ANALYZING THE COUPLING COORDINATION BETWEEN DIGITAL ECONOMY DEVELOPMENT AND WATER RESOURCE UTILIZATION EFFICIENCY: EVIDENCE FROM THE YANGTZE RIVER ECONOMIC BELT

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Abstract. As digital technologies advance rapidly, their role in promoting resource efficiency has gained increasing attention. This study examines the coupling coordination between the Digital Economy Development Level (DEDL) and the Water Resource Utilization Efficiency (WUE) in China's Yangtze River Economic Belt (YREB) from 2013 to 2022. The research aims to evaluate whether the expansion of the digital economy contributes to improved water efficiency and balanced regional development. Using a coupling coordination degree (CCD) model with entropy-weighted indices, we assess spatial and temporal dynamics across 11 provinces, dividing the YREB into upstream, midstream, and downstream regions to capture regional heterogeneity. The results reveal a clear upward trend in CCD values, with downstream provinces such as Shanghai and Jiangsu achieving the highest coordination due to strong digital infrastructure and effective water management. In contrast, upstream regions face persistent challenges. Sensitivity analysis confirms the robustness of these regional differences. The findings suggest that digital development can enhance water resource efficiency, but region-specific strategies are essential. Policymakers should focus on infrastructure investment, digital technology adoption, and cross-regional collaboration to close the coordination gap. This study provides empirical evidence for integrating digital and environmental policy in support of sustainable development.

Keywords: *digital economy, water resource utilization, coupling coordination degree, regional disparities, sustainable development*

Introduction

The development and utilization of water resources has undergone continuous evolution since the inception of human civilization. Water serves as a critical factor of production, influencing economic activities across diverse sectors and regions worldwide. However, as urbanization and industrialization accelerate, the tension among socio-economic development, water resource availability, and environmental sustainability has become increasingly pronounced (Gleick, 2000; Distefano and Kelly, 2017).

In China, the challenge of managing water resources is particularly pressing, as the country faces both limited water supply and inefficiencies in water treatment and reuse. The rational development and efficient utilization of water resources are essential for

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ensuring long-term socio-economic stability. Consequently, water resource management has become a crucial global issue, requiring strategic policies and innovative solutions for sustainability (Hubacek et al., 2009).

In response to these challenges, the Chinese government has implemented a series of policies aimed at managing and conserving water resources. For example, the State Council's "red line" policy for water resources management, introduced in 2012, sets strict limits on water use, targeting a cap of 700 billion cubic meters by 2030 (State Council, 2012). Additionally, the "Fourteenth Five-Year Plan" for Water Security, released in January 2022, emphasizes controlling water usage, protecting aquatic ecosystems, and implementing region-specific water management strategies (National Development and Reform Commission, 2021). In 2023, the "Outline of the National Water Network Construction Plan" was introduced to improve national water resource distribution and sustainability (Ministry of Water Resources, 2023).

Simultaneously, the rapid advancement of digital technologies offers new opportunities to address challenges in water resource management. The digital economy, powered by innovations in information and communication technologies (ICT), is reshaping modern economies. The integration of digital technologies, such as big data, artificial intelligence, and cloud computing, into traditional sectors, including water resource management, presents significant potential for improving water efficiency and developing sustainable solutions (Bowman, 1996; Bukht and Heeks, 2017; Avom et al., 2020; Wang et al., 2022).

For water-scarce regions like the Yangtze River Economic Belt (YREB), digital tools can optimize water use, enhance distribution strategies, and support long-term sustainability efforts. Thus, the intersection of the digital economy and water resource utilization is vital for fostering regional resilience and promoting sustainable development.

The integration of digital technologies into water resource management has gained increasing attention in recent years. Several studies have explored the potential of digital tools for improving resource efficiency, particularly in sectors such as energy and agriculture, yet few have examined the coupling of digital economy development with water resource utilization efficiency (WUE) in a comprehensive manner.

For instance, Tomar and Grover (2024) explored how digital transformation enhances energy efficiency in industrial sectors, emphasizing the potential of technologies like artificial intelligence (AI) and big data in optimizing resource allocation (Tomar and Grover, 2024). Similarly, Aivazidou et al. (2021) investigated the role of ICT in sustainable water management in regions facing water scarcity, highlighting how digital technologies can enhance water use monitoring and optimize supply chains (Aivazidou et al., 2021).

In the context of China, Zhou and Qin (2024) studied the influence of digital economy tools on agricultural water efficiency, demonstrating how the integration of digital tools can improve irrigation practices and reduce water wastage (Zhou and Qin, 2024). Moreover, Yang and Cheng (2024) explored the coupling of economic growth and environmental sustainability in the Yangtze River Economic Belt, finding significant regional disparities but not focusing on the interaction between digital economy development and water resource efficiency (Yang and Cheng, 2024).

While these studies have made valuable contributions, none have specifically addressed the coupling coordination between digital economy development and water resource utilization efficiency in China's Yangtze River Economic Belt. Our study fills this gap by analyzing the spatial and temporal evolution of the coupling coordination degree (CCD) between these two systems, offering a fresh perspective on integrating digital transformation with sustainable water management.

As the digital economy continues to expand, fueled by advancements in information and communication technologies, its impact on various sectors, including water resource management, has become increasingly evident (Benzidia et al., 2021). However, while digital technologies such as big data, cloud computing, and artificial intelligence hold the potential to improve efficiency in resource management, the challenge of achieving sustainable water resource utilization remains particularly pressing in regions like the Yangtze River Economic Belt (YREB).

The YREB, spanning multiple provinces, is a crucial economic region in China but also faces significant water resource challenges, including regional disparities in water availability, water pollution, and inefficient utilization. Although water plays an essential role in economic development, the region struggles to balance economic expansion with sustainable resource management. This necessitates a deeper understanding of how digital economy growth interacts with water resource utilization efficiency and whether the two systems develop in a coordinated manner (Kong et al., 2021).

While existing research has separately explored digital economy development and water resource management, few studies have comprehensively analyzed the degree of coupling coordination between these two systems, particularly within the YREB (Liu et al., 2021; Aivazidou et al., 2021). Most prior studies have focused on either the role of digital transformation in economic growth or strategies for improving water use efficiency, leaving a research gap in understanding their interdependent relationship at a regional level.

This study addresses this gap by quantifying the coupling coordination degree (CCD) between digital economy development (DEDL) and water resource utilization efficiency (WUE) across the 11 provinces of the YREB from 2013 to 2022. By applying a coupling coordination model, this research evaluates the spatial and temporal evolution of CCD, identifying regional disparities in the interaction between digital economy expansion and water efficiency.

The findings of this study provide empirical insights into the degree of alignment between digital economic growth and water resource utilization. *Figure 1* presents a conceptual framework illustrating the coordinated development mechanism between DEDL and WUE, emphasizing their bidirectional relationship. The results contribute to the broader discussion on regional economic sustainability, offering a foundation for future policy considerations aimed at enhancing coordinated regional development.

Therefore, the primary objectives of this study are to:

- Analyze the coupling coordination between DEDL and WUE across the Yangtze River Economic Belt (YREB).
- Investigate the spatial and temporal evolution characteristics of the CCD between DEDL and WUE from 2013 to 2022.
- Identify regional disparities in coupling coordination across the upstream, midstream, and downstream areas within the YREB.
- Provide targeted policy recommendations tailored to each region to enhance sustainable economic and environmental development.

