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Study on the relationship between urbanization and sustainable utilization of water resources in Xiamen, Zhangzhou, and Quanzhou

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ABSTRACT

With the rapid development of urbanization, population sizes and the demand for water are drastically increasing, resulting in water scarcity, water quality deterioration, and water pollution. Due to its unique geopolitical characteristics, the Fujian triangle (Xiamen, Zhangzhou, and Quanzhou) is among the most dynamic economic integration industrial areas in eastern China. In this study, the interaction between urbanization and water resources was investigated and the coupling stages of urbanization and water resource utilization were examined to provide a basis for the prediction of future urbanization trends and the sustainable utilization of water resources. Specifically, an evaluation index system of urbanization and water resources in Xiamen, Zhangzhou, and Quanzhou was established based on the driving force-pressure-state-response (DPSR) model. The main factors affecting the interaction between urbanization and water resources were identified via grey relational analysis, and their coupling degree was calculated. Additionally, the level of water resource constraint was quantified via the analytic hierarchy process supported by entropy technology to identify the coupling stages of urbanization and water resource systems in different cities. Our findings demonstrated that economic and spatial urbanization are key indices influencing the sustainable utilization of water resources and the background and environmental pressures on water resources are key factors influencing urbanization. The coupling degrees of economically developing cities were higher than those of economically developed cities. Additionally, the constraint intensity of water resources in the three cities was calculated (0.1468–0.4522), among that Xiamen and Zhangzhou exhibit low constraint intensities, whereas Quanzhou exhibits high. Regarding the coupling stage of urbanization and water resources, Xiamen is at an advanced coordination stage, Quanzhou is at a stage between the running-in and the advanced coordination stage, and Zhangzhou is at the running-in stage. Therefore, the water resources of the three cities must be consolidated via the integration of the metropolitan area by exploiting their respective advantages and complementing their weaknesses.

Keywords: Xiamen, Zhangzhou, and Quanzhou; Urbanization; Water resource; Sustainable utilization; Coupling; Integration

1. Introduction

Urbanization is an inevitable trend of economic and social development and an important symbol of industrialization and modernization. The process of urbanization includes the economic, demographic, social and spatial transformation processes. Urbanization refers to the historical process of the gradual transformation from the traditional rural society mainly based on agriculture to the modern urban society mainly dominated by non-agricultural industries such as industry and service industry, with the

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development of social productive forces, the progress of science and technology and the adjustment of industrial structure. The process of urbanization includes the economic, demographic, social and spatial transformation processes. The urbanization ratio in China is projected to reach 65% by 2030. Urbanization has become a huge engine for China's economic and social development after industrialization [1]. Nevertheless, the urbanization of China is also increasingly faced with constraints and challenges from a series of factors, including population, resource availability, and ecological challenges [2]. Among these, the most pressing challenges are related to water resources, including increased water consumption, low water utilization efficiency, irrational water utilization, low urban sewage disposal ratio, and water pollution. To characterize the many water resource rationing issues brought by urbanization, additional efforts are needed to gain a thorough understanding of the coupling of urbanization and water resource systems, identify sensitive indices of the interaction between water resources and urbanization systems, verify the presence of water resource constraints, and determine the coupling stage of urbanization and water resource systems. This knowledge would provide a solid basis for the resolution of regional water resource issues during the urbanization process, in addition to promoting sustainable regional development [3].

Several previous studies have systematically analyzed the obstacles to sustainable urban development or eco-city construction during the urbanization process from the perspectives of regional resources, environment, the economy, and society. However, most of them focused on two perspectives: (1) the basic concepts of sustainable urbanization and urban sustainability (theoretical discussion) and (2) the application of evaluation index system design and evaluation methods. For example, Li et al. [4] established a two-level index system to differentiate water scarcity caused by human and physical factors to quantitatively evaluate water scarcity within a city. Furthermore, the authors used Pearson correlation analysis to evaluate the relationship between water scarcity and its occurrence in specific cities and determined the driving forces and spatiotemporal trajectory of the water scarcity. Other studies on urbanization and the depletion of environmental resources have adopted RS, GIS, and neural network models. For instance, Sultan and Fiske used a combination of RS and GIS to monitor and investigate the urbanization process in the Nile Delta region [5]. Al-Kharabsheh and Taany [6] used RS technology for positioning and tracking of urbanization and surface water quality. Varis and Jussila [7] used Bayesian network models to investigate the water resource utilization in the Senegal River Basin in the West Sahel, Africa, and found that rapid and disordered urbanization exacerbated the water resource crisis, which in turn further exacerbated urbanization disorder. Taking water accessibility as a prerequisite condition, Fang evaluated the urbanization process and water resources in the arid area of Northwest China and used RS and GIS technology to reveal the influence of water resource changes on the urbanization process. Additionally, dynamic simulation and scenario analysis of the urbanization process under different water resource constraints were conducted [8].

