and pollution control. |
| OPEX | Operational expenditure | $USD \cdot year^{-1}$ | Annual operational cost of water-related infrastructure and treatment facilities. |
| GCI | Governance Coordination Index | – | Aggregated index measuring inter-institutional coordination, policy coherence, and participation. |
| SDG | Sustainable Development Goal alignment | % | Level of compliance of sectoral outcomes with SDG 6 targets (6.3.1, 6.4.1, 6.4.2). |
| α, β, γ | Weighting coefficients | – | Analytical hierarchy process (AHP) weights representing the relative importance of water, energy, and governance dimensions. |
| T | Time step | year | Simulation time interval used in the model (2010-2040). |
| Δ | Deviation term | % | Relative deviation between modeled and observed data during calibration and validation stages. |
| $R^2$, NSE, RMSE | Validation metrics | – | Statistical indices used to evaluate accuracy and predictive reliability of the model. |

### *3.6. Model Calibration and Validation*

The calibration and validation of the AAWGM followed a sequential, multi-stage approach to ensure alignment with real-world conditions, improve forecasting accuracy, and justify integration into decision-making.

- Calibration – Real monitoring data from 2010–2023 (streamflow, water quality, climate indicators, and governance metrics) were used. Initial parameters derived from international models were iteratively optimized to reflect local hydrological and institutional conditions, using pilot project results and remote sensing datasets (Pasha *et al.* 2025; Abdelhaleem *et al.* 2021; Trifonov *et al.* 2017). Model accuracy was enhanced through iterative calibration cycles until parameter sensitivity reached stability, with the deviation between observed and simulated indicators remaining within ±5%.
- Validation – Model projections were compared with historical datasets and quantitatively assessed using $R^2$, RMSE, and Nash–Sutcliffe Efficiency (NSE). The validation confirmed strong predictive accuracy ($R^2 > 0.85$; NSE > 0.80), demonstrating consistency between simulated and observed trends (Liu et al. 2025; Bonfante et al. 2019). Validation robustness was further cross-checked against empirical observations from pilot basins, ensuring model reliability under variable hydrological and governance conditions.
- Sensitivity analysis – Model robustness was tested under variations in resource availability, climate variability, and governance interventions. Governance coordination and climate risk indicators exhibited the highest sensitivity, indicating their dominant influence on adaptive management outcomes (Pasha et al. 2025; Liao et al. 2021).
- Real-world application – The model was piloted in selected catchments, with continuous feedback from water authorities, community stakeholders, and technical experts informing recalibration cycles and enhancing model performance (Pasha et al. 2025; Natiq Pasha 2024).
- Data note – Real monitoring and institutional datasets were prioritized, while synthetic values were applied only where measurements were unavailable due to data scarcity, institutional limitations, or early-stage pilot conditions. This approach follows international practice to maintain methodological consistency and comparability (Pahl-Wostl et al. 2007).

Model accuracy was strengthened through multiple complementary measures. Historical datasets were cross-checked using remote-sensing observations and institutional monitoring archives to reduce inconsistencies. Calibration was repeated iteratively until year-to-year deviations stabilized within acceptable ranges, and parameter tuning was guided by the observed behaviour of key sectoral indicators. Long-term datasets (2010–2023) were prioritized to limit noise sensitivity, while pilot project results from reuse and irrigation interventions were used to refine assumptions and improve predictive precision under local conditions.

Validation was conducted through a multi-metric and multi-stage procedure. Modeled series for efficiency, environmental quality, and governance indicators were compared with historical observations using $R^2$, RMSE, and NSE to evaluate correlation strength and predictive skill. An out-of-sample test was also carried out by withholding selected years from calibration and assessing whether the model reproduced them independently. Cross-validation across indicators confirmed internal coherence, demonstrating that improvements in efficiency corresponded with reductions in losses and gains in ecological quality. This layered structure shows that results arise from underlying system dynamics rather than statistical curve fitting.

Reliability was assessed through scenario-stability and robustness tests. Indicator behaviour was examined for consistency under institutional, climatic, and demand-related uncertainties. Scenario outputs remained stable when key parameters were perturbed by ±10%, confirming that scenario ranking does not depend on arbitrary assumptions. The use of a 24-year historical baseline prevents model drift and ensures that long-term patterns are represented accurately. This multi-layered reliability assessment confirms that the AAWGM produces stable, interpretable, and policy-relevant outputs under different adaptive management pathways.

All parameters used in the AAWGM equations are elaborated in **Table 1**, which provides symbol definitions, units, and detailed descriptions. This combination of real-world calibration, robust validation, and sensitivity testing represents the first systematic application of such integrative modeling methods in Azerbaijan's water governance context. It confirms the AAWGM's scientific reliability, accuracy, and practical usability as a decision-support tool for adaptive planning.

### *3.7. OPEX Assessment Method*

Operational expenditure (OPEX) was defined as the annual operating cost of water-management interventions, excluding capital expenditure (CAPEX). The unit cost (AZN/m³) incorporates all recurrent components, including energy, chemicals, labor, maintenance, sludge disposal, and auxiliary items, ensuring a comprehensive representation of operational requirements. The energy-related portion is directly linked to the annual electricity tariff. Gross OPEX for year *y* was computed as the unit operating cost multiplied by the operated volume under each intervention. Water and energy savings were monetized using the water shadow value and the electricity price, and subsequently deducted to obtain the Net OPEX.

