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Study on the coordinated development of urbanization and water resources utilization efficiency in China

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ABSTRACT

This paper uses the Lotka-Volterra model to illustrate the synergistic relationship between urbanization and water resources utilization efficiency. Combined with a multi-choice goal programming model, the ideal cooperation coefficient between urbanization and water resources utilization efficiency in each provincial region was calculated under the condition of a coordination equilibrium. The results show that the urbanization level of China's provincial regions is uneven. The urbanization level of the eastern coastal developed areas is the highest, followed by the central area, and the western area is the lowest. Guangdong, Jiangsu, Zhejiang, Shanghai, Beijing and Shandong are at a high level of urbanization. The total factor productivity (tfp) of two-thirds of the provincial regions changed to be >1. During the observation period, water use efficiency of most provinces in China improved. The distribution characteristics of urbanization level and water resources utilization efficiency are not consistent. There is no mutually beneficial relationship between urbanization and water resources utilization in most provincial regions. In a few areas, there is a partial benefit cooperation relationship between them. There is a mutually beneficial relationship in a few regions but the level of coordination in the provincial Chinese mainland is relatively low, and needs to be improved.

Key words: coordinated development, Lotka-Volterra model, urbanization, water resources

HIGHLIGHTS

- Uses the Lotka-Volterra model to study the coordination between urbanization and water resources utilization.
- Uses a multi-choice goal programming model to evaluate their coordination.
- Evaluates the efficiency of water use in China and provides a theoretical reference for the government to adopt appropriate policies.

1. INTRODUCTION

Urbanization is a process of population gathering to cities and towns, expanding the scale of cities and towns and resulting in a series of economic and social changes. Its essence is the change of economic, social and spatial structures. Urbanization is an important outcome of economic development, and also a huge driving force to support the economy to achieve a qualitative leap. Urbanization has become the focus of China's social development. China's rapid urbanization has attracted international attention (Yang 2013). Measured by the proportion of urban population in the total population, the level of urbanization increased from 17.92% in 1978 to 60.60% in 2019 (China Statistical Yearbook 1979, 2020). China's urbanization is promoted against the background of large population, relative shortage of resources, fragile ecological environment and unbalanced development of urban and rural areas. The promotion of urbanization level is one of the key tasks of China's economic and social development. In the next two decades, if the current urbanization trend can be held, the urban population in China is estimated to exceed 1 billion (1×109) which will cause a surge in consumption in China (Bai *et al.* 2014). China's urbanization has had a profound impact on China's as well as the world's economy. However, China's urbanization has also led to several problems. With the continuous expansion of cities and towns, the demand of various resources and energy for production and living is increasing, and the total amount of resource factors for production is limited, so there has been a huge contradiction between the limited resource constraints and the growing demand for urban

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construction. As a basic natural resource, water has become the threshold constraint of urban expansion. Although water resources can be obtained by different forms of circular transformation, human beings often waste and pollute in the process of using water resources for production and living activities, which leads to the gradual reduction of the total amount of available water resources.

Urbanization will lead to an increase in the consumption of water (Hao *et al.* 2015), which will in turn affect the environment and the availability of water resources (Bhaskar *et al.* 2015). Excessive development and utilization of water resources and the lack of proper protection will eventually sound the alarm for water resources, restrict human production activities, and hinder regional economic progress and social development. From the perspective of sustainable development, the quantity of available water resources will seriously restrict the speed and quality of urban construction. As an engine of economic development, urbanization is often constrained by water resources. Urbanization has brought vast profits and has been associated with resource scarcity (Wang 2014; Zhao & Chai, 2015). Water crisis is an anticipated problem (Biswas 1991). Water is one of the most critical resources in the world (Brown 2001). There is interaction between water resources and urbanization.

Jeffrey & Konstantine (2008) explored the problems of water resources and urban construction from the perspective of sustainable development, emphasizing the importance of paying attention to ecological protection and green development. Patricia Goher (2010) found that the situation of water resources will be affected by climate conditions, and the carrying capacity of an urban population will not be the same. It is necessary to explore the support of water resources for urban construction according to regional characteristics and different climate environments. Ding *et al.* (2016) emphasized the importance of improving the utilization efficiency of water resources for urban construction. Xu *et al.* (2016) proposed that water resources comprise domestic water and production water, which can meet not only the daily needs of human life, but also the consumption of industrial production, and are one of the most important natural resources. In addition to directly supporting economic and social development as domestic and production water, water resources can also beautify the regional ecological environment in the form of ecological water, so as to attract more material and human capital accumulation (Hubacek *et al.* 2009) to indirectly accumulate social essential resources for urbanization construction, and to improve the speed and quality of urbanization development. In addition to studying how water resources play a dominant role in urban construction, scholars also show that if there is a lack of sufficient water resources or that water pollution is serious, it will become a threshold constraint for the further development of urbanization. Ruth & Paul (2001) believed that the expansion of urban scale will increase the demand for water, resulting in the shortage of regional water supply and restricting the further expansion and development of urbanization. Elias *et al.* (2013) emphasized the effect of 'urban river syndrome'. When human activities destroy the natural environment, resulting in the degradation of river structure, it will directly affect the quantity and quality of surface water resources, thus the water resources can't support the normal life and production of human beings, and ultimately affecting them.

Biswas (2010) said that if urbanization development lacks scientific and reasonable guidance, it will cause irreversible harm to water resources, which is more prominent in small and medium-sized cities with weak scientific and technological strength and a low level of social development. While expanding the urban area, urbanization has occupied a large amount of agricultural and rural land. After cultivated land and forest land have been transformed into urban construction land, the role of water conservation and ecological environment beautification has been greatly weakened, which can't improve the problem of water shortage (Li *et al.* 2016), and the regulation capacity of water pollution and air pollution has also decreased accordingly (Driscoll *et al.* 2011). The results show that the urban heat island effect is becoming more obvious in China (Zhou *et al.* 2016).

Research about urbanization and water resource utilization has focused on water resource carrying capacity (Ait-Aoudia & Berezowska-Azzag 2016), relationships between urbanization and water resource utilization (Sudha *et al.* 2013), relationships between urbanization and water consumption (Rockaway *et al.* 2011), relationships between urban development and water utilization efficiency (Sun *et al.* 2015), and the coordination between urban development and water resource utilization (Derui & Yimin 2009). Some studies focus on the negative effect of the lack of water resources on urban development (Yang *et al.* 2014). However, few studies explore the level of urbanization that could be supported with a limited amount of water supply (Feng *et al.* 2018).

