

Resource governance in Central Asia: a water-energy-food nexus perspective on sustainable development

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Abstract

Resource governance shapes how interdependent water, energy, and food systems are coordinated, yet long-term comparative measurement of governance-related vulnerability remains limited in Central Asia. Using institutional fit as the theoretical lens, this study develops a Governance-related Multidimensional Vulnerability Index (GMVI) for Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan from 2002 to 2024 and examines its association with water-energy-food (WEF) sustainability performance. GMVI combines agricultural withdrawal-to-value-added intensity, a broad governance-capacity deficit, and exposure to seasonal hydropower-irrigation trade-offs. WEF sustainability is measured with a compact Water-Energy-Food Sustainability Index (WEFSI) used as the empirical outcome. The balanced descriptive panel contains 115 country-year observations, and one-year-lag models use 110 observations. World Bank, United Nations SDG, and FAOSTAT series are harmonised under explicit source-precedence rules; uncertainty in 25 unavailable 2024 endpoints is propagated through 100 multiple-imputation draws. The Rubin-pooled association between lagged GMVI and WEFSI is -0.1527 (95% CI [-0.2989, -0.0065], $p = 0.041$). Exposure to seasonal hydropower-irrigation trade-offs provides the most explicit dimension-level signal. Country profiles further show that similar resource pressures can coexist with different sustainability outcomes when governance capacity and coordination exposure differ. The framework provides a comparative empirical lens for identifying governance-related vulnerabilities across countries and over time.

1. Introduction

Resource governance concerns the rules, authority, information, and implementation processes through which societies allocate and coordinate natural resources. These arrangements become especially important when water, energy, and food systems are tightly connected. Irrigation requires energy for pumping, treatment, and distribution. Electricity generation can depend on river flows and reservoir storage. Food production changes both water demand and energy use. Decisions in one sector can therefore transfer costs and benefits across sectors, locations, and seasons.

The water-energy-food nexus provides a useful perspective for examining these governance demands. The United Nations Economic Commission for Europe (UNECE) uses the water-food-energy-ecosystems nexus and emphasises cross-sectoral cooperation, intersectoral synergies, trade-offs, policy coherence, transparent information exchange, benefit sharing, and coordinated resource management (UNECE 2015, 2018). This article uses the shorter water-energy-food (WEF) label because the empirical outcome contains water, energy, and food dimensions, with ecosystem limits retained in the conceptual discussion.

Institutional fit refers to the correspondence between governance arrangements and the environmental and resource processes they are expected to manage (Young 2002). In a transboundary WEF system, fit involves spatial, temporal, cross-sectoral, and distributional correspondence. Spatial and temporal misalignment, fragmented authority, weak information exchange, policy incoherence, and unevenly

distributed costs and gains can increase coordination difficulty. These mechanisms provide the theoretical basis for examining governance vulnerability in interconnected resource systems.

Central Asia provides a coherent comparative setting for this problem. Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan constitute the five post-Soviet Central Asian states and remain linked through shared river systems, power networks, irrigation infrastructure, and a common institutional legacy in regional resource management (Hamidov et al. 2022). A recent review of Central Asian transboundary basins confirms that water, energy, and food governance remains organised around these shared systems (Bamgboye et al. 2025). Upstream Kyrgyzstan and Tajikistan rely heavily on hydropower and face strong winter electricity demand. Downstream Uzbekistan, Turkmenistan, and parts of Kazakhstan need summer releases for irrigated agriculture. The same regional resource system therefore operates through five national governance regimes with different capacities, priorities, and resource structures.

This coordination challenge has significant historical foundations. Recent Central Asian nexus research traces the Soviet-era system that linked upstream water releases with downstream energy supply and shows how the breakup of that system reshaped cross-border coordination after independence (Hamidov et al. 2022). The rivers, reservoirs, and transmission networks remained connected, while authority, ownership, and payment arrangements were divided among five states. Recent work in Europe-Asia Studies links current water governance in Central Eurasia to the region's centralised hydro-engineering legacy and its later national reorganisation (Spoor and Thiemann 2025). Ministries gained separate mandates, national development priorities diverged, and exchanges that had operated within one planning system became cross-border negotiations. A recent regional assessment identifies data exchange, institutional cooperation, and coordinated water-energy planning as continuing priorities across Central Asia (Kato 2025). Regional interdependence therefore persisted under a fragmented institutional structure.

The Aral Sea disaster shows the long-term cost of decisions that favour one use while ignoring the wider system. Large irrigation withdrawals supported farming while reducing river inflows and damaging ecosystems, health, and livelihoods (Micklin 2007). Climate change adds pressure through glacier loss, drought, floods, and rising demand, and it can intensify disputes when institutions do not adapt at the same pace as hydrological conditions (Bernauer and Siegfried 2012). The World Bank (2024) identifies Central Asia as one of the subregions in Europe and Central Asia most exposed to future water insecurity.

Research on the regional nexus has expanded rapidly. Recent work addresses long-term resource allocation, transboundary cooperation, crop production, and environmental pressure across Central Asia. Saidmamatov et al. (2023) and Guo et al. (2024) illustrate this broader regional focus, and related modelling is developed by Hu et al. (2024) and Ma et al. (2024). Hu et al. (2026), for example, show how coordinated reservoirs and seasonal pumped-hydropower storage could reduce tensions among irrigation, hydropower, and ecological flows in the Aral Sea Basin. This literature establishes the physical

interdependence of the nexus and evaluates technical interventions. Long-term comparative evidence on how rules, authority, information, compensation, and implementation shape sustainability performance remains limited.

The central empirical gap lies in governance measurement and longitudinal comparison. Technical studies identify feasible allocations and potential gains from cooperation. Their implementation depends on compatible plans, administrative capacity, seasonal coordination, information exchange, and credible arrangements for distributing costs and gains. Recent comparative nexus research identifies organisational coordination and implementation arrangements as central to WEF governance (Jones-Crank 2024). Water-governance scholarship further links institutional performance to the fit between governance arrangements and connected social-ecological processes (Moore et al. 2024). Similar resource pressures can therefore produce different outcomes when these governance conditions vary across countries and over time.

Institutional fit provides the main theoretical lens for this study. Recent water-governance scholarship develops institutional fit through the correspondence between governance arrangements and spatially and temporally connected environmental processes (Moore et al. 2024). Updated vulnerability scholarship continues to link exposure and system response capacity within vulnerability analysis (Turner and Zhou 2023). For WEF systems, governance difficulty also arises from cross-sectoral and multi-level coordination across shared resources. These strands of literature support a framework built around resource pressure, broad governance capacity, and seasonal coordination exposure. Recent Central Asian analysis further highlights institutional cooperation and coordinated planning as key conditions for managing shared water-energy systems (Kato 2025).

The empirical measures translate this literature-derived structure into comparable annual indicators. Agricultural withdrawal-to-value-added intensity (AWI) captures pressure by relating agricultural water dependence to recorded economic contribution, consistent with Central Asian research that evaluates irrigation demand together with agricultural production efficiency (Han et al. 2022). The broad governance-capacity deficit (GCD) uses Government Effectiveness and Regulatory Quality to capture policy formulation and implementation capacity (Kaufmann and Kraay 2024). Seasonal hydropower-irrigation trade-off exposure (STE) captures the temporal coordination demand created by joint dependence on hydropower and irrigation, a recurring feature of Central Asian water-energy relations (Kato 2025). Their equal-weighted average forms the Governance-related Multidimensional Vulnerability Index (GMVI), while each dimension remains available for separate analysis.

The article makes three contributions. First, it applies institutional fit to a longitudinal comparison of resource governance in Central Asia and places governance-related vulnerability at the centre of the empirical design. Second, it develops a transparent GMVI that combines resource pressure, governance capacity, and seasonal coordination exposure and reports each dimension alongside the aggregate index. Third, it evaluates the empirical relevance of the index by examining whether changes in GMVI are associated with subsequent WEF sustainability performance within countries from 2002 to 2024.

2. Literature review

2.1 Resource governance and institutional fit

Resource governance concerns the rules, authority, information, accountability, and implementation processes through which allocation decisions are made. Institutional fit describes whether these arrangements correspond to the environmental processes they govern (Young 2002). Functional-fit research evaluates how well institutions correspond to ecosystems (Ekstrom and Young 2009), while systems-based analysis shows how environmental change can alter that correspondence over time (Ekstrom and Crona 2017). In WEF systems, this correspondence extends across sectors, political jurisdictions, and operating time scales; misalignment among ecological processes, decision boundaries, and administrative authority can weaken performance (Cash et al. 2006; Cumming et al. 2006).

Institutional fit provides an umbrella for several related governance mechanisms. Scalar fit concerns spatial and temporal correspondence, while institutional interplay concerns interactions among rules and organisations across sectors and levels (Pahl-Wostl et al. 2021). Policy coherence focuses on whether sector plans recognise shared effects and trade-offs. These mechanisms all concern the capacity of governance arrangements to match the resource interactions that require coordination.

This distinction is useful for empirical design because governance problems arise through different channels. Institutional-fit research shows that governance arrangements can underperform when institutional scales fail to match interconnected environmental processes (Moore et al. 2024). Fragmented mandates, weak coordination mechanisms, and limited information exchange can constrain nexus implementation even when physical resource pressure is moderate (Jones-Crank 2024). The framework therefore treats pressure, capacity, and coordination exposure as related dimensions with distinct meanings.