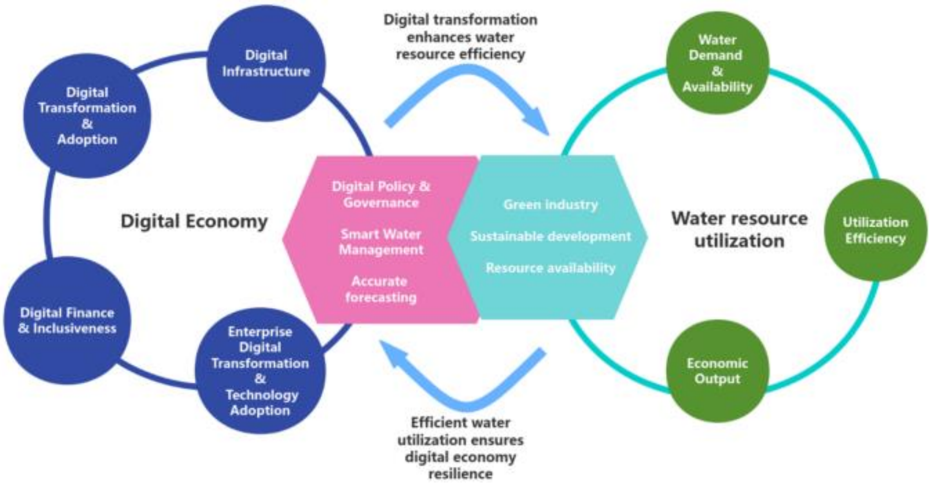

Figure 1. *Conceptual framework of the coordinated development between digital economy development level (DEDL) and water use efficiency (WUE)*

Materials and methods

Study area

The Yangtze River Economic Belt (YREB) spans 11 provinces, including Sichuan, Yunnan, Chongqing, Guizhou, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Zhejiang, and Shanghai, covering nearly one-fifth of China’s land area. As the longest river in China, it plays a vital role in economic development, water resource management, and ecological sustainability. The YREB is divided into three regions: Upstream, Midstream, and Downstream. The upstream region faces challenges in digital infrastructure and economic modernization despite abundant water resources, while the midstream region shows moderate growth in digitalization and water management. The downstream region, the most economically advanced, benefits from high digital transformation and efficient water resource management. This study uses this regional classification to analyze the coupling relationship between DEDL and WUE, providing insights for regional sustainable development strategies (*Fig. 2*).

Figure 2. *Geographical location of the Yangtze River Economic Belt (YREB). Source: Xia et al. (2023)*

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Data sources

All fundamental data for this study were obtained from authoritative national and regional statistical reports, covering the period 2013–2022. The primary sources include the China Statistical Yearbook (NBS, 2013–2022), the China Environmental Statistics Yearbook (NBS, 2013–2022), the China Water Resources Bulletin (NBS, 2013–2022), the China Fixed Asset Investment Statistical Yearbook (2013–2022), and the China Fixed Asset Investment Statistical Annual Report (2013–2022). Additionally, provincial statistical yearbooks from individual administrative regions were incorporated to ensure a comprehensive and region-specific dataset.

However, it is important to note that official datasets, such as those from provincial statistical yearbooks, may contain biases due to differences in data collection methodologies, inconsistencies in reporting standards, or incomplete data submissions from local governments. These biases could affect the reliability and comparability of the data across regions. In this study, missing values were handled using linear interpolation and regression estimation, though these techniques may introduce uncertainties, especially in cases of large data gaps. Further, the use of the Peking University Digital Inclusive Finance Index (Provincial, Municipal, and County Levels) provides additional insights into digital financial development, though similar biases could be present in the calculation of this index. The potential impact of such biases should be acknowledged, and efforts to improve data collection consistency at the provincial level could strengthen future research.

Digital economic development level variables

The indicators selected to measure DEDL capture four essential aspects: digital infrastructure, digital technology application and innovation, digital finance and inclusiveness, and enterprise digital transformation and technology adoption. These indicators were chosen for their relevance, representativeness, and ability to reflect different dimensions of digital economic growth.

- Digital Infrastructure: Includes Internet broadband access users (IBAU), mobile base station density (MBSD), and long-distance optical cable length per unit area (LOCL). These indicators measure basic connectivity, network coverage, and data transmission capabilities, essential for supporting digital economic activities and innovation.
- Digital Technology Application and Innovation: Includes the proportion of information technology service revenue in GDP (PITSR), proportion of enterprises engaged in e-commerce transactions (EETP), number of computers per 100 employees in enterprises (NC100EE), number of authorized patent applications (PA), and number of R&D projects in large-scale industrial enterprises (R&DP). These variables comprehensively represent both the economic contributions and innovation potential of digital technologies in various sectors (Zhang et al., 2021; Prieger and Heil, 2009; Sopoeva et al., 2020; Mohamed et al., 2022).
- Digital Finance and Inclusiveness: Consists of the digital inclusive finance index (DIFI) and the proportion of telecommunication business volume in GDP (PTBV), reflecting the accessibility, penetration, and economic significance of digital financial services and telecommunications (China Financial Research Center, Peking University, n.d.).

- Enterprise Digital Transformation and Technology Adoption: Uses the total transaction value of technology contracts (TTC), number of websites per 100 enterprises (NW100E), and proportion of e-commerce transactions in GDP (PET) to assess the extent and economic impact of digital technology adoption by businesses (Mohamed et al., 2022; Sopoeva et al., 2020).

Water resource utilization efficiency variables

Indicators of water resource utilization efficiency (WUE) are selected based on their ability to reflect resource availability, economic outputs, and environmental sustainability. Guided by established theories, including the Resource-Based View (RBV) and Production Function Theory, the following categories are defined clearly (Xiao et al., 2022; Bach et al., 2020):

- Resource Variables: Total water resources (TWR), total water supply (TWS), and water supply pipeline length (WSPL), representing the available freshwater resources and infrastructure capacities for water distribution.
- Output Variables: Water supply comprehensive production capacity (WSCPC) and gross domestic product (GDP), measuring the economic outputs directly associated with water resource availability and use.
- Efficiency Variables: Water economic efficiency (WEE), daily urban sewage treatment capacity (USTC), and chemical oxygen demand (COD) emission. These indicators highlight water productivity, environmental management capabilities, and pollution control effectiveness.

These carefully selected indicators collectively allow a holistic evaluation of water resource utilization, capturing both economic efficiency and environmental sustainability, and align with the objectives of enhancing resource management and sustainable development across the Yangtze River Economic Belt.

Model and indicator system construction

The coupling degree refers to the level of interaction and mutual influence between two systems. The coordination degree model is employed to assess the extent of this interaction (Xiao et al., 2022). The goal of evaluating the Coupling Coordination Degree (CCD) between DEDL and WUE is to assess whether water resources are being utilized efficiently, if they have become a constraint on economic development, and whether they are sufficiently sustainable to support long-term economic growth. This study utilizes two sets of indicators: EDL indicators and WUE indicators. The weights assigned to both sets and their individual indicators are determined using the Entropy Weight Method (EWM). The CCD model is then applied to compute the degree of coordination between the WUE system and the EDL system.

Entropy weight method (EWM)

The Entropy Weight Method (EWM) was adopted to objectively determine the weights of indicators in both the DEDL and WUE systems. This method assigns higher weights to indicators with greater variability and more information content, ensuring that more discriminative indicators play a greater role in the comprehensive evaluation. The procedure includes:

- Data standardization

- Calculation of indicator proportions
- Computation of entropy values
- Derivation of final weights

A detailed explanation of these steps is provided in the *Appendix*.

In this study, entropy weights were calculated based on aggregated panel data covering 11 provinces from 2013 to 2022, and this single set of weights was applied uniformly across all years. This approach enhances intertemporal comparability and allows for consistent evaluation of changes and disparities. However, we acknowledge that recalculating weights annually might reflect dynamic changes in indicator importance over time. To address this, a sensitivity analysis was conducted by recalculating weights for different regions. The results confirm that applying uniform weights did not significantly alter the overall coupling coordination trends, suggesting the robustness of our methodological choice.