Many past studies depended on results derived from individual indicators rather than considering all aspects of urban development as a more comprehensive approach to obtaining an integrated and optimal solution. As regards research content, some researchers focus on the supporting and restricting role of water resources on urbanization; some researchers focus on the reaction of urbanization on water resources, which is divided into two factions: positive promotion and negative destruction; some researchers demonstrate the correlation between the two and measure the degree of their relationship. These researches are rich in content and have great reference value. However, unilateral research can take into account the impact of factors, and yet there are few papers that continue to explore impact factors in the two-way analysis. Therefore, this paper supplements the main factors that affect the coordination of urbanization and water resources utilization efficiency.

Many studies focus on the negative effect of a lack of water resources on urban development, and only a few studies explore what level of urbanization could be supported with a limited amount of water (Yang *et al.* 2014; Feng *et al.* 2018). At the same time, although the Chinese government has been strengthening the regulation of water saving and emission reduction in recent years, and has achieved many results, it is still difficult to achieve the goal of improving water efficiency from the perspective of China's rising water use scale, water use proportion and wastewater discharge. It has become a key problem to know how to reasonably develop and utilize limited water resources, to give full play to their positive supporting role in the urbanization construction, to explore the suitable urbanization mode, and to form a benign interaction between urbanization construction and water resources protection. Based on the study of the relationship between urbanization and water resources, this paper analyzes the equilibrium point of their coordinated development.

This paper builds an index system of urbanization made up of five dimensions, considering the urbanization level with population, economic, social development, spatial urbanization and environment protection. It evaluates urbanization based on the similarity between optimal values in the sample data. The entropy method was used to determine the weight of the three populations in the evaluation. And then, the paper uses the technique for order preference by similarity to an ideal solution (TOPSIS) method to evaluate the similarity.

The organizational structure of this paper is as follows: (1) A measurement index system of urbanization level is constructed, using the entropy method to assign a weight for each index, and to calculate the urbanization index of each province. (2) Based on the determination of input and output indicators, a DEA-Malmquist model is used to calculate the water resources utilization efficiency of each province. (3) The urbanization development level and water resources utilization efficiency are regarded as two interactive subsystems. According to the population symbiosis equilibrium model, the coordinated development of the two systems is calculated by objective optimization, and the corresponding collaborative types are determined according to the calculation results.

The highlights of this paper are: (1) the urbanization system and water resources utilization system are regarded as symbiotic systems, and the two species symbiosis model (Lotka-Volterra model) is used to study the coordination between urbanization and water resources utilization. (2) The Lotka-Volterra equilibrium condition is embedded into the multi-choice goal programming (MCGP) model to evaluate the coordination between urbanization level and water resources utilization efficiency.

2. METHODS

2.1. Measurement of urbanization level

Researchers are agreed on the indicators of sustainable development of urbanization including economic development, basic public service quality, ecological environment development, urban–rural heterogeneity, and population urbanization. For example, Zhao & Wang (2015) evaluated the sustainable development level of urbanization from nine aspects: city scale and infrastructure, economic growth and economic structure, public welfare and living, environmental quality and environmental improvement, and urban–rural integration. Hezri (2004) built a sustainable index system from health, education, social welfare, environmental conditions, and the economy. Zhong *et al.* (2020) built an urbanization index with the perspective of population urbanization, economic development, ecological environment, urban–rural heterogeneity, and basic public service quality. According to relevant research (Xu *et al.* 2016), the establishment of this index system is in accordance with the principles of scientificity, measurability, hierarchy, and accessibility. Details of the index system are shown in Table 1.

As shown in Table 1, the index system for urbanization consists of five dimensions. This paper considers the urbanization level with population, economy, social development, spatial urbanization and environment protection.

This paper evaluates urbanization based on the differences between observations. The evaluation matrix is A.

$$A = [a_{ij}]_{m\times n} \tag{1}$$

where a_{ij} is the evaluation value of each evaluation index of urbanization.

Table 1 | Urbanization index

	First Level Indicators	Basic Level Indicators
Comprehensive indicator: Urbanization level	A1.Population urbanization	a11.Proportion of urban population
	A2.Economic Urbanization	a21.Per capita gross domestic product (GDP) (yuan)
		a22.Proportion of output value of secondary and tertiary industries in GDP
	A3.Social development	a31.Number of health professionals per thousand people
		a32.Education Fund (ten thousand yuan)
		a33.Number of patents granted
	A4.Spatial Urbanization	a41.Investment in real estate development (100 million yuan)
	A5.Environment protection	a51.Investment in industrial pollution control (ten thousand yuan)

This study uses the entropy method to determine the weight of the indicators in the evaluation. The TOPSIS method is used to evaluate the urbanization level of provincial regions. The ideal value (max value) of the urbanization can be regarded as 8 criteria for evaluating the urbanization of 31 provincial regions on the Chinese mainland.

The entropy weight method reduces the subjective impact of decision makers and increases objectivity (Lee & Chang 2018). Shannon applied entropy to information theory to deal with uncertainty (Zou *et al.* 2006). The less the entropy value is, the more information can be provided. Therefore, the criterion can be assigned a bigger weight (Ye 2010). The calculation of entropy weight is presented as follows (Lotfi & Fallahnejad 2010). Assuming that m represents alternatives (A_1, A_2, …, A_m) and n the criteria (C_1, C_2, …, C_n) for a decision problem, then the initial decision matrix is:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} = [a_{ij}]_{m\times n} \tag{2}$$

Step 1: Normalize the evaluation matrix;

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \tag{3}$$

where r_{ij} is the normalized value of a_{ij}.

Step 2: Compute entropy;

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} r_{ij}\ln r_{ij}, j = 1, 2, \cdots, n \tag{4}$$

where e_j is the entropy value of different indicators.

Step 3: The weights of each criterion are calculated.

$$w_j = \frac{1 - e_j}{\sum_{i=1}^{n}(1 - e_j)}, j = 1, 2, \cdots, n \tag{5}$$

where w_j is the entropy weight value of different indicators.

TOPSIS is a popular method proposed by Hwang & Yoon (1981). The main rule of TOPSIS is that the best alternative should have the shortest distance from the positive-ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS) (Chitsaz & Banihabib 2015). The algorithm of the TOPSIS method is presented as follows:

Step 1: Construct the normalized decision matrix R;

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \tag{6}$$

Step 2: Construct weighted normalized decision matrix V;

$$v_{ij} = w_j r_{ij}, \ \sum_{j=1}^{n} w_j = 1, \quad w_j \text{ is the weight of } j\text{th criterion.} \tag{7}$$

Step 3: Determine the PIS and NIS, denoted respectively as A^+ and A^-, defined in the following way;

$$\begin{aligned} A^+ &= \{(\max v_{ij} | j \in J) \text{ or } (\min v_{ij} | j \in J')\}, i = 1, 2, \cdots, m \\ &= \{v_1^+, v_2^+, \cdots, v_n^+\} \end{aligned} \tag{8}$$

$$\begin{aligned} A^- &= \{(\min v_{ij} | j \in J) \text{ or } (\max v_{ij} | j \in J')\}, i = 1, 2, \cdots, m \\ &= \{v_1^-, v_2^-, \cdots, v_n^-\} \end{aligned} \tag{9}$$

where J and J′ are sets of benefit and cost criteria, respectively.