Nexus governance requires horizontal and vertical coordination. Recent comparative work identifies joint planning, communication, and cross-level coordination as important nexus-governance mechanisms (Jones-Crank 2024). Horizontal coordination links water, energy, agriculture, and environmental agencies at the same level. Vertical coordination connects local users, basin bodies, national governments, and regional institutions. Both forms matter in Central Asia because national ministries coordinate domestic plans and states jointly manage rivers, reservoirs, transmission networks, and energy exchanges. Recent Central Asian assessments show that these arrangements depend on institutional cooperation, data exchange, and workable rules for jointly managed infrastructure (Kato 2025). Cross-sectoral and transboundary coordination therefore work through connected institutional processes.

Several governance approaches address this complexity by connecting multiple centres of authority through common rules and information channels (Srigiri and Dombrowsky 2022). Sorek et al. (2022) and Jones-Crank (2024) further show that organisational capacity, coordination procedures, and implementation arrangements shape nexus governance outcomes. These studies reinforce the

institutional-fit focus on how governance arrangements correspond to the interactions that require management.

2.2 Resource interdependence and governance coordination

The nexus approach emerged as a response to separate sector planning (Simpson and Jewitt 2019). Integrated modelling is now common in Central Asian studies of resource allocation and environmental pressure, including Guo et al. (2024) and Ma et al. (2024). These models identify potential gains from coordination. Orimoloye (2022) shows that implementation also depends on policy and institutional conditions. Operating rules, financing, authority, enforcement, and the capacity to reconcile seasonal demands therefore remain central to nexus governance, as recent work on implementation and institutional arrangements also indicates (Andersson 2024; Jones-Crank 2024).

UNECE describes this task through cross-sectoral cooperation and policy coherence: decision processes should recognise intersectoral effects, disclose conflicts, and connect policy and technical measures (UNECE 2015, 2018). Benefit sharing addresses the distribution of gains and costs through compensation, energy exchanges, joint investment, or risk sharing. These arrangements can make technically efficient cooperation politically and institutionally credible.

This literature identifies a specific gap for Central Asia: long-term comparative evidence on governance-related vulnerability conditions remains limited. Existing studies provide detailed evidence on physical interdependence, basin allocation, and technical coordination, while annual cross-country comparison of resource pressure, governance capacity, and seasonal coordination exposure remains much less developed. This gap motivates a governance-focused composite index that can be compared across the five states and over time.

Technical optimisation and governance implementation address different parts of the same resource problem. Quantitative models can identify lower-cost reservoir schedules, estimate the benefits of electricity exchange, and demonstrate welfare gains from joint operation. Implementation then depends on institutional authority, credible payment arrangements, information exchange, and an acceptable distribution of gains. This link provides the basis for evaluating governance-related conditions against observed WEF sustainability performance.

Implementation research increasingly treats scale, institutional interplay, and political strategy as governance conditions that shape nexus performance (Pahl-Wostl et al. 2021). Weitz et al. (2017) frame integrative governance as a means of closing coordination gaps across nexus sectors. Orimoloye (2022) places these concerns within practical barriers to implementation, and research on connected decision arenas shows how authority can be coordinated across institutions (Srigiri and Dombrowsky 2022). Andersson (2024) extends the discussion to synergies and trade-offs across the Sustainable Development Goals. Together, these studies clarify the rules, authority, and coordination processes that carry resource plans into practice.

Two methodological implications follow. The governance index should retain the meanings of its constituent dimensions, and the sustainability outcome should remain conceptually separate so that the empirical association can be interpreted clearly.

2.3 Measuring governance-related vulnerability and composite indices

Comparative resource-governance measurement draws on broad institutional indicators and sector-specific resource frameworks. Kaufmann and Kraay (2024) describe Government Effectiveness and Regulatory Quality as measures of administrative capacity, policy formulation and implementation, and regulatory quality; the World Bank (2025) provides these dimensions in the annual Worldwide Governance Indicators. In shared resource systems, UNECE (2015, 2018) frames governance through cross-sectoral coordination, policy coherence, information exchange, and implementation capacity. Pahl-Wostl et al. (2021) and Weitz et al. (2017) connect these institutional conditions with the governance of interdependent resource systems. These sources provide the institutional basis for the governance-capacity component of the present framework.

Resource pressure and coordination exposure also require observable measures. FAO (2022) links agricultural economic output with water use in its water-use-efficiency guidance, providing a methodological basis for relating agricultural production to water pressure. In Central Asia, Jalilov et al. (2016) show the importance of irrigation and water-energy interactions in the Amu Darya Basin. Later regional analyses document wider patterns of irrigation dependence and cross-sectoral resource pressure (Saidmamatov et al. 2023; Guo et al. 2024). Hu et al. (2024, 2026) further highlight the seasonal coordination demands created by hydropower and irrigation. This evidence supports separate measures of agricultural withdrawal intensity and seasonal hydropower-irrigation exposure.

Composite-indicator methodology requires explicit choices about direction, normalisation, weighting, and aggregation (OECD/European Union/EC-JRC 2008). Pooled min-max scaling provides a common 0–1 range for country-year comparison, and equal weighting keeps the aggregation rule transparent. Because composite scores can conceal offsetting dimensions, the analysis reports AWI, GCD, and STE separately and tests alternative PCA and entropy weights as sensitivity checks. WEF sustainability is measured separately using a compact outcome index informed by the WEF Nexus Index literature (Simpson et al. 2022).

2.4 Resource governance and comparative setting in Central Asia

Central Asia's geography and institutional history create a regional resource-governance system with a shared physical base and nationally differentiated governance. The main rivers rise largely in Kyrgyzstan and Tajikistan, while major irrigation areas lie downstream. The upstream states rely heavily on hydropower, whereas Kazakhstan, Turkmenistan, and Uzbekistan have larger fossil-fuel resources. Recent regional nexus research traces the continuing effects of the Soviet-era water-energy system on

upstream and downstream coordination after independence (Hamidov et al. 2022). Recent regional evidence also shows that agricultural and hydropower demands still compete within the same transboundary system (De Keyser et al. 2026). This combination of common resource interdependence and institutional variation makes the five-country region suitable for longitudinal comparison.

Temporal coordination is particularly important. Upstream hydropower systems can value winter releases when electricity demand is high, while downstream irrigated agriculture can value summer releases during the growing season. Annual water availability may look adequate even when the timing of release creates shortages for one use. Annual national data therefore provide a useful measure of broad seasonal exposure across countries and years.

Agriculture introduces a third source of resource demand. Irrigation supports crops, exports, food supply, and rural employment, while ageing canals and weak water accounting can increase losses. Environmental pressures remain part of the same resource system. The Aral Sea crisis, salinisation, glacier change, drought, and floods alter both water availability and the value of competing uses (Mayar et al. 2024). Agricultural withdrawals relative to value added therefore provide one comparable indicator of resource pressure within this wider governance context.

Basin-scale research has long examined the gains, losses, and allocation effects created by interconnected water, energy, and agricultural systems in Central Asia, as illustrated by Jalilov et al. (2016). More recent studies extend the analysis to regional environmental pressure, cooperation, and resource coordination (Saidmamatov et al. 2023; Guo et al. 2024; Ma et al. 2024). Hu et al. (2026) add a detailed assessment of seasonal reservoir and hydropower coordination. UNECE's Syr Darya assessment also emphasises intersectoral trade-offs, policy coherence, and transboundary cooperation (UNECE 2015). The present study complements this literature with a common annual comparison covering all five post-Soviet Central Asian states over twenty-three years.

2.5 Governance-related vulnerability framework and empirical operationalisation

GMVI is derived from three connected bodies of scholarship: vulnerability analysis, institutional fit, and WEF nexus governance. Updated vulnerability scholarship retains the interaction between exposure and system response as a core part of sustainability-oriented vulnerability analysis (Turner and Zhou 2023). Recent institutional-fit research focuses on whether governance arrangements match the social-ecological and cross-scale processes they are expected to manage (Moore et al. 2024). Applied to WEF systems, vulnerability can rise when resource demands cross sectoral, territorial, or temporal boundaries faster than governing arrangements can coordinate them. Comparative nexus research links these pressures to cross-sectoral coordination and implementation arrangements (Jones-Crank 2024).

The synthesis supports three analytical dimensions. Resource pressure represents the intensity of demand placed on the coupled resource system. Governance capacity represents the administrative and regulatory ability to formulate, coordinate, and implement policy. Seasonal coordination exposure

represents temporal misfit when hydropower and irrigation depend on shared water at different times of the year. Recent vulnerability research retains the connection between external stresses and the capacity of social-environmental systems to respond (Turner and Zhou 2023). Institutional-fit research distinguishes broad governing capacity from the spatial and temporal correspondence between institutions and environmental processes (Moore et al. 2024). Comparative WEF governance research further shows that cross-sectoral and multi-level coordination shape implementation in practice (Jones-Crank 2024). Figure 1 summarises how these foundations support the indicator structure and the meaning assigned to each measure.

The first dimension is operationalised through agricultural withdrawal-to-value-added intensity. Central Asian research links irrigation expansion, water demand, agricultural output, and production efficiency within the land-water-food nexus (Han et al. 2022). This provides a direct empirical basis for treating high agricultural water dependence relative to economic contribution as a resource-pressure signal. Mayar et al. (2024) further link agricultural water use to environmental stress in the Aral Sea Basin. AWI adapts this literature to the available annual panel by dividing agriculture's share of freshwater withdrawals by agriculture's share of value added. Higher values indicate heavier withdrawal pressure relative to recorded economic contribution.

The second dimension measures broad governance capacity. Government Effectiveness and Regulatory Quality are used together because they represent administrative and regulatory aspects of state capacity relevant to policy formulation and implementation (Kaufmann and Kraay 2024). Nexus-governance research also treats organisational and procedural capacity as central to coordination and implementation (Jones-Crank 2024). Their pooled mean is reversed to form GCD, so higher scores indicate greater capacity constraints. The source indicators measure economy-wide institutions, so GCD serves as a broad enabling condition for resource governance.