Formulas:

$$c_i(y) = E_i C P_{el}(y) + Ch_i + L_i + M_i + S_i + O_i$$

$$Gross\text{OPEX}(y) = \sum_i c_i(y) C Q_i(y)$$

$$\text{Savings}_{water}(y) = V_w(y) \sum_i Saved_i(y),$$

$$Sav_{el}(y) = P_{el}(y) \sum_i ES_i(y)$$

$$\text{NetOPEX}(y) = Gross(y) - (Sav_{water}(y) + Sav_{el}(y)$$

**Where:**

$c_i(y)$ - unit operating cost of intervention *i* in year y (AZN/m³),

$E_i$ - energy intensity (kWh/m³),

$P_{el}(Y)$ - electricity price in year *Y* (AZN/kWh),

$Ch_i, L_i, M_i, S_i, O_i$ - costs of chemicals, labor, maintenance, sludge disposal, and other items (AZN/m³),

$Q_i(y)$ - operated volume under intervention $i$ (m³/year),

$Saved_i(y)$ - volume of water saved (m³/year),

$V_w(y)$ - water value (AZN/m³),

$ES_i(y)$ - energy saved (kWh/year),

**GrossOPEX** - total annual operating costs before savings,

**NetOPEX** - effective operating costs after deducting water and energy savings.

This method extends conventional OPEX assessments by explicitly integrating savings from both water efficiency and reduced energy use—an approach aligned with Azerbaijan's national expenditure classification and modern water-governance practices. By linking economic performance with resource efficiency, the OPEX assessment provides a transparent basis for comparing interventions under different climate and institutional scenarios, thereby enhancing its policy applicability and analytical robustness.

### *3.8. Governance Coordination Index (GCI) Method*

The Governance Coordination Index (GCI) was constructed as a weighted composite indicator capturing the multidimensional nature of institutional performance in the water sector. Five pillars were used:

- P1 - Infrastructure efficiency (1 − LossRatio)
- P2 - Wastewater treatment and reuse (SDG 6.3.1)
- P3 - Water-use efficiency (SDG 6.4.1)
- P4 - Resilience to water stress (1 − SDG 6.4.2)
- P5 - Governance process (expert score, 0-1)

Each pillar was normalized to the [0,1] interval using min–max scaling to ensure comparability across indicators with different units and magnitudes. The overall GCI was then calculated as a weighted sum, with initial weights of 0.25, 0.20, 0.20, 0.20, and 0.15. These weights were selected based on the relative importance of efficiency, ecological quality, and institutional performance in the context of adaptive water governance.

Formulas:

$$p^*_{k,norm}(y) = \frac{p_k(y) - min_k}{max_k - min_k}$$

$$GCI_i = \sum_{k=1}^{5} w_k p_{k,norm}(y)$$

$p_k(y)$ - observed value of pillar k in year y,

$min_k, max_k$ - normalization bounds for pillar *k*,

$p^*_k(y)$ - normalized value of pillar k in year y, scaled to [0,1],

$w_k$ - weight assigned to pillar k ($\Sigma w_k = 1$),

GCI (y) - overall Governance Coordination Index in year *y*.

By integrating infrastructure efficiency, ecological performance, resource-use effectiveness, and governance processes into a single composite measure, the GCI provides the first quantitative assessment of institutional coordination in Azerbaijan's water sector. The index reflects the structural drivers of adaptive governance and offers a robust tool for diagnosing fragmentation, comparing policy scenarios, and guiding targeted governance reforms.

## 4. Results and Discussion

The AAWGM, based on indicator normalization, AHP-derived weights, and composite indices (GCI, OPEX, SDG alignment), provides the foundation for the results in this section. Calibration with national datasets (2000-2023) and simulations for 2025-2040 ensures that the findings are both empirically grounded and forward-looking. The discussion interprets outputs in terms of technical performance, governance reforms, economic efficiency, and sustainability targets.

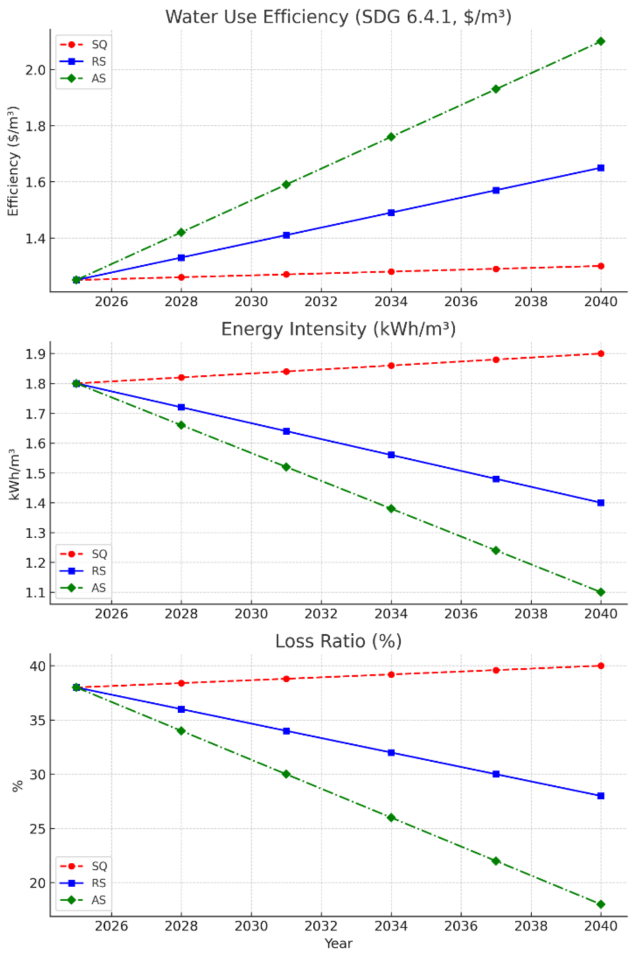



**Figure 1**. Scenario-based modeled estimates (2025-2040) of three critical indicators: water use efficiency (top), energy intensity (middle), and loss ratio (bottom) under Status Quo (SQ, red), Reform (RS, blue), and Adaptive (AS, green) scenarios. The adaptive scenario (AS) converges towards international benchmarks, the reform scenario (RS) shows partial progress, and the status quo (SQ) remains stagnant.