Despite its advantages, EWM also has some limitations. One major issue is its sensitivity to outliers, where extreme values may distort entropy calculations and lead to biased weights (Zhu et al., 2020). Additionally, EWM assumes independence among indicators, which may not hold in practice, especially considering potential correlations between digital economy development and water resource utilization.

To overcome these limitations, future research could incorporate alternative weighting methods, such as the Analytical Hierarchy Process (AHP), which integrates expert judgment and can better capture indicator interdependence. A comparison of EWM and AHP-based results could further validate and improve the reliability of coupling coordination assessments. The indicators selected for the DEDL and WUE systems, which form the basis for entropy weight calculation, are listed in *Table 1*. This table presents the indicator name, definition, data source, direction of impact on the system (“+” for positive, “–” for negative), and the system to which each indicator belongs. All indicators are normalized to a range between 0 and 1 before weight assignment. These indicators were selected to comprehensively capture the multidimensional characteristics of digital economy development and water resource utilization efficiency in the YREB.

Coupling coordination degree model

The Coupling Coordination Degree (CCD) model is a vital analytical tool for assessing the interactions and balanced development between two interrelated complex systems. In this study, the CCD model was selected because it explicitly measures the coordination degree between subsystems rather than merely identifying correlation or causality. Compared with alternative methods such as regression analysis or system dynamics modeling, the CCD model provides clearer insights into how evenly and harmoniously digital economy development (DEDL) and water resource utilization efficiency (WUE) evolve together over time. Furthermore, this approach has been widely validated in studies examining resource-environment-economic interactions, demonstrating its effectiveness in capturing dynamic subsystem relationships (Zhang et al., 2022; Li et al., 2024). To address regional disparities and scale effects, the YREB was divided into three regions: upstream, midstream, and downstream. This regional classification accounts for variations in economic and infrastructural development, ensuring an accurate representation of the coordination between DEDL and WUE. Additionally, the Entropy Weight Method was employed to minimize the influence of scale differences, ensuring indicator weights reflect information content rather than regional size or developmental disparities.

Table 1. *Indicator system for evaluating the coupling between DEDL and WUE*

Subsystems	Categorization	Evaluation indicators	Direction	Weights
DEDL	Digital infrastructure	IBAU	+	0.05
		MBSD	+	0.14
		LOCL	+	0.12
	Digital technology application and innovation	PITSR	+	0.10
		EETP	+	0.01
		NC100EE	+	0.05
		PA	+	0.10
		R&DP	+	0.09
	Digital finance and inclusiveness	DIFI	+	0.03
		PTBV	+	0.11
	Enterprise digital transformation and technology adoption	TTC	+	0.11
		NW100E	+	0.02
		PET	+	0.06
WUE	Resource	TWR	+	0.11
		TWS	+	0.12
		WSPL	+	0.16
	Output	WSCPC	+	0.15
		GDP	+	0.12
	Efficiency	WEE	+	0.13
		USTC	+	0.14
		COD	-	0.07

DEDL = Digital Economy Development Level, WUE = Water Use Efficiency, IBAU = Internet Broadband Access Users, MBSD = Mobile Base Station Density, LOCL = Long-distance Optical Cable Length, PITSR = Proportion of IT Service Revenue in GDP, EETP = Enterprises Engaged in E-commerce Transactions, NC100EE = Number of Computers per 100 Employees, PA = Patent Applications, R&DP = R&D Projects, DIFI = Digital Inclusive Finance Index, PTBV = Proportion of Telecommunication Business Volume in GDP, TTC = Total Transaction Value of Technology Contracts, NW100E = Number of Websites per 100 Enterprises, PET = Proportion of E-commerce Transactions, TWR/TWS/WSPL/WSCPC = Various water resource indicators, GDP = Gross Domestic Product, WEE = Water Efficiency of Economic Output, USTC = Utilization of Standard Treatment Capacity, COD = Chemical Oxygen Demand

Indicators are normalized between 0 and 1. “+” indicates a positive contribution to the target system, while “–” indicates a negative contribution

The coupling coordination degree (CCD) between DEDL and WUE was calculated using a standard three-step procedure. First, the comprehensive evaluation indices for DEDL and WUE were obtained based on the entropy weight method. Second, the coupling degree (C) was computed to reflect the degree of interaction between the two systems. Third, the coordination index (T) and final CCD value were derived to assess the synchronization between DEDL and WUE. Detailed formula derivations and computation steps are provided in the *Appendix*.

A D_i value closer to 1 indicates a higher CCD between DEDL and WUE, reflecting more balanced development. Conversely, a value closer to 0 suggests weaker coordination. For interpretability, all CCD values are normalized between 0 and 1, where values below 0.3 indicate severe imbalance, 0.3–0.5 suggest low coordination, 0.5–0.6 indicate basic coordination, 0.6–0.8 reflect moderate coordination, and values above 0.8 represent well-coordinated development (Zhu et al., 2020). The specific evaluation criteria are summarized in *Table 2*.

Table 2 outlines the degree of coupling coordination along with clearly defined conceptual meanings, ranging from "risky diseases"—indicating severe disconnection requiring urgent interventions—to "quality harmonize," representing optimal integration of digital economy and water resource systems, serving as an exemplary benchmark for sustainable development policies.

Table 2. *Classification criteria for coupling coordination degree (CCD) and corresponding coordination types*

Degree of coordination	Coupling coordination	Type of coordination	Conceptual definition
Decline	0 ~ 0.10	Risky diseases	Extremely poor interaction, both systems hinder each other significantly, urgent intervention needed
	0.11 ~ 0.20	Stern diseases	Serious imbalance, major dysfunctions, immediate targeted improvements required
On the verge of harmonization	0.21 ~ 0.30	Moderate disorder	Noticeable imbalance, systems are partly dysfunctional, short-term corrective actions recommended
	0.31 ~ 0.40	Mild disorder	Slight imbalance, certain coordination exists but not sustainable, focused improvements beneficial
Over-harmonize	0.41 ~ 0.50	About to experience dissonance	Coordination is emerging, but instability risks remain, continuous monitoring and minor adjustments needed
	0.51 ~ 0.60	Inadequately organized	Basic coordination established but lacks stability, further strategic enhancement advised
Basic harmonize	0.61~ 0.70	Primary harmonize	Initial stable coordination, systems support each other moderately, continued policy support necessary
	0.71 ~ 0.80	Secondary harmonize	Stronger coordination, systems mutually reinforce significantly, policies to maintain current trajectory essential
High level of harmonize	0.81 ~ 0.90	Good harmonize	Well-established coordination, systems effectively integrated, further optimization and innovation encouraged
	0.91 ~ 1.00	Quality harmonize	Optimal integration, excellent coordination and sustainability, exemplary regional model

CCD values range from 0 to 1, with higher values indicating better coordination between DEDL and WUE. Classification thresholds refer to Zhu et al. (2020)

Potential multicollinearity considerations

Given the comprehensive nature of the selected indicators for assessing DEDL and WUE, potential multicollinearity among indicators should be acknowledged.

Multicollinearity may arise because indicators within the same category—such as digital infrastructure indicators (e.g., broadband users, base station density)—could be highly correlated, leading to redundancy and influencing the accuracy of weighting and coordination analysis.

To address this concern, prior to calculating the CCD, we conducted a preliminary correlation analysis among indicators to identify and evaluate the severity of multicollinearity. Results indicated moderate correlations among certain indicators, particularly within digital infrastructure and technology adoption categories. Despite these correlations, we opted to retain the selected indicators due to their unique conceptual significance and the comprehensive perspective they provide on digital economy and water management systems.