Step 4: Calculate the distances of each alternative from the PIS and NIS;

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2}, i = 1, 2, \cdots, m \tag{10}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, i = 1, 2, \cdots, m \tag{11}$$

where S_i^+ is the distance from the evaluation unit to the PIS, and S_i^- is the distance from the evaluation unit to NIS.

Step 5: Calculate the closeness coefficient and rank the order of alternatives.

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-}, 0 < C_i^+ < 1, i = 1, 2, \cdots, m \tag{12}$$

where the collaboration score, $C_i^+ \in [0,1]$ with $i = 1, 2, \ldots, m$. The best alternative can therefore be found according to the preference order of C_i^+. The higher the value, the better. If C_i^+ is close to 1, it indicates that the alternative A_i is closer to the PIS.

2.2. Calculation of water resources utilization efficiency

Data envelopment analysis (DEA) is widely used to evaluate water use efficiency across multiple periods. Liao & Dong (2011), Ali & Klein (2014) and Feng *et al.* (2019) used the DEA-Malmquist Index to estimate the agricultural water efficiency. Ren *et al.* (2017) used two-stage DEA to analyze water resource use efficiency. Wang *et al.* (2018a, 2018b) estimated water efficiency with a DEA-Tobit model. The DEA method does not need to take into consideration the functional relationship between various inputs and outputs, nor does it need to estimate the parameters in advance; it avoids subjective factors, simplifies the calculation method and reduces error. The DEA method can analyze multiple input and output indexes at the same time. The analysis results of each DMU can be optimized. Since its introduction, DEA has attracted much attention for its unique advantages, and it has become a common analysis tool and method.

On the basis of the index system of water resource efficiency constructed by some scholars (Cao *et al.* 2017; Wang *et al.* 2018a, 2018b, Hsieh *et al.* 2019), this research chooses five factors as water resource inputs and outputs.

As shown in Table 2, this paper employs total water resources, soil erosion control area and gross domestic product (GDP) as output indicators. This research uses the DEA-Malmquist Index approach to evaluate water resource use efficiency, and the

Table 2 | Input and output index system of water use efficiency evaluation

Indicators	Index (unit)	Index nature
Resource dimension	(I1) supply water (100 million cubic meters)	Input
	(O1) total water resources (100 million cubic meters)	Output
Economic dimension	(O2) GDP (100 million yuan)	Output
Environmental dimension	(I2) Investment in industrial wastewater treatment (10,000 yuan)	Input
	(O3) Soil erosion control area (1,000 hectare)	Output

data from 2016–2019 as the analytical data. The annual statistical data comes from China's National Bureau of Statistics (2017–2020).

In order to further analyze water use efficiency, total factor productivity (tfp) is used as a measure of technological progress, and the Malmquist Index was measured. The input-based total factor productivity index (tfpch) can be expressed by the Malmquist index, namely:

$$M_0^{t+1} = \left[\frac{D^t(x_0^{t+1}, y_0^{t+1})}{D^t(x_0^t, y_0^t)} \times \frac{D^{t+1}(x_0^{t+1}, y_0^{t+1})}{D^{t+1}(x_0^t, y_0^t)}\right] \tag{13}$$

The Malmquist Index can be combined with the Data Envelopment Analysis (DEA) Method to measure changes in population productivity, and the Index can be decomposed into two parts, namely, efficiency changes (effch) and technology changes (techch). The Malmquist Index Formula can be expressed as:

$$MI = \frac{D^{t+1}(x_0^{t+1}, y_0^{t+1})}{D^t(x_0^t, y_0^t)}\left[\frac{D^t(x_0^{t+1}, y_0^{t+1})}{D^{t+1}(x_0^{t+1}, y_0^{t+1})} \times \frac{D^t(x_0^t, y_0^t)}{D^{t+1}(x_0^t, y_0^t)}\right] = \text{effch} \times \text{techch} \tag{14}$$

Total factor productivity changes can be decomposed into technology changes (techch) and efficiency changes (effch), and efficiency changes can be decomposed into pure technical efficiency changes (pech) and scale efficiency changes (sech), namely:

$$\text{tfpch} = \text{effch} \times \text{techch} \tag{15}$$

$$\text{effch} = \text{pech} \times \text{sech} \tag{16}$$

Here, effch > 1 means efficiency improvement, effch < 1 means efficiency reduction; techch > 1 means technological progress, and techch < 1 means technological decline.

2.3. Analysis of the synergistic effect of urbanization and water resources utilization

In urbanization and water resources utilization systems, competition can occur between systems that use common resources. Symbiosis in the system does not exclude competition. Urbanization and water resources utilization systems in completely or part of the same living space need to conduct technology, talent, and market interaction in the factor market. However, when one party in the system relies on another core or dominant population to obtain resources and living space, a parasitic relationship is formed. Under the parasitic relationship, the symbiotic subject has a one-way exchange of interests. Because of the one-way asymmetric exchange, this state is not extensive. Therefore, the system will gradually develop in the direction of symbiosis that is conducive to mutual dependence and mutual benefit. According to the Logistic model (Verhulst, 1838), this paper constructs an internal relationship model of a water resources utilization system ($\mathbf{S_1}$) as follows.

$$g_1(t) = \frac{dN_1(t)}{dt} = \alpha_1 N_1\left(1 - \frac{N_1}{K_1}\right) \tag{17}$$

where $g_1(t)$ indicates the growth rate of phase t. $N_1(t)$ indicates the efficiency of water resources utilization in phase t. Within a certain period of time (phase t), K_1 is the maximum efficiency in a constant environment. $\alpha_1$reflects the promotion of the growth of the water resources utilization efficiency. $\left(1-\frac{N_1}{K_1}\right)$reflects the retardation of growth due to the consumption of limited resources.

If $g_1(t) > 0$, then $\Delta N_1(t) > 0$. Synergistic effects are the dominant effects in this water resources utilization system. Resources within a water resources utilization system can support an increase in the efficiency of the system. Thus, the water resources utilization system can be sustainable.

If $g_1(t) < 0$, then $\Delta N_1(t) < 0$. The competition effect is dominant in this water resources utilization system. Such a system is less able to support the increase in the number of individuals in the water resources utilization system. Thus, the system is unsustainable.