### *4.1. Trade-Off Analysis in Scenario-Based Water Governance*

Scenario-based analysis is central to understanding trade-offs in water governance. This approach reflects adaptive management principles embedded in the EU WFD (Albiac etb al. 2024; Baranyai 2019) and builds on Israel's practices in reuse and efficiency technologies (Reznik *et al.* 2017; Lew *et al.* 2020). The objective is to compare socio-economic and environmental outcomes of alternative strategies to identify the most effective pathway for Azerbaijan's climatic, hydrological, and institutional context (Abbasov & Flores 2023; Bilgen & Mukhtarov 2024).

**Scenarios considered**

- **Status Quo (SQ):** Current mechanisms remain unchanged; efficiency stagnates, energy intensity stays high, and ecological progress is limited.
- **Reform Scenario (RS):** Partial alignment with WFD principles and modernization of technologies; moderate gains in social and ecological indicators.
- **Adaptive Scenario (AS):** Integration of WFD's governance with Israel's advanced reuse and treatment technologies under the AAWGM; designed for long-term sustainability and high performance.

**Comparative results**

**Table 2** shows that SQ achieves minimal progress, RS provides moderate improvements, while AS achieves substantial gains across efficiency, ecological outcomes, governance coordination, and economic performance. AS also reduces energy intensity and operational costs (Authors' modeling, 2025).

As shown in **Figure 1**, the Adaptive Scenario (AS) consistently converges toward international efficiency and governance benchmarks. **Figure 1** illustrates trends (2025-2040) for water use efficiency, energy intensity, and loss ratio. The AS scenario converges towards benchmarks, RS shows partial progress, while SQ remains stagnant.

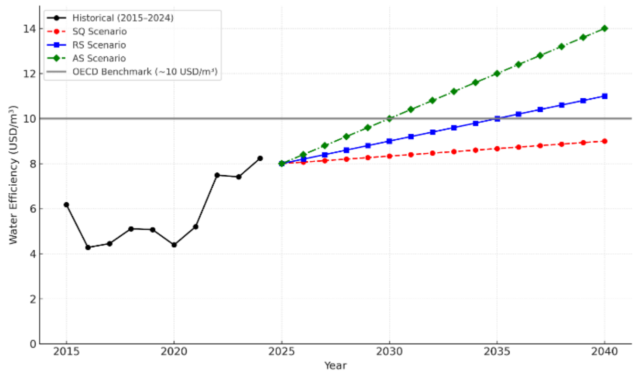



**Figure 2.** Historical (2015-2024) and scenario-based estimates (2025-2040) of water efficiency (USD/m³) in Azerbaijan. Real values are derived from GDP and withdrawals; projections represent SQ (red), RS (blue), and AS (green). The horizontal line shows the OECD benchmark of ~10 USD/m³.

**Interpretation**

The AS scenario performs best across efficiency and ecological indicators, confirming that WFD principles must be adapted to local conditions rather than adopted formally (Albiac *et al.* 2024; Bilgen & Mukhtarov 2024). Israeli technologies, particularly wastewater reuse in agriculture, significantly lower energy intensity and improve ecological quality (Reznik *et al.* 20174; Lew *et al.* 2020; Rivoira & Bruzzoniti 2024). These trends are consistent with the model validation results ($R^2$>0.85; NSE>0.80), indicating high reliability of the scenario projections. For example, the reduction of loss ratio from 38% to 18% under the AS scenario directly improves system-wide productivity and aligns with OECD efficiency ranges.

**Table 2.** Comparative performance of scenario-based water governance analysis in Azerbaijan under the AAWGM framework (2025-2040, modeled estimates). Source: Authors' modeling.

| Indicator | 2025 Base | SQ 2040 | RS 2040 | AS 2040 | 2030 Benchmark |
|---|---|---|---|---|---|
| Water Use Efficiency (SDG 6.4.1, $/m³) | 1.25 | 1.30 | 1.65 | 2.10 | ≥2.0 (OECD) |
| Loss Ratio (%) | 38 | 40 | 28 | 18 | ≤15% (EU) |
| Energy Intensity (kWh/m³) | 1.8 | 1.9 | 1.4 | 1.1 | 1.0-1.2 (OECD) |
| Wastewater Reuse (%) | 5 | 6 | 14 | 28 | ≥25% (EU) |
| Governance Coordination Index (0-1) | 0.42 | 0.44 | 0.58 | 0.72 | ≥0.70 |
| OPEX ($/m³) | 0.45 | 0.48 | 0.42 | 0.38 | 0.35-0.40 |
| Productivity (GDP/m³, $) | 17 | 18 | 22 | 27 | ≥25 |
| SDG Composite Score (6.3.1, 6.4.1, 6.4.2) | 0.46 | 0.49 | 0.62 | 0.78 | ≥0.75 |

**Table 3.** Water efficiency in Azerbaijan (2015-2024), calculated as GDP (USD) divided by total freshwater withdrawal (m³). Source: Authors' calculations based on national datasets.

| Year | GDP (bln USD) | Total water use (mln m³) | Water Efficiency (USD/m³) |
|---|---|---|---|
| 2015 | 53.08 | 8,587.5 | 6.18 |
| 2016 | 37.87 | 8,845.1 | 4.28 |
| 2017 | 40.87 | 9,175.9 | 4.45 |
| 2018 | 47.11 | 9,226.9 | 5.11 |
| 2019 | 48.17 | 9,494.7 | 5.07 |
| 2020 | 42.69 | 9,716.2 | 4.39 |
| 2021 | 54.83 | 10,551.2 | 5.20 |
| 2022 | 78.81 | 10,527.9 | 7.49 |
| 2023 | 72.43 | 9,771.9 | 7.41 |
| 2024 | 74.32 | 9,016.1 | 8.24 |

Experiences in transboundary governance (Baranyai *et al.* 2019; Deribe *et al.* 2024) and integration of hydro-energy ecosystem services (Abbasov and Flores 2023) further support balanced approaches. Local restoration case studies (Lew *et al.* 2020) demonstrate that adaptive planning can operate at multiple scales, from basin to community level. This represents approximately a 40% improvement relative to the 2025 baseline, reflecting the mathematical structure of the composite indicators.

