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Article

The Spatiotemporal Variation Characteristics of Urban Sustainability Based on the SDGs in Yangtze River Delta, China

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Abstract: At present, most developing countries need to improve the quality of the built environment by means of large-scale infrastructure construction, thereby promoting rapid urbanization. The quality of the built environment (Q_U) and its environmental pressure (P_U) have become our primary focus to achieve a globally acknowledged vision of the Sustainable Development Goals (SDGs). In this study, we proposed an overall workflow by combining the proven urban sustainability (S_U) assessment tool with the evaluation process and the analysis of the spatiotemporal dimension to investigate the urban characteristics of the 41 cities in the Yangtze River Delta. Our results showed an upward trend of urban sustainability from 2010 to 2018, but there are still 19 cities with unsustainable urbanization processes. The megalopolis is rapidly progressing toward an imbalanced state. Specifically, the urban sustainability of the southern region performs better than the northern region, coastal cities perform better than the inland cities, and the regional peripheral cities perform better than the inner cities. Across the 41 cities in the delta, five different relational trends between Q_U and P_U have been found to predict their future development. The results of this research will help decision-makers to coordinate the future development of regional integration between cities and to target the alleviation of the adverse chain reaction brought about by the situation of imbalance or further improving urban sustainability.

Keywords: urban sustainability; Sustainable Development Goals (SDGs); quality of the built environment; environmental pressure; spatiotemporal variation



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1. Introduction

Urban areas, due to their high population concentration, both drive and bear development challenges [1,2]. During urbanization, cities often face problems such as limited infrastructure land, traffic congestion, harsh environments, and the spread of diseases, especially in developing countries like China [3–6]. These challenges stem from competing interests between the urban built and natural environments [7–9]. Despite these obstacles, the urban built environment can enhance local citizens' quality of life. Factors such as economic growth, functional land development, residential areas, efficient transit networks, and external competitiveness are critical to promoting healthy urban development [10–12]. While many other factors such as the quality of education, the ability to innovate, and the availability of renewable energy may influence the development of cities, the built and natural environments have a profound impact on the health of citizens as well as the cities' urbanization level [13,14]. For these reasons, the concept of sustainable development is a necessary goal for urban development.

The SDGs account for the intricate urban landscape and serve as a critical framework for numerous scholars to assess urban development using quantitative measures [15–20]. In many studies, scholars are focusing on the designation of the indicator system, yet these assessment tools are still questioned [21] for the following reasons. (1) Different indicator systems are formulated for different cities, and comparisons cannot be made between different cities. Shen and Zhou, 2014 [22], examine the effectiveness of eight of the sustainable urbanization indicator systems in China in helping policymakers' decisions. The results show that due to the large inconsistency between the existing indicator systems, there are limitations to them in practice. (2) Urbanization is a dynamic process, but few studies consider this system in a dynamic way. It is believed that the assessment indicators based on the index system can represent multiple sustainability-related processes, and while they are easy to use, they do not have enough complexity to describe a city [23]. (3) The data collection and calculation methods are complex, and the setting of some indicators is subjective, with vague definitions and quantifications. Due to the decentralized nature of these urban evaluation methods, the cost of using these kinds of indicator systems is high, their promotion is difficult, and they place local departments under great pressure, resulting in the consumption of many internal government resources [23,24].

The optimization of human activities, resources, and the environment forms a crucial foundation for achieving sustainable social development. Chen et al., 2022 [25], believed that some methods only focus on the performance of different cities, while ignoring spatial characteristics or spatial patterns, evolution mechanisms, and the interaction between different indicators. It is necessary to evaluate the effectiveness of established sustainable urbanization methods [26], and on this basis, it is also an important challenge [27] to make more accurate judgments and descriptions of observational data on multiple spatial and temporal scales. Spatiotemporal environmental data are usually characterized by spatial and temporal correlations, and capturing these dependencies is an extremely important task [28]. Few studies have explored the spatial and temporal differences in environment-related SDGs at the national and regional scales [29].

This paper aims to establish an overall workflow for an urban sustainability assessment from the indicator system to the evaluation process and the analysis of the spatiotemporal dimension so as to provide a theoretical reference and suggestions for the implementation of sustainable strategies, ranging from the microcity to the macroregional scale. This paper examines a representative megalopolis (the Yangtze River Delta) as a case study, focusing on the period between 2010 and 2018, which holds significant importance for the future of China's urbanization. We use a proven evaluation system of urban sustainability based on SDGs [30], further analyze the spatiotemporal variation characteristics and action mechanisms, and then propose strategies for both cities and the megalopolis. The remainder of this paper is structured as follows: Section 2 provides a critical literature review; Section 3 introduces the research framework, study area, assessment system, and research methods; Section 4 conducts a spatiotemporal feature analysis based on indicator measurements; and Sections 5 and 6 draw conclusions and propose appropriate sustainable development directions for urban megalopolises, respectively.

2. Literature Overview and Research Objective

2.1. Sustainable Development and Its Evaluation System

The United Nations General Assembly's "2030 Agenda" report has established 17 overarching sustainable development goals and 169 specific objectives [31]. Achieving sustainable development typically involves collaborative efforts among government decision-making and coordination agencies. Some experts believe that if sustainability can be understood by the public, it will be a far more powerful and productive strategy than if it is left to the experts [32–34]. Since the beginning of the twentieth century, various sustainability evaluation systems have been utilized and developed. Some of these tools have been proven effective such as LEED, BREEAM, CASBEE, UN 17/169, and so on [35]. Although these tools have served the same goal, they vary widely in development

background, measurement standards, the degree of availability, operability, and so on. Therefore, their universality is often brought into question, especially when used as an evaluation tool for developing countries like China [36–41].

Because the variation in needs and priorities for developing countries is substantial, it is important for these countries to consider local conditions in their urban sustainability assessments. In these countries, economic and infrastructural aspects of urban development are considered to be more important [42]. At the same time, environmental quality has become a key endogenous factor that determines a city's competitiveness. Many scholars to date have evaluated a single SDG or a single sub-goal at the provincial or municipal level in China. Zhou, Q. et al., 2021 [43], has pointed out that China has an uneven performance for environment-related SDG indicators. Javanbakht et al., 2021 [44], proposed an urban environmental quality (UEQ) system from the quantitative measurement of the ability of the environment to respond to the needs of the urban population. Xu et al., 2019 [45], evaluated the implementation of SDG 11 in the Yangtze River Delta, while Wang et al., 2020 [46], modeled the spatial variability of the SDGs at the provincial level to assess the sustainable development of Fujian Province. However, in the face of the complexity of rapid urbanization in developing countries, driven by the government's strong political guidance, the scope and thoroughness of the abovementioned objectives are still lacking.

2.2. *The Exploration of Urban Characteristics through Spatiotemporal Distribution*

Environmental spatiotemporal data are usually characterized by spatial and temporal correlations [28] and it is an important topic in the study of urbanization in megalopolises [47]. However, this analysis requires information from multiple locations, especially over large areas [48]. The geographic information system (GIS) is a popular tool that has the ability to provide various ways to display the spatial qualities of an event on a map [2,49] and is considered one of the most powerful tools for analyzing the characteristics of spatiotemporal changes. Li et al., 2013 [47], analyzed the temporal and spatial dynamics of the Shanghai metropolitan area between 1989 and 2005, revealing both similarities and unique aspects of Shanghai's urban expansion patterns. They proposed a complex diffusion–condensation model to account for these findings. Xia et al., 2020 [4], employed geospatial techniques to investigate the relationship between urban form and carbon emissions, offering influential data to inform spatial planning policies. Brown et al., 2020 [50], underscored the significance of sociodemographic factors in shaping individuals' environmental attitudes. Additionally, researchers found that participants perceived environmental problems at a global scale to be more severe than those in their local communities (i.e., spatial bias) [51]. Therefore, sustainability and related indicators have a relationship with both space and time. To better understand the variation of these parameters, capturing these dependencies is an extremely important task.

