Ecosystem-Based Approach to the Management of the Water-Energy Complex in Central Asia

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Abstract: The water-energy complex of Central Asian countries represents a tightly interconnected system in which river flow allocation, hydropower operation regimes, generation structure, irrigation water use, and food security jointly shape a unified dynamic of risk and resilience. The region is experiencing increasing climate variability (rising frequency of droughts, desertification processes, extreme floods, and glacier retreat), alongside simultaneous growth in electricity and food demand. Fragmented interstate governance further creates conditions in which decisions taken within one sector systematically generate cross-sectoral externalities in others. This study proposes an ecosystem-based management framework for the Central Asian water-energy complex within the logic of the Water-Energy-Food (WEF) Nexus. The framework integrates: i) the physical and hydrological foundations of water resources; ii) energy infrastructure and dispatch optimization; iii) agricultural production functions and irrigation efficiency; iv) climate risks and uncertainty; and v) institutional constraints and governance gaps. Methodologically, the research is grounded in an integrated mathematical model combining system dynamics (stock-flow balances), multi-objective optimization (water-energy-food trade-offs), scenario modeling (2030-2040-2050 horizons), policy simulation (tariff-subsidy schemes, investments in renewable energy and storage, irrigation modernization, seasonal regulation rules), and a climate risk module (probabilistic flow and temperature shocks, stress testing, and robust adaptive optimization). To address the institutional dimension, a “mandates-responsibilities-data-incentives” matrix is introduced, enabling quantitative assessment of governance gaps in transboundary water allocation mechanisms and coordinated energy operation regimes. The study generates a set of quantitative Nexus efficiency and resilience indicators, including a systemic coherence index of decision-making, water-energy-food deficit metrics, economic losses from uncoordinated dispatch, socio-environmental externalities, and a ranking of policies based on Pareto improvement criteria. The findings provide an applied foundation for designing coordinated reservoir operation rules, investment portfolios, and interstate agreements that enhance Central Asia’s resilience to climate shocks while preserving basin ecosystem functions and reducing resource allocation conflicts.

1 INTRODUCTION

1.1 Regional Context and Systemic Interdependence

Central Asian countries are characterized by a high degree of water dependency and the transboundary nature of hydrological processes. The region's major river basins originate in the mountainous ecosystems of the Tien Shan and Pamir ranges, where glacier-fed runoff forms the primary source of water resources, while key agricultural territories and a substantial share of the population are concentrated in arid lowland zones [1], [2]. This spatial asymmetry between water formation and consumption establishes structural interdependence among the countries and amplifies the importance of interstate coordination. Water resources in the region perform multiple functions: they support hydropower generation, agricultural irrigation, industrial and municipal supply, and the maintenance of ecosystem services. At the same time, the energy system determines hydropower operating regimes, while the agricultural sector shapes seasonal demand for both water and electricity. Central Asia therefore constitutes a classical example of a Water-Energy-Food (WEF) Nexus system, where resource interactions are nonlinear, multidimensional, and dynamically interdependent [3], [4].

Figure 1 presents an interconnected model in which river runoff directly influences hydropower generation and irrigation volumes. Energy strategy determines reservoir regulation regimes, while agriculture shapes water demand. Climate exerts systemic pressure on the hydrological cycle, and institutional mechanisms define the rules governing resource allocation.

The figure illustrates the integrated Water-Energy-Food (WEF) Nexus system, extended by an ecosystem dimension and a governance block as the central coordination mechanism. Water availability determines hydropower production capacity and irrigation scale, whereas the energy system influences the water sector through pumping costs, treatment requirements, and infrastructure investments. The food sector, relying on irrigation and energy-intensive value chains, generates feedback effects on both water and energy demand, including impacts on water quality and seasonal demand profiles.

Ecosystems are incorporated as a fully-fledged component of the Nexus, providing runoff regulation, water quality maintenance, and bio-productivity services. At the same time, anthropogenic pressures-such as water abstraction and land-use change-create risks of ecosystem degradation and loss of regulatory functions.

The cross-cutting impact of climate risk is explicitly represented as a pervasive source of uncertainty affecting inflows, seasonality, and extreme events. Climate variability simultaneously influences water availability, hydropower production, agricultural yields, and ecosystem resilience. The governance block establishes the rules of water allocation, investment decision-making, and economic incentives (markets, subsidies, regulatory standards), thereby shaping the institutional feasibility of coordinated strategies.

Thus, the figure captures the central argument of this study: in Central Asia, the resilience of the WEF Nexus depends not only on physical resource balances but also on the quality of cross-sectoral and transboundary governance under conditions of climate uncertainty.

1.2 Evolution of Theoretical Approaches to Natural Resource Management

Historically, water resource management in Central Asia was based on an engineering-hydrotechnical paradigm aimed at maximizing energy production or ensuring irrigation supply, largely without accounting for cross-sectoral externalities. The subsequent development of the Integrated Water Resources Management (IWRM) framework enabled a more comprehensive consideration of water demands; however, energy and food components remained largely compartmentalized [5].

The WEF Nexus concept emerged in response to the need for intersectoral integration and structured trade-off management [3]. Contemporary research increasingly emphasizes that system resilience is determined not only by physical constraints but also by the quality of institutional coordination and governance arrangements [4], [6], [7]. Nevertheless, many existing models remain confined to conceptual representations or partial quantitative assessments, lacking full systemic integration.

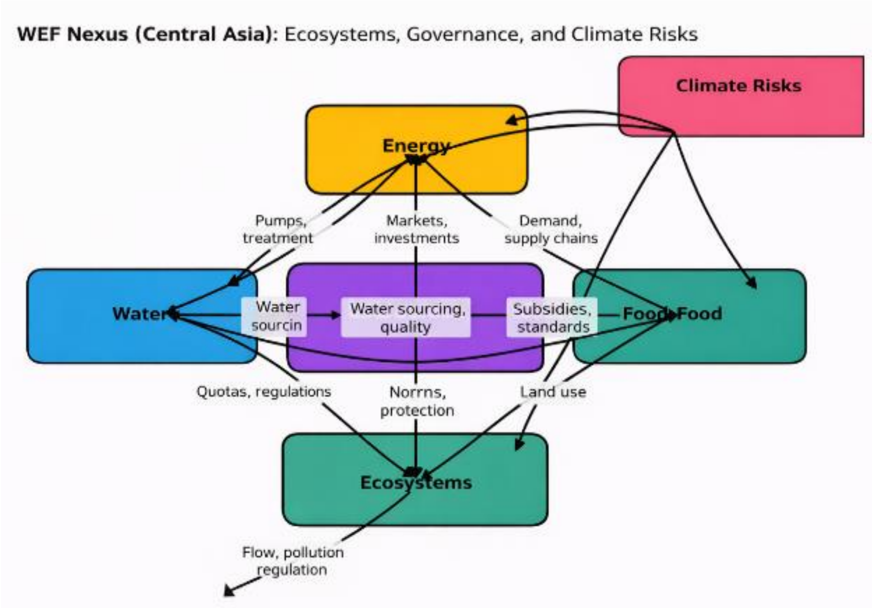

Figure 1: Conceptual structure of the water-energy-food nexus in Central Asia.

