

The constraining mechanism of institutional water stress on regional economic vitality: evidence from the Capital Economic Circle

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Abstract: Institutional water stress is no longer an exogenous constraint imposed upon economic systems but has instead become an endogenous force embedded within specific institutional logics that actively shapes the geography of regional economic development. Taking China's Capital Economic Circle (CCEC) as a case study, this research moves beyond the prevailing analytical paradigm centered on physical water scarcity and constructs an integrated framework that couples an institutional water stress accounting model with a water–economic vitality nexus analysis. Using this framework, we examine the mechanisms through which the institutional allocation of water resources constrained regional economic vitality from 2010 to 2023 and propose the conceptual framework of Institutional Water Deficit (IWD) to better capture its dynamic formation processes. The findings reveal pronounced institutional favoritism in metropolitan water allocation: core cities such as Beijing and Tianjin enjoy high security and low stress by virtue of policy prioritization, whereas peripheral cities are persistently subjected to elevated institutional water stress. Institutional water stress does not suppress economic vitality directly; rather, it erodes regional development momentum indirectly by inflating water related costs ($\beta = 0.406$, $p = 0.036$) and narrowing industrial choices, thereby generating differentiated predicaments across city types including protection suppression dynamics in ecological buffer cities and transformation hollowing trajectories in industrial cities. The underlying drivers of this allocation pattern lie in an administratively anchored bias in water distribution, infrastructure driven flow path determination, and the externalization of costs concealed by the absence of compensatory mechanisms. Together, these factors allow initial policy deviations to propagate through cost transmission and structural lock in, continuously reinforcing core–periphery disparities and entrenching a closed loop of cumulative causation between institutional water stress and flagging economic vitality. On the basis of these insights, we contend that resolving the water–economy impasse necessitates an institutional reorientation. Measures including the establishment of compensation mechanisms commensurate with ecological contributions, the promotion of market based reforms in water rights, and the implementation of differentiated industrial water policies are essential to transform lucid waters and lush mountains into invaluable assets for peripheral regions, thereby fostering genuine sustainable development capacity. Such interventions can disrupt the urban shadow effects and low level equilibrium traps perpetuated by institutional arrangements, advancing the prospects for authentic regional integration and resource justice.

Key Words: institutional water stress; water economic vitality coupling; Institutional Water Deficit (IWD); urban shadow effect; capital economic circle

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1 Introduction

Institutional water stress constitutes a pivotal conceptual lens for understanding

water crises across the developing world (*D'Odorico et al., 2024*). It refers to a state of water resource constraint engendered by imbalanced management regimes, inadequate policies and regulations, and distorted institutional mechanisms (*Ma et al., 2020; Niazi et al., 2024*). Diverging from physical water scarcity stemming from inherent natural conditions, institutional water stress originates from deficiencies in the structural optimization of water rights allocation, pricing schemes, and cross regional governance frameworks (*Ma et al., 2020; Elisa & Pablo, 2014*). Such deficiencies routinely impede the efficient, equitable, and sustainable distribution of water resources, thereby exacerbating social inequality and obstructing progress toward the Sustainable Development Goals (SDGs) (*Vörösmarty et al., 2015; Mekonnen et al., 2016*). In numerous highly urbanized regions worldwide, including China's Capital Economic Circle, India's Delhi Mumbai Corridor, and the metropolitan areas of Mexico, institutional asymmetries have transformed water stress into a core mechanism that suppresses economic development in peripheral zones (*Silva, 2024; Kumar et al., 2024; Mehta et al., 2019*). A systematic theoretical elucidation of its spatial economic ramifications and transmission pathways is urgently required.

Existing research on the relationship between water resources and economic development clusters around three principal dimensions. First, studies develop models of water quantity and water use efficiency to evaluate how water resources shape economic trajectories (*Kahil et al., 2024*), examining implications for agriculture (*Rapella et al., 2025*), urban systems, and ecological conditions (*Sun et al., 2025; Dehghani et al., 2022*) through metrics such as absolute water availability (*Mooij et al., 2019*) or efficiency indicators. Second, geographic information systems and spatial statistical methods are employed to delineate the spatiotemporal patterns of water scarcity and lagging developmental vitality (*Leijnse et al., 2024; Gu et al., 2024*). Third, a distinct line of inquiry focuses on institutional drivers (*Lampinen et al., 2023*), disentangling how natural endowments (*Mekonnen et al., 2020*) and socioeconomic mechanisms (*Galli et al., 2022*) collectively shape water use behaviors.

Existing research predominantly remains confined to analytical paradigms centered on physical water scarcity or inefficient water use technologies, thereby systematically overlooking the institutional drivers underlying water allocation and the implicit spatial power structures these drivers entail (*Savelli et al., 2023; Babuna et al., 2023*). At the metropolitan scale in particular, the disequilibrium of resource distribution embedded within core periphery configurations is frequently entrenched through institutional instruments such as prioritization rights, interbasin transfer

77 projects, and industrial entry restrictions. Yet few studies have rigorously elucidated
78 how such mechanisms, via cost transmission and industrial lock in hierarchies,
79 persistently suppress the economic vitality of peripheral territories (*Wang et al., 2023;*
80 *Goswami & Ghosal, 2022*). This theoretical lacuna renders linear water allocation
81 policies fundamentally incapable of addressing the crux of the water economy nexus:
82 namely, the constitutive and reinforcing role of institutional water stress in shaping
83 regional economic geographical patterns.

84 To address the aforementioned research gap, this study takes the China Capital
85 Economic Circle (CCEC), encompassing Beijing, Tianjin, and Hebei, as the case
86 region to examine how intense water resource competition and institutional allocation
87 mechanisms drive spatially uneven regional economic development through
88 institutional water stress. The study pursues three primary objectives. First, it
89 constructs a two tier analytical framework that integrates physical water scarcity and
90 institutional water stress, thereby quantifying institutional biases in water allocation
91 and revealing the spatial patterns of which actors bear pressure due to institutional
92 arrangements. Second, employing a coupled water economy vitality model, it
93 identifies the critical pathways through which institutional water stress suppresses
94 economic vitality by escalating water costs and constraining industrial choices. Third,
95 it proposes the conceptual framework of Institutional Water Deficit (IWD) and derives
96 policy implications from the perspectives of institutional restructuring and
97 differentiated governance, thereby offering theoretical foundations and governance
98 pathways for breaking the adverse cycle of regional water economy suppression.

99 **2 Methodology**

100 **2.1 Study area**

101 The CCEC is situated within the water stressed Haihe River Basin (**Figure 1**)
102 and encompasses Beijing Municipality, Tianjin Municipality, and select areas of
103 Hebei Province. Annual precipitation across this region averages merely 500 to 600
104 millimeters, a volume grossly insufficient to satisfy local water demands, and
105 prolonged groundwater overdraft has already precipitated pronounced land subsidence.
106 To alleviate acute water scarcity, the region relies heavily on the South to North Water
107 Diversion Project; however, prevailing institutional allocation policies have
108 engendered a stark misalignment between water entitlements and developmental
109 rights. Owing to preferential policy frameworks, Beijing secures an average of
110 approximately 3 billion cubic meters of externally diverted water annually to underpin
111 its expansion, whereas Hebei Province, despite enduring comparable water deficits
112 and hosting the main conveyance arteries of the diversion scheme, confronts a

paradox wherein physical access to water does not equate to allocative access. Per capita water availability in Hebei stands at merely one ninth of the national average. The consequent disequilibrium in water resource apportionment has further accentuated regional economic divergence (*Hao et al., 2023*). In 2024, Hebei's per capita gross domestic product, recorded at 64,200 yuan, constituted only 28.2 percent of Beijing's 228,000 yuan, exemplifying a pronounced capital peripheral economic suppression belt (*Everard, 2019; Rusca et al., 2023*). The water allocation predicament within the CCEC thus epitomizes the compounded duress of superimposed institutional inequity upon natural scarcity, urgently necessitating policy driven water rights reform and enhanced regional coordination to ameliorate development disparities rigidified by hydrological constraints.