2.3. *Chinese Urban Development toward Sustainability*

Since 2000, the rapid acceleration of urbanization in China's administrative regions has brought about significant economic growth and urban development, but has also placed immense pressure on environmental resources and led to severe pollution [5,6]. However, some aspects of China's development plan diverge significantly from the "standard" Western model [52]. Since the "Twelfth Five-Year Plan" in 2010, China's urban population has exceeded the rural population and is continuing to grow at an unprecedented rate [5]. At the same time, a series of other problems have arisen that affect the sustainable development of cities. Although China has made some progress in transitioning from traditional industry-led urbanization to a new type of urbanization since 2014 [53], environmental pressures that impede significant development have continued to rise [54–56].

At present, China utilizes a composite mechanism for development [57], and has put forward a number of planning strategies to promote the regional integration of urban megalopolises. It intends to use the agglomeration effect to drive regional development, focusing especially on the three major urban megalopolises of the Yangtze River Delta, the

Pearl River Delta, and the Jingjinji. It is expected that they will gradually become the main “growth poles” leading China’s development [58,59]. Due to these different approaches, the study of these Chinese urban development patterns will contribute to Western urban studies and urban entrepreneurship [60]. This will provide alternative solutions for the coordinated development of megalopolises, which currently face enormous challenges [61]. Given the complexity of urban environments in regions like China, an effective quantitative assessment is critical in identifying coping strategies, and it also provides valuable experience and reference for more underdeveloped regions and developing countries that are about to experience this same level of urban growth.

3. Methodology

3.1. Research Framework

This research flow is designed to include four steps (Figure 1). Firstly, basic information on the megalopolis and its evolution of urbanization are investigated and a database is created to house the temporal statistical data of all indicators and the spatial GIS database of targeted cities in the megalopolis. It should be noted that statistical data were collected from the China Statistical Yearbook Series [62], published on authoritative websites by the National Bureau of Statistics of China. Secondly, an urban sustainability assessment was conducted. At this stage, we finish determining indicator weights based on the evaluation period and complete the data processing and calculations necessary to obtain evaluation results using the database. Then, the temporal statistical analyses are performed using the curve estimation regression method to reveal the time-series variation characteristics of indicators and their coupling mechanisms. Lastly, based on geographic information, spatial statistical tools are used to visualize the temporal characteristics of indicators in the geospatial dimension. We combine the evaluation system with the spatiotemporal analysis method to effectively complete a comprehensive evaluation of the spatiotemporal characteristics of each index during the process of urban development. With this comprehensive process, we can not only diagnose each target city at the microlevel, but also understand the overall development structure of the megalopolis at the macrolevel.

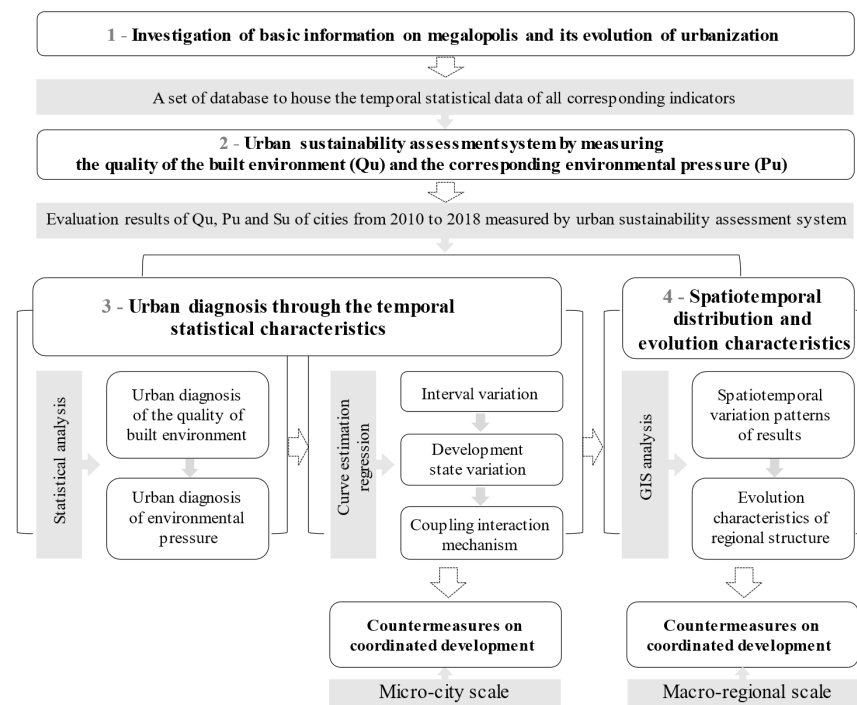


Figure 1. Research workflow of spatiotemporal variation characteristics of urban sustainability.

3.2. Study Area

The Yangtze River Delta, which is one of the world's six largest megalopolises, is a key strategic developmental region [63] and serves as an international gateway on China's eastern coast to the Asia-Pacific region. It plays a significant role in economic cooperation among Japanese and Korean cities as part of the Yellow Sea Rim. Additionally, it dominates the development of the domestic Yangtze River Economic Belt. The Yangtze River Delta began with the establishment of the Shanghai Economic Zone in 1982 [64,65], and has expanded from 14 cities to 41 cities in 2019, including Shanghai and cities in Zhejiang Province, Jiangsu Province, and Anhui Province [66]. However, many experts continue to use outdated planning areas in their research [67–69], and there are relatively few studies on urban agglomerations based on the latest extent of 41 cities.

The region's urbanization rate hit 67.31% in 2018, with a population density of 629.3 people per square kilometer [62]. This growth is especially evident in the eastern coastal cities, which have become densely populated. However, inland areas have also seen an influx of people thanks to inter-regional ties and policy support for integrated regional planning (Figure 2). Despite the success of the Yangtze River Delta as a model for quality urban development, the extensive production methods and resource consumption have led to growing environmental problems, including acid rain and a degraded water quality in the river basin. As such, it is clear that while urbanization has brought many benefits to the region, it has also led to some significant challenges that must be addressed. [70–72]. With regard to the future of urban development, the Chinese government has endorsed rapid economic growth and continued expansion. Therefore, the sustainable development of regional cities is an unavoidable issue to consider.

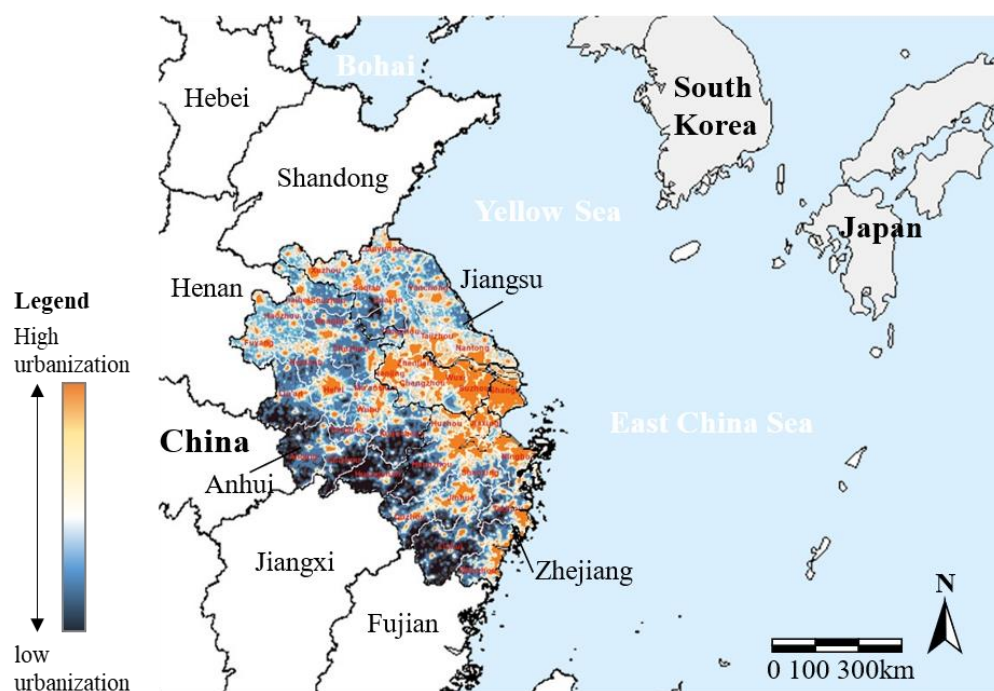


Figure 2. The location and the level of urbanization based on nighttime light data in Yangtze River Delta in 2018. (Note: The deeper yellow color represents higher urbanization).