According to the Logistic model, this paper constructs an internal relationship model of an urbanization system (S_2) as follows.

$$g_2(t) = \frac{dN_2(t)}{dt} = \alpha_2 N_2\left(1-\frac{N_2}{K_2}\right) \tag{18}$$

where $N_2(t)$ represents the urbanization index (UI) in period t. Researchers should consider the impact of system 2 on system 1. Then, the logistic model can be modified as follows:

$$g_1(t) = \frac{dN_1(t)}{dt} = \alpha_1 N_1\left(1-\frac{N_1}{K_1}+\frac{\beta_{12}N_2}{K_2}\right) \tag{19}$$

where β_{12} is the influence coefficient of system 2 on system 1. If $\beta_{12} > 0$, system 2 has a synergistic effect on system 1. If $\beta_{12} < 0$, system 2 has a competitive effect on system 1. After the formation of the dependent symbiosis system, due to the promotion of system 1, the level of system 2 will also increase. The change of system 2 can be described as:

$$g_2(t) = \frac{dN_2(t)}{dt} = \alpha_2 N_2\left(1-\frac{N_2}{K_2}+\frac{\beta_{21}N_1}{K_1}\right) \tag{20}$$

where β_{21} is the influence coefficient of system 1 on system 2. If $\beta_{21} > 0$, system 1 has a synergistic effect on system 2. If $\beta_{21} < 0$, system 1 has a competitive effect on system 2. In the system of S_1 and S_2, the symbiosis mathematical model is:

$$\begin{cases} g_1(t) = \dfrac{dN_1(t)}{dt} = \alpha_1 N_1\left(1-\dfrac{N_1}{K_1}+\dfrac{\beta_{12}N_2}{K_2}\right) \\ g_2(t) = \dfrac{dN_2(t)}{dt} = \alpha_2 N_2\left(1-\dfrac{N_2}{K_2}+\dfrac{\beta_{21}N_1}{K_1}\right) \end{cases} \tag{21}$$

Among outcomes, $1 > \beta_{12} > 0$, $1 > \beta_{21} > 0$. β_{12} is the contribution of system 2 to system 1, which means that the resources that system 2 supplies to system 1 are β_{12} times the resources that system 2 supplies to itself. According to the dependence and independence conditions, then $1 > \beta_{12} > 0$. Similarly, we can get $1 > \beta_{12} > 0$.

Equation (21) is called the Lotka-Volterra model. The Lotka-Volterra model of dual-population or multi-system growth is a differential dynamic system to simulate dynamic relationship systems in an innovation ecosystem. Based on the numerical value of β, the type of interaction between species can be judged as:

(1) When $\beta_{12} = 0$, $\beta_{21} = 0$, it means that the systems are independent, and they develop independently, and do not affect each other. At this time, the Lotka-Volterra model expresses no symbiotic relationship.
(2) When $\beta_{12} < 0$, $\beta_{21} < 0$, it means that the two systems compete with each other. One party grows while the other party declines. There is no symbiotic relationship between the two systems.
(3) When $\beta_{12} > 0$, $\beta_{21} < 0$ or $\beta_{12} < 0$, $\beta_{21} > 0$, it means that one party is attached to the other party during the symbiotic evolution of the system, showing a parasitic mode of constantly requesting resources from the other party to maintain its own growth.

(4) When $\beta_{12} > 0$, $\beta_{21} = 0$ or $\beta_{12} = 0$, $\beta_{21} > 0$, it means that both sides of the system have obtained extra high-quality resources in the evolution process, but the symbiosis coefficient of one system is zero, indicating that it has not obtained extra resources, and the system is now in a symbiotic mode of partial benefit.

(5) When $\beta_{12} > 0$, $\beta_{21} > 0$, it means that the system is in a mutually beneficial symbiosis mode. Among them, if $\beta_{12} \neq \beta_{21}$, it means that the symbiotic relationship between the two parties is asymmetric and a mutually beneficial symbiosis; when-$\beta_{12} = \beta_{21}$, it means that the system has obtained equal benefits in the process of symbiotic evolution, and the resources are exchanged in equal amounts, forming a symmetric and mutually beneficial symbiosis.

The Lotka-Volterra model is often used to analyze the cooperative or competitive relationship of systems. Studies have shown that the introduction of Lotka-Volterra, a competition model in biology, into market competition and diffusion has produced better analysis results. In recent years, MCGP has been widely used to resolve many practical decision-making problems. This paper builds MCGP and Lotka-Volterra MCGP models for innovative population scale optimization. On the basis of successful use of the MCGP method (Wang *et al.* 2021), considering the symbiotic relationship, this problem can be formulated as follows:

$$\begin{cases} \text{Min } d_1^+ + d_1^- + e_1^+ + e_1^-; \\ \textit{restrictions} \\ y_1 = F(x); \quad \text{for output goal, the more the better} \\ y_1 - e_1^+ + e_1^- = O_T; \\ x_1 = \dfrac{k_1(1+\beta_{12})}{1-\beta_{12}\cdot\beta_{21}}; \text{ equilibrium value for tfpch} \\ x_2 = \dfrac{k_2(1+\beta_{21})}{1-\beta_{12}\cdot\beta_{21}}; \text{ equilibrium value for urbanization} \\ x_1 > 0; x_2 > 0; d_1^+ >= 0; d_1^- >= 0; e_1^+ >= 0; e_1^- >= 0 \\ -1 < \beta_{12} < 1; \text{ for ranges of } \beta_{12} \\ -1 < \beta_{21} < 1; \text{ for ranges of } \beta_{21} \\ \dfrac{x_1}{x_2} = \dfrac{k_1(1+\beta_{12})}{k_2(1+\beta_{21})}; \text{ ratio constraint between tfpch and urbanization} \end{cases} \tag{22}$$

3. EMPIRICAL ANALYSIS

The data for this paper is selected from the China Statistical Yearbook 2017–2020 (http://www.stats.gov.cn/tjsj/ndsj/2020/indexch.htm).

In Table 3, statistical characteristics of urbanization sample data are provided. Entropy weight is calculated based on the data in the example.

As shown in Table 4, entropy weight is calculated.

As shown in Table 5, this paper can successfully evaluate urbanization in different provincial regions. Guangdong, Jiangsu, Zhejiang, Shanghai, Beijing and Shandong are at a high level of urbanization. Tibet has the lowest level of urbanization in China.