In February 2019, the Guiding Opinions on Cultivating and Developing the Modern Metropolitan Area issued by the National Development and Reform Commission proposed the acceleration of the development and modernization of metropolitan areas. This was China's first central government document that mentioned the concept of "metropolitan areas," marking the official arrival of the metropolitan area era. A total of 15 emerging metropolitan areas in China, including the Xiamen-Zhangzhou-Quanzhou metropolitan area, were mentioned in Top Ten Most Potential Metropolitan Areas in China: 2019. In virtue of its unique geographical advantage, the cities in the Fujian triangle (Xiamen, Zhangzhou, and Quanzhou) can complement each other in terms of economic development, and be interconnected in terms of resource integration, joint prevention, and governance to achieve community intensification, linkage, and complementary development in the metropolitan area. In this study, the correlation between urbanization level and water resources was investigated in Xiamen, Zhangzhou, and Quanzhou. The coupling degree of urbanization and the water resource system was calculated via grey relational analysis, and the main factors that determine the interaction between water resources and urbanization systems were identified. The constraint intensity of water resources was calculated through the analytic hierarchy process (AHP) approach supported by entropy technology, and the presence of water resource constraints was verified. Moreover, the coupling stage of water resources and urbanization in Xiamen, Zhangzhou, and Quanzhou was determined. Therefore, our findings provide a theoretical basis to facilitate decision-making on urban development, as well as suggestions for coupling of urbanization process and sustainable utilization of water resources in the Xiamen-Zhangzhou-Quanzhou metropolitan area.

2. Data processing and research methods

2.1. Identification of coupling degree of urbanization and water resource

2.1.1. Data sources and processing

All data used in this study were obtained from the Statistical Yearbook of Cities in China, the Statistical Yearbook of Fujian Province, water resource bulletins, and statistical yearbooks of the three cities in 2001–2019 [9–11]. Different data series were not comparable owing to different dimensions. Therefore, the data was nondimensionalized before calculation via grey relational analysis [12]:

$$X = \left(1, \frac{X(2)}{X(1)}, \frac{X(3)}{X(1)} \ldots\ldots \frac{X(n)}{X(1)}\right) \tag{1}$$

where X is the standard value after dimensionless processing and $X(1)$~$X(n)$ are the initial values of each sequence.

2.1.2. Calculation method

Grey relation analysis provided a quantitative measure for the development and change of a system, which was rather suitable for dynamic history analysis. In this study, grey relational analysis was employed to calculate the coupling degree of urbanization and water resources and identify key influencing factors [12,13].

2.1.2.1. Calculation of correlation coefficient

$$\xi_{ij}(t)=\frac{\left(\min_i \min_j \left|Z_i^X(t)-Z_i^Y(t)\right|+\rho \min_i \max_j \left|Z_i^X(t)-Z_i^Y(t)\right|\right)}{\left|Z_i^X(t)-Z_i^Y(t)\right|+\rho \max_i \max_j \left|Z_i^X(t)-Z_i^Y(t)\right|} \quad (2)$$

where $Z_i^X(t)$ refers to the normalized value of the urbanization system at time t in each region (spatial section) or each time in t region (temporal section); $Z_i^Y(t)$ refers to the normalized value of the water resource system index at time t in each region (spatial section) or each time in t region (temporal section); ϱ refers to the resolution coefficient, generally 0.5; $\xi_{ij}(t)$ refers to the correlation coefficient at time t.

2.1.2.2. Calculation of coupling degree

$$C(t)=\frac{1}{m\times l}\sum_{i=1}^{m}\sum_{j=1}^{l}\xi(t) \quad (3)$$

where $C(t)$ refers to the coupling degree of urbanization and water resource systems; m refers to the number of indices in the urbanization system; l refers to the number of indexes in the water resource system; $\xi(t)$ refers to the correlation coefficient.

2.2. Identification of constraint intensity and constraint of water resources

2.2.1. Data source and processing

The raw data to evaluate constraint intensity of water resources were obtained from the Statistical Yearbook of Cities in China, the Statistical Yearbook of Fujian Province, water resource bulletins, and the statistical yearbooks of the nine cities in 2001–2019 [8–10]. The indices were not comparable owing to their different dimensions. Hence, the ambiguity membership function was employed to nondimensionalize these indices [14]. To avoid instances in which high scores were too high, the low score was too low, and the minimum value of indices might be zero in the actual data processing process, the power coefficient method was employed. 0.6 is the basic score value, that guarantee the normalized value to be no less than 0.6. Then multiplied by 0.4, which narrows the gap after the normalization of different indices.

2.2.1.1. Positive indices

$$V_{ij}=\frac{x_j-\min(x_j)}{\max(x_j)-\min(x_j)}\times 0.4+0.6 \quad (4)$$

2.2.1.2. Negative indices

$$V_{ij}=\frac{x_j-\min(x_j)-x_j}{\max(x_j)-\min(x_j)}\times 0.4+0.6 \quad (5)$$

where V_{ij} refers to the normalized index value; $\max(x_j)$ refers to the maximum value of the jth index; $\min(x_j)$ refers to the minimum value of the jth index.

2.2.2. Calculation method

AHP was used to establish a hierarchical index system for overall urbanization and sustainable utilization of water resources. The weight of each layer of indices was determined via the expert scoring method, after which an entropy-based method was used to modify the weight coefficient determined by AHP. Afterward, the overall urbanization index and potential index of sustainable utilization of water resources were calculated and the coupling stage of the urbanization system and the water resource system in Fujian was identified [15].

2.2.2.1. AHP supported by entropy technology

The product of AHP weight and information weight of a single index divided by the sum of the products of AHP weight and information weight of all indexes was the entropic weight. AHP supported by entropy technology could avoid the subjectivity of AHP calculated by experts and the narrow scope of the entropy method.

$$\omega_i=\frac{\omega_{aj}\omega_{jj}}{\sum_{j=1}^{n}\omega_{aj}\omega_{jj}} \quad (6)$$

where ω_i refers to index and entropic AHP weights in the AHP supported by entropy technology; ω_a refers to the AHP weight; ω_j refers to the information weight.