However, we acknowledge that such correlations could affect the EWM, potentially skewing indicator weights. Therefore, the study conducted additional sensitivity analyses. The sensitivity results confirmed that our findings remained stable and robust, indicating limited practical impacts from multicollinearity on our overall conclusions.

Nevertheless, the presence of multicollinearity underscores the importance of cautious interpretation of results. Future research might consider employing dimension reduction techniques, such as Principal Component Analysis (PCA), to mitigate these effects and enhance indicator selection.

Sensitivity analysis

To verify the robustness of the overall analysis results, this study divides the YREB into upper, middle, and lower reaches, calculates the DEDL and WUE for each region, and further computes the coupling coordination degree for each region. The analysis results show that the coupling coordination degrees of the upper, middle, and lower reaches are highly consistent with the overall results, all demonstrating a steady upward trend. For example, the average coupling coordination degree of the upper reaches increased from 0.405 in 2013 to 0.607 in 2022, the middle reaches increased from 0.447 to 0.669, and the lower reaches increased from 0.434 to 0.641, aligning with the upward trend of the overall coupling coordination degree (e.g., Anhui Province increased from 0.346 to 0.491). Although there are numerical differences between regions (e.g., the coordination degree of the lower reaches is generally higher than that of the upper reaches), the consistency in their trends fully demonstrates the robustness of the overall analysis results. Furthermore, the sensitivity analysis based on regional division reveals the spatial heterogeneity in the level of coordinated development within the Yangtze River Economic Belt, providing more refined insights for policy formulation. In conclusion, the sensitivity analysis results validate the reliability of the overall analysis conclusions, indicating that the coupling coordination level between the digital economy and water resource utilization efficiency in the YREB has shown a steady improvement trend both temporally and spatially.

Results

Analysis of DEDL

As shown in *Figure 3*, from 2013 to 2022, the DEDL across the YREB showed significant regional disparities. While most provinces experienced growth, the downstream regions, especially Shanghai, led the way. Shanghai’s DEDL index surged from 0.18 in

2013 to 0.69 in 2022, representing a relative growth of approximately 283%, highlighting its strong digital transformation in sectors like commerce and government services.

In contrast, provinces like Guizhou, Yunnan, and Anhui showed slower digital adoption, with Guizhou's DEDL index increasing from 0.069 in 2013 to 0.12 in 2022, representing a relative growth of approximately 74% over the study period. This slower progress is due to factors such as limited infrastructure, lower industrialization, and lack of digital investments.

The downstream provinces (Shanghai, Jiangsu, Zhejiang, Anhui) consistently exhibited higher DEDL values, benefiting from better infrastructure and industrialization. The upstream (Chongqing, Sichuan, Guizhou, Yunnan) and midstream regions (Jiangxi, Hubei, Hunan) faced challenges like geographic isolation and insufficient investments, leading to slower digital integration. The upstream region even saw a decline in DEDL between 2020 and 2021, but recovery began after 2021.

In conclusion, the YREB shows overall growth in digital economy development, but disparities remain, especially between downstream and upstream regions. Targeted investments in digital infrastructure and policies to support digital adoption are needed in less developed regions.

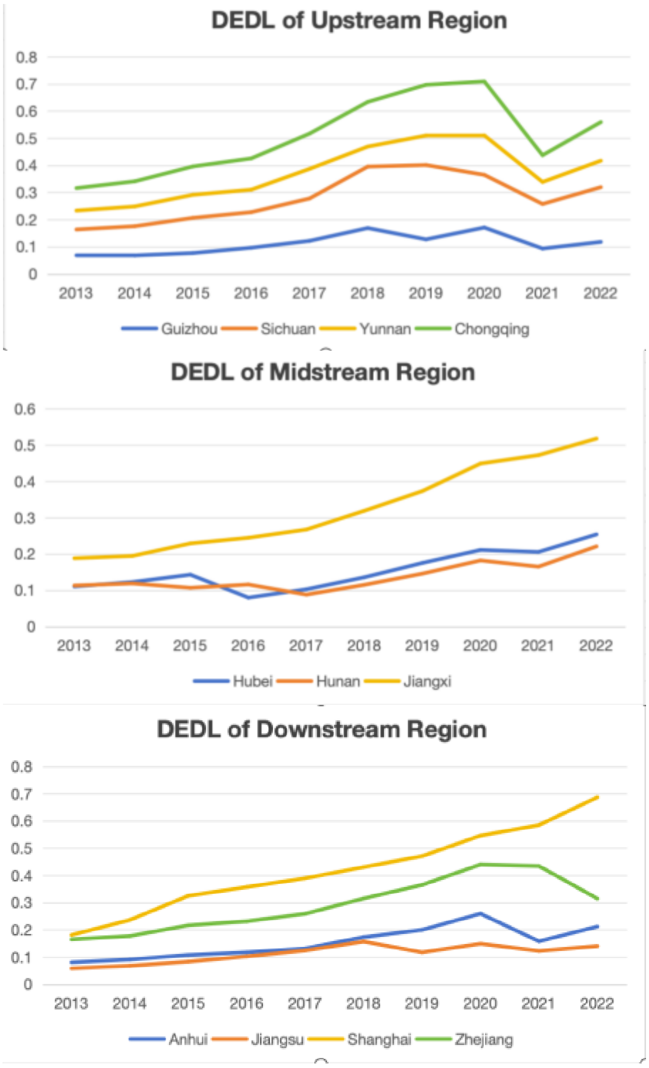

Figure 3. *Spatial and temporal evolution of the DEDL across the YREB from 2013 to 2022*

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Analysis of WUE

The WUE index across the YREB from 2013 to 2022 shows significant regional variations. Jiangsu and Zhejiang consistently had the highest WUE indices, driven by advanced industrial systems and robust infrastructure that support effective water management. By 2022, Jiangsu’s WUE index reached 0.756 and Zhejiang’s 0.676, representing increases of approximately 96% and 80%, respectively, compared to their 2013 baseline levels, indicating sustained improvements in water efficiency.

In contrast, Hunan and Hubei made slower progress. From 2013 to 2022, Hunan’s WUE index increased by approximately 59.5% (from 0.1907 to 0.3043), while Hubei’s index reached 0.354 in 2022, reflecting a growth of about 54.7% compared to its 2013 baseline. Despite benefiting from infrastructure upgrades, these provinces face challenges in industrial modernization and water management, resulting in more modest improvements.

Guizhou, Yunnan, and Anhui had the lowest WUE indices, with Guizhou’s index increasing by approximately 84.3% from 0.0925 in 2013 to 0.1705 in 2022. These regions struggle with industrialization, insufficient infrastructure, and limited investment in water-efficient technologies, which hinders faster improvements.

Overall, the downstream provinces lead in water efficiency, while the midstream and upstream regions require more targeted investments and policies to bridge the gap in water resource utilization (*Fig. 4*).

Comparison of coupling coordination degrees’ results based on time perspective

Comparison of CCD in the three regions of YREB

Using STATA software, this study calculated the CCD between DEDL and WUE for the 11 provinces of the YREB from 2013 to 2022. In accordance with previous studies, the analysis applied an equal weight ratio of $\alpha = 0.5$ and $\beta = 0.5$, ensuring a balanced assessment of the interaction between the two systems. This equal-weight model was chosen because, in the absence of empirical evidence indicating significant differences in the importance of the variables, it provides a straightforward and fair approach to evaluate the coupling coordination (Li et al., 2024; Zhang et al., 2022).

However, it is important to acknowledge that this assumption may oversimplify the complex interactions between the digital economy and water resource utilization, as the relative importance of these two systems might vary temporally and spatially across regions. Future research should consider employing alternative weighting methodologies, such as the Analytical Hierarchy Process (AHP) or expert elicitation, to capture possible variations in system dynamics more accurately and to validate the robustness of the CCD results obtained from the equal-weight approach.

