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ORIGINAL RESEARCH ARTICLE

Water scarcity in Asian nations and the path to resilience

Muhammad Khalid Anser[1], Muhammad Zaheer Akhtar[2], Syed Tahir Hussain Shah[3], Muhammad Azhar Khan[2], and Khalid Zaman[2]*

[1]Department of Economics, Faculty of Economics and Administrative Sciences, Recep Tayyip Erdoğan University, Rize, Türkiye

[2]Department of Economics, Faculty of Social and Administrative Sciences, The University of Haripur, Haripur, Khyber Pakhtunkhwa, Pakistan

[3]Department of Economics, Faculty of Social Sciences and Humanities, University of Wah, Wah Cantonment, Punjab, Pakistan

***Corresponding author:** Khalid Zaman (khalid.zaman@uoh.edu.pk)

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Abstract: Water, the most essential component for life and ecological balance, is scarce worldwide, particularly in underprivileged countries. This research uses panel data from 39 Asian nations spanning from 1996 to 2022 to examine the impact of water scarcity (WS) on climate change, socioeconomic issues, governance instability, food production, and sustainable groundwater planning. The generalized method of moments estimator results reveal that government effectiveness, regulatory quality, and crop production reduce WS by 17.581%, 55.049%, and 0.171%, respectively. In contrast, agricultural land degradation, renewable energy demand, and climate funding exacerbate WS by 0.001%, 1.551%, and 10.397%, respectively. The study underscores the importance of effective governance and climate financing in securing Asia's water future.

Keywords: Water stress; Climate risk; Governance; Climate financing; Population growth; Renewable energy demand; Asian economies

1. Introduction

Water, as the most crucial component and a vital resource, plays a pivotal role in sustaining human life and maintaining ecological equilibrium on a global scale. It is irrefutable that survival for any living organism is impossible without water.[1] Despite covering 71% of the Earth's surface, only a small fraction – approximately 2.5% – is fresh and usable for human consumption.[2] Moreover, the increasing demand for water, driven by population growth (POPG), has led to over a third of the world facing various water scarcity (WS) challenges. This alarming trend of WS has become a major global issue, particularly affecting underprivileged nations, which remain vulnerable if swift and effective measures are not implemented.[3] Water insecurity primarily affects developing countries, often exacerbated by ineffective policies and management. In the context of the ever-changing global ecosystem, climate change has emerged as the most pressing environmental concern of the Anthropocene age, driven primarily by the escalating use of fossil fuels since industrialization. Consequently, the impacts of climate change on freshwater ecosystems and water supplies are expected to be among the key challenges faced by nations in the 21st century.[4]

The interconnections between climate change, WS, and various socioeconomic issues – such as political strife, food security, and sustainable groundwater planning – pose serious global challenges. Agriculture, the cornerstone of many Asian economies, is particularly affected by WS, which in turn impacts food production, livelihoods, and economic growth.[5] In addition, rising sea levels and groundwater depletion threaten coastal areas and drinking water supplies, potentially leading to increased risks of poverty, hunger, and waterborne diseases. Recognizing the urgency and importance of addressing WS, global attention has focused on water access, allocation, and management, as these are fundamental for both human and ecosystem health. Achieving some of the Sustainable Development Goals requires access to sufficient and safe water.[6] Nevertheless, in certain countries, especially those under dictatorships, strict water restrictions may be imposed to control the populace, exacerbating WS for vulnerable individuals. To mitigate this, appropriate regulations and stringent laws must be enacted, and governments must initiate water-related projects and awareness programs to promote water conservation and prevent over-exploitation of water resources.[7] With growing concerns over climate change and the need for sustainable practices, efforts should be directed toward making the energy sector and water management more eco-friendly. Moreover, good governance, rule of law, anti-corruption measures, and accountability are essential for improving water resource management and streamlining the energy sector.[8]

The present study identifies key research questions to be addressed through detailed empirical testing. First, it explores the potential of integrated governance strategies in mitigating WS, focusing on institutional factors that contribute to ineffective water resource management. Second, it examines the relationship between the use of renewable energy sources and WS in Asia, considering the interdependencies between water, energy, food, and ecosystems. Third, the study investigates the effects of POPG on WS, acknowledging that a growing population impacts water demand, consumption habits, and overall water availability.