As shown in Figure 1, the urbanization level of provincial regions on the Chinese mainland show a significant imbalance. The provincial regions with a prominent urbanization level are mainly distributed in economically developed areas. The urbanization level of the underdeveloped areas in the central and western regions is relatively low. The lag of economic

Table 3 | Statistical characteristics of urbanization sample data

Indicators	**a11**	**a21**	**a22**	**a31**	**a32**	**a33**	**a41**	**a51**
Maximum	88.3	164,220.0	99.7	12.6	42,684,258.0	527,390.0	15,852.2	1,130,995.0
Minimum	30.9	28,497.0	76.7	4.9	1,857,714.0	420.0	40.4	694.0
Average (mean)	59.9	65,114.8	91.2	7.0	12,461,376.2	69,698.5	3,895.0	212,719.3
Std Dev	11.7	29,748.2	4.9	1.2	7,800,856.3	97,500.4	3,276.6	220,923.7

Table 4 | Urbanization index weight based on entropy method

Indicators	a11	a21	a22	a31	a32	a33	a41	a51
w_j	0.154	0.140	0.157	0.154	0.126	0.069	0.107	0.093

Table 5 | Result of TOPSIS

	Year				Year		
Area	2019	2018	2017	Area	2019	2018	2017
Beijing	0.410	0.392	0.370	Hubei	0.272	0.254	0.236
Tianjin	0.253	0.281	0.273	Hunan	0.242	0.220	0.197
Hebei	0.281	0.265	0.252	Guangdong	0.660	0.648	0.573
Shanxi	0.222	0.238	0.230	Guangxi	0.186	0.166	0.149
Inner Mongolia	0.203	0.233	0.226	Hainan	0.135	0.129	0.123
Liaoning	0.202	0.199	0.185	Chongqing	0.234	0.215	0.200
Jilin	0.136	0.145	0.135	Sichuan	0.306	0.278	0.249
Heilongjiang	0.127	0.132	0.128	Guizhou	0.183	0.160	0.134
Shanghai	0.407	0.395	0.375	Yunnan	0.211	0.172	0.150
Jiangsu	0.627	0.561	0.502	Tibet	0.068	0.053	0.041
Zhejiang	0.526	0.498	0.434	Shaanxi	0.264	0.226	0.206
Anhui	0.289	0.260	0.238	Gansu	0.110	0.100	0.090
Fujian	0.312	0.279	0.253	Qinghai	0.125	0.115	0.103
Jiangxi	0.203	0.170	0.151	Ningxia	0.143	0.140	0.130
Shandong	0.532	0.533	0.504	Xinjiang	0.160	0.143	0.133
Henan	0.381	0.367	0.343	*Mean*	*0.271*	*0.257*	*0.236*

development will significantly affect social progress. Because there are social development indicators in the evaluation index system of urbanization in this paper, the difference between the urbanization level of the eastern developed areas and the western areas is particularly obvious. The urbanization level of the eastern regions is higher than that of the central and western regions. From the regional distribution of urbanization level, the eastern regions have a higher urbanization level, while the central and western regions have a lower urbanization level. The economically developed provinces in the eastern regions are the provincial regions with the highest urbanization level, while the provincial regions in the central and western regions have lower urbanization level. On the one hand, this is related to the level of economic and social development and industrial structure of provincial regions, and the developed provinces can obtain more economic benefits; on the other hand, it is also related to the blind expansion and extensive development of some underdeveloped provinces in the absence of industrial support and absorption capacity.

This paper finds that the urbanization level of most regions has not changed significantly in recent years. This is significantly different from existing studies. Some researchers found the urbanization level of most regions in China generally increased.

Wang *et al.* (2019) found the success of China's urbanization at poverty reduction and environmental improvement. Environmental protection, economic and social development are considered in the evaluation index system of urbanization in this paper. Some of the these points are supported by their research.

The calculation results of the Malmquist index are shown in Table 6 (Data envelopment analysis programme (DEAP) software was used to calculate the Malmquist index).

As shown in Table 6, the overall situation in the country was that the efficiency of water-resource utilization was above 1.000, and there are obvious differences among the areas. Shanghai, Heilongjiang, Xinjiang and Hunan have relatively

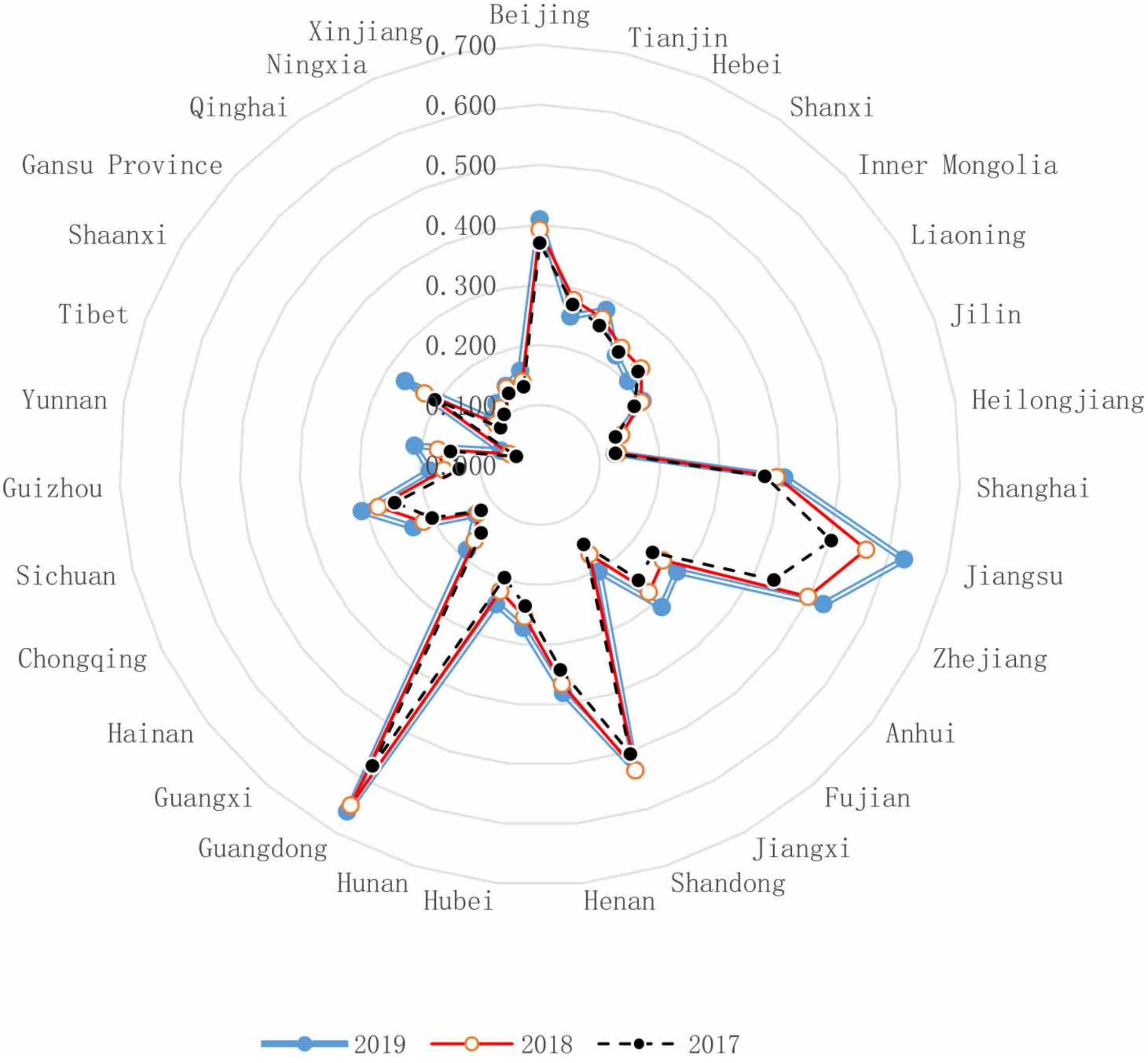

Figure 1 | The urbanization level of provincial regions. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2021.238.

high tfpch. The tfpch value of Inner Mongolia, Liaoning, Jilin, Anhui, Henan, Hubei, Guangxi, Chongqing and Yunnan are less than 1, the total factor productivity of water use in these regions is declining.