According to *Figure 5*, the downstream region consistently exhibited the highest CCD, increasing by approximately 44.2% from 0.43 in 2013 to 0.62 in 2022. This increase reflects a transition from over-harmonization to basic harmonization, although it has not yet reached the high level of harmonization (above 0.8). The steady rise suggests a strong and sustained coordination between digital economic development and water resource utilization, driven by advanced digital infrastructure, industrial modernization, and effective resource management strategies.

The midstream region experienced fluctuations from 2016 to 2018, with a temporary decline followed by recovery. By 2022, the region achieved 0.54, remaining in the over-harmonization range, indicating gradual improvement but still short of basic harmonization. The temporary dip reflects external disruptions or policy shifts affecting the interaction between DEDL and WUE, which requires further attention.

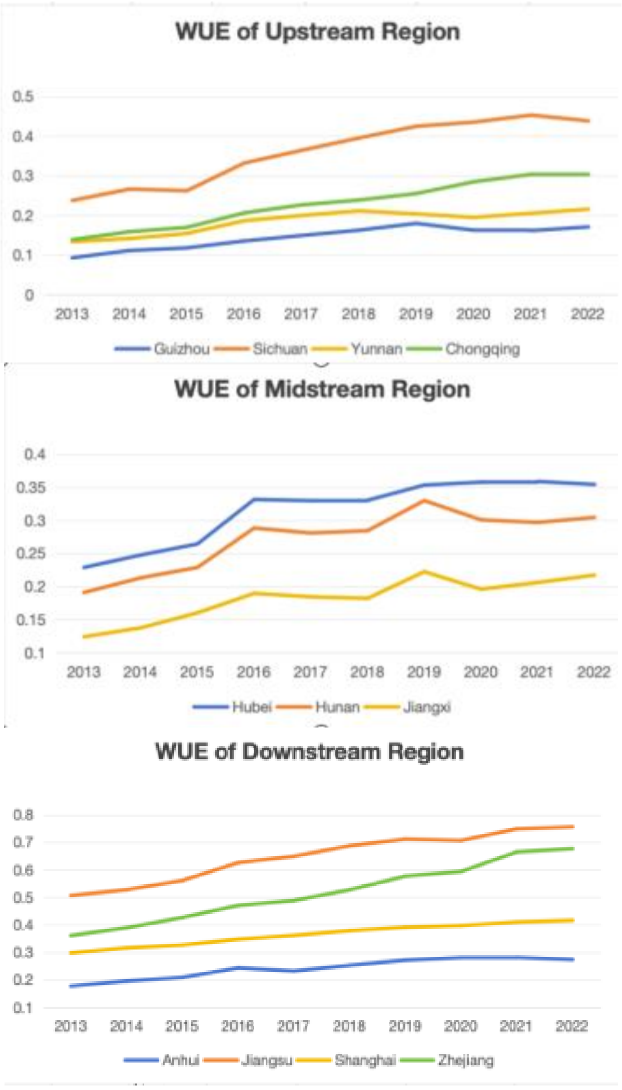

Figure 4. *Spatio-temporal evolution of WUE in the YREB, 2013–2022*

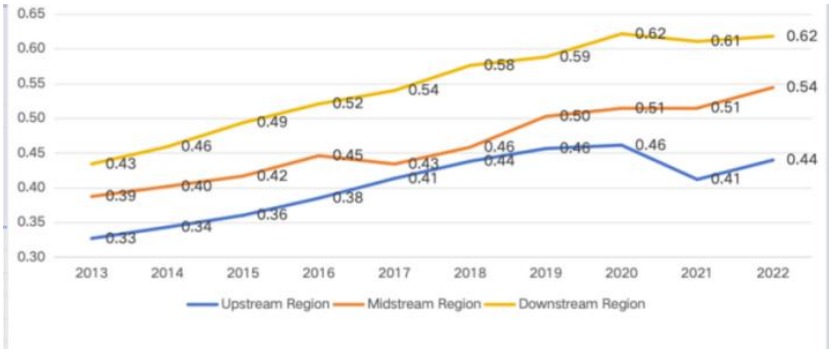

Figure 5. *Temporal evolution of CCD in the upstream, midstream, and downstream regions of the YREB (2013–2022)*

The upstream region exhibited the most instability, particularly marked by a sharp CCD decline from 2020 to 2021, mirroring the trend of the DEDL index. The CCD remained predominantly within the “on the verge of harmonization” range (0.21–0.40), indicating persistent regional imbalances. This suggests that the upstream region faces significant challenges in terms of weaker digital infrastructure and lower water efficiency integration, which hampers progress.

To better reflect the interaction between digital economy development and water resource utilization efficiency, this study further compared the regional patterns of DEDL and WUE alongside the CCD values. It was observed that provinces with higher DEDL scores, such as Shanghai and Jiangsu, generally exhibited higher WUE and correspondingly higher CCD values, indicating a synergistic relationship between digital transformation and efficient water use. Conversely, provinces such as Guizhou and Yunnan, with low DEDL scores, also showed poor WUE and low CCD, suggesting that insufficient digital infrastructure may limit the improvement of water resource management. These patterns imply a reinforcing mechanism in which the growth of digital economy capabilities facilitates better water monitoring, allocation, and conservation, thereby enhancing overall coordination between the two systems. Integrating these three dimensions reveals not only their individual trajectories but also the dynamic feedback loops that drive regional disparities in CCD within the YREB.

Analysis of CCD in upstream of Yangtze River Economic Belt

The CCD in the upstream region of the YREB, showed a general upward trend from 2013 to 2022 in *Figure 6,* albeit with significant fluctuations across the different provinces.

Among the four provinces, Sichuan recorded the highest CCD, peaking at 0.58 in 2019, which placed it in the Over-harmonize category. However, this improvement was followed by a decline, with Sichuan’s CCD dropping to 0.55 in 2022. This decrease indicates that the coordination between water resource utilization and digital economy development weakened, failing to sustain the previous upward trend.

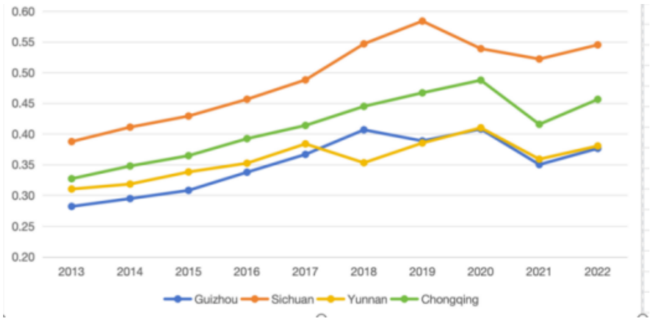

Figure 6. *Temporal evolution of CCD in the upstream region of the YREB Belt (2013–2022)*

Chongqing, in contrast, exhibited a distinct pattern of decline. The CCD steadily increased until 2020, peaking at 0.49, before declining to 0.42 in 2021. This decline came later than that of Sichuan, suggesting that while the province initially maintained a stable coordination trajectory, external factors or policy shifts after 2020 may have impacted its progress. Despite the decline, Chongqing, like Sichuan, shifted toward the “primary harmonize” category in the latter half of the period, signaling more effective policies and strategies aimed at improving both systems.

Guizhou and Yunnan demonstrated more pronounced fluctuations in their CCD values. In Guizhou, the CCD began at 0.28 in 2013, indicating a significant imbalance between water resource utilization and economic development. It increased by approximately 46.4% to reach 0.41 by 2018, before slightly declining and ending at 0.38 in 2022—still representing an overall increase of about 35.7% from the initial value. This fluctuation reflects ongoing challenges in achieving consistent coordination, and despite some progress, Guizhou's overall improvement remains slower compared to other provinces in the upstream region.