While the literature on water-related issues is extensive, there is limited research on how governance indicators, climate policy, and food security measures can reduce water stress.[9,10] This study uses the generalized method of moments (GMM) estimator with panel data from 39 Asian nations, spanning 1996 to 2022, to identify causal links between climate adaptation techniques in water management, agricultural sustainability, and governance quality. This distinction sets this study apart in the field. In addition, the present study quantifies how climate funding and efficient governance may influence water stress, with implications for policy, especially for national and international organizations designing efficient water management systems.

2. Literature review

The present study draws on resource dependency theory and institutional theory. According to resource dependency theory,[11] systems and organizations must rely on external resources to remain robust and sustainable. This theory emphasizes the importance of adaptive resource management in the context of WS, highlighting how renewable energy, agriculture, and government policies affect resource viability. Institutional theory[12] examines how social and organizational standards affect behavior. This perspective is useful for evaluating governance and policy frameworks aimed at providing long-term solutions to WS. In recent years, research on resource reliance and WS management has increased significantly. Ahmad *et al*.[13] examined how resource reliance and external economic constraints impact the adoption of renewable energy in developing countries, with their findings indicating that these adjustments led to reduced water usage. Anser *et al*.[14] stressed the necessity of institutional frameworks for sustainable agriculture as a means of alleviating environmental stress. These findings support the theory that strong institutional frameworks and resource-reliance management may mitigate WS. Research on institutional quality and environmental policy illuminates the significance of governance in sustainable resource management. Strong leadership is critical for improving environmental policy implementation, thereby reducing resource loss and enhancing sustainability.[15]

The present study applies institutional theory to examine how effective governance mediates the relationship between renewable energy adoption and agricultural sustainability in the context of water constraints. Rao *et al*.[16] examined how institutional reforms could accelerate the adoption of renewable energy and the role of governance in addressing resource limitations. Their research investigates the widespread use of renewable energy sources to reduce water stress. Malla *et al*.[17] found that renewable energy sources help minimize water consumption in power generation, particularly in water-scarce regions. Yang and Solangi[18] stressed the necessity for coordinated conservation measures, focusing on the intersection of renewable energy, WS, and sustainable agriculture.

Du Plessis[19] notes that South Africa is among the regions experiencing significant water stress, with global water shortages projected by 2050. The study advocates for water policy reforms, expanding monitoring networks, and fostering water diplomacy among stakeholders to effectively address these challenges. Scanlon *et al*.[20] considered the interconnection between groundwater and surface water while analyzing trends in water resource development. Their study revealed substantial variations in total water storage across regions over the past century, with climate variability and human activities, particularly irrigation, significantly influencing these changes. They recommended the implementation of diverse management techniques to enhance water resource resilience.

Richter[21] assessed water use in 28 utilities serving 23 million people reliant on rivers. Despite a 24% increase in population, over half of the cities reduced per capita water use. However, water consumption in the Colorado River Basin increased by 1%. Suna *et al*.[22] highlighted the worsening water availability in India due to climate change, which is negatively impacting agriculture and rural livelihoods. Effective irrigation management was emphasized as a solution to these challenges. Liu *et al*.[23] quantified agricultural WS in China using the agricultural WS index (AWSI), noting that climate change could increase the value of the AWSI, especially in Inner Mongolia. They suggested improving irrigation efficiency as a potential solution.