The index systems for both overall urbanization and sustainable utilization of water resource comprise the overall layer (A), standard layer (O), criterion layer (C), and index layer (P). It is necessary to calculate the entropic AHP weight (ω_i^p) of the index layer to the criterion layer, the entropic AHP weight (ω_i^c) of the criterion layer to the standard layer, and the entropic AHP weight (ω_i^o) of the standard layer to the overall layer. The entropic weight (ω_i^{pa}) of the index layer to the overall layers is the product of the three indices.

$$\omega_i^{\text{pa}}=\omega_i^p\omega_i^c\omega_i^o \quad (7)$$

2.2.2.2. Water resource and overall urbanization index

$$F_a=\sum_{j=1}^{n}\omega_i^{\text{pa}}\times V_{ij} \quad (8)$$

where F_a refers to the potential index of sustainable utilization of water resources or overall urbanization index; ω_i^{pa} refers to the entropic weight of the index layer to the overall layer; V_{ij} refers to the degree of membership of the jth index of the ith scheme.

2.2.2.3. Calculation of constraint intensity of water resource

$$\mathrm{WRCI} = \alpha \times \left(1 - F_{\omega}\right) + \beta \times \left(1 - F_u\right) \quad (9)$$

where WRCI refers to the constraint intensity of water resource on urbanization; $F\omega$ refers to the potential index of sustainable utilization of water resource; F_u refers to the overall urbanization index; α and β refer to the impact sharing coefficient of the system, which is typically 0.6 and 0.4.

3. Results and analysis

3.1. Coupling of urbanization development and sustainable utilization of water resources in Xiamen, Zhangzhou, and Quanzhou

3.1.1. Establishment of index system to assess the coupling between urbanization and water resources

Both urbanization and the water resource environment are complex systems comprising various factors. Therefore, it is essential to establish a comprehensive index system to reflect its utilization ratio based on the rational, dominant, dynamic, and hierarchical principles of index system selection [16]. In this study, the driving force-pressure-state-responses (DPSR) model was used to analyze the response relationship between overall urbanization and water resource utilization. In turn, the DPSR model is based on the pressure-state-responses (PSR) and driving force-state-responses (DSR) models. An evaluation index model was constructed from perspectives of driving forces, pressure, state, and response. This model comprises economic, social, environmental, and policy factors and has been widely used in environmental assessment systems [17]. Unlike the conventional DPSR model, the relationship between various factors in parallel was considered from a bidirectional perspective of water resources and urbanization in this study. According to the characteristics of water resource and urbanization system, a progressive DPSR feedback system for coupling of urbanization and water resource was established [18]. Economic development and social development (overall urbanization) were the driving forces of the urbanization system. Sustainable utilization of water resources was the long-term driving force (D) for the utilization ratio of water resources, and pressure (P) was applied to the water resource system, resulting in the state (S) changes of the water resource system under pressure. In turn, this represented the human response (R) to changes in the utilization of water resources [19].

In this study, 2 driving force indices (overall urbanization and sustainable utilization of water resource), 7 pressure indices, 18 state indices, and 47 response indices were evaluated [13].

3.1.2. Identification of key factors influencing the coupling of overall urbanization and sustainable utilization of water resources

3.1.2.1. Identification of key factors influencing the overall sustainable utilization of water resources

The correlation matrices of the coupling between urbanization and water resource systems in Xiamen, Zhangzhou, and Quanzhou from 2001 to 2019 were determined. The correlation matrix was averaged over the *Y*-axis, and the influencing factors of overall urbanization on sustainable utilization of water resources could be obtained based on the values of correlation degree. Therefore, in terms of indices, the proportion of working population in the tertiary industry, the proportion of the industry output in the GDP (0.8344), the proportion of the tertiary industry output in the GDP (0.8309), the popularity ratio of urban water utilization (0.8404), and the proportion of working population in the tertiary industry (0.8310) were the main factors of overall urbanization influencing the sustainable utilization of water resources in Xiamen, Zhangzhou, and Quanzhou. In terms of the state, economic structure, economic growth, population structure, infrastructure, and spatial density had relatively high correlations with the water resource system. In terms of pressure, economic urbanization and spatial urbanization had higher correlations with the water resource system compared with population urbanization and social urbanization. Economic urbanization and spatial urbanization played a dominant role in the urbanization process. In terms of driving forces, the correlation between the overall urbanization and the water resource environment was 0.8046, indicating that the overall urbanization of Xiamen, Zhangzhou, and Quanzhou was strongly correlated with water resource utilization (Table 1).

3.1.2.2. Identification of key factors of sustainable utilization of water resources influencing overall urbanization

The average of the correlation matrix to *X* was used to determine the water resource environment factors that influence urbanization, and the key factors influencing the coupling of the water resource environment on urbanization could be identified according to this value (Table 2).

In terms of the response, the annual precipitation (0.8405), the urban sewage disposal ratio (0.8588), the utilization ratio of water resources (0.8610), the water consumption by agricultural irrigation per mu (0.8492), and the compliance ratio of industrial sewage emission (0.8530) were key factors influencing the coupling of sustainable utilization of water resource with overall urbanization in Fujian. In terms of the state, resource abundance and environmental governance were highly correlated with the urbanization system. In terms of pressure, the correlation between the background and environmental pressure of water resources and the urbanization system was relatively high. The impact factor of sustainable utilization of water resources on overall urbanization was 0.8044 (Table 2).

3.1.3. Differentiation of coupling degree of sustainable utilization of water resource and overall urbanization

The indicators of Xiamen, Zhangzhou, and Quanzhou were taken as data sources over several years. The coupling degree of urbanization and water resources from 2001 to 2019 was calculated according to the coupling degree formula, and Fig. 1 illustrates the changes in the degree of urbanization and water resource coupling as a function of time. From a time perspective, the coupling degree of urbanization and water resources exhibited a fluctuating trend.

