博 士 論 文

Study on the Sustainability Performance of Urbanization and its Environment among Megalopolises in China

中国における都市化とその環境の持続可能性に関する研究

北九州市立大学国際環境工学研究科

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Preface

This study aims to explore the sustainability performance of urbanization and its environment in the scope of megalopolises in China, based on the proposed assessment system of urban sustainability. That is defined as the ratio of the two dimensions: quality of the built environment and environmental pressure. The quality of the built environment includes urbanization economies, infrastructure development, and urban attraction. With the help of statistical data analysis and geoinformatics methods, the corresponding assessment and spatio-temporal analysis results are obtained using national official statistics. The empirical results of four Chinese major megalopolises (Yangtze River Delta, Pearl River Delta, Shandong Peninsula and JingJinJi) show that the urban sustainability model is applicable to conveniently combine various analytical methods to help multiple parties reach a common consensus for guiding a reasonable, efficient, and sustainable urbanization process.

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STUDY ON THE SUSTAINABILITY PERFORMANCE OF URBANIZATION AND ITS ENVIRONMENT AMONG MEGALOPOLISES IN CHINA

ABSTRACT

In the 21st century, the world is experiencing a process of rapid, especially in Asian developing countries. Focusing on efficient measurement and planning towards achieving sustainable urbanization in a mainstream scope of megalopolis will become crucial for national competitiveness and potentially have an impact on the new global economic order. The sustainability assessment system has been proved to be an efficient tool involved in urban policymaking, thus it has become and one of the hottest topics in the academic world.

This study aims to explore the sustainability performance of urbanization and its environment in the scope of megalopolises in China, based on the proposed assessment system of urban sustainability. That defined as the ratio of the two dimensions: quality of the built environment and environmental pressure. The quality of the built environment includes urbanization economies, infrastructure development, and urban attraction. The data of all indicators are in the period from 2010 to 2018, which was collected from the public authoritative China Statistical Yearbook. The empirical results of four Chinese major megalopolises (Yangtze River Delta, Pearl River Delta, Shandong Peninsula and JingJinJi) show that the urban sustainability model is applicable to conveniently combine various analytical methods to help multiple parties reach a common consensus for guiding a reasonable, efficient, and sustainable urbanization process.

In Chapter 1, ***INTRODUCTION***, the background and significance of the study are elaborated from three perspectives: world urbanization trends, the urbanization and shrinkage phenomenon in Asia, and its effect on the urban environment. And the purpose of and research structure is put forward after reviewing previous studies.

In Chapter 2, ***URBAN SUSTAINABILITY ASSESSMENT AND RESEARCH METHODOLOGIES***, benefiting from public consensus on the SDGs, the critical literature review and experts' comments, especially successful worldwide assessment tools and widely used tools in China, the urban sustainability assessment system of this study was established. And the definition of the assessment system, corresponding indicator system, data sources, and its processing calculation process are described in detail. Besides, other used spatio-temporal methodologies of Statistics and Geoinformatics used in the article to support the analysis are also introduced.

In Chapter 3, ***OVERVIEW OF URBANIZATION AND ITS ENVIRONMENT INVESTIGATION IN CHINA***, the process of urbanization in China (excluding autonomous administrative divisions, Hong Kong, Macao and Taiwan regions) is studied. This includes the investigation on urbanization and its environmental status and development trends from administrative divisions' perspective of provincial-level divisions, and from megalopolises' perspective, respectively. A general understanding of the basic performance of relevant indicators is obtained through the analysis of spatial patterns and descriptive statistics using the original data from China Statistical Yearbooks.

In Chapter 4-7, ***MEASURING THE PERFORMANCE OF URBAN SUSTAINABLITY IN YANGTZE RIVER DELTA / PEARL RIVER DELT / SHANDONG PENINSULA / JINGJINJI***, the sustainability evaluation results from 2010 to 2018 of four megalopolises are analyzed in each chapter separately. The detailed research flow includes: (1) the general introduction of each megalopolis, (2) the assessment results' presentation and coupling interaction mechanism analysis between the quality of the built environment and its environmental pressure for each city (3) spatio-temporal variation patterns of assessment results and their evolution track characteristics, and (4) providing the countermeasures on the quality of built environment and its environmental pressure for each city in the corresponding megalopolis.

In Chapter 8, ***COMPARATIVE STUDY AND CLASSIFICATION DISCUSSION AMONG FOUR MEGALOPOLISES***, the performance comparison of the four studied megalopolises in China is discussed including assessment results comparative analysis and spatial autocorrelation analysis based on the Local Indicators of Spatial Association (LISA) cluster methord. In addition, characteristics and implications of urban sustainability are discussed based on geographic location and urban population classification, and the sustainability performance clustering classification, respectively.

In Chapter 9, ***CONCLUSION***, the main conclusions of each chapter have been summarized.

CONTENTS

Chapter 3. Overview of Urbanization and its Environment Investigation in China

Chapter 4. Measuring the Performance Urban Sustainability in Yangtze River Delta

Chapter 5. Measuring the Performance Urban Sustainability in Pearl River Delta

Chapter 6. Measuring the Performance Urban Sustainability in Shandong Peninsula

Chapter 7. Measuring the Performance Urban Sustainability in JingJinJi

Chapter 8. Comparative study and classification discussion among four megalopolises

Chapter 9. Conclusion

CONTENTS OF FIGURES

CONTENTS OF TABLES

Chapter 1. Background and purpose of the study

1.1. Introduction

The world is experiencing a process of rapid urbanization, especially in developing countries. For the first time in human history, over half of the world's population now live in cities [1,2] (Fig.1-1). The most intuitive embodiment of urbanization is the number of urban populations. In most of the countries all over the world, urban shares have been increasing. While the process of urbanization keeps going on, the phenomenon is having a massive impact on the economic, social, environmental landscape all over the world.

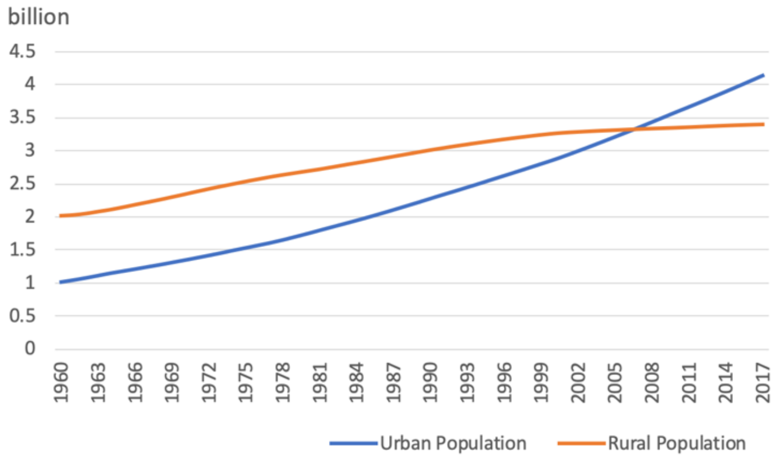


Fig. 1-1 Urban population and rural population, 1960-2017.
(Source: World Bank, OurWorldinData.org)

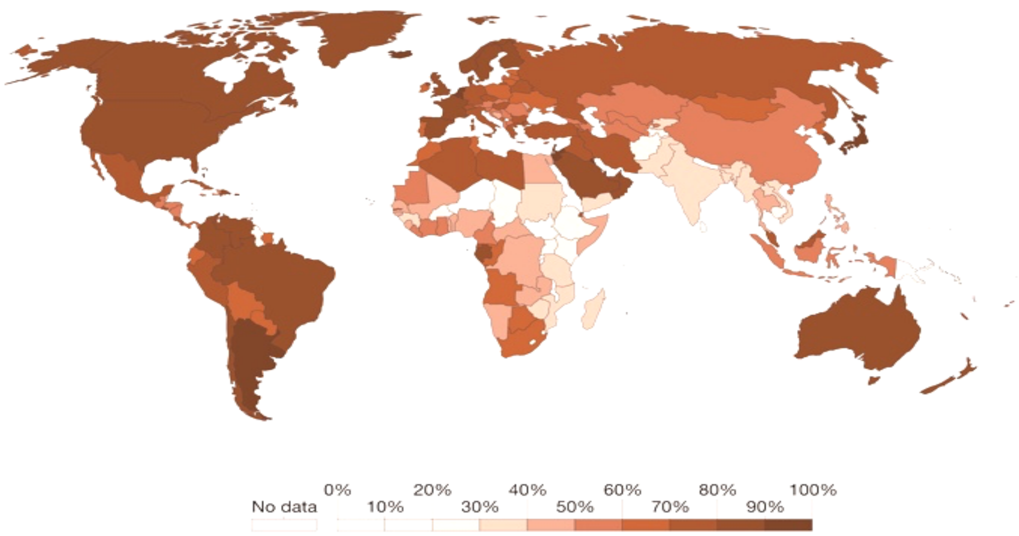


Fig. 1-2 World Urbanization Rate Map, 2017. (Source: World Bank, OurWorldinData.org)

At the beginning of the twentieth century, just 16 cities in the world—the vast majority in Current industrial countries-contained a million people or more [3]. According to the 70% urbanized population indicator, in the mid-20th century urbanization was basically completed in high-income countries like Europe, North America and Australasia [1,4]. And some smaller developed city-based nations such as Japan, Puerto Rico and Israel tend to have large urban populations. A handful of countries across Asia and Latin America, most countries of Sub-Saharan Africa, Asia-Pacific are in the range of 10% to 40% with lower rates [5] (Fig.1-2, 1-3). Nowadays, in Northern America, more than half of the population resided in cities with 500,000 inhabitants or more in 2018 and one in five people lived in a city of 5 million inhabitants or more [6]. Latin America and the Caribbean is the region with the largest proportion of the population concentrated in megacities: of the total population of the region in 2018, 14.2 percent resided in the six cities with 10 million inhabitants or more [7,8]. In both Africa and Asia, over half of the population lived in rural areas in 2018, a share that is declining in both regions. Between 2018 and 2030, the number of cities with 500,000 inhabitants or more is expected to grow by 57 percent in Africa and by 23 percent in Asia [9,10]. (Fig.1-4)