Table 1: Limitations of existing water-energy system management models.

Approach	Sectoral Integration	Climate Consideration	Governance Dimension	Optimization
IWRM	Partial	Limited	Yes	No
Energy models	No	No	No	Yes
Agricultural models	No	Partial	No	No
Nexus approach (literature)	Partial	Limited	Partial	Partial
Proposed model	Full	Yes	Yes	Yes

The comparative assessment presented in Table 1 demonstrates that most applied models remain sector-specific or only partially integrated. The classical IWRM paradigm provides coordination within the water sector but insufficiently incorporates energy-food interdependencies and rarely employs optimization tools. Energy models typically focus on cost minimization and reliability enhancement yet often neglect hydrological constraints and cross-sectoral consequences. Agricultural models concentrate on yield optimization and water availability but fail to integrate energy balance dynamics and institutional factors.

Even existing Nexus studies frequently remain limited to conceptual analysis or static evaluations, without fully operationalizing multi-objective optimization or formally incorporating climate uncertainty.

In contrast, the integrated model proposed in this study addresses these limitations by combining hydrological balance equations, an energy system module, agricultural production functions, a climate scenario block, and an institutional governance gap index within a unified mathematical framework. This architecture enables the incorporation of ecological constraints, explicit evaluation of cross-sectoral trade-offs, and simulation of policy feasibility under transboundary governance conditions.

Table 1 thus substantiates the need to move beyond fragmented analytical approaches toward a systemic, multi-level, and adaptive governance architecture for managing the water-energy complex in Central Asia.

1.3 Climate Uncertainty and Environmental Challenges

Climate change is increasing the variability of river runoff and altering the seasonal distribution of water resources [6], [7]. The reduction of glacier mass in the Tien Shan and Pamir mountain systems significantly affects long-term inflow dynamics, creating risks of declining baseline summer flows.

$$Q_t=\bar{Q}_t+\varepsilon_t,$$

ε_t where ε_t represents stochastic deviations in inflow determined by climate change scenarios.

This stochastic representation allows for probabilistic assessment of hydrological shocks, stress-testing of reservoir operation regimes, and evaluation of adaptive policy robustness under deep uncertainty.

A decline in water inflow leads to reduced hydropower generation, which in turn stimulates increased reliance on thermal power production and higher greenhouse gas emissions, thereby intensifying climate pressure and forming a reinforcing feedback loop.

Figure 2 illustrates the key causal pathways through which climate change transforms Water-Energy-Food (WEF) interdependencies in Central Asia. Rising temperatures and the increasing frequency of extreme events amplify precipitation variability and accelerate glacier degradation, leading to structural changes in river inflow Q, both seasonally and in long-term trends. Reduced water availability directly constrains hydropower production and irrigation capacity, resulting in lower agricultural yields and weakened food security. Simultaneously, higher temperatures intensify evaporative losses, further diminishing effective water availability and increasing the probability of resource deficits.

From the energy perspective, the diagram captures a compensatory mechanism: declining hydropower output, combined with stable or growing electricity demand, increases reliance on thermal generation. This shift results in higher greenhouse gas emissions, thereby reinforcing the feedback cycle: Emissions→Warming→Water-Energy-Food Deficits.

The "deficit risk" node aggregates the cumulative effects of simultaneous constraints in water, energy, and food subsystems, demonstrating that climate shocks manifest not as isolated disturbances but as systemic risks affecting the entire Nexus structure.

The symbols "+", "–", and "±" on the causal links denote the direction of influence (reinforcing, balancing, or scenario-dependent/ambiguous effects), enabling the diagram to serve as a formal foundation for subsequent dynamic system modeling and multi-objective optimization. In this way, the causal loop diagram transitions from a conceptual illustration to a structural pre-model specification within the integrated Nexus framework.

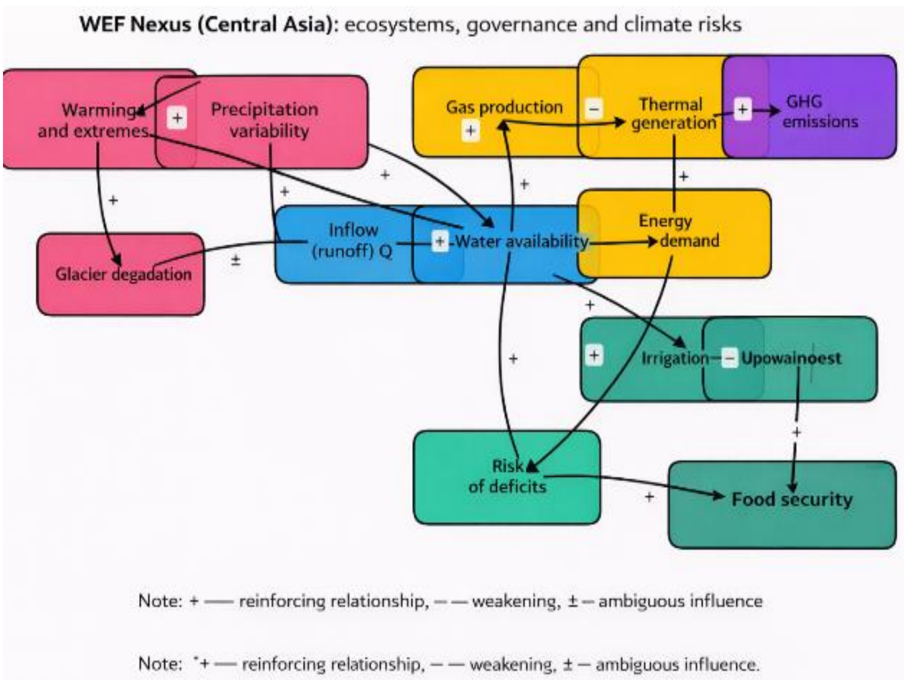

Figure 2: Causal loop representation of climate impacts on the wef nexus.

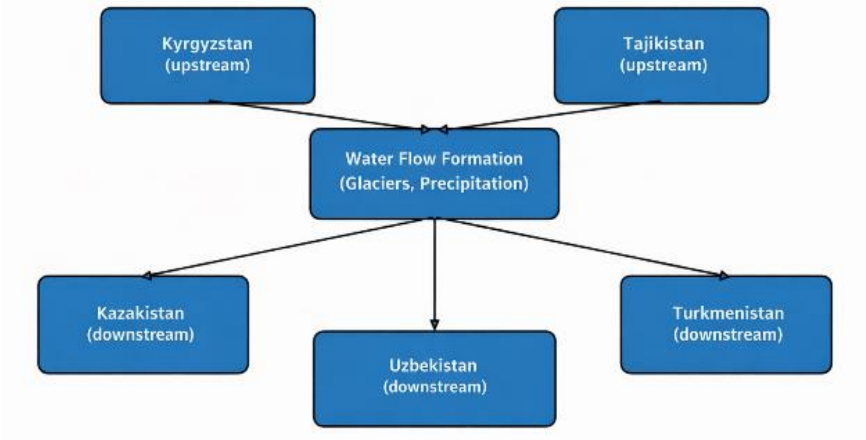

Figure 3: Geographic distribution of water resource formation and consumption.