The third dimension follows the temporal-fit problem identified in both theory and regional evidence. In Central Asia, upstream hydropower and downstream irrigated agriculture create seasonal demands on shared river systems. A recent review identifies competition between agricultural and hydropower demands as a continuing regional governance problem (De Keyser et al. 2026), while a recent Central Asian assessment emphasises coordinated water-energy planning and stronger institutional cooperation (Kato 2025). STE therefore uses the geometric mean of agricultural withdrawal share and hydropower generation share. This construction makes a high score dependent on both forms of exposure and aligns the aggregation rule with the intended concept of joint dependence, consistent with recent composite-index research that calls for aggregation choices to match the underlying conceptual framework (Usubiaga-Liaño and Ekins 2024).

AWI, GCD, and STE are combined through an equal-weighted arithmetic mean. Recent composite-index research stresses explicit alignment between the conceptual framework and choices of indicator selection, normalisation, weighting, and aggregation (Usubiaga-Liaño and Ekins 2024). Equal weights are used because the reviewed literature treats pressure, capacity, and seasonal coordination exposure as

complementary parts of vulnerability and provides no established basis for assigning one a fixed larger weight. GMVI is therefore reported alongside AWI, GCD, and STE, and PCA and entropy weights are tested in the robustness analysis.

The derivation follows a clear sequence. Vulnerability and institutional-fit theory define the structure of the framework; nexus-governance studies identify the coordination mechanisms; sectoral and regional research guides the observable proxies; and composite-indicator methodology governs normalisation and aggregation. Section 3 sets out the formulas, data sources, direction rules, and sensitivity tests used to implement this literature-derived framework.

2.6 Hypotheses

Higher GMVI values indicate a less favourable combination of the three observable governance-related conditions: greater withdrawal intensity, weaker broad governance capacity, or higher seasonal exposure. Institutional fit suggests that these conditions can increase the difficulty of coordinated adjustment and can therefore be associated with lower WEF sustainability performance. The analysis evaluates the aggregate GMVI association and the three dimension-specific associations.

- H1: Higher GMVI values are associated with lower WEFSI within countries over time.
- H2: Higher agricultural withdrawal-to-value-added intensity is associated with lower WEFSI within countries over time.
- H3: A higher broad governance-capacity deficit is associated with lower WEFSI within countries over time.
- H4: Higher seasonal hydropower-irrigation trade-off exposure is associated with lower WEFSI within countries over time.

H1 tests the association between aggregate GMVI and WEFSI. H2, H3, and H4 test the associations of AWI, GCD, and STE with WEFSI in the dimension models. The hypotheses are formulated as directional within-country associations between the observable vulnerability conditions and WEFSI.

3. Creating a Governance-related Multidimensional Vulnerability Index

3.1 Research design, cases, and sample

The analysis covers Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan from 2002 to 2024. The final dataset contains 115 country-year observations, with 110 observations used in the one-year-lag models. Data were collected from the World Bank, the United Nations SDG Global Database, and FAOSTAT. For 25 values that were unavailable for 2024, forecasting models were selected using rolling validation, and 100 multiple-imputation draws were used to account for prediction uncertainty. Further details on data sources, time-period alignment, the treatment of undernourishment data, and the

estimation of missing 2024 values are provided in Supplementary Methods S1. Variable definitions and data-coverage information are reported in Supplementary Tables S1–S2.

3.2 Selection of governance vulnerability dimensions

Variable selection follows the institutional-fit framework developed in Section 2.5. GMVI combines three conditions that capture distinct sources of governance vulnerability in the Central Asian resource system: resource pressure, administrative and regulatory capacity, and seasonal coordination exposure. AWI represents pressure generated by agricultural water dependence, drawing on the water-use-efficiency logic set out by FAO (2022). GCD captures constraints in policy formulation and implementation through the governance dimensions developed by Kaufmann and Kraay (2024). STE represents joint dependence that creates seasonal coordination demands, a recurring feature of Central Asian nexus research (Guo et al. 2024; Hu et al. 2024, 2026). Pahl-Wostl et al. (2021) provide the broader governance rationale for treating scale and coordination as central features of nexus management.

3.3 Normalisation and weighting

To combine indicators with different units and directions, continuous components are transformed to the 0–1 range using pooled min-max normalisation. Benefit indicators increase with stronger performance, while cost or deficit indicators are reversed before aggregation. One set of pooled bounds is fixed across the relevant construction sample so that country-year scores remain comparable over time and across imputations. This procedure follows standard composite-indicator practice on direction, normalisation, weighting, aggregation, and sensitivity analysis (OECD/European Union/EC-JRC 2008).

Benefit indicator: $z_{itk} = (x_{itk} - \min(x_k)) / (\max(x_k) - \min(x_k))$

Cost indicator: $z_{itk} = (\max(x_k) - x_{itk}) / (\max(x_k) - \min(x_k))$

3.4 Creation of governance vulnerability indices

3.4.1 Agricultural withdrawal-to-value-added intensity

Agricultural withdrawal-to-value-added intensity is the ratio of agriculture's share of freshwater withdrawals to agriculture, forestry, and fishing value added as a share of GDP. FAO (2022) provides the broader water-use-efficiency logic that links agricultural economic output with water use; the present measure adapts that relationship to a share-based annual comparison across the five countries. Research on Central Asia also identifies irrigation dependence and agricultural water use as major sources of resource pressure (Saidmamatov et al. 2023; Mayar et al. 2024). A high ratio indicates that agriculture accounts for a large share of withdrawals relative to its recorded share of economic value added.

AWI is dimensionless because it divides one percentage share by another. It is interpreted as relative withdrawal intensity and captures the relationship between agricultural water dependence and recorded

agricultural value added. SDG 6.4.1 uses value added per volume of water and therefore serves a different water-use-efficiency purpose (FAO 2022).

$$R_{it} = AWW_{it} / AVA_{it}$$

AWI_{it} = min-max normalisation of R_{it}

3.4.2 Broad governance-capacity deficit

The broad governance-capacity deficit combines the WGI Government Effectiveness and Regulatory Quality estimates. Kaufmann and Kraay (2024) define Government Effectiveness through perceptions of public services, civil-service quality, policy formulation and implementation, and the credibility of government commitments. Regulatory Quality captures perceptions of the ability to formulate and implement policies and regulations, with annual estimates reported in the World Bank's WGI dataset (World Bank 2025). These dimensions correspond to the administrative and regulatory capacity required for coordinated resource governance, a concern also identified in institutional analyses of nexus governance (Jones-Crank 2024). The two series are normalised so that higher values indicate stronger capacity, averaged, and then reversed.

Their reverse average forms GCD, with higher values indicating a larger broad governance-capacity deficit. The construction preserves the WGI meaning of the two source dimensions while placing them on the same 0–1 vulnerability scale used by AWI and STE.

$$C_{it} = (z^{GE}_{it} + z^{RQ}_{it}) / 2$$

$$GCD_{it} = 1 - C_{it}$$

3.4.3 Seasonal hydropower-irrigation trade-off exposure

Seasonal hydropower-irrigation trade-off exposure (STE) captures the joint dependence that creates recurring temporal coordination demands in Central Asia. Jalilov et al. (2016) demonstrate how water allocation can generate linked gains and losses across sectors in the Amu Darya Basin. Governance research identifies temporal and scale-related coordination as a central nexus challenge (Pahl-Wostl et al. 2021), and recent Central Asian studies further document the importance of hydropower operation and irrigated agriculture for regional resource management (Guo et al. 2024; Hu et al. 2024, 2026). STE is constructed as the geometric mean of normalised agricultural freshwater-withdrawal share and normalised hydropower generation share. A high value requires both forms of dependence to be present. The geometric mean gives joint dependence a direct role in the score and follows composite-indicator practice for aggregating interacting components (OECD/European Union/EC-JRC 2008).

$$STE_{it} = \sqrt{(z^{AWW}_{it} \times z^{HYD}_{it})}$$

3.4.4 Governance-related Multidimensional Vulnerability Index

$$GMVI_{it} = (AWI_{it} + GCD_{it} + STE_{it}) / 3$$

AWW denotes agricultural freshwater withdrawals; AVA agriculture value added; GE Government Effectiveness; RQ Regulatory Quality; HYD hydropower generation share; AWI agricultural withdrawal-to-value-added intensity; GCD broad governance-capacity deficit; and STE seasonal hydropower-irrigation trade-off exposure.

GMVI is the equal-weighted average of AWI, GCD, and STE. Equal weighting gives each conceptual dimension the same contribution and keeps the aggregation rule transparent (OECD/European Union/EC-JRC 2008). The updated sample has variance-inflation factors below 5 for the three dimensions. Dimension scores are reported alongside GMVI because similar aggregate values can reflect different combinations of pressure, capacity, and seasonal exposure. PCA, entropy weighting, and alternative specifications are retained as sensitivity checks.

4. Econometric application and results

4.1 Water-Energy-Food Sustainability Index as the outcome measure

The empirical application uses the Water-Energy-Food Sustainability Index (WEFSI) as the outcome measure of resource sustainability performance. The index follows the three-domain logic of WEF nexus measurement and uses annual indicators that provide comparable coverage across all five Central Asian states (Simpson and Jewitt 2019; Simpson et al. 2022). It contains one water indicator, two food indicators, and three energy indicators (Supplementary Table S1). Water stress, undernourishment, and electricity transmission and distribution losses are cost indicators. Cereal yield, electricity access, and renewable energy share are benefit indicators. Governance variables are kept outside WEFSI so that governance vulnerability and sustainability performance remain separate empirical constructs.

