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Unveiling the spatio-temporal characteristics and driving factors of water infrastructure financialization in China

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ABSTRACT

Financialization is an emerging and crucial means to address the challenge of funding the water infrastructure development shortage. However, the spatio-temporal characteristics and influencing mechanisms of the state-based water financialization remain unclear. To this end, this study constructed an indicator of the water infrastructure financialization(WIF), using China as a typical case, and thoroughly investigated the spatio-temporal characteristics and driving factors of the WIF in China from 2008 to 2020 based on spatial analysis methods. The results show that the current level of WIF in China is not high, and the construction of water infrastructure mainly relies on the traditional model led by the government. The spatial distribution shows a pattern of gradient decline from Henan and Zhejiang as the center to the surrounding areas. The uneven development of WIF has been improved under the effect of policies. The urbanization and demand for water infrastructure are the main driving factors affecting regional water financialization. The interaction of the driving factors has a more obvious impact on WIF. This study enriches the global knowledge system of infrastructure financialization and provides a reference value for other developing countries regarding water infrastructure financing.

Key words: financialization, spatial analysis, water financing, water governance, water infrastructure

HIGHLIGHTS

- Identifying the spatio-temporal characteristics and driving factors of water infrastructure financialization in China.
- Constructing an indicator of the water infrastructure financialization.
- The construction of water infrastructure mainly relies on the traditional model led by the government.
- The urbanization and the demand for water infrastructure are the main driving factors affecting the water financialization.

1. INTRODUCTION

The scarcity and uneven distribution of water resources are not only basic national conditions of China but also challenges faced by many countries around the world (Barnett *et al.* 2015). Water infrastructure is an important approach to addressing the challenge of water resources and sustainable water development (Feng *et al.* 2022), but the construction of water infrastructure has a large investment, long cycle, and strong risk (Jeuland *et al.* 2023). Especially, the huge funds and financing model are key factors restricting the development of water infrastructure (Gurung *et al.* 2017). In addition, the complex technology of large-scale hydraulic infrastructure projects also leads to high costs and high risks (Daneshfaraz *et al.* 2023; Norouzi 2023; Tansar *et al.* 2024). Traditional water investment is dominated by government funds but limited by the fiscal funds and budget, resulting in lagging water infrastructure construction (Loftus *et al.* 2019). Broadening financing channels for water infrastructure based on marketization has become an agenda for governments and academia around the world (Mason 2022).

In 2015, the World Water Council (WWC) and the Organization for Economic Co-operation and Development (OECD) jointly published *Water: Fit to Finance?* The report argues that the rapidly growing global water crisis is posing a serious threat to the global population and economy and that water infrastructure is key to achieving long-term water security; unfortunately, water infrastructure is 'not fit to finance' at the time (WWC & OECD 2015). Privatization, which began in the 1990s, shows that efforts to privatize the water sector did not necessarily reduce the burden on public finances (Bel & Warner 2008). After the 2008 global financial crisis, with the development of the financial industry, the increasingly mature global financial market, and the establishment of global financial networks, the trend of financialization has spread across the world (Loftus *et al.* 2019). The WWC, OECD, and the World Bank are working together to design new models that can bring private finance into the water sector. The initiative has proved effective, attracting firms such as The Blackstone Group, the largest investment firm in the United States, to participate in water infrastructure (Ahlers & Merme 2016). In addition, London's water and sanitation service provider has been transformed from a public company to a private company, and the city's water infrastructure is now a reliable source of income for pensioners in Canada and the UK (Pryke & Allen 2017). This worldwide financing reform of water infrastructure has also made water infrastructure finance become a hot spot in the academic community, attracting many scholars to participate in the research.

Financialization is a highly complex and dynamic phenomenon, which generally refers to the process in which financial institutions, financial markets, and financial actors play a growing role in the economy). Financialization, with globalization and neoliberalism, have been the three most important features of world capitalism in recent decades (Bonizzi 2013). In the context of economic globalization, there is also a trend of financialization in China (Wu 2022). As a product of economic growth and globalization, financialization has had an important impact on the global economy and urbanization. On the one hand, financialization helps promote the development of the real economy. Economic financialization can optimize resource allocation by improving liquidity, balancing supply and demand, and improving the efficiency of resource allocation (Sawyer 2017). On the other hand, there is also the debate about over financialization, which leads to the increase of government debt, such as China's current local government debt crisis (Liu & Dixon 2022; Li *et al.* 2023a). In addition, due to imperfect supervision and excessive market freedom, there are serious financial risks; the 2008 global financial crisis is a typical example (Christophers 2015; Mawdsley 2018).

Financialization originated in the economic field and extended to urban and infrastructure development (Aalbers 2020). Urban financialization covers many areas such as ecology, land, real estate, infrastructure, health, and energy (Kaika & Ruggiero 2016; Peck & Whiteside 2016; Wu *et al.* 2020). There have been many recent studies on the financialization of land and real estate, but few studies on infrastructure financialization (Wu 2022). Infrastructure financialization is an important potential way to address the funding shortage of infrastructure development (O'Neill 2018). The key models of infrastructure financialization include traditional bonds, funds, trusts, and innovative models such as Public Private Partnerships (PPPs), Real Estate Investment Trusts (REITs), and Asset-Backed Securities (ABS) (Y. Li *et al.* 2023b).

Although there is no universal definition of water infrastructure financialization, financialization in water infrastructure can be understood as the behavior of attracting private capital to invest in water projects through diversified market-oriented financial instruments and services such as bonds, funds, and PPPs. Financialization can effectively supplement the shortage of government funds, broaden the financing channels for water infrastructure, improve the efficiency of the funds used, allocate risks reasonably between different actors, and promote the construction of water infrastructure and allocation of water resources (Grafe 2020). The financial sector transforms fixed infrastructure investments into tradable financial products, offering the possibility of value extraction and return on investment (Peck & Whiteside 2016). The financialization of the water sector has shown a strong trend (Hilbig & Rudolph 2019). Therefore, studies on investment and financing of water infrastructure are an emerging and hot topic globally (Bayliss 2014). For example, Loftus & March (2016) revealed the apparent rewards of large-scale water infrastructure under financialization using a case study of the Thames Water Desalination Plant, arguing that the financialization of water infrastructure constitutes a fundamental shift in the structure of public service and infrastructure in contemporary capitalist society. Cousins & Hill (2021) examined the application of different fees and financial instruments by municipalities to pay for stormwater emission reduction through green and gray infrastructure, and to increase their capacity to cope with the impacts of climate change, which suggests that deeper financial market integration in urban environmental governance is a major trend. Bresnihan (2016) described how neoliberalization of water services can be inspired by the convergence of aging water infrastructure and the Irish government's fiscal challenges and financial needs, which is categorized as 'the process of bio-financialization.'

