Climate Resilience of Infrastructure Systems Under Extreme Weather Threats in Central Asian Countries

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Abstract: Amid the intensification of extreme weather events, enhancing the climate resilience of infrastructure systems has become a central pillar of sustainable development in Central Asian countries. The region exhibits high climate vulnerability driven by its continental climate, increasing temperature extremes, more frequent droughts, floods, and debris flows, as well as the strong dependence of socio-economic development on the reliable functioning of energy, water, and transport infrastructure. The objective of this study is to provide a comprehensive assessment of climate risks and infrastructure resilience in Central Asia using an integrated risk-based and spatial analytical framework. The methodology is grounded in the IPCC conceptual framework and includes the analysis of climate hazards, infrastructure exposure, and vulnerability, followed by the calculation of integrated Climate Risk (CR) and Climate Resilience Index (CRI_res) indicators. Climate inputs are derived from ERA5 reanalysis data, complemented by socio-economic and infrastructure datasets from international and national statistical sources. Spatial heterogeneity and sectoral differences are examined using geospatial analysis and comparative country case studies of Kazakhstan, Uzbekistan, and the Kyrgyz Republic. The results reveal pronounced cross-country, subnational, and sectoral disparities in climate risk and infrastructure resilience levels. The largest resilience gaps relative to climate risk are identified in the water and energy sectors, particularly under conditions of high aridity and temperature extremes. Spatial analysis demonstrates that aggregated national indicators obscure localized vulnerability hotspots, underscoring the necessity of multi-level approaches to climate risk assessment and management. The findings provide important practical implications for regional development strategies, including the prioritization of adaptation investments, the integration of climate risks into infrastructure and spatial planning, and the strengthening of transboundary cooperation in Central Asia. The proposed methodological framework may be applied to other environmentally vulnerable regions facing escalating climate hazards.

1 INTRODUCTION

1.1 The Relevance of Climate Resilience Research for Infrastructure Systems

In the 21st century, climate change has emerged as a key determinant of socio-economic sustainability in Central Asian countries. The increasing frequency and intensity of extreme weather events-such as heatwaves, droughts, heavy precipitation, floods, debris flows, and severe cold spells-exert both direct and indirect impacts on infrastructure systems that underpin economic activity and societal well-being [1], [2]. Under global warming conditions, infrastructure can no longer be regarded as a static development asset; instead, it is increasingly conceptualized as a dynamic system requiring adaptability, flexibility, and recovery capacity [3].

The concept of climate resilience has gained central importance in climate adaptation research.

Climate resilience of infrastructure systems refers to their capacity to withstand climate-related stresses, adapt to changing environmental conditions, and recover rapidly from extreme weather impacts without substantial loss of functionality [4]. For highly climate-vulnerable regions such as Central Asia, this concept is of particular significance.

Central Asia is characterized by a unique combination of climatic, geographic, and socio-economic conditions. The region includes arid and semi-arid zones, mountainous territories with high seismicity, and extensive lowland areas prone to droughts and dust storms. These features shape a complex climate risk profile that directly affects the resilience of energy, transport, water management, and urban infrastructure systems [5].

1.2. Extreme Weather Risks in Central Asian Countries

Over recent decades, Central Asian countries have experienced a persistent increase in extreme weather events. Rising average annual temperatures are accompanied by more frequent heatwaves, which critically affect energy systems-particularly thermal power plants and electricity distribution networks [6]. Intensifying drought conditions reduce water availability, undermine hydropower potential, and degrade water management infrastructure.

Simultaneously, the risk of intense precipitation and flash floods has increased, particularly in mountainous areas of the Tien Shan and Pamir ranges. These hazards threaten transport corridors, bridges, power transmission lines, and municipal infrastructure. During winter periods, extreme frost and heavy snowfall impose additional stress on infrastructure systems originally designed according to outdated climatic standards [7].

At the same time, hydrometeorological extremes of cold and wet types-including floods, debris flows, and severe frost-are particularly relevant in mountainous and foothill regions. Intense precipitation and glacier melt generate high risks for transport infrastructure and electricity transmission networks, leading to physical damage and service interruptions. Sudden winter temperature drops critically affect municipal and district heating networks, increasing the probability of failures and supply disruptions. Collectively, these patterns illustrate the multi-dimensional nature of climate threats and reinforce the need for a comprehensive, cross-sectoral approach to climate resilience assessment and enhancement in the region (Table 1).

Table 1: Major extreme weather risks and their impacts on infrastructure systems in Central Asia.