WEFSI differs in scope from the global WEF Nexus Index described by Simpson et al. (2022), which uses a larger indicator set and a different pillar structure. The present index is designed for consistent annual comparison from 2002 to 2024. Water stress represents pressure on available freshwater resources; cereal yield and undernourishment capture production and food-deprivation conditions; and the energy indicators capture access, renewable composition, and distribution losses. Together they provide a compact longitudinal measure of WEF performance for the empirical application.

Water, food, and energy each contribute one third of the final score. Indicators within the food and energy dimensions are equally weighted within their respective domains. This nested structure gives each WEF domain the same contribution regardless of the number of available indicators and follows the transparent weighting principles used in composite-indicator construction (OECD/European Union/EC-JRC 2008).

$$W_{it} = z_{it}^{WS}$$

$$F_{it} = (z_{it}^{CY} + z_{it}^{UN}) / 2$$

$$E_{it} = (z_{it}^{EA} + z_{it}^{RE} + z_{it}^{EL}) / 3$$

$$WEFSI_{it} = (W_{it} + F_{it} + E_{it}) / 3$$

Here, WS denotes water stress; CY cereal yield; UN undernourishment; EA electricity access; RE renewable energy; and EL electricity losses.

All normalised indicators are added after their directions have been aligned. Electricity losses are reverse-normalised, so a higher normalised EL score indicates lower physical losses. The dimension scores are reported separately, and PCA and entropy weighting are used as sensitivity checks for the aggregation choice.

WEFSI is designed as a compact performance index for comparative panel analysis. Electricity access contributes limited within-country variation because it is close to universal in most observations. The available annual panel provides one water indicator, while the food and energy dimensions contain multiple indicators. These features are considered when interpreting the aggregate and dimension results.

4.2 Econometric model and inference

The empirical application uses a two-way fixed-effects panel model, which estimates within-country associations after time-invariant country characteristics and shocks shared across years are absorbed (Wooldridge 2010). The focal predictor is GMVI lagged by one year. Country effects account for stable differences among the five states, while year effects account for common shocks. The specification therefore links changes in governance-related vulnerability within a country to subsequent changes in WEF sustainability performance.

The coefficient beta represents the expected change in WEFSI associated with a one-unit change in lagged GMVI within a country, conditional on country effects, year effects, and any included controls.

$$WEFSI_{it} = \alpha + \beta GMVI_{i,t-1} + \mu_i + \lambda_t + \varepsilon_{it}$$

Here, μ_i and λ_t denote country and year fixed effects, and ε_{it} is the error term. Model 1 is the parsimonious specification. Model 2 adds lagged log GDP per capita. Models 3 and 4 replace the overall vulnerability index with lagged AWI, GCD, and STE, without and with GDP. Population density is reserved for sensitivity analysis because its slow within-country movement can absorb a substantial share of long-run variation. GDP is included as a broad economic control.

HC3 heteroskedasticity-robust standard errors are used for main inference because HC3 has improved finite-sample properties relative to simpler heteroskedasticity corrections (MacKinnon and White 1985). Because the panel includes only five countries, conventional cluster-robust inference would rely on too few clusters for standard asymptotic approximations (Cameron and Miller 2015); the analysis therefore pairs HC3 inference with extensive specification and influence checks. Models are estimated in each of 100 imputed panels and combined using Rubin's multiple-imputation rules (Rubin 1987). Confidence intervals and p values use the Barnard-Rubin finite-sample degrees-of-freedom adjustment (Barnard and Rubin 1999). Tests are two-sided and 95% confidence intervals are reported.

4.3 Descriptive patterns

The 2002–2024 panel contains 115 complete country-year observations. Of 1,495 required variable-country-year cells, 25 are author-estimated 2024 endpoints; the remainder are official series values or source-supported official estimates from WGI and PoU. Detailed source-status coverage is reported in Supplementary Table S2. No unresolved missing values enter index construction.

Across all 115 observations, mean GMVI is 0.422 and mean WEFSI is 0.589. The seasonal exposure dimension has the largest standard deviation among the three GMVI dimensions, followed by AWI and GCD. Table 1 reports the descriptive distribution, and Fig. 2 visualises the mean, dispersion, and observed range of the normalised governance-vulnerability and sustainability measures. The wide ranges for STE, AWI, and GCD show the importance of reading the aggregate GMVI together with its dimensions.

Table 1
Descriptive statistics, 2002–2024

Variable	N	Mean	SD	Min	Max
WEFSI	115	0.589	0.112	0.385	0.757
Water dimension	115	0.578	0.334	0.000	1.000
Food dimension	115	0.609	0.175	0.137	1.000
Energy dimension	115	0.579	0.092	0.330	0.882
GMVI	115	0.422	0.097	0.225	0.652
AWI	115	0.329	0.285	0.000	1.000
GCD	115	0.511	0.238	0.019	1.000
STE	115	0.425	0.372	0.000	0.941
GDP per capita	115	3,293.33	3,442.13	186.95	14,154.63
Population density	115	35.825	25.555	5.799	82.519

Note. Higher WEFSI values indicate stronger sustainability. Higher GMVI, AWI, GCD, and STE values indicate greater intensity, deficit, or exposure.

Note

Points show sample means across 115 country-year observations. Thick horizontal segments show mean plus or minus one standard deviation, and thin segments show the observed minimum-to-maximum range. The figure includes the 0–1 normalised sustainability and vulnerability measures; GDP per capita and population density are omitted because they are reported in their original units.

4.4 Country profiles

Table 2 reveals distinct combinations of governance-related vulnerability and WEF sustainability performance over the full 2002–2024 period.

Kazakhstan combines the highest mean WEFSI (0.704) with high agricultural withdrawal-to-value-added intensity. Kyrgyzstan and Tajikistan have the highest mean GMVI values, driven mainly by seasonal exposure. Turkmenistan has the largest broad governance-capacity deficit and the lowest mean WEFSI, while Uzbekistan has the lowest mean GMVI and a comparatively low WEFSI. These profiles show that the composition of governance vulnerability matters: pressure, capacity, and seasonal exposure vary substantially across countries even when aggregate scores are similar.

These contrasts highlight the importance of examining dimension profiles alongside aggregate indices. Figure 3 makes the composition of each country profile visible, while Fig. 4 places mean vulnerability and mean sustainability in a common comparative space.

Table 2
Country-level mean index values, 2002–2024

Country	GMVI	AWI	GCD	STE	WEFSI
Kazakhstan	0.373	0.769	0.243	0.107	0.704
Kyrgyzstan	0.515	0.269	0.378	0.898	0.668
Tajikistan	0.483	0.098	0.546	0.805	0.612
Turkmenistan	0.404	0.411	0.794	0.007	0.445
Uzbekistan	0.334	0.097	0.594	0.310	0.516
Note. Means use the final 23-year panel and may conceal offsetting dimension values.					

Note

Cells report 2002–2024 country means. Darker cells indicate higher values. Higher AWI, GCD, STE, and GMVI values indicate greater governance-related vulnerability, while higher WEFSI values indicate stronger WEF sustainability.

Points show 2002–2024 country means. The horizontal and vertical dashed lines mark the sample means of WEFSI and GMVI. Bubble size represents seasonal hydropower-irrigation exposure (STE), and colour represents the broad governance-capacity deficit (GCD). The external bubble-size legend is provided below the plot area for readability.

4.5 Main fixed-effects results

The central result is a negative within-country association between lagged GMVI and WEFSI. H1 is supported in both primary specifications, in which the GMVI coefficient is negative and statistically significant.

In Model 1, the Rubin-pooled lagged GMVI coefficient is -0.1527 (95% CI [-0.2989, -0.0065], $p = 0.041$; Barnard-Rubin $df = 80.3$; $N = 110$). In substantive terms, a 0.10-unit increase in lagged GMVI is associated with a 0.0153 decrease in WEFSI. A one-standard-deviation increase in GMVI (0.097) corresponds to a 0.0148 decrease in WEFSI, equivalent to approximately 0.13 standard deviations of the outcome.

Adding lagged GDP gives a similar GMVI estimate (-0.1522, 95% CI [-0.2996, -0.0048], $p = 0.043$). In the dimension model, STE is negative with an interval below zero (-0.1618, 95% CI [-0.2705, -0.0530], $p = 0.004$). AWI is negative with an interval spanning zero, and GCD is positive with an interval spanning zero. Adding GDP to the dimension model leaves the signs and interval pattern broadly similar. A one-standard-deviation increase in STE (0.372) is associated with a 0.0602 decrease in WEFSI, equivalent to approximately 0.54 standard deviations of the outcome.

The dimension results provide clear assessments of H2-H4. H2 is not supported because the AWI estimate is negative and its confidence interval includes zero. H3 is not supported: the GCD estimate is positive and its confidence interval includes zero. H4 is supported: the STE estimate is negative and its confidence interval remains below zero with and without the GDP control. Figure 5 summarises the four hypothesis-specific estimates and confidence intervals.

Note

Points show Rubin-pooled coefficient estimates from Model 1 for H1 and Model 3 for H2-H4; horizontal bars show 95% confidence intervals and the dashed line marks zero. H1 is supported in the primary aggregate model, H4 is supported in the dimension model, and H2 and H3 are not supported.

4.6 Robustness and model sensitivity

Robustness checks address four sources of uncertainty. Specification checks add lagged population density, combine GDP and density, include country-specific trends, change timing, and first-difference the data. Outcome and weighting checks remove renewable energy from WEFSI and apply PCA and entropy weighting. Influence checks exclude each country and drop 2024. Data-construction checks move every author estimate to its prediction bound, recalculate pooled bounds separately by imputation, and set

interval-censored undernourishment values to their published upper bound. Single-estimate influence, VIF, variation, and Monte Carlo diagnostics are retained in the reproducibility package.