Existing studies have mainly focused on the traditional financing approach of water infrastructure, and a few studies have focused on water infrastructure financialization. In addition, the methods in current studies are mainly case analysis and qualitative methods. There is a lack of empirical research on water infrastructure financialization based on a geographical perspective. Therefore, from the perspective of financial geography and on the basis of constructing the evaluation indicators system for water infrastructure financialization, this study comprehensively applied spatial analysis methods to explore the spatio-temporal characteristics and driving factors of water infrastructure financialization in China. This study not only enriches the global infrastructure financialization knowledge system but also provides a reference for promoting the decision-making of China's water infrastructure financialization.

The rest of the article is organized as follows. The next section illustrates the research design and data. After providing descriptive analyses in the fourth section, we discuss the empirical results in the penultimate section. The last section concludes the article.

2. MATERIALS AND METHODS

2.1. Methods

2.1.1. Constructing an indicators system of water infrastructure financialization

In this study, the financialization rate of water infrastructure was constructed to characterize the degree of water infrastructure financialization. The considerations for constructing the indicator financialization rate of water infrastructure are as follows. On the one hand, draw on the indicator financial interrelations ratio (FIR), which is used to measure the degree of economic financialization proposed by the American economist Raymond Goldsmith. The FIR is the ratio of the value of a country's total financial assets to the country's total economic activity in a given period. The equation for calculating the FIR can be simplified as the ratio of total financial assets to gross domestic product (GDP). Financial assets include financial instruments issued by the non-financial sector such as stocks and bonds, and financial instruments issued by the financial sector such as currency and deposits. The financialization of water infrastructure operates under a similar logic: the increasing share of private sector investment relative to total investment implies the increasing importance of financial assets in the water sector. On the other hand, in the *China Water Resources Statistical Yearbook* issued by the Ministry of Water Resources of China, the investment in water infrastructure construction is divided into government investment, domestic loans, enterprise and private investment, foreign debt, bonds, and other sources according to the source of funds. Government investment is defined as 'all financial funds (including non-operational funds within the budget, special funds for national debt and water infrastructure construction funds) and self-raised investment by government departments.'

The equation of the financialization rate of water infrastructure in this study is as follows:

$$\mathrm{Fr} = \frac{(\mathrm{It} - \mathrm{Ig})}{\mathrm{It}}$$

where Fr refers to the financialization rate of water infrastructure, It refers to the total investment in water infrastructure construction, and Ig refers to the government investment in water infrastructure construction, all data come from the *China Water Resources Statistical Yearbook*.

2.1.2. Coefficient of variation and gini coefficient of location

In this study, the coefficient of variation and the Gini coefficient of location were used to analyze the inter-provincial differences and spatial patterns of the water infrastructure financialization in China. The equation for the coefficient of variation is as follows:

$$C_v = \frac{s}{\bar{x}}$$

where C_v is the coefficient of variation, s is the sample standard deviation, and $\bar{x}$ is the mean value. The greater the coefficient of variation, the more discrete the data, and the greater the difference in the level of financialization of water infrastructure at the provincial level in China.

The Gini coefficient of location is an index proposed by Paul Krugman, founder of new economic geography, to measure spatial inequality. The equation is as follows:

$$G = 1 + \frac{1}{n} - \frac{2}{n^2\bar{x}} \Sigma \mathrm{i} x_i$$

where $\bar{x}$ refers to the mean value of the financialization rate of water infrastructure, n is the number of provinces in China, x_i is the financialization rate of water infrastructure by region, and $i = 1,2,3, \ldots, n$. The smaller the G value, the more balanced the distribution of water infrastructure financialization.

2.1.3. Moran's index

Moran's index is a popular method of spatial statistical analysis, which is used to measure the clustering of spatial unit attributes. The Moran's index includes the Global Moran's I and Local Moran's I. Because the coefficient of variation and Gini coefficient of location can only show the overall situation of the financialization degree of water infrastructure in various provinces in China, this study further analyzed the degree of spatial aggregation of regions by measuring the local Moran's I. The equation is as follows:

$$I_i = \frac{(x_i - \bar{x})}{s^2} \sum_j w_{ij}(x_j - \bar{x})$$

where I_i is the local Moran's I, and x_i and x_j are the financialization rates of water infrastructure in i and j regions, respectively. $\bar{x}$ refers to the average of financialization rate and w_{ij} is the spatial weight matrix.

2.1.4. Geodetector

Geodetector is a spatial statistical method to detect spatial differentiation and reveal the driving force (Wang *et al.* 2021). The GeoDetectors is based on the assumption that if an independent variable has a significant effect on a dependent variable, then the spatial distribution of the independent variable and the dependent variable should be similar (Wang & Xu 2017). GeoDetector includes a factor detector, interaction detector, risk detector, and ecological detector. The purpose of this study was to explore the driving factors of water infrastructure financialization in various provinces of China and the interactive effects of the driving factors. Only factor and interactive detectors were applied in this study.

The principle of the factor detector is to detect the spatial differentiation of the dependent variable and the extent to which an influence factor explains the spatial differentiation of the dependent variable (Wang *et al.* 2021). The equation is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{\mathrm{SSW}}{\mathrm{SST}}$$

$$\mathrm{SSW} = \sum_{h=1}^{L} N_h \sigma_n^2, \quad \mathrm{SST} = N\sigma^2$$

where $h = 1, \ldots$; L is the stratification of dependent variables and factors, for example, classification or partitioning; N_h and N are the number of units in strata and the whole area, respectively; σ_h^2 and σ^2 are the variances of the dependent variables of strata and the whole area, respectively; and SSW and SST are within sum of squares and total sum of squares, respectively. The range of q is [0,1], and the larger the value, the more obvious the influence of factors on water infrastructure financialization.

Another unique advantage of GeoDetectors is to detect the interaction of two factors (Wang *et al.* 2021). By calculating and comparing the q values of each single factor and the q values of the two factors superimposed, the GeoDetectors can judge whether there is an interaction between the two factors, as well as the strength and direction (linear or nonlinear) of the interaction. The GeoDetectors classifies the interaction between the two factors into five types (Table 1).

2.2. Factors and data sources

Water infrastructure financialization is affected by many factors, not only by the development of the financial industry but also by water infrastructure construction and social and economic factors (Borgomeo *et al.* 2022). The driving factors selected in this study were divided into four categories including social and economic dimension, hydrological dimension, financial dimension, and fiscal dimension (Table 2).