Harik *et al*.[24] used agent-based modeling (ABM) to predict farmers' decisions under potential WS scenarios induced by climate change. Their study found that farmers primarily adopted adaptive actions, such as switching crops or seeking alternative water sources, under low-to-moderate water constraints. However, severe water shortages led many farmers to cease farming, urbanize their lands, or leave them fallow. Including social influences in the ABM reduced adaptability, resulting in increased land selling or abandonment in response to WS. Essaber *et al*.[25] focused on climate project funding in Egypt, Morocco, and Tunisia. They identified local and international funding sources and advocated for an integrated financing approach involving all actors to effectively combat climate change. Cao *et al*.[26] introduced a methodology to analyze the Virtual Water Footprint in Chinese provinces, highlighting strategies for reducing agricultural water footprints and alleviating national water stress. Moursy *et al*.[27] compared drip and surface irrigation in the Nile Delta, finding drip irrigation to be more effective in water use and conservation across various crops. Fang *et al*.[28] examined the water footprint and virtual water trade of Belt and Road Initiative (BRI) nations, noting that economic and population expansion has led to an increased water footprint. The study emphasized the importance of collaboration on water resource management to address WS challenges within the BRI.

Based on the existing literature, the present study proposes several hypotheses related to WS and governance challenges in Asian countries:

H_1: Government regulatory quality (RQ) and effectiveness are crucial in mitigating climate risks and addressing WS challenges in Asian countries.

H_2: Mitigating climate hazards and resolving water shortages in Asia can be achieved through the implementation of renewable energy sources and climate funding initiatives.

H_3: Increasing populations, unsustainable agricultural practices, and land degradation exacerbate drought conditions in Asia.

This research aims to illuminate the region's water deficit and sustainable water resource management issues by evaluating these hypotheses.

While there is considerable research on the economic factors, governance, and WS in Asian nations, there remains a gap in the literature concerning the effectiveness of specific government initiatives in this context.[29,30] Previous studies have outlined the high-level role of governance but have not sufficiently explored how governance can mitigate climate change and address water shortages.[31,32] In addition, early studies have overlooked the potential of renewable energy to alleviate WS.[33,34] Renewable energy technologies may improve water availability and usage, yet the literature has not adequately addressed this relationship.[35,36]

For sustainable resource management, it is important to explore the relationship between renewable energy consumption (REC) and water shortages in Asia. While climate funds have been mentioned, their usage and effectiveness in solving water shortages have not been fully examined.[37,38] A detailed review of the impact and efficiency of climate funding in mitigating water shortages would significantly contribute to the field. Moreover, the interconnectedness of water shortages, POPG, crop yields, and agricultural land degradation (AGLD) requires further investigation. Understanding how these factors influence water availability and consumption patterns is essential for developing sustainable water resource management strategies.

3. Data and methodology

The present study adopts a methodological approach designed to ensure the replicability and clarity of the research techniques. To address endogeneity issues frequently encountered in environmental and resource management research, the analysis employs dynamic panel data with the GMM estimator. GMM is particularly well-suited to capturing dynamic relationships, as it accounts for unobserved heterogeneity, lagged dependent variables, and instrumental effects. Recent studies by Arellano and Bond[39], Blundell and Bond[40] confirm the effectiveness of this method for panel data analysis. In line with this approach, the following section details the variables employed in the model:

(i). Dependent variable

- WS (indicating climate risk): Measured as water productivity – total gross domestic product (GDP) (constant 2015 US$) per m^3 of total freshwater withdrawal – sourced from the World Development Indicators.[41]

(ii). Independent variables

- RQ: Captures the government's ability to establish and enforce robust policies and regulations that support private sector development. Values range from −2.5 to 2.5, expressed in standard normally distributed units, obtained from the World Governance Indicators[42]
- Government effectiveness (GEF): Reflects the quality of public services, civil service independence from political influences, and the quality of policy formulation and implementation. Also expressed in standard normally distributed units (−2.5 to 2.5), sourced from the World Governance Indicators.[42]

(iii). Controlled variables

- REC: The share of renewable energy in total final energy consumption, sourced from the World Development Indicators[41]
- POPG: Measured as the annual percentage change in population, sourced from the World Development Indicators[41]
- AGLD: Represented by the percentage of land area designated for agriculture, sourced from the World Development Indicators[41]
- Climate financing (CLF): Constructed using principal component analysis, this index incorporates weighted components of foreign direct investment inflows, REC, carbon damages, and trademark application (direct resident) expenditure. The method is adapted from Khan *et al.*,[43] with data sourced from the World Development Indicators.[41]