3.3. Urban Sustainability Assessment System

Urban sustainability (S_U) draws inspiration from the “ratio model (input/output)” of the X-efficiency theory in economics [73,74]. We utilized this model with our own variables (quality/pressure) by measuring the quality of the built environment (Q_U) and the corresponding environmental pressure (P_U) of each city. The degree of urban sus-

tainability (S_U) is measured by the ratio of the performance of Q_U and P_U across several indicator categories:

$$S_U = \frac{Q_U}{P_U} = \frac{\sum_{i=1}^n Q_{Ui}}{\sum_{i=1}^m P_{Ui}} \quad (1)$$

where Q_{Ui} represents the total value of indicator category i for the quality of the built environment and P_{Ui} represents the value of indicator category i for environmental pressure. S_U value of less than or equal to 1 indicates that the pace of environmental pressure (P_U) is growing faster than the quality of the built environment (Q_U), which suggests that the city is undergoing an unsustainable urbanization process. Conversely, an S_U value of greater than or equal to 1 suggests that the pace of environmental pressure (P_U) is growing slower than the quality of the built environment (Q_U), indicating a relatively sustainable urbanization process.

3.3.1. Indicator System

The selection of indicators for this study strictly follows the represented indicators provided in the urban sustainability evaluation system [30] based on SDGs and the 14 Chinese assessment tools. The 14 existing reports include Ecological Counties, Ecological Cities Construction Evaluation System (trial version, 2003), China's Livable Cities Scientific Evaluation Standards (2007), Low-Carbon City Evaluation System of China (2011), Green and Low-Carbon Cities Evaluation Indicators (trial version, 2011), National Environmental Protection Model City Assessment Index and Implementation Rules (2011), National Ecological Civilization Pilot Policy Evaluation System (trial version, 2013), Technical Criterion for Eco-environmental Status Evaluation (draft, 2015), Evaluation System for the Construction of National Ecological Civilization Model City (trial version, 2016), China Green Development Index System (2016), Evaluation System for Ecological Civilization Construction (2016), Green City Evaluation Index System (draft, 2017), Evaluation System of the Construction Target of the National Ecological Civilization Pilot Zone (2018), Indicators for City Services and Quality of Life (2019), and New-Type Urbanization Evaluation Index System of New Urbanization Quality City (trial version, 2020). Within the indicator system of 17 representative indicators, there are three categories of 11 positive indicators that can either directly or indirectly reflect the Q_U . Here, the categories of economic urbanization (Q_{U1}) and infrastructure development (Q_{U2}) are related to the size of the urban population, so their indicators need to be converted to reflect the average adult value. The indicators of urban attraction (Q_{U3}) are not affected by the scale at all, and the existing statistical values can be used. These three categories of indicators reflect the three dimensions (economy, society, and culture) of sustainable development and correspond to SDG 8 (decent work and economic growth), SDG 11 (sustainable cities and community) and SDG 17 (partnership), respectively [75–77]. Additionally, two categories of 6 negative indicators can represent urban environmental pressure of regional concern. The categories of resource consumption (P_{U1}) and environmental pollution (P_{U2}) highlight the importance of the environmental dimension of sustainable development, corresponding to SDG 12 (responsible consumption and production), SDG 6 (clean water and sanitation), and SDG 13 (climate action).

3.3.2. Data Source and Processing

To determine the appropriate contribution of component scores in each corresponding category, the principal component analysis (PCA) method based on statistical data [78] from the Yangtze River Delta from 2010 to 2018 was used. And each indicator category in the dataset had to pass the Kaiser–Meyer–Olkin (KMO) test with acceptable values greater than 0.5 [79] in order to ensure that the data were suitable for PCA. Therefore, data processing is first standardized:

$$u_{(p/q)i}' = \frac{u_i - \min(u_i)}{\max(u_i) - \min(u_i)} \quad (2)$$

where u_i is the original data value of each indicator category i ; $\min(u_i)$ and $\max(u_i)$, respectively, refer to the minimum and maximum value in the 9-year dataset for the corresponding indicator category, and the standardized value is $u_{(p/q)i}'$.

And then weights ($W_{(p/q)i}$) are calculated:

$$W_{(p/q)i} = \frac{|\lambda_{(p/q)i}|}{\sum_{i=1}^{n/m} |\lambda_{(p/q)i}|} \quad (3)$$

where $|\lambda_{(p/q)i}|$ represents the component score coefficient matrix and $\sum_{i=1}^{n/m} |\lambda_{(p/q)i}|$ represents the sum of the component scores of each indicator category i of Q_U or P_U calculated by the PCA method.

The sum of the standardized value $u_{(q)i}'$ or $W_{(p)i}$ multiplied by the corresponding weight $W_{(q)i}$ or $W_{(p)i}$ is the comprehensive score (Q_{U_i} or P_{U_i}) of each dimension for the urban sustainability assessment:

$$Q_{U_i} = W_{(q)i} \cdot u_{(q)i}'; \quad P_{U_i} = W_{(p)i} \cdot u_{(p)i}' \quad (4)$$

Table 1 shows the weights of each indicator constructed with 11 represented indicators of Q_U and 6 indicators of P_U , which have the greatest impact on their respective indicator categories.

Table 1. The 17 indicators and their weights for the urban sustainability assessment. This table is derived from our proven assessment system [30] and has been edited.

| Basic Dimensions | Indicator Categories | Weight (%) | Represented Indicators Description | Weight (%) |
|--|---|--|---|------------|
| Urban built environment quality (Q_U) | Urbanization economies (Q_{U1}) | 33.33 | q1: Urban population percentage (% of total population) | 8.56 |
| | | | q2: GDP per capita (USD/person) | 8.52 |
| | | | q3: Services value added (% of GDP) | 8.51 |
| | | | q4: Income per capita (USD/person) | 7.74 |
| | Infrastructure development (Q_{U2}) | 33.33 | q5: Construction land per capita (m^2 /person) | 9.30 |
| | | | q6: Residential floor space per capita (m^2 /person) | 9.00 |
| q7: Green area per capita (m^2 /person) | | | 9.01 | |
| q8: Road area per capita (m^2 /person) | | | 6.02 | |
| Urban attraction (Q_{U3}) | 33.33 | q9: Number of tourists (1000 person) | 10.99 | |
| | | q10: Foreign direct investment (USD 106) | 10.09 | |
| | | q11: Export volume of trade (USD 106) | 12.25 | |
| Urban environmental pressure (P_U) | Resource consumption (P_{U1}) | 50.00 | p1: Energy consumption per capita (GJ/person) | 25.00 |
| | | | p2: Water consumption per capita (ton/person) | 25.00 |
| | Environmental pollution (P_{U2}) | 50.00 | p3: Wastewater discharged per capita (ton/person) | 10.47 |
| | | | p4: SO_2 discharged per capita (kg/person) | 15.03 |
| | | | p5: NO_x discharged per capita (kg/person) | 9.56 |
| | | | p6: Soot and dust discharged per capita (kg/person) | 14.94 |

Notes: (1) To convert Chinese currency (RMB) into U.S. currency (USD), we multiplied the RMB amount by the annual average closing price of the USD/RMB exchange rate. We used the annual exchange rate data for the years 2010 to 2018, provided by Macrotrends for currency. (2) Income refers to disposable income, which represents the actual income available to residents for final consumption, other non-compulsory expenditures, and savings. (3) Green area includes public parks, community parks, and green areas located near streets. (4) Energy consumption includes coal, crude oil, natural gas, electricity, and other sources of energy.

3.4. Spatiotemporal Methodologies Based on Statistics and Geoinformatics

3.4.1. Curve Estimation Regression

Regression analysis, a commonly used statistical technique, involves fitting a line to the data that best represents the relationship between dependent variables and an independent variable [80]. Linear regression is a basic statistical method that aims to establish a linear

connection between two variables. On the other hand, non-linear regression is more suitable for modeling complex relationships between variables, and can often lead to a better match with the data than linear regression. However, it is important to note that a regression model must meet the assumptions of homoscedasticity and independence to be trustworthy and valid. Otherwise, breaches of these assumptions can lead to incorrect inferences and biased estimates of the regression coefficients. The interaction relationship can be seen in Figures 2–5 and the predictable regression model are as follows:

$$\text{Linear model : } P_{Ui} = a + (b \cdot Q_{Ui}) \tag{5}$$

$$\text{Quadratic model : } P_{Ui} = a + (b \cdot Q_{Ui}) + (c \cdot Q_{Ui}^2) \tag{6}$$

$$\text{Cubic model : } P_{Ui} = a + (b \cdot Q_{Ui}) + (c \cdot Q_{Ui}^2) + (d \cdot Q_{Ui}^3) \tag{7}$$

where a , b , c , and d are coefficients of the regression models. Here, we model how the change in Q_U affects the value of P_U .