Risk Type	Description	Vulnerable Infrastructure Systems
Heatwaves	Temperatures exceeding climatic norms	Energy systems, urban infrastructure
Droughts	Prolonged precipitation deficit	Water supply, hydropower systems
Floods and debris flows	Intense precipitation and glacier melt	Transport networks, power transmission
Extreme frost	Sudden and severe temperature drops	коммунальные и тепловые сети

1.3 Infrastructure Systems as a Critical Pillar of Climate Resilience

Infrastructure systems play a foundational role in societal resilience to climate risks. Energy infrastructure ensures the functioning of industry, transport, and public services. Water infrastructure guarantees access to potable water, irrigation for agriculture, and flood protection. Transport infrastructure connects regions, sustaining population mobility and the resilience of supply chains [8].

Under changing climatic conditions, conventional approaches to infrastructure design and operation are increasingly inadequate. Most existing infrastructure assets were constructed based on historical climate data that no longer reflect current or projected operating conditions. This mismatch leads to increased failure rates, higher operational costs, and declining system reliability [9].

Figure 1 illustrates the conceptual relationship between climate hazards, infrastructure vulnerability, and resilience capacity, providing the analytical foundation for the integrated risk-based framework applied in this study.

Figure 1 presents a conceptual model illustrating the sequential and interrelated logic underlying the formation of climate resilience in infrastructure systems. At the upper level of the scheme, the principal climate hazards-heatwaves, droughts, floods and debris flows, and extreme cold events-are depicted. In combination with infrastructure exposure and vulnerability, these hazards generate climate risk and determine the nature and magnitude of potential impacts.

Exposure reflects the spatial distribution of population and infrastructure assets, while vulnerability incorporates the technical condition of infrastructure, design standards (including climatic thresholds), and the broader socio-economic context. This framing allows climate risk to be conceptualized as the outcome of complex interactions between natural and anthropogenic factors rather than as a purely environmental phenomenon.

The lower tiers of the framework emphasize the role of resilience capacity in mitigating adverse impacts and ensuring the continuity of infrastructure services. Core resilience attributes-robustness, redundancy, resourcefulness, and rapid recovery-define the ability of systems to maintain functionality, reduce downtime, and minimize socio-economic losses. A feedback loop, represented as an adaptive cycle, highlights the dynamic nature of resilience, encompassing learning processes, targeted investments, and institutional transformation based on accumulated experience. Accordingly, the conceptual framework demonstrates that infrastructure climate resilience is not a static condition but an evolving adaptive process in response to intensifying climate risks.

1.4 Scientific Approaches to Assessing Climate Resilience

Contemporary scientific literature has developed several approaches to evaluating the climate resilience of infrastructure systems. One of the most widely applied is the risk-based approach, which focuses on the probability of extreme events and their potential impacts [10]. Within this framework, resilience is conceptualized as a function of exposure, sensitivity, and adaptive capacity.

Another prominent approach involves the construction of integrated resilience indices, combining climatic, technical, socio-economic, and institutional indicators into composite measures [11], [12]. Such indices facilitate cross-country and cross-regional comparisons and enable the identification of the most vulnerable infrastructure segments.

Despite substantial methodological advances, most existing studies concentrate on individual sectors or single-country analyses. Comprehensive cross-sectoral assessments of infrastructure climate resilience in Central Asia remain limited.

1.5 Research Gap and Rationale

A review of the literature indicates that studies of infrastructure climate resilience in Central Asia remain fragmented. Most research focuses on hydropower, water resources, or specific extreme events such as droughts and floods [13]-[15]. Systemic approaches accounting for interdependencies among infrastructure sectors and their collective resilience to climate risks are largely underdeveloped.

Furthermore, insufficient attention has been devoted to spatial analysis of climate risks and infrastructure impacts using advanced geospatial technologies. This limitation constrains the development of evidence-based adaptation strategies and reduces the policy relevance of existing research.

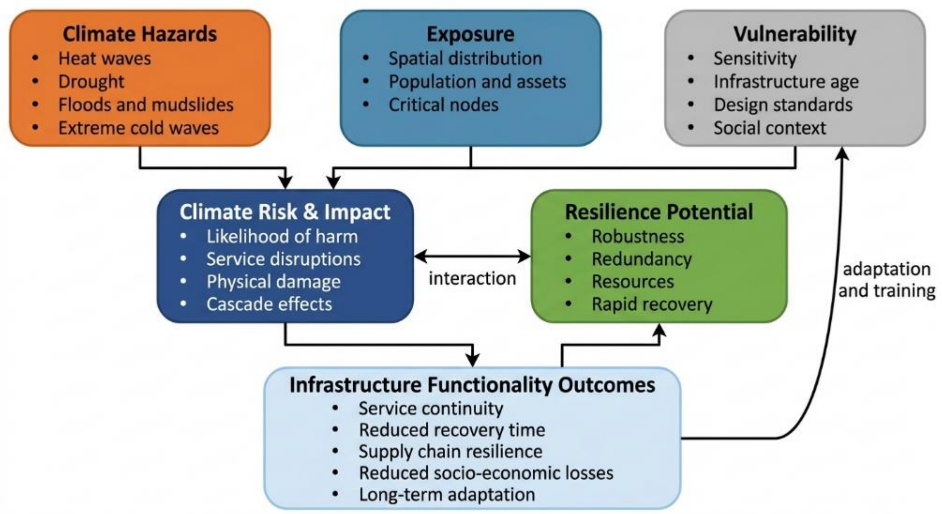

Figure 1: Conceptual framework of the relationship between climate risks and infrastructure resilience.