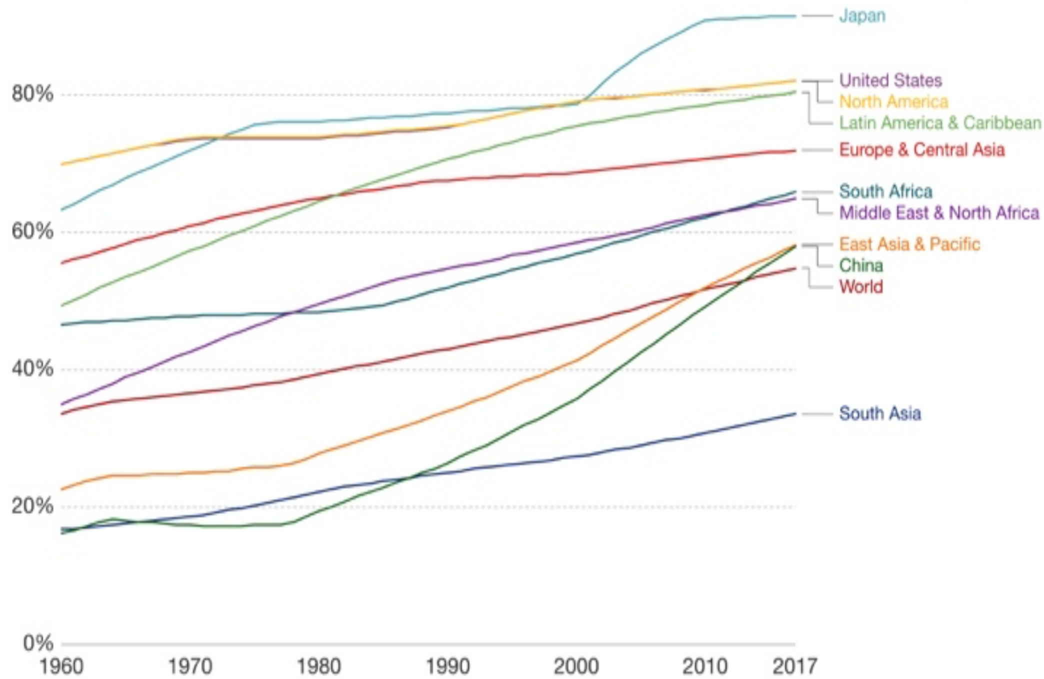


Fig. 1-3 World Urbanization Rate Trend, 1960-2017
(Data Source: World Bank, OurWorldinData.org)

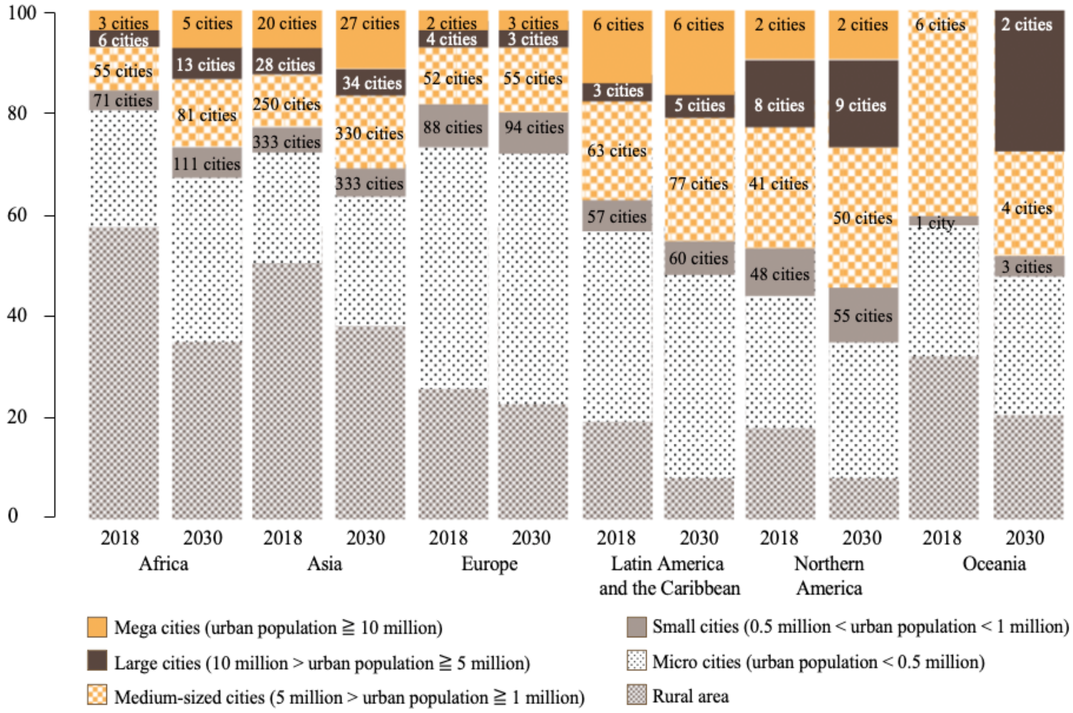


Fig. 1-4 Population distribution by size class of city and region, 2018 and 2030. (Source: UN World urbanization prospects: The 2018 version).

At present, due to wars, debts, lack of labor, an aging population especially environmental problems, some cities have inevitably entered a state of "shrinkage" [11]. More and more regions are showing a trend of urban development with decreasing population from a global perspective. Urban shrinkage is the phenomenon of massive population loss in a short period of time. With the evolution of industrialization, urbanization, and globalization, population agglomeration in cities brings urban economic growth, which has become the development route for many developed cities [12,13]. The decrease in population will bring about unbalanced development among regions, leading to economic recession, and adversely affecting the quality of urban construction.

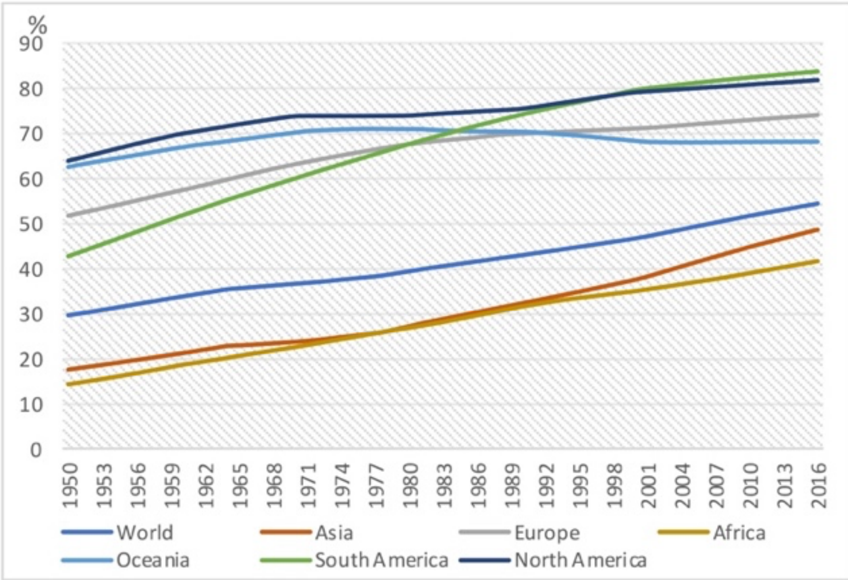
1.2. Research background and significance

1.2.1. Urbanization and shrinkage phenomenon in Asia

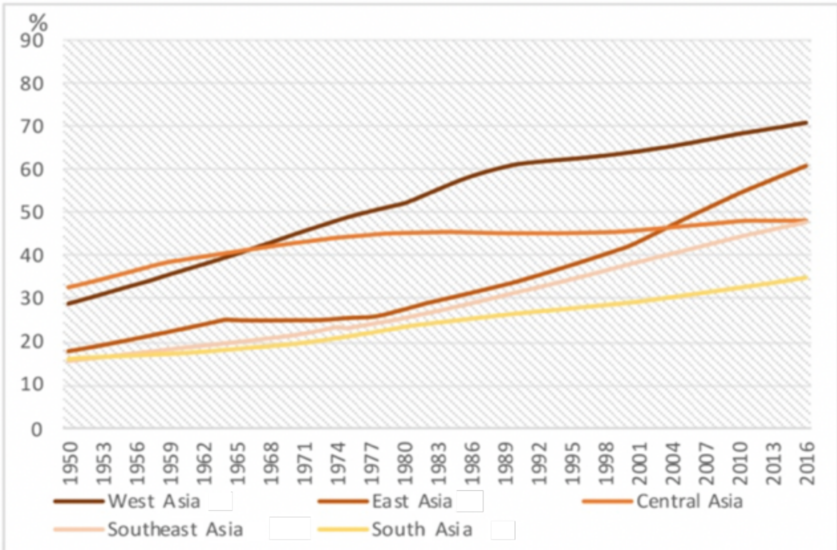
The trend of urbanization has been historically suggested as the precondition for development in the developing world [14].By 2015, 16 of the world's 24 megacities (cities with more than 10 million people) will be located in Asia [15]. Most of these megacities will be located in the population giants [16]. There are many developed cities in the Americas, Europe, and Oceania in which industrialization and urbanization have developed earlier. So, the urbanization rate has basically reached a high level of more than 70%, but the speed of urbanization has been extremely slow as entering the stagnation period [17]. And Asia and Africa show a clear upward trend. In Asia, there are major disparities in the pace of urbanization within the region. The urbanization rate in West Asia reached a high level of 70%, followed by Southeast Asia [18]. Urbanization started at a slower rate but gained momentum during the 1970s and 1980s then gradually reached 60% [19]. Until 1970, due to the European immigration movement, Central Asia's urbanization rate was twice that of Southeast Asia and South Asia. However, the urbanization rate slowed after the 1970s because of internal population movements, terrain and landform restrictions [20]. The urbanization process in South Asia is also steadily accelerating, basically equal to that of Central Asia. The population of Southeast Asia has increased steadily but is still in a stage of backward development. (Fig. 1-5)

Subsequently, the process of urbanization in developing countries has captured media attention. This is partly because the year 2008 marked a watershed in world history – the point where more than half the world's population lived in places designated as urban [21]. With rapid economic growth in many countries, Asia is on a similar path, though with a significant lag. The region is expected to take some 15 years for the urban segment of its overall population to increase from 42.2% in 2010 to 50 percent at the beginning of 2026 [22]. Asia is the largest of all major regions with 30%of the global landmass and 60% of the world's population, it ranked as the second least-urbanized major region of the world after Africa's 40% [10]. Asian cities are home to 1.7 billion people, nearly half the urban population of the world. This proportion is expected to increase slightly by 2020 when Asian cities will be host to 2.2 billion of the world's 4.2 billion urban population [4]. Between 2010 and 2020, a total of 411 million people will be added to Asian cities, or 60 percent of the growth in the world's urban population [16].