Table 1 | Types of interaction of two factors

Judgment basis	Interaction
$q(X1 \cap X2) < \mathrm{Min}(q(X1), q(X2))$	Nonlinear weakening
$\mathrm{Min}(q(X1), q(X2)) < q(X1 \cap X2) < \mathrm{Max}(q(X1)), q(X2))$	Single factor nonlinear weakening
$q(X1 \cap X2) > \mathrm{Max}(q(X1), q(X2))$	Two-factor enhancement
$q(X1 \cap X2) = q(X1) + q(X2)$	Independent
$q(X1 \cap X2) > q(X1) + q(X2)$	Nonlinear enhancement

Table 2 | Driving factors for the water infrastructure financialization

Indicators	Factors	Explaination
Dependent variable	Rate of the water infrastructure financialization (%)	(Total investment – Government investment)/Total investment
Social and economic dimension	$X1$: Degree of government intervention (%)	Government investment in water infrastructure/GDP
	$X2$: Urbanization (%)	Urbanization rate
	$X3$: Economic growth (Yuan)	GDP per capita
	$X4$: Total investment in water infrastructure projects under construction(ten thousand yuan)	
Hydrological dimension	$X5$: Carrying capacity of water resources (%)	GDP/water consumption
Financial dimension,	$X6$: Financial development level (100 million yuan)	The added value of the financial industry
Fiscal dimension	$X7$: Fiscal revenue (100 million yuan)	
	$X8$: Fiscal expenditure (100 million yuan)	

The socio-economic dimension includes the degree of government intervention ($X1$), urbanization ($X2$), economic growth ($X3$), and the total investment in water infrastructure projects under construction ($X4$). The degree of government intervention is represented by the proportion of government investment in water infrastructure to GDP, which mainly considers the different roles played by the government and market in water infrastructure financialization. Economic growth and urbanization are the basic conditions to promote water infrastructure financialization. The total investment of water infrastructure projects under construction represents the investment and construction of water infrastructure. Theoretically, when the construction funds of water infrastructure projects reach a certain level, the financial pressure on the government will increase, and there is a need for financialization (Humphreys & Schwartz 2018). The hydrological dimension represents the carrying capacity of water resources by the ratio of GDP to water consumption ($X5$) and explores the impact of water security on water infrastructure financialization. The financial dimension reflects the financial development level of provinces in China by the added value of the financial industry ($X6$). In the fiscal dimension, fiscal revenue ($X7$) and fiscal expenditure ($X8$) are selected. Given that the GeoDetector has the function of analyzing the interaction of factors, the influence of the interaction of fiscal revenue and fiscal expenditure on water infrastructure financialization can be analyzed.

This study selected panel data of 31 provinces in China from 2008 to 2020, and the data came from the *China Water Resources Statistical Yearbook*, *China Urban Construction Statistical Yearbook*, and *China Statistical Yearbook*. Descriptive statistics of the variables are shown in Table 3.

3. RESULTS

3.1. Spatial-temporal evolution of water infrastructure financialization in China

3.1.1. Overall characteristics

Based on the data in 2020, we found that government investment still dominates water infrastructure financing in China (Figure 1). The financialization rate of water infrastructure in China is 18.9%. The highest province is Henan, but the

Table 3 | Descriptive statistics of variables

Variables	Attribute	Mean	S.D.	Min	Max
Rate of the water infrastructure financialization	%	0.1642	0.10239	0	0.41
Degree of government intervention	%	0.0083	0.00475	0	0.02
Urbanization rate	%	0.6373	0.11056	0.36	0.89
GDP per capita	Yuan	70,786.58	31,325.74	35,995	164,889
Total investment in water infrastructure projects under construction	100 million yuan	10,233,674	8,584,838	1,237,914	42,693,944
Carrying capacity of water resources	%	213.4276	170.7819	24.19	889.23
The added value of the financial industry	100 million yuan	2,718.725	2,492.278	138.56	9,906.99
Fiscal revenue	100 million yuan	3,230.425	2,824.276	220.99	12,923.85
Fiscal expenditure	100 million yuan	6,793.014	3,544.107	1,480.36	17,430.79

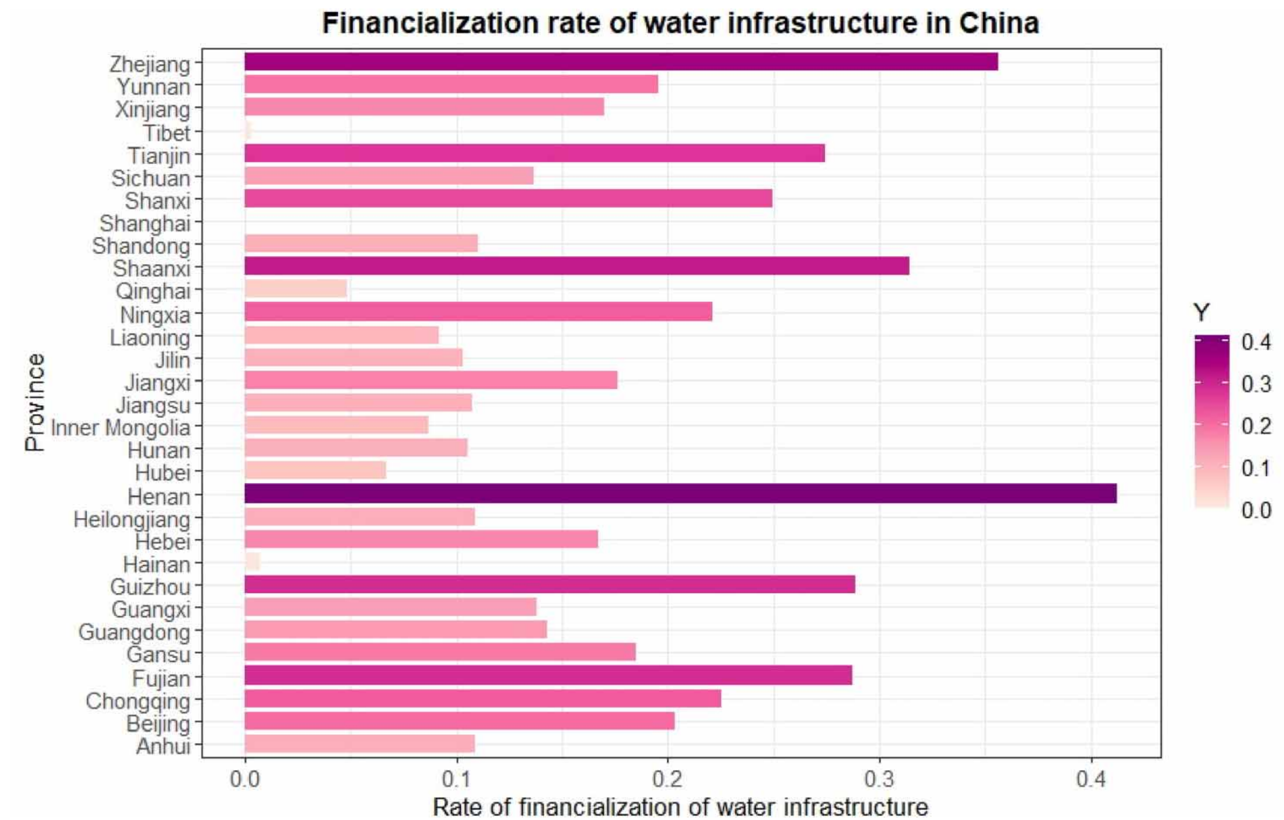

Figure 1 | Financialization rate of water infrastructure in China, 2020.

financialization rate is only 41.3%. Provinces with low financialization rates include Tibet, Shanghai, and Hainan. Shanghai's nongovernmental investment in water infrastructure in 2020 was 0. As the most economically developed region in China, this indicates that on the one hand, the government has strong financial funds to support water infrastructure construction in Shanghai; on the other hand, Shanghai is a highly urbanized area and lacks mega water infrastructure projects.