Table 1
Overall urbanization factors influencing the sustainable utilization of water resources in Xiamen, Zhangzhou, and Quanzhou

Driving force	Pressure	State	Response
Overall urbanization (0.8046)	Population urbanization (0.7945)	Population size (0.8001)	Total population at the end of the year (0.8090)
			Non-agricultural population (0.7913)
		Population structure (0.8185)	Proportion of non-agricultural population (0.8059)
			Proportion of working population in the tertiary industry (0.8310)
		Population change (0.7650)	Growth rate of population (0.7809)
			Growth rate of the proportion of non-agricultural population (0.7491)
	Economic urbanization (0.8083)	Economy of scale (0.7815)	GDP (0.7852)
			Industrial output (0.7802)
			Tertiary industry output (0.7790)
		Economic structure (0.8327)	Proportion of the industrial output in the GDP (0.8344)
			Proportion of the tertiary industry output in the GDP (0.8309)
		Economic growth (0.8194)	Growth rate of GDP (0.8242)
			Growth rate of industrial output (0.8112)
			Growth rate of tertiary industry output (0.8229)
		Economic benefits (0.7995)	GDP per capita (0.8029)
			Industrial output per capita (0.8017)
			Tertiary industry output per capita (0.7939)
	Social urbanization (0.8045)	Quality of life (0.8075)	Disposable income of urban residents (0.8062)
			Consumption expenditure of urban residents (0.8088)
		Infrastructure (0.8115)	Urban road area per capita (0.8112)
			Number of doctors per ten thousand people (0.8124)
			Number of public transport vehicles owned per ten thousand people (0.7981)
			Popularity ratio of urban water utilization (0.8404)
		Science and technology culture (0.7904)	Ratio of investment in science and education (0.8290)
			Number of college students per ten thousand people (0.7730)
			Number of books in public libraries per 100 people (0.7692)
	Spatial urbanization (0.8112)	Spatial scale (0.7809)	Built-up area (0.7832)
			Urban construction land area (0.7797)
		Spatial density (0.8140)	Proportion of urban construction land in downtown area (0.7985)
			Population density of municipal districts (0.8295)

Footnote: The numbers underlined means large values of correlation degree represented by urbanization factors.

Table 2
Factors of sustainable utilization of water resources influencing overall urbanization in Xiamen, Zhangzhou, and Quanzhou

Driving force	Pressure	State	Response
Sustainable utilization of water resource (0.8044)	Background pressure of water resource (0.8144)	Resource per capita (0.7898)	Water resource per capita (0.7794)
			Overall water consumption per capita (0.8001)
		Resource abundance (0.8391)	Annual precipitation (0.8405)
			Water production modulus (0.8376)
	Environment pressure of water resource (0.7898)	Environmental load (0.7879)	Industrial sewage discharge (0.7894)
			Urban domestic sewage discharge (0.8195)
			Rural domestic sewage discharge (0.7548)
		Resource utilization (0.7916)	Annual water supply (0.7670)
			Utilization ratio of water resources (0.8610)
			Water consumption by industry (0.7820)
			Water consumption by agriculture irrigation (0.7566)
	Environment management pressure of water resource (0.8089)	Environmental governance (0.8289)	Urban sewage disposal ratio (0.8588)
			Compliance ratio of industrial sewage emission (0.8530)
			Investment in industrial pollution control (0.7748)
		Resource utilization efficiency (0.7889)	Water consumption per 10,000 yuan GDP (0.7640)
			Water consumption per 10,000 yuan of industrial added value (0.7535)
			Water consumption by agricultural irrigation per mu (0.8492)

Footnote: The numbers underlined means large values of correlation degree represented by water resources factors.

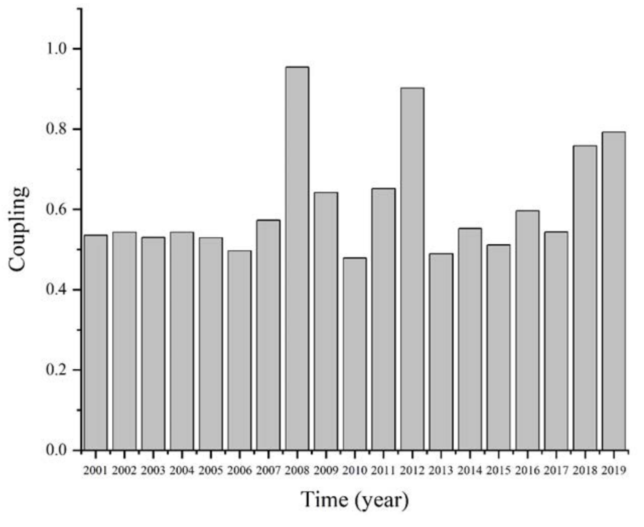

Fig. 1. Temporal trends of coupling degree between urbanization and water resources in Xiamen, Zhangzhou, and Quanzhou.

The coupling degree ranged between 0.48 and 0.95 and was high in 2008–2012. Particularly, there were two peaks in 2008 (0.95) and 2012 (0.90). Then, the coupling degree decreased and increased again after 2018.