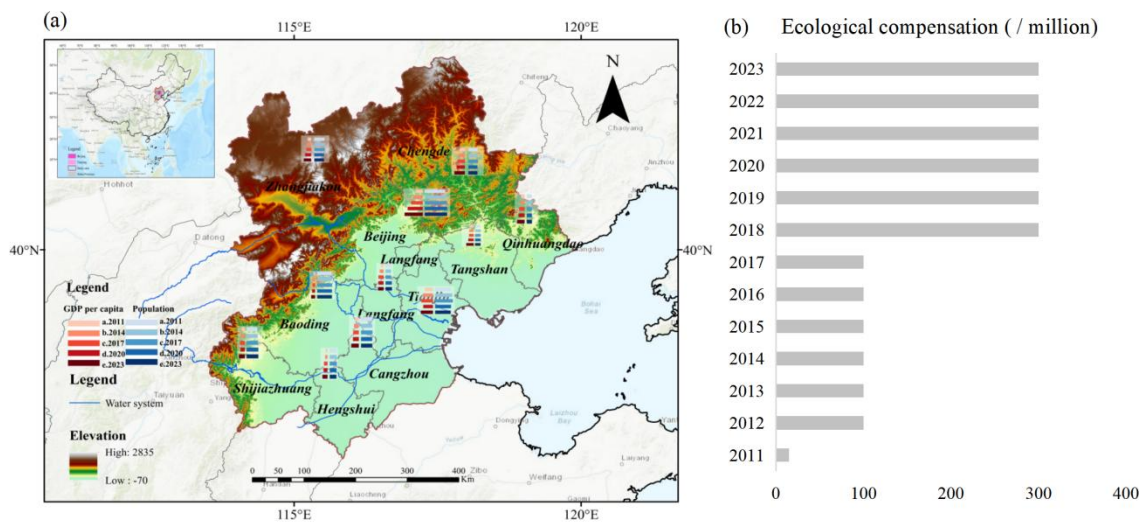


Figure.1 Geographical location and general situation of CCEC

2.2 Data sources and preprocessing

This study utilizes panel data at five time points 2011 2014 2017 2020 and 2023 covering key variables for cities within the capital economic region including local water resources imported water volume interregional water transfer volume annual GDP and groundwater overdraft areas. Detailed data sources and units are provided in **Table 1**. Data preprocessing followed a systematic procedure. Raw data were first cleaned by removing missing entries and obvious outliers. To address dimensional discrepancies water resource and socioeconomic time series data were standardized. Subsequently GIS based spatial interpolation techniques were applied to augment and smooth regional water allocation data thereby constructing a continuous spatial distribution field. For water use and water demand indicators ratio methods and weighted averaging were employed for normalization to ensure cross regional and cross type comparability. Principal component analysis and multiple regression were then integrated to synthesize and test the multidimensional variables. This process

provides a robust data foundation for the subsequent construction of an institutional water stress accounting model and a water economy coupling dynamics model.

Table 1 Data sources and preprocessing in this paper

Data type	Specific indicators	Data source	Preprocessing operations
Water resource data	Total water resources, water supply volume, actual water consumption volume (10 ⁸ per cubic meter)	<i>China Water Resources Bulletin</i> and <i>China Water Conservancy Statistical Yearbook</i>	Missing values are supplemented by interpolating with data from hydrological stations in the basin.
Institutional policy text	Water allocation plan, industrial ban and restriction list	The official websites of the governments of Beijing Municipality, Tianjin Municipality and Hebei Province	Text quantification: assigning values to policy intensity (0-5 points)
Social and economic data	Per capita GDP, fiscal self-sufficiency rate, proportion of secondary and tertiary industries, comprehensive water cost, road density	<i>Beijing bureau of statistics</i> , <i>Tianjin bureau of statistics</i> , <i>Hebei bureau of statistics</i>	Outliers are removed after being detected by box plots.
Geospatial data	Watershed boundary, ecological reserve, precipitation	Cloud platform for resources and environmental data	ArcGIS topological correction and overlay analysis

2.3 Methods

This study designed the following three analytical steps to systematically elucidate the impact of institutional water resource gaps within the CCEC on regional economic vitality and the associated transmission mechanisms (**Figure 2**). First, a water supply and demand analysis model was employed to quantitatively assess the overall degree of water scarcity and the spatial imbalance pattern across the CCEC. Second, an accounting model for institutional water resource gaps was constructed to identify disparities in water access driven by policy and allocation mechanisms, and to analyze how such disparities constrain the growth potential of different cities. Third, a coupled water economic vitality analysis model was applied to clarify the mechanisms by which water insufficiency intensifies the self reinforcing suppression of economic vitality, including rising water costs and restricted industrial options.

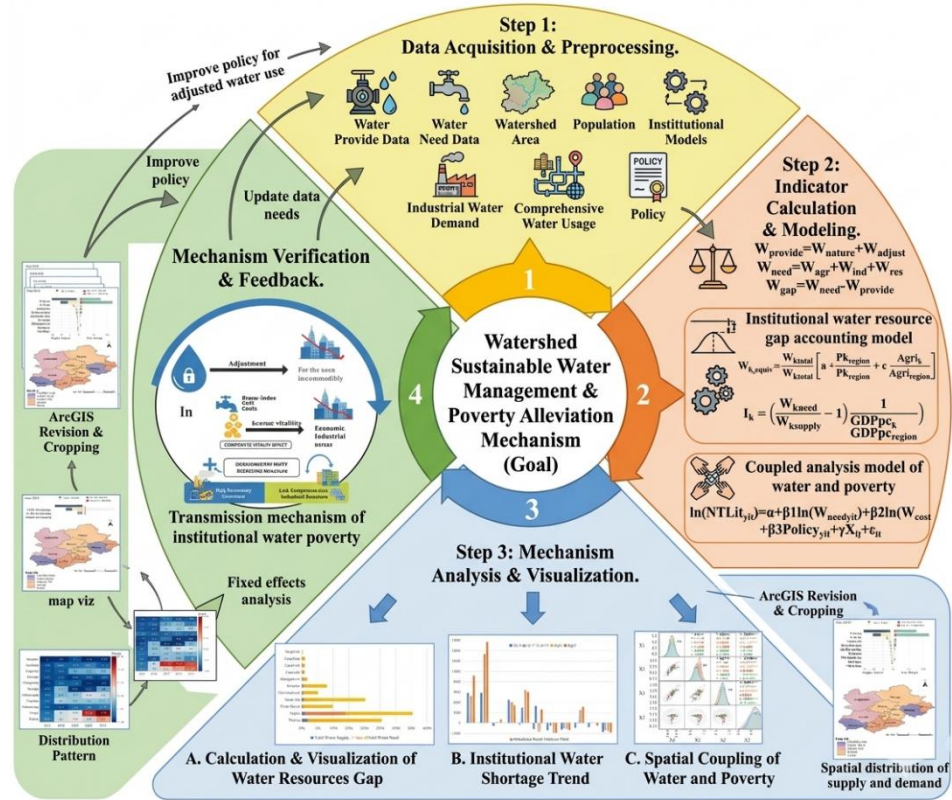


Figure.2 Overview of the study design

To achieve this research objective, the present study establishes an integrated assessment framework that combines physical scarcity and institutional deprivation, aiming to systematically delineate the spatial patterns and institutional drivers of water resource allocation within the CCEC region. The framework first employs a water supply demand analysis model to identify the magnitude and spatiotemporal characteristics of physical water deficits across individual cities, thereby confirming the fundamental existence of regional water shortages. It subsequently incorporates an IWD accounting model to evaluate disparities in water access arising from policies and allocation mechanisms, thereby revealing the structural bias that delineates who experiences greater water scarcity due to institutional factors. This approach provides a critical explanatory variable for the subsequent analysis of economic suppression effects.

2.3.1 Assessment framework for water supply demand gap and institutional deprivation

To comprehensively characterize the water resource allocation pattern of the capital economic circle from the two dimensions of physical scarcity and institutional deprivation, this paper constructs a two-layer assessment framework that integrates the water supply and demand analysis model and the institutional water resource gap accounting model. The design logic is as follows: first, the supply and demand

analysis model identifies the physical water gaps of each city and their spatiotemporal evolution, revealing the basic facts of regional water scarcity; on this basis, the institutional water resource gap accounting model is introduced to further evaluate the institutional deviations in regional water allocation and their deprivation effect on economic development, to answer the question of institutional attribution of water scarcity, and thereby to provide core explanatory variables for subsequent coupling poverty effect analysis.

(1) The water supply-demand analysis model aims to understand the current water supply and demand situation in the ccec and to reveal the evolution process of its supply-demand imbalance (*Liu et al., 2017*). By quantifying the core indicators on both the supply and demand sides, the model identifies the extent and distribution of regional physical water scarcity.

Water resource supply (W_{supply}) : this includes both natural water resources within the basin and the volume of water transferred from external sources. The calculation is as follows:

$$W_{\text{supply}} = W_{\text{nature}} + W_{\text{adjust}}$$

In the formula: W_{nature} represents the natural water resources within the basin, including precipitation, surface runoff, and groundwater recharge. W_{adjust} denotes the amount of water transferred from external sources.