As shown in Figure 2, the relationship between total factor productivity change, technological progress and efficiency change is similar in most provincial regions. The change is also relatively mild. There are significant changes in a few areas, such as Heilongjiang and Shanghai.

Affected by geography, resource endowment, social history and other factors, the water environment problem is more prominent, although the eastern region has certain resource advantages and good industrial and economic support. In this regard, we need to improve the supervision and market access mechanism of regional water consumption industries, promote the upgrading of water-saving equipment and technology by accelerating industrial water circulation, plan and screen high water consumption industries, and moderately transfer some water consumption industries to south and central China, so as to control high water consumption in east China during the process of promoting regional economic growth. Central China has a relatively high concentration of thermal power, steel, petroleum and petrochemical high water consumption

Table 6 | Malmquist index summary of annual means

Area	tfpch	techch	effch	pech	sech	Area	tfpch	techch	effch	pech	sech
Beijing	1.000	1.205	1.000	1.000	1.205	Henan	0.939	1.083	0.995	0.944	1.017
Tianjin	1.000	0.819	1.000	1.000	0.819	Hubei	0.889	1.046	0.953	0.933	0.930
Hebei	1.036	1.063	0.965	1.074	1.102	Hunan	1.253	1.047	1.069	1.172	1.312
Shanxi	1.000	1.010	1.000	1.000	1.010	Guangdong	1.126	0.932	1.000	1.126	1.049
Inner Mongolia	0.985	1.012	1.000	0.985	0.997	Guangxi	0.908	1.084	0.955	0.951	0.984
Liaoning	0.946	1.069	0.855	1.106	1.011	Hainan	1.000	1.125	1.000	1.000	1.125
Jilin	0.786	0.874	0.787	0.999	0.687	Chongqing	0.991	0.963	0.992	0.999	0.954
Heilongjiang	1.519	0.999	1.361	1.116	1.517	Sichuan	1.148	0.957	1.000	1.148	1.099
Shanghai	1.703	0.861	1.175	1.449	1.466	Guizhou	1.000	1.013	1.000	1.000	1.013
Jiangsu	1.055	1.086	1.163	0.907	1.146	Yunnan	0.974	1.012	1.000	0.974	0.986
Zhejiang	1.186	0.887	1.000	1.186	1.052	Shaanxi	1.000	1.049	1.000	1.000	1.049
Anhui	0.981	0.951	0.893	1.098	0.932	Gansu	1.133	1.051	1.095	1.035	1.191
Fujian	1.043	0.946	0.934	1.117	0.987	Ningxia	1.038	1.024	1.103	0.941	1.063
Jiangxi	1.051	0.945	0.923	1.139	0.993	Xinjiang	1.298	1.133	1.297	1.001	1.471
Shandong	1.041	0.968	1.000	1.041	1.008						

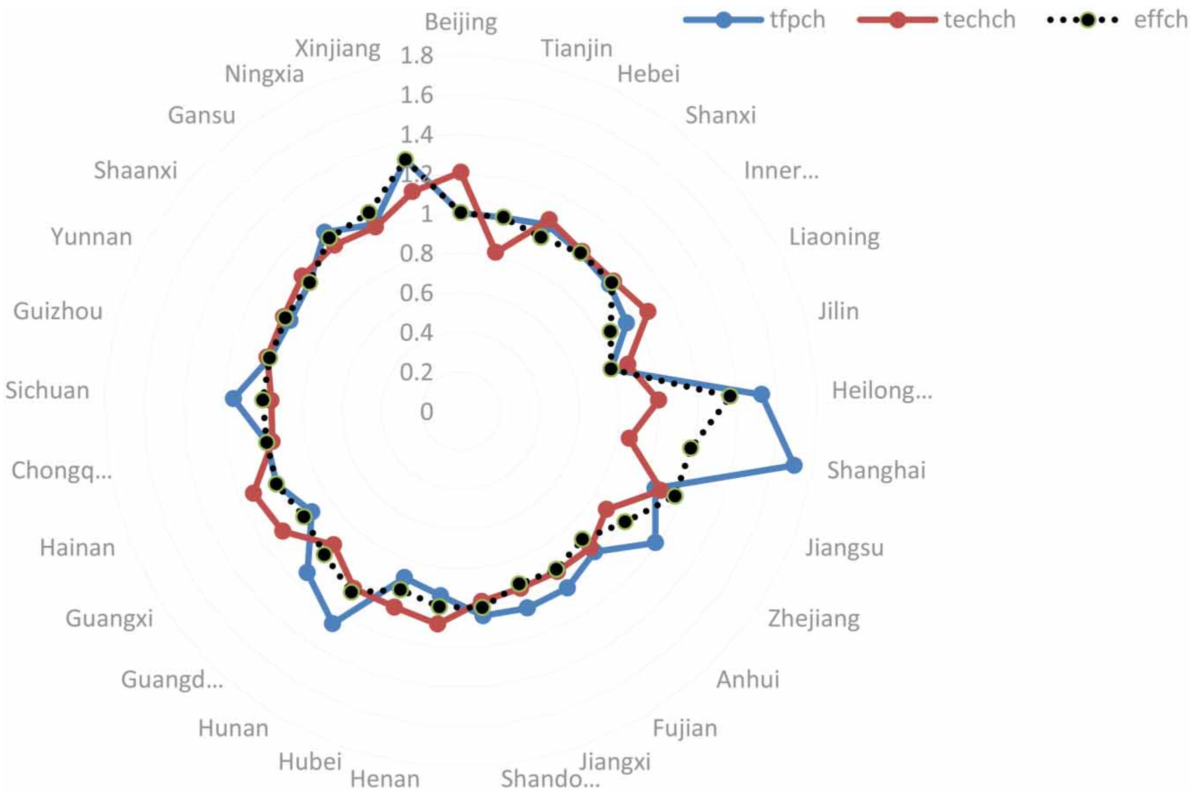

Figure 2 | The water resources utilization efficiency of provincial regions. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2021.238.

industries. Such industries should strictly control the growth rate of new production capacity, improve the access threshold, and try to gradually shift the industrial focus on water consumption product processing to the southern region while improving their water-saving technology capacity. There are abundant coal and gas resources in the west, which determines that thermal power and coal chemical industries are the leading industries in the industrial layout. However, the development of this kind of high water consumption industry should follow the 'moderation' principle, especially the implementation of the strictest water resources management systems, in-depth demonstration and analysis of industrial water use, and water environment problems caused by large water consumption and poor economic benefits. Old, redundant industrial enterprises should be shut down, and the coal chemical industry bases or parks should be encouraged to expand, so as to promote the cascade utilization and centralized treatment of water resources.