The indicators of Xiamen, Zhangzhou, and Quanzhou were taken as the data sources and analyses were conducted for each city. The coupling degree between urbanization and water resources of Xiamen, Zhangzhou, and Quanzhou was calculated using the coupling degree formula, after which the data was visualized on a spatial

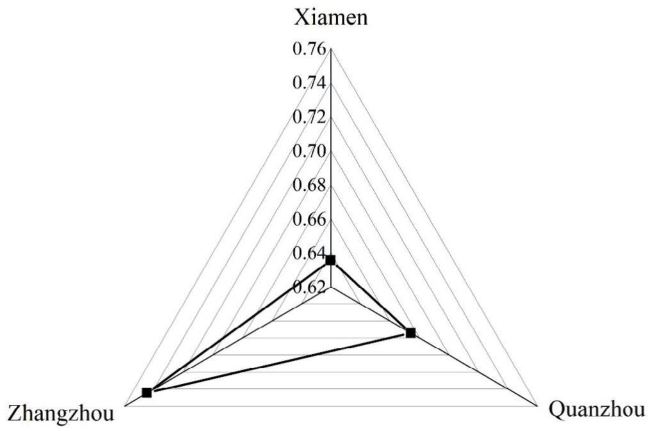

Fig. 2. Spatial trends of the coupling degree of urbanization and water resources in Xiamen, Zhangzhou, and Quanzhou.

variation diagram (Fig. 2). Zhangzhou exhibited the highest coupling degree (0.7445), followed by Quanzhou (0.6741), and finally Xiamen (0.6356). Overall, the coupling degree of economically developed cities was lower than that of economically developing cities.

3.2. Identification of constraint intensity of water resources in the overall urbanization process in Xiamen, Zhangzhou, and Quanzhou

The proposed overall urbanization and water resource utilization index system was used to construct a hierarchical index system to assess the relationship between the overall urbanization and sustainable water resource utilization [17], where the driving force layer corresponded to the overall layer, the pressure layer corresponded to the standard layer, the state layer corresponded to the criterion layer, and the response layer corresponded to the index layer.

3.2.1. Calculation of entropic AHP weights in the overall urbanization system

The AHP weight of the overall urbanization index system was obtained via the expert scoring method, which is inevitably subjective. Therefore, the entropy method was used to calculate the information weights of the overall layer, standard layer, criterion layer, and index layer of all cities over the past years. AHP supported by entropy technology was used to modify weights, and finally the entropic AHP weight of each level of the overall urbanization system was obtained. In this study, only the correction weight of the index layer of the overall layer was listed (Table 3).

3.2.2. Entropic AHP weight calculation of sustainable utilization of water resource at all levels

Similar to the overall urbanization index, the entropy method was used to calculate the information weights of the overall layer, standard layer, criterion layer, and index layer of all cities over the past years. AHP supported by entropy technology was used to modify weights, and finally

Table 3
Correction weights of the index layer of the overall layer of the urbanization index system

Overall layer	Index layer	Index nature	Information weight	AHP weight	Entropic AHP weight
Overall urbanization	Total population at the end of the year	Positive	0.0339	0.0028	0.0019
	Non-agricultural population	Positive	0.0328	0.0139	0.0091
	Proportion of non-agricultural population	Positive	0.0327	0.0154	0.0100
	Proportion of working population in tertiary industry	Positive	0.0315	0.0461	0.0290
	Growth rate of population	Positive	0.0399	0.0066	0.0056
	Growth rate of proportion of non-agricultural population	Positive	0.0288	0.0197	0.0122
	GDP	Positive	0.0338	0.0042	0.0057
	Industrial output	Positive	0.0418	0.0096	0.0160
	Tertiary industry output	Positive	0.0297	0.0109	0.0130
	Proportion of industrial output in GDP	Negative	0.0287	0.0178	0.0127
	Proportion of tertiary industry output in GDP	Positive	0.0387	0.0533	0.0511
	Growth rate of GDP	Positive	0.0395	0.0172	0.0272
	Growth rate of industrial output	Positive	0.0305	0.0109	0.0133
	Growth rate of tertiary industry output	Positive	0.0307	0.0270	0.0332
	GDP per capita	Positive	0.0289	0.1019	0.1198
	Industrial output per capita	Positive	0.0294	0.0276	0.0330
	Tertiary industry output per capita	Positive	0.0350	0.0044	0.0619
	Disposable income of urban residents	Positive	0.0287	0.2042	0.1307
	Consumption expenditure of urban residents	Positive	0.0302	0.0681	0.0459
	Urban road area per capita	Positive	0.0364	0.0242	0.0386
	Number of doctors per ten thousand people	Positive	0.0375	0.0119	0.0196
	Number of public transport vehicles owned per ten thousand people	Positive	0.0382	0.0749	0.1254
	Popularity ratio of urban water utilization	Positive	0.0345	0.0390	0.0589
	Ratio of investment in science and education	Positive	0.0379	0.0470	0.0561
	Number of college students per ten thousand people	Positive	0.0425	0.0276	0.0370
	Number of books in public libraries per 100 people	Positive	0.0302	0.0081	0.0077
	Built-up area	Positive	0.0299	0.0100	0.0039
	Urban construction land area	Positive	0.0290	0.0033	0.0012
	Proportion of urban construction land in urban area	Negative	0.0289	0.0355	0.0135
	Population density of municipal district	Positive	0.0299	0.0178	0.0070

the entropic AHP weight of the sustainable utilization of water resources for each layer was obtained. Here, only the correction weight of the index layer on the overall layer was listed (Table 4).

3.2.3. Overall urbanization index and potential index of sustainable utilization of water resources

The final values of the potential indices of sustainable utilization of water resources and overall urbanization were calculated based on the weighted averages of the annual and city data of potential indices of sustainable utilization of water resource and overall urbanization (Figs. 3 and 4).