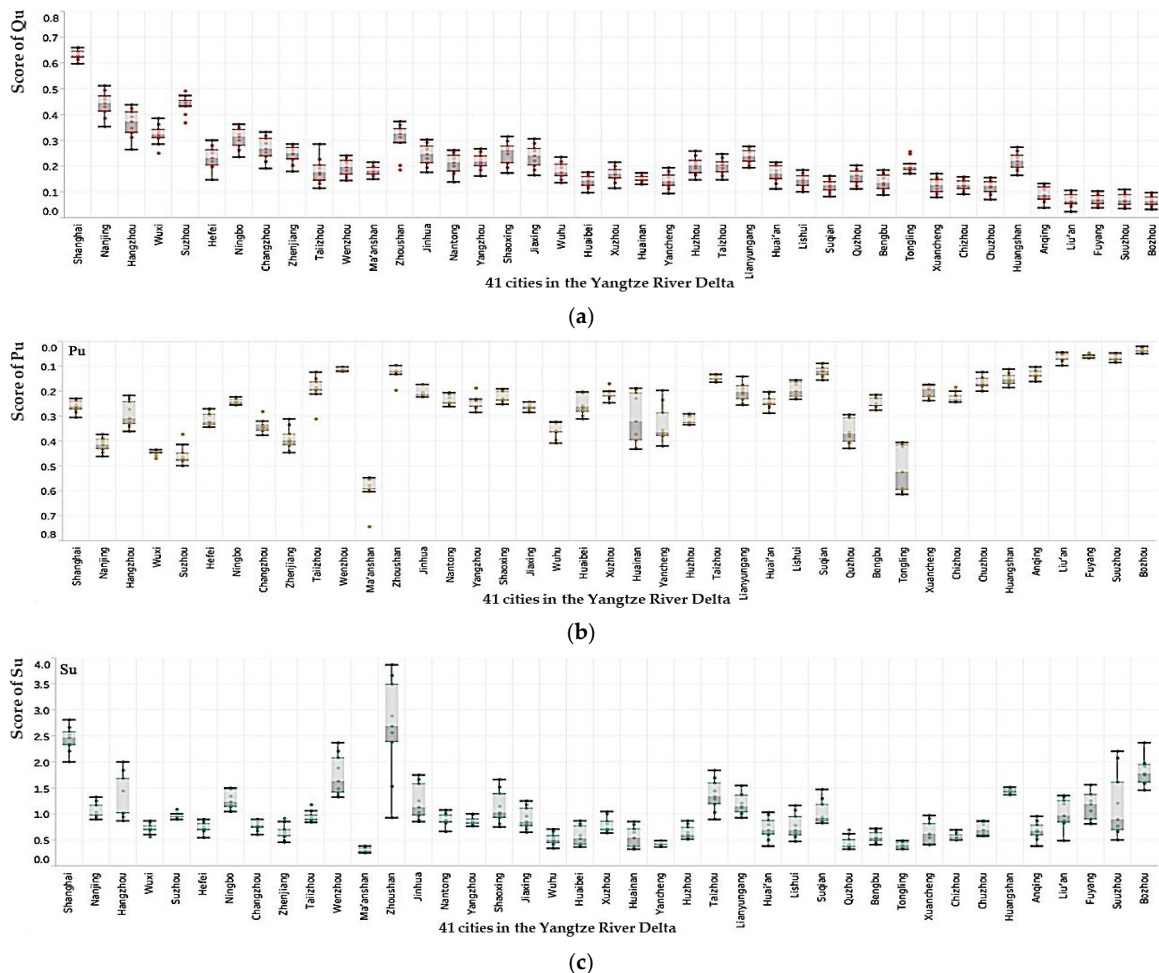


Figure 3. The score range results of Q_U , P_U , and S_U for the 41 cities in Yangtze River Delta from 2010 to 2018. (a) Box plot of the score range of the quality of built environment (Q_U). (b) Box plot of the score range of environmental pressure (P_U). (c) Box plot of the score range of urban sustainability (S_U).

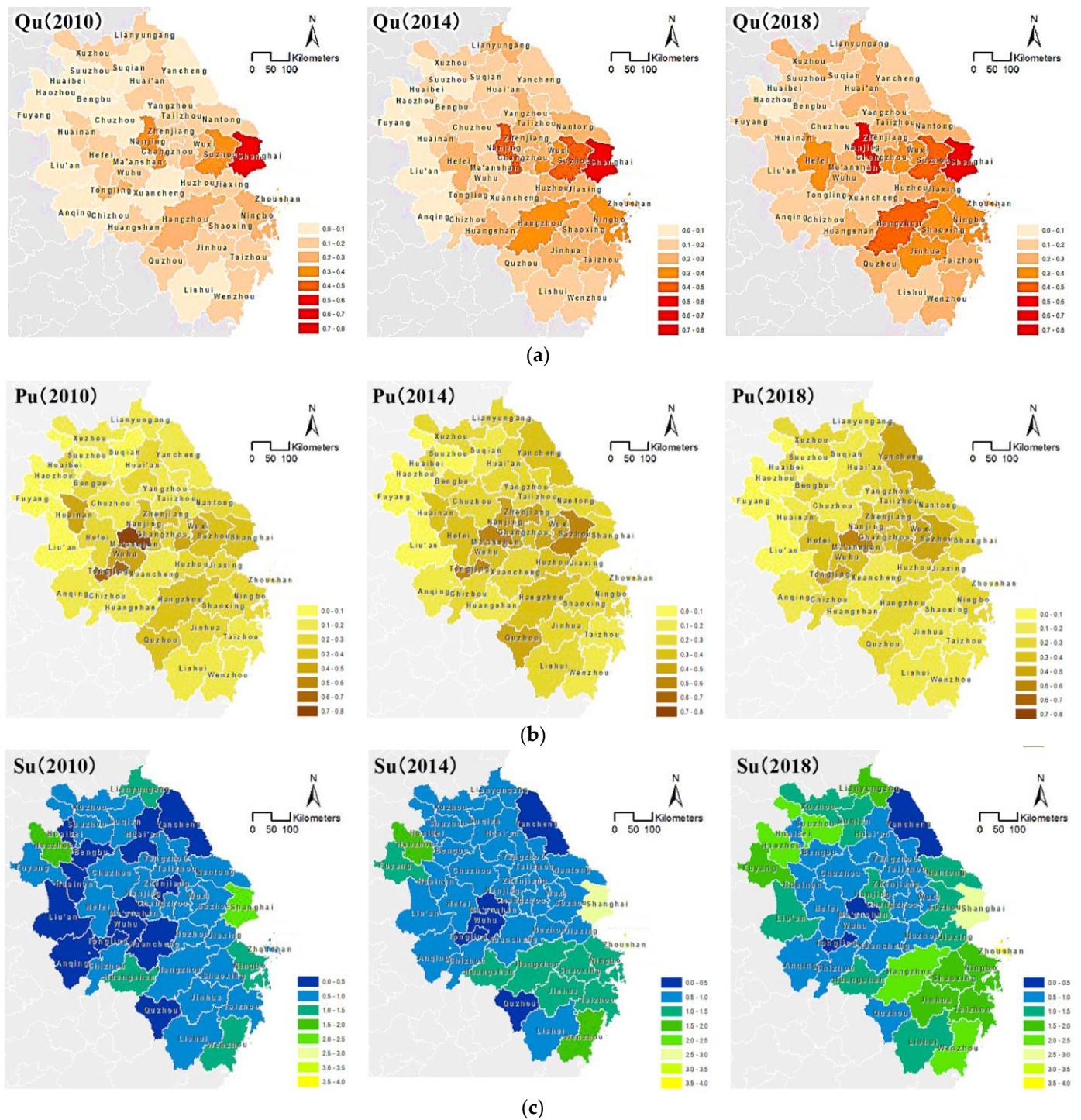


Figure 4. The spatiotemporal variation patterns in the Yangtze River Delta from 2010 to 2018. (a) The spatiotemporal variation of the quality of built environment (Q_U). (b) The spatiotemporal variation of environmental pressure (P_U). (c) The spatiotemporal variation of urban sustainability (S_U).