Table 3 reports the four primary fixed-effects models. The focal estimates are the GMVI coefficient in Models 1 and 2 and the AWI, GCD, and STE coefficients in Models 3 and 4.

Robustness estimates vary across specifications. Contemporaneous, two-year-lag, and first-difference estimates are negative with intervals below zero. The estimate based on WEFSI excluding renewable energy remains negative and is less precise, with an interval that narrowly includes zero. PCA and entropy alternatives also yield negative estimates with intervals below zero.

The estimate changes sign after adding population density and becomes nearly zero when Tajikistan is excluded. Country-specific trends retain a negative point estimate and widen the interval across zero. These results show that the overall association varies with slow-moving structure and influential country trajectories. Figure 6 shows this specification sensitivity across the reported robustness checks.

Table 3
Two-way fixed-effects estimates of WEFSI, 2003–2024

Variable	Model 1: GMVI	Model 2: GMVI + GDP	Model 3: Dimensions	Model 4: Dimensions + GDP
GMVI, t-1	-0.1527 (0.0735) [-0.2989, -0.0065] p = 0.041	-0.1522 (0.0741) [-0.2996, -0.0048] p = 0.043		
Agricultural withdrawal- to-value-added intensity, t-1			-0.0533 (0.0378) [-0.1286, 0.0220] p = 0.163	-0.0586 (0.0403) [-0.1390, 0.0217] p = 0.150
Broad governance- capacity deficit, t-1			0.0357 (0.0521) [-0.0681, 0.1394] p = 0.496	0.0445 (0.0525) [-0.0600, 0.1489] p = 0.399
Seasonal hydropower- irrigation exposure, t-1			-0.1618 (0.0547) [-0.2705, -0.0530] p = 0.004	-0.1603 (0.0549) [-0.2697, -0.0509] p = 0.005
Log GDP per capita, t-1		0.0124 (0.0352) [-0.0576, 0.0824] p = 0.726		0.0251 (0.0377) [-0.0500, 0.1002] p = 0.508
N	110	110	110	110
Countries	5	5	5	5
Adjusted R-squared	0.876	0.874	0.884	0.883
<i>Note. Coefficients are followed by Rubin-pooled standard errors, 95% confidence intervals, and p values. Confidence intervals and p values use Barnard-Rubin finite-sample degrees of freedom. All models include country and year fixed effects and use HC3 covariance estimation.</i>				

The first row shows the Rubin-pooled primary estimate; the remaining rows summarise reported alternative specifications and sensitivity checks. Points are coefficient estimates, horizontal bars are 95% confidence

intervals, and the dashed line marks zero.

Most timing, outcome, data-construction, and alternative-weighting checks remain negative. Controls for population density and country-specific trends weaken the estimate. Figure 6 shows the recurring negative direction of the GMVI coefficient together with the sensitivity of its magnitude and precision across specifications.

5. Discussion

5.1 Interpretation of the main finding

The principal finding is a negative within-country association between lagged GMVI and WEFSI. This result supports the institutional-fit argument that sustainability depends on how governance arrangements correspond to connected resource processes (Young 2002; Moore et al. 2024). It also agrees with comparative WEF governance research that links coordination and implementation arrangements to nexus performance (Pahl-Wostl et al. 2021; Jones-Crank 2024). H1 is supported in the primary specifications, and the negative direction recurs in several timing, first-difference, and alternative-weighting models. Slow-moving controls and influential country trajectories reduce the precision of the aggregate estimate. H4 provides the clearest dimension-level evidence because higher STE is consistently associated with lower subsequent WEFSI.

Country profiles add context to the aggregate result. Kazakhstan combines high WEFSI with high AWI; Kyrgyzstan and Tajikistan combine high GMVI with strong seasonal exposure; Turkmenistan combines the largest GCD with the lowest WEFSI; and Uzbekistan records the lowest GMVI alongside moderate WEFSI. This variation illustrates why composite scores should be interpreted together with their components, a principle emphasised by Usubiaga-Liaño and Ekins (2024). Simpson et al. (2022) demonstrate the value of a common WEF index for comparison. The present profiles extend that approach by showing how separate governance-related dimensions produce different national pathways over time.

5.2 Significance of seasonal hydropower-irrigation trade-offs

STE provides the clearest dimension-level result. Jalilov et al. (2016) identify the economic gains and losses created by water-energy coordination in the Amu Darya Basin. Hamidov et al. (2022) also describe the seasonal tension between upstream hydropower and downstream irrigation. Recent assessments continue to identify release timing, electricity exchange, and cross-border coordination as central regional issues (Kato 2025; De Keyser et al. 2026). Its negative estimate matches the regional challenge of coordinating reservoir releases between winter electricity demand and summer irrigation demand, giving H4 the strongest empirical support among the dimension hypotheses.

Hydropower and irrigation depend strongly on release timing. Technical models show that coordinated allocation, reservoir operation, and storage can improve nexus performance (Ma et al. 2024; Hu et al. 2026). The present result adds longitudinal evidence that joint seasonal dependence is linked to lower subsequent WEF sustainability. The weaker AWI result adds a qualification to work that emphasises irrigation dependence and agricultural resource pressure in Central Asia (Han et al. 2022; Saidmamatov et al. 2023). These pressures remain important. Their annual national variation does not explain WEFSI as consistently as joint seasonal exposure in this sample.

A more rigorous assessment of seasonal coordination would use monthly or weekly data on reservoir storage, releases, generation, electricity load, irrigation requirements, ecological flow targets, and water deliveries. Pahl-Wostl et al. (2021) show why temporal scale is a governance issue. Kato (2025) further identifies data exchange and coordinated water-energy planning as practical regional requirements. Future tests should therefore code the operating rules that determine who can change releases, under what conditions, and with what compensation or verification procedures. Such data could separate structural exposure from institutional response and test whether specific coordination mechanisms reduce the effect of seasonal co-dependence.

5.3 Linking technical instruments and governance arrangements

Hu et al. (2026) show gains from coordinated allocation and storage. The STE result adds an institutional implication. Technical interventions require agreed reservoir schedules, irrigation calendars, electricity exchanges, drought protocols, forecasts, financing rules, and revision procedures. These arrangements help translate nexus options into practice by linking polycentric authority to common rules and information channels (Srigiri and Dombrowsky 2022).

Han et al. (2022) connect agricultural development with land, water, and food pressures in Central Asia. FAO (2022) also treats water-use efficiency as a relationship between output and water use. These studies support attention to irrigation efficiency, crop choice, maintenance, and water accounting. Agricultural value also includes rural employment, food security, exports, livelihood stability, and distributional effects. Water-saving investments need clear allocation and monitoring rules because efficiency gains may support expansion and leave total withdrawals unchanged. Water-use efficiency should be assessed with volume-based measures, and AWI serves as a relative pressure indicator in the present panel.

Government Effectiveness and Regulatory Quality provide comparable measures of broad administrative and regulatory capacity (Kaufmann and Kraay 2024). Their broad scope leaves specific coordination processes unobserved. Sorek et al. (2022) identify organisational and human factors that condition WEF governance. Srigiri and Dombrowsky (2022) extend this point by emphasising coordination among multiple centres of authority. Hence future measurement should include shared data standards, cross-sector review, coordinating authority, and implementation links to domestic budgets, agency work plans, electricity dispatch, reservoir rules, and irrigation planning.

The UNECE framework provides operational categories for this evidence: cross-sectoral cooperation identifies participating actors, policy coherence connects sector plans, transparent information supports verification, and benefit sharing addresses gains and costs (UNECE 2015, 2018).

Guo et al. (2024) describe cooperation as an evolving process in transboundary basins, and Kato (2025) highlights data exchange and coordinated water-energy planning. These findings support exchange arrangements that specify quantities or operating ranges, timing, pricing or compensation, data verification, drought exceptions, dispute procedures, and revision rules. Joint investment, coordinated dam operation, electricity trade, flood-risk reduction, and ecosystem improvement can widen the set of gains available to participating states.

5.4 Influence of slow-moving structural trends

Population density changes the estimate most strongly: with density, the GMVI coefficient becomes positive with substantial uncertainty. Central Asian research shows that agricultural development, land use, and water pressure evolve together over long periods (Han et al. 2022). Population concentration can affect infrastructure, demand, agricultural structure, and service provision, while also moving gradually with development. The sensitivity of GMVI to density indicates that slow structural change overlaps with part of the within-country signal. Specifications with and without density are therefore reported side by side.

The Tajikistan exclusion result shows a different form of sensitivity. Tajikistan combines high seasonal exposure with substantial changes in WEFSI, so its trajectory contributes strongly to the estimated within-country relationship. Recent reviews also emphasise large differences among Central Asian countries and transboundary basins in resource structure, exposure, and governance arrangements (Bamgboye et al. 2025). This concentration of influence highlights the importance of country-specific mechanisms and basin-level heterogeneity in interpreting the regional pattern.

Country-specific trends remove part of the slow movement shared by vulnerability and sustainability measures. The wider interval under these controls shows how strongly the estimate depends on long-run country trajectories. This sensitivity is consistent with comparative nexus research showing that implementation conditions differ across institutional and sectoral settings (Andersson 2024; Orimoloye 2022). The regional coefficient should be interpreted together with the country profiles and influence checks.