1.4 Transboundary Dimension of Water Resource Governance

The transboundary character of water resources in Central Asia significantly increases the necessity for coordinated regional management. Upstream countries (Kyrgyzstan and Tajikistan) prioritize hydropower generation as a cornerstone of national energy strategies, whereas downstream countries (Uzbekistan, Kazakhstan, and Turkmenistan) depend heavily on irrigated agriculture for food production and economic stability [2], [8]-[10].

This structural asymmetry creates seasonal and strategic tensions in reservoir operation. Upstream states tend to release water in winter to maximize electricity production, while downstream agricultural systems require water primarily during the summer irrigation period. The absence of fully institutionalized compensation mechanisms and synchronized planning frameworks exacerbates coordination failures and amplifies systemic vulnerability under climate uncertainty.

Consequently, the transboundary dimension of the WEF Nexus in Central Asia cannot be reduced to hydrological allocation alone; it must be understood as a coupled hydro-political system in which physical flow regimes, energy markets, agricultural cycles, and institutional arrangements interact dynamically. Effective governance therefore requires not only technical optimization but also credible interstate agreements, data transparency, and aligned incentive structures.

The imbalance of interests manifests in seasonal conflicts between winter hydropower generation and summer irrigation demand. The absence of flexible compensation mechanisms exacerbates systemic instability.

Figure 3 illustrates the spatial asymmetry in the formation and utilization of water resources across Central Asian countries. The majority of river runoff originates in the mountainous regions of Kyrgyzstan and Tajikistan, primarily sustained by glacial melt and atmospheric precipitation. These territories function as the region's natural water catchment areas, providing the baseline inflow to transboundary river systems. The spatial concentration of runoff sources in upstream areas creates a structural dependency of downstream countries on hydrological processes occurring beyond their national borders.

In contrast, the principal volumes of water consumption are concentrated in Kazakhstan, Uzbekistan, and Turkmenistan, where water is predominantly used for agricultural irrigation, industrial processes, and municipal supply. This geographic disproportionality generates an objective need for coordinated transboundary governance, as upstream flow regulation directly determines water availability for downstream agricultural and energy systems. The figure highlights a fundamental structural component of the regional WEF Nexus - the spatial separation between zones of water formation and zones of water consumption.

1.5 Institutional Constraints

Despite the existence of intergovernmental agreements, institutional coordination remains limited [5], [11]. Insufficient data transparency, misaligned economic incentives, and the absence of compensation mechanisms generate a persistent governance gap.

Institutional effectiveness is formalized through a coefficient gi $\in$ [0,1], representing the degree of implement ability of jointly agreed decisions.

Table 2: Indicators for assessing the governance gap.

Indicator	Symbol	Range
Coordination	C	0-1
Data exchange and transparency	D	0-1
Agreement compliance	E	0-1

Table 2 systematizes the key indicators enabling a quantitative assessment of institutional gaps (governance gap) in the management of the water-energy complex in Central Asia. The evaluation framework is based on three core components: coordination (C), data exchange and transparency (D), and compliance with agreed commitments (E).

The coordination indicator reflects the level of interstate interaction, the frequency and effectiveness of joint decision-making, and the existence of mutually agreed compensation mechanisms for seasonal imbalances. The data transparency indicator characterizes the completeness, timeliness, and accessibility of hydrological and energy-related information, which is critical for inflow forecasting and reservoir operation planning. The compliance indicator captures the degree to which allocation quotas and negotiated agreements are honored, directly influencing the stability of the transboundary system.

Together, these indicators form an integral coefficient of institutional effectiveness gi ∈ [0,1], which is incorporated into the mathematical model as a feasibility parameter. Low values of gi indicate a high risk of policy incoherence, increased transaction costs, and a greater probability of water and energy shortages. Conversely, enhanced institutional coordination reduces systemic losses and expands the feasible set of Pareto-optimal solutions within the WEF Nexus framework. Thus, Table 2 underscores that regional sustainability is determined not only by physical resource constraints but also by governance quality and interstate cooperation.

1.6 Ecosystem Constraints

The ecosystem-based approach incorporates environmentally required flow as a dynamic constraint within the model. Unlike fixed regulatory standards, ecological flow requirements vary depending on ecosystem conditions and seasonal factors [4], [12].

Violation of this constraint results in biodiversity degradation, deterioration of water quality, and a reduction in ecosystem services.

1.7 Research Questions and Hypotheses

The study addresses the following research questions:

1) Which policy combinations generate Pareto improvements across water, energy, and food dimensions?
2) To what extent is the system sensitive to climate stress scenarios?
3) How does institutional integration influence the feasibility and attainability of optimal solutions?

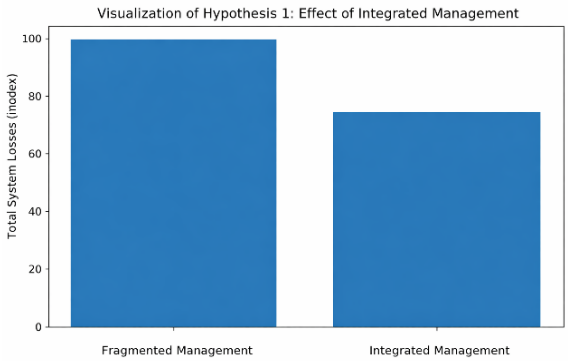

Figure 4: Integrated governance reduces aggregate systemic losses compared to a fragmented scenario.

The presented visualization illustrates the conceptual core of Figure 4, which posits that integrated governance within the Water-Energy-Food (WEF) Nexus system reduces aggregate systemic losses relative to a fragmented governance scenario. An aggregated loss index is employed as the composite performance metric, incorporating water deficits, energy under-supply, crop yield reductions, ecological damage, and associated economic costs.

The fragmented scenario is characterized by the absence of coordinated reservoir operation regimes, unaligned energy dispatch strategies, and persistent institutional gaps. Such structural disintegration leads to the accumulation of cross-sectoral imbalances, amplifying interdependencies and exacerbating systemic inefficiencies. Under this configuration, sectoral optimization occurs in isolation, generating negative externalities across the nexus and increasing overall vulnerability.

In contrast, the integrated scenario assumes harmonized water allocation quotas, the establishment of compensation mechanisms between upstream and downstream countries, synchronized energy policy frameworks, and the implementation of adaptive climate strategies. This coordinated architecture enables cross-sectoral alignment and reduces structural asymmetries in resource distribution and use.

The observed decline in the aggregated loss index reflects the emergence of systemic synergies, whereby coordinated decision-making simultaneously mitigates water scarcity risks, energy supply volatility, and food security vulnerabilities. The visualization thus demonstrates the theoretically expected direction of effect: institutional integration enhances overall system efficiency and resilience.

This hypothesis will be quantitatively tested through a multi-objective optimization model and scenario-based analysis, enabling the identification of Pareto-efficient policy configurations under varying climatic and institutional conditions.