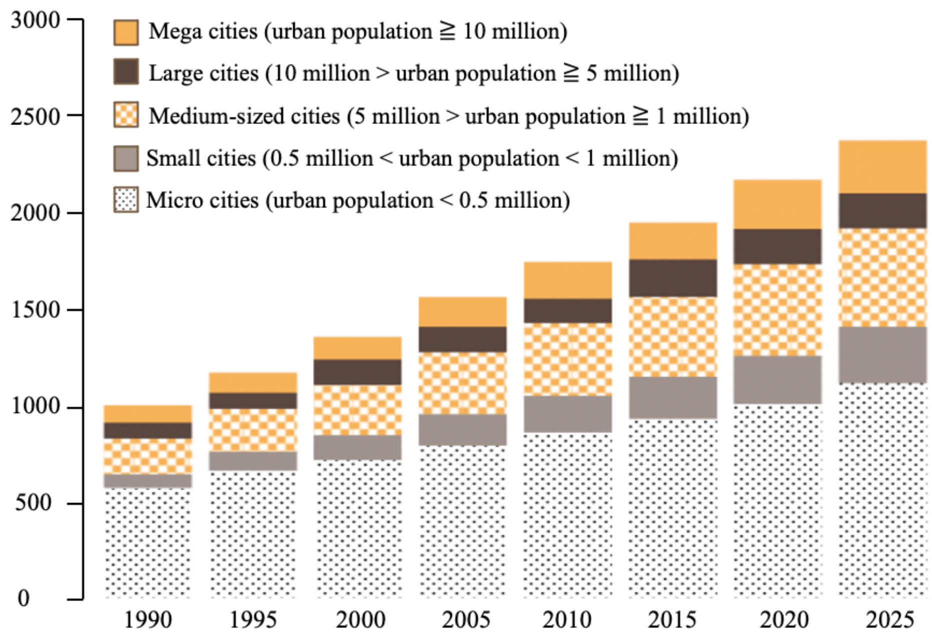
The number of megacities (with populations of 10 million or more) is increasing around the world, and half of the world's megacities are found in Asia (12 out of 21). These highly urbanized areas attract and are home to a large share of development investment. They are also hubs of creativity and often serve as knowledge centers with the best national education and cultural institutions, allowing for vibrant, mixed-use and culturally diverse urban spaces [23]. However, in recent decades more urban Asians have lived in smaller cities and towns than in all the megacities in the region, a trend expected to continue over the next two decades. Today, 60 percent of Asia's urban population lives in urban areas with populations under one million. (Fig. 1-5)



(1) Urbanization trends in the world
(Data Source: World Bank, OurWorldinData.org)



(2) Urbanization trends in Asia
(Data Source: World Bank, OurWorldinData.org)



(3) Population distribution by size class of city in Asia, 2019-2025.
(Data Source: UN-HABITAT, ESCAP, The State of Asian Cities 2010/1)

Fig. 1-5 Urbanization trends in Asia

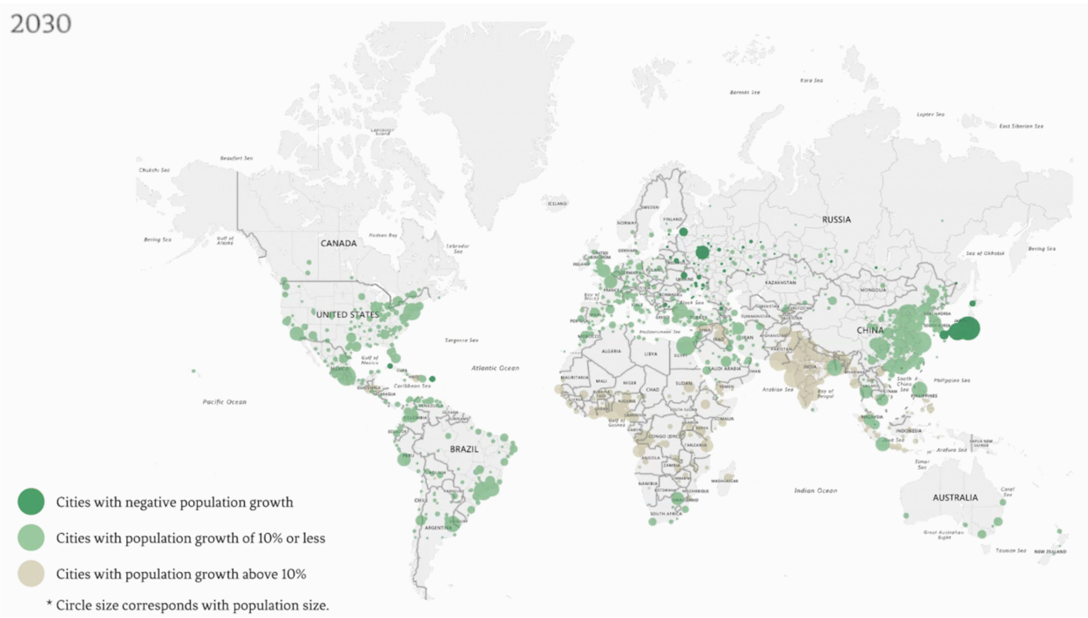


Fig. 1-6 Map showing population growth of cities with at least 300,000 inhabitants (2030).
(Source: United Nations Population Division, “World Urbanization Prospects: The 2014 Revision.”)

What is worrying is that Asia's population could also start shrinking recently (Fig 1-6). In East Asia, Statistics Korea projected that the country's population would start declining in the 2020s, and the United Nations forecast that South Korea's population would start shrinking in 2025. Japan is among the countries facing substantial population declines that have shied away from immigration, preferring to “maintain a linguistic and culturally homogeneous society” that – at least for now – outweighs “the economic, fiscal, and geopolitical risks of declining populations.”. It is reported by Minoru Nogimori, chief economist at the Japan Research Institute that compared to Japan, the pace of population decline is much faster in the rest of Asia, and growth led by a booming population is coming to an end [24–26]. In China, urban shrinkage has gradually become an emerging phenomenon in recent years. The research on the Chinese context is limited, but the existing studies show that there are cities in both, the less- developed provinces and border areas, and in the most developed areas in the Coastal region that have been experiencing population declines [27–30]. Besides, Southeast Asia's population could also start falling earlier than expected. While the region has seen a sharp increase in population, growth in Thailand and Vietnam is already slowing [31].

The main reasons for the shrinkage can be summarized as follows: (1) Residents relocate due to urban environmental pollution or facing the dilemma of resource exhaustion; (2) Some small-sized or developing cities due to the lack of competitiveness and supportive policies adjacent to advanced cities leading to population loss. (3) With the decline in industry, many jobs were lost or outsourced, resulting in urban decline and massive demographic movement. (4) Reasons for population aging or fertility decline and (5)some political or planning adjustments and other reasons. The 21st century has been called the Asian century of rapid urbanization, but if the region is to truly shape global trends and culture it must correct its population decline. Many experts [27–31] believe that Asian economies could face a much longer period of low growth than the one Japan has experienced unless their sustainability improves dramatically through effective means.

1.2.2.The effect of urbanization on the urban environment

The trend of urbanization has been historically suggested as the precondition for development in the developing world [14]. In the context of developing countries, this kind of urbanization possesses a dualistic nature of opportunities as well as challenges. Therefore, cities have both positive and negative dimensions. Positively, it is a central place of modernization and communication, and the engine of a country’s economic development [32,33]. Driven by the desire for better living conditions, education, medical care and culture, this new migration is one of the most significant shifts in human habitation ever witnessed. One of the results of this is a change in the sources of economic prosperity, with 60% of the world’s GDP now generated by roughly 600 cities [34]. BHowever, in the past, urban development only emphasized the number and scale of cities, while ignoring the cost of resources and the environment. The urban development policy of the 20th century only emphasized the number of cities and the size of the population, while ignoring the cost of resources and the environment, leading to more prominent urban problems in Asia, such as dense population, tight land use, environmental pollution, insufficient energy, shortage of resources, and transportation. Congestion, insufficient public facilities, health effects, etc [19,35,36]. The main impacts of urbanization on the urban environment are described in detail as follows:

Economic growth

The link between urbanization and economic growth has been well-documented [37,38] and have a strong positive correlation relationship between urban population and GDP by analyzing the relationship between the share of the population living in urban areas on the y-axis and average income (gross domestic product per capita) on the x-axis in Asia (Fig.1-7). The main reasons for economic growth are manufacturing growth, such as promoting Japan's industrialization; and implementing open economic policies, such as China's reform and opening up in the 1970s, increasing economic openness and export-led growth models in Malaysia, the Philippines, Indonesia, India, and Thailand.

Especially since the 1980s, the economic growth of Asian cities has been catalyzed by increases in foreign direct investment (FDI), including financial investment, technical assistance, public-private partnerships, innovative sharing and so on [14,39,40]. This has been particularly pronounced in East and Southeast Asian countries (Singapore, Thailand, Indonesia, China, and Vietnam) but has also been evident in South Asia (India and Pakistan). The Asian currency crisis of 1997 produced only a short-term drop in FDI to most of these countries. It shows the trends in FDI in the major Asian countries in Fig.1-8. These FDI inflows which are described as "Pacific-Asia urban corridors" [41] are viewed as an additional driver of economic growth and the basis for making sound economic policies.

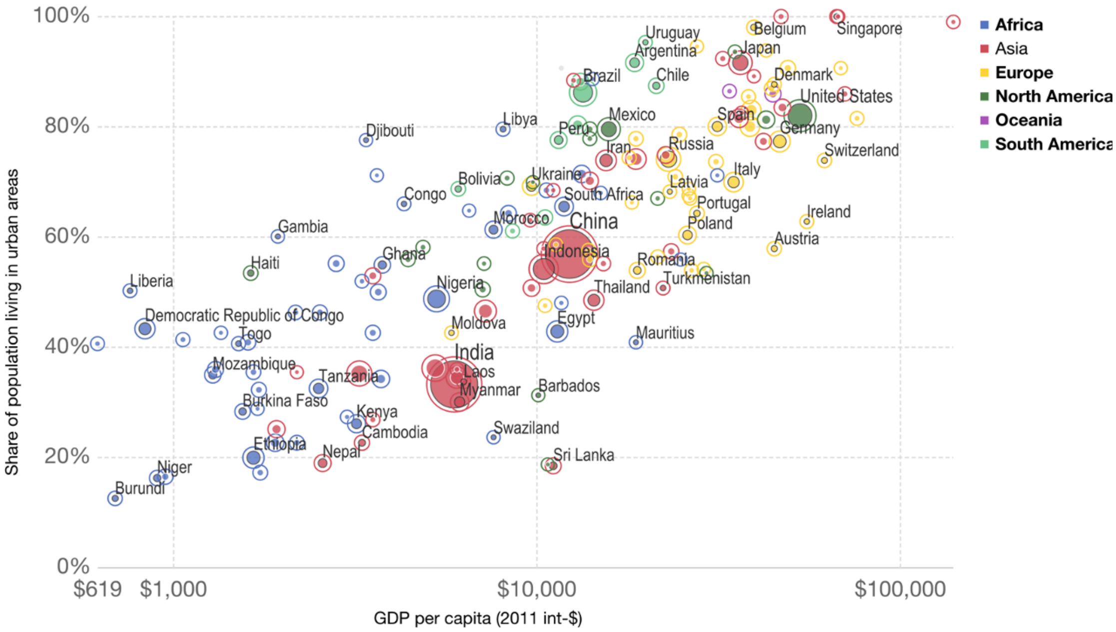


Fig. 1-7 Urban population vs. GDP per capita, 2016

(Source: OWID based on UN World Urbanization Prospects (2018), Maddison Project Database)