Analysis of CCD in midstream of Yangtze River Economic Belt

The CCD in the midstream region of the YREB, showed a general trend of improvement from 2013 to 2022 in *Figure 7*, although with some fluctuations in the growth trajectories of individual provinces.

Jiangxi exhibited the most consistent upward trend, with its CCD increasing by approximately 48.7%, rising from 0.39 in 2013 to 0.58 in 2022, placing it firmly in the upper range of the "over-harmonization" category. This continuous improvement indicates that Jiangxi has effectively enhanced the coordination between digital economy development and water resource utilization, suggesting successful integration of both systems.

Hubei, on the other hand, followed a more variable trajectory. After reaching 0.44 in 2015, the CCD fell to 0.40 in 2016, before recovering to 0.46 in 2018 and steadily increasing thereafter, reaching 0.55 by 2022. This fluctuation suggests that Hubei faced periodic challenges in maintaining stable coordination, but the long-term trend indicates a positive shift toward a more harmonized relationship between the two systems.

Hunan experienced the most pronounced fluctuations, marked by alternating periods of growth and decline. Its CCD rose from 0.38 in 2013 to 0.40 in 2015, further increasing to 0.43 in 2017, before experiencing another drop in 2018. By 2022, Hunan's CCD reached 0.51, transitioning into the "over-harmonization" category. However, the inconsistent pattern suggests that Hunan's development remains more sensitive to external factors compared to Jiangxi and Hubei.

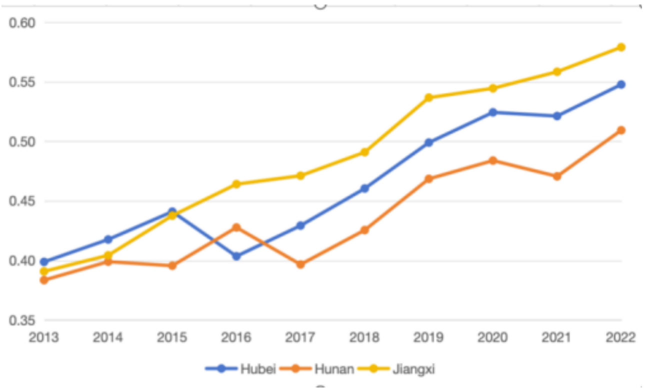

Figure 7. *Temporal evolution of CCD in the midstream region of the YREB (2013–2022)*

Analysis of CCD in downstream of Yangtze River Economic Belt

The CCD in the downstream region of the YREB (*Fig. 8*), exhibited consistently high levels of coordination from 2013 to 2022, with a general upward trend. Compared to the midstream and upstream regions, the downstream provinces demonstrated stronger coupling between digital economy development and water resource utilization efficiency, maintaining higher CCD values throughout the period.

Shanghai and Zhejiang consistently led the region, both achieving the “basic harmonization” level by 2020. Shanghai’s CCD increased by approximately 52.1%, rising from 0.48 in 2013 to 0.73 in 2022, marking the highest coordination level among all provinces in the YREB. Zhejiang followed a similar trajectory, reaching its peak at 0.73 in 2021, before slightly declining to 0.68 in 2022. This reflects an overall increase of approximately 41.7% from its 2013 value of 0.48 to 0.68 in 2022. The steady rise in these two regions reflects their robust digital economy, advanced infrastructure, and effective water resource management policies.

Jiangsu exhibited steady progress, with its CCD increasing by over 35% from 2013 to 2022, despite some fluctuations in 2020 and 2021. Jiangsu remained within the “over-harmonization” category, suggesting a well-integrated approach to balancing economic growth with water resource efficiency. Despite minor declines in certain years, Jiangsu’s overall trend aligns with its strong economic base and policy-driven improvements in resource management.

Anhui recorded the lowest CCD among the downstream provinces, though it still demonstrated an upward trajectory. Anhui’s CCD rose by approximately 49% from 2013 to 2020, followed by a slight dip in 2021 and a partial recovery in 2022, still represent significant progress compared to the midstream and upstream provinces. These fluctuations reflect challenges in maintaining stable coordination but still represent significant progress compared to the midstream and upstream provinces.

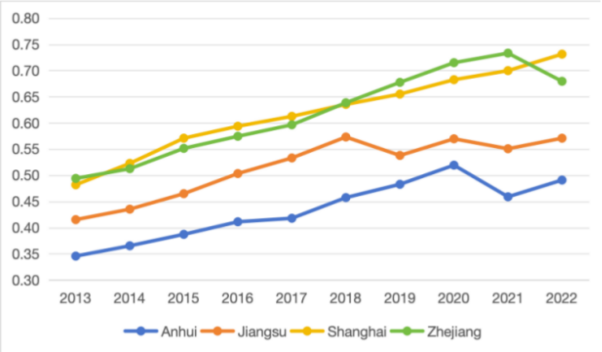

***Figure 8.** Temporal evolution of CCD in the downstream region of the YREB (2013–2022)*

Trend of CCD based on spatial perspective

In order to further illustrate the spatial evolution of the CCD between DEDL and WUE, this study analyzes and visualizes CCD trends using spatial mapping for the years 2013, 2018, and 2022. The spatial distribution of CCD across the YREB highlights regional disparities and evolutionary patterns over time.

In 2013, most provinces fell into the “mild disorder” (0.31–0.40) or “about to experience dissonance” (0.41–0.50) categories, indicating relatively weak coordination between DEDL and WUE. The upstream region, particularly Guizhou and Yunnan, was predominantly in the “moderate disorder” (0.21–0.30) range, signaling structural imbalances and limited synergy between the two systems. The downstream region (Shanghai, Jiangsu, Zhejiang) showed better coordination, reaching the “about to experience dissonance” or “inadequately organized" (0.51–0.60) levels, reflecting a more developed interaction between digital transformation and water resource management (*Fig. 9*).

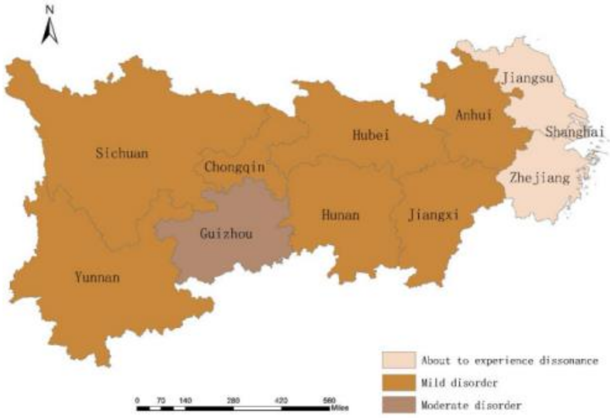

Figure 9. *Spatial distribution of CCD across provinces in the YREB in 2013*

By 2018, CCD values across most provinces improved, with the downstream region advancing to the "inadequately organized" or "primary harmonize" (0.61–0.70) levels. This shift indicates a more stable coordination between digital economy growth and water efficiency. In contrast, the midstream region (Jiangxi, Hubei, Hunan) fluctuated between "about to experience dissonance" and "inadequately organized," suggesting regional disparities in digital adoption and water resource optimization. While the upstream region showed some improvement, provinces like Guizhou and Yunnan remained in the "mild disorder" to "about to experience dissonance" range, reflecting ongoing challenges in bridging the gap between economic digitalization and sustainable water management (*Fig. 10*).