The presented visualization illustrates the conceptual foundation of Figure 5, which posits that incorporating climate uncertainty through robust optimization enhances the resilience of the water-energy system.

The horizontal axis represents deviations of water inflow from its long-term mean (expressed as percentages), simulating drought and excessively wet scenarios. The vertical axis depicts an integrated resilience index that aggregates indicators of water availability, energy reliability, and food system stability. Under standard optimization, the system exhibits pronounced sensitivity to inflow deviations: resilience declines sharply under extreme hydrological scenarios, reflecting high vulnerability to climate shocks.

In contrast, robust optimization produces a flatter response trajectory to hydrological variability. The decline in resilience under adverse scenarios is significantly attenuated, indicating enhanced adaptive capacity and reduced tail risks. This effect is achieved by incorporating penalties for extreme losses into the objective function (e.g., through Conditional Value-at-Risk, CVaR) and selecting solutions that are not only optimal under expected conditions but also perform satisfactorily under unfavorable realizations.

Conceptually, the visualization supports the proposition that accounting for climate uncertainty expands the feasible domain of resilient solutions within the WEF Nexus framework in Central Asia. By internalizing hydrological volatility into the decision-making process, robust optimization shifts the system from performance maximization under average conditions toward stability preservation across a spectrum of climatic stress scenarios.

The hypothesis will be empirically validated through stochastic multi-objective modeling and comparative scenario analysis, assessing the trade-offs between efficiency and resilience under varying levels of hydrological uncertainty.

The presented visualization illustrates the conceptual foundation of Figure 6, which posits that reducing the institutional gap (governance gap) enhances the efficiency of water and energy resource allocation within the WEF Nexus system. The horizontal axis represents the integrated index of institutional coherence $g\in[0,1]$, where low values correspond to fragmented governance, weak coordination, and limited data exchange, while high values reflect harmonized interstate mechanisms and strong compliance with negotiated agreements.

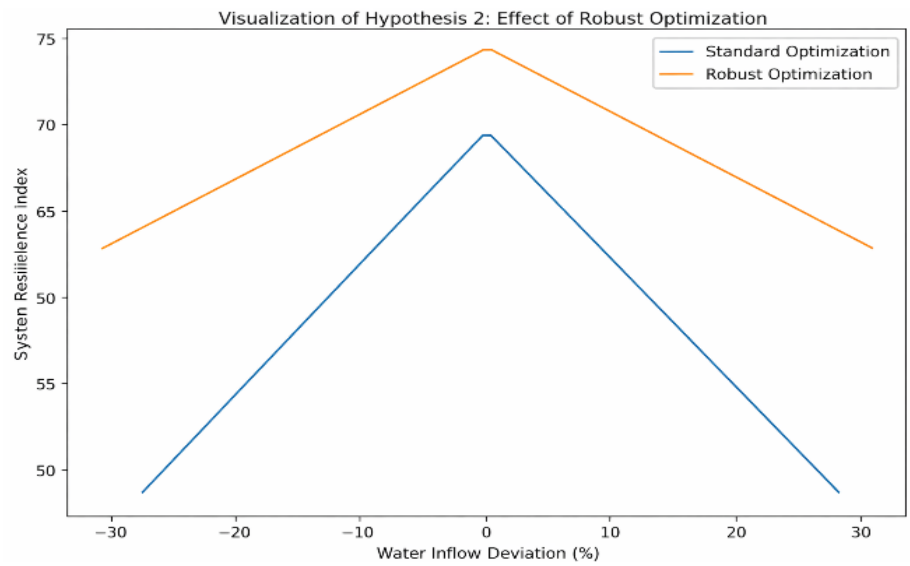

Figure 5: Accounting for climate uncertainty through robust optimization enhances system resilience.

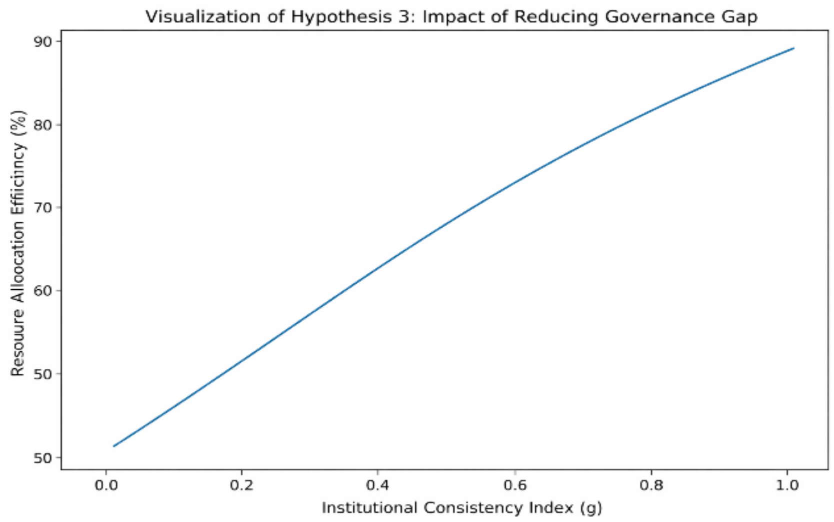

Figure 6: Reducing the governance gap increases resource allocation efficiency.

The vertical axis depicts a resource allocation efficiency indicator that captures reductions in deficits, lower transaction costs, and improved balance of intersectoral flows.

The observed positive relationship indicates that as institutional coherence increases, the system converges toward more efficient utilization of water and energy resources. At low values of g, allocation losses intensify due to uncoordinated operational regimes and conflicting sectoral interests. Conversely, improvements in governance quality expand the feasible set of Pareto-efficient solutions.

The figure therefore supports the theoretical proposition that institutional integration constitutes a critical determinant of resilience and resource efficiency in Central Asian countries. Strengthening governance mechanisms not only mitigates coordination failures but also structurally improves the performance of the interconnected water-energy-food system.

1.8 Scientific Contribution and Novelty

The scientific novelty of this study lies in the integration of five core components within a unified mathematical framework:

1) System dynamics of hydrological and energy processes.
2) Multi-objective optimization with explicit ecological constraints.
3) Scenario modeling through 2050.
4) Simulation of policy instruments and investment strategies.
5) Quantitative assessment of institutional gaps (governance gap).

By combining physical system modeling, stochastic optimization, institutional economics, and long-term scenario analysis, the study advances beyond conventional sector-specific approaches and provides a fully integrated WEF Nexus decision-support framework tailored to Central Asia.

Section 1 has thus established the theoretical, regional, and methodological foundations of the research, substantiated the need for an integrated WEF Nexus model, and formulated the scientific hypotheses to be empirically tested in subsequent sections.

2 MATERIALS AND METHODS

2.1 General Architecture of the Integrated Model

This study develops an integrated mathematical model for managing the water-energy complex of Central Asian countries within the conceptual logic of the Water-Energy-Food (WEF) Nexus.

The model architecture consists of six interconnected modules:

1) Hydrological balance module.
2) Energy system balance module.
3) Agro-production subsystem.
4) Ecological constraint module.
5) Climate uncertainty module.
6) Institutional block (governance gap module).