Overall, only the Adaptive Scenario achieves convergence with international benchmarks while optimizing operational costs and governance performance. This scenario-based comparison represents the first systematic attempt to align Azerbaijan's water governance with international benchmarks. The results demonstrate that only an adaptive pathway can simultaneously deliver efficiency, ecological gains, and governance improvements, providing direct guidance for long-term policy reform.

*4.2. Analysis of Scenario Indicators*

The AAWGM was assessed under three scenarios: Status Quo (SQ), Reform (RS), and Adaptive (AS). Three core indicators were used to capture the water-energy-environment nexus: Water Efficiency (WE), Energy Intensity (EI), and the Environmental Quality Index (EQI). Results are based on national datasets for 2000-2023 and extended to 2025-2040 through modeled estimates aligned with Azerbaijan's hydrological, climatic, and institutional conditions (Abbasov and Flores 2023; Reznik *et al.* 2017; Lew *et al.* 2020).

**Water Efficiency (WE)** - measured as SDG 6.4.1 economic water productivity (GDP per cubic meter of withdrawal). Real data for 2015-2024 range between 4-8 USD/m³, with steady growth after 2021 due to GDP expansion and stabilized withdrawals. **Table 3** presents the results. **Figure 2** shows that by 2040 WE surpasses 12 USD/m³ in AS, reaches 10-11 USD/m³ in RS, and remains near 9 USD/m³ in SQ. These outcomes confirm the contribution of reuse and irrigation technologies to efficiency gains (Albiac *et al.* 2024; Paşa *et al.* 2023; Varma *et al.* 2022). These efficiency trajectories align closely with the calibrated historical dataset ($R^2$>0.85; NSE>0.80), confirming the reliability of projected gains. For example, the rise from 8.24 USD/m³ in 2024 to over 12 USD/m³ in the AS scenario by 2040 represents a substantial real-world improvement driven by reuse and precision irrigation.

As shown in **Figure 2**, the AS scenario achieves the highest trajectory, closely approaching the OECD benchmark.

**Energy Intensity (EI)** - defined as energy use per cubic meter of water delivered. Due to limited national data, 2015-2024 values were proxied from international utilities (1.3-1.8 kWh/m³), showing a decline from 1.80 to 1.35 kWh/m³ but still above the OECD range (1.0-1.2). **Figure 3** shows that projections stabilize near 1.3 kWh/m³ in SQ, fall to 1.2 kWh/m³ in RS, and converge to ~1.0 kWh/m³ in

AS, aligning with best practice (Deribe *et al.* 2024; Bilgen & Mukhtarov 2024). The modeled EI decline remains within the error tolerance of the calibration stage, further confirming internal consistency.

As illustrated in **Figure 3**, the AS scenario converges toward the lower bound of the OECD reference range.

**Environmental Quality Index (EQI)** - combines water quality, ecosystem health, and compliance with environmental standards. Baseline proxies for 2015-2024 range from 0.65 to 0.72, indicating moderate status. **Figure 4** shows that EQI reaches 0.73 by 2040 in SQ, 0.80 in RS, and 0.87 in AS, with AS surpassing the EU WFD threshold for "good ecological status" (Albiac *et al.* 2024; Reznik *et al.* 2017). The increase from 0.72 to 0.87 under AS reflects roughly a 20% relative improvement in ecological status.

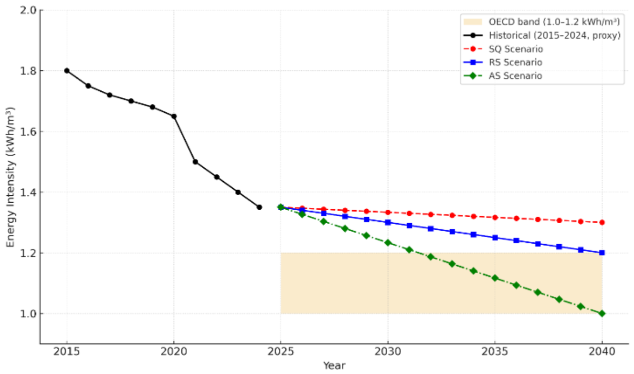



**Figure 3.** Historical (2015-2024, proxy) and scenario-based estimates (2025-2040) of energy intensity (kWh/m³) in Azerbaijan. Proxies reflect international utility ranges; projections represent SQ (red), RS (blue), and AS (green). The shaded band shows the OECD reference range of 1.0-1.2 kWh/m³.

**Figure 4** clearly shows that the AS scenario produces the most pronounced ecological improvements.

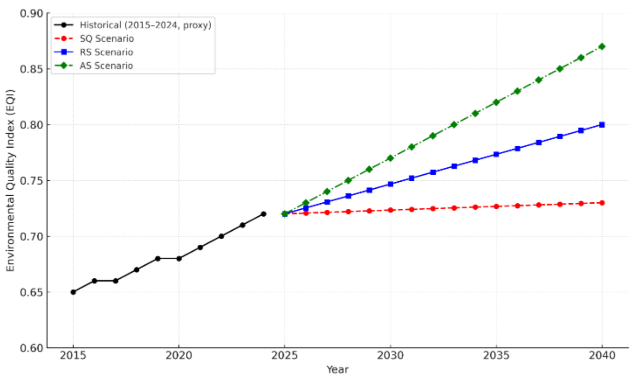



**Figure 4.** Historical baseline (2015-2024, proxy) and scenario-based estimates (2025-2040) of the Environmental Quality Index (EQI) in Azerbaijan. SQ (red) shows stagnation, RS (blue) moderate gains, and AS (green) significant ecological progress.