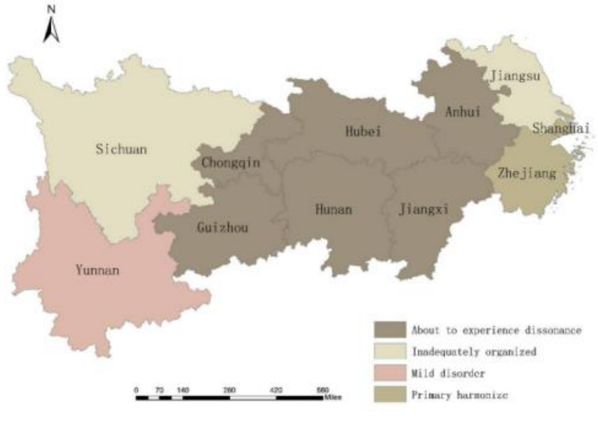

Figure 10. *Spatial distribution of CCD across provinces in the YREB in 2018*

By 2022, CCD values further increased across the YREB, although regional imbalances persisted. Shanghai, Zhejiang, and Jiangsu entered the "secondary harmonize" (0.71–0.80) category, indicating well-established coordination. Midstream provinces, especially Jiangxi and Hubei, advanced toward the "primary harmonize" stage, signaling better alignment between digital economy development and water resource utilization.

However, the upstream region remained constrained, with some provinces (e.g., Guizhou, Yunnan) still struggling to achieve coordination beyond the “about to experience dissonance” level. Sichuan, which peaked in 2019, experienced a slight decline in CCD, indicating fluctuations in its coordination progress, while Chongqing saw a decline starting in 2020, deviating from its earlier growth trajectory (*Fig. 11*).

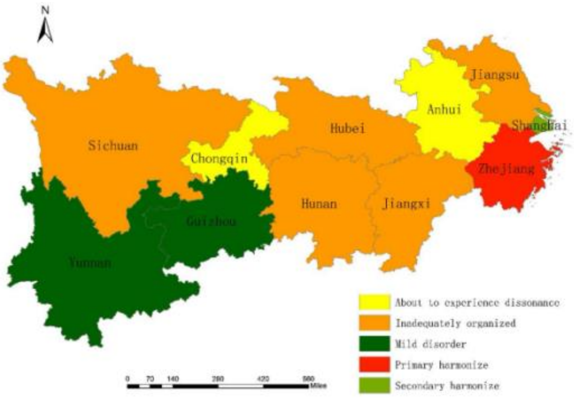

Figure 11. *Spatial distribution of CCD across provinces in the YREB in 2022*

Overall, the spatial evolution of CCD highlights a strong positive correlation between digital economy development and water resource utilization efficiency, with regions having higher digital transformation levels consistently demonstrating better coordination. However, the widening gap between downstream and upstream provinces emphasizes the need for targeted policy interventions to strengthen regional digital infrastructure, improve water efficiency, and foster a more balanced and sustainable development trajectory within the YREB.

Discussion

This study analyzed the CCD between the DEDL and WUE across the YREB from 2013 to 2022. The results reveal substantial regional disparities, with distinct differences in CCD trends observed across the upstream, midstream, and downstream regions. This discussion interprets the trends in these disparities, explores the factors driving regional differences, and compares the findings with previous research, providing insights into potential policy implications. As shown by the CCD categorization (*Table 2*), the downstream regions (Shanghai, Jiangsu, Zhejiang) reaching “secondary harmonize” demonstrate strong mutual reinforcement between digital infrastructure and water efficiency, suggesting policies here should emphasize sustaining innovation and integration. Conversely, the upstream regions, such as Guizhou and Yunnan, remain at the “about to experience dissonance” level, highlighting an urgent need for significant infrastructure investments and targeted digitalization strategies.

Regional disparities in CCD and the influence of digital economy development

The overall upward trend in CCD across the YREB indicates growing synergy between digital economy development and water resource management. However,

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substantial disparities exist. Downstream provinces (Shanghai, Jiangsu, Zhejiang) consistently exhibited the highest CCD values, achieving steady progress toward the "secondary harmonize" level by 2022. These regions benefit from robust digital infrastructure, high industrialization, and well-implemented water management policies. Previous research has highlighted the positive correlation between digital infrastructure and resource efficiency, with Goldfarb (2019) emphasizing the role of digitalization in improving resource efficiency in technologically advanced regions (Goldfarb, 2019). The success of Shanghai, which saw its DEDL index rise from 0.18 in 2013 to 0.69 in 2022, underscores the impact of comprehensive digital transformation across key sectors such as commerce, governance, and industry (Goldfarb, 2019; Hernández-Chover et al., 2022).

For example, Shanghai has embraced digital technologies to enhance water management, implementing smart water monitoring systems that use sensors and big data analytics to detect leaks, optimize water distribution, and track consumption patterns in real time (Xinyue et al., 2019). This advanced system has played a crucial role in improving water efficiency, aligning with the higher CCD values observed in the downstream regions. A similar integration of digital technologies in Jiangsu has contributed to more efficient water use in agriculture, especially through IoT-based irrigation systems, reflecting the advantages of digital infrastructure in enhancing water management (Ma and Lv, 2024).

In contrast, the upstream and midstream regions (Guizhou, Yunnan, Sichuan, Hunan) exhibited slower progress. Sichuan, which had the highest CCD in 2019, experienced a decline in subsequent years, highlighting challenges in balancing digital transformation with efficient water management (Cai et al., 2020). Fluctuations in the upstream CCD values can be attributed to factors such as limited digital infrastructure, lower industrialization, and geographic constraints, as noted in previous studies (Palermo et al., 2022), which identified similar struggles in less industrialized regions to integrate digital and water systems effectively (Goldfarb, 2019).

These regional disparities in CCD can be further explained through socio-economic, ecological, and policy-related dimensions. Socio-economically, downstream provinces such as Shanghai, Jiangsu, and Zhejiang enjoy greater fiscal capacity, higher urbanization levels, and a diversified industrial base, which collectively support both digital transformation and efficient water governance. Ecologically, upstream regions like Guizhou and Yunnan are constrained by mountainous terrain, scattered settlements, and limited access to infrastructure, which hinders both digital technology deployment and effective water distribution. From a policy perspective, downstream regions benefit from earlier and more consistent implementation of national-level digital economy strategies, stronger regulatory enforcement, and greater alignment between local governments and central planning goals. In contrast, midstream and upstream provinces often face fragmented governance and lack regionally tailored strategies that integrate digital innovation with water management priorities. These structural and institutional gaps contribute to the slower and less stable coordination progress observed in these areas. Addressing such disparities will require not only investments in infrastructure but also differentiated policy approaches that reflect the unique development conditions of each region.

Impact of regional development on the coordination of digital economy and water resource utilization

The observed regional disparities in CCD values can be largely attributed to differences in economic development, digital infrastructure, and water management practices. The downstream region's higher CCD values reflect its strong economic base and advanced infrastructure, which enable effective integration of digital and water systems. As pointed out by Zhao et al. (2024), these regions are better positioned to harness the benefits of digital economy growth for improving water efficiency (Zhao et al., 2024). The success of these provinces in coordinating DEDL and WUE serves as a model for other regions.

The midstream region (Jiangxi, Hubei, Hunan) has made moderate progress, though fluctuations in CCD values—especially in Hunan—indicate that additional targeted policies are needed. Balancing digital adoption and water management is key to improving coordination in these regions. Policies should focus on fostering digital adoption and improving water efficiency, especially in sectors like agriculture and manufacturing that are pivotal to these regions' economies.

The upstream region's slower progress, marked by fluctuating CCD values, highlights the difficulties faced by less industrialized regions. Similar to the findings by Zhang et al. (2020), the challenges in Sichuan and Chongqing's CCD declines reflect insufficient digital infrastructure, limited water management systems, and geographic barriers. Focused investments in digital infrastructure and water management are critical to improving coordination in these regions (Zhang et al., 2020; Li et al., 2024).