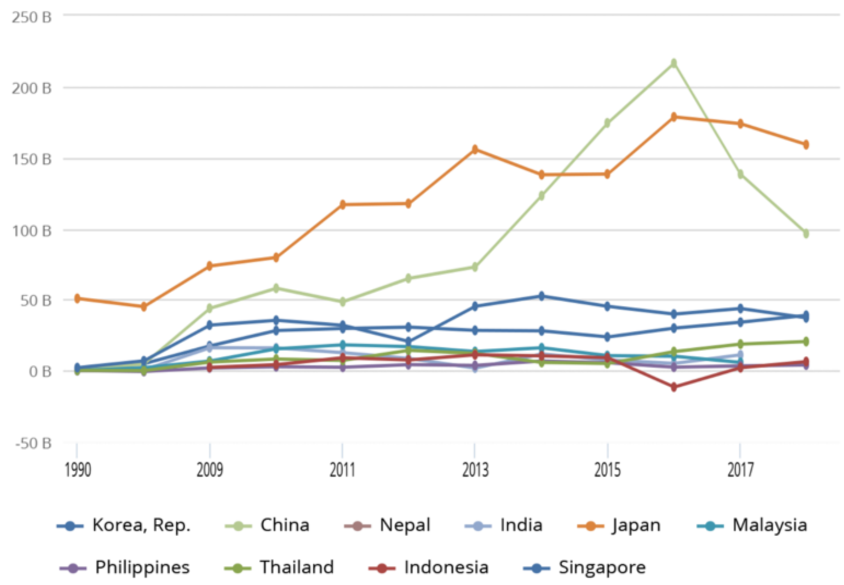


Fig. 1-8 Foreign direct investment of Asian countries (Bop, current US$), 1990-2017
(Source: World Development Indicators)

Insufficient in infrastructure

As more and more people migrate to urban areas, urban boundaries often expand to accommodate new residents. From 2000 to 2015, the expansion of urban land in all regions of the world exceeded the growth of urban population. This ratio increased from 1.22 in 1990 to 1.28 in 2000 to 2015 [42]. This means that unplanned urban expansion has a negative impact on the sustainability of urban development and has led to serious urban poverty in many Asian cities, including increasing numbers of slum dwellers, lack of appropriate land and housing policies, and basic services. Insufficiency and infrastructure. Here, we see that in the 2014 data, 10% to 30% of the urban population in most Asian countries live in slum families. Families in slums in West Asia account for a relatively high percentage, up to 70% [35].

In addition, infrastructure construction is vital to the millions of poor people and other disadvantaged groups in the region. For example, in terms of public transportation construction, in cities such as Bangkok, Jakarta, Manila, and Mumbai, public transportation methods account for 40% to 60% of the total number of people traveling, which is much lower than the developed cities in the region, Hong Kong, Singapore and Tokyo. The share is 70% [43].

Excessive resource consumption

Unplanned urban sprawl negatively affecting the sustainability of urban development which has led to increasing demand and waste for resources, especially primary energy and water, which are the basic resource for both urban construction and human activities. [44–46]

The U.S. Energy Information Administration (EIA) project predicts that between 2018 and 2050, energy consumption will almost double, making Asia the largest and fastest growing region in the world. The industrial sector (including oil refining, mining, manufacturing, and construction) may account for more than half of the final use of energy consumption, with the largest share of energy consumption in all end-use sectors [47]. Moreover, urbanization, rising income will also lead to rising demand for motorized transportation and living activities.

In addition, Asia is facing immense challenges and risks of water stress. By 2050, more than 60% of the Asia Pacific population will live in cities [48]. However, we are facing an alarming 1.7 billion people who do not have access to basic sanitation 80% of wastewater is discharged in water bodies (rivers, lakes and oceans) with little or no primary treatment [49]. For example, in Indonesia, only 14% of Wastewater is treated in the Philippines, with a figure of 10%, India with 9%, and Vietnam with 4% [50]. Seven of the world's 15 largest groundwater extracts are located in Asia and the Pacific. Bangladesh, India, Nepal, and Pakistan spend $3.78 billion a year on water withdrawals. However, for example, Indonesia, which has a large population, is seriously underfunded and water resources are not balanced. The above indicates a strong probability of future water scarcity [51,52].

At the same time, urbanization seems to have played a positive role. More and more cities move to energy-intensive industries, clean fuels and technologies, and stronger energy efficiency policies, manufacturing continues to improve its emissions performance. Moreover, the 2030 Agenda for sustainable development of United Nations published in 2017 proposed one of the core objectives is to decouple economic growth from resource use and environmental degradation [53]. But for low-income cities, growing resources and energy consumption have been the main culprit for causing many urban problems for a long time, such as environmental pollution.

Air pollution and health problem

Air pollution in Asia is composed of a mixture of pollutants emitted in large quantities from many different combustion sources, because of rapid urbanization, industrialization, and motorization. Several Asian cities in China, India, and Vietnam have the highest levels of outdoor air pollution in the world [54]. The World Health Organization (WHO) highlights that air pollution might contribute to approximately 800,000 deaths and 6.4 million lost life–years worldwide in 2000, with two thirds of these losses occurring in rapidly developing Asian countries [55]. In addition, according to model data derived from satellite estimates, in 2014, nine out of ten people living in urban areas did not breathe clean air. Air pollution has a series of negative effects, including damage to human health, ecosystems, agricultural systems, and the urban construction environment. Therefore, air pollution is the greatest environmental risk to human health in the world, especially in Asian and African countries. No urban area meets the world air quality guidelines [56].

We can clearly see from Fig.1-9 that the death rate caused by Ozone, PM and indoor pollution (per 100,000 people). In Asia, PM has the greatest impact on overall mortality (up to 65%). South Asia is more affected by three types of air pollution than other regions. The higher the level of urbanization, the less indoor fuel use, the better the indoor air pollution control, and the better the indoor air quality in high-income countries, almost no impact on health. Ozone, that arise from high emissions of NOx and of various reactive hydrocarbons, exposure the death rate is higher in South Asia and Eastern Asia (more than 10%) [57,58].

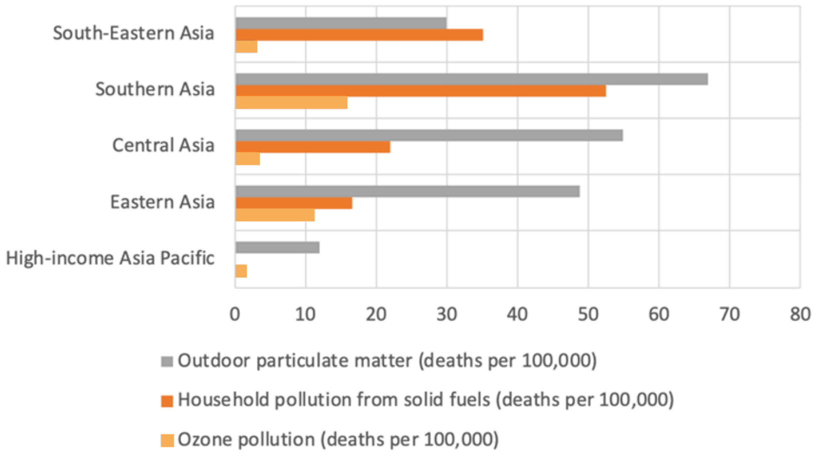


Fig. 1-9 Death rates from air pollution in Asia, 2017
(Source: IHME, Global Burden of Disease)

1.2.3.Research Significance

Urbanization took place over a period of several decades in European countries and North American countries. And it is happening in East Asia for only a few years. Although in the next 40 years, the global urbanization level is expected to reach 70%, Asia's overall urbanization rate is still admittedly low [21]. This kind of urbanization possesses a dualistic nature of making a great influence on the urban environment of positively promoting the quality of the city and negatively increasing the environmental load. And the important mission is to maintain the increase in the urbanization rate and prevent these developing countries from entering a state of urban shrinkage prematurely due to environmental problems. Moreover, it’s an essential role for urban decision-makers that they take the responsibility for making all the residents living in the urban areas a better living environment. The importance of sustainable urban development for the quality of life has been proved by multi-parties over three decades. the concept of urban sustainable development has been a worldwide consensus to overcome the development and environmental problems in the context of urbanization [59,60]. It continues to influence the approaches in relevant theories and practices of urban management. Therefore, the sustainable urbanization process has become one of the most challenging challenges facing human society in the 21st century and one of the hottest topics in the academic world.

In the context of globalization, world cities take an important position in the global economy and trade system. Centered with these cities, their surrounding metropolitan areas’ urbanization processes have become classic models because of their strong impetus and mature development mechanism. As a new type of urban morphology, the metropolitan areas mean that the joint development of the central cities and their surrounding small towns produced an agglomeration effect and contributed to the rational allocation of resources within the regions. In the developed countries, metropolitan areas have gradually become an important driving force of regional and national economic growth. From the most recent World Cities Report 2016 by the United Nations Habitat [61], the metropolitan areas of the world have begun merging toward “super-megalopolises”. These trends clearly show that urban agglomerations are becoming one of the most important geographic units for countries to effectively participate in global competition and international division of labor. Obviously, focusing on efficient planning, effective management and sustainable development of urban agglomerations will become the key to improving national competitiveness and may have an impact on the new global economic order.

The complexity of urban research itself makes it more and more necessary to use various concepts and tools. In addition, in order to facilitate monitoring, there are multiple tools to track and visualize the progress of achieving goals. These tools can guide many aspects, such as cooperation between different parties involved in the formulation of urban policies, promotion efforts by local and national governments, and the availability of incentive mechanisms to promote their acceptance. All the intentions are to make data more accessible, easier to understand, and serve as an effective guide for the future development of the city. Therefore, studying the mechanism and performance of sustainable urbanization within megacities is of great significance for guiding a reasonable, efficient, and sustainable urbanization track.

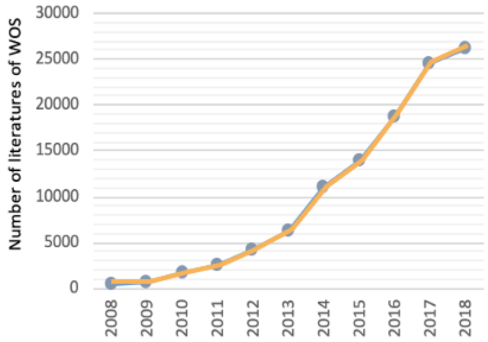
1.3.Review of previous study

1.3.1.Study on research trends of urbanization and urban shrinkage

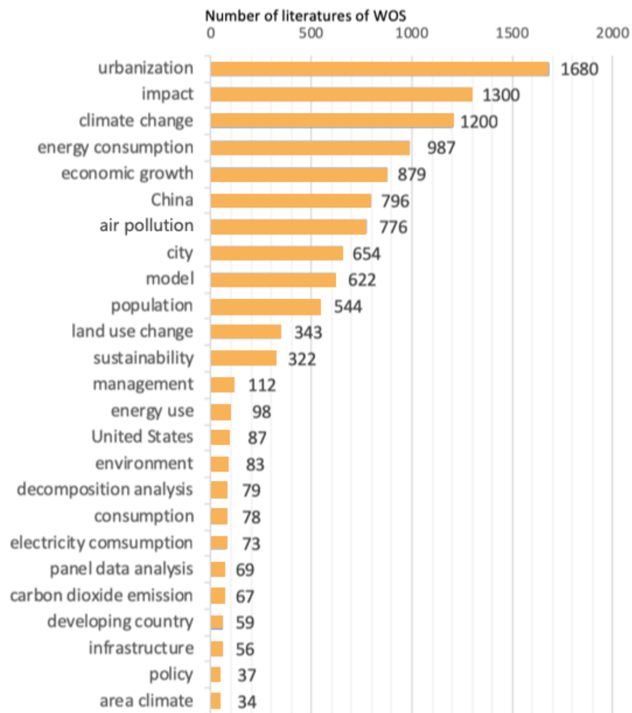
Research trend of urbanization

In order to better understand the domestic and foreign research progress, this paper attempts to use the methods of knowledge visualization by HistCite software and literature collation and statistical methods to analyze the research trends and key points in the field of urbanization research. The extraction of literature data is derived from the authoritative academic databases of WOS (Web of Science). In the SCI and SSCI databases of Web of Science, the subject terms are limited to "Urbanization" and the time is limited to the year from 2008 to 2018. A total of 1794 articles were searched.