1.6 Research Aim and Objectives

The primary objective of this study is to conduct a comprehensive assessment of the climate resilience of infrastructure systems in Central Asia under intensifying extreme weather risks.

To achieve this objective, the study addresses the following tasks:

- To analyze climate trends and extreme weather risks in Central Asia;
- To assess the vulnerability of key infrastructure systems (energy, transport, water management);
- To develop integrated indicators of climate resilience;
- To identify spatial patterns in the distribution of climate risks;
- To formulate scientifically grounded recommendations for strengthening infrastructure resilience.

Accordingly, this research seeks to bridge the identified scientific gap by developing a comprehensive understanding of infrastructure climate resilience in Central Asia, contributing both theoretically and practically to sustainable regional development.

2 METHODS

2.1 Methodological Foundation and Principles of Replicability

The sequence of research stages, data sources, and analytical procedures are summarized and visually represented in Figure 2, which illustrates the logical progression from raw climate data to the calculation of climate risk and resilience indices, followed by spatial analysis.

The methodological framework adheres to internationally recognized standards for transparency, scientific rigor, and reproducibility. All analytical steps-including data preprocessing, normalization, index construction, and spatial modeling-are explicitly documented to ensure methodological consistency and facilitate replication in other regional contexts.

The research design integrates:

1) Climate hazard assessment based on standardized extreme event indices;
2) Exposure and vulnerability analysis using socio-economic and infrastructure data;
3) Construction of composite risk and resilience indices;
4) Spatial mapping and hotspot identification using GIS tools;
5) Comparative cross-country evaluation of infrastructure climate resilience.

This integrated approach enables a multidimensional assessment of climate resilience that captures both quantitative risk metrics and spatial heterogeneity, thereby enhancing the robustness and policy relevance of the findings.

The methodology of this study was developed in line with key Q1 journal requirements, including scientific rigor, transparency of calculations, and the reproducibility (replicability) of results. The conceptual foundation is the IPCC risk-based framework, in which climate risk is defined as a function of climate hazards, exposure, and vulnerability, moderated by the adaptive capacity of infrastructure systems [16]. This approach is widely applied in contemporary climate resilience research and ensures comparability with international scientific literature [17].

The research is designed as a multi-stage analytical process that includes: (i) acquisition and preprocessing of climate data; (ii) computation of extreme-event indices; (iii) construction of exposure and vulnerability metrics; (iv) derivation of integrated climate risk and resilience indices; and (v) spatial analysis and visualization using geographic information systems (GIS). The sequencing of steps, input datasets, and analytical procedures is standardized, enabling replication for other regions or time periods.

2.2 Methods for Assessing Climate Hazards and Extreme Weather Events

A comprehensive list of climate indices, socio-economic indicators, infrastructure parameters, and corresponding data sources is provided in Table 2, ensuring methodological transparency and facilitating replication by other researchers.

The assessment of climate hazards is based on the analysis of extreme weather events that exert the strongest impacts on infrastructure systems in Central Asia. Consistent with IPCC and World Meteorological Organization guidance, the study uses standardized climate extreme indices that quantify the intensity, frequency, and duration of temperature and hydro-meteorological extremes [18].