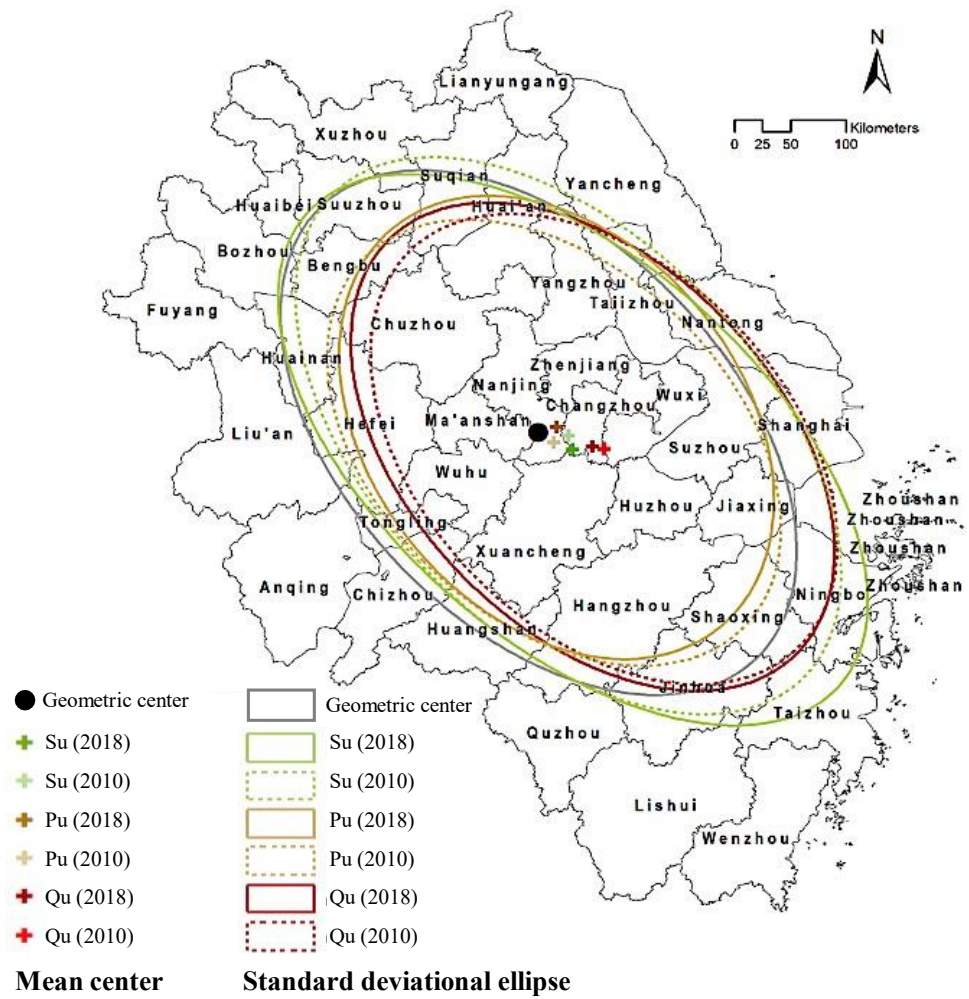


Figure 5. The geographic distribution of $Q_U/P_U/S_U$ in the Yangtze River Delta from 2010 to 2018.

3.4.2. Geographic Distributions

Spatial statistics tools are commonly employed to analyze geographic data and identify patterns and trends in the data over time by calculating characteristic values. It is represented by a circle, the radius of which equals the standard distance called the standard deviational ellipse, centered on the geographic geometric center identified by the mean center [81,82]. And the standard distance is a measure of distribution that expresses the compactness of a set of spatial characteristics. The time-series results of the standard deviation ellipses, which covered approximately 68% of the features analyzed, present three pieces of information about spatiotemporal characteristics: (1) the dispersion of a univariate feature around its geometric center; (2) the distribution of indicators and the location offset of the center; and (3) the migration direction and speed of the center.

We utilized tools for geographic distribution in our study to examine the connection between the spatial features of urban sustainability and the displacement of the geographic geometric center. This measurement provides an intuitive assessment of whether the regional development is unbalanced, and it serves as a crucial foundation for devising macroregional planning strategies. The related formulas are shown below.

The coordinates of geometric center (or mean center):

$$\bar{X}_{tcoord} = \frac{\sum_{t=1}^k X_i}{k}; \bar{Y}_{tcoord} = \frac{\sum_{t=1}^k Y_t}{k} \tag{8}$$

The standard distance in the X and Y directions:

$$SD_X = \sqrt{\frac{\sum_{t=1}^k (X_t - \bar{X}_{tcoord})^2}{k}}; SD_Y = \sqrt{\frac{\sum_{t=1}^k (Y_t - \bar{Y}_{tcoord})^2}{k}} \quad (9)$$

where X_t and Y_t are the coordinates of feature Q_U , P_U , or S_U in the t year, and k is equal to the number of cities.

4. Empirical Results of Spatiotemporal Variation

4.1. The Evaluation Results through the Temporal Statistical Analysis

4.1.1. Temporal Performance and Urban Characteristic Diagnosis

The urban sustainability assessment method described above was applied to evaluate the performance of 41 cities in the Yangtze River Delta from 2010 to 2018. Figure 3 displays box charts illustrating the ranges of Q_U , P_U , and S_U values for each city.

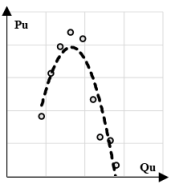
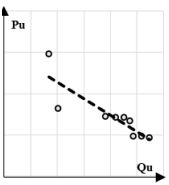
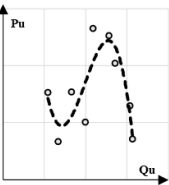
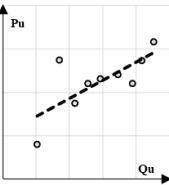
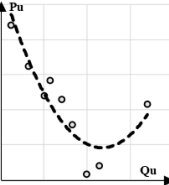
In Figure 3a, the Q_U values for the 41 cities ranged from 0.022 to 0.658, with a CAGR between 0.61% and 19.14% over the 9-year period. The city of Shanghai had the highest initial score, whereas Lu'an had the lowest score initially but showed the most significant improvement over the span of nine years. According to Figure 3b, the P_U index varied from 0.020 to 0.743 in 2010, and Bozhou and Ma'anshan consistently had the lowest and highest environmental stress levels, respectively, throughout the entire study period. The CAGR ranged from -8.73% to 8.84% , with 19 cities exhibiting a negative growth rate, indicating a reduction in environmental pressure, while 22 cities experienced adverse effects with CAGR values exceeding 0. Heavy industry was the primary cause of environmental degradation in cities such as Ma'anshan and Lianyungang. In Figure 3c, unfortunately, some cities, such as Ma'anshan, Yancheng, Tongling, Chizhou, Quzhou, and Wuhu, continued to experience severe unsustainability with little change over the 9-year period, especially Ma'anshan City, which had the lowest S_U score (0.259) in 2010.

4.1.2. Temporal Performance and Urban Characteristic Diagnosis

The future direction of urban development can be predicted by understanding the logic and strength of the mutual coupling mechanism between Q_U and P_U . While general linear regression is commonly used to explore this relationship, it has limitations when matching nonlinear datasets. We utilized SPSS Statistics (version 26) for the regression analysis and obtained the significant results less than 0.05 with the p-value test.