From a temporal perspective, the overall urbanization index increased in terms with time and all cities exhibited increases in the urbanization index (0.41%–2.12%). Specifically, the increases in the overall urbanization index exhibited the following decreasing order: Quanzhou (2.12%) > Xiamen (2.06%) > Zhangzhou (0.41%). From a spatial perspective, the overall urbanization index exhibited the following order: Xiamen (0.7716) > Quanzhou (0.7612) > Zhangzhou (0.7594). In summary, the overall urbanization index is proportional to the urbanization level.

From a temporal perspective, the potential index of sustainable utilization of water resources increased in a fluctuating pattern. Specifically, the increase of the potential index of sustainable utilization of water resources exhibited the following order: Zhangzhou (1.42%) > Quanzhou (3.49%) > Xiamen (1.42%). From a spatial perspective, the potential index of sustainable utilization of water resource exhibited the following order: Zhangzhou (0.7241) > Xiamen (0.6341) > Quanzhou (0.5688). Although Xiamen was an extremely water-deficient city, the

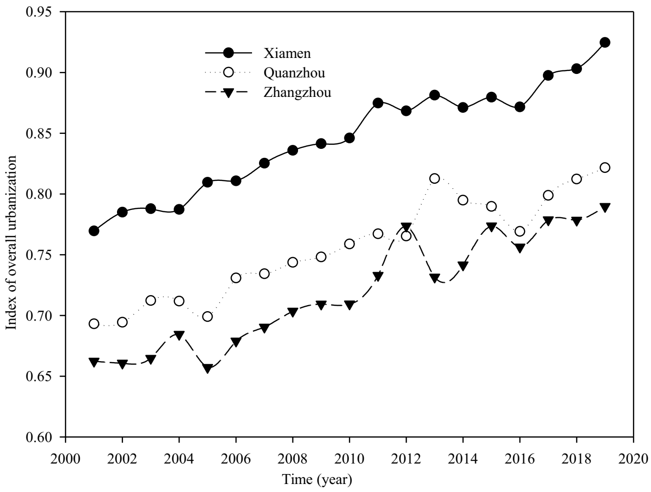

Fig. 3. Final weighted average of overall urbanization index in Xiamen, Zhangzhou, and Quanzhou.

Table 4
Correction weights of index layer for the overall layer of the sustainable use of water resource index system

Overall layer	Index layer	Index nature	Information weight	AHP weight	Entropic AHP weight
Sustainable utilization of water resources	Water resource per capita	Positive	0.0560	0.4301	0.3336
	Overall water consumption per capita	Negative	0.0591	0.0860	0.0704
	Annual precipitation	Positive	0.0354	0.0206	0.0106
	Water production modulus	Positive	0.0644	0.0826	0.0618
	Industrial sewage discharge	Negative	0.0602	0.0267	0.0389
	Urban domestic sewage discharge	Negative	0.0559	0.0419	0.0567
	Rural domestic sewage discharge	Negative	0.0616	0.0085	0.0127
	Annual water supply	Negative	0.0597	0.0052	0.0098
	Utilization ratio of water resource	Negative	0.0605	0.0095	0.0180
	Water consumption by industry	Negative	0.0558	0.0028	0.0049
	Water consumption by agriculture irrigation	Negative	0.0614	0.0018	0.0034
	Urban sewage disposal ratio	Positive	0.0584	0.0562	0.0735
	Compliance ratio of industrial sewage emission	Positive	0.0587	0.0323	0.0426
	Investment in industrial pollution control	Negative	0.0667	0.0062	0.0093
	Water consumption per 10,000 yuan GDP	Negative	0.0557	0.0519	0.0603
	Water consumption per 10,000 yuan of industrial added value	Negative	0.0681	0.1211	0.1721
	Water consumption by agricultural irrigation per mu	Negative	0.0622	0.0165	0.0214

local authorities prioritized the rational allocation of water resources and introduced external water sources from multiple channels. Quanzhou was a moderately water-deficient city, and the available water resource potential was small. Zhangzhou was a mild water-deficient city, so compared with Xiamen and Quanzhou, this city was rich in water resources and the water resource potential was higher.

3.2.4. Constraint intensity of water resource

As previously reported, the constraint intensity of water resources can be classified as weak, relatively strong, strong, and extremely strong (Table 5).

Based on the final weighted average of the potential index of sustainable utilization of water resources and the overall urbanization index, the constraint intensity of water resources on urbanization in cities of Fujian (0.1468–0.4522) was obtained (Fig. 5).

From a temporal perspective, the overall constraint intensity of water resource decreased between 2001 and 2019 and the constraint intensities of the water resources of all three cities decreased (28.16%–60.26%). When the constraint intensity remained unchanged, Xiamen showed the largest decrease (60.26%), followed by Quanzhou, Zhangzhou. From a spatial perspective, Xiamen and Zhangzhou exhibited weak constraints (Xiamen, 0.2812; Zhangzhou, 0.2776), whereas Quanzhou exhibited a relatively strong constraint (0.3564).