Water resource demand (W_{need}): including agricultural water use, industrial water use and domestic water use of residents. The calculation formula is:

$$W_{\text{need}} = W_{\text{agr}} + W_{\text{ind}} + W_{\text{res}}$$

In the formula: W_{agr} denotes the volume of water resources required for agricultural production. W_{ind} denotes the volume required for industrial production. W_{res} denotes the volume required for residential domestic use.

Water resources gap (W_{gap}): the indicator quantifies the supply demand imbalance of water resources across regions, enabling further analysis of water scarcity and associated management challenges. The calculation formula is:

$$W_{\text{gap}} = W_{\text{need}} - W_{\text{supply}}$$

In the formula: W_{need} represents total water demand. W_{provide} represents available water supply, and their difference reflects the magnitude of the water deficit.

(2) The institutional water resource gap accounting model, based on the System of Environmental-Economic Accounting (SEEA) framework (*Hein et al., 2020; Edens et al., 2022*), introduces the institutional water scarcity index (In) to quantify the degree of deviation in administrative allocation from water resource distribution equity and its deprivation effect on regional development. The model proceeds in two dimensions. First, it constructs a theoretically equitable water volume as a reference benchmark to measure the deviation of each city's actual water allocation from the equitable expectation based on area, population, and industrial demand. Second, it introduces a development deprivation coefficient, using Beijing's per capital GDP as a reference, to reveal the structural mismatch between water rights allocation and development rights. The calculation formula is presented as follows:

$$I_k = \left(\frac{W_{\text{need}}^k}{W_{\text{equit}}^k} - 1 \right) \times \frac{1/\text{GDP}_{\text{pc}}^k}{1/\text{GDP}_{\text{pc}}^{\text{BJ}}}$$

$$W_{\text{equit}}^k = W_{\text{total}} \times \left[a \times \frac{S^k}{S_{\text{region}}} + b \times \frac{P^k}{P_{\text{region}}} + c \times \frac{Q_{\text{sector}}^k}{Q_{\text{sector}}^{\text{region}}} \right]$$

In the model, W_{need}^k represents the actual water consumption of city k, W_{equit}^k is the theoretically equitable water volume, and W_{total} denotes the baseline total water resources. The term $\frac{1/\text{GDP}_{\text{pc}}^k}{1/\text{GDP}_{\text{pc}}^{\text{BJ}}}$ defines the development deprivation coefficient, where GDP_{pc}^k represents the per capita GDP of city k, and $\text{GDP}_{\text{pc}}^{\text{BJ}}$ is the per capita GDP of Beijing, reflecting the degree of relative economic deprivation. S^k is the effective area of city k within its basin, P^k is the population of city k in the basin, Q_{sector}^k is the sectoral (productive) water demand of city k in the basin. If $I_k > 0$, it indicates that the administrative allocation favors the city, suggesting that Beijing benefits from institutional advantage. Conversely, $I_k < 0$ signifies that the city experiences institutional deprivation, meaning that it receives less water allocation than the equitable principle would suggest.

2.3.2 Water resource economic vitality coupling analysis model

To identify the critical pathways through which institutional water stress propagates into the attenuation of economic vitality, this study constructs a coupled water resources–economic vitality analytical model, with particular emphasis on examining how institutionally induced water scarcity suppresses regional economic

development by escalating water use costs and constraining industrial options. In model construction, and in order to quantify the stringency of industrial policy constraints, this study assigns a policy intensity score ranging from 1 to 5 based on the industrial prohibition and restriction measures specified for each city within the region according to the Major Function Oriented Zoning Plan. The scoring criterion is determined by the proportion of the total industrial output value accounted for by sectors listed in the prohibition and restriction catalogue (**Table 2**). This scoring approach follows the general logic of policy quantification, wherein the economic scale of constrained industries serves as a proxy for policy restrictiveness: a higher proportion indicates a broader scope of curtailed industrial activity and correspondingly greater policy stringency, thereby exerting a more profound influence on local economic structure and patterns of water resource utilization. The scoring process further incorporates the distinct functional positioning of individual cities within the CCEC and the contextual background of policy implementation, ensuring that the stringency indicator retains both cross regional comparability and policy representativeness. The calculation formula is as follows:

$$\ln(\text{NTLI}_{it}) = \alpha + \beta_1 I_n + \beta_2 \ln(W_{\text{cost}}) + \beta_3 \text{Policy}_{it} + \gamma X_{it} + \epsilon_{it}$$

In this formula, NTLI_{it} represents the nighttime light index of city i , W_{cost} represents the comprehensive water cost (yuan/m³), Policy_i represents the intensity of industrial ban and restriction policies (1-5 points; **Table 2**), X_i represents control variables, and ϵ_i represents the disturbance term (error term).

Table 2 Assignment rules

Percentage of industrial output value covered by the Prohibited and Restricted Catalog	Policy Score
<20%	1
20%-40%	3
>40%	5

Using panel data for cities within the CCEC from 2010 to 2023 (**Table 3**), we employed a fixed-effects model in STATA 17.0 to estimate the coefficients and assess their statistical significance.

Table 3 Theoretical basis for variable selection

Variable category	Variable name	Theoretical basis	References
Dependent variable	Nighttime Light Index (NTLI)	The decline in lighting conditions characterizes the decline in economic vitality and the spatial differentiation of multi-dimensional poverty, reflecting the "development shadow" under institutional deprivation.	(McCallum et al., 2022)
Core explanatory	Institutional water shortage intensity	Administrative power distorts development opportunities through water resource allocation, and	(Amankwaa et al., 2025)

variable	$(\ln_k)$	quantifies the spatial injustice of "water rights deprivation"	
Mediating variable	Water cost $\ln(W_{\text{cost}})$	The scarcity of resources is magnified by the system and transformed into economic costs.	(Farzanegan et al., 2017)
Covariate variable	Industrial policy (Policy _i)	Policy barriers enhance the industrial lock-in effect of water resources, leading to "low-end path dependence"	(Zhang et al., 2018)
	Proportion of the secondary and tertiary industries	The core indicator of the regional development stage is that regions with a high proportion have stronger resilience to risks.	(Ballabriga & Villegas, 2017)
	Road density	The accessibility of infrastructure determines the efficiency of factor flows, and affects the cost of water resource allocation and the adaptability of industries.	(Scott et al., 2021)
Control variables	Fiscal self-sufficiency rate	The fiscal autonomy of local governments determines their investment in water conservation and their capacity for compensation, and affects the effectiveness of institutional responses.	(Bai et al., 2025)
	建成区占比	城镇化率表征人口集聚与经济密度, 排除城镇化对灯光的直接影响	(Wu et al., 2025)

3 Results

3.1 Institutional bias and spatial polarization of water scarcity gaps

Based on a model analysis of urban water supply and demand across the CCEC region from 2011 to 2023, it was found that water resource allocation, profoundly shaped by institutional forces, exhibits a characteristic spatial polarization pattern (Figure 3). This polarization manifests not only in the substantial gap disparity between core cities and peripheral areas but also, more fundamentally, reflects the unevenness of regional development rights as embedded within institutional arrangements.

First, policies and infrastructure prioritization have secured the water requirements of core cities. The water use patterns of Beijing and Tianjin represent the most direct manifestation of institutional favor. Despite the CCEC region facing significant local water deficits, the policy precedence conferred by their status as political and economic centers has enabled both cities to establish intensive external replenishment systems centered on interbasin water transfer projects. In 2023, up to 91.45 percent of Beijing's water supply relied on external transfers, predominantly the South to North Water Diversion Project. This outcome is determined not by market forces or natural conditions but by national level strategic resource reallocation. Similarly, Tianjin's water supply increased from 0.745 billion cubic meters in 2011 to 1.066 billion cubic meters in 2023, a change closely tied to the national strategic positioning of the Binhai New Area and guiding industrial policy. This resource allocation model, characterized by high demand, high deficit, and high security of supply, reflects a cumulative cycle of institutional advantage. Policy inclination ensures water inflow, and this ample water supply, in turn, further consolidates

economic agglomeration and population carrying capacity, thereby reinforcing the cities' core status within the region.