The study focuses on 39 Asian countries as the unit of analysis, chosen from a total of 48 countries in the region based on data availability. The panel dataset spans 26 years, covering the period from 1996 to 2022. The countries are categorized into subregions as follows:

- Eastern Asia: China, Japan, Mongolia, North Korea, and South Korea
- Southern Asia: Afghanistan, Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan, and Sri Lanka.
- South-Eastern Asia: Brunei Darussalam, Cambodia, Indonesia, Laos, Myanmar, Malaysia, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam
- Western Asia: Armenia, Bahrain, Cyprus, Georgia, Jordan, Iraq, Israel, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, State of Palestine, Turkey, United Arab Emirates, and Yemen
- Central Asia: Azerbaijan, Kyrgyzstan, Kazakhstan, Tajikistan, Turkmenistan, Uzbekistan.

The study utilizes a regression model to explore the relationship between governance indicators and water governance across Asia. This model, referred to as the Good Governance and Water Resources Model or the Water Governance Model, is grounded in theoretical relationships established in the present research. It aims to examine how governance indicators influence water governance practices in the region. The model is specified as follows:

$$WS_t = \propto_0 + \propto_1 WS_{t\text{-}1} + \propto_2 GEF_t + \propto_3 RQ_t + \propto_4 REC_t + \propto_5 POPG_t + \propto_6 CROP_t + \propto_7 AGLD_t + \propto_8 CLF_t + \mu_t \quad \text{(I)}$$

Where WS, GEF, RQ, REC, POPG, AGLD, and CLF retain their previously defined meanings, and crop production (CROP) denotes CROP.

Dynamic GMM is frequently applied by economists for parameter estimation in changing panel data simulations.[39] It proves particularly valuable in addressing challenges such as unobserved heterogeneity, endogeneity, and serial correlation within panel datasets. A commonly used variant is the two-step differenced GMM estimator, which involves differencing the data to eliminate individual-specific effects and generate valid instruments for accurate estimation. This estimator operates in two phases. In the first phase, data differencing removes time-invariant unobserved heterogeneity, thereby mitigating endogeneity concerns. In the second phase, the system of equations is estimated using the GMM framework, incorporating instruments derived from the differenced data to ensure robust parameter estimates.

4. Results

Table 1 presents descriptive statistics for selected Asian countries from 1996 to 2022. The mean WS level across these countries was 43.751 m^3 of total freshwater withdrawal per constant 2015 US$ of GDP, with considerable variability, as indicated by a standard deviation of 114.613. GEF and RQ exhibited overall negative evaluations, with mean indices of −0.036 and −0.112, respectively, reflecting diverse governance performances across the region. REC accounted for an average of 25.223% of GDP, highlighting a regional commitment to sustainability. POPG averaged 1.597%, while CROP recorded an average index of 87.603, suggesting variability in agricultural productivity.

The percentage of land area designated for agriculture (AGLD) averaged 400,195.4, with large variability indicated by a standard deviation of 945,180.9. CLF had a mean index of 0.0003, reflecting relatively low financial support for climate-related projects, yet with the potential for notable fluctuations (standard deviation: 1.183).

The kurtosis coefficients offer additional insights into variable distributions. Leptokurtic distributions have heavier tails and sharper peaks compared to a normal distribution, whereas platykurtic distributions exhibit flatter peaks and lighter tails. The high kurtosis value of 34.634 for WS indicates significant heterogeneity and substantial variability across Asian nations. GEF and RQ have kurtosis values of 2.977 and 2.951, respectively, suggesting distributions that are approximately normal, with moderate variability. In contrast, REC, with a kurtosis of 2.679, demonstrates a platykurtic distribution, signifying lower variability. The POPG kurtosis of 6.108 indicates a leptokurtic distribution characterized by limited variability but heavier tails. CROP shows a modestly peaked distribution, with a kurtosis of 4.031, exhibiting minor variability in agricultural output. AGLD, with a kurtosis of 18.688, displays a strongly leptokurtic distribution, indicating significant variability likely driven by diverse regional land-use patterns. CLF, with a kurtosis of 3.217, suggests a distribution that is approximately normal with somewhat pronounced tails. Collectively, these results illustrate the diverse distributional characteristics of the variables examined across the investigated sites, enhancing the understanding of their statistical behavior. The analysis presented in Table 2 employs a two-step GMM dynamic panel data approach to investigate the factors influencing WS governance in selected Asian countries.