There are significant spatial differences in water infrastructure financialization in China, showing the spatial distribution characteristics of 'central polarization and decreasing gradient.' The two centers are Henan and Zhejiang, which have higher water infrastructure financialization rates of 41.3 and 33.4%, respectively, whereas the financialization rates of their surrounding provinces decrease with the increase in distance, as shown in Figure 2.

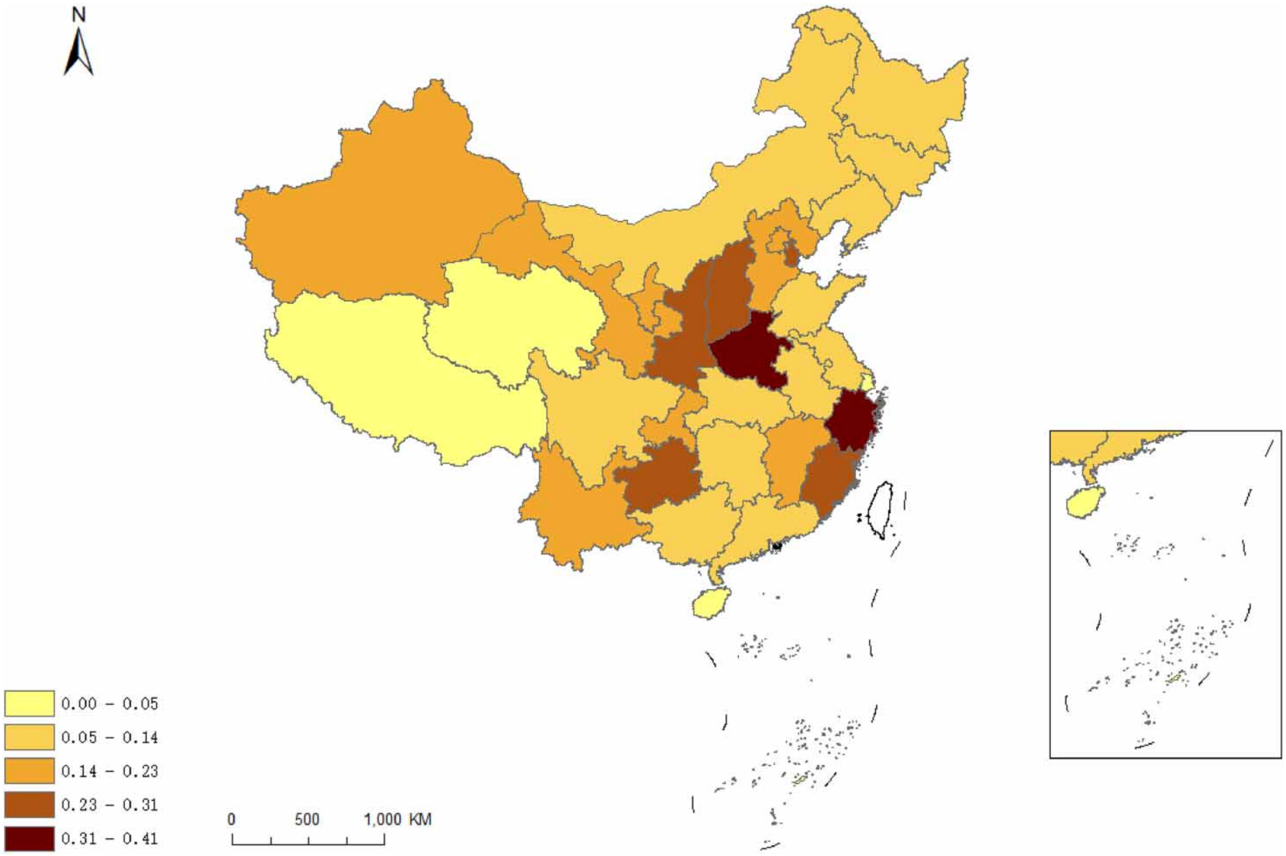

Figure 2 | Spatial pattern of water infrastructure financialization in China, 2020.

3.1.2. Development process

The coefficient of variation and spatial Gini coefficient of China's water infrastructure financialization from 2008 to 2020 show that the overall variation coefficient is at a relatively high level, but it begins to decrease gradually after 2015, indicating that the differences in water infrastructure financialization in China at the provincial level are convergent (Figure 3). Due to the impact of the global financial crisis in 2008, the coefficient of variation has a slight downward curve. The wave of financialization that swept the world in 2010 also reshaped the development of China's financial industry, and the coefficient of variation increased slowly between 2010 and 2015, with the eastern provinces gaining a head start in promoting the financialization based on their developed economic levels, at which time there were large differences in water infrastructure financialization across the provinces. In 2016, the Chinese government issued the *Opinions on Deepening the Reform of the Investment and Financing System*, which put forward constructive suggestions for the reform of the infrastructure investment and financing system, and provinces have formulated policies on financialization, which has promoted the development of water infrastructure financialization. Benefiting from the increase in the overall level of financialization, regional differences have decreased, and the coefficient of variation from 2015 to 2020 has gradually decreased.

The change in the spatial Gini coefficient from 2008 to 2020 fluctuated considerably, but the overall trend shows a gradual decline, indicating that the development of water infrastructure financialization in China tends to be regionally balanced. The spatial Gini coefficient increased slightly from 2008 to 2010, had a clear downward trend from 2010 to 2015, and then began to float and decrease again, and its overall evolution tends to be consistent with the coefficient of variation.

3.1.3. Spatial features

Because the coefficient of variation and spatial Gini coefficient cannot reflect the internal structure of the space, the spatial structure and changes in water infrastructure financialization at the provincial level are revealed by measuring the local Moran'I in 2008, 2015, and 2020 (Figure 4). The spatial agglomeration of water infrastructure financialization in China is