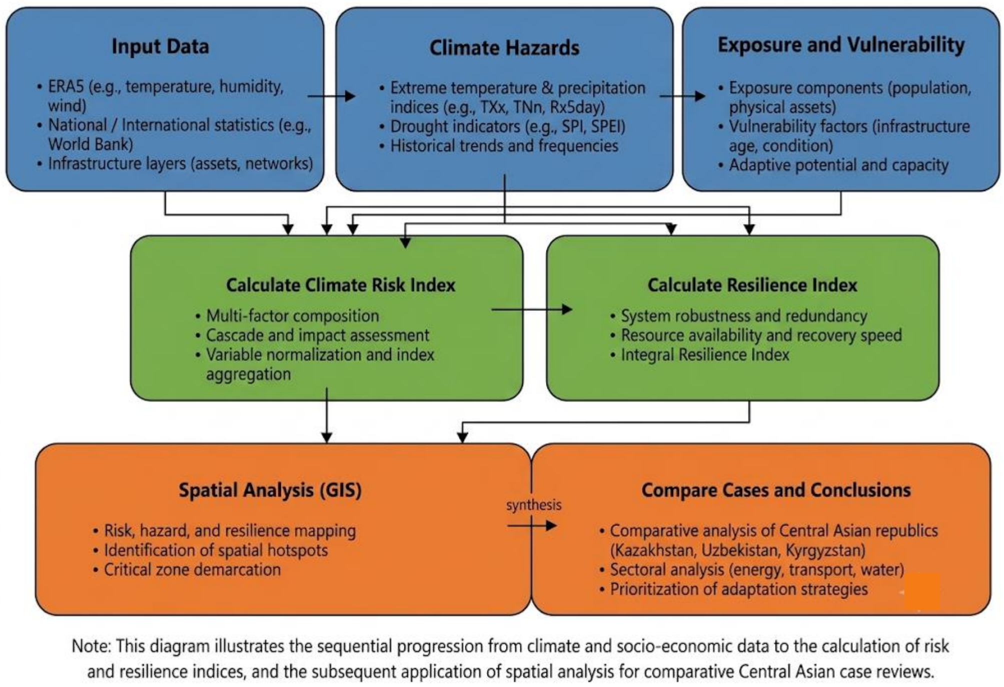

Figure 2: Methodological framework for assessing climate risks and infrastructure resilience: from raw climate data to integrated indices and spatial analysis.

To capture temperature extremes, the analysis employs TXx (annual maximum daily temperature) and TNn (annual minimum daily temperature), which represent extreme heat and cold conditions, respectively. Drought conditions are evaluated using the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI), the latter incorporating both precipitation and evaporative demand. Intense precipitation and flood-related hazards are characterized using Rx5day, which measures the maximum accumulated precipitation over five consecutive days [19].

Time series of climate indicators are examined using statistical trend techniques, including linear regression and the non-parametric Mann-Kendall test. This combination enables the identification of persistent shifts in the behavior of extreme events and provides an empirical basis for assessing increasing climatic pressure on infrastructure systems [20]. The use of harmonized indices and open climate datasets strengthens reproducibility and cross-study comparability.

2.3 Exposure Assessment of Infrastructure Systems

Within this study, exposure is defined as the spatial and quantitative distribution of infrastructure assets and populations potentially affected by climate hazards. Exposure constitutes a critical component of climate risk assessment because impacts may vary substantially across areas with different concentrations of assets and critical network nodes, even under similar hazard intensity [21].

Exposure metrics include population density, the spatial location of energy, transport, and water infrastructure, and data on the length and structural characteristics of infrastructure networks. Data sources comprise World Bank databases, national statistical agencies, and open geospatial datasets [22]. All exposure variables are harmonized to a common spatial resolution, enabling integration with climate data within the GIS framework.

Exposure is assessed both at the national (aggregated) level and at subnational scales, allowing the identification of risk concentration zones and critical regions requiring prioritization in adaptation planning.

2.4 Vulnerability Assessment and Construction of the Climate Resilience Index

Infrastructure vulnerability is conceptualized as the outcome of sensitivity to climate stressors combined with limited adaptive capacity. A multi-factor approach is applied, incorporating technical, socio-economic, and institutional indicators recommended by the scientific literature and IPCC assessment reports [23].

Key vulnerability indicators include the age and physical condition of infrastructure assets, redundancy and reserve capacity, the degree of diversification of energy and water supply sources, and the availability of financial and managerial resources. All indicators are normalized using the min-max method, mapping values onto a common 0-1 scale [24].

Based on the normalized indicators, an integrated Vulnerability & Resilience Index is constructed as a weighted sum of individual components. Weights are determined using expert elicitation and international guideline recommendations, consistent with established practice in infrastructure resilience research [12], [25]. This weighting approach supports transparent calculation procedures and replicability.

2.5 Spatial Analysis and the Use of Geographic Information Systems

GIS tools are used to spatially integrate climate, infrastructure, and socio-economic datasets and to visualize climate risk and resilience outcomes. Spatial analysis is essential for identifying geographic heterogeneity in climate threats and detecting vulnerability hotspots that may be obscured by aggregated national metrics [26].

The study produces maps of hazard distributions, vulnerability indices, and integrated resilience indicators. To detect risk concentration areas, hotspot analysis and spatial clustering techniques are applied [27]. The use of standard GIS procedures and open-source software supports reproducibility and enhances practical applicability for spatial and infrastructure planning.