The study finds that GEF has a significant negative impact on WS governance. Specifically, a 1% improvement in GEF leads to a substantial 17.581% reduction in WS issues. This suggests that nations with stronger governance systems are better equipped to manage water shortages and promote sustainable water resource management. Similarly, the coefficient of RQ also exhibits a significant and negative impact on WS governance. A 1% enhancement in RQ results in a remarkable 55.049% reduction in WS issues. This finding suggests that fragmented water resource institutions – often stemming from poor inter-agency coordination – hinder the efficient management of

Table 1. Descriptive statistics

Methods	WS	GEF	RQ	REC	POPG	CROP	AGLD	CLF
Mean	43.751	−0.036	−0.112	25.223	1.597	87.603	400195.4	0.0003
Maximum	996.803	2.436	2.260	96.041	7.349	203.570	5290386	4.689
Minimum	0.196	−2.307	−2.344	0.0005	−3.6296	19.210	6.600	−3.086
Std. Dev.	114.613	0.870	0.878	29.704	1.279	27.439	945180.9	1.183
CV	261.966	−2416.670	−783.929	117.765	80.087	31.321	236.179	394333.3
Skewness	5.220	0.501	0.116	1.020	0.859	0.148	3.806	0.242
Kurtosis	34.634	2.977	2.951	2.679	6.108	4.031	18.688	3.217

Source: Author's estimate. CV: Coefficient of variation; Skewness measures the asymmetry of distribution: a value of 0 indicates symmetry, while positive and negative values indicate right- and left-skewed distributions, respectively; Kurtosis values >3 indicate heavy-tailed distributions, <3 indicate light-tailed, a normal distribution has a kurtosis of 3.

Abbreviations: AGLD: Agricultural land degradation; CLF: Climate financing; CROP: Crop production; GEF: Government effectiveness; POPG: Population growth; REC: Renewable energy consumption; RQ: Regulatory quality; Std. Dev.: Standard deviation; WS: Water scarcity.

Table 2. Panel two-step generalized method of moment estimates

Variables	Coefficient	S.E.	*t*-statistic	Prob.
WS(−1)	0.878	0.0008	991.661	0.000
Governance indicators (used as explanatory variables)				
GEF	−17.581	0.180	−97.388	0.000
RQ	−55.049	0.162	−339.306	0.000
Macroeconomic variables (used as controlled variables)				
REC	1.551	0.098	15.721	0.000
POPG	−5.172	0.059	−87.506	0.000
CROP	−0.171	0.003	−55.549	0.000
AGLD	0.0006	3.3×10^{-05}	18.527	0.000
CLF	10.397	0.152	68.164	0.000
Effect specification				
Cross-section fixed (first differences)				
Mean dependent variable	1.869	Std. Dev. dependent variable		19.386
S.E. of regression	28.265	Sum squared residual		708,669.5
J-statistic	27.795	Instrument rank		40
Probability (*J*-statistic)	0.679			

Source: Author's estimate.

Abbreviations: AGLD: Agricultural land degradation; CLF: Climate financing; CROP: Crop production; GEF: Government effectiveness; POPG: Population growth; Prob.: Probability; REC: Renewable energy consumption; RQ: Regulatory quality; Std. Dev.: Standard deviation; S.E.: Standard error; WS: Water scarcity.

water resources. This research also finds that renewable energy sources have a notable beneficial effect on water shortage management. A 1% increase in REC leads to a 1.551% reduction in WS issues, highlighting the potential of renewable energy to support sustainable water resource management. Consistent with previous studies, these results are encouraging: Areas facing water shortage can benefit from integrating renewable energy sources. One major advantage of this shift is reduced reliance on water-intensive energy production techniques such as coal-fired power plants and nuclear reactors. Transitioning to renewable energy can reduce a country's water footprint in the energy sector, freeing up water for other essential uses.

