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

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\textbf{ABSTRACT}

The paper uses Lotka-Volterra model to illustrate the synergistic relationship between urbanization and water resources utilization efficiency. Combined with the multi-choice goal programming model, the ideal 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 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 of two-thirds of provincial regions changed to more than one. During the observation period, water use efficiency of most provinces in China has been 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. The coordination level of them in the provincial of Chinese mainland is relatively low, and needs to be improved.

\textbf{Key words:} coordinated development, Lotka-Volterra model, urbanization, water resources

\textbf{HIGHLIGHTS}

\begin{itemize}
\item Using Lotka-Volterra model to study the coordination between urbanization and water resources utilization.
\item Using MCGP model to evaluate the coordination of them.
\item Evaluating the efficiency of water use in China and provides a theoretical reference for the government to adopt appropriate policies.
\end{itemize}

1. \textbf{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 structure, social structure and spatial structure. Urbanization is an important outcome of economic development, and also a huge driving force to support the economy to achieve a qualitative leap. The 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. That will cause a surge in consumption in China (Bai \textit{et al.} 2014). China's urbanization has had a profound impact on China's as well as the world's economy (David 2016). However, China's urbanization has also lead 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 factor resources for production is limited, so there has been a huge contradiction between the limited resource constraints and the growing
demand for urban construction. As a basic natural resource, water resource 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 resource (Bhaskar et al. 2015). Excessive development and utilization of water resources and the lack of proper protection means 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 urbanization construction. As an engine of economic development, urbanization is often constrained by water resources. Urbanization brought vast profits and was associated with resource scarcity (Wang 2014; Zhao et al. 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 urban population is not the same. It is necessary to explore the support of water resources for urban construction according to the regional characteristics and different climate environments. Lei and Li considered the limitation and vulnerability of water resources, Chen (2016) emphasized the importance of improving the utilization efficiency of water resources for urban construction. Xu et al. (2016) proposed that water resources comprises domestic water and production water, which can meet not only the daily needs of human life, but also the consumption of industrial production, and is 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) believes 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 affect human beings.

Biswas (2010) said that if the 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 low level of social development. While expanding the urban area, urbanization has occupied a large amount of agricultural and rural land in space. After the 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 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 (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). In recent years, research related to urbanization and water resource utilization mainly focused on water resource carrying capacity (Ait-Aoudia & Berezowska-Azzag 2016), and water utilization efficiency (Sun et al. 2015).

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 the 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 the 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 on how to reasonably develop and utilize the limited water resources, to give full play to its 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 the index system of urbanization made up of five dimensions, considering the urbanization level with population, economic, social development, spatial urbanization and environment protection. This paper evaluates the urbanization based on the similarity between optimal value in sample data. 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) The measurement index system of urbanization level is constructed, using entropy method to assign weight for each index, and to calculate the urbanization index of each province. (2) Based on the determination of input and output indicators, 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 as follows: (1) the urbanization system and water resources utilization system are regarded as symbiotic system, and the two species symbiosis model (Lotka-Volterra model) is used to study the coordination between urbanization and water resources utilization. (2) 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 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 (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 the Indicators system of urbanization with the perspective of population urbanization, economic development, ecological environment, urban–rural heterogeneity, 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 of urbanization consists of five dimensions. This paper considers the urbanization level with population, economy, social development, spatial urbanization and environment protection.
This paper evaluates the urbanization based on the differences between observations. The evaluation matrix is $A$.

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

(1)

This study uses the entropy method to determine the weight of the indicators in the evaluation. The technique for order preference by similarity to an ideal solution (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 in Chinese mainland.

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 $m$ is alternatives ($A_1, A_2, \ldots, A_m$) and $n$ is criteria ($C_1, C_2, \ldots, C_n$) for a decision problem. Then initial decision matrix is:

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

(2)

Step 1: Normalize the evaluation matrix;

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

(3)

Step 2: Compute entropy;

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

(4)

Step 3: The weights of each criterion are calculated.

$$w_j = \frac{1 - e_j}{\sum_{i=1}^{n} (1 - e_i)}, j = 1, 2, \ldots, n$$

(5)