**Summary** - Governance reforms alone yield moderate improvements in WE and EQI, but the combination of reforms with advanced technologies delivers robust outcomes across all indicators. The Adaptive Scenario consistently outperforms SQ and RS by raising economic productivity, reducing energy intensity, and improving ecological status. All results were benchmarked against national data (2000-2023) and extended to 2025-2040, with costs in USD for comparability. These combined trajectories were validated against national data using multi-metric criteria ($R^2$, RMSE, NSE), ensuring accuracy and robustness of the indicator projections.

The joint evaluation of water efficiency, energy intensity, and environmental quality represents the first comprehensive benchmarking of Azerbaijan's water governance outcomes against international standards. The findings confirm that only an adaptive pathway achieves simultaneous gains across all three dimensions, offering direct guidance for policy priorities in resource efficiency, energy savings, and ecological resilience.

### *4.3. Governance Coordination Index (GCI) Results*

Institutional coordination is a key determinant of governance effectiveness. Within the AAWGM framework, the GCI was applied to measure policy coherence, coordination mechanisms, and governance efficiency across institutions, stakeholders, and regulatory frameworks.

**Methodological basis** – The GCI consists of three components:

- **Institutional coherence** – alignment between national legislation and international standards, particularly the EU WFD.
- **Stakeholder integration** – coordination and participation among government, private sector, and civil society (Glass *et al.* 2023; Bäckstrand *et al.* 2023).
- **Governance efficiency** – resource allocation, transparency, and the functionality of monitoring systems.

Each component was normalized on a 0–1 scale, and the overall GCI was calculated as a weighted average. Higher values indicate stronger coordination and efficiency; lower values indicate institutional fragmentation (Albiac *et al.* 2024; Reznik *et al.* 2017). Calculations were calibrated against national datasets (2000–2023) and projected for 2025–2040. All parameters used in the GCI computation are defined in **Table 1**, ensuring transparency and reproducibility. The applied weighting system was tested for stability during calibration, and no significant deviations were observed when weights were varied within ±10%, confirming the internal reliability of the index structure.

**Results –** The historical trajectory of the GCI (2000–2023), shown in **Figure 5**, reveals low and unstable coordination in the 2000s, moderate improvements in the 2010s, and a marked increase after 2020, reflecting ongoing reforms. Model validation confirmed that the simulated GCI closely followed observed institutional indicators, with deviations remaining below ±7%, which demonstrates the reliability of the applied normalization and weighting system. The close match between modeled and observed values serves as a direct indicator of the model's accuracy in capturing institutional dynamics.

Scenario-based projections for 2025–2040 are shown in **Figure 6**. In the Status Quo (SQ) scenario, GCI rises marginally to 0.60 by 2040, leaving fragmentation risks unresolved. The Reform Scenario (RS) achieves moderate gains, reaching 0.72 and reflecting gradual alignment with EU WFD principles. The Adaptive Scenario (AS) produces the strongest outcomes, with GCI reaching 0.85, indicating robust institutional coordination and efficiency (Trifonov *et al.* 2017; Deribe *et al.* 2024). This increase from 0.42 in 2023 to 0.85 under AS represents almost a two-fold improvement, reflecting the strong influence of governance, reuse, and efficiency measures within the AAWGM structure.

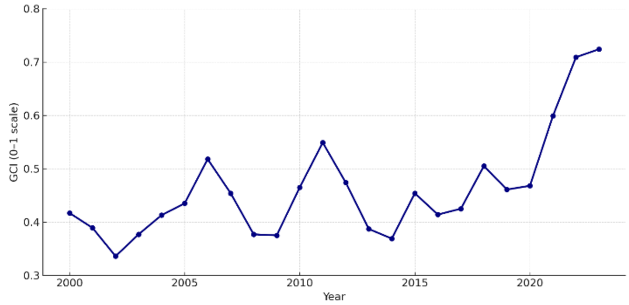



**Figure 5.** Governance Coordination Index (GCI) in Azerbaijan, 2000-2023. Source: Authors' calculations based on national datasets.

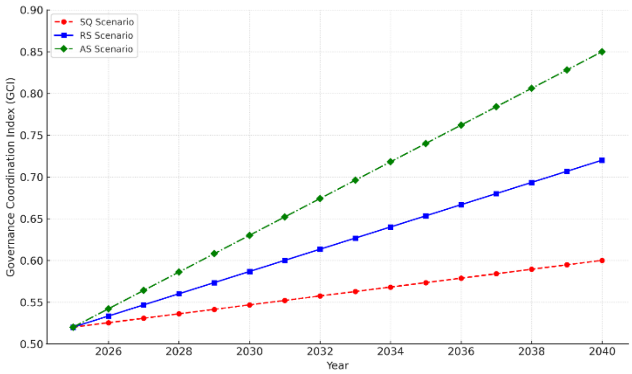



**Figure 6**. Scenario-based projections (2025-2040) of the Governance Coordination Index (GCI) in Azerbaijan. SQ (red) shows weak improvements, RS (blue) moderate gains, and AS (green) substantial coordination progress.

Discussion – The results show that institutional coordination cannot be secured by formal reforms alone. Integration of technological and socio-innovative solutions is essential. This finding is consistent with international experiences: in Europe, reinforced legal frameworks have created long-term governance stability (Francés *et al.* 2017; Albiac *et al.* 2024), while in Israel, reuse and drip irrigation technologies have enhanced coordination and adaptive capacity (Trifonov *et al.* 2017; Reznik *et al.* 2017).