The coefficient for POPG indicates a significant negative impact on WS governance. Specifically, a 1% increase in POPG corresponds to a 5.172% reduction in WS issues. This finding suggests that, in some contexts, POPG may drive improvements in water infrastructure or governance, although further investigation is needed to clarify this dynamic. The coefficient of CROP also shows a significant negative impact on WS governance. A 1% increase in CROP is associated with a 0.171% decline in WS issues. However, the study warns that agricultural WS may worsen in regions experiencing soil desiccation and reduced precipitation due to global warming, ultimately affecting crop yields. Conversely, the coefficient for AGLD significantly influences water shortage governance. For every 1% increase in AGLD, water shortage problems rise by 0.0006%. This underscores the need for more effective water management in agriculture. Degraded soil retains less water and results in higher runoff and lower groundwater recharge, reducing the availability of farmable water and threatening farmers' livelihoods. As AGLD directly contributes to water shortages, governments should implement strategies to improve water retention in soils and prevent further land degradation. Sustainable land management strategies, such as soil conservation, afforestation, and reforestation, are essential in this regard. The coefficient for CLF shows a significant positive impact on WS governance. A 1% increase in CLF leads to a 10.397% rise in WS issues. This result highlights the influence of climate change – particularly the growing risks of droughts and weather variability – on water availability. Table 3 presents the results of the Arellano–Bond serial correlation test for the first and second lagged terms.

Table 3. Arellano–Bond serial correlation estimates

Test order	m-statistic	Rho	S.E. (rho)	Prob.
AR (1)	−0.006	−306886.996	48696645.623	0.995
AR (2)	NA	11900.195	NA	NA

Source: Author's estimate.
Abbreviations: AR: Autocorrelation; Prob.: Probability; S.E.: Standard error.

The GMM methodology employs the Arellano–Bond tests for autocorrelation (AR) (1) and AR (2) serial correlation to assess model validity. Under the null hypothesis of no autocorrelation, the test results indicate that the AR(1) probability value is 0.995. Therefore, at the 5% significance level, the null hypothesis is not rejected, confirming the absence of first-order autocorrelation in the model.

5. Discussion

Integrating water pollution control with water resource planning is recommended to ensure water resource management that is both socially and economically beneficial.[44] Improved WS regulation can yield long-term economic benefits. When government agencies fail to coordinate water resource management effectively, institutions may become fragmented. This fragmentation can lead to wasted resources, conflicting strategies, and unnecessary duplication of efforts, leading to inefficient water management.

Streamlining water resource planning and eliminating legislative inefficiencies can help nations improve both water consumption and cost management.[45] Disjointed water resource institutions may also deter businesses and investors. Inconsistent policies and regulatory uncertainty can restrict investment in water-dependent industries, ultimately slowing economic growth. By contrast, a more efficient governmental response to water shortages can produce positive financial impacts.

First, improved water governance can optimize water use across sectors such as agriculture, manufacturing, and domestic consumption. Efficient resource utilization enhances productivity and supports overall economic growth.[46] Second, better water shortage management may stabilize the economy and attract greater investment. Businesses are more likely to invest in regions where water resources are reliable, contributing to job creation and broader economic development. Investments in renewable energy also support innovation, economic growth, and resilience to external shocks. Countries with energy security are better positioned to manage their water resources effectively.[47]

As the global population continues to grow, intelligent water resource management becomes increasingly crucial. To meet rising demand, nations must prioritize water balance – ensuring that water supply aligns with consumption needs. This includes strategies such as optimizing agricultural irrigation, promoting water reuse, and encouraging conservation practices. These approaches help reduce water waste and improve efficiency, thereby aiding efforts to meet population-driven water demand.[48]