Existing research on water resource efficiency in the provinces of China shows that the absolute number and relative proportion of agricultural water use are important influence factors of water resources efficiency (Li *et al.* 2017). In this regard, this paper has a different view. Here, it is found that the difference of water resource efficiency in China is mainly caused by resource protection and pollution control.

After calculating the urbanization level and water resource efficiency, this paper will further analyze the interaction mechanism between them. On the basis of the MCGP, considering the symbiotic relationship, this problem can be formulated as model (23):

$$\begin{cases} \text{Min } \; d_1^+ + d_1^- + e_1^+ + e_1^-; \\ \textit{restrictions} \\ y_1 = 15{,}044x_1 + 177{,}231x_2 - d_1^+ + d_1^-; \quad \text{for output goal, the more the better} \\ y_1 - e_1^+ + e_1^- = O_T; \\ x_1 = \dfrac{k_1(1+\beta_{12})}{1-\beta_{12}\cdot\beta_{21}}; \text{ equilibrium value for tfpch} \\ x_2 = \dfrac{k_2(1+\beta_{21})}{1-\beta_{12}\cdot\beta_{21}}; \text{ equilibrium value for urbanization} \\ x_1 > 0; x_2 > 0; d_1^+ >= 0; d_1^- >= 0; e_1^+ >= 0; e_1^- >= 0 \\ -1 < \beta_{12} < 1; \text{ for ranges of } \beta_{12} \\ -1 < \beta_{21} < 1; \text{ for ranges of } \beta_{21} \\ \dfrac{x_1}{x_2} = \dfrac{k_1(1+\beta_{12})}{k_2(1+\beta_{21})}; \text{ ratio constraint between tfpch and urbanization} \end{cases} \tag{23}$$

The objective function in the model is:

Table 7 | Solution of the MCGP model

Area	tfpch	UI	β_{12}	β_{21}	Area	tfpch	UI	β_{12}	β_{21}
Beijing	1.204	0.712	0.112	0.684	Henan	0.939	0.363	0.000	0.000
Tianjin	1.232	0.516	0.121	0.745	Hubei	0.889	0.308	0.000	0.215
Hebei	1.036	0.266	0.000	0.000	Hunan	1.253	0.219	0.000	0.000
Shanxi	1.000	0.230	0.000	0.000	Guangdong	1.126	0.627	0.000	0.000
Inner Mongolia	0.985	0.292	0.000	0.323	Guangxi	0.907	0.167	0.000	0.000
Liaoning	0.946	0.237	0.000	0.216	Hainan	0.999	0.210	0.000	0.629
Jilin	0.786	0.223	0.000	0.614	Chongqing	0.991	0.301	0.000	0.397
Heilongjiang	1.519	0.129	0.000	0.000	Sichuan	1.148	0.278	0.000	0.000
Shanghai	1.703	0.643	0.000	0.637	Guizhou	1.000	0.159	0.000	0.000
Jiangsu	1.055	0.563	0.000	0.000	Yunnan	0.974	0.178	0.000	0.000
Zhejiang	1.186	0.486	0.000	0.000	Shaanxi	1.000	0.267	0.000	0.153
Anhui	0.981	0.262	0.000	0.000	Gansu	1.133	0.100	0.000	0.000
Fujian	1.043	0.439	0.000	0.566	Ningxia	1.038	0.211	0.000	0.529
Jiangxi	1.129	0.175	0.074	0.000	Xinjiang	1.298	0.169	0.000	0.169
Shandong	1.041	0.523	0.000	0.000					

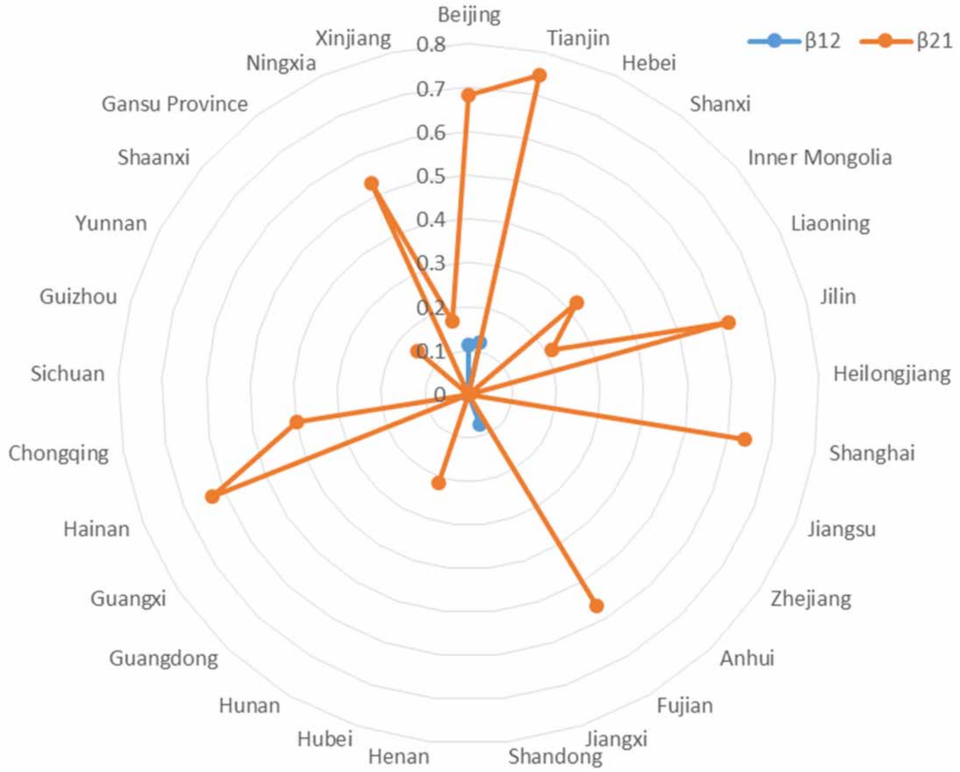

Figure 3 | Interaction between urbanization and water efficiency. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2021.238.

$F_1(X) = 15{,}044x_1 + 177{,}231x_2$ (Per capita GDP, output goal, the more the better). x_1, x_2 respectively represent the level of urbanization and the efficiency of water resources utilization. The problem is solved using LINGO (Schrage 2002) software, and is shown in Table 7.