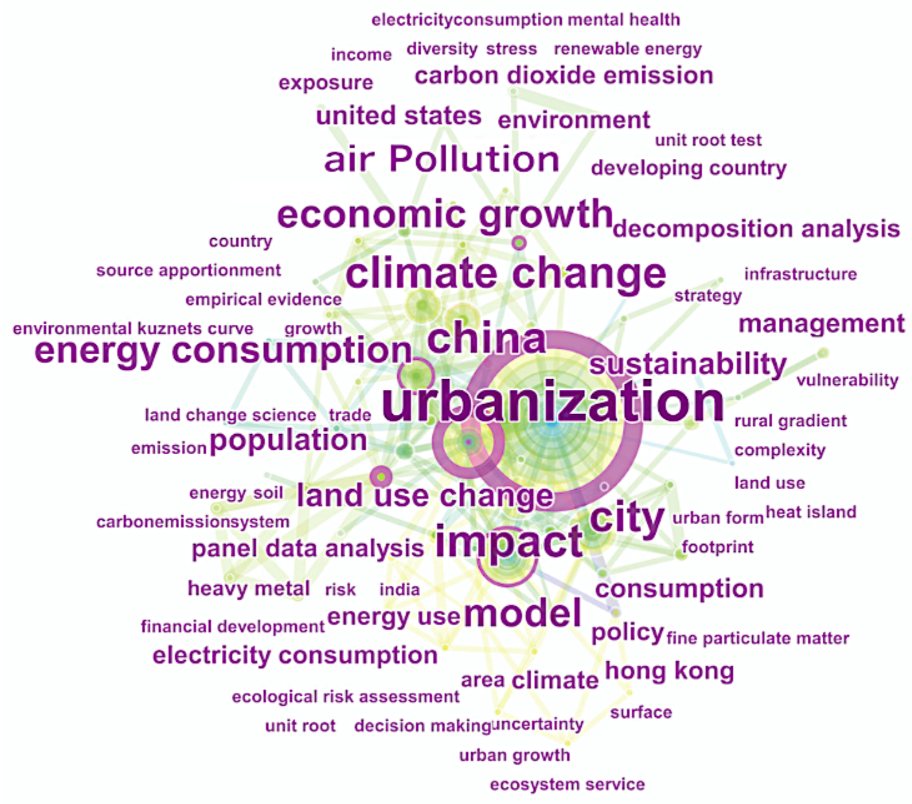
Based on the above analysis, a comprehensive understanding of domestic and international research can be formed in the field of urbanization. It indicates that the study of sustainable urbanization is on the rise all over the world. That fully demonstrates that the urbanization process has increased its influence on various aspects, and the degree of attention has shown a stable overall growth trend in recent years. Moreover, the focus of urbanization research has changed from the previous economic, population and urbanization measures to urban sustainable development, urban environment, urban economy, climate change, human settlements environment, resources and energy consumption and relevant urban planning, management and policies are presented in Fig. 1-10. Those focus points above are the features which can reflect the evolution and trends of urbanization, urban problems in the context of urbanization and the impact of urbanization on sustainable urban development, so as to formulate more scientific and rational urban planning policies and strategies. That’s the reason for our study of global urbanization.



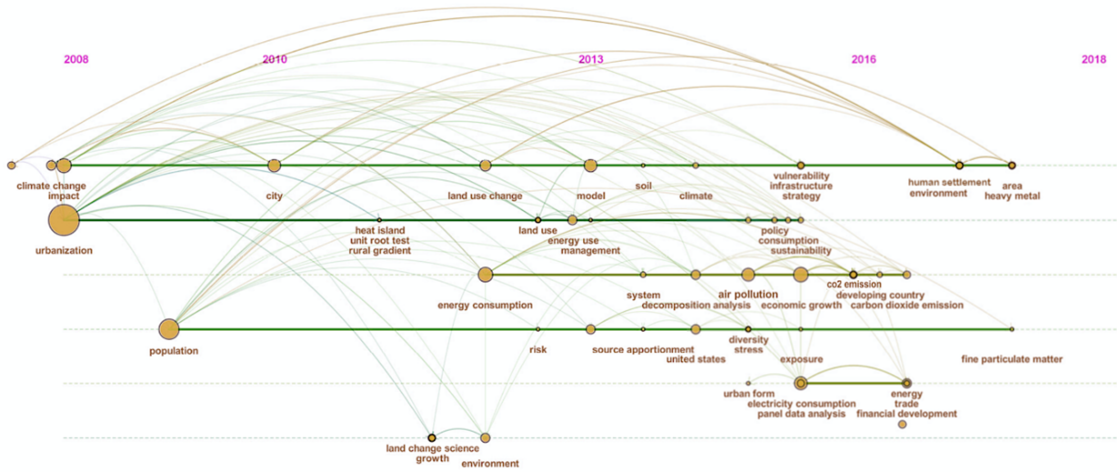
(a) Number of literatures of WOS



(b) The frequency of keywords



(c) The visualization result of keywords



(d) The relationship between keywords and research time

Fig. 1-10 Urbanization Research Trends (2008-2018)
(Data Source: Web of Science (WOS))

Research trends of urban shrinkage

Urban shrinkage has become a global phenomenon that has seriously affected the sustainable development of cities and even led to urban decline. To understand the causes of shrinkage and the focus of its solution strategies in-depth and clarify the key areas that should be paid attention to achieve sustainable urbanization, an investigation of literature collation on existed research by using approximate string matching was made. The extraction of literature data is derived from Elsevier's Scopus, which is the largest abstract and citation database of peer-reviewed literature. In Scopus databases, the search conditions were limited to the title that limited containing "shrink OR shrinking OR shrinkage" and "cities OR city OR urban”. To ensure the scientific, objectivity and accuracy of the literature analysis, the search results are deduplicated, and irrelevant entries such as journal conference call for papers, volume headlines, topic research, post-reading, overseas newsletters, news reports, no authors, etc. The retrieval time started from 1998 to 2020.6 at the earliest.

We extracted the abstract content of the collected 399 articles and made an annual analysis using text mining. By comparative analysis shown in Table 1-1, we found that the research process can be divided into five stages, which can be roughly summarized as "discovering the shrinkage phenomenon--causes and effects --economic strategies-- social policies--environmental assessment", Therefore, environmental issues will become important research topics in the future. For the research subjects, the previous studies are mainly about cities in developed countries. And now there are more and more studies on the shrinkage of cities in developing countries.

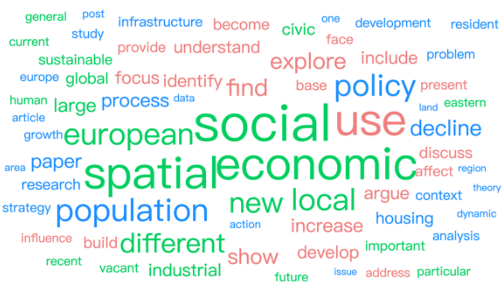
Table 1-1 The research trends of urban shrinkage.

Text mining results	Descriptive analysis
	**1998～2006** **Keywords: new, face, present and population** Researchers began to realize that new and dramatic development phenomena have emerged in the city [62]. Cities have been facing the new task of declining population and migration figures [63]. Thus, most articles aimed to present the surprising empirical findings on the shrinkage of cities by the combination of global processes and local configurations [13].
	**2006~2011** **Keywords: local, base, different, land and model** Researchers found urban shrinkage is the result of different processes such as deindustrialization or demographic change [64], that directly caused the impact on local stakeholders, especially from the perspective of lacking land demand and investments [65,66]. The improvement policy should be based on the spatially explicit way, the simulative modelling techniques and distribution of population and of infrastructure.

2012～2016

Keywords: economic, new, policy and focus

The economic vitality faced by the city is limited [67], and the demographic structure is changing increasingly obvious. Most researchers focused on the effects of economic development which should be seen as a priority for the research agenda [12]. New planning approaches or policies should be considering urban shrinkage as an alternative to the "growth paradigm" as well as financial support to stave off decline [68,69].



2017～2018

Keywords: social, economic, spatial and use

There are more and more cities shrinking caused by social problems, such as ageing of the population or job loss rising socio-spatial inequality [70], especially in developed country. While the shrinkage challenges in developing countries are increasing due to the slowdown of economic growth [71]. Cities need to identify the potential of their use and to explore the possible locally-based factors of urban shrinkage [72].

2019～2020.6

Keywords: environmental, population, new and suburban

Environmental degradation and climate change have become main drivers of population migration [73,74], making environmental studies a hot topic. In addition, regional decay especially outer suburban shrinkage [75,76] is an urgent policy and planning issue. New quantitative evaluation methods [77] and environmental strategies [78] have been proposed to evaluate population loss and its impact.

In developed countries, urban shrinkage mainly caused by social and environmental problems, especially aging and climate change. The developing countries are still in the stage of economic development, and the economy is considered as the primary condition. But according to the development path of developed countries, social and environmental factors should be paid attention to as soon as possible. In terms of responding to policies and strategies, due to the complex influencing factors and mechanism of urban contraction, it is still in the stage of continuous exploration and experimentation and is mostly based on the growth paradigm of developed cities.

1.3.2.Study on urban sustainability and its assessment

It has been suggested that the building of a “green” city is equivalent to the building of sustainability [79]. Many countries are planning and engaged in building green cities and “eco-cities” as starting points for the building of sustainable development. Yet, it is important to understand cities’ sustainability as a broader concept which integrates social development, economic development, environmental management and urban culture, which refers to the management and investment decisions taken by municipal authorities in coordination with national authorities and institutions.