2.6 Selection of Country Case Studies and Comparative Analysis

Kazakhstan, Uzbekistan, and the Kyrgyz Republic were selected as country case studies due to their climatic, geographic, and infrastructure diversity. Kazakhstan is characterized by extensive infrastructure networks and high exposure to temperature extremes. Uzbekistan represents an arid context with limited water resources and strong economic dependence on climate-sensitive sectors. The Kyrgyz Republic is distinguished by mountainous terrain and frequent hydro-meteorological extremes, including floods and debris flows.

Comparative analysis across these cases enables the identification of both common regional patterns and country-specific characteristics of infrastructure climate resilience, strengthening the analytical value and generalizability of the findings.

2.7 Data Sources and Information Processing

Climate data were obtained from the ERA5 reanalysis dataset, which provides high-resolution and internally consistent time series of meteorological variables [28]. Socio-economic and infrastructure data were compiled from World Bank datasets and national statistical sources [14]. Methodological guidance and conceptual framing draw on IPCC reports and peer-reviewed scientific publications [18], [29]. All data preprocessing, indicator normalization, and index construction steps were fully documented to ensure transparency and methodological reproducibility.

2.8 Formalization of Calculations and Indices

To ensure replicability, climate risk and infrastructure resilience calculations are formalized using standard mathematical expressions widely employed in climate and infrastructure research [30].

Climate Risk (CR) is defined as a function of climate hazards (H), exposure (E), and vulnerability (V):

$$CR = H \times E \times V,$$

where:

- H captures the intensity and frequency of extreme weather events;
- E represents the spatial concentration of population and infrastructure assets;
- V reflects sensitivity and constrained adaptive capacity of infrastructure systems [26], [31].

Normalization of raw indicators is performed using min-max scaling:

$$X\_norm = (X_i - X\_min) / (X\_max - X\_min).$$

where X_i is the observed value of an indicator, and X_min and X_max are the minimum and maximum values within the sample [24], [32].

The integrated Climate Resilience Index (CRI_res) is computed as a weighted sum of normalized resilience components:

$$CRI\_res = \Sigma (w_j \times R_j),$$

where R_j denotes normalized indicators of robustness, redundancy, resourcefulness, and recovery capacity of infrastructure systems, and $\mathbf{w_j}$ are the corresponding weights, derived from expert judgment and IPCC-based recommendations [25]. The use of these formulas ensures transparent methodology and enables direct replication in other regional assessments.

3 RESULTS

This section reports the results of hazard, exposure, and vulnerability assessments, as well as the derived integrated indices of Climate Risk (CR) and infrastructure Climate Resilience (CRI_res), computed according to the formalization described in Section 2 (see 2.8). To avoid interpretative bias, the section focuses on neutral presentation of empirical regularities and identified spatial/sectoral heterogeneity.

3.1 Spatiotemporal Characteristics of Climate Hazards

Climate extreme indices derived from ERA5 indicate intensifying temperature extremes and increased climate variability across Central Asia. The observation sample shows rising frequency and intensity of extremely high temperature episodes (captured by TXx and related indicators), alongside longer durations of heat stress. These changes are most pronounced in arid and lowland zones, consistent with climate trends reported in comparable regional studies [26].

Hydro-meteorological hazards are also intensifying, but their spatial distribution is highly heterogeneous. In mountainous and foothill areas of Kazakhstan and the Kyrgyz Republic-where hydrological regimes are closely linked to seasonal precipitation and snow/glacier melt-indices of extreme precipitation (e.g., Rx5day) increase, thereby elevating the probability of floods and debris flows. In Uzbekistan and southern Kazakhstan, the most persistent signal is increasing aridity (SPI/SPEI), creating adverse conditions for water supply and irrigation systems.

Overall, the hazard assessment indicates that the region faces simultaneous pressure from “hot” extremes (heatwaves and droughts) and “wet” extremes (intense precipitation and flood events), with dominant hazard types shaped by local physical-geographic conditions.

3.2 Exposure and Vulnerability: Distribution of Infrastructure Assets and Sensitivity Drivers

Exposure results show that infrastructure assets and population are concentrated in a limited number of nodes and corridors, including major urban agglomerations, primary transport routes, water management facilities, and energy hubs. This concentration amplifies potential damages under extreme weather scenarios: similar hazard intensity can yield markedly different impacts depending on asset density, critical interdependencies, and network connectivity.

Vulnerability assessment reveals substantial variation both across countries and across sectors. The most vulnerable infrastructure segments are those characterized by high asset age, limited modernization, low redundancy, and strong dependence on climate-sensitive resources-particularly water. Vulnerability increases further in areas with limited institutional capacity for operation and recovery, as well as territories with insufficient financing for infrastructure maintenance [18], [28].

The combined assessment of exposure and vulnerability indicates that risk “peaks” emerge not only from high hazard intensity but also from the overlap of extreme climatic pressures with concentrated assets and constrained resilience capacities. These patterns provide an empirical basis for identifying high-risk zones and evaluating the gap between climate threats and adaptation potential.