5.5 Limitations and directions for future research

The main measurement limitation concerns the level of aggregation. AWI, GCD, and STE provide annual indicators of resource pressure, broad governance capacity, and seasonal exposure. One composite-index research shows that normalisation, weighting, and aggregation choices shape interpretation (Usubiaga-Liaño and Ekins 2024). The annual measures also leave finer institutional processes unobserved, including cross-sectoral authority, reservoir operating rules, compliance, compensation, information sharing, and benefit sharing. These processes are central to scale-related and integrative

governance frameworks (Pahl-Wostl et al. 2021; Weitz et al. 2017). Twenty-five 2024 endpoints are model-based estimates with uncertainty propagated through multiple imputation, and interval-censored PoU values add a separate source-data uncertainty. STE captures annual joint exposure; direct observation of seasonal release timing requires higher-frequency basin-level data.

Inference is based on five countries and 110 lagged observations. HC3 errors address heteroskedasticity, and the reported sensitivity checks examine timing, weighting, influential countries, trends, and data construction. The small number of countries limits the range of feasible cross-country error corrections and places greater weight on transparent sensitivity analysis (Cameron and Miller 2015). The observational design supports interpretation of the coefficients as within-country associations, with causal attribution reserved for research designs that provide stronger identification.

Bamgboye et al. (2025) identify limited data availability and uneven application of nexus approaches as continuing gaps in Central Asian research. Future research should develop dated policy and implementation records and monthly basin-level data on generation, reservoir storage and releases, electricity demand, irrigation requirements, ecological flows, compensation, and compliance. Policy coding should distinguish formal adoption from budget allocation, implementation, monitoring, and enforcement. Mooren et al. (2025) provide a recent governance approach that combines quantitative modelling, governance assessment, policy-coherence analysis, and stakeholder co-creation. Applying this design in Central Asian basins would permit more direct tests of institutional fit, temporal coordination, and benefit sharing.

A second research direction is to test whether specific institutions moderate physical exposure. Pahl-Wostl et al. (2021) treat temporal coordination and institutional interplay as central governance conditions. From a polycentric perspective, Srigiri and Dombrowsky (2022) show how coordination can be organised across multiple centres of authority. The effect of hydropower-irrigation co-dependence may be weaker where states exchange verified forecasts, use joint operating rules, or maintain credible compensation mechanisms. Such designs would connect the institutional-fit perspective more closely to observed coordination mechanisms and sustainability outcomes.

A third research direction is to examine distribution within countries. Hermans et al. (2025) call for better data and interdisciplinary research on water scarcity and rural change in Central Asia. National averages can conceal basin differences, regional inequality, and the effects of policies on farmers, electricity users, ecosystems, and local communities. Basin and subnational evidence would improve both measurement and policy relevance, especially where national indicators combine very different hydrological and economic systems.

6. Conclusion

Improving WEF sustainability in Central Asia depends on resource efficiency and on the governance conditions under which interdependent water, energy, and food systems are coordinated. The findings support the institutional-fit view that governance arrangements need to correspond to connected

resource processes (Young 2002; Moore et al. 2024). They also align with integrative and scale-sensitive WEF governance studies that emphasise cross-sectoral and multi-level coordination (Pahl-Wostl et al. 2021; Weitz et al. 2017). Country profiles show that similar aggregate vulnerability scores can reflect very different combinations of agricultural withdrawal pressure, broad governance capacity, and seasonal hydropower-irrigation exposure.

The panel results show a negative association between lagged GMVI and WEFSI in both primary specifications and several timing and weighting alternatives. Selected controls for slow-moving structural change weaken the aggregate estimate. Seasonal hydropower-irrigation exposure provides the clearest and most stable negative dimension-level evidence. This result matches Central Asian research on the timing conflict between upstream hydropower and downstream irrigation (Hamidov et al. 2022; Kato 2025). It also adds longitudinal empirical evidence to technical studies of coordinated allocation and reservoir operation (Jalilov et al. 2016; Hu et al. 2026).

The principal contribution lies in developing a reproducible longitudinal governance-vulnerability framework for Central Asia. GMVI provides a transparent summary of three observable conditions, while the dimension models show the distinct roles of AWI, GCD, and STE. Reporting the dimensions alongside the composite follows established guidance for composite indicators (OECD/European Union/EC-JRC 2008). The policy implications also follow earlier nexus-governance work: cross-sectoral cooperation, policy coherence, information exchange, seasonal operating rules, water-energy exchanges, benefit-sharing arrangements, and implementation authority remain central priorities (UNECE 2015, 2018; Kato 2025). Basin-level institutional coding and finer temporal operational data can provide more detailed tests of these mechanisms.

Declarations

Data availability

The datasets and supporting materials used in this study are provided in the Supplementary Information accompanying the revised submission. The shared materials include source-data snapshots from the World Bank World Development Indicators, the World Bank Worldwide Governance Indicators 2025 Revision, the United Nations SDG Global Database, and FAOSTAT; cleaned and processed datasets; the 2002-2024 analysis panel; 100 multiple-imputation datasets; variable definitions and coding schemes; source-provenance records; data-processing and transformation procedures; index-construction formulae; statistical code; and outputs supporting the main and robustness analyses. The underlying public datasets are also accessible from their original repositories, with source URLs and access details documented in the accompanying provenance materials. The README records the software environment, script order, required inputs, and expected outputs.

Code availability

The code used for data preparation, index construction, multiple-imputation processing, fixed-effects estimation, robustness analyses, and validation is provided in the Supplementary Information. The accompanying README documents the software environment, script order, required inputs, and expected outputs for reproducing the reported results.

Ethics declaration

The study uses publicly available country-level data. It does not involve human participants, personal data, or animals, and no ethics approval was required.

Author contributions

Y.Q. contributed to the conceptualization of the study, development of the research framework, and critical review of the manuscript. Z.W. prepared the original draft and was primarily responsible for manuscript development, writing, and revision. S.D. provided detailed critical review and substantive revision suggestions, including recommendations on the literature, argumentation, and manuscript development. F.X. reviewed the manuscript and contributed to its revision. All authors reviewed and approved the final manuscript.

Competing interests

The author declares no competing interests.

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Use of artificial intelligence tools

OpenAI ChatGPT and Codex were used to assist with data-processing scripts, analytical checks, and language editing. The author checked the source data, index calculations, model outputs, citations, and final interpretation and takes responsibility for the manuscript.