Technique for order preference by similarity to an ideal solution (TOPSIS) is a popular method proposed by Hwang & Yoon (1981). The main rule of TOPSIS is that the best alternative should have shortest distance from the positive-ideal

| Table 1 | Index system of urbanization |
|-----------------|-----------------------------|
| **First Level Indicators** | **Basic Level Indicators** |
| Comprehensive indicator: Urbanization level | a11. Proportion of urban population |
| A1. Population urbanization | a21. Per capita GDP (yuan) |
| A2. Economic Urbanization | a22. Proportion of output value of secondary and tertiary industries in GDP |
| A3. Social development | a31. Number of health professionals per thousand people |
| A3. Social development | a32. Education Fund (ten thousand yuan) |
| A3. Social development | 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) |
solution and the farthest distance from the negative ideal solution (Chitsaz & Banihabib 2015). The algorithm of the TOPSIS method is presented as follows, according to Huang and Yoon (2011).

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;

\[ v_{ij} = w_{j} r_{ij}, \quad \sum_{j=1}^{n} w_{j} = 1, \quad w_{j} \text{ is the weight of jth criterion.} \tag{7} \]

Step 3: Determine the positive-ideal solution (PIS) and negative-ideal solution (NIS), denoted respectively as \( A^+ \) and \( A^- \), are defined in the following way;

\[ A^+ = \{( \max v_{ij} | j \in J) \text{ or } ( \min v_{ij} | j \in J') \}, \quad i = 1, 2, \ldots, m \]
\[ = \{ v_{1}^+, v_{2}^+, \ldots, v_{n}^+ \} \tag{8} \]

\[ A^- = \{( \min v_{ij} | j \in J) \text{ or } ( \max v_{ij} | j \in J') \}, \quad i = 1, 2, \ldots, m \]
\[ = \{ v_{1}^-, v_{2}^-, \ldots, v_{n}^- \} \tag{9} \]

where \( J \) and \( J' \) are sets of benefit and cost criteria, respectively.

Step 4: Calculate the distances of each alternative from positive-ideal solution (PIS) and negative-ideal solution (NIS);

\[ S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{ij}^+)^2}, \quad i = 1, 2, \ldots, m \tag{10} \]
\[ S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{ij}^-)^2}, \quad i = 1, 2, \ldots, m \tag{11} \]

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

\[ C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-}, \quad 0 < C_i^+ < 1, \quad i = 1, 2, \ldots, m \tag{12} \]

where \( C_i^+ \in [0,1] \) with \( i = 1, 2, \ldots, m \). The best alternative can therefore be found according to the preference order of \( C_i^+ \). The more is 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 the two-stage DEA to analyze water resource use efficiency. Wang et al. (2018a, 2018b) estimated the water efficiency with DEA-Tobit model. 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 the subjective factors, simplifies the calculation method and reduces the error. DEA method can analyze multiple input and output indexes at the same time. The analysis results of each DMU can be optimized. Since its birth, 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 GDP as output indicators. This research uses the DEA-Malmquist Index approach to evaluate water resources’ use efficiency, and the 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 is measured. The input-based Total Factor Productivity Index (tfpch) can be expressed by the Malmquist index, namely:

$$M_{t+1}^{f} = \frac{D'(x_{t+1}^{0}, y_{t+1}^{0})}{D'(x_{t}^{0}, y_{t}^{0})} \times \frac{D'(x_{t+1}^{0}, y_{t+1}^{0})}{D'(x_{t+1}^{0}, y_{t}^{0})}$$

(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 (effch) and technology (techch). The Malmquist Index Formula can be expressed as:

$$MI = \frac{D'(x_{t+1}^{0}, y_{t+1}^{0})}{D'(x_{t}^{0}, y_{t}^{0})} \times \frac{D'(x_{t+1}^{0}, y_{t+1}^{0})}{D'(x_{t+1}^{0}, y_{t}^{0})} = effch \times techch$$

(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:

$$tfpch = effch \times techch$$

$$effch = pech \times sech$$

(15)

(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 on 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, 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, this paper constructs an internal relationship model of water resources utilization system ($S_1$) as follows.

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

(17)

$g_1(t)$ 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 \( \Delta N_1(t) > 0 \). The synergistic effects are dominant effects in the water resources utilization system. Resources within a water resources utilization system can support an increase in the efficiency of water resources utilization 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 the water resources utilization system. Water resources utilization system is less able to support the increase in the number of individuals in the water resources utilization system. Thus, the water resources utilization system is unsustainable.