Table 2: Indicators and data sources used in the study.

Indicator Group	Indicator	Brief Description	Source
Climate hazards	TXx, TNn	Temperature extremes	ERA5 [28]
Climate hazards	SPI, SPEI	Drought indices	ERA5, IPCC [28], [29]
Precipitation	Rx5day	Extreme precipitation	ERA5 [28]
Exposure	Population density	Spatial concentration of population	World Bank [24], [26]
Exposure	Infrastructure assets	Location of key assets	National statistics [25], [29]
Vulnerability	Infrastructure age	Technical condition of assets	World Bank [24], [26]
Resilience	Capacity redundancy	Reserve capacity and flexibility	IPCC [25]
Spatial analysis	Hotspot analysis	Identification of high-risk zones	GIS methods [21]

3.3 Integrated Climate Risk and Resilience Indices: Cross-Country Differences

The integrated indices of Climate Risk (CR) and Climate Resilience (CRI_res), normalized to the 0-1 range, exhibit stable cross-country differences. At the national level, Kazakhstan and Uzbekistan demonstrate higher climate risk values relative to the Kyrgyz Republic, reflecting the combination of intense temperature extremes/aridity and high exposure of key infrastructure assets.

By contrast, the climate resilience index (CRI_res) displays a different profile: Kazakhstan shows comparatively higher CRI_res values than Uzbekistan and the Kyrgyz Republic, consistent with the hypothesis of stronger institutional and resource capacity to maintain infrastructure performance and respond to climate-related disruptions. These findings are complemented by the spatial climate risk distribution presented in Figure 3, which highlights regional differences in climate hazard intensity across Central Asia.

Figure 3 presents a regional map of climate risks across the Central Asian countries, illustrating their spatial differentiation from very low to very high risk levels. The highest concentration of high and very high climate risks is observed in the southern and mountainous regions, particularly in the Kyrgyz Republic and Tajikistan, as well as in selected areas of Uzbekistan. These territories are characterized by complex physical and geographical conditions, a high frequency of extreme hydro-meteorological events, and increased infrastructure vulnerability. In contrast, northern and central Kazakhstan predominantly exhibit low to moderate climate risk levels, reflecting comparatively more stable climatic conditions and a higher adaptive capacity. The observed spatial heterogeneity underscores the need for differentiated approaches to climate risk assessment, infrastructure planning, and adaptation strategies. Figure 3 provides an empirical basis for the subsequent analysis of infrastructure vulnerability, resilience, and the prioritization of adaptation measures across Central Asia. A quantitative summary of national-level results is reported in Table 3. The table also includes sector-specific values and a computed gap indicator (Gap = CR - CRI_res), interpreted as the relative mismatch between the magnitude of climate threats and the capacity of infrastructure systems to sustain functionality and recover following extreme events.

Figure 3: Spatial distribution of climate risks in Central Asian countries by intensity levels.

Table 3: Integrated indices of climate risk and infrastructure resilience (normalized 0-1).

Country	CR (mean)	CRI_res (mean)	Gap = CR - CRI_res	Energy: Gap	Water: Gap	Transport: Gap
Kazakhstan	0.78	0.56	0.22	0.30	0.26	0.20
Uzbekistan	0.82	0.42	0.40	0.42	0.48	0.35
Kyrgyz Republic	0.64	0.38	0.26	0.34	0.40	0.28

Note: Values are presented on a normalized 0-1 scale and computed according to the formulas in Section 2.8. Sectoral Gap values aggregate results across key indicators for the corresponding infrastructure systems.

3.4 Sectoral Differences: Where the Largest Risk-Resilience “Gap” Emerges

Sectoral decomposition indicates that the most pronounced gaps are concentrated in water and energy infrastructure. In Uzbekistan, the largest sectoral gap is observed in the water sector (Gap = 0.48), reflecting the combined effects of persistently high climatic pressure (aridity and high variability of water inflows) and limited capacity of water infrastructure systems to maintain reliability and recover rapidly. The Uzbek energy sector also exhibits an elevated gap (Gap = 0.42), consistent with the sensitivity of power systems to thermal extremes and peak-load stress.

Kazakhstan displays a smaller average gap (0.22); however, sectoral analysis reveals that energy infrastructure exhibits a higher gap (0.30) than transport (0.20). This suggests that even where overall resilience is comparatively stronger, critical bottlenecks may emerge in sectors where redundancy and rapid recovery are essential. In the Kyrgyz Republic, the largest gap is observed in the water sector (0.40), consistent with high exposure to hydro-meteorological extremes in mountainous areas and comparatively constrained adaptation resources.