The 1987 report of the World Commission on Environment and Development, also known as the Brundtland Commission, defined sustainable development as development that meets the needs of the present, without compromising the ability of future generations to meet their own needs [80]. In 1991, the United Nations Centre for Human Settlements (UNCHS) Sustainable Cities Programme attempted to define a sustainable city as one “where achievements in social, economic and physical development are made to last” [81]. However, this definition was still too general and neglected the fact that a sustainable city must have a low ecological footprint and reduce risk transfer (economic, social and environmental) to other locations and into the future [82]. The concept of sustainable cities and their links with sustainable development has been discussed since the early 1990s. Sustainable cities should meet their “inhabitants’ development needs without imposing unsustainable demands on local or global natural resources and systems” [83]. And it should focus on better living and working conditions for everyone, including affordable access to, and improvement of, housing, health care, water and sanitation, and electricity. The 1992 Rio Declaration integrated the economic, social, environmental and governability dimensions of sustainability and argued for the eradication of unsustainable patterns of production and consumption, the eradication of poverty, and the role of the State, civil society and the international community in protecting the environment. Another outcome of the United Nations Conference on Environment and Development was Agenda 21, which aimed at preparing the world for the challenges of the twenty-first century, defined sustainability in the context of economic, social, environmental and governance issues, noting the decisive role of authorities and civil society at the local, national and international levels for the implementation of sustainable development policies. Yet, Agenda 21 did not explain how the concept of sustainability could become the basis for the creation of sustainable cities. The Habitat Agenda, adopted by the United Nations Conference on Human Settlements (Habitat II), held in Istanbul from 3 to 14 June 1996, echoed the concerns expressed in Agenda 21 with respect to the multidimensionality of development, and discussed the relevant principles and content of urban sustainability [84–86]. That can be summarized as the following three points: (1) urban environment should be ecologically sustainable, that is, the use of environmental resources and the environmental pollution caused by them should not exceed nature’s ability. (2) Urban areas should have social sustainability and ensure basic living and working conditions for residents. (3) Urban sustainability needs to coordinate the interaction between economic development, social needs and environmental protection. Therefore, the development characteristics of indicators related to economy, society and environment should be considered comprehensively in the process of achieving sustainability.

At the first session of the World Urban Forum convened at the headquarters of the United Nations Human Settlements Programme (UN-HABITAT) in Nairobi from 29 April to 3 May 2002, an in-depth discussion was held on urbanization in the context of sustainable development. The Forum affirmed that addressing economic, social, environmental and governance issues were integral to the creation of sustainable cities and that the inability to address those issues would prevent the achievement of sustainable development [87]. The main messages of the Forum were comprehensively discussed and reaffirmed at the World Summit on Sustainable Development, held in Johannesburg, South Africa, from 26 August to 4 September 2002 [88].

In the central UN platform of the High-level Political Forum on Sustainable Development, the follow-up and review of the "2030 Agenda" for Sustainable Development adopted at the United Nations Sustainable Development Summit on 25 September 2015. At that time, the Sustainable Development Goals (SDGs) were set up in the "2030 Agenda" and are intended to be achieved by the year 2030. The SDGs or Global Goals are a collection of 17 interlinked global goals designed to be a "blueprint to achieve a better and more sustainable future for all" [89]. The SDGs were developed in the Post-2015 Development Agenda as the future global development framework to succeed the Millennium Development Goals which ended in 2015. Though the goals are broad and interdependent, two years later (6th of July,2017) the SDGs were made more "actionable" by a UN Resolution adopted by the General Assembly. The resolution identifies specific targets for each goal, along with indicators that are being used to measure progress toward each target. The year by which the target is meant to be achieved is usually between 2020 and 2030. For some of the targets, no end date is given. To facilitate monitoring, a variety of tools exist to track and visualize progress towards the goals. All intention is to make data more available and easily understood, and as an effective guiding basis for urban future development.

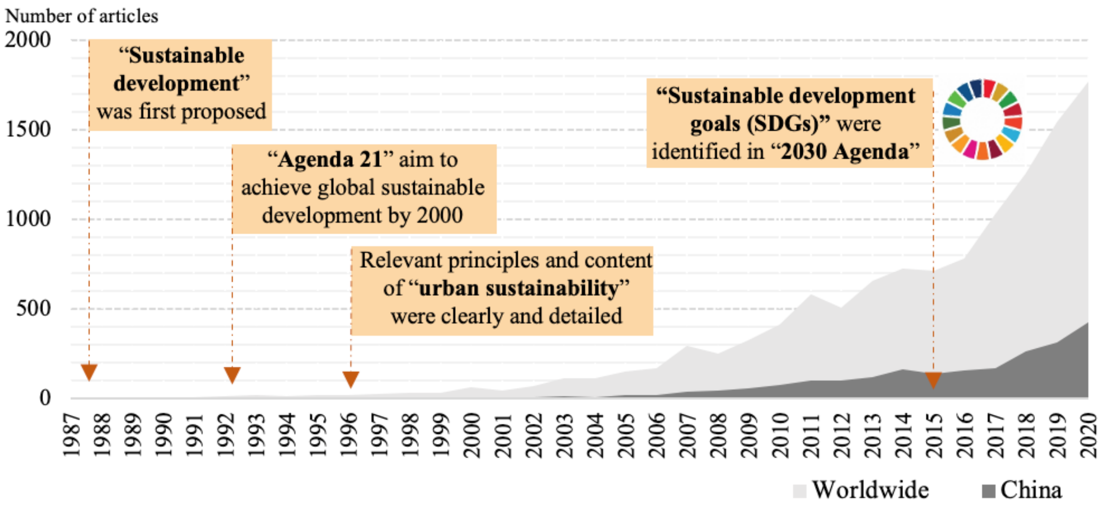


Fig. 1-11 The research trends related to urban sustainability using Elsevier's Scopus databases.

In Elsevier's Scopus databases, the search conditions were limited to the title or abstract or keywords that limited containing "urban or city" and "cities or city or urban" and "sustainability or sustainable development" and "evaluation or assessment or measurement". A total of 11798 articles were searched in the screening during the period of 1987 to 2020, of which 2281 articles were regarded on the context of China. Figure 1-11 show that since the concept of sustainable development was proposed in 1987, research related to urban sustainability evaluation has also begun. At the Istanbul Conference in 1996, the relevant principles and content of urban sustainability were clearly and detailed[85,86]. Subsequently, some assessment research results were published one after another and continued to grow. Then, the United Nations General Assembly has further identified 17 sustainable development goals and 169 specific goals, announced in the 2015 "2030 Agenda" report [90], have become an international policy pursued by global governments and related institutions [5,91]. It has also made urban sustainability evaluation research quickly become a hot spot for scholars, and the publication of related research results has accelerated.

1.3.3.Study on megalopolis development pattern

The development course of the world megalopolises reflects the spectacular evolution of the urbanization process. With the rise of the city center and surrounding small towns, megalopolitan regions are formed and display the utilization of natural resources, management mechanisms, and planning visions to shape better living and working environments.

The term “World city” was first proposed by Geddes to describe those cities that hold an important position in the operation of the global system of finance and trade in his book “Cities in Evolution” [92]. American sociologist Sassen popularized the term “Global City” from the producer services' point of view. She pointed out that along with the global economy wave, global cities should be those that take their unique economic advantages in the global capital system to create their unique positions in the world, which are the production and consumption centers with advanced services [93]. Later, British scholar Taylor studied the concept of world cities network from the perspective of network and node through analyzing the connectivity between large multi-country service companies. He proposed several cities that have global or regional service functions and defined them as world cities and established the Globalization and World Cities Research Network [94].

Then, French geographer Gottmann proposed the term “Megalopolis” for the mega-cities as the center of densely populated areas in “Megalopolis: or the Urbanization of the Northeastern Seaboard” [95]. The author mentioned that a series of metropolitan areas were formed because of the agglomeration effects in short term, and each metropolitan area was developed by a strong core city. There are two most important impact factors for promoting the megalopolis formation: one is polynuclear structure and the other is the hub effect reflected in the economy of the American eastern shore cities. Gottmann (1978) [96] recognized six such megalopolitan systems around the world that stand out for their extraordinary growth including (Fig.1-12): (1) the American Northeastern Megalopolis- from Boston to New York, Philadelphia, Baltimore and Washington D.C.; (2) The Great Lakes Megalopolis-located along the Great Lakes, from Chicago to Detroit, Cleveland, Pittsburgh, and extended to Toronto and Montreal in Canada; (3) the Tokaido Megalopolis in Japan – from Tokyo, Yokohama, Nagoya to Kyoto, Osaka and Kobe; (4) the megalopolis in England - London to Liverpool as the axis, including Greater London, Birmingham, Sheffield, Liverpool, Manchester and other large cities, as well as many small and medium-sized cities and towns; (5) the megalopolis of northwestern Europe - extending from Amsterdam to the Ruhr and to the French northern industrial conglomeration; (6) the Urban Constellation in China-the Yangtze River Delta megalopolis - centered in Shanghai including Suzhou, Wuxi, Changzhou, Yangzhou, Nanjing, and other cities [96,97].

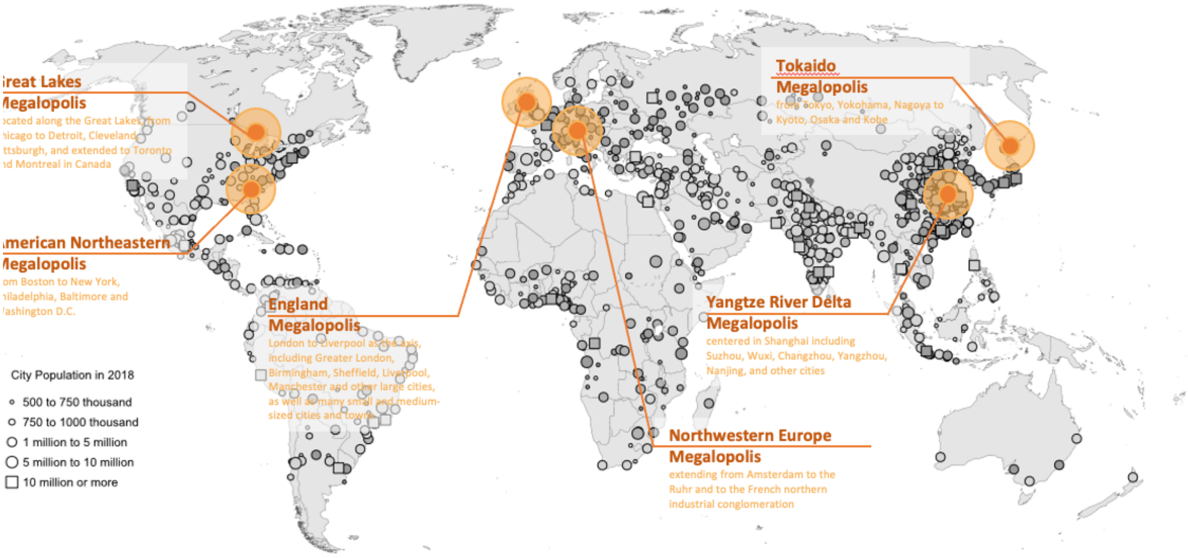


Fig. 1-12 The world's six outstanding megalopolis (Gottmann,1978)
(Data source: World Urbanization Prospects: The 2018 Revision)