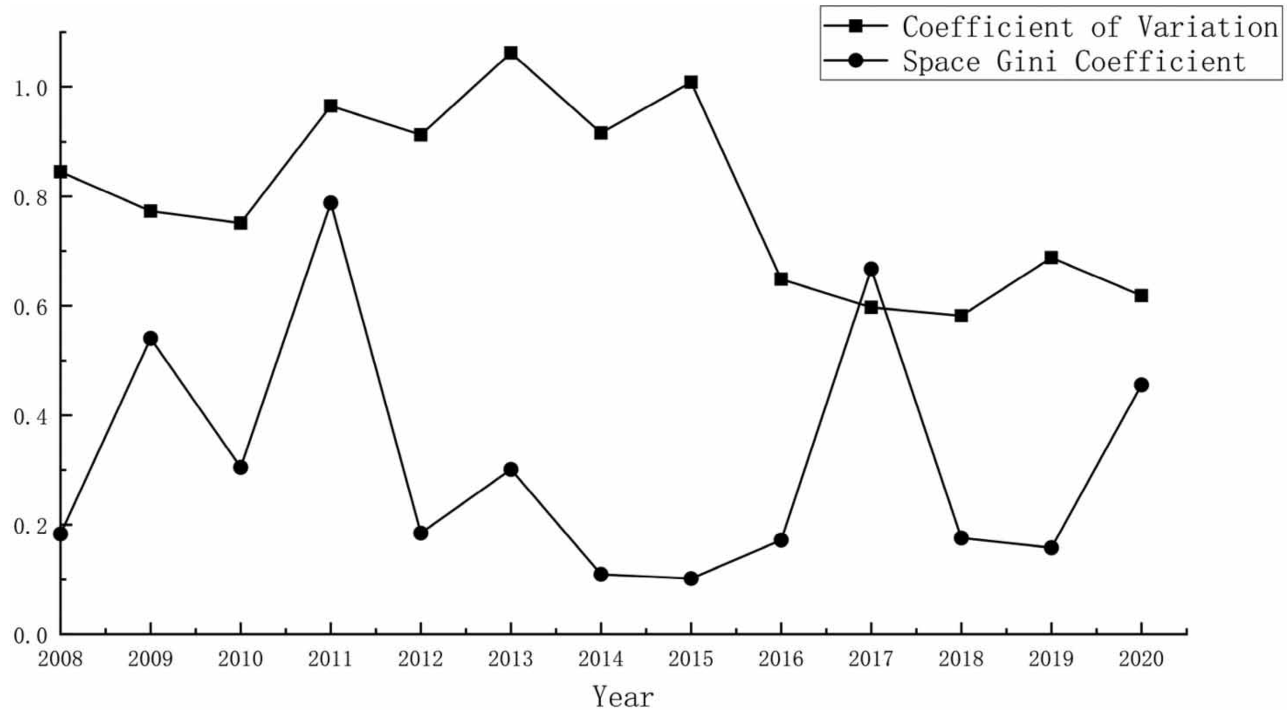

Figure 3 | Change in coefficient of variation and spatial Gini coefficient.

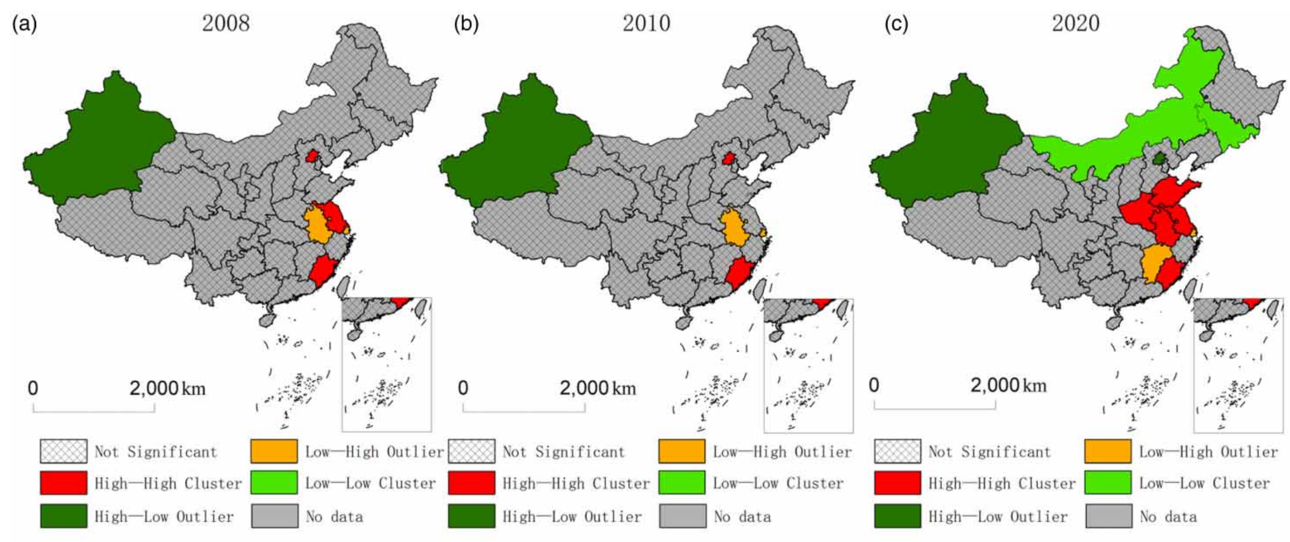

Figure 4 | Local Moran'I of the water infrastructure financialization in China.

gradually increasing, but the overall degree of spatial agglomeration is not high. In 2008 and 2015, there were only 5–6 provinces with spatial agglomeration: Jiangsu, Fujian, and Beijing were in the high-high agglomeration region, Tibet was in the high-low state, and Anhui was in the low-high state. In 2020, the number of provinces with spatial aggregation increased, mainly concentrated in eastern China. A small area of high-high aggregation occurs, centered on the provinces of Anhui, Jiangsu, and Fujian, spreading to the periphery, illustrating the leading role of Anhui, Jiangsu, and Fujian in eastern China. In addition, from 2008 to 2020, Tibet was in a state of high-low aggregation and was relatively stable, indicating that Tibet will be the key to promote the development of water infrastructure financialization in northwest China.

In summary, water infrastructure financialization in China started in the post-financial crisis, and developed slowly from 2010 to 2015, with a low overall level and uneven development. From 2015 to 2020, water infrastructure financialization developed rapidly, but the unevenness of the financialization still exists. This study adopted the GeoDetector method to further quantitatively analyze the influencing factors and explore the potential mechanism.

3.2. Driving factors of water infrastructure financialization in China

3.2.1. Changes in the influence degree of driving factors

The *q* value of the GeoDetector is a key index used to measure the spatial differentiation and interaction between factors. In this study, the *q* value of the selected driving factors was calculated to analyze the change of the influence degree of indicators on water infrastructure financialization (Figure 5).

In the socio-economic dimension, the q value of urbanization is in a fluctuating state. On the one hand, the *q* value of urbanization is between 0.2 and 0.6 from 2008 to 2020, which has an important impact on water infrastructure financialization. On the other hand, the impact of urbanization is regional and phased, for example, the rapid urbanization stage and central and western China need to build a large number of water infrastructure projects, which also have a greater impact on water infrastructure financialization. In contrast, in highly urbanized phases and regions, there is less need for water infrastructure project construction and less impact of financialization.

The *q* value of economic growth decreased year by year; on the contrary, the *q* value of total investment in water infrastructure projects under construction increased, whereas the *q* value of government intervention showed an 'inverted U-shaped' trend of rising first and then decreasing, which was closely related to changes in the macroeconomic policy of the economy after the 2008 global financial crisis. In other dimensions, the *q* value of water resources' carrying capacity fluctuates in a low range, whereas the *q* values of the financial development, fiscal revenue, and fiscal expenditure all show an upward trend.