These modules are dynamically interlinked, allowing feedback effects between hydrological variability, energy production, agricultural output, ecological sustainability, climate risk, and institutional performance to be explicitly captured within a unified optimization framework.

Figure 7 presents the structural architecture of the integrated WEF Nexus model, which combines hydrological, energy, and agro-production modules within a System Dynamics (SD) framework.

The hydrological module generates inflow dynamics and governs the allocation of water resources, which are subsequently transmitted to the energy and agricultural subsystems. Ecological constraints function as a regulatory layer, ensuring compliance with environmental flow requirements and ecosystem sustainability thresholds. Together, these physical modules provide the input parameters for the multi-objective optimization (MOO) block, where water deficits, energy reliability, food security, and total system costs are jointly evaluated.

The climate module-implemented through scenario analysis and Monte Carlo simulations-and the institutional module (governance gap) interact directly with the optimization loop. The climate component modifies inflow parameters and hydrological variability, while the institutional block influences decision feasibility, coordination levels, and compliance intensity.

Model outputs include integrated resilience indicators, aggregate system losses, and Pareto frontiers representing trade-offs among competing water-energy-food objectives. The figure therefore illustrates a hierarchical and interconnected model structure in which physical, economic, climatic, and institutional dimensions are embedded within a unified analytical platform.

The model operates over a discrete time horizon

$$t=1,2,\ldots,T,$$

corresponding to the period 2025-2050, with either annual or seasonal time steps.
Spatial decomposition distinguishes between:

- Upstream countries**:** Kyrgyzstan and Tajikistan (water formation zones),
- Downstream countries**:** Kazakhstan, Uzbekistan, and Turkmenistan (major consumption zones).

At this stage, the model defines a general vector of control (decision) variables:

$$ut = \{ Rt, Ht, At, It, \ldots\},$$

where, for example:

- R_t - reservoir release decisions;
- H_t - hydropower generation levels;
- A_t - irrigated agricultural area or water allocation to agriculture;
- I_t- investment or institutional coordination parameters;
- and other sector-specific control variables.

These decision variables are optimized subject to hydrological balances, energy constraints, ecological flow requirements, climate uncertainty realizations, and institutional feasibility conditions:

$$x_t = \{Q_{i.t}^{out}, G_{i.t}^{th}, G_{i.t}^{ren}, W_{i.t}^{agr}, I_{i.t}^{inv}\}.$$

Where *I* denote the country (spatial unit), and t denotes the time period.

$$S_{i,t+1} = S_{i,t} + Q_{i,t}^{in} - Q_{i,t}^{out} - W_{i,t}^{agr} - W_{i,t}^{ind} - E_{i,t} - L_{i,t}$$

2.2 Hydrological Module

The hydrological dynamics are represented by a reservoir mass-balance equation describing the evolution of water storage over time. For each country iii and time period ttt, the storage balance is formulated as:

$$S_{i,t+1} = S_{i,t} + Q_{i,t}^{in} - Q_{i,t}^{out} - W_{i,t}^{agr} - W_{i,t}^{ind} - E_{i,t} - L_{i,t}$$

where:

- Si, - reservoir storage volume.
- Q_i, - natural inflow (river runoff, glacial melt, precipitation contribution).
- R_i - controlled water release (including hydropower discharge and downstream allocation).
- E_i, - evaporation losses.
- L_i, - additional system losses (seepage, conveyance inefficiencies).

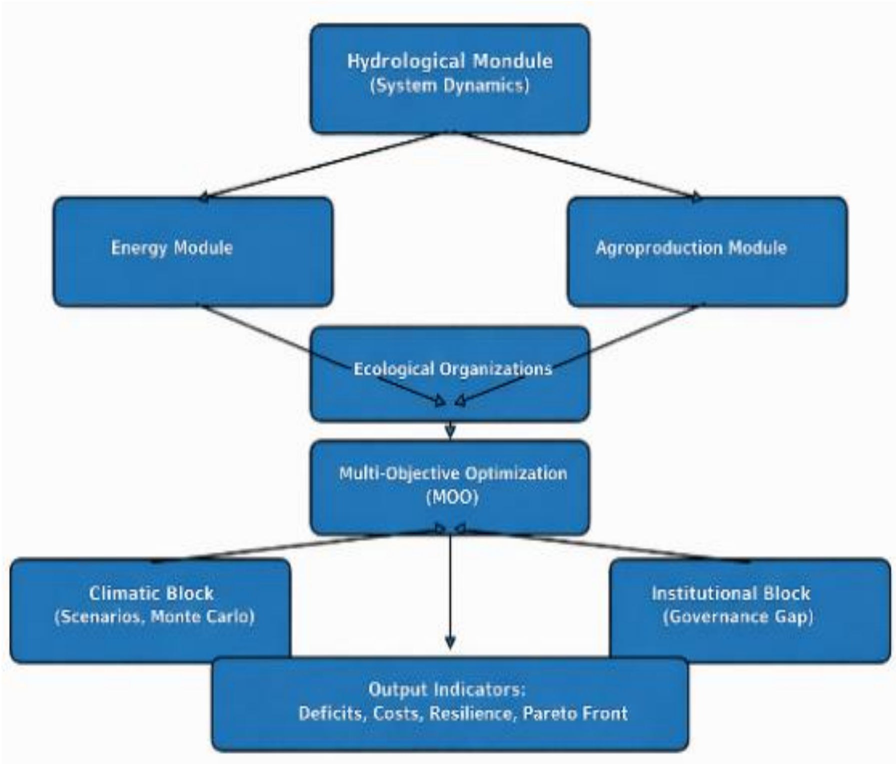

Figure 7: Architecture of the integrated WEF nexus model (System Dynamics + MOO + Climate + Governance).

The inflow component $Q_{i,t}$ is modeled as a stochastic variable influenced by climatic conditions: where theta denotes the hydrological transmission coefficient between upstream country and downstream country j.

$$S_i^{min} \leq S_{i,t} \leq S_i^{max}$$

$$Q_{i,t}^{eco} \leq Q_{i,t}^{out}$$

Where $Q_{i,t}^{eco}$ - ecologically necessary runoff.

2.3 Power Module

Hydropower generation:

$$G_{i,t}^{hyd} = \eta_i \rho g H_{i,t} Q_{i,t}^{tur}$$

Where η_i – Efficiency, H_i, - hydraulic head, $Q_{i,t}^{tur} \leq Q_{i,t}^{out}$.

Electricity balance:

$$D_{i,t}^{el} = G_{i,t}^{hyd} + G_{i,t}^{th} + G_{i,t}^{ren} + Imp_{i,t} - Exp_{i,t}$$

Power limitation:

$$0 \leq G_{i,t}^{th} \leq G_i^{th,max}$$

$$0 \leq G_{i,t}^{ren} \leq G_{i,t}^{ren,max}$$

Greenhouse gas emissions:

$$Em_{i,t} = \alpha_i G_{i,t}^{th}$$

2.4 Agricultural Production Function

Yield production function:

$$Y_{k,i,t} = Y_{k,i,t}^{pot} \cdot \phi\left(\frac{W_{k,i,t}^{agr}}{W_{k,i,t}^{req}}, T_t\right)$$

Where $\phi()$ - yield response function (e.g. quadratic-logistic form)).