Peripheral areas exhibit differentiated water scarcity conditions constrained by their assigned functional roles. In stark contrast to the core cities, the water resource situation in Hebei province is deeply constrained by its prescribed regional functional positioning, exhibiting a structured water scarcity that constitutes an institutional outcome derived from the division of regional labor rather than a consequence of inherent resource endowments. First, for cities designated as ecological barriers, such as Zhangjiakou and Chengde, the functional positioning of ecological conservation areas directly restricts developmental space for productive water use through institutional instruments like ecological protection redlines and conservation zoning. This has resulted in water quotas for these cities being limited to below 70 percent of the regional average. The further decline in water supply observed between 2017 and 2020 due to groundwater governance policies illustrates how these areas bear localized development costs for the sake of overall regional ecological security. Second, industry dominated cities, such as Tangshan and Shijiazhuang, while allocated certain water quotas, rely heavily on local groundwater for development, leading to pronounced overexploitation. This reflects their predicament of pursuing growth under finite local resource constraints, subject to the combined pressures of resource depletion and industrial transition. Third, major agricultural production zones, such as Cangzhou and Hengshui, exhibit water use patterns where transferred water accounts for less than 35 percent and reliance on groundwater persists. The apparent deficits or localized surpluses in these areas, to some extent, occur at the expense of industrial water rights, reflecting the prioritization of their grain production base function in water resource distribution and resulting in a lock in effect on industrial structure.

Policy interventions serve as the pivotal lever reinforcing the aforementioned spatial polarization pattern. The commencement of the central route of the South to North Water Diversion Project in 2014, a major infrastructure investment, provided immediate anticipation and security for the scale expansion and growth of core cities. The sharp increase in Tianjin's water deficit after 2017 coincided with the deployment of heavy and chemical industries in the Binhai New Area, indicating the direct pull of policy driven industrial planning on water resource demand. Concurrently, the comprehensive groundwater overexploitation control policies implemented in Hebei province, while mitigating the ecological crisis of urban subsidence, have inadvertently led agricultural cities like Hengshui to achieve surplus conditions through consumption curtailment. Moreover, these policies have further solidified the

low quota development trajectory of ecological barrier cities such as Zhangjiakou and Chengde, thereby unintentionally exacerbating inequities in water resource allocation among different functional zones within the CCEC region.

In summary, core cities have internalized external resources through institutional advantages, achieving an anomalous state of scarcity without supply shortage. In contrast, peripheral cities remain locked into their respective structural constraints due to functional designation, bearing tangible pressures of water stress.

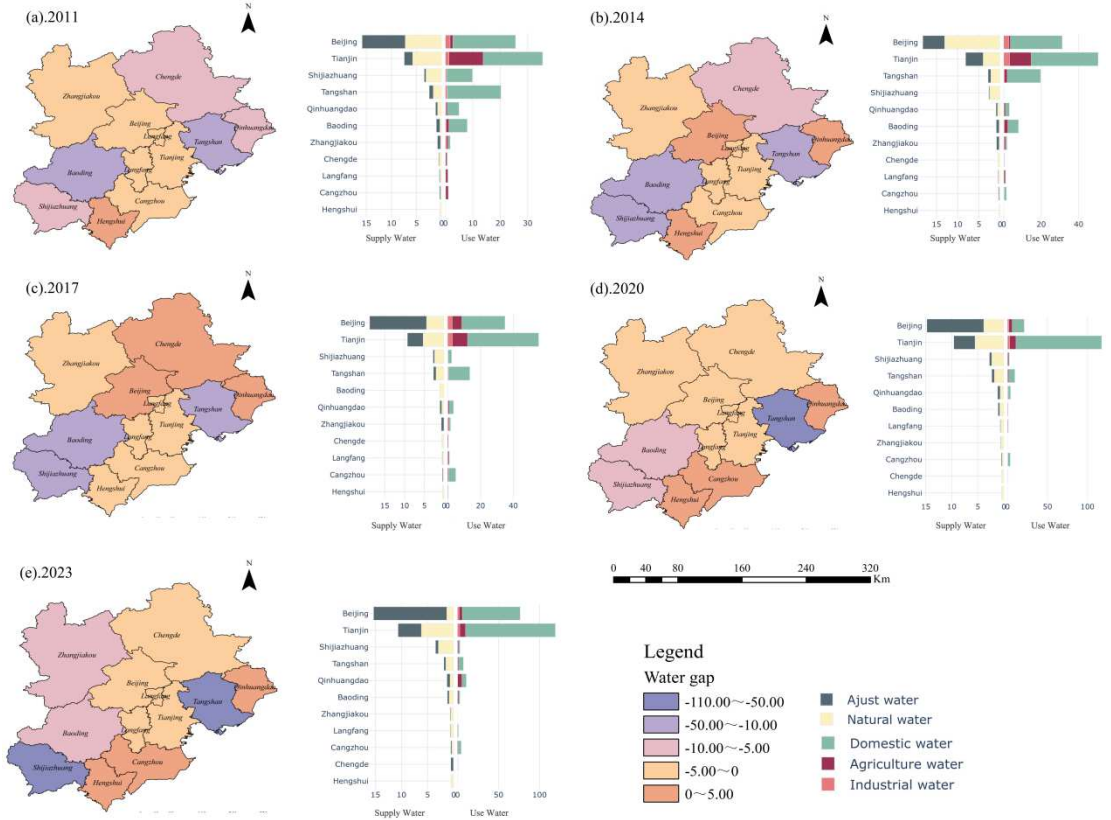


Figure.3 Supply and demand of water resources in the CCEC (2011-2023)

3.2 Institutional water stress spatial differentiation patterns and cumulative effects

Based on assessments derived from the institutional water stress accounting model, water resource pressures across the CCEC region from 2011 to 2023 were found to be far from uniform, instead exhibiting a pronounced and progressively intensifying spatial hierarchy driven by institutional factors. This pattern manifested not only as static disparities between core urban centers and peripheral areas but more significantly as a dynamic cumulative process wherein pressure gradients self reinforced over time. Consequently, a persistent urban shadow effect emerged, characterized by centralized benefits accruing to core zones while peripheral regions disproportionately bore escalating water stress burdens (Figure 4).

3.2.1 Path dependence of core gains and periphery pressures

The spatiotemporal evolution of the institutional water stress index reflects a path dependent concentration of water resource allocation toward central cities. Beijing and Tianjin, as regional cores, leverage their administrative hierarchical advantages to transform policymaking authority into stable water access capacity. Beijing's stress index shifted from negative to positive values following the initiation of the South to North Water Diversion Project in 2014, surging from minus 0.87 in 2011 to 9.89 in 2014 and further climbing to 13.72 by 2023. This trajectory is a direct consequence of substantial institutional investment through the national water transfer project, signifying a developmental transition from resource scarcity to institutionally secured supply. Tianjin presents an even more pronounced case, with its index remaining firmly within positive territory since 2011 at 0.15 and escalating to 23.84 in 2023, thereby illustrating the cumulative effect of entrenched initial institutional advantages. Through the prioritization mechanisms embedded within administrative hierarchies, these two municipalities internalize external water resources as safeguards for their development, engendering an anomalous state wherein severely water scarce regions achieve positive stress indices via long distance water transfers.

In stark contrast, the majority of cities in Hebei Province remain locked within the negative value domain of the institutional water stress index, enduring constraints on water resource distribution. Index values for locations such as Zhangjiakou and Chengde have persistently remained below minus 2, with Zhangjiakou descending to an extreme low of minus 4.17 in 2023. Although the regional mean index turned positive in 2023, reaching 2.96 driven by the influence of Beijing and Tianjin, twenty three of the twenty seven evaluation units in Hebei continued to reside in the negative range. Consequently, the apparent improvement in the overall CCEC regional index constitutes a statistical artifact, propelled by extreme gains in core cities while simultaneously obscuring the structural entrenchment of water stress in peripheral areas. This demonstrates that institutional water stress has evolved into a solidified pattern of water resource allocation, reinforcing a strong path dependence and disequilibrating amplification effect within the core periphery structure.

3.2.2 Urban functional positioning and institutional responsibility bundling

The spatial differentiation of institutional water stress reflects the divergent functional roles assigned to cities within the regional division of labor and the corresponding institutional responsibilities embedded in those designations. This stress is deeply coupled with urban functional identity, manifesting as typified constraining mechanisms across three primary dimensions.

First, ecological barrier cities experience a pronounced imbalance between

conservation obligations and compensatory returns. Cities such as Zhangjiakou and Chengde are tasked with the core function of providing ecosystem services to the CCEC, resulting in two extreme conditions: an elevated proportion of ecological water use exceeding 30 percent alongside compressed industrial and domestic water quotas falling below 70 percent of the regional average. Yet the existing vertical ecological compensation framework, despite annual transfers exceeding 1.5 billion yuan, has failed to adequately offset the costs incurred by curtailed developmental rights. Consequently, these cities are trapped in a developmental dilemma wherein intensified conservation efforts paradoxically magnify their burdens, a predicament that fundamentally represents an institutional cost exacted for safeguarding regional ecological security.