As shown in Table 2, the regression analysis indicated that there were five coupling relationships between Q_U and P_U identified in 83% of cities in the Yangtze River Delta (seven cities showed no significant relationship). (1) An inverted U-shaped relationship, in which the P_U initially increased swiftly with Q_U improved, but was subsequently controlled through environmental protection policies and technology, resulting in a decline in environmental pressure, while Q_U continued to improve in cities such as Hangzhou, Nanjing, and Jiaxing. The injection of a new city planning through international cooperation, incorporating strong sustainability features, in cities such as Shanghai, Suzhou, and Zhoushan likely has led to the phenomena. (2) A negative linear relationship, in which Zhoushan and Taizhou continuously improved environmental pressure without initial degradation. (3) An S-shaped relationship, in which seven cities showed a rebound trend in environmental pressure after initial improvement around 2013, indicating the need for continuous attention to environmental issues. (4) A positive linear relationship, with environmental pressure increasing along with improved Q_U in four cities, highlighting the importance of effective environmental governance. (5) A U-shaped relationship, in which environmental pressure initially decreased and then increased with urban construction in cities such as Huai'an City, emphasizing the need for resource consumption and pollution control measures.

Table 2. The coupling interaction mechanism between $f(Q)$ and $g(P)$ by a curve regression analysis of the 41 cities.

| Model | Quadratic Model | Linear Model | Cubic Model | Linear Model | Quadratic Model | - |
|--------------------------|---|---|---|--|---|---|
| Type |  |  |  |  |  | - |
| Interaction relationship | Inverted U-shaped relationship | Negative linear relationship | S-shaped relationship | Positive linear relationship | U-shaped relationship | No significant relationship |
| Related cities | Zhenjiang, Wenzhou, Jinhua, Nantong, Yangzhou, Shaoxing, Jiaxing, Huaibei, Yancheng, Suqian, Chizhou, Chuzhou, Anqing, Fuyang, Suuzhou, Bozhou, Nanjing, Hangzhou, and Suzhou | Zhoushan and Taizhou | Ningbo, Xuzhou, Huzhou, Lianyungang, Lishui, Quzhou, and Bengbu | Hefei, Changzhou, Taiizhou, Huangshan, and Liu'an | Huai'an | Shanghai, Wuxi, Ma'anshan, Wuhu, Huainan, Tongling, and Xuancheng |

4.2. Spatial–Temporal Distribution and Evolution Characteristics

4.2.1. Spatiotemporal Variation Patterns of Urban Sustainability

The Arc-GIS 10.3 tool is used to visualize the data of 41 cities to reveal the characteristics of the development change of the spatial–temporal pattern of cities in the Yangtze River Delta in 2010, 2014, and 2018, as shown in Figure 4.

Figure 4a illustrates that the areas with superior urban built environments were initially concentrated around Shanghai due to its favorable location. Subsequently, the positive effects emanating from Shanghai gradually contributed to the enhancement of urban quality in the neighboring eastern cities. This distribution pattern aligns with the evolution of urbanization depicted in Figure 2. Being an international metropolis, Shanghai was the first city in the region to attract more population. As development progressed, policies such as industrial alliances were implemented, uniting cities like Hangzhou and Nanjing, which possess greater economic power when working together. Consequently, the core area of urbanization is shifting from the coast to the inland areas because of the rapid development of industrialization and infrastructure construction in the inland areas. But parts of the interior such as the west and north are still underdeveloped.

The distribution pattern of urban environmental pressure is shown in Figure 4b. Our findings indicate that the central and southern inland areas were the most severely affected regions. The central and southern interior regions appear to be impacted more severely. This may be attributed to the fact that these areas heavily rely on capital-intensive industries, such as large factories and industrial parks, as well as transportation facilities like subway projects. The construction of these facilities results in a higher energy consumption and waste emissions. As a result, the southern region has implemented specific environmental policies to address these concerns since 2014, leading to some relief in environmental pressure. But the northern region still continues to face more significant or even worsening environmental issues.

Figure 4c depicts the variation pattern of urban sustainability. In the northern region of the Yangtze River Delta, there is a notable contrast between the outer areas exhibiting a high level of sustainable development, and the inner cities with a lower level of sustainable

development. Despite the relatively low quality of urban construction in certain small and medium-sized cities, they have managed to maintain a favorable urban environment, resulting in a steady increase in sustainable urbanization. The southern inland areas also exhibit a positive trend toward sustainable urbanization. Currently, the majority of southern cities have transitioned from an unsustainable state in 2010 to a sustainable development state, forming a benign area of coordinated development.

4.2.2. Evolution Characteristics of Regional Structure

In Figure 5, we utilized geographic distribution tools such as weighted mean center and standard deviation ellipse to examine the spatial evolution with the corresponding results. It revealed that the Yangtze River Delta region remains in a state of imbalanced development even after 9 years since 2010. More specifically, the centers of Q_U , which are located in the city of Changzhou, have shifted closer to the geometric center, but still offsets 58.72 km away from the geographic center. The mean centers of P_U and S_U , however, have increased in distance from the geometric center by 1.23 km and 7.71 km, respectively, for a total distance of 20.04 km and 39.46 km in 2018. These increases show that the regional imbalance is increasing. While the shape changes of the ellipses differ significantly, the standard deviation ellipses for all variables indicate a consistent principal axis orientation in the southeast–northwest direction. The elongated long axes of Q_U and S_U , as well as the elongated short axes of Q_U and P_U , suggest a heterogeneous spatial change over time.

The average speeds of the mean centers' annual migration are relatively similar, with P_U being the fastest ($V_{P_U} = 1.87$ km/year), followed by Q_U ($V_{S_U} = 1.77$ km/year) and Q_U ($V_{Q_U} = 1.51$ km/year). These findings suggest that the Yangtze River Delta region is rapidly moving toward an imbalanced situation, which may result in a widening sustainable development gap between northern and southern cities. This trend is strongly associated with the escalating environmental pressure faced by cities in the north. Currently, there exists a considerable gap between the northern and southern regions. To address the adverse effects of imbalanced development in the Yangtze River Delta region, it is crucial to prioritize the enhancement of governance and management in cities located in the north, particularly in the areas surrounding Nanjing.

5. Discussion

At present, many developing countries are trying to base the future development of their cities on achieving certain urbanization goals [83,84]. Although it is a fact that Chinese cities with a high level of urbanization tend to have a better quality of Q_U , this model of development also has substantial environmental implications and costs. This means that the risk of sustainability in these cities is real and cannot be underestimated. Zhu et al. (2016) [69] and other scholars have also discovered similar findings from their studies. In rapidly growing cities with low-quality urban built environments, the scale of development often leads to an increased pollution and environmental degradation. However, in the higher quality stage, the pace of urban growth tends to slow down and pollution reduction efforts can match or even surpass the scale of development. As the demand for a cleaner environment increases, there is a greater potential for environmental improvements to be made. This is shown by the famous Kuznets curve [85,86].

In some cases, however, an increased efficiency has accelerated economic growth with technological advances or dedicated policy support. However, when the demand is particularly high, the demand or consumption of resources may also increase, and a rebound phenomenon may occur, which is the so-called Jevons paradox [87]. This is often overlooked by policymakers who blindly declare the need to emulate large cities. This would cause urban residents to be tempted by short-term interests and ignore long-term and stable urban environment solutions. For example, the infrastructure and public services of most small and medium-sized cities are still insufficient, and the large-scale construction activities and outdated production techniques carried out by some of these cities in order to maintain output value have severely damaged the environment and excessively consumed

resources [88–91]. Furthermore, a lack of planning at scale causes an imbalance of urban development in the region. This will result in an unfavorable chain of events in any region in the process of rapid urbanization. In turn, it exacerbates urban environmental problems and threatens the sustainable development of megalopolises [92,93]. In the coming decades, China's urbanization rate will continue to increase steadily at a rate of about 1% per year [88], and it is firmly believed that urbanization is the only way for the country to modernize. However, we can clearly see that the sustainable development level of each city in the region is significantly different. We suggest that on the premise of coordinating the balanced development of Q_U and P_U in the region, we should understand the temporal and spatial characteristics of each city and give priority to implementing corresponding policy support and resource allocation within the scope of impact factors. By comparing the heat map of each indicator, it is possible to clearly identify key areas where the city needs improvement (as shown in Figures 6 and 7). This information can be used to develop more targeted urban development strategies that are better coordinated with the needs of the city.