4. Discussion

With the rapid development of urban economy and society, water scarcity and water pollution are becoming more serious. In turn, the deterioration of water resources restricts urbanization. Therefore, the relationship between these two factors can be regarded as a coupling process. Research on the coupling between urbanization and water resources can provide a theoretical basis for future urbanization planning and sustainable utilization of water resources. The coupling degree of Xiamen, Zhangzhou, and Quanzhou was studied through grey relational analysis. Our findings indicated that the coupling degrees between the urbanization and water resources in the three regions were high, and therefore the acceleration of the urbanization process must be based on the sustainable utilization of water resources. Through AHP supported by entropy technology, the constraint intensity of water resources of the three cities was further calculated, among which Xiamen (0.2812) and Zhangzhou (0.2776) exhibited weak constraints, whereas the constraints of Quanzhou were relatively strong (0.3564), thus confirming the existence of water resource constraints. Importantly, our conclusions matched the actual resources, environment, economy, and social development of Xiamen, Zhangzhou, and Quanzhou. Additionally, the development stage of the urbanization and water resource system of the three cities must also be evaluated to provide a theoretical basis for the rational allocation of water resources and ensure the economic and social development of each city.

Northam's theory revealed a rising S-shaped urbanization curve [20] and the utilization ratio of water resources was also on the rise, with both of these trends being closely related. Urbanization and water resources have experienced the primary coordination stage, antagonistic stage, the running-in stage and the advanced coordination stage at roughly the same time [21]. Combining the urbanization level, the water utilization efficiency, overall water consumption per capita, total water consumption, constraint intensity, and coupling degree of water resources in 2019,

Table 5
Criteria for classification of constraint intensities of water resource

Constraint intensity	WRCI
Weak	<0.3
Relatively strong	0.3–0.5
Strong	0.5–0.7
Extremely strong	>0.7

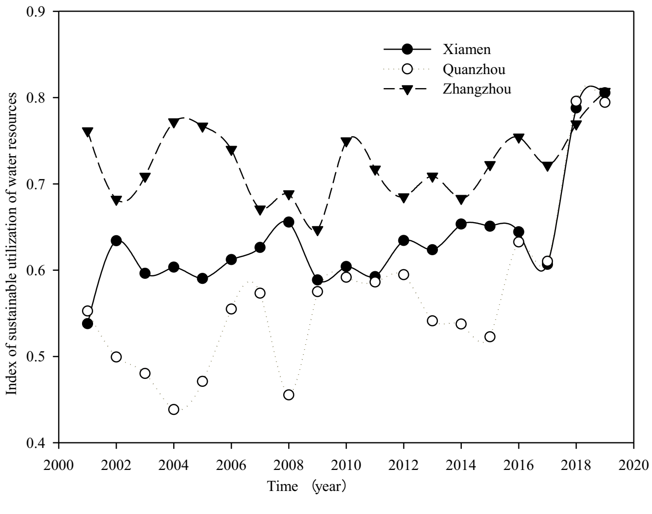

Fig. 4. Final weighted average of the potential index of sustainable utilization of water resources in Xiamen, Zhangzhou, and Quanzhou.

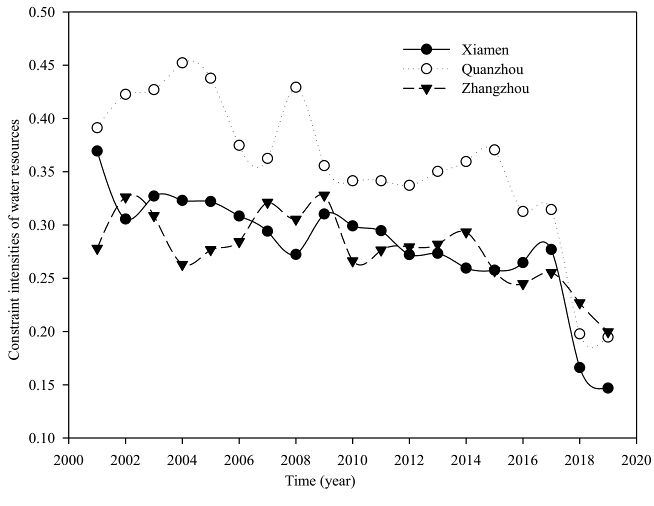

Fig. 5. Constraint intensities of water resources on urbanization in Xiamen, Zhangzhou and Quanzhou.

Table 6
Identification of the coupling stage of water resources and urbanization in Xiamen, Zhangzhou, and Quanzhou

City	Water resource constraint type	Water shortage condition	Water utilization efficiency (yuan/m^3)	Overall water consumption (m^3) per capita	Total water consumption (100 million m^3)	Urbanization level (%)	Coupling degree	Coupling stage
Xiamen	Weak	Extreme dehydration	880.33	159	6.81	89.2	0.6356	Advanced coordination
Quanzhou	Relatively strong	Moderate dehydration	351.35	324	28.31	67.2	0.6741	Running-in and advanced coordination
Zhangzhou	Weak	Mild dehydration	223.57	411	21.21	60	0.7445	Running-in

the coupling stages of Xiamen, Zhangzhou, and Quanzhou were identified (Table 6).

4.1. Primary coordination stage

In the early stage of urban development, the urbanization process is slow, the demand for water is low, and urbanization is coordinated with the available water resource environment.

4.2. Antagonistic stage

When urbanization is entering the middle stage, the urbanization process accelerates, the speed of industrialization increases, urban population grows, and the demand for water increases. At this stage, water pollution can become serious and the available water resources are not enough to meet the demands for future urbanization, thus restricting further urbanization. Currently, Xiamen, Zhangzhou, and Quanzhou have all passed this stage.

4.3. Running-in stage

At this mid urbanization stage, the urbanization and industrialization process is further accelerated, the urban population continues to increase, the demand for water resources increases, and water pollution becomes more serious. Relevant government departments strengthen water pollution control, develop water-saving projects, and adjust water utilization structures. The water saving awareness of the residents is continuously enhanced, and the relationship between urbanization and water resources is stable.