Second, industrial and agricultural cities face structural substitution pressures arising from institutional arrangements governing intersectoral water allocation. In industrial centers such as Tangshan and Shijiazhuang and primary agricultural production areas like Hengshui, stress profiles reflect contested trade offs between competing water uses. In Tangshan, water supply volumes contracted by nearly 30 percent under industrial water saving mandates, yet the stress index remained negative, indicating that industrial restructuring is simultaneously constrained by both resource scarcity and environmental regulation. Conversely, localized improvements in water use metrics observed in Hengshui and comparable agricultural zones have been achieved at the expense of reduced industrial water allocations. This pattern essentially embodies an institutional substitution mechanism wherein the imperative to secure agricultural production functions overrides industrial development rights, thereby reinforcing long term structural lock in of the regional industrial portfolio.

Third, peripheral node cities are subjected to shadow effect pressures. Municipalities such as Langfang and Cangzhou, situated in the immediate vicinity of core urban centers, encounter developmental constraints imposed by the pronounced resource absorption capacity of dominant metropolitan hubs, a phenomenon characterized as the circum Beijing shadow effect (*Tang et al., 2025*). Occupying a subordinate position within institutional allocation frameworks, these cities receive only a limited degree of water supply security while being exposed to elevated systemic risks without commensurate compensatory measures. As a result, their water stress indices have remained persistently negative.

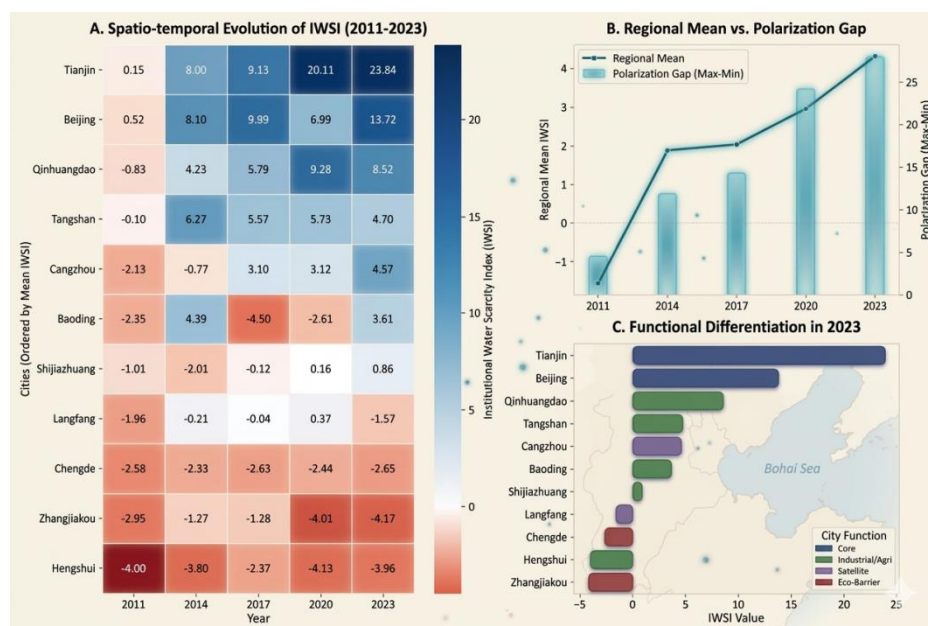


Figure.4 The institutional water resources gap in the CCEC (2011-2023). A: Distribution p
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3.3 Institutional water stress inhibitory effect on regional economic development

The impact of institutional water stress on regional economies fundamentally reflects a spatially uneven allocation of development rights. By elevating factor costs and constraining industrial options, this mechanism systematically compresses the developmental space of peripheral regions, thereby exerting a pronounced suppressive effect on economic vitality. To elucidate this process, the present study integrates correlation analysis with fixed effects modeling to empirically examine the dual pathways through which institutional water stress operates: cost transmission and structural constraint. These pathways ultimately crystallize into a mechanism that perpetuates regional economic disparities.

Within the CCEC region, the influence of institutional water stress on the economic landscape similarly stems from an asymmetric spatial distribution of development rights. Although this pattern arises as a negative externality of water resource reallocation policies, it consistently raises factor costs and restricts industrial choices, compressing the developmental scope of peripheral areas and generating a significant institutional dampening of economic dynamism. To further dissect this process, this study employs both correlation analysis and fixed effects models to empirically verify the dual channels of cost transmission and structural constraint, demonstrating how institutional water stress consolidates into a persistent mechanism widening regional economic divergence.

3.3.1 Water resources economy nexus characteristics and spatial heterogeneity

We first examined linear associations among core variables using Pearson correlation coefficients, revealing significant relationships between institutional water stress intensity, water use cost, industrial policy, and the NTLI (**Figure 5**). Notably, institutional water stress exhibited a significant negative correlation with the NTLI, a widely adopted proxy for economic vitality ($r = 0.686$, $p < 0.01$), indicating that institutional disadvantages in water access are directly linked to subdued economic activity. Concurrently, institutional water stress was significantly positively correlated with comprehensive water use cost ($r = 0.532$, $p < 0.05$), whereas water use cost displayed an even stronger negative correlation with the NTLI ($r = 0.761$, $p < 0.01$). This pattern of associations suggests that water use cost likely functions as a key mediating variable through which institutional water stress transmits into the economic domain.

Spatial heterogeneity analysis further substantiated this inference. In institutionally advantaged cities such as Beijing and Tianjin, the correlation between water stress indices and water use cost was nonsignificant ($p > 0.1$), demonstrating the buffering effect of institutional advantage against cost pressures. Conversely, in most cities of Hebei Province, the two variables were significantly positively correlated ($r > 0.5$), confirming that peripheral cities internalize institutional water stress as explicit cost burdens. This spatial heterogeneity clearly reflects an unequal pattern whereby core cities and peripheral regions bear disparate levels of water use cost burden.