The presented visualizations capture the spatial and sectoral characteristics of the relationship between climate risk and infrastructure resilience across Central Asian countries. The spatial distribution of the integrated Climate Risk (CR) and Climate Resilience (CRI_res) indices reveals pronounced cross-country heterogeneity driven by the interaction of climate hazards, infrastructure exposure, and differences in adaptive capacity. Higher CR values are predominantly associated with territories experiencing intensified temperature extremes and persistent arid conditions, whereas the distribution of CRI_res reflects disparities in institutional, technical, and resource-based capacities to sustain infrastructure functionality.

To provide a compact representation of country-sector variation in the risk-resilience gap, a heatmap is constructed (Fig. 4). This format enables simultaneous comparison across sectors and countries, highlighting the country-sector combinations where the mismatch (Gap) is largest.

The heatmap of the sector-country gap (Gap = CR - CRI_res) provides further disaggregation across key infrastructure sectors. The largest gap values are observed in the water and energy sectors, indicating a mismatch between the magnitude of climate threats and the current adaptive and recovery capacities of infrastructure systems. At the same time, the visualization underscores substantial variation both across countries and sectors, forming a heterogeneous vulnerability profile. These results provide a quantitative foundation for subsequent interpretation of the drivers of observed disparities and for identifying priority directions for strengthening infrastructure climate resilience.

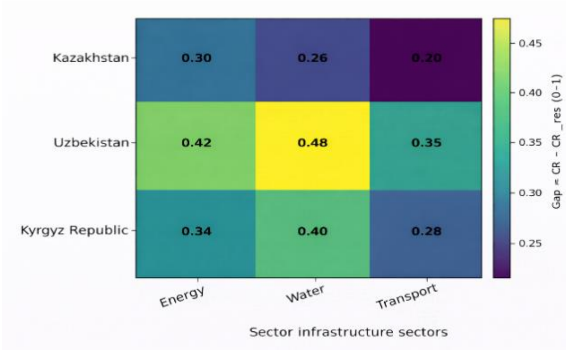

Figure 4: Heatmap of the sector-country “Gap” between climate risk and infrastructure resilience.

Overall, sectoral analysis highlights the necessity of accounting for infrastructure heterogeneity in adaptation planning. Even under comparable levels of hazard intensity and exposure, resilience may differ significantly depending on sector-specific characteristics, including recovery time, capital intensity, dependence on natural resources, and network interdependencies.

3.5 Interregional Heterogeneity and Implications for Further Analysis

The results demonstrate that national average index values do not fully capture the nature of risk at the subnational scale. Even in countries with relatively higher average resilience levels, localized zones of elevated vulnerability may persist-for example, remote regions with limited access to backup capacity and recovery resources. Conversely, in countries with high overall risk, localized pockets of relatively strong resilience may exist, particularly near modernized infrastructure nodes.

The presence of pronounced interregional heterogeneity confirms the necessity of multilevel (national-subnational) analysis and the use of spatial tools to identify climate risk and infrastructure constraint hotspots. Collectively, Section 3 provides the empirical foundation for the subsequent Discussion, including comparison with international literature, interpretation of identified risk-resilience gaps, and formulation of policy-relevant recommendations for strengthening infrastructure climate resilience in Central Asia.

4 DISCUSSION

This section interprets the empirical findings within a broader scientific and policy context, drawing on contemporary climate resilience frameworks, IPCC risk-based methodologies, and peer-reviewed research on infrastructure systems under extreme weather stress. The discussion is structured around the principal findings presented in the Results section and aims to elucidate underlying drivers, situate the findings within existing literature, and derive policy-relevant implications.

4.1 Interpretation of Spatial Differences in Climate Risk and Resilience

The pronounced spatial heterogeneity of climate risk and infrastructure resilience across Central Asia reflects the complex interplay of climatic, geographic, and institutional determinants. Elevated CR values in southern and arid regions align with international evidence documenting intensifying heat and drought extremes in continental climate zones [14]. However, variations in CRI_res indicate that hazard intensity alone does not determine final risk outcomes.

Comparative analysis of Kazakhstan, Uzbekistan, and the Kyrgyz Republic suggests that countries with stronger infrastructure bases and institutional governance mechanisms exhibit relatively higher resilience, even under comparable or elevated hazard levels. This finding reinforces the central role of adaptive capacity and governance quality in shaping infrastructure climate resilience.

4.2 Sectoral Implications and Vulnerability of Critical Infrastructure

Sectoral results identify energy and water infrastructure as the most climate-sensitive domains. Elevated sectoral gap values are consistent with Q1-level studies emphasizing the vulnerability of capital-intensive and resource-dependent infrastructure systems under increasing climate variability [29]. Rising temperature extremes and altered hydrological regimes intensify systemic stress on these sectors, warranting prioritization in adaptation planning and investment strategies.