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Figures

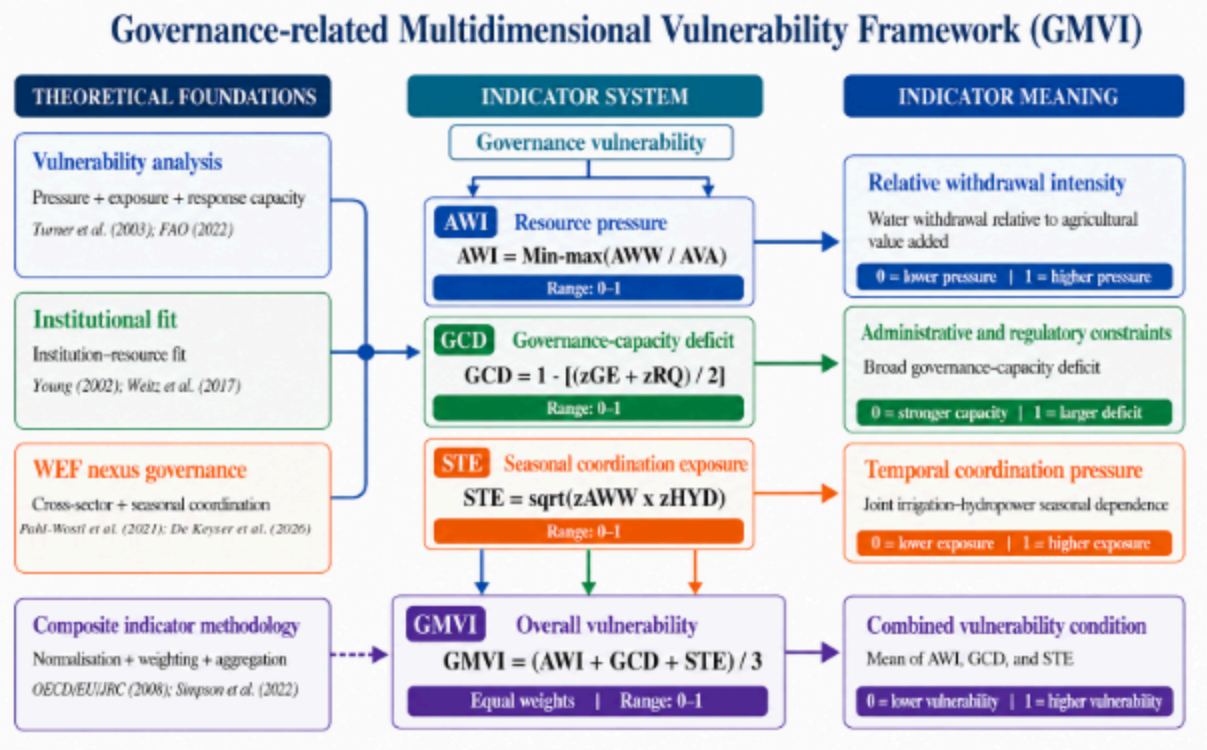


Figure 1

Construction of the Governance-related Multidimensional Vulnerability Index

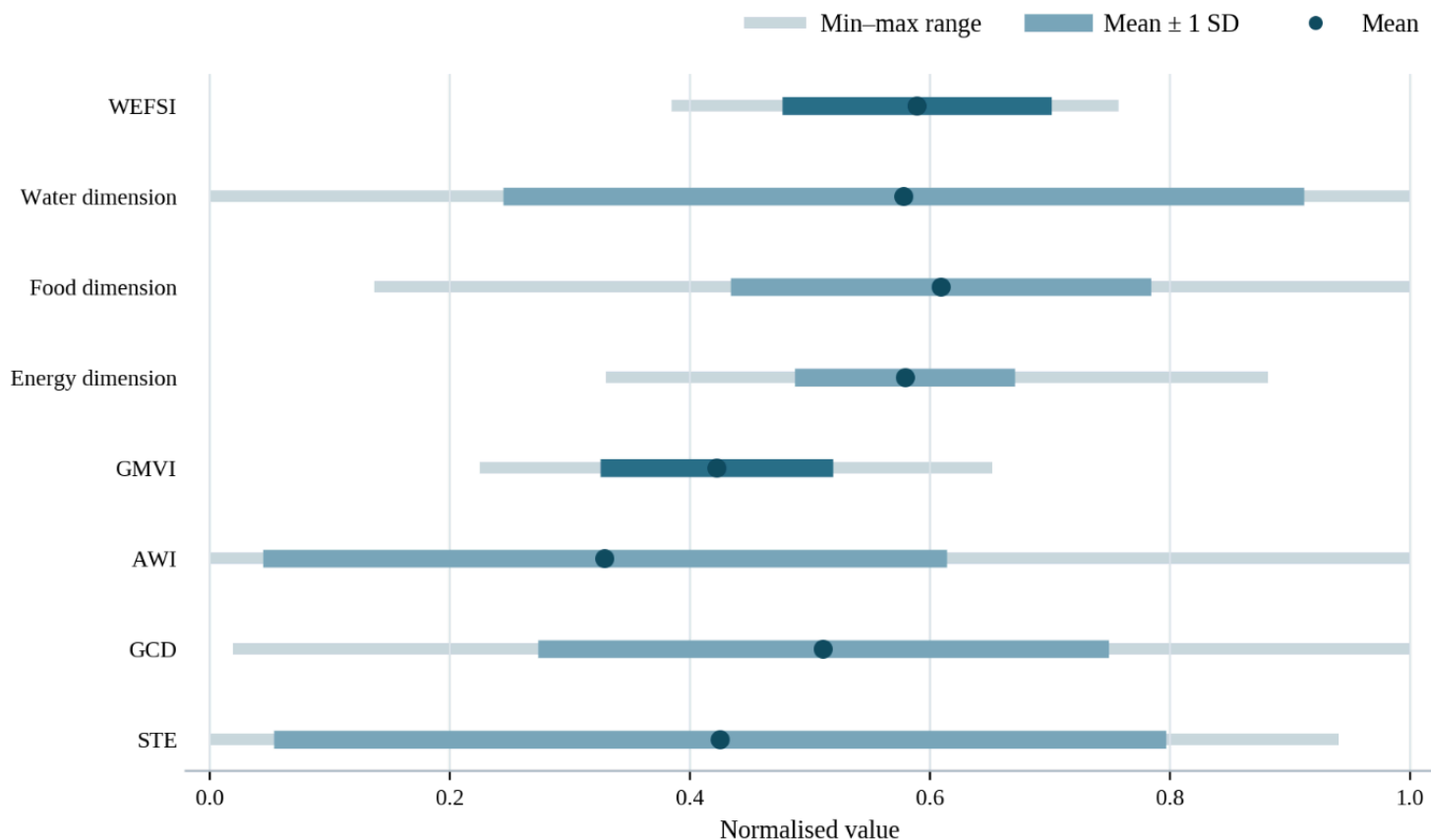


Figure 2

Distribution of governance vulnerability and WEF sustainability measures, 2002-2024.

Note. Points show sample means across 115 country-year observations. Thick horizontal segments show mean plus or minus one standard deviation, and thin segments show the observed minimum-to-maximum range. The figure includes the 0-1 normalised sustainability and vulnerability measures; GDP per capita and population density are omitted because they are reported in their original units.

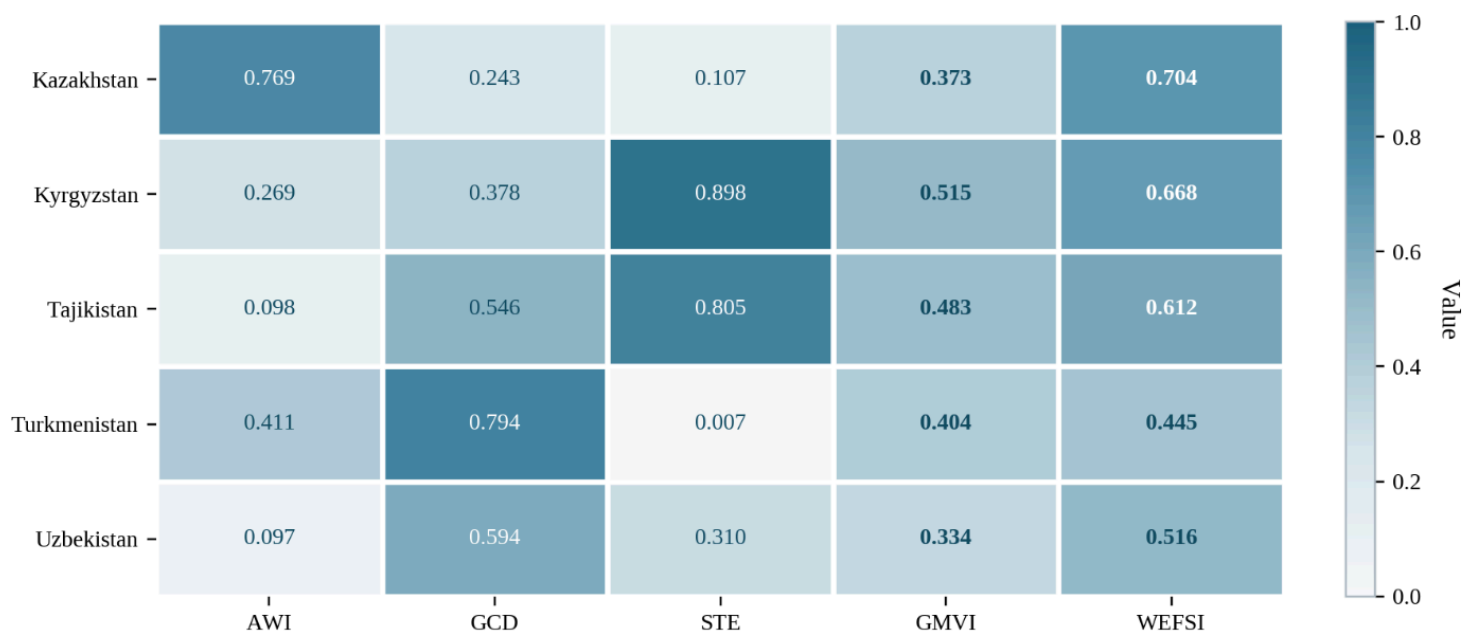


Figure 3

Country-level multidimensional heatmap, 2002-2024.

Note. Cells report 2002-2024 country means. Darker cells indicate higher values. Higher AWI, GCD, STE, and GMVI values indicate greater governance-related vulnerability, while higher WEFSI values indicate stronger WEF sustainability.

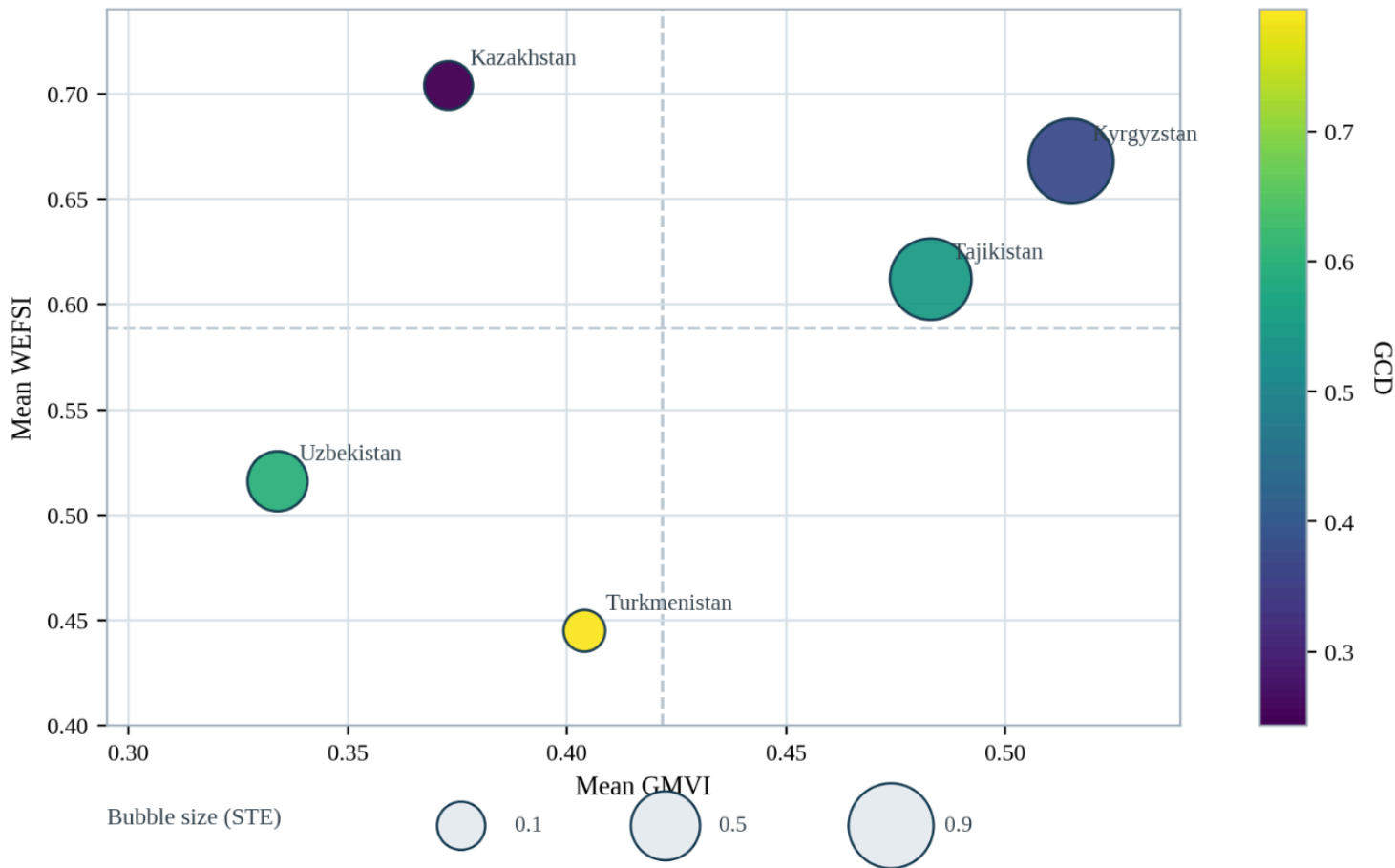


Figure 4

Country profiles of governance-related vulnerability and WEF sustainability, 2002-2024.