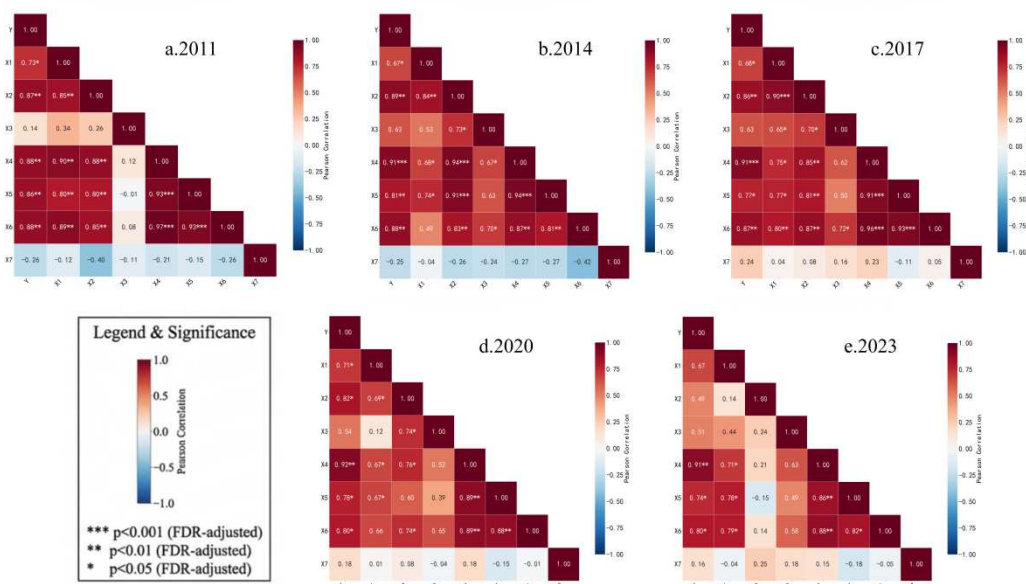


Figure.5 Correlation between variables. a:2011. b:2014. c:2017. d:2020. e:2023

3.3.2 Fixed effects of the cost mediated transmission mechanism and the moderating effect of industrial structure

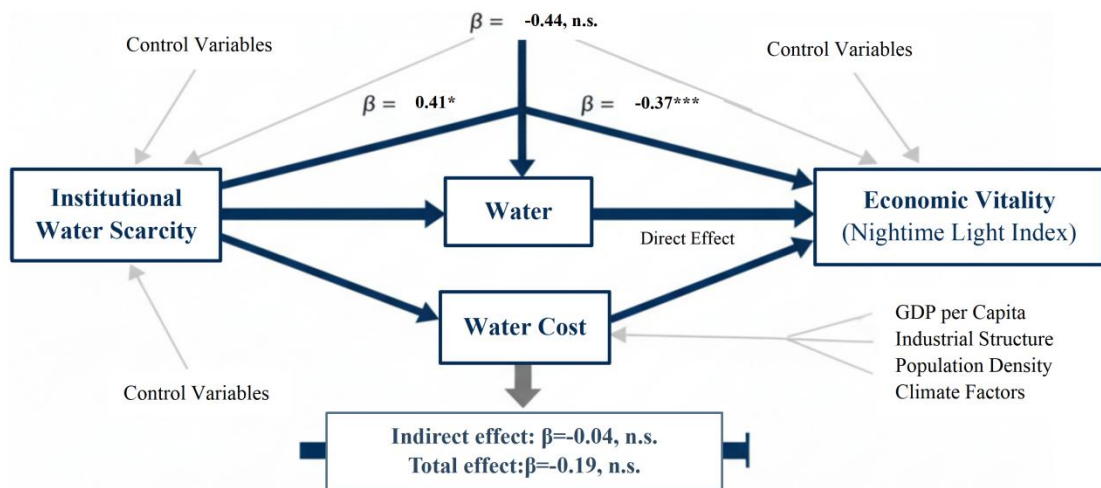
To precisely delineate the mechanistic pathway, this study employed a panel fixed effects model to conduct mediation analysis (**Table 4**). The results reveal a clear transmission chain: the direct effect of institutional water stress on the NTLI is not statistically significant ($\beta = -0.044$, $p = 0.791$), whereas the cost of water use functions as a significant positive mediator ($\beta = 0.406$, $p = 0.036$). Once water use cost is incorporated into the model, it exerts a pronounced inhibitory effect on economic vitality ($\beta = -0.371$, $p < 0.001$), while the direct effect of institutional water stress remains nonsignificant ($\beta = -0.041$, $p = 0.737$). A Sobel test further confirms the full mediation effect of water use cost ($Z = 2.13$, $p < 0.05$). These findings indicate that institutional water stress does not directly suppress economic activity; rather, it indirectly undermines regional economic vitality through a critical channel: elevating water use costs borne by enterprises and society.

Table 4 Direct economic effects of institutional water scarcity

value	β	Standard error	z	p	Significance
X1	-0.044	0.167	-0.265	0.791	n.s.
X2	-0.344	0.142	-2.432	0.015	*
X3	-0.03	0.097	-0.305	0.76	n.s.
X4	0.636	0.139	4.585	<0.001	**
X5	0.331	0.365	0.906	0.365	n.s.
X6	-0.27	0.315	-0.857	0.392	n.s.
X7	-0.259	0.276	-0.936	0.349	n.s.

Note: Significance marks: "****": $p < 0.001$, "***": $p < 0.01$, "**": $p < 0.05$, ".": $p < 0.1$, "n.s.": not significant.

Industrial structure serves as a key moderating factor in this transmission process (**Figure 6**). The proportion of secondary industry exhibits a significant positive association with the NTLI ($\beta = 0.636$, $p < 0.001$), yet its interaction with water cost is significantly negative ($\beta = -0.082$, $p < 0.05$), indicating that in cities with a higher manufacturing share, economic vitality is more sensitive to variations in water cost, and the impact of rising water expenses is more pronounced. In contrast, cities dominated by the tertiary sector demonstrate a degree of cost resilience. Validation across city typologies reveals that ecologically constrained cities (water cost elasticity of -0.48%) and industrial transition cities (industrial electricity consumption elasticity of -0.52%) are particularly vulnerable. These findings substantiate the economically suppressive effect of water stress operating through cost mechanisms, with its magnitude moderated by regional industrial structure.



Note: Significance marks: "****": $p < 0.001$, "***": $p < 0.01$, "**": $p < 0.05$, ".": $p < 0.1$, "n.s.": not significant.

Figure.6 The framework of mediating effect: schematic diagram of the path from institutional water shortage to the decline in economic vitality due to the increase in water prices

3.3.3 Cumulative effects of institutional water stress cycles and development space compression

The foregoing analyses substantiate that institutional water stress first translates into escalating real economy costs and exerts heterogeneous inhibitory effects contingent upon industrial structure. For peripheral cities, persistent institutional water stress entails elevated water expenditures, more constrained industrial options, where water intensive sectors face proscription or restriction, and heightened fiscal strain on local governments compelled to invest in conservation measures or alternative supply sources. These factors collectively dampen economic vitality, compress developmental space, and precipitate progressive marginalization in regional competition. Such economic subordination further erodes bargaining power in transboundary water allocation negotiations, rendering these cities less capable of securing favorable institutional water supply arrangements and thereby perpetuating a locked condition of high water stress and low development trajectory. Conversely, core cities enter a virtuous cycle of low water stress, robust development, and augmented resource acquisition capacity. Ultimately, the initial institutional tilt in water resource allocation policy, operating through cost transmission and structural constraint mechanisms, unfolds as a Matthew effect type cumulative dynamic in urban development. This process not only ossifies the spatial configuration of water resource distribution but more profoundly entrenches regional economic disparities. Institutional water stress thus ceases to be an exogenous constraint on the economic system and instead emerges as an endogenous force embedded within specific institutional logics that actively participates in shaping the geography of economic development.

4 Discussion

4.1 Institutional water scarcity induced cost and industry double helix trap and its chain reaction mechanism

This study reveals that the suppression of regional economic vitality by institutional water stress is not a single linear process but rather a chain reaction formed through the coupling of consecutive mechanisms involving cost transmission, structural constraint, and spatial fixation (Figure 7). In contrast to existing research that predominantly focuses on the physical scarcity of water resources (Mekonnen & Hoekstra, 2016) or improvements in water use efficiency (Grafton et al., 2018), this paper emphasizes how the disequilibrium of institutional allocation transforms natural water shortages into a persistent and structurally embedded economic depressant. Our empirical findings indicate that institutional water stress does not exert a direct impact on economic vitality; instead, it operates through the complete mediating variable of elevated comprehensive water costs (Sobel test significant), and the intensity of this transmission is moderated by industrial structure, with cities exhibiting a higher proportion of secondary industry demonstrating greater cost sensitivity.

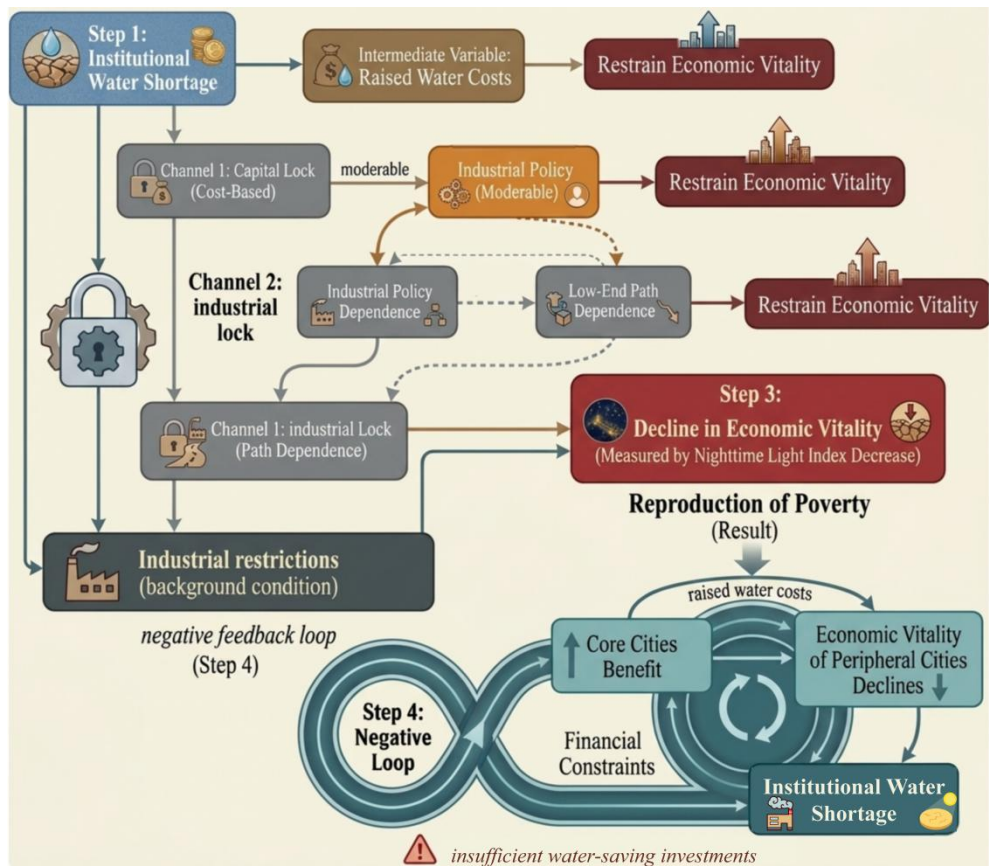


Figure 7 Chain transmission mechanism coupling institutional water scarcity and economic performance