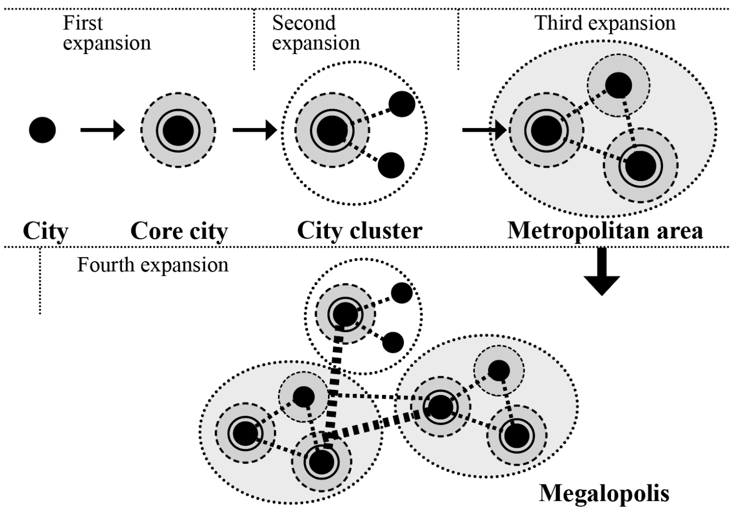


Fig. 1-13 Spatio-temporal evolution path of a megalopolis
(Source: Fang, C., & Yu, D. (2017) [98])

The beginning time of development of megalopolis varies between the areas. Because of the unique historical background of each society, the course of each megalopolis area's development is an individual path and pattern. But the evolution of a megalopolis roughly follows a spatiotemporal path from a core city to city cluster, metropolitan area, and a megalopolis [98] (Fig.1-13). Evidently, each expansion enables the megalopolis to become increasingly radiating regional, national, and eventually international growth centers [99,100]. The core area stands out because of its unique internal advantages in combination with powerful external forces. With the agglomeration effect, the core area continuously attracts resources and population from the adjacent cities scattered around the area and leads to regional development. The rapid and steady development of the core city led to the simultaneous development of small and medium-sized cities around the metropolitan area as an initial megalopolitan shape. Such a path is a clear representation of the gradient evolution and multi-layer structure of the megalopolises.

However, after the simultaneous development with the core cities, their adjacent cities in the megalopolitan areas might not always benefit from the core cities. Some cities may gradually grow into "sub-centers" that lack liberty in development policies due to the core cities occupy too many resources. Even they may experience a delay in further development. Meanwhile, excessive centralization and agglomeration in the core cities can cause have some unexpected side effects, such as congestion, inefficiency and pollution. The government has to take into account and intervene in regional planning from a more macro perspective of the megalopolis, based on the development situation of each city. Because of the different national political systems, various approaches had been adopted to solve the problems and led to different results.

1.4. Purpose and Research Structure of this Study

This study aims to explore the sustainability performance of urbanization and its environment in the scope of megalopolises in China, based on the proposed assessment system of urban sustainability. That defined as the ratio of the two dimensions: quality of the built environment and environmental pressure. In particular, we not only focus on the design of method and its indicator system, but also the applicable analysis of evaluation results. On this basis, relevant statistics and geoinformatics are separately used to find the coupling interaction mechanism and the characteristics of spatio-temporal variation patterns of each city in the period from 2010 to 2018. Moreover, the countermeasures for cities in the corresponding megalopolis are also discussed in order to guide a reasonable, efficient, and sustainable urbanization process.

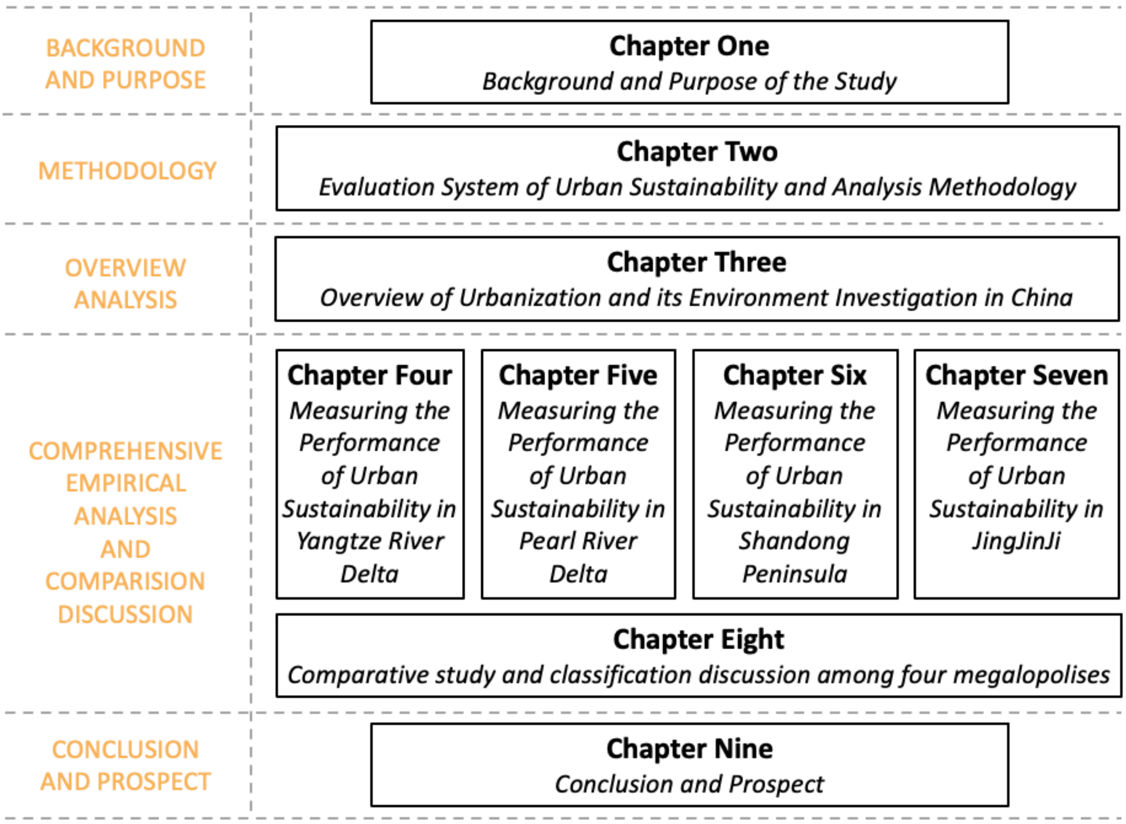


Fig. 1-14 The research structure of this study

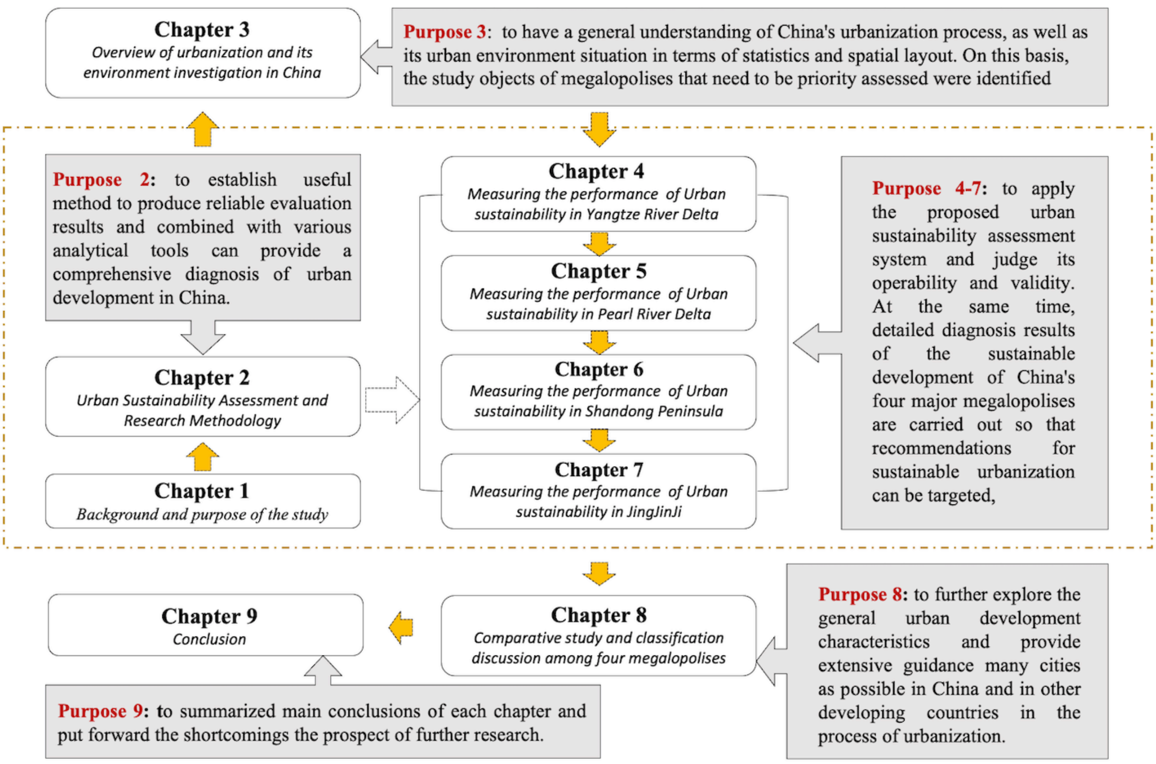


Fig. 1-15 The research flow and purpose of this study

The purpose and research structure of this study is as follows (Fig.1-14,1-15):

In Chapter 1, background and purpose of the study:

The 21st century has been recognized as the Asian century of rapid urbanization. This kind of urbanization possesses a dualistic nature of making a great influence on the urban environment. In order to maintain a sustainable increase in urbanization rates and to prevent these developing countries from prematurely entering a state of urban shrinkage due to environmental concerns, the scope of parties' attention is shifting from individual cities to megalopolises, and the focus is extending from urban economic and social development to take environmental factors into account as well. Therefore, after introduced the above research background, the previous studies about urbanization and urban shrinkage, urban sustainability and megalopolis development pattern were reviewed. The purpose is to clarify the content of the study and the necessity of provide guidance to assist efficient planning towards achieving sustainable urbanization in a mainstream scope of megalopolis.

In Chapter 2, evaluation system of urban sustainability and analysis methodology:

Firstly, a critical review of the SDGs, relevant literature on the world's and Chinese widely used sustainability assessment tools was presented. Then, benefiting from that and inspired by the ratio model of the X-efficiency, an assessment system for measuring the capacity of urban sustainable development was proposed, which defined as the ratio of the two dimensions: quality of the built environment and environmental pressure. In addition, other methodologies based on Statistics and Geoinformatics used in this study were introduced, including statistical data analysis using SPSS and spatial relationships analysis using GIS model. The purpose is to provide an urban assessment system in an easy-to-understand form with a certain target, validity and usability for sustainable development. So that this method can be used in subsequent studies to produce reliable evaluation results and combined with various analytical tools can provide a comprehensive diagnosis urban development in China.

In Chapter 3, overview of urbanization and its environment investigation in China:

Data collected from 2010 to 2018 for each provincial-level administrative region of China (excluding autonomous administrative divisions, Hong Kong, Macao and Taiwan regions) and for each city in the four major megalopolises were used to sort out and analyze from administrative divisions' perspective and from megalopolises' perspective, respectively. The purpose is to have a general understanding of China's urbanization process, as well as its urban environment situation in terms of statistics and spatial layout. On this basis, the study objects that need to be priority assessed were identified, i.e., the four most important urban agglomerations in China at present. The descriptive data analysis of the development of these four urban agglomerations within the scope of China was also investigated.