Points show 2002-2024 country means. The horizontal and vertical dashed lines mark the sample means of WEFSI and GMVI. Bubble size represents seasonal hydropower-irrigation exposure (STE), and colour represents the broad governance-capacity deficit (GCD). The external bubble-size legend is provided below the plot area for readability.

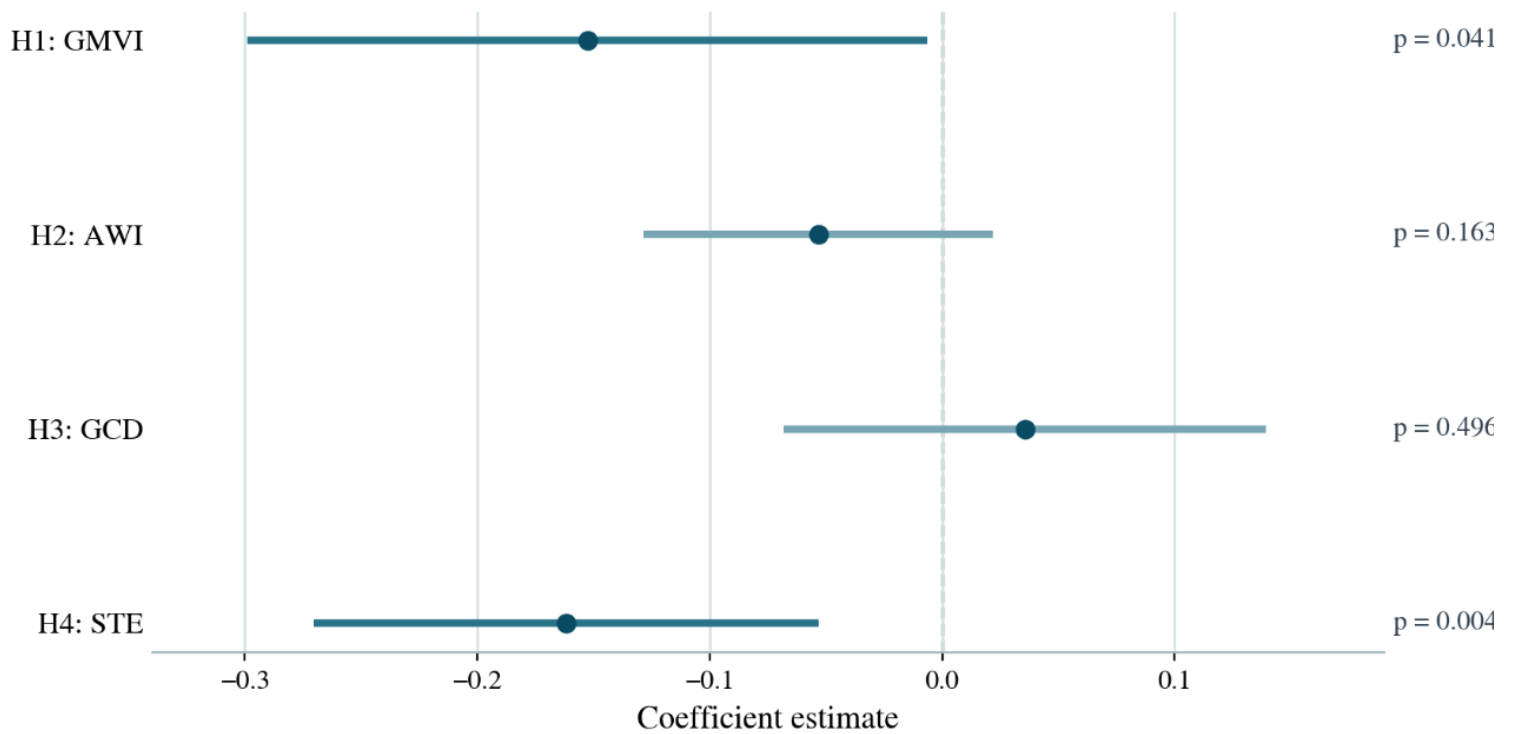


Figure 5

Assessment of the four parallel hypotheses in the primary fixed-effects models.

Note. Points show Rubin-pooled coefficient estimates from Model 1 for H1 and Model 3 for H2-H4; horizontal bars show 95% confidence intervals and the dashed line marks zero. H1 is supported in the primary aggregate model, H4 is supported in the dimension model, and H2 and H3 are not supported.

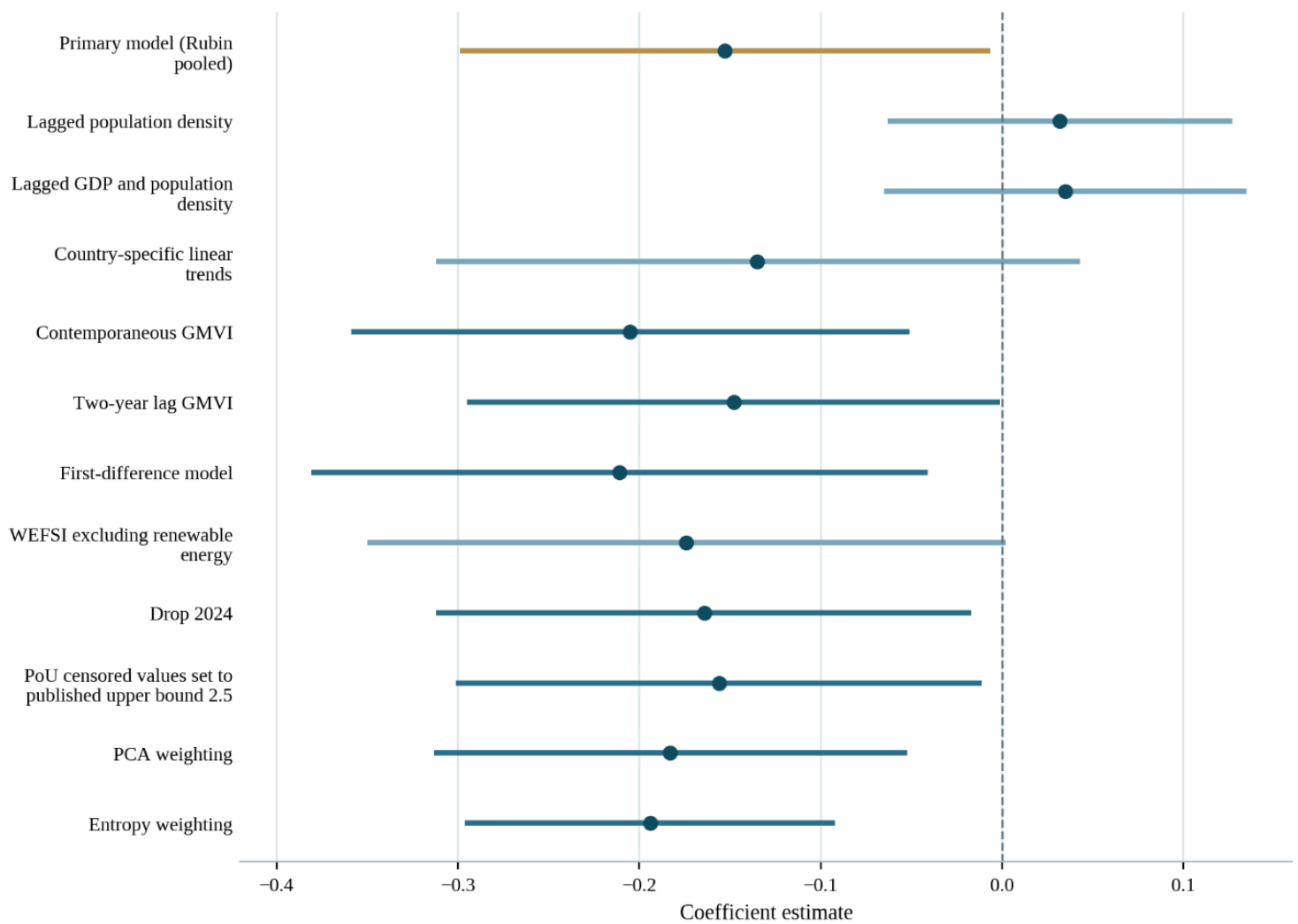


Figure 6

Robustness of the GMVI association across reported specifications.

The first row shows the Rubin-pooled primary estimate; the remaining rows summarise reported alternative specifications and sensitivity checks. Points are coefficient estimates, horizontal bars are 95% confidence intervals, and the dashed line marks zero.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supplementarymaterials.docx](#)
- [ReproducibilityPackage.zip](#)