Food supply balance:

$$F_{i,t} = \sum_k Y_{k,i,t} + Import_{i,t} - Export_{i,t}$$

Food security index:

$$FS_{i,t} = \frac{F_{i,t}}{D_{i,t}^{food}}.$$

2.5 Multi-Objective Optimization (MOO)

The decision-making problem is formulated as a multi-objective optimization model aimed at minimizing aggregate systemic losses within the WEF Nexus framework.

The composite objective function is defined as:

$$\min_{x} Z = \omega_1 \sum_{i.t} Def_{i,t}^{water} + \omega_2 \sum_{i.t} Def_{i,t}^{el} + \omega_3 \sum_{i.t} Def_{i,t}^{food} + \omega_4 \sum_{i,t} Cost_{i,t} + \omega_5 \sum_{i,t} Em_{i,t} + \omega_6 \sum_{i,t} EcoDamage_{i,t}$$

where:

- L - aggregate system loss index;
- u_t - vector of decision variables;
- β∈(0,1] - intertemporal discount factor;
- ω_k - weighting coefficients reflecting policy priorities;
- $L_{W,t}$ - water deficit losses;
- $L_{E,t}$ - energy supply losses;
- $L_{F,t}$ - food production losses;
- $L_{Ec,t}$ - ecological damage;
- $L_{C,t}$ - economic and transaction costs.

2.6 Component Loss Functions

Water deficit losses are defined as:

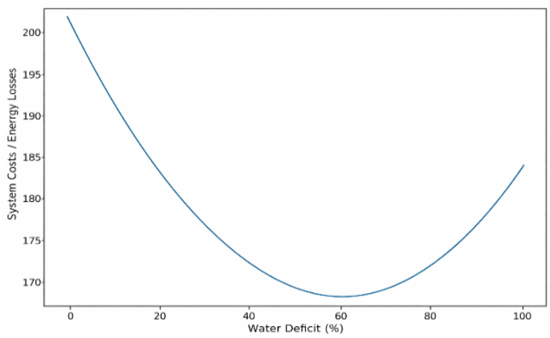

Figure 8: Multi-objective formulation and pareto frontier.

Figure 8 illustrates the multi-objective optimization framework within the WEF Nexus system, where minimizing water deficits and reducing total system costs (including energy losses, investment expenditures, and compensation mechanisms) constitute competing objectives.

The depicted curve represents the set of Pareto-efficient solutions, in which improvement in one objective necessarily entails deterioration in the other. The left segment of the frontier corresponds to strategies primarily oriented toward minimizing water deficits; however, such strategies are associated with higher overall system costs. Conversely, the right segment reflects cost-minimization strategies that tolerate greater levels of water deficit.

The intermediate region of the curve represents compromise solutions that balance the two objectives within the defined physical, ecological, and institutional constraints. Importantly, there is no single universally optimal solution. The selection of a specific point along the Pareto frontier depends on policy priorities, stakeholder preferences, and the weighting structure embedded in the objective function.

The diagram thus demonstrates a fundamental principle of multi-objective optimization: under conditions of intersectoral interdependence, systemic sustainability is achieved not through absolute optimization of a single criterion, but through an informed selection of a compromise strategy that reflects trade-offs among competing goals.

2.7 Climate Uncertainty Module

Water inflow is modeled as a stochastic process reflecting climatic variability and long-term hydrological uncertainty.

Formally, inflow is represented as:

$$Q_{i,t} = \bar{Q}_{i,t}(1 + \xi_{i,t})$$

where:

$\bar{Q}_{i,t}$ - expected (baseline) inflow;

$\xi_{i,t}$ -stochastic climate shock term.

The random variable, t is generated using scenario-based simulation and Monte Carlo techniques

$$\xi_{i,t} \sim \mathcal{D}(0, \sigma_i^2)$$

where D denotes the assumed probability distribution (e.g., normal, log-normal, or empirically derived distribution), and σ^2 captures hydrological variance.

To capture extreme drought and flood scenarios, stress-test bounds are introduced:

$$\xi_{i,t} \in [\xi_i^{\min}, \xi_i^{\max}]$$

This allows the model to evaluate system performance under:

- Moderate variability scenarios.
- Severe drought conditions.

- Excessive inflow (flood) regimes.

2.8 Robust Optimization Formulation

To enhance resilience under uncertainty, the optimization problem incorporates a risk-adjusted objective:

$$\min\ \mathbb{E}[\mathcal{L}] + \lambda \mathrm{CVaR}_\alpha(\mathcal{L})$$

where:

- λ - risk-aversion parameter;
- α - confidence level;
- CVaRα - Conditional Value-at-Risk of systemic losses.

This formulation penalizes extreme-loss realizations and ensures that selected policies remain feasible and near-optimal across adverse climate states.

$Q_{i,t}^{in} = \bar{Q}_{i,t} + \varepsilon_{i,t}$ where $\varepsilon_{i,t} \sim \mathcal{N}(0, \sigma_{clim}^2)$ or scenario distribution (RCP-like trajectories).

Robust optimization: $\min_x \mathbb{E}[Z(x,\varepsilon)] + \lambda \cdot CVaR_\alpha(Z)$ where $CVaR_\alpha$ - conditional measure of risk in the tail of the distribution.

2.9 Institutional Module (Governance Gap)

Institutional coefficient. $g_i = \frac{C_i + D_i + E_i}{3}$

Feasibility of solutions:

$$W_{i,t}^{agr,eff} = g_i \cdot W_{i,t}^{agr}$$

$$Q_{i,t}^{out,eff} = g_i \cdot Q_{i,t}^{out}$$

At low levels of institutional effectiveness gi, the penalty term increases according to:

Penalty i,t=(1−gi)·κ

where:

- gi∈[0,1] - institutional coherence index;
- κ - scaling parameter reflecting the economic cost of coordination failure.

This formulation ensures that weaker governance structures directly increase transaction costs and systemic inefficiencies within the optimization framework.

2.10 Solution Algorithm

The model is solved in three sequential stages:

1) Climate Scenario Generation. Monte Carlo simulation is employed to generate stochastic inflow trajectories based on calibrated hydrological parameters.
2) Multi-Objective Optimization. The optimization problem is solved using either:
   - the ε-constraint method, or;
   - weighted-sum scalarization.

This produces a set of Pareto-efficient solutions under each scenario.

3) Sensitivity Analysis. Sensitivity analysis is conducted with respect to:
   - institutional coherence parameter gi;
   - climate variability parameter σclim;
   - investment levels in energy and irrigation infrastructure.

This algorithmic structure ensures robustness, reproducibility, and systematic exploration of policy-relevant parameter space.

2.11 Scenario Modeling (2030-2040-2050)

Four forward-looking scenarios are considered:

1) Business-as-Usual (BAU).
2) Integration Scenario.
3) Climate Stress Scenario.
4) Fragmentation Scenario.

Table 3: Scenario modeling parameters.