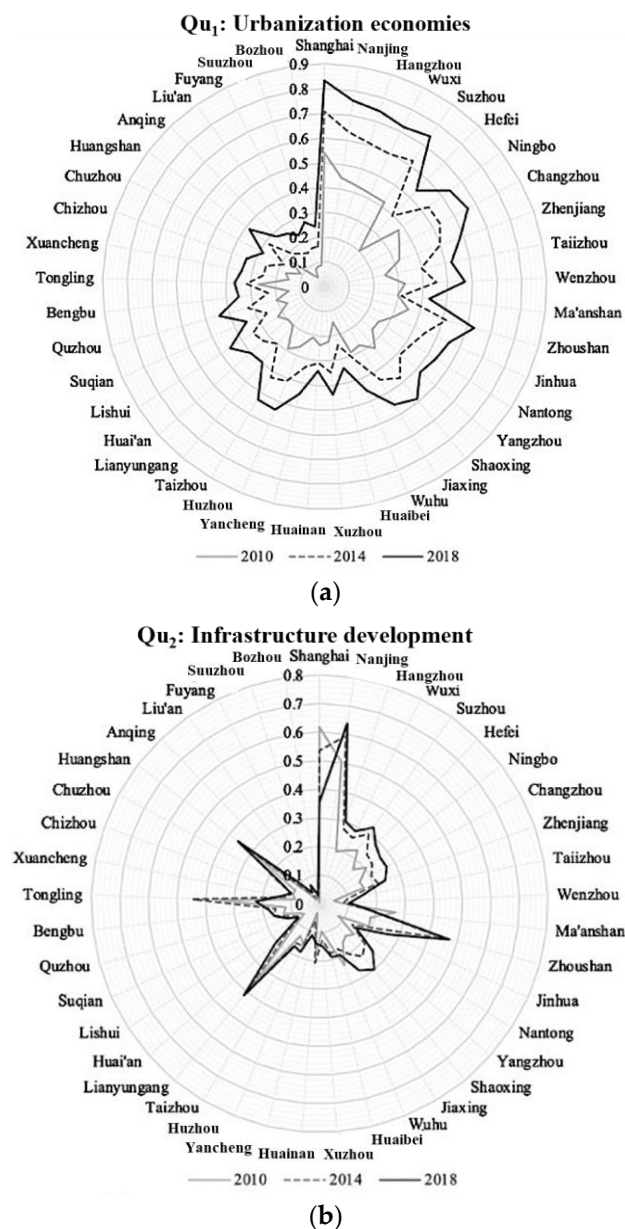


Figure 6. Cont.

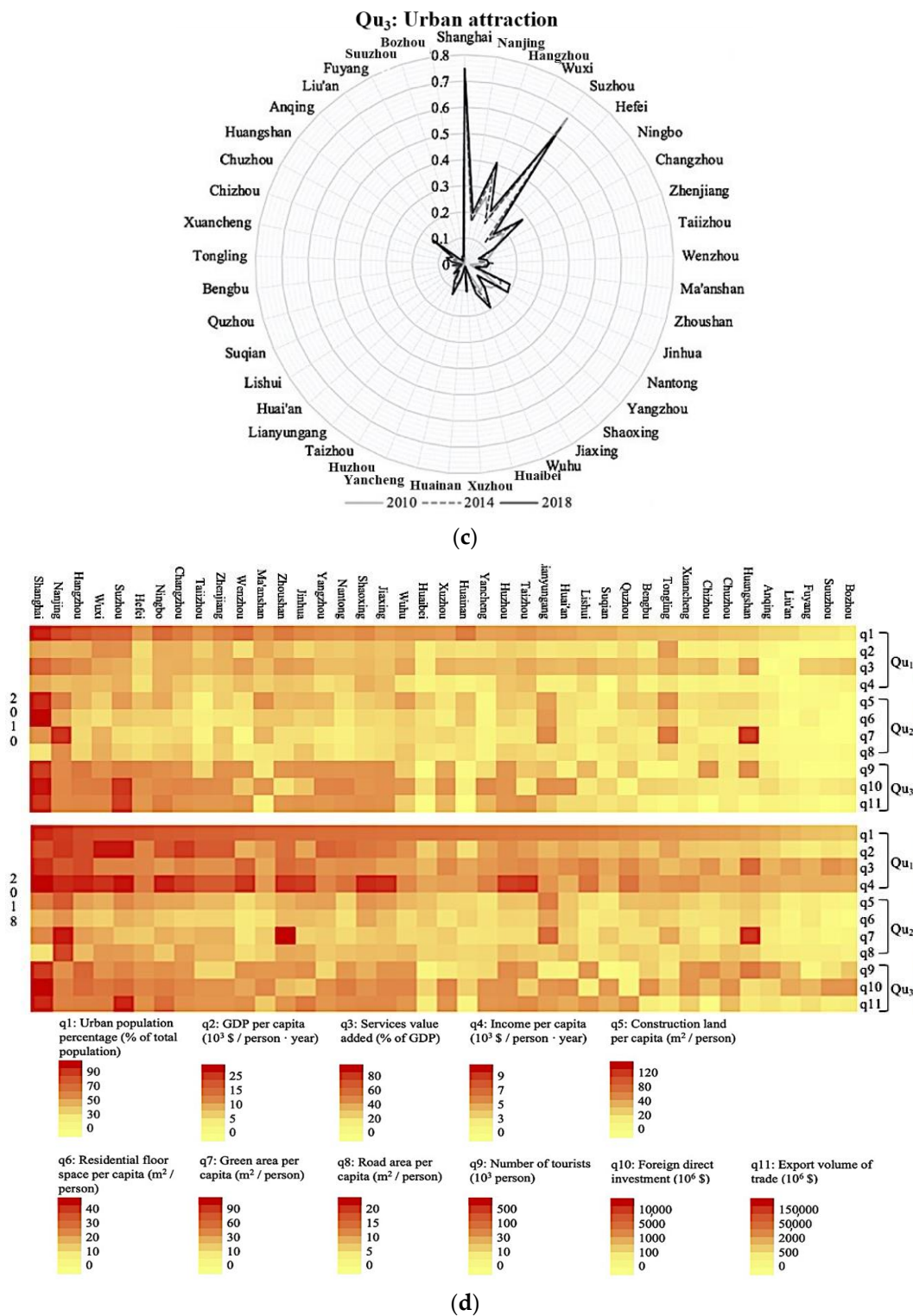


Figure 6. The performance of each of the indicator categories of the quality of the built environment (Q_U) in Yangtze River Delta, measured by the weighted scores from 2010 to 2018. (a) Radar chart of measurement values of urbanization economics in Q_U . (b) Radar chart of measurement values of infrastructure development in Q_U . (c) Radar chart of measurement values of urban attraction in Q_U . (d) Heat maps of each original indicator of Q_U .