According to the Logistic model, this paper constructs an internal relationship model of urbanization system (S₂) as follows:

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

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

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

\( \beta_{12} \) 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:

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

\( \beta_{21} \) 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:

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

Among them, \( 1 > \beta_{12} > 0,1 > \beta_{21} > 0 \). \( \beta_{12} \) is the contribution of system 2 to system 1, which means that the resources that system 2 supplies to system 1 are \( \beta_{12} \) 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 \( 1 > \beta_{21} > 0 \).

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 the dynamic relationship systems in the innovation ecosystem. Based on the numerical value of \( \beta \), 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.
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.

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 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, multi-choice goal programming (MCGP) has been widely used to resolve many practical decision-making problems. This paper builds multi-choice goal programming (MCGP) and Lotka-Volterra MCGP models for innovation populations scale optimization. On the basis of MCGP achievement (Wang et al. 2021), considering the symbiotic relationship, this problem can be formulated as follows:

\[
\begin{align*}
\text{Min} & \quad d_1^+ + d_1^- + e_1^+ + e_1^-; \\
\text{s.t.} & \quad y_1 = F(x); \quad \text{for output goal, the more the better} \\
& \quad y_1 - e_1^+ - e_1^- = 0; \\
& \quad x_1 = \frac{k_1(1 + \beta_{12})}{1 - \beta_{12} \cdot \beta_{21}}; \quad \text{equilibrium value for tfpch} \\
& \quad x_2 = \frac{k_2(1 + \beta_{21})}{1 - \beta_{12} \cdot \beta_{21}}; \quad \text{equilibrium value for urbanization} \\
& \quad x_1 > 0; x_2 > 0; d_1^+ >= 0; d_1^- >= 0; e_1^+ >= 0; e_1^- >= 0 \\
& \quad -1 < \beta_{12} < 1; \quad \text{for bound of } \beta_{12} \\
& \quad -1 < \beta_{21} < 1; \quad \text{for bound of } \beta_{21} \\
& \quad x_1 = \frac{k_1(1 + \beta_{12})}{1 - \beta_{12} \cdot \beta_{21}}; \quad \text{ratio constraint between tfpch and urbanization}
\end{align*}
\]

3. EMPIRICAL ANALYSIS

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

As shown 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 get the evaluation of 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, urbanization level of provincial regions in Chinese mainland shows a significant imbalance. The provincial regions with 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 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, it 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 the existing studies. Some researchers found the urbanization level of most regions in China generally increased (Xia et al. 2020).

Wang et al. (2020) found the success of China’s urbanization at poverty reduction and environmental improvement. The environmental protection, economic and social development are considered in the evaluation index system of urbanization in this paper. Some of the above points are supported by the research.

The calculation results of Malmquist index are shown in Tables 6 (DEAP software is 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

### 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

| Area       | Year 2019 | 2018 | 2017 | Year 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 Mongol | 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 | 0.233 | Qinghai   | 0.125 | 0.115 | 0.103 |
| Jiangxi    | 0.205     | 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 |
Figure 1 | The urbanization level of provincial regions.

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  | 0.933 | 0.930| 0.930|
| Hebei         | 1.056 | 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|               |       |        |       |      |      |
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 geographical space, resource endowment, social history and other factors, the water environment problem is more prominent, although the eastern region has certain resource endowment advantages and good industrial and economic support. In this regard, we need to improve the supervision and market access mechanism of regional water consumption industry, 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 China and central China, so as to control high water consumption in East China during the process of promoting regional economic growth. Central China has relatively high concentration of thermal power, steel, petroleum and petrochemical high water consumption 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 products 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 industry 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 system, the in-depth demonstration and analysis of industrial water use, and the water environment problems caused by large water consumption and poor economic benefits.

The destroyed industrial enterprises should be shut down, and the coal chemical industry bases or parks should be encouraged to build, so as to promote the cascade utilization and centralized treatment of water resources.

Existing research on water resource efficiency in 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 different views. It is found that the difference of water resource efficiency in China is mainly caused by resource protection and pollution control.