Building upon this foundation, institutional water stress manifests pronounced

heterogeneous transmission mechanisms across cities with distinct functional classifications, collectively constituting a cost industry double helix trap. Within the core periphery structure of the capital metropolitan region, core cities (Beijing and Tianjin) leverage policy instruments such as the South to North Water Transfer Project to construct a high deficit high security model, thereby externalizing institutional pressures (*Cai et al., 2023*). In contrast, peripheral cities have been drawn into a developmental vortex due to differentiated functional positioning. Specifically, cities designated as ecological barriers (e.g., Zhangjiakou and Chengde) face protective suppression characterized by compressed production water quotas and inadequate compensation under the primacy of ecological conservation (*Namara et al., 2010*). Satellite cities (e.g., Langfang and Cangzhou) endure the superimposed pressures of siphoning effects from core cities and inferior institutional allocation, resulting in a development pattern marked by high exposure and low compensation (*Derdouri et al., 2024*). Industrial cities (e.g., Tangshan and Shijiazhuang) confront the dual impacts of industrial hollowing and escalating costs under the constraints of capacity reduction and stringent water use limitations (*Wen et al., 2023*). These divergent pathways underscore that the economic suppression induced by water stress is fundamentally a product of the interplay between regional functional division and institutional configuration.

Further analysis demonstrates that institutional water stress persistently suppresses economic vitality in peripheral areas and amplifies developmental constraints through three chain processes: capitalization, industrial lock in, and spatial spillover (*Wada et al., 2016*). Institutional instruments such as water transfer prioritization, quota regulation, and ecological redlines initially convert water scarcity into explicit and implicit costs borne by enterprises (e.g., development of unconventional water resources, compliance expenditures, and facility amortization), thereby curtailing productive investment and leading to a decline in economic vitality as proxied by NTLI. Mediation tests confirm that the direct effect of institutional water scarcity becomes nonsignificant after controlling for water costs, substantiating that cost serves as the key mediating variable (*Apostolaki et al., 2019*). Concurrently, a significant interaction exists between industrial policy and water scarcity: cities dominated by secondary industry exhibit heightened sensitivity to cost escalation, whereas the tertiary sector, despite possessing a degree of buffering capacity, remains susceptible to low end path dependency and structural contraction.

The three mechanisms of mediation, moderation, and spillover are further coupled and amplified through spatial allocation channels. Core cities, by virtue of institutional advantages, continuously accrue resource dividends, while the actual

pressures are shifted to peripheral areas via transfer and quota mechanisms, culminating in a polarized pattern of center benefits and periphery burdens. Over the long term, the attenuation of economic vitality diminishes local fiscal capacity and curtails investment in water saving infrastructure, thereby exacerbating the degree of water scarcity and establishing a negative feedback loop encompassing water stress, economic suppression, and institutional marginalization. Spatially, this process manifests as a persistently accumulating urban shadow effect (*Sharma & Chandrasekhar, 2014*), giving rise to a systemic trap in which institutional water scarcity and economic decline are mutually reinforcing.

In conclusion, institutional water scarcity triggers a chain reaction characterized by spatial heterogeneity and path dependence across functionally diverse cities through a cost industry double helix mechanism. This process not only elucidates the institutionally constructed nature of the water economy constraint nexus but also underscores a critical policy imperative: addressing regional water predicaments necessitates a departure from institutional restructuring and synergistic governance mechanisms.

4.2 Institutional water stress and the institutional roots of development disparities in CCEC

Against the backdrop of widespread regional integration and balanced development pursued by major global urban agglomerations, the CCEC presents a stark pattern of core periphery differentiation, where siphoning effects and urban shadow effects coexist (*Chen et al., 2024*). This phenomenon stands in marked contrast to the coordinated governance pathways observed in global city regions such as London and Tokyo, where water resource management and economic development have been aligned through collaborative mechanisms (*Koop et al., 2022; Zhang & Lu, 2024*). The root cause of this divergence does not lie in constraints imposed by natural endowments but rather in a regional institutional design that fails to effectively reconcile the tensions between development rights and conservation obligations. In particular, the implementation of China's Major Function Oriented Zoning (MFOZ) system lacks sufficient support from ecological compensation mechanisms, thereby transforming institutional water stress into a critical conduit for widening regional disparities.

First, while the MFOZ system delineates clear regional functional orientations, it has objectively entrenched a hierarchical pattern of water resource allocation. Under the CCEC planning framework, Beijing and Tianjin are designated as core growth poles for optimized development, whereas vast areas of Hebei are categorized as key ecological function zones, primary agricultural production zones, and other restricted

development areas (*Yang et al., 2025*). Although this functional specialization holds strategic merit in principle, its implementation has evolved into a bundled allocation of development entitlements and resource access. Core cities, by virtue of their political and economic prominence, enjoy preferential treatment in institutional arrangements such as water transfer projects and water use quotas, resulting in a supply model characterized by high demand and high security. Conversely, peripheral cities tasked with providing ecological safeguards (e.g., Zhangjiakou, Chengde) face stringent restrictions on their development rights through instruments such as ecological conservation redlines and negative lists for industrial entry. Water resources in these areas are mandatorily directed toward ecological uses, while quotas for productive and domestic water consumption are compressed. These institutional constraints on peripheral development rights have not been accompanied by adequate and effective ecological compensation mechanisms, meaning that the custodians of ecological assets do not equitably share in the benefits accruing to the developers.

Second, the absence and insufficiency of ecological compensation mechanisms have resulted in the unidirectional transfer of institutional water stress onto the economic systems of peripheral cities. The MFOZ system mandates the establishment of both vertical (central to local) and horizontal (beneficiary to provider) ecological compensation frameworks (*Deng et al., 2026*) to offset the developmental costs arising from functional differentiation. In practice, however, compensation standards tend to be undervalued, the modalities are often simplistic (predominantly fiscal transfer payments), and the compensation fails to adequately cover the opportunity costs of forgone development. For instance, to secure the water source safety of the Beijing Tianjin region, cities such as Zhangjiakou and Chengde have shuttered numerous industrial and mining enterprises, yet the ecological compensation received falls far short of what is required to cultivate alternative industries and achieve economic transformation and upgrading (*Zhang & Lu, 2024*). This dynamic traps peripheral cities in a vicious cycle whereby they contribute ecological resources, endure developmental restrictions, receive insufficient compensation, and suffer declining economic vitality. Institutional water stress manifests not only as direct increases in the cost of water use but also as institutional constriction of developmental space. This constriction erodes the fiscal foundation and innovation capacity of peripheral cities, making it difficult for them to break free from path dependence on traditional water intensive industries or placing them at a competitive disadvantage in industrial upgrading, thereby perpetuating and intensifying the developmental gap with core cities.

From a global perspective, successful governance of urban agglomerations

invariably achieves an institutional equilibrium between functional division and benefit sharing. For example, the New York metropolitan area has established market based water rights trading and compensation mechanisms through cross jurisdictional bodies such as the Delaware River Basin Commission, while cities along the Rhine River watershed have achieved collaborative water management and shared developmental returns via transnational agreements. In contrast, the current institutional framework of the Capital Economic Circle excessively reinforces the division of functions while neglecting the integration of interests. As a result, the MFOZ system, which is intended to promote coordinated regional development, has been distorted in practice by imperfections in water resource allocation and ecological compensation mechanisms, inadvertently exacerbating regional imbalances. The prosperity of core cities rests, in part, on the low cost or uncompensated appropriation of the ecological services and resource development rights of peripheral cities. This amplifies siphoning effects and renders urban shadow effects increasingly pronounced.

In summary, the considerable developmental disparities observed within the Capital Economic Circle are, upon closer examination, an inevitable consequence of institutional water stress operating within an imbalanced regional governance structure. Addressing this predicament necessitates moving beyond purely technological water conservation approaches and undertaking profound regional institutional innovation. The crux of the solution lies in reconstructing the regional interest coordination mechanism and establishing a comprehensive, market oriented, and legally grounded ecological compensation system that is commensurate with the positioning defined by the MFOZ framework. This entails: (1) formulating differentiated compensation standards based on precise accounting of the ecological service value of water resources; (2) exploring diversified compensation pathways, including water rights trading and green liability funds, to enable peripheral regions to genuinely benefit from their ecological contributions; and (3) promoting the establishment of an authoritative cross jurisdictional coordinating body to ensure the effective implementation of compensation policies. Only by transforming lucid waters and lush mountains into tangible golden mountains for peripheral regions through institutional design can the vicious cycle of institutional water stress aggravating developmental disparities be broken, thereby steering the CCEC toward genuine integration and sustainable development.