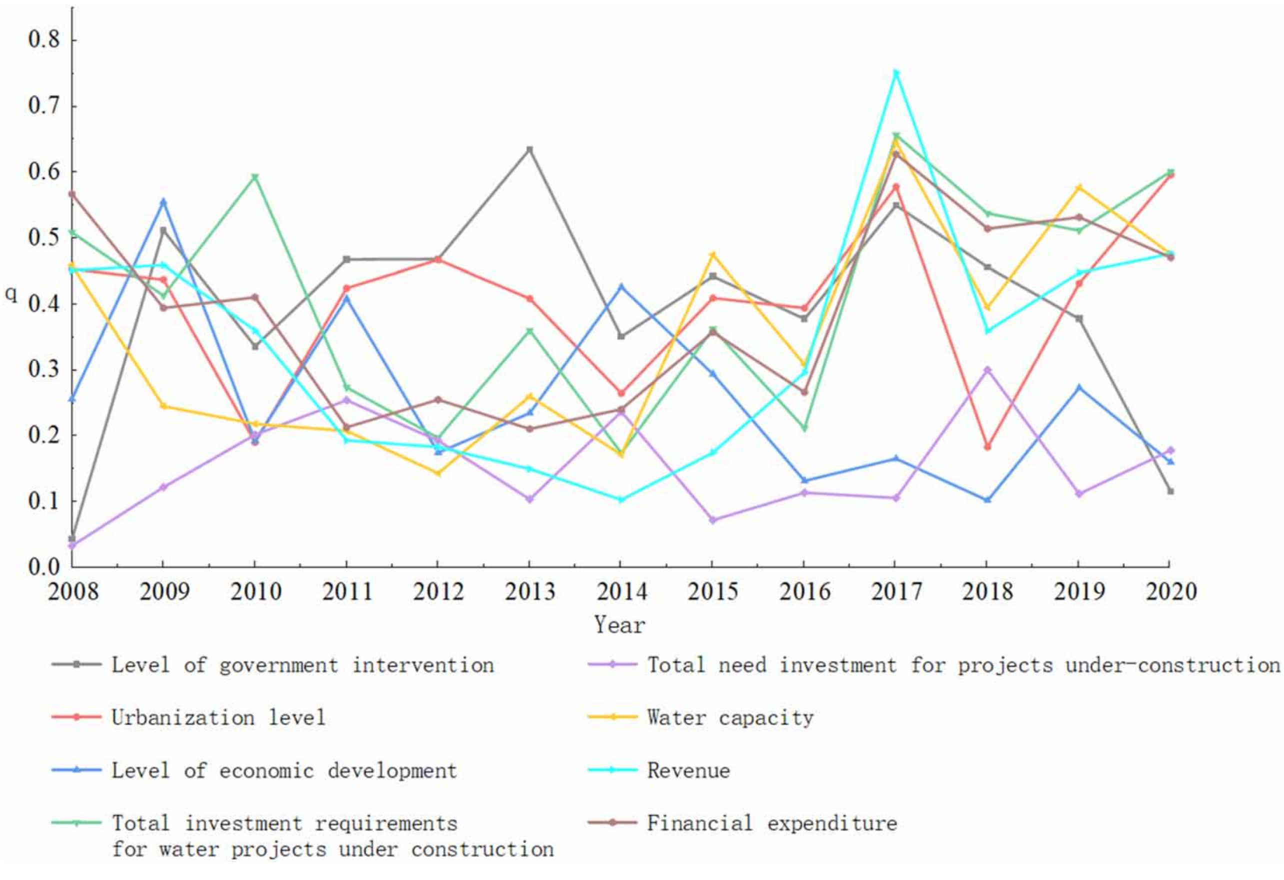

Figure 5 | Changes of *q* value of the driving factors.

The '*Opinions on Deepening the Reform of the Investment and Financing System*' issued by the Chinese government in 2016 is very important. Government policies have promoted the marketization of financing of water infrastructure in China, and in 2017, the q values of most driving factors reached their peaks. Through the detection and analysis of the single factor (Figure 6), we found that the lowest single factor q value is $X1$ government intervention degree with 0.12, followed by $X3$ economic growth with 0.16 and $X5$ water resources' carrying capacity with 0.18. $X2$ urbanization and $X4$ total investment in water infrastructure projects under construction are the main driving factors affecting water infrastructure financialization in China, and the q values are all 0.6, indicating that the demand for water infrastructure construction in the rapid urbanization is the leading reason to promote financialization.

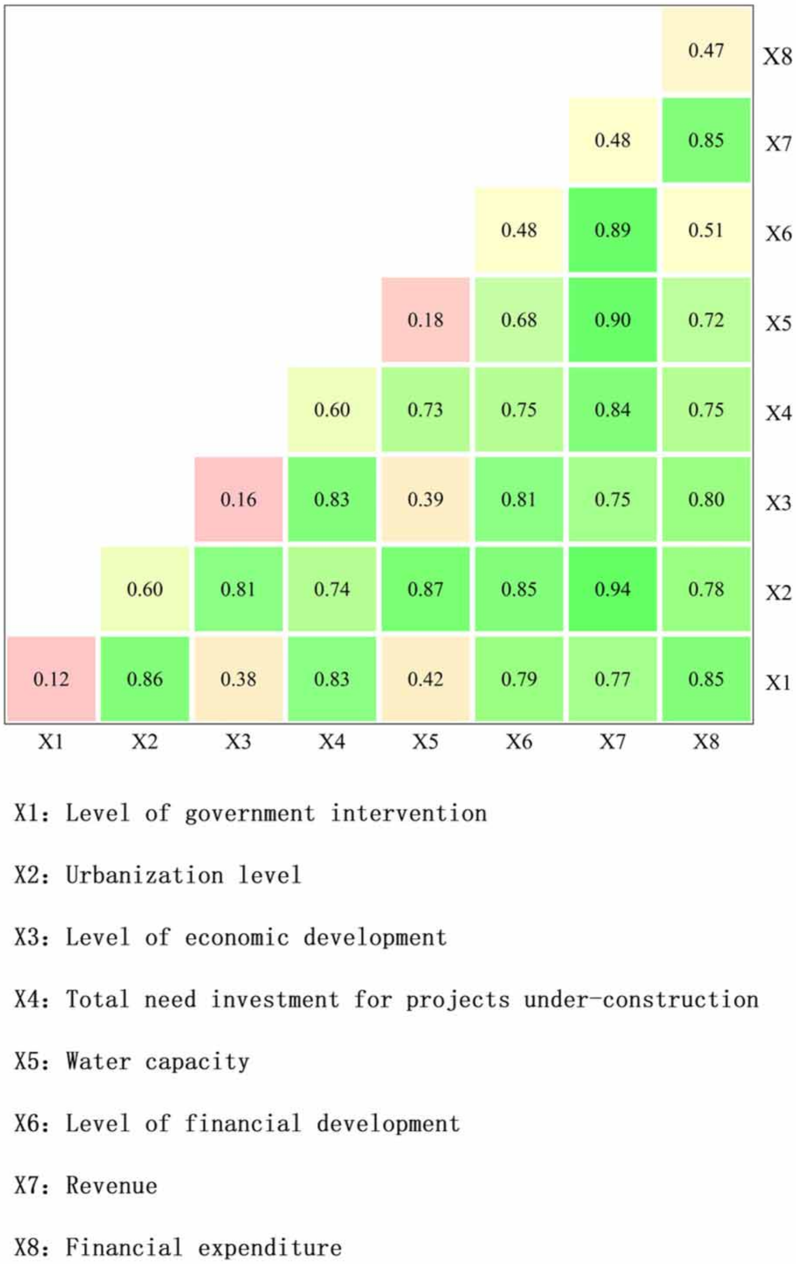

Figure 6 | Factor detection result of the driving factors.