![Figure 2](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.238/915768/ws2021238.pdf)

**Figure 2** | The water resources utilization efficiency of provincial regions.
After calculating the urbanization level and water resource efficiency, this paper will further analyze the interaction mechanism between them. In basis of MCGP achievement, considering the symbiotic relationship, this problem can be formulated as model (23):

\[
\begin{align*}
\text{Min} & \quad d_1^+ + d_1^- + e_1^+ + e_1^-; \\
\text{s.t.} & \quad y_1 = 15,044x_1 + 177,231x_2 - d_1^+ + d_1^-; \quad \text{for output goal, the more the better} \\
& \quad y_1 - e_1^+ + e_1^- = O_T; \\
& \quad x_1 = k_1(1 + \beta_{12}) , \quad \text{equilibrium value for tfpch} \\
& \quad x_2 = k_2(1 + \beta_{21}) , \quad \text{equilibrium value for urbanization} \\
& \quad x_1 > 0; x_2 > 0; d_1^+ >= 0; d_1^- >= 0; e_1^+ >= 0; e_1^- >= 0 \\
& \quad -1 < \beta_{12} < 1; \quad \text{for bound of } \beta_{12} \\
& \quad -1 < \beta_{21} < 1; \quad \text{for bound of } \beta_{21} \\
& \quad x_1 = k_1(1 + \beta_{12}) , \quad \text{for bound of } \beta_{12} \\
& \quad x_2 = k_2(1 + \beta_{21}) , \quad \text{for bound of } \beta_{21} \\
& \quad y_1 = k_1(1 + \beta_{12}) , \quad \text{ratio constraint between tfpch and urbanization}
\end{align*}
\]

The objective function in the model is:
\[F_1(X) = 15,044x_1 + 177,231x_2 \quad \text{(Per capital GDP, output goal, the more the better).}
\]

\[x_1, x_2 \text{ respectively represent the level of urbanization and the efficiency of water resources utilization. The problem is solved using the LINGO (Schrage 2002) software, and is shown in Table 7.}
\]

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 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 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 level has a positive effect on improving the

| Area          | tfpch | UI    | $\beta_{12}$ | $\beta_{21}$ | Area          | tfpch | UI    | $\beta_{12}$ | $\beta_{21}$ |
|---------------|-------|-------|--------------|--------------|---------------|-------|-------|--------------|--------------|
| 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        | 0.000        |
| Hebei         | 1.036 | 0.266 | 0.000        | 0.745        | 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        | 0.000        |
| Jilin         | 0.786 | 0.223 | 0.000        | 0.614        | Chongqing     | 0.991 | 0.301 | 0.000        | 0.000        |
| 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        | 0.657        | 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        | 0.000        |
| 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        | 0.000        |
| Jiangxi       | 1.129 | 0.175 | 0.074        | 0.000        | Xinjiang      | 1.298 | 0.169 | 0.000        | 0.000        |
| Shandong      | 1.041 | 0.523 | 0.000        | 0.000        |
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. Result

In China, urbanization of provincial regions show a significant imbalance. The provincial regions with 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.

The research chooses 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. This research 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 value 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: there is a two-way synergy between urbanization and water resources utilization; there is no interaction between urbanization and water resources utilization; and there is 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 level has 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 the 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 study showed that most regions still need improvement (Wang et al. 2018a, 2018b). Some findings on regional differences showed 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 Chinese mainland is relatively low, and needs to be improved.

This paper also makes some useful attempts on the method. Various optimization algorithms were 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 Lotka-Volterra equilibrium model with multi-choice goal programming method to explore the synergy between urbanization and water resource efficiency under the current output scale.

5. Conclusion

This paper focuses on the current urbanization, water resources utilization efficiency and their interaction in China. Through the review of related research, the evaluation index system is constructed. Based on the determination of input and output indicators, DEA-Malmquist model is used to calculate the water resources utilization efficiency of each province. Lotka-Volterra model is used to illustrate the synergistic relationship between urbanization and water resources utilization efficiency. Combined with the multi-choice goal programming 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 in the provincial level of 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 the efficiency, sustainability and coordination of development. (2) The output variables in collaborative research are relatively single. 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 platform and 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 cross regional spillover effect on cities with low efficiency. Regions with high water use efficiency should maintain the
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 form the follow-up effect 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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