Zhangzhou is currently at this stage. Zhangzhou is a city with a mild water shortage. The constraint intensity is the lowest, the coupling degree ranks first, and the water utilization efficiency, overall water consumption per capita, and total water consumption are all at a moderate level. The urbanization level is low and the contradiction between urbanization and water resources is alleviated.

4.4. Advanced coordination stage

In the late stage of urbanization, the speed of urbanization is steadily slowing down, the urban population is large, and the industry and tertiary industry are developed. The local authorities increase the governance and regulation of the water environment, and the utilization efficiency and utilization ratio of water resources are optimized. The water saving awareness of the residents has generally improved, and overall water consumption per capita decreases. At this stage, urbanization and water resources have reached an advanced coordination level.

Xiamen is at this stage. Although its own water resources are limited and water shortage is high, its water utilization efficiency ranks first in Fujian Province, with low overall water consumption, low water consumption per capita, and high urbanization degree. Nevertheless, Xiamen exhibited the lowest coupling degree and a low constraint intensity of water resources, demonstrating that Xiamen is currently in the advanced coordination stage. Quanzhou is at a stage between the running-in stage and the advanced coordination stage. The urbanization level of Quanzhou is relatively high and the city has moderate water shortages, but its water utilization efficiency is high and its overall water consumption per capita is low. Therefore, Quanzhou's constraint intensity is strong, and its coupling degree ranks second.

The economic and social urbanization levels of Xiamen, Zhangzhou, and Quanzhou are different, and water resources and urbanization are in different stages. Therefore, to promote the integration of the three cities, the unique advantages of each city must be given full play and each region must learn from each other's strengths. Zhangzhou focuses on the primary and secondary industries, and develops eco-tourism. Xiamen focuses on finance, business, tourism, and high-end technology industries, whereas Quanzhou focuses on shipping and export trade. All of these cities have varying degrees of water shortage. Therefore, the water resources of the three cities must be integrated by building a large water grid, thus facilitating the interconnection, exchange, and complementation of water resources. More importantly, as a core city, Xiamen should change its single center urban structure from "Lujiang Road-Gulangyu" to "Guanyin Mountain-Xiang'an" as soon as possible. This dual center would link the east and west regions to Zhangzhou and Quanzhou, respectively, thus enabling the integration of the economy, resources, and transportation. These three cities complement each other, and play an important role in the integration of the metropolitan area.

5. Conclusions

An index system was established using the DPSR model, and grey relational analysis was used to identify the key factors linking urbanization to sustainable utilization of water resources, as well as the key factors of sustainable utilization of water resources to support urbanization. The key urbanization factors influencing the sustainable utilization of water resources included the proportion of working population in the tertiary industry, the proportion of the industrial output in the GDP, the proportion of the tertiary industry output in the GDP, and the popularity ratio of urban water utilization and population density of municipal districts mainly at the state level (e.g., population structure, economic structure, economic growth, infrastructure, and spatial density). Our main findings indicated that economic urbanization and spatial urbanization dominate the overall urbanization process. The key factors of sustainable water resource utilization influencing overall urbanization included annual precipitation, urban sewage disposal ratio, utilization ratio of water resources, water consumption by agricultural irrigation per mu, and compliance ratio of industrial sewage emission mainly at the state level (e.g., resource abundance and environmental governance), indicating that the background and environment pressure of water resource dominate the sustainable utilization of water resources.

The spatial and temporal coupling degrees of urbanization and water resources of Xiamen, Zhangzhou, and Quanzhou were also calculated. The results indicated that the temporal coupling degree exhibites a fluctuating trend, whereas the spatial coupling degrees of economically developing cities are higher than those of economically developed cities.

AHP supported by entropy technology was used to calculate the weight of each indicator, through which the overall urbanization index and potential index of sustainable utilization of water resource were obtained, and finally the constraint intensity of water resources was calculated. The overall urbanization index followed the sequence of Xiamen (0.7716) > Quanzhou (0.7612) > Zhangzhou (0.7594), whereas the potential index of sustainable utilization of water resource followed the sequence of Zhangzhou (0.7241) > Xiamen (0.6341) > Quanzhou (0.5688). The water resource constraints of Xiamen, Zhangzhou, and Quanzhou ranged between 0.1468 and 0.4522. Xiamen and Zhangzhou exhibited weak constraints (Xiamen, 0.2812; Zhangzhou, 0.2776), while Quanzhou exhibited a relatively strong constraint (0.3564). Additionally, the coupling stage of urbanization and water resources in the three cities was identified based on the urbanization level, water utilization efficiency, water utilization structure, overall water consumption per capita, coupling degree of total water consumption and urbanization with water resources, and the constraint intensity of water resources in 2019. Among them, Xiamen is at the advanced coordination stage, Quanzhou is at a stage between the running-in stage and the advanced coordination stage, and Zhangzhou is at the running-in stage.

Future studies will use calculation methods and mathematical models to clarify the advanced coordination of urbanization and water resources, optimize the scheduling of water resources, and develop future urban planning programs in a larger scale to ensure a steady development of the city and effective exploitation of water resources. Notably, the development conditions and resource and environmental conditions of different cities may be different, and appropriate development planning and water resource allocations should be implemented according to local conditions to facilitate the sustainable development of the region. Additionally, the research on the coupling between urbanization and water resources encompasses various fields, including natural environments, the economy, and technological development. Therefore, cross-field and multi-disciplinary cooperation using multiple methods and angles is encouraged to investigate the coupling of urbanization and water resources to ensure that future decisions on urban development are rational and data-driven.

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