Implications for policy and sustainable development

The disparities in digital economy development and water resource utilization across the YREB call for region-specific policy interventions. For downstream regions, the focus should remain on sustaining the current advancements and expanding the digital infrastructure, as seen in Jiangsu and Zhejiang, which have successfully integrated digital technologies with water management. Policies should continue to promote the adoption of IoT and AI for optimizing water use in both urban and rural settings. In these regions, further investments in digital technologies could foster the creation of a fully integrated system for managing water efficiently and sustainably.

In the upstream and midstream regions, policies should prioritize the development of digital infrastructure and the introduction of digital tools for water management. These regions could benefit from lessons learned in the Netherlands, where smart water systems are utilized for flood control and water level management. The Netherlands' integration of sensors and real-time data analytics in flood-prone areas has significantly improved the management of water resources (Loos and Velickov, 2011). This type of smart water infrastructure, which can be adapted for specific regional challenges, could help bridge the gap in the YREB's upstream and midstream regions.

The sensitivity analysis reveals significant regional disparities in the CCD across the YREB, with downstream regions exhibiting higher CCD levels compared to upstream and midstream regions. This highlights the need for targeted policies to address the specific challenges faced by each region. For upstream regions, where digital infrastructure and water resource utilization efficiency are relatively low, policies should prioritize investments in broadband networks, mobile base stations, and smart water management systems, particularly for flood control and drought mitigation. Midstream regions, which show moderate CCD levels, should focus on enhancing digital literacy and promoting the adoption of digital tools for water management, such as smart irrigation systems. Downstream regions, with their advanced digital economies, should continue to lead in innovation and serve as hubs for technology transfer and knowledge sharing with upstream and midstream regions.

In addition,

- Upstream provinces should consider ecological compensation policies and rural digital inclusion programs, supporting water efficiency goals while aligning with local economic incentives.
- Midstream regions would benefit from integrated planning efforts combining digital development goals with local environmental management priorities, such as watershed protection or agricultural restructuring.
- Downstream provinces are encouraged to establish regional digital-water innovation demonstration zones and extend capacity-building support to neighboring less developed areas.

By incorporating these regionally nuanced policy pathways, the YREB can not only narrow existing coordination gaps but also build a more resilient and sustainable framework for future economic and environmental development.

Study limitations

Despite the valuable insights provided, this study has several limitations. First, the analysis relies on provincial-level data, which may obscure intra-provincial disparities and localized dynamics. Second, the use of the entropy weight method (EWM) may be sensitive to outliers, and although widely adopted, alternative weighting schemes like AHP could yield different results. Third, the equal-weight assumption in the CCD model does not account for potential differences in the relative importance of digital economy development and water resource efficiency. Lastly, the availability and consistency of statistical data across provinces and over time may affect result accuracy. These limitations suggest caution in generalizing the findings and highlight the need for more granular, multi-source data and advanced modeling in future research.

Conclusion

This study examines the coupling coordination between DEDL and WUE in the YREB from 2013 to 2022. The results reveal significant regional disparities in coupling coordination, with the downstream regions demonstrating higher coordination due to advanced digital infrastructure and efficient water management practices. In contrast, the upstream and midstream regions face slower progress due to challenges such as limited infrastructure and industrialization. These findings underscore the importance of targeted policies to improve digital infrastructure and optimize water resource utilization, particularly in less developed regions.

However, this study has certain limitations, including potential data constraints and assumptions regarding the equal-weight model. Future research should address these by exploring alternative weighting methods, such as Analytical Hierarchy Process (AHP), and conducting sensitivity analysis to validate the robustness of the findings.

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APPENDIX: METHODOLOGICAL DETAILS

Calculation process of entropy weight method (EWM)

The following steps outline how the entropy weight method is applied:

Data standardization

A total of 21 indicators from eleven provinces in the YREB from 2013 to 2022 are treated in this study.

In the analysis of the DEDL indicators, the data is first normalized to ensure all indicators are on a comparable scale. Normalization is done using the following formula:

$$X_{ij}^{'} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} \quad \text{(Eq.1)}$$

where X_{ij} is the original value of the i-th indicator for the j-th year, and $\max(X_j)$ and $\min(X_j)$ represent the maximum and minimum values of the indicator across all provinces and years.

For the WUE indicators, the data undergoes both forward normalization and reverse normalization (also known as reverse transformation). For positive indicators (forward normalization), the normalization process follows the same formula as for DEDL. However, for negative indicators (those where a higher value indicates worse performance, such as Chemical Oxygen Demand), reverse normalization is applied. The formula for reverse normalization is:

$$X_{ij}^{'} = \frac{\max(X_j) - X_{ij}}{\max(X_j) - \min(X_j)} \quad \text{(Eq.2)}$$

This ensures that lower values of the negative indicators are transformed into higher scores, reflecting better performance in the context of water efficiency.

Calculate the proportion of each indicator

After data standardization, the proportion of each indicator is calculated for each region:

$$p_{ij} = \frac{X_{ij}^{'}}{\sum_i X_{ij}^{'}} \quad \text{(Eq.3)}$$

where: n is the number of regions or alternatives; p_{ij} is the proportion of the i-th indicator for the j-th region.

Calculate the entropy value (E)

The entropy value for each indicator is calculated to measure the degree of uncertainty or dispersion. The formula is:

$$E_i = -\frac{1}{\ln(n)} \sum_{j=1}^{n} p_{ij} \ln(p_{ij}) \qquad \text{(Eq.4)}$$

where: n is the number of regions or alternatives; p_{ij} is the proportion of the i-th indicator for the j-th region.

Calculate the entropy weight (W)

The entropy weight is derived from the entropy value and represents the importance of each indicator. It is calculated as follows:

$$W_i = \frac{1 - E_i}{\sum_{i=1}^{m} (1 - E_i)} \qquad \text{(Eq.5)}$$

where: W_i is the weight of the i-th indicator; E_i is the entropy value for the i-th indicator; m is the total number of indicators.

Calculation process of the coupling coordination degree (CCD)

The following section provides the mathematical derivation and computational procedures used in this study:

The specific calculation steps for the CCD of DEDL and WUE are as follows:

Calculate the index for each system

After determining the weights for each indicator (*Table 1*), the next step is to calculate the composite index for both systems (DEDL and WUE) for each province over the evaluation years.

For the DEDL system, the index U_i is calculated by aggregating the weighted normalized values of all indicators:

$$U_i = \sum_{j=1}^{m} z_{ij} \cdot W_j \qquad \text{(Eq.6)}$$

where Z_{ij} is the normalized value for the jth indicator for province i in year j, and W_j is the weight of the jth indicator.

Similarly, for the WUE system, the index N_i is calculated using the same formula:

$$N_i = \sum_{j=1}^{m} z_{ij} \cdot W_j \qquad \text{(Eq.7)}$$

where Z_{ij} represents the normalized value for the jth indicator for province i in year j, and W_j is the corresponding weight.

Calculate the CCD

Once the indices for both the DEDL and WUE systems have been calculated, the CCD can be calculated to assess the interaction between the two systems. The CCD measures the degree of coordination between the two systems, and it is calculated as follows:

Coupling degree C_i represents the degree of interaction between the two systems:

$$C_i = 2k\left[\frac{U_i \times N_i}{(U_i + N_i)^2}\right]^{1/2} \tag{Eq.8}$$

where *k* is a constant (usually set to 1 for simplification).

Comprehensive coordination index T_i considers the balance between the two systems:

$$T_i = \alpha U_i + \beta N_i \tag{Eq.9}$$

where: α and β represent the weights of the DEDL and WUE systems, respectively.

Coordination degree D_i reflects the coordination between the two systems:

$$D_i = \frac{U_i \cdot N_i}{U_i + N_i} \tag{Eq.10}$$