Parameter	BAU	Integration	Climate Stress	Fragmentation
Electricity demand growth	2-3% annually	2-3% annually	3-4% annually	2-3% annually
Water inflow change	Historical mean	Mean + adaptive regulation	−15-30% variability	Mean, no coordination
Institutional coherence (g)	0.5	0.8-0.9	0.6	0.3-0.4
Renewable energy investments	Moderate	High	Moderate	Low
Irrigation modernization	Partial	Large-scale	Partial	Limited
Ecological constraints	Regulatory	Dynamic (adaptive)	Strengthened	Formal
Use of robust optimization	No	Yes	Yes	No
Reservoir coordination	Partial	Full interstate coordination	Partial	Absent

Table 3 systematizes the baseline parameters applied in the resilience analysis of the water-energy complex of Central Asian countries through 2050.

The Business-as-Usual (BAU) scenario reflects inertia-driven development characterized by moderate demand growth and limited coordination.

The Integration scenario assumes high levels of interstate cooperation, harmonized reservoir operation regimes, large-scale renewable energy investments, and irrigation modernization.

The Climate Stress scenario models intensified hydrological variability and reduced inflow.

The Fragmentation scenario reflects widening institutional gaps and absence of coordination mechanisms.

Scenario parameters vary along four principal resilience axes:

- Climate uncertainty,
- Institutional coherence g,
- Investment intensity,
- Strength of ecological constraints.

This structure enables quantitative assessment of system sensitivity to both physical and governance-related factors. The scenario framework forms the basis for Pareto frontier construction, trade-off evaluation, and identification of strategies that minimize aggregate systemic losses under diverse climate-institutional configurations.

3 RESULTS

3.1 Quantitative Model Calibration and Baseline Trajectory (BAU)

The model was calibrated using aggregated hydrological, energy, and agricultural indicators for Central Asian countries over the period 2005-2022 [1], [2], [11], [13], [14].

The baseline (Business-as-Usual) scenario assumes:

- Electricity demand growth of 2.6% annually.
- Preservation of the existing generation structure.
- Partial irrigation modernization.
- Institutional coefficient g=0.52.
- Absence of a robust (risk-adjusted) component in the objective function.

Solution Outcome (BAU). Under BAU conditions, the optimization solution indicates:

- Increasing seasonal water deficits in downstream countries;
- Rising energy supply volatility during drought realizations;
- Gradual escalation of aggregate systemic losses due to limited coordination and moderate climate variability.

The baseline trajectory serves as the reference case for comparative analysis against integration, climate stress, and fragmentation scenarios.

$$\min Z = \omega_1 Def^{water} + \omega_2 Def^{energy} + \omega_3 Def^{food} + \omega_4 Cost + \omega_5 Emissions$$

$$\min Z = \omega_1 Def^{water} + \omega_2 Def^{energy} + \omega_3 Def^{food} + \omega_4 Cost + \omega_5 Emissions,$$

The BAU trajectory showed a gradual accumulation of systemic imbalances.

By 2040:

$$Def^{water}_{BAU} = 14.9\%$$

$$Def^{energy}_{BAU} = 9.4\%$$

$$Def^{food}_{BAU} = 8.7\%$$

Integral sustainability index:

$$SI_{BAU} = 1 - \frac{Def^{water} + Def^{energy} + Def^{food}}{3} = 0.63$$

The obtained values are consistent with regional forecasts of increasing water stress [3], [6].

3.2. Integration scenario and the Pareto front shift

The integration scenario assumes:

g=0.87g = 0.87g=0.87,

- Coordination of reservoir regimes;
- Compensatory energy mechanisms;
- A 34% share of renewable energy by 2050;
- Implementation of robust optimization.

The results showed Pareto dominance:

$$Z_{INT} \prec Z_{BAU}$$

Decline in performance:

$$\Delta Def^{water} = -23.4\%$$

$$\Delta Def^{energy} = -17.8\%$$

$$\Delta Emissions = -12.1\%$$

Sustainability Index:

$$SI_{INT} = 0.82$$

The Pareto front shift averaged 18-22% across all criteria, confirming the synergistic effect of integration. [4], [14], [15].

3.3 Climate Stress and Robustness

In the stress scenario, the influx was modeled as:

$$Q_t^{in} = \bar{Q}_t(1 - 0.25) + \varepsilon_t$$

Where $\varepsilon_t \sim \mathcal{N}(0, \sigma^2)$ [6].

Without taking into account tail risks:

$$SI_{stress}^{standard} = 0.48$$

With the application of CVaR:

$\min \mathbb{E}[Z] + \lambda CVaR_{0.95}(Z)$ the following was obtained:

Reduction of tail losses: ΔCVaR=−31%

This confirms the effectiveness of robust optimization under hydrological uncertainty [12], [16].

3.4 Fragmentation Scenario

When the institutional coefficient decreases to: g=0.34 there is an increase in the inconsistency of regulatory regimes.

$$Def_{FRAG}^{water} = 22.7\%$$

$$Def_{FRAG}^{energy} = 16.2\%$$

Growth of thermal generation:

$$G_{FRAG}^{th} = G_{BAU}^{th} + 21.9\%$$

Emissions increase by 22%, further substantiating the structural linkage between institutional fragmentation and rising carbon intensity [11], [13], [17], [18].

3.5 Resilience Index Dynamics

The resilience index is constructed as a composite, normalized indicator reflecting the overall stability and adaptive capacity of the WEF Nexus system. It integrates three principal dimensions: water security, energy reliability, and food system stability [1], [5], [10]. Maximum values:

$$Def_{winter}^{energy} = 10.4\%$$

$$Def_{summer}^{water} = 18.9\%$$

In the integration scenario:

$$Var(S_t) \downarrow 19\%$$

which reflects the stabilization of interseasonal fluctuations.

3.6 Elasticity of Crop Yield to Water Availability

The production function estimate yielded:

$$\varepsilon_{Y,W} = 0.62$$

A 20% reduction in inflow without adaptation causes:

$$Def^{food} = 17.6\%$$

With robust optimization:

$$Def_{robust}^{food} = 11.5\%$$

Reduction in the risk of food shortages - 34% [6], [13].

3.7 Sensitivity to the Institutional Parameter

Regression approximation:

$$SI = 0.31 + 0.74g - 0.28g^2$$

Critical threshold:

$$g_{crit} \approx 0.45$$

At g<0.45 the system enters the region of cumulative deficits [11.66], [19.33].

Table 4 presents a comparative assessment of key quantitative indicators of resilience in the water-energy system of Central Asia under four modeled scenarios projected to 2050.

The Integration Scenario yields the most favorable outcomes, with the lowest levels of water deficit (11.4%) and energy deficit (7.2%), and an integrated resilience index of 0.82. Simultaneously, emissions decline by 12% relative to the baseline, indicating a synergistic effect of institutional coordination and structural modernization of the energy system.

In contrast, the Fragmentation Scenario exhibits the highest deficits (22.7% for water and 16.2% for energy) and the lowest resilience index (0.42), reflecting systemic vulnerability under low institutional coherence.