3.2.2. The interaction of driving factors

Factor interaction detection reveals the interaction and coupling of multiple driving factors. The results show that the interaction results of most of the driving factors are nonlinear enhancement, indicating that the interaction of any two driving factors has a more obvious driving effect on water infrastructure financialization. In other words, the interaction between factors can better explain the regional differences in the spatial distribution of water infrastructure financialization (Table 4).

More specifically, $X2 \cap X7$ has the strongest influence with a q value of 0.94, indicating that urbanization has a strong demand for water infrastructure financialization, whereas the lack of fiscal revenue stimulates financialization. The coupling of the two factors has a significant promoting effect on water infrastructure financialization. Financialization is an important means to address the gap between the development needs of water infrastructure and the shortage of financial funds. The q value greater than 0.85 is also $X1 \cap X2$, $X1 \cap X8$, $X2 \cap X5$, $X2 \cap X6$, $X5 \cap X7$, $X6 \cap X7$, $X7 \cap X8$, indicating that two factors

Table 4 | Interactive results of the driving factors

$C = A \cap B$	$A + B$	Results	Interaction type
Government intervention ∩ Urbanization	0.71	$C > A + B$	Nonlinear enhancement
Government intervention ∩ Economic growth	0.28	$C > A + B$	Nonlinear enhancement
Government intervention ∩ Total investment in water infrastructure projects under construction	0.72	$C > A + B$	Nonlinear enhancement
Government intervention ∩ Carrying capacity of water resources	0.29	$C > A + B$	Nonlinear enhancement
Government intervention ∩ Financial development	0.59	$C > A + B$	Nonlinear enhancement
Government intervention ∩ Fiscal revenue	0.59	$C > A + B$	Nonlinear enhancement
Government intervention ∩ Fiscal expenditure	0.59	$C > A + B$	Nonlinear enhancement
Urbanization ∩ Economic growth	0.76	$C > A + B$	Nonlinear enhancement
Urbanization ∩ Total investment in water infrastructure projects under construction	1.20	$C > \max(q(X1),q(X2))$	Two-factor enhancement
Urbanization ∩ Carrying capacity of water resources	0.77	$C > A + B$	Nonlinear enhancement
Urbanization ∩ Financial development	1.07	$C > \max(q(X1),q(X2))$	Two-factor enhancement
Urbanization ∩ Fiscal revenue	1.07	$C > \max(q(X1),q(X2))$	Two-factor enhancement
Urbanization ∩ Fiscal expenditure	1.07	$C > \max(q(X1),q(X2))$	Two-factor enhancement
Economic growth ∩ Total investment in water infrastructure projects under construction	0.76	$C > A + B$	Nonlinear enhancement
Economic growth ∩ Carrying capacity of water resources	0.34	$C > A + B$	Nonlinear enhancement
Economic growth ∩ Financial development	0.64	$C > A + B$	Nonlinear enhancement
Economic growth ∩ Fiscal revenue	0.64	$C > A + B$	Nonlinear enhancement
Economic growth ∩ Fiscal expenditure	0.63	$C > A + B$	Nonlinear enhancement
Total investment in water infrastructure projects under construction ∩ Carrying capacity of water resources	0.78	$C > \max(q(X1),q(X2))$	Two-factor enhancement
Total investment in water infrastructure projects under construction ∩ Financial development	1.08	$C > \max(q(X1),q(X2))$	Two-factor enhancement
Total investment in water infrastructure projects under construction ∩ Fiscal revenue	1.08	$C > \max(q(X1),q(X2))$	Two-factor enhancement
Total investment in water infrastructure projects under construction ∩ Fiscal expenditure	1.07	$C > \max(q(X1),q(X2))$	Two-factor enhancement
Carrying capacity of water resources ∩ Financial development	1.07	$C > \max(q(X1),q(X2))$	Nonlinear enhancement
Carrying capacity of water resources ∩ Fiscal revenue	0.65	$C > A + B$	Nonlinear enhancement
Carrying capacity of water resources ∩ Fiscal expenditure	0.65	$C > A + B$	Nonlinear enhancement
Financial development ∩ Fiscal revenue	0.95	$C > \max(q(X1),q(X2))$	Two-factor enhancement
Fiscal revenue ∩ Fiscal expenditure	0.95	$C > \max(q(X1),q(X2))$	Two-factor enhancement

play a greater role in driving water infrastructure financialization than a single factor. Among the multifactor interactions with q values greater than 0.85, $X7$ occurs most frequently, further demonstrating the critical role of fiscal revenue in water infrastructure financialization. Meanwhile, the interaction types of each factor interacting with $X1$ and $X3$ are all non-linear enhancement, indicating the important role of government intervention and economic growth in water infrastructure financialization.

Further comparative analysis of the interaction effect of factors and the effect of a single factor shows that the interaction effect of multiple factors is significantly enhanced compared with that of a single factor (Table 5). The interaction between government intervention and other factors has the largest increase, followed by economic growth and water resources' carrying capacity. The single factor q value of the three driving factors is the lowest, but the q value of interaction with other factors has achieved significant growth. First, the single factor q value of government intervention is 0.12, which is the lowest level, indicating that the government has a low impact on water infrastructure financialization through direct financial means such as financial allocation and transfer payment. However, compared to the single factor, the q value of interaction with urbanization, fiscal expenditure, and total investment in water infrastructure projects under construction increased by 616.67,

Table 5 | Degree of increase in the interaction of driving factors

Driving fctors	*q* Value	Interaction	*q* Value of interaction	Rate of increase
Government intervention	0.12	Government intervention ∩ Urbanization	0.86	616.67%
		Government intervention ∩ Fiscal expenditure	0.85	608.33%
		Government intervention ∩Total investment in water infrastructure projects under construction	0.83	591.67%
Urbanization	0.6	Urbanization ∩ Fiscal revenue	0.94	56.67%
		Urbanization ∩ Carrying capacity of water resources	0.87	45.00%
		Government intervention ∩ Urbanization	0.86	43.33%
Economic growth	0.16	Economic growth ∩ Total investment in water infrastructure projects under construction	0.83	418.75%
		Economic growth ∩ Financial development	0.81	406.25%
		Urbanization ∩ Economic growth	0.81	406.25%
Total investment in water infrastructure projects under construction	0.6	Total investment in water infrastructure projects under construction ∩ Fiscal revenue	0.84	40.00%
		Economic growth ∩ Total investment in water infrastructure projects under construction	0.83	38.33%
		Government intervention ∩ Total investment in water infrastructure projects under construction	0.83	38.33%
Carrying capacity of water resources	0.18	Carrying capacity of water resources ∩ Fiscal revenue	0.90	400.00%
		Urbanization ∩ Carrying capacity of water resources	0.87	383.33%
		Total investment in water infrastructure projects under construction ∩ Carrying capacity of water resources	0.73	305.56%
Financial development	0.48	Financial development ∩ Fiscal revenue	0.89	85.42%
		Urbanization ∩ Financial development	0.85	77.08%
		Economic growth ∩ Financial development	0.81	68.75%
Fiscal revenue	0.48	Urbanization ∩ Fiscal revenue	0.94	95.83%
		Carrying capacity of water resources ∩ Fiscal revenue	0.90	87.50%
		Financial development ∩ Fiscal revenue	0.89	85.42%
Fiscal expenditure	0.47	Government intervention ∩ Fiscal expenditure	0.85	80.85%
		Fiscal revenue ∩ Fiscal expenditure	0.85	80.85%
		Economic growth ∩ Fiscal expenditure	0.80	70.21%