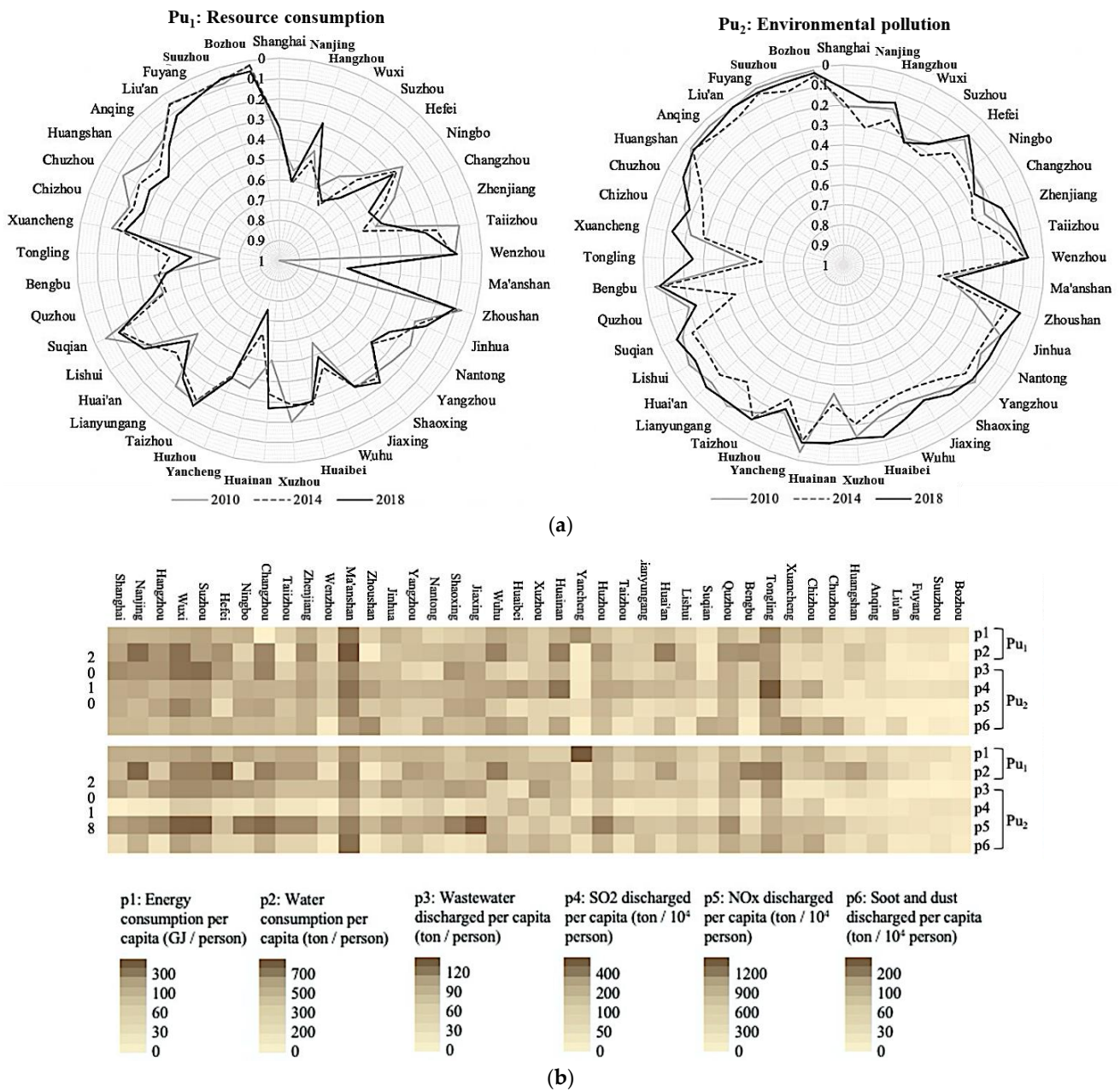


Figure 7. The performance of each of the indicator categories of environmental pressure (P_U) in Yangtze River Delta measured by the weighted scores from 2010 to 2018. (a) Radar chart of the values of resource consumption and environmental pollution in P_U . (b) Heat maps of each indicator of P_U from 2010 to 2018.

Regarding the quality of the built environment (Q_U) (as shown in Figure 6), the industrial sector has traditionally been a key driver of economic development in these cities. However, with the shift toward a stock-and-investment capital-based economy, it is now important for these cities to prioritize the optimization of their industrial structure and provide preferential treatment or support policies to those cities with less developed urbanization economies in order to stimulate their economic growth. In 2022, the Chinese government announced plans for macroeconomic adjustments [94], with a focus on supporting infrastructural development through measures such as prioritizing cities with significant infrastructure shortages for support under these policies. In addition, it is worth noting that many cities in the Yangtze River Delta region currently lack competitive urban features. These cities should consider leveraging and promoting local cultural heritage or

improving the natural environment to attract international events and increase visibility. Furthermore, promoting a diversified and knowledge-based economy by attracting high-tech industries, creative industries, and advanced services can also help to enhance their competitive edge.

Regarding the environmental pressure (P_U) (Figure 7), more than half of the cities in the Yangtze River Delta region have shown an increase in resource consumption since 2010. The primary reason for this is the substantial energy consumption by industries, particularly in economically underdeveloped cities that rely on traditional, high-energy-consuming industrial practices. Moreover, poor water-saving awareness and inadequate mechanisms to regulate water consumption have led to the wastage of water resources. To address these issues, there is a need for sufficient funds, advanced technology, and spontaneous environmental awareness. It is worth noting that since 2010, pollution levels in most cities have decreased, especially the cities with a lower urbanization level. But the outdated purification treatment technology still leads to a large amount of pollutant discharge. Special vigilance is required to control nitrogen oxides and solid waste emissions to manage risks and develop strategies for climate mitigation and adaptation [6].

6. Conclusions

There has been an overall improvement in the quality of the built environment, while environmental pressure has been on a declining trend over the past years. This paper provides a perspective that combines a concise urban sustainability assessment system with effective spatiotemporal analysis methods. Our results reveal the urban development status of megalopolises in the current urbanization period in China represented by the Yangtze River Delta by highlighting the improvement of urban construction quality, the magnitude of environmental impact, regional geographic and spatial distribution differences, the interaction between sustainable impact dimensions, and the priority focal points of future development. The following are the key findings from the empirical analysis of the Yangtze River Delta between 2010 and 2018:

1. The sustainability of the urban environment in the Yangtze River Delta shows obvious differences and spatial heterogeneity. By 2018, there are still 19 cities in an unsustainable state of development. From the perspective of the regional structure of the whole megalopolis, the gap between the East and the West has changed to the gap between the North and the South and continues to increase. It is necessary to formulate a master plan for integrated regional development on rationally distributing and efficiently gathering various production factors to prioritize the development of cities in the northwest, so as to achieve a balanced development.
2. From two major dimensions of evaluation, the quality of the built environment (Q_U) of the Yangtze River Delta appears high in the Southeast than in the Northwest, while the urban environmental pressure (P_U) develops from the center to the North at a rapid rate. Fortunately, after a certain level of economic growth in southern cities, it has driven the rapid adjustment of the industrial structure, which is good for the environment. However, this has led to the blind consumption of resources by northwestern cities to reduce the gap. Therefore, it is very important to build an inter-regional cooperation platform, eliminate confrontation, and establish mutual assistance in technological, industrial, and many other aspects.
3. A curve estimation regression analysis of the relationship between Q_U and P_U has revealed five distinct types of urban development trends in the Yangtze River Delta. Among them, the inverted U-shaped and negative linear types of cities mean that the environmental load caused by the improvement of Q_U is less than in other cities. But the inverted U-shaped city is relatively sensitive to environmental changes due to environmental degradation and may rebound due to minor factors. This benign development trend needs to be maintained by insisting on the implementation of energy-saving and emission reduction. In order to avoid turning into an unstable S-shaped type of city, we should prevent overexploitation or the overspeed of urbanization,

and instead implement a constant focus on seeking to balance urban development with the environment. However, cities of S-shaped, U-shaped, and positive linear types are facing different degrees of environmental degradation. Decision-makers should appropriately slow down the speed of urbanization and give priority to taking targeted measures to deal with urban environmental problems in order to minimize the impact of urban development on the environment. Also, we need to strengthen sustainable publicity efforts to raise public awareness of environmental protection in the near future.

Our research results offer a comprehensive assessment and detailed diagnosis, providing urban planners and policymakers with crucial information. The findings reveal potential hotspots and areas that require immediate attention, directing resources and interventions where they are most needed. This allows them to identify the strengths and weaknesses of different cities concerning specific targets and prioritize actions accordingly, leading to more effective and sustainable outcomes. Moreover, our research findings have the potential to be transformed into a user-friendly and interactive visualized tool in the future, enabling a rapid and efficient means of evaluating and analyzing a city's sustainability, providing valuable insights, and guiding recommendations.

However, this study is particularly relevant for developing and underdeveloped cities experiencing or approaching rapid urbanization. We recognize that urbanization is a dynamic process, and cities' needs and priorities may evolve over time. Consequently, it is essential to regularly review, improve, and update our indicators and conclusions to ensure their continued relevance and effectiveness in addressing changing circumstances and emerging sustainability challenges during the next stage of urbanization.

In addition, our study primarily interprets urban development through the lens of objective indicators, which may limit the depth of understanding from an on-the-ground perspective. For future work, we plan to conduct more detailed research and engage more closely with local decision-makers and residents. By actively seeking insights and feedback from stakeholders, we can gain a deeper understanding of the nuanced challenges and opportunities faced by these cities in their development journey. Through this iterative and collaborative process, we aim to bridge the gap between objective indicators and comprehensive understanding, thereby supporting the sustainable development aspirations of these cities and contributing to their long-term well-being.

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