As seen in Table 7, the synergy of urbanization and water use efficiency can be divided into the following three categories: (1) There is a two-way synergy between urbanization and water resources utilization, such as in Beijing and Tianjin. (2) There is no interaction between urbanization and water resources utilization. They are isolated systems. (3) There is a one-way promotion between urbanization and water resources utilization such as in Inner Mongolia, Liaoning, Jilin, Shanghai, Fujian, Hubei, Hainan, Chongqing, Shaanxi, Ningxia and Xinjiang.

As shown in Figure 3, the efficiency of water resources utilization in some provincial regions has a significant synergistic effect on urbanization. However, only a few provincial-level urbanization levels have a positive effect on improving the efficiency of water resources utilization. There is no synergy between water resources utilization and urbanization in most provincial regions.

4. RESULTS AND DISCUSSION

4.1. Results

In China, urbanization of provincial regions show a significant imbalance. The provincial regions with a prominent urbanization level are mainly developed areas. Guangdong, Jiangsu, Zhejiang, Shanghai, Beijing and Shandong are at a high level of urbanization. The urbanization level of the underdeveloped areas in the central and western regions are relatively low. Tibet has the lowest level of urbanization in China. The lag of economic development will significantly affect social progress with negative influence. The difference between the urbanization level of the eastern developed areas and the western areas is particularly obvious.

This research chose supply water and investment in industrial wastewater treatment as water resource inputs, and employs total water resources, soil erosion control area and GDP as output indicators. It uses the DEA-Malmquist Index approach to evaluate water resources use efficiency. The total factor productivity change (tfpch) of water resources utilization in different provinces is also uneven. Shanghai, Heilongjiang, Xinjiang and Hunan have relatively high tfpch. The tfpch values of Inner Mongolia, Liaoning, Jilin, Anhui, Henan, Hubei, Guangxi, Chongqing and Yunnan are less than 1, and the total factor productivity of water use in these regions is declining. The relationship between total factor productivity change, technological progress and efficiency change is similar in most provincial regions.

The synergy of urbanization and water use efficiency can be divided into the following three categories: a two-way synergy between urbanization and water resources utilization; no interaction between urbanization and water resources utilization; and a one-way promotion between urbanization and water resources utilization. The efficiency of water resources utilization in some provincial regions has a significant synergistic effect on urbanization. However, only a few provincial urbanization levels have a positive effect on improving the efficiency of water resources utilization. There is no synergy between water resources utilization and urbanization in most provincial regions.

4.2. Discussion

There are similarities and differences between the results of this paper and existing studies. The existing studies on water resource efficiency in China show that water resource efficiency has increased in recent years (Yang 2020). This paper has similar findings. In the study of regional differences of water resources efficiency, some studies show that most regions still need improvement (Wang *et al.* 2018a, 2018b). Some findings on regional differences show the best average efficiency value in southwest China and the worst in north China (Hsieh *et al.* 2019). This paper supports the view that there are efficiency differences among regions. This means that not all regions need to improve water use efficiency.

The existing research mainly discusses the relationship between urbanization and water resource use. Wang *et al.* (2018a, 2018b) found long-term equilibrium relationships between urbanization and water use. An *et al.* (2018) found that the drag effect of water consumption on urbanization has significant spatial correlation. There are also some new findings about the relationship between urbanization and water resource efficiency. There is no mutually beneficial relationship between urbanization and water resources utilization in most provincial regions. In a few areas, there is a partial benefit cooperation relationship between urbanization and water resources utilization. There is a mutually beneficial relationship between urbanization and water resources utilization in a few regions. The coordination level of urbanization and water resources utilization in the provincial level of the Chinese mainland is relatively low, and needs to be improved.

This paper also makes some useful attempts on methods. Various optimization algorithms have been developed and applied to many fields of study, such as genetic algorithms (Asadi *et al.* 2014), cuckoo optimization algorithm (Rajabioun 2011), artificial neural networks (Al-Zahrani & Abo-Monasar 2015), harmony search algorithm (Bashiri-Atrabi *et al.* 2015), and their modified versions (Srinivasan & Kumar 2018). Among them, the evolutionary search, non-dominated sorting genetic algorithm (Deb *et al.* 2002) is one of the most popular multi-objective genetic algorithms. However, the existing optimization models mentioned in this paragraph do not take into consideration the synergy between urbanization level and water resources utilization efficiency. This study combines the Lotka-Volterra equilibrium model with the multi-choice goal programming method to explore the synergy between urbanization and water resource efficiency at the current output scale.

5. CONCLUSION

This paper focuses on current urbanization and water resources utilization efficiency, and their interaction in China. Through the review of related research, an evaluation index system is constructed. Based on the determination of input and output indicators, a DEA-Malmquist model is used to calculate the water resources utilization efficiency of each province. The Lotka-Volterra model is used to illustrate the synergistic relationship between urbanization and water resources utilization efficiency. Combined with the MCGP model, the cooperation coefficient between urbanization and water resources utilization efficiency in each provincial region is calculated under the condition of coordination equilibrium. The results show that there is no mutually beneficial relationship between urbanization and water resources utilization in most provincial regions. In a few areas, there is a partial benefit cooperation relationship between urbanization and water resources utilization. There is a mutually beneficial relationship between urbanization and water resources utilization in a few regions. The coordination level of urbanization and water resources utilization at the provincial level on the Chinese mainland is relatively low, and needs to be improved.

The deficiencies of this paper are mainly reflected in the following aspects: (1) There is a lack of internal mechanism research on the interaction between urbanization and water resources utilization efficiency. In the process of urbanization, economic and social benefits are often emphasized. As an ecological or environmental factor, the efficiency of water resources is characterized by ecological and technological effects. The sustainable development of the two requires efficiency, sustainability and coordination of development. (2) The output variables in collaborative research are single, not rich enough, and not systematic. In the MCGP optimization model, GDP is selected as the main output index. Sustainable and environmental indicators should be added as expected output indicators. (3) The positive role of technological innovation in the process of urbanization and water resources utilization has been ignored. We should actively promote the improvement of water-saving technology, build efficient utilization platforms and a corresponding experimental base, and improve the production, living and ecological water appliances and processes to varying degrees, so as to improve the comprehensive utilization efficiency of water resources. (4) There is a lack of inter-regional interaction mechanism research. In the process of urbanization, different regions should strengthen coordination and cooperation in all aspects, because cities with high water use efficiency will form a cross-regional spillover effect on cities with low efficiency. Regions with high water use efficiency should maintain a demonstration effect, continue to play a radiation role, and drive the improvement of water resources efficiency in surrounding areas, while regions with relatively slow efficiency progress should promote a follow up catch up effect.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

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

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