608.3, and 591.67%, respectively. This shows that government intervention has a limitation and must be integrated with other factors, such as formulating tailored policies based on the local context of urbanization and economic growth. Second, compared with the single factor, the *q* value of the interaction between economic growth and the total investment in water infrastructure projects under construction, the level of financial development, and urbanization increased by 418.75, 406.25, and 406.25%, respectively, further explaining the basic role of the economy. On the one hand, economic growth provides financial capital and a market for financialization. On the other hand, economic growth has spurred the need for water infrastructure financialization. Finally, this study selected the water resources' carrying capacity to represent the level of water security, and the *q* values of the interaction between water resources' carrying capacity and financial level, urbanization, and total investment of water projects under construction increased by 400, 383.33, and 305.56%, respectively. The carrying capacity of water resources is an important factor affecting the construction of water infrastructure. The improvement of the carrying capacity of water resources requires the construction of much water infrastructure, and the lack of funds for the construction of water infrastructure stimulates financialization.

4. FURTHER DISCUSSION

Water is a basic resource for human lives and production and plays a key role in economic growth and urbanization. The increasing urbanization not only intensifies the demand for water resources, but also brings enormous pressure on existing water resources management and water infrastructure (Adeoti *et al.* 2023). The construction of water infrastructure, especially mega water projects, often requires huge investment, and the traditional financing model mainly relies on government fiscal funds (Wang *et al.* 2024). However, on the one hand, the government's fiscal funds are limited, and on the other hand, it is easy to increase the risk of local government debt (Akhmouch & Kauffmann 2013). Therefore, the traditional government investment model has limited the construction, maintenance, and management of water infrastructure, and it is urgent to broaden the financing channels (Lima *et al.* 2021). The financialization of water infrastructure comes into being in this context. Financialization has provided diversified funding sources for water projects. In particular, the introduction of innovative models and financial instruments such as PPPs, REITs, and ABS provide novel financing channels for water infrastructure. At the same time, the participation of market actors has also provided the possibility of risk sharing (Bayliss 2014).

The development of globalization and marketization has provided institutional and market environments for water infrastructure financialization (Stockholm International Water Institute 2019). In particular, the rise of green finance and socially responsible investment has provided more options for raising capital. Governments and financial institutions can attract investors who are concerned about sustainable development and social responsibility by issuing financial products such as green bonds and water project bonds. These financial instruments are not only a vehicle for the financial reallocation of water resources, but also a way to convey the concept of the sustainable use of water resources by the government and society. Through the design and use of these financial instruments, the transparency and traceability of projects can be enhanced, and investors can assess the environmental, social, and governance performance of projects.

Financialization is a market-based process, but the government plays an important role in the financialization process (Pan *et al.* 2021). Governments must encourage private capital to participate in the investment, construction, and operation of water infrastructure by formulating appropriate policies. This requires not only clear policy guidance but also efforts in the construction of legal systems to ensure the rational allocation and effective use of water resources, while also protecting the legitimate interests of investors (Cheng *et al.* 2022). Governments must also consider the long-term benefits and sustainability of projects and prevent the risk of over financialization. In addition, as the results of this study reveal, policies must be closely integrated and coupled with other factors for better effects.

Economic growth and water security have a delicate balance (Dolan *et al.* 2021). Economic growth has promoted urbanization and improved people's lives, but it has also increased the demand for water. Therefore, while promoting economic development, it is particularly important to strengthen water resources management and water infrastructure construction, and the sustainable management and protection of water resources is the cornerstone of sustainable social and economic development. When the balance between water development and protection is reached, the goal of water security and the sustainable development of the economy and society can be truly realized.

There is also significant spatial heterogeneity in water infrastructure financialization (Ahlers & Merme 2016). On the one hand, regional uneven development has a significant impact on financialization; for example, the higher the fiscal revenue of local governments, the less the demand for financialization. On the other hand, the development of water infrastructure financialization also has regional differences due to the comprehensive impact of policies, markets, and water resources endowments. Therefore, governments must promote water infrastructure financialization in accordance with local conditions, rather than a one-size-fits-all approach.

The financialization of water infrastructure is complex and dynamic (Loftus & March 2016). Economic growth and urbanization have driven demand for water infrastructure, and when governments cannot meet this demand with their own funds, the gap creates the need for financialization. The development of the financial industry provides support for water infrastructure financialization. Therefore, the development and practice of water infrastructure financialization should pay attention to the integration of resources, build a collaborative governance mechanism, and prevent financial risks, which is also an important direction for future research on water infrastructure financialization.

5. CONCLUSION

The phenomenon of financialization is extending beyond the economy and into urban development. Water infrastructure also exists in the financialization phenomenon, although currently, few studies have focused on this emerging topic. Enhancing the infrastructure financialization knowledge system and expanding understanding of China's financialization can be achieved by identifying the features and driving forces of China's water infrastructure financialization from a spatial perspective. To this end, this study built an indicator of water infrastructure financialization, identified the spatio-temporal pattern and evolutionary characteristics of water infrastructure financialization in China, employed the GeoDetectors method to analyze the driving forces behind water infrastructure financialization, and evaluated the interactive effects of the driving factors.

The key findings of this study are as follows. First, the overall degree of water infrastructure financialization in China is not high, only Zhejiang, Henan, and Shaanxi provinces have a financialization rate of more than 30%, and Henan has the highest rate of 41.3%, indicating that China's water infrastructure construction is still dominated by traditional government investments. Second, there are significant spatial differences in water infrastructure financialization, it shows the spatial distribution pattern of Henan and Zhejiang as the center and the surrounding area gradually decrease. Third, there is a dynamic and complex evolution process of China's water infrastructure financialization. China's water infrastructure financialization started in the post-financial crisis and developed slowly from 2010 to 2015. From 2015 to 2020, China's water infrastructure financialization has developed rapidly, but the overall level is still not high. Finally, urbanization and water resources' carrying capacity are the main driving factors affecting water infrastructure financialization. Water infrastructure financialization is affected by the integration of multiple factors, and the interaction effect of factors is far greater than that of a single factor.

This study systematically assessed the development degree and influence mechanism of water infrastructure financialization in China. The results of the study are not only helpful for government decision-making optimization but also for practitioners and scholars to understand infrastructure financialization in China. However, this study also has some limitations, such as the limitation of data acquisition, and the limitation of research methods. In addition, comparative studies across multiple countries can be conducted in the future.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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