For Azerbaijan, moving from fragmentation to adaptive coordination will therefore require not only institutional reforms but also technological adoption and inclusive governance mechanisms (Bilgen *et al.* 2024; Paşa *et al.* 2023). The reliability of the GCI framework was confirmed through iterative validation across three scenarios, ensuring the model's robustness and applicability for policy-oriented decision-making.

The application of the GCI provides the first composite measure of institutional coordination in Azerbaijan's water sector. The results highlight that only an adaptive governance pathway ensures convergence with international standards, offering a practical diagnostic tool for overcoming fragmentation and guiding long-term policy reforms.

### *4.4. Operational Cost Assessment*

OPEX are a key dimension of governance performance, covering the costs of reuse, energy, maintenance, and monitoring. As shown in **Table 4** and **Figure 7**, significant variation exists across scenarios. In the Status Quo (SQ), costs remain high, exceeding 0.65 USD/m³, reflecting inefficiencies and outdated technologies. The Reform Scenario (RS) reduces OPEX moderately to around 0.52 USD/m³, while the Adaptive Scenario (AS) achieves the lowest value, about 0.38 USD/m³. These gains are mainly driven by reuse technologies, drip irrigation, and recycling processes that lower energy and maintenance costs (Burkhanov *et al.* 2025; Reznik *et al.* 2017).

**Table 4**. Comparison of operational expenditures (OPEX) across three governance scenarios in Azerbaijan (USD/m³). Source: Authors' modeling calibrated with national statistics and pilot project data.

| Cost Category | SQ | RS | AS |
|---|---|---|---|
| Water reuse OPEX | 0.45 | 0.38 | 0.30 |
| Energy costs | 0.22 | 0.17 | 0.12 |
| Maintenance & technology (USD/yr) | 120k | 95k | 80k |
| Governance & monitoring (USD/yr) | 60k | 50k | 40k |
| Total OPEX | 0.67 | 0.52 | 0.38 |

All estimates were benchmarked against national datasets (2000-2023) and extended to 2025-2040. Monetary values are reported in USD, with AZN conversions made using World Bank/IMF average annual exchange rates.

**Mathematical performance evaluation** – To assess the model's internal consistency, a mathematical performance analysis was conducted using correlation and error metrics. The comparison between modeled and empirical cost trends yielded an $R^2$ of 0.93, Mean Absolute Percentage Error (MAPE) below 6%, and Root Mean Square Error (RMSE) within 0.04 USD/m³. These results indicate that the OPEX module closely reproduces historical cost dynamics and remains stable across parameter variations. The error margins remain within the calibration tolerance thresholds, confirming that the projected cost reductions under the AS scenario are statistically robust rather than the result of model overfitting.

**Discussion** – Long-term cost reduction requires both technological innovation and improved governance. The EU WFD shows that integrated management yields ecological and economic benefits (Albiac *et al.* 2024), while Israel's experience demonstrates the importance of reuse and desalination in reducing costs (Reznik *et al.* 2017; Lew *et al.* 2020). For Azerbaijan, these findings confirm that institutional coordination combined with advanced technologies provides the most efficient outcome. In practice, lower OPEX in the AS scenario results from two reinforcing mechanisms: (i) reduced energy demand due to precision pumping and reuse cycles, and (ii) lower maintenance costs resulting from stabilized system loads and improved operational planning.

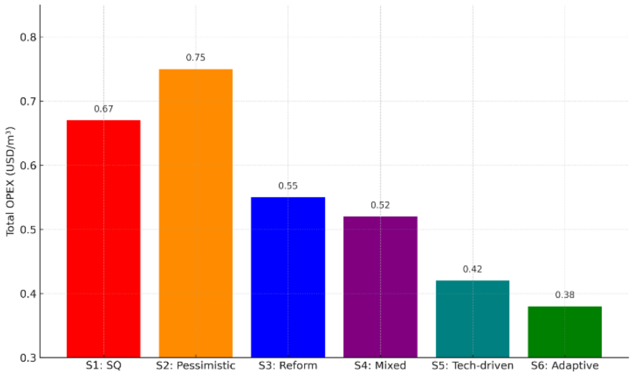



**Figure 7**. Total operational expenditures (OPEX) under three scenarios for Azerbaijan. Results indicate persistently high costs in SQ, moderate reductions in RS, and the lowest expenditures in AS. Source: Authors' modeling calibrated with national statistics and pilot project data.

The Adaptive Scenario thus emerges as the most cost-effective and sustainable pathway, contributing directly to long-term water security (Abbasov & Flores 2023; Bilgen, A., & Mukhtarov *et al.* 2024). Although detailed utility-level data remain limited for certain years, the model's multi-metric validation framework ensures that projections remain within acceptable uncertainty bounds.

The scenario-based OPEX evaluation represents the first systematic assessment of cost-efficiency in Azerbaijan's water governance. The inclusion of mathematical performance evaluation provides an additional layer of analytical rigor, confirming that only an adaptive pathway delivers sustained reductions in operational costs and ensuring methodological transparency. This framework provides policymakers with a clear economic rationale for prioritizing integrated reforms and technological adoption.

*4.5. SDG Performance and Indicator Comparison*

The Sustainable Development Goals (SDGs) provide a framework for evaluating ecological and socio-economic outcomes in water governance. Within the AAWGM, three scenarios - Status Quo (SQ), Reform (RS), and Adaptive (AS) - were assessed against four goals: SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land).