The condition of global water supplies is directly tied to population trends. As water sources come under increasing stress, protecting both human health and ecosystems requires a strong emphasis on maintaining water quality. Adequate wastewater treatment and pollution control are especially important in densely populated regions that are more vulnerable to contamination.[49] Sustaining a growing population demands adequate water resources for agriculture, domestic use, and industrial activity. However, uncontrolled POPG can lead to the overexploitation of water resources, aquifer depletion, and ecosystem degradation. Comprehensive land reforms are therefore essential to ensuring a sustainable water supply in the face of continued population pressure. Such reforms should include proper land-use planning to strategically allocate land among agricultural, industrial, and urban uses.[50] Promoting sustainable, water-efficient agriculture and incorporating water-sensitive design into urban planning are key strategies for effective long-term water resources management.

The impact of CROP on WS governance is closely tied to the agricultural sector, which is a major water consumer in many countries. As CROP increases, so does the demand for irrigation water. This rising need places additional pressure on water supplies, particularly in arid regions. The cultivation of crops can exacerbate water shortage; therefore, nations must prioritize environmentally sustainable farming practices. Adopting water-saving irrigation methods – such as drip irrigation – can assist in optimizing water consumption and reducing water wastage.[51] Agricultural planning and crop selection based on local water availability and climatic conditions can further enhance water-use efficiency. Environmentally, agricultural production has significant implications for WS governance. In regions already experiencing soil desiccation and severe WS due to global warming and decreasing precipitation, increased agricultural water demand may worsen the situation. This could jeopardize food security and the livelihoods of vulnerable populations by reducing agricultural yields. To address these challenges, climate-resilient agricultural practices are essential. Farmers should adopt drought-resistant crop varieties, improve soil health through sustainable agricultural practices, and invest in upgraded water storage and harvesting systems.[52]

Advanced agriculture offers a solution by reducing waste of water, fertilizers, and pesticides through the use of technology. Tools such as soil moisture sensors, automated irrigation systems, and satellite imagery enable precise irrigation, thereby enhancing water conservation and agricultural productivity. Techniques such as drip irrigation, rainwater collecting, and other advanced systems can significantly reduce water loss and improve water-use efficiency. Degraded soil causes sedimentation and the deterioration of water quality – issues that may negatively affect aquatic ecosystems and human health.[53] Addressing these concerns requires land restoration and protection. Sustainable land management practices aimed at rehabilitating degraded lands can improve soil health, increase water retention, boost agricultural productivity, and enhance water availability. Investments in farmer training and agricultural extension services are also critical for disseminating best practices and building capacity in water-efficient agriculture. In addition, governments should improve the monitoring and enforcement of regulations against illegal land clearing and deforestation to mitigate AGLD and reduce the risk of water shortages.

Long-term environmental changes and catastrophic events pose serious threats to ecosystems and increase pressure on water demand. To mitigate the impacts of climate change on water resources, projects and initiatives must be adequately funded. Investment in climate-resilient infrastructure – particularly water storage and distribution systems – can help manage the effects of shifting weather patterns and fluctuating water supply. CLF can also support the development of technologies aimed at improving water efficiency and reducing waste.[54] Changes in precipitation patterns, prolonged droughts, and more intense weather events directly affect water supplies. These changes not only affect the quantity and quality of water but also endanger ecosystems, biodiversity, and human livelihoods. CLF plays a critical role in safeguarding water resources and natural ecosystems from climate variability.[55] In addition, climate change adaptation and mitigation strategies may be more effective when coordinated across neighboring nations that share transboundary water resources.

This study presents several limitations that highlight directions for future research. First, the analysis covers 39 Asian countries from 1996 to 2022; however, the absence of comprehensive data may have excluded relevant factors that could have enhanced the findings. Due to inconsistencies in reporting across countries, several socioeconomic and environmental aspects of WS may have been overlooked. Future studies should incorporate larger and more detailed datasets, including information on national water regulations and governance systems, to improve the robustness of the results. Although this study employs GMM to address endogeneity, it may not fully capture all dynamic changes in water management and governance over time. Alternative econometric models, such as spatial models or dynamic panel threshold models, could offer deeper insights into the complex interactions among variables.