4.3 Proposal and connotation of the institutional water deficit framework

The core contribution of this study lies in revealing how institutions serve as a critical variable that amplifies the economic consequences of water scarcity. This

analysis focuses on the dynamic process through which institutional water scarcity suppresses economic vitality via policy mechanisms and, building upon this foundation, innovatively proposes the conceptual framework of IWD . This framework aims to transcend the static analytical paradigm centered on scarcity and suppression (*Al-Zu'bi et al., 2025*). From a systemic feedback perspective, it constructs a dynamic model comprising five interconnected stages to elucidate the deep mechanisms and modern governance dilemmas through which institutional water stress, via self reinforcing feedback loops, ultimately precipitates regional developmental imbalances (*Edwards et al., 2024*).

The essence of the IWD framework resides in a rigid closed loop system characterized by positive feedback properties, whose operation involves five mutually reinforcing stages.

Stage one: Formation of institutional rigidity and policy distortion. This constitutes the genesis of the IWD cycle. Within hierarchical administrative systems, the initial allocation of water rights frequently relies on non market factors such as historical precedent and administrative rank, engendering structural imbalances. Policy instruments, exemplified by water transfer prioritization, fundamentally represent an alienation of the commodity attributes of water by administrative power, transforming public resources into tiered control mechanisms and generating institutional rent differentials. The sunk costs associated with major water infrastructure projects further entrench this skewed allocation pattern, rendering the resource distribution model rigid and resistant to flexible adjustment.

Stage two: Cost externalization and spiraling escalation. Institutional rigidity directly precipitates the distortion and transfer of costs. Peripheral regions situated at a distributive disadvantage are compelled to bear elevated compliance costs, including the development of unconventional water sources and ecological restoration, to compensate for deficits. These genuine costs are not fully internalized within water pricing structures; instead, they are externalized across ecological interdependencies and fiscal transfers, accumulating nonlinearly across temporal and spatial dimensions into a cost spiral, exemplified by the intergenerational transfer of ecological liabilities from water diversion projects.

Stage three: Structural lock in and dual regulatory failure. The interplay between distorted cost signals and direct industrial prohibition policies collectively shapes and locks in regional industrial structures. Water intensive industries face suppression, while emerging water saving sectors struggle to cultivate due to inadequate supporting infrastructure, resulting in industrial structural adjustment lagging significantly behind water resource carrying capacity. This institutional stickiness

exacerbates the contradiction between phasing out obsolete capacity and local fiscal dependencies, leading to the concurrent failure of both market mechanisms and policy interventions.

Stage four: Systemic market obstruction and efficiency degradation. The sustained interaction of the preceding stages precipitates a precipitous decline in the overall efficiency of water resource allocation. Excessive administrative intervention continuously constricts the operational space for water pricing mechanisms and water rights trading, impeding the flow of factors toward higher efficiency applications. Localized factor misallocation thereby escalates into a region wide, systemic obstruction, with the deepening of market failure obliterating any scope for Pareto improvement in resource distribution.

Stage five: Self reinforcing descent into a low level development trap. The preceding four stages collectively constitute a positive feedback loop. Peripheral regions, experiencing diminished economic vitality, suffer a corresponding erosion of institutional bargaining power, further impeding equitable access to resource allocation and thereby entrapping them in a path dependent trajectory of high water stress, low economic dynamism, weak institutional voice, and subsequently heightened water stress. The overall system collapses toward a low level equilibrium, manifesting as diminishing marginal returns on water saving technologies and insufficient incentives for unconventional water resource development, thereby forging an inescapable evolutionary trap. This trap, in a self fulfilling manner, validates and reinforces the perceived necessity for intervention, compelling the administrative hierarchy to further consolidate the initial distortive policies. This culminates in a state of rigid deadlock characterized by the self replication of institutional deficiencies, exponential escalation of governance costs, and erosion of systemic resilience.

The policy implications of the IWD framework underscore that resolving the water economy nexus necessitates fundamental institutional restructuring rather than a mere pursuit of technical efficiency gains. The critical imperative lies in dismantling the rigid closed loop constituted by the five aforementioned stages. Specifically, this requires: first, the establishment of a comprehensive ecological compensation mechanism that aligns with major function zoning principles and integrates market based instruments with the rule of law, thereby internalizing the institutional costs associated with preserving ecological assets into tangible developmental dividends. Second, the substantive advancement of market based water rights trading to mitigate distortions arising from administrative allocation and restore the regulatory function of price signals. Third, the implementation of differentiated industrial water resource

coordination policies that furnish development pathways tailored to cities with distinct functional designations. Only through the self reinforcing redesign of institutional systems, transforming the negative feedback loops that suppress vitality into positive incentives that foster coordination, can a robust institutional foundation be established for the sustainable development of the capital economic region and analogous areas.

5 Conclusion

This study presents an empirical analysis of the CCEC, revealing that the economic ramifications of water scarcity are far from a passive outcome of natural endowment. Rather, they constitute a socially constructed process actively shaped and continuously reinforced by institutional arrangements. The conventional physical scarcity paradigm proves inadequate in explaining the pronounced divergence in economic vitality across the region. The true core mechanism lies in institutional water stress, which operates through a cost industry double helix trap to transmute initial inequities in water allocation into persistently widening gaps in economic development.

The central theoretical contribution of this study is the formulation of the IWD analytical framework. This framework demonstrates that the suppressive effect of water shortage on economic performance is not a static relationship of scarcity inhibition but a dynamic positive feedback process encompassing the formation of institutional rigidity, the externalization spiral of costs, structural lock in, systemic market failure, and a low level development trap. Within this framework, mega engineering projects such as the South to North Water Diversion, when implemented without equitable supporting institutions, fail to mitigate scarcity and instead reinforce existing core periphery power structures, thereby exacerbating path dependence in regional development and entrenching systemic institutional deadlock.

The empirical findings further substantiate this understanding from three dimensions. First, institutional favoritism coupled with incomplete ecological compensation mechanisms has magnified disparities. From 2010 to 2023, Beijing with an index reaching 13.72 and Tianjin leveraged policy prioritization to secure institutional gains characterized by high demand and high security, whereas most cities in Hebei province, exemplified by Zhangjiakou with an index as low as minus 4.17, remained in a state of chronic deprivation. This divergence stems not from differences in governance capacity but directly from the administrative hierarchy logic deeply embedded in initial water rights allocation. Second, cost transmission serves as the central mediating pathway. Institutional water scarcity does not directly suppress economic vitality; instead, it exerts its effect entirely through the mediating

variable of significantly elevated water costs (beta equals 0.406, p equals 0.036). This indicates that peripheral regions bear a form of transferred institutional cost, and their economic disadvantage is to a considerable extent a consequence of institutional pricing. Third, industrial structure functions as both a critical moderator and the ultimate bearer of stress. The study identifies distinct modes of predicament: protective suppression in ecological barrier cities, risks of industrial hollowing out in manufacturing based cities, and patterns of high exposure paired with low compensation in satellite cities. Collectively, these patterns reveal that water stress systematically constrains the economic adaptability and transformation space of peripheral areas by locking in existing industrial development trajectories.

Based on these findings, the core of policy formulation must pivot decisively from the conventional engineering mindset of augmenting supply and enhancing efficiency toward a systemic governance approach centered on institutional reconfiguration. Future reforms should prioritize the following measures: establishing cross regional ecological compensation mechanisms that are strictly aligned with Major Function Oriented Zoning and grounded in legal and market principles, thereby enabling ecological contributors to equitably share in developmental gains; substantively advancing the construction of water rights trading markets to dismantle the rigid distortions of administrative allocation and restore the guiding function of price signals in resource distribution; and implementing differentiated industrial water policy coordination schemes that design adaptive transformation pathways tailored to distinct functional zones, thereby avoiding the exacerbation of structural imbalances by uniform policies.

A limitation of this study lies in its reliance predominantly on macroeconomic data to gauge IWD. Future research could employ qualitative interviews and micro level survey data to further capture localized variability in policy implementation. Moreover, the application of spatial econometric techniques or quasi experimental methods would enhance the robustness of causal inference. In conclusion, addressing the nexus between water and economic development hinges on the recognition that the water crisis is fundamentally an institutional crisis. Its resolution resides in the construction of a novel water governance system capable of fostering justice, adaptation, and resilience.

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Declaration of Competing Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflict of interest:

No potential conflict of interest was reported by the authors.

This article does not contain any studies with human participants performed by any of the authors.

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