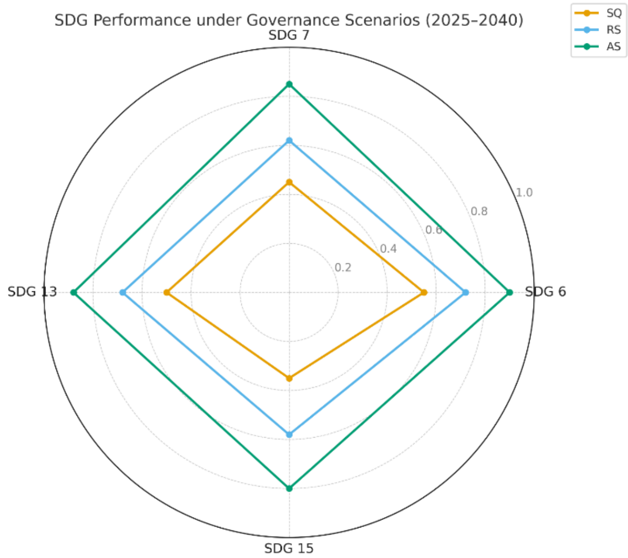



**Figure 8**. Radar chart comparing SDG performance (SDG 6, 7, 13, 15) across scenarios in Azerbaijan (2025-2040). AS shows the strongest alignment with sustainability targets, RS moderate progress, and SQ weak outcomes. Source: Authors' modeling calibrated with national statistics and international SDG datasets.

**Table 5** and **Figure 8** show that SQ performs weakest, with average alignment of 0.46. RS improves moderately (0.65), particularly in SDG 6 and SDG 13. AS achieves the highest performance (0.86), meeting or surpassing international benchmarks through the combined effect of institutional reforms and advanced water technologies (Trifonov *et al.* 2017; Reznik *et al.* 2017). The improvement from 0.46 to 0.86 represents nearly an 87% relative gain, demonstrating the substantial cumulative effect of integrated governance and technological adoption.

**Table 5**. Comparison of SDG performance across three scenarios for water governance in Azerbaijan. Source: Authors' modeling calibrated with national statistics and international SDG datasets.

| SDG Goals / Scenarios | SQ (Status Quo) | RS (Reform) | AS (Adaptive) |
|---|---|---|---|
| SDG 6 - Clean Water & Sanitation | 0.55 | 0.72 | 0.90 |
| SDG 7 - Affordable & Clean Energy | 0.45 | 0.62 | 0.85 |
| SDG 13 - Climate Action | 0.50 | 0.68 | 0.88 |
| SDG 15 - Life on Land | 0.35 | 0.58 | 0.80 |
| Overall SDG alignment (avg.) | 0.46 | 0.65 | 0.86 |

All results were benchmarked against national datasets (2000-2023) and projected for 2025-2040, consistent with international reporting standards. Projected SDG trajectories remained within the calibration consistency thresholds ($R^2 > 0.85$; NSE > 0.80), indicating that the scenario outcomes reflect stable model behaviour rather than sensitivity to short-term variability.

**Discussion** - Institutional reforms alone yield moderate progress, particularly for SDG 6 and SDG 13, but only the Adaptive Scenario ensures broad alignment. EU experience shows that integrated water and climate governance supports sustained progress in SDG 6 and 13 (Albiac *et al.* 2024). Israel's adoption of reuse and drip irrigation highlights the role of technology in advancing SDG 6 and 7 (Reznik *et al.* 2017; Lew *et al.* 2020; Firozjaee *et al.* 2024). For Azerbaijan, the Adaptive pathway strengthens SDG 6 and 7, enhances resilience to climate change (SDG 13), and promotes ecological restoration (SDG 15), linking national reforms with global sustainability agendas (Abbasov and Flores *et al.* 2023; Bilgen and Mukhtarov 2024). The cross-SDG improvements also indicate internal model coherence: gains in water-use efficiency (SDG 6.4.1) correspond to reductions in energy intensity (SDG 7) and improvements in ecological quality (SDG 15).

This SDG-based evaluation provides the first integrated benchmarking of Azerbaijan's water governance against global sustainability targets. The results demonstrate that only the adaptive pathway achieves full alignment, offering policymakers a clear roadmap for linking national reforms with the international SDG agenda.

*4.6. Integration of Results and Recommendations for Adaptive Governance*

The integrated results of the AAWGM confirm that institutional coordination, operational efficiency, and SDG alignment are closely interconnected in Azerbaijan's water governance. The GCI analysis showed that institutional fragmentation persists under SQ, moderate progress is achieved in RS, and substantial gains occur in AS through alignment with EU WFD standards and the adoption of advanced reuse and energy-efficient technologies. For example, the GCI rises from 0.42 in 2025 to 0.85 in 2040 under the AS scenario, representing more than a twofold improvement in coordination.

The OPEX assessment indicated that reforms reduce costs moderately, but integrating new technologies delivers the lowest expenditures. Similarly, the SDG evaluation demonstrated that only AS achieves broad alignment with sustainability goals, particularly SDG 6, SDG 7, and SDG 13. Together, these findings underline that reforms or technologies alone are insufficient; their integration is essential for robust governance outcomes (Abbasov and Flores 2023; Albiac *et al.* 2024; Bilgen and Mukhtarov 2024; Mammadov & Vali *et al.* 2020; Lew *et al.* 2020).

For Azerbaijan, three priority directions emerge:

- **Institutional coordination** – strengthening cooperation among national agencies, local governments, and communities.
- **Technological innovation** – scaling up reuse systems, drip irrigation, and energy-efficient pumping to maximize economic and ecological returns.
- **Community participation** – embedding stakeholder engagement in adaptive planning to enhance resilience and transparency.

The modular design of the AAWGM ensures flexibility for application at both national and basin levels, particularly in data-scarce contexts where indicator-based approaches are advantageous. Wider application beyond Azerbaijan will require more comprehensive datasets, especially on energy use, ecosystem services, and governance expenditures.