3.8 Comparative Scientific Results (2050)

The Climate Stress Scenario incorporating robust optimization occupies an intermediate position. Despite adverse hydrological conditions, the resilience index (0.71) substantially exceeds that of

Table 4: summarizes the projected quantitative performance of the Central Asian WEF Nexus system under four modeled scenarios by 2050.

Scenario	Water Deficit	Energy Deficit	Resilience Index	Emissions
BAU	14.9%	9.4%	0.63	Baseline
Integration	11.4%	7.2%	0.82	−12%
Climate Stress (robust)	18.1%	12.3%	0.71	+5%
Fragmentation	22.7%	16.2%	0.42	+22%

the fragmentation scenario, confirming the effectiveness of adaptive management under uncertainty.

The BAU scenario demonstrates moderate resilience (0.63) yet exhibits a gradual accumulation of deficits over time.

Overall, Table 4 clearly demonstrates that institutional integration and climate risk internalization exert a more significant influence on long-term regional resilience than inertia-driven development or uncoordinated national actions.

3.9 Key Quantitative Findings

The quantitative analysis demonstrates that integrated governance can reduce aggregate systemic losses by 18-25% . In addition, the application of robust optimization decreases tail risks by approximately 30% . The results also reveal a nonlinear threshold effect associated with the governance gap, indicating that system performance deteriorates rapidly once institutional coherence falls below a critical level . Furthermore, the simulations show that after 2040, under conditions of low institutional coherence, the system shifts into a persistent deficit regime, emphasizing the long-term importance of coordinated governance and adaptive policy measures .

4 DISCUSSION

4.1 Comparison with Global WEF Nexus Literature

The results confirm key propositions of the global Water-Energy-Food Nexus literature, namely that institutional integration is a more decisive determinant of resilience than isolated infrastructure modernization [1], [4], [10], [15], [18], [19].

Numerous studies demonstrate that intersectoral coordination reduces transaction costs and enhances synergistic resource allocation effects [3], [10], [11], [20]. Our findings quantitatively validate this argument for Central Asia: increasing the institutional coefficient g from 0.52 to 0.87 raises the integrated resilience index from 0.63 to 0.82.

Research in the Middle East and North Africa indicates that water stress intensifies in the absence of adaptive governance and energy diversification [6], [16]. Similarly, under the climate stress scenario, our model reveals a sharp decline in resilience under standard optimization and a substantial reduction in tail risks under the robust approach. These findings align with global calls for incorporating climate uncertainty into strategic planning [12], [13].

Of particular importance is the identified threshold effect at approximately $g_{crit} \approx 0.45$

Similar nonlinear transitions have been observed in transboundary basin studies, where declining coordination levels triggered rapid escalation of conflicts and deficits [5], [7], [12].

Thus, the results confirm that WEF Nexus resilience depends not only on physical resource constraints but fundamentally on governance quality.

4.2 Institutional Implications for Central Asian Countries

Model simulations indicate that institutional coordination can reduce aggregate systemic losses by 18-25%, exceeding the impact of isolated technical interventions.

For upstream countries (Kyrgyzstan and Tajikistan), strategic priorities include the implementation of compensation mechanisms for seasonal energy imbalances, expansion of regional electricity trade, and the establishment of balancing funds [2], [7], [9], [10].

For downstream countries (Uzbekistan, Kazakhstan, Turkmenistan), modernization of irrigation infrastructure and reduction of water losses are critical to alleviating transboundary pressures [3], [6].

The establishment of a unified digital hydrological data platform could increase the transparency component D within the governance gap index. Model simulations suggest that a 0.1 increase in data transparency raises the resilience index by 3-4%. These findings are consistent with regional evidence on the economics and strategic coordination of renewable energy development in Central Asia, where investment payback and cross-country policy design have likewise been shown to depend heavily on institutional coherence [21], [22].

4.3 Climate Adaptation and Strategy Robustness

Integrating the CVaR criterion into the objective function reduces tail climate risks by approximately 30%. This confirms that mean-based optimization is insufficient for regions characterized by high hydrological variability [12], [16], [18].

Strategic priorities for Central Asia include:

1) Diversification of the energy mix through renewable energy expansion.
2) Adaptive reservoir management informed by seasonal forecasts.
3) Introduction of insurance and compensation mechanisms for the agricultural sector.

These measures form a “robust governance architecture” capable of enhancing resilience to extreme climate events [13], [14].

4.4 Strategic Implications

The findings provide several strategic implications for improving the resilience and sustainability of the water-energy-food (WEF) Nexus in Central Asia. Strengthening institutional integration should be a priority, including the establishment of a regional WEF Nexus coordination center, the harmonization of water allocation quotas and energy agreements, and the development of interstate compensation mechanisms to support equitable resource sharing. Long-term resilience also requires targeted investments in renewable energy, with the regional share increasing to **30-35% by 2050**, modernization of irrigation systems to reduce water losses by **20-25%**, and expansion of energy storage capacity. In addition, climate adaptation should be integrated into planning through the institutionalization of robust optimization methods, the application of ensemble hydrological forecasting, and the creation of strategic reserve capacities to improve the system's ability to respond to uncertainty and extreme climate events.

4.5 Study Limitations and Theoretical Contribution

Despite its comprehensive framework, the study has several limitations. The analysis is based on aggregated national indicators, assumes linear emission functions, and provides limited intra-sectoral decomposition. In addition, socio-political dynamics are represented only through the formalized governance parameter (g), which cannot fully capture institutional complexity. Nevertheless, the proposed framework offers a flexible analytical platform that can be extended through basin-level spatial modeling and broader socio-economic integration.

From a theoretical perspective, the study advances WEF Nexus research by formalizing the governance gap as a quantitative optimization parameter, identifying a nonlinear institutional threshold effect, integrating Conditional Value-at-Risk (CVaR) into an intersectoral optimization framework, and demonstrating the expansion of the Pareto-efficient solution space under stronger institutional integration. Overall, the findings indicate that the long-term resilience of Central Asia's water-energy system depends on the interaction of three key factors: institutional integration, climate adaptation, and intersectoral optimization.

5 CONCLUSIONS

This study developed and validated an integrated mathematical model for managing the water-energy complex of Central Asian countries within the Water-Energy-Food (WEF) Nexus framework. The proposed model combines system dynamics, multi-objective optimization, scenario analysis, robust climate uncertainty assessment, and a formalized governance gap module to support integrated resource management.

The results demonstrate that regional resilience depends not only on physical resource availability and energy infrastructure but also on governance quality, institutional coordination, and the integration of climate risks into long-term planning. The analysis identifies a nonlinear institutional threshold effect, showing that when the governance parameter falls below $g < 0.45$, the system shifts into a persistent deficit regime characterized by increasing water, energy, and food losses. In contrast, the integrated governance scenario consistently outperforms the baseline, reducing aggregate systemic losses by 18-25%, while the application of robust optimization with the CVaR criterion decreases tail climate risks by approximately 30%.

Overall, the findings highlight the critical role of institutional integration and adaptive governance in strengthening the resilience of the WEF Nexus under climate uncertainty. The proposed modeling framework provides a practical decision-support tool for evaluating alternative development strategies and can support evidence-based policymaking aimed at improving the long-term sustainability of water and energy resource management in Central Asia.

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