Although transport infrastructure exhibits comparatively lower average gap values, it remains critical due to systemic interdependencies. Localized disruptions in key transport nodes can generate cascading effects across economic and social systems, highlighting the importance of integrating climate risk considerations into transport and spatial planning processes.

4.3 Alignment with Existing Scientific Literature

The findings are broadly consistent with global and regional climate risk assessments reported by the IPCC and peer-reviewed research [29]. In particular, the observed asymmetry between hazard intensity and adaptive capacity corroborates evidence of an "adaptation deficit" in developing and transition economies [14], [30], [33].

At the same time, this study contributes to the literature by integrating spatial analysis, sectoral decomposition, and composite risk-resilience indices within a unified analytical framework tailored to Central Asia. By moving beyond aggregated national metrics, the approach reveals localized patterns with direct relevance for infrastructure governance and policy implementation.

4.4 Institutional and Governance Implications

From a policy perspective, the findings emphasize the need to transition from uniform adaptation strategies toward differentiated approaches that account for spatial and sectoral heterogeneity of climate risk. Investment prioritization should target zones and sectors exhibiting the largest risk-resilience gaps, particularly water and energy systems.

The results further underscore the importance of mainstreaming climate risk into long-term infrastructure and territorial development planning. The application of spatial analytics and scenario-based approaches can enhance the robustness of adaptation strategies under uncertainty.

Strengthened intergovernmental cooperation within Central Asia is also critical. Given the transboundary nature of water resources, energy grids, and transport corridors, coordinated adaptation strategies, harmonized resilience standards, and shared data systems can significantly enhance regional climate resilience [33], [34].

4.5 Limitations and Directions for Future Research

Despite its contributions, the study has several limitations. The use of aggregated and normalized indicators, as well as schematic spatial representations, may not fully capture fine-grained local characteristics of infrastructure systems. Furthermore, the analysis primarily relies on historical climate data and does not explicitly incorporate forward-looking climate change scenarios.

Future research should integrate climate projection scenarios, more granular infrastructure datasets, and dynamic modeling approaches to assess the temporal evolution of risk and resilience. Such extensions would enhance policy relevance and support long-term adaptation planning under deep uncertainty.

5 CONCLUSIONS

This study provides a comprehensive assessment of climate resilience of infrastructure systems in Central Asia under intensifying extreme weather risks. By applying the IPCC risk-based conceptual framework and integrating ERA5 climate data, socio-economic indicators, and spatial analysis, the research offers a holistic representation of climate risk distribution and infrastructure adaptive capacity across the region.

The findings confirm that climate risks in Central Asia are spatially heterogeneous and arise from the interaction of climate hazards, infrastructure exposure, and disparities in institutional and resource capacities. A key scientific contribution of the study is the identification of a persistent imbalance between climate risk and current resilience levels. Even countries with comparatively advanced infrastructure systems exhibit substantial gaps between hazard intensity and recovery/adaptation capacity, pointing to systemic climate vulnerabilities and limitations of traditional engineering-based approaches that do not fully account for evolving climate extremes.

Sectoral analysis demonstrates that water and energy infrastructure are particularly vulnerable, reflecting heightened exposure to drought intensification, temperature extremes, and hydrological variability. These sectors are critical for socio-economic stability and may generate cascading, cross-sectoral impacts under extreme events. Transport infrastructure, while showing relatively lower average gaps, remains systemically important due to network interdependencies.

Spatial analysis further reveals that aggregated national indicators mask subnational variability. Each country contains localized zones of elevated vulnerability shaped by physical geography, infrastructure concentration, and differential access to adaptive resources. This underscores the need for multilevel risk assessment frameworks that integrate national and subnational perspectives.

From a policy standpoint, the results highlight several strategic priorities for Central Asian countries. First, adaptation investments should be reallocated toward sectors and territories with the largest risk-resilience gaps, particularly water and energy systems. Second, climate risk considerations must be embedded into long-term infrastructure and territorial planning, supported by spatial tools, scenario analysis, and uncertainty assessment. Third, enhanced regional cooperation is essential, given the transboundary interdependencies of water systems, energy networks, and transport corridors.

Scientifically, the study advances climate resilience research by integrating composite quantitative indices, spatial analysis, and sectoral decomposition within a unified analytical framework. The methodological approach is transferable to other continental and resource-constrained regions, enhancing its broader applicability.

In conclusion, escalating extreme weather risks under climate change make strengthening infrastructure resilience a central pillar of sustainable development in Central Asia. The implementation of comprehensive, spatially and sectorally differentiated adaptation strategies-grounded in robust risk and resilience assessment-constitutes a necessary condition for reducing vulnerability and ensuring long-term socio-economic stability in the region.

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