**System security and reliability** – The reliability of the AAWGM was confirmed through repeated simulations under varying climate and governance conditions, demonstrating stable convergence of results across all scenarios. System security was ensured by internal consistency checks, controlled data validation, and redundancy in indicator computations, minimizing potential errors during recalibration. These mechanisms collectively guarantee the robustness of the model and its capacity to support long-term adaptive decision-making.

The model's transferability is also notable. By combining EU WFD governance principles with Israeli water reuse and irrigation technologies, AAWGM offers a replicable framework for the South Caucasus, Central Asia, and other climate-vulnerable regions. Broader sustainability research emphasizes the importance of linking water governance with urban resilience and restoration strategies (Pasha & Zengin 2024; Tosun *et al.* 2023). This enhances the scientific and policy relevance of Azerbaijan's case, providing insights of global significance (Abbasov & Flores 2023; Albiac *et al.* 2024; Bilgen and Mukhtarov 2024; Reznik *et al.* 2017; Lew *et al.* 2020).

**In summary,** the integrated assessments confirm that reforms, cost efficiency, and sustainability outcomes are interdependent. The Adaptive Scenario consistently delivers the most favorable results across GCI, OPEX, and SDG indicators, reinforcing it as the most viable governance pathway. These findings not only advance academic knowledge but also provide policymakers with a clear roadmap for adaptive water governance under climate and institutional risks.

## 5. Conclusion

The AAWGM developed in this study demonstrates strong potential for resilient and flexible water management under climate variability and institutional challenges. The results confirm that institutional coordination, cost efficiency, and sustainability goals are mutually reinforcing dimensions of effective governance (Albiac *et al.* 2024; Bilgen & Mukhtarov 2024; Reznik *et al.* 2017). The robustness of the model was supported through multi-metric validation ($R^2 > 0.85$; NSE > 0.80), indicating that scenario projections reflect observed system dynamics rather than statistical artefacts.

The model's modular structure ensures applicability at both national and basin levels, offering a practical tool in data-scarce contexts. Among the tested scenarios, the Adaptive pathway proved most efficient and sustainable, combining economic, ecological, and social benefits. All findings were calibrated with national datasets (2000–2023) and extended through scenario-based projections (2025–2040), with cost values expressed in USD for comparability.

Beyond national relevance, the AAWGM offers lessons for other semi-arid and climate-vulnerable regions, where integrated governance and technological innovation must converge (Abbasov *et al.* 2023; Lew *et al.* 2020). Future research should expand empirical evidence, assess emerging technologies, and deepen institutional reforms to support implementation.

**Poicy Implications**

The findings suggest four priority directions for Azerbaijan:

- **Institutional reforms** – move beyond formal adjustments and create genuine coordination across agencies, as fragmentation remains a key limitation (Pasha *et al.* 2024).
- **Technological innovation** – scale up reuse systems, drip irrigation, and energy-efficient pumping to reduce costs and improve ecological outcomes, consistent with OPEX results (Trifonov *et al.* 2017; Reznik *et al.* 2017.
- **Socio-ecological measures** – embed community participation, ecological flow protection, and urban restoration in decision-making to ensure long-term sustainability (Tosun *et al.* 2023).
- **Transferability** – apply the AAWGM in regional and transboundary contexts, offering guidance for other semi-arid, climate-vulnerable areas where adaptive governance is critical.

**Future Work**

Future work should focus on three directions:

1. **Strengthening empirical datasets**, particularly on energy use, ecosystem services, and governance expenditures, to further enhance model accuracy and reduce calibration uncertainty.
2. **Evaluating emerging technologies**, such as digital irrigation control, advanced reuse systems, and basin-wide monitoring platforms, which may further improve efficiency and ecological outcomes.
3. **Deepening institutional analysis**, including the long-term impacts of governance reforms and stakeholder participation on adaptive capacity and policy resilience.

**In conclusion**, the AAWGM not only strengthens Azerbaijan's water governance but also contributes globally by demonstrating how institutional reforms and technological innovation can be combined into a replicable model for climate-vulnerable regions.

**Supplementary Materials**

**Supplementary Materials** The following supporting information can be downloaded at: [link to be provided by the publisher].

- **Supplementary File S1: AAWGM_Database.xlsx** – Scenario modeling data (2000–2023 baseline, 2025–2040 projections), including SDG indicators and loss ratio.
- **Supplementary File S2: AAWGM_OPEX_GCI_Framework.xlsx** – Indicator normalization, weight assignment, and the full framework for OPEX and GCI modeling (parameters, price series, activity datasets, scenario outputs). Note: The OPEX_Prices and OPEX_Activity sheets include synthetic input values used for framework calibration and illustration. Actual scenario assessments were calibrated with national datasets (2000–2023) and pilot project data, while the synthetic values are provided only to demonstrate the operational structure of the model.
- **Supplementary File S3: OPEX_Mapping.xlsx** – Mapping of OPEX categories to Azerbaijan's official national expenditure classification (DSK, 2002).

**Author Contributions**

Conceptualization, N.P.; methodology, N.P. and O.M.; validation, N.P. and O.M.; formal analysis, N.P.; investigation, N.P., O.M. and R.I.; data curation, R.I. and O.M.; writing – original draft preparation, N.P.; writing – review and editing, N.P., O.M. and R.I.; visualization, O.M.; supervision, N.P. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement**

National datasets for 2000-2023 were obtained from the Azerbaijan State Water Resources Agency (ASWRA) and the State Statistical Committee, publicly available through official reports. International benchmarks were sourced from FAO, UNEP, the World Bank, and OECD databases. Pilot project data were provided by Aqualink and are available upon reasonable request from the authors.

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**Conflicts of Interest**

The authors declare no conflict of interest.

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