This research primarily focuses on governance indicators, climate-related factors, and economic variables affecting water shortage. However, future studies could incorporate additional dimensions, such as technology innovation, institutional capacity, and localized water management practices. Future research may also examine how renewable energy integration, advanced irrigation technologies, and water conservation strategies contribute to reducing global water stress. To improve the granularity of findings, future analyses should consider subnational or city-level data, offering a better understanding of localized water governance issues and solutions. In addition, examining the long-term effects of climate adaptation policies on sustainable water resource management would be valuable, particularly given the current study's emphasis on CLF in addressing water shortages. Expanding the dataset to include other water-stressed regions outside Asia would enhance the generalizability of findings and allow for cross-regional comparisons of policy effectiveness.

6. Conclusion and policy recommendations

The present study analyzes key drivers of water shortage governance – specifically, GEF, RQ, REC, POPG, CROP, AGLD, and CLF – across 39 Asian countries from 1996 to 2022. The findings reveal the complex dynamics between GEF, CLF, and agricultural practices in shaping WS outcomes. The results suggest that renewable energy adoption can reduce water shortages and promote sustainability in resource-constrained countries. Governance quality emerged as a critical factor, highlighting the importance of strong institutional frameworks in effective resource management. CLF was also found to support water adaptation strategies. In the agricultural sector, sustainable practices – including crop diversity and environmentally responsible land use – can mitigate water shortages and improve resilience.

The use of dynamic panel data analysis provides new insights into how these variables interact over time, filling a gap in the literature and offering practical recommendations for policymakers. The study emphasizes the need for integrated solutions to WS. By merging empirical evidence with theoretical perspectives, it contributes to both academic understanding and real-world policy applications for countries striving to balance sustainable development with effective resource management.

This research advances academic discourse by highlighting the importance of interdisciplinary approaches to global water issues. It offers significant theoretical and practical contributions by integrating renewable energy, agricultural approaches, and governance indicators into a unified analytical framework, thereby enhancing scholarly knowledge on resource management. The study's findings are also relevant for policymakers and practitioners working to address water shortages through research. The study concludes that cross-sector collaboration is essential for achieving long-term sustainability. It identifies key drivers and solutions that can support effective water governance in the face of climate and resource pressures.

The following policy recommendations are proposed for Asian economies to mitigate climate-related risks through a water governance approach:

(i) Implement immediate measures to enhance water governance frameworks by fostering collaboration among governments, stakeholders, and communities. Establish transparent and efficient water management systems to optimize water allocation and utilization
(ii) Encourage the rapid adoption of renewable energy sources, such as solar and wind power, to reduce reliance on water-intensive energy production. This transition will alleviate pressure on water resources and contribute to sustainable development
(iii) Develop pricing strategies that incentivize responsible water consumption across industrial, agricultural, and domestic sectors. Such mechanisms can promote water conservation and reduce wasteful practices
(iv) Launch public awareness campaigns to educate citizens about water conservation practices, efficient water usage, and the importance of preserving water resources. An informed public can play an active role in reducing water demand and managing scarcity
(v) Develop and implement immediate drought management plans in water-stressed regions. These plans should include measures to mitigate the impact of droughts on agriculture, communities, and ecosystems.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: Muhammad Khalid Anser, Muhammad Zaheer Akhtar, Khalid Zaman
Formal analysis: All authors
Investigation: Muhammad Khalid Anser, Muhammad Zaheer Akhtar
Methodology: Muhammad Khalid Anser, Muhammad Zaheer Akhtar, Syed Tahir Hussain Shah
Writing – original draft: All authors
Writing – review & editing: All authors

Availability of data

The data used in this study are freely available from the World Development Indicators and the World Governance Indicators, both published by the World Bank (https://databank.worldbank.org/source/world-development-indicators).

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