In Chapter 4-7, measuring the performance of urban sustainability in Yangtze River Delta / Pearl River Delta / Shandong Peninsula / JingJinJi:

The four urban agglomerations as empirical objects are analyzed and interpreted one by one in each chapter for their evaluation results from 2010 to 2018, covering detailed analysis from the spatial pattens characteristics of each megalopolis to the diagnosis of the interactive mechanism of indicators and countermeasures for each city. The detailed research flow includes: (1) the general introduction of each megalopolis, (2) the assessment results' presentation and coupling interaction mechanism analysis between the quality of the built environment and its environmental pressure for each city (3) spatio-temporal variation patterns of assessment results and their evolution track characteristics, and (4) providing the countermeasures on the quality of built environment and its environmental pressure for each city in the corresponding megalopolis. The purpose is to apply the proposed urban sustainability assessment system and judge its operability and validity. At the same time, detailed diagnosis results of the sustainable development of China's four major megalopolises are carried out so that recommendations for sustainable urbanization can be targeted, not only at the macro-level of regional planning for the entire megapolis but also at the micro-level of future development responses for each city.

In Chapter 8, comparative study and classification discussion among four megalopolises:

To compare the performance results of the above four major megalopolises in China, the assessment results were subjected to not only the comparative statistical analysis, but also the spatial autocorrelation analysis based on the Local Spatial Association Index (LISA) clusters. In addition, characteristics and implications of urban sustainability are discussed based on geographic location and urban population classification, and the sustainability performance clustering classification, respectively. The purpose is to further explore the general urban development characteristics and provide extensive guidance many cities as possible in China and in other developing countries in the process of urbanization.

In Chapter 9, conclusion:

This part summarized the research of previous chapters. And based on the conclusions, the shortcomings of this study and as well as the prospect of further research urban sustainability assessment are put forward.

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Chapter 2. Urban Sustainability Assessment and Research Methodology

2.1. Introduction

Sustainable development is considered a solution to address the existing urban problems [1]. In line with sustainable development, sustainable urbanization was promoted as a significant component [2]. Sustainable urbanization is a characteristic of an urbanization process that is consistent with the principles of sustainable development [3]. Urban sustainability is typically characterized by the intersection of the two concepts of urbanization and sustainability [4]. Sustainable urbanization can be defined at two perspectives, the first being sustainable cities and the second being sustainable urban development [5]. Sustainable city is used to introduce the current status of the city, such as ecological protection, appropriate use of resources, individual welfare, satisfaction of basic human needs, etc. [6,7].

Indeed, the complexity of the above challenges cannot be addressed in a single and unchanging way. It usually requires the concerted efforts of governmental coordination and policy-making bodies. But scholars believe that the powerful power of the strategy will be facilitated if it is understood by the public. The concept of sustainable urban development takes into account the more complex urban development context and serves as an important indicator basis for their quantitative evaluation of urban development [8–12].

2.1.1.The world's sustainability assessment tools and their effectiveness concerns

Sustainability assessment tools have been evolving and practiced since the early 20th century. There are many assessment methods, such as Life Cycle Assessment (LCA), Sustainable Cities Index, Sustainability Assessment Project, assessment frameworks, rating system methodologies and certification systems [13–15], all with varying resolution, scope and application areas. Over the past decade, a number of well-known international assessment tools have been developed. Many tools have been developed to cover assessments at different scales, ranging from micro-unit building scale, meso-community scale to macro-urban scale (Fig. 2-1). Some of them have been proven effective and authoritative by many stakeholders [16]. For example, local authorities are likely to find assessment tools useful for performance monitoring and improving government transparency and objectivity in decision making. Regardless of the target audience group, it can be argued that the overall motivation for developing and implementing sustainability assessment tools is to promote sustainability. While the literature is replete with sustainability assessment tools, many of these tools are rarely used in the real world. Only a few tools have been used to a good extent domestically and/or globally. The successful implementation of these tools can be attributed to a variety of factors, such as collaboration among parties involved in urban decision making, facilitation efforts by local and national governments, and the availability of reward mechanisms to promote their adoption [17].

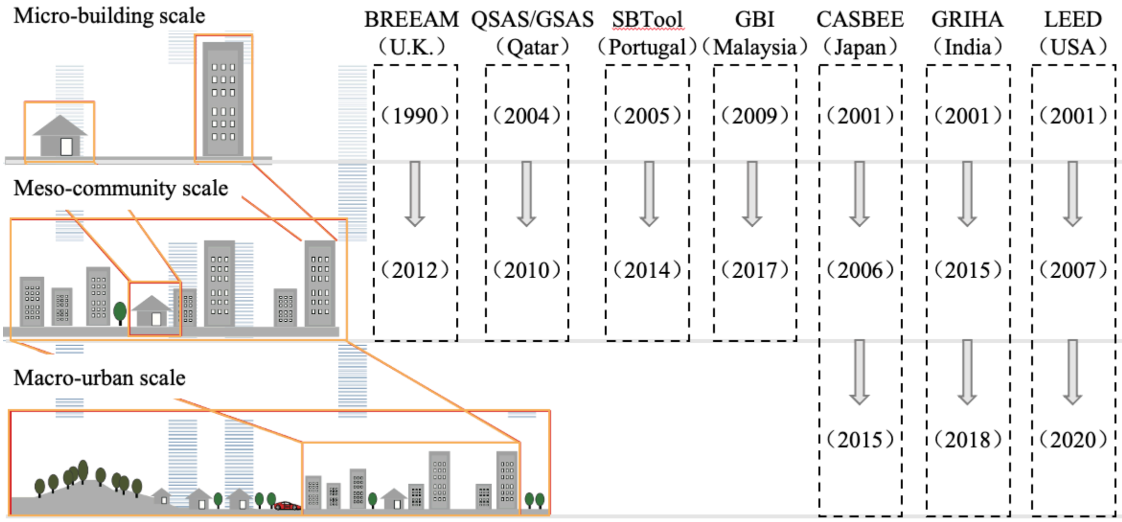

Fig. 2-1 The evolution of the sustainability assessment tools with different evaluation scales. (Edited from https://www.ibec.or.jp/CASBEE/)

At the beginning, there were a number of integral projects in the field of urban sustainability assessment. These projects were mainly international initiatives used by several countries and focused on pressing international issues, especially climate change. The environmental, social and economic aspects of sustainability were also included [18]. Recently, sustainability assessment tools for urban development have become an active area of research. In fact, they have attracted attention when they expand the scale of assessment from individual buildings, community scale to the urban scale, and before other tools. According to analytical studies of these tools, the main reason for this is the emphasis on environmental aspects, such as consistent energy efficiency and air pollution, which are currently attracting worldwide attention. Currently, the following sustainability assessment tools are widely known and used around the world. [19–21]: BREEAM (Building Research Establishment Environmental Assessment Method) Community, QSAS/GSAS (Qatar/Global Sustainability Assessment System), SBToolPT (sustainability assessment tools)-Urban Planning, CASBEE (Comprehensive Assessment System for Built Environment Efficiency), GBI (Green Building Index) for townships, GRIHA (Green Rating for Integrated Habitat Assessment) and LEED (Leadership in Energy and Environmental Design). All assessment tools emphasize four interrelated and interconnected aspects of sustainability: environmental, social, economic, and cultural, with different perspectives on the emphasis on sustainability issues depending on the specific context, and these reflect the nature and quality of the indicators expressed in the sustainability aspects of each tool. Although sustainability assessment tools for urban development have been developed for the same objective, they differ considerably in shape, potential, boundaries and context of application [15], which are shown in Table 2-1.

Table 2-1 The general information list of eight worldwide urban sustainability assessment tools.

Sustainability assessment tools	BREEAM Community	QSAS/GSAS	SBTool^{PT}-Urban Planning	CASBEE		GBI for townships (2.0)	GRIHA		LEED-v4.1
				CASBEE-UD	CASBEE-City		GRIHA-LD	GRIHA for cities	
Version year	2012	2010	2014	2014	2015	2017	2015	2018	2020
Scope									
***National and local**	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
***Global**	No	No	No	No	Yes	No	No	Yes	Yes
Scoring method	The final rating is the sum of weighted percentage of credits achieved under each BREEAM section, provided that minimum standards are met for the rating level.	The credits gathered from the collection points every individual indicator during the assessment process for the project.	Using normalization method to convert the parameters into a classification from A+ to E and summing up through a weighted Diaz-Balteiro equation.	Based on the ratio between building environmental quality (Q) and building environmental loadings (L), named Environmental efficiency (BEE = Q/L).		All categories make up a total of 100 points (a final score) and the GBI certification depends on the amount of points it has collected.	The net impact on quantitative and qualitative parameters (In and Iq respectively) will be totalled and compared against the base case impact of 100 per cent.		The sum of points gained under different credits, provided that the pre-requisites are met.
Indicator catigories	Governance; Socialand economic wellbeing; Resource and energy; Land use and ecology; Transport and movement	Urban Connectivit; Compactness; Diversity; Transportation; Density; Passive Solar Design; Mix land use; Greening the urban	Climate and Energy: Community; Place Shaping; Ecology and Diversity; Transport; Resources; Business; Buildings	Q1: Environment; Q2: Society; Q3: Economy; L: CO_2 emissions		Climate, energy & water; Ecology & Environment; Community planning & design; Transportation & connectivity; Building & Resources; Business & innovation	Site Planning; Energy; Water and waste water; Solid waste management; Transport; Social	Smart Governance; Water Supply and Management; Sanitation and Municipal Solid Waste Management; Sustainable Mobility; Energy Optimization and Management; Quality of Life	Integrative process; Natural system and ecology; Transportation and land use; Water efficiency; Energy and greenhouse gas emissions; Materials and resources; Quality of life; Innovation; Regional priorty
Rating benchmarks	Unclassified (<30%); Pass (⩾30%); Good (⩾45%); Very good (⩾55%); Excellent (⩾70%); Outstanding (⩾85%)	One star (<0); Two stars (0-0.5); Three stars (1-1.5); Four stars (1.5-2); Five stars (2-2.5); Six stars (2.5-3)	A+(> 1); A (0.7-1); B (0.4-0.7); C (0.1-0.4); D (0-0.1); E (<0)	Poor (<0.5); Fairly poor (0.5–1); Good (1–1.5); Very good (1.5–3); Excellent (⩾3)		Platinum (>86); Gold (76-85); Silver (66-75); Certified (50-65)	One star (25-35); Two stars (36-45); Three stars (46-55); Four stars (56-65); Five stars (66-75)	One star (25-40); Two stars (41-55) ; Three stars (56-70); Four stars (71-85); Five stars (>86)	Certified (40–49); Silver (50–59); Gold (60–79); Platinum (⩾ 80)

Most of the trends in urban sustainability assessment tools and methods are context-specific, that is, rooted in the locations and contexts in which they were originally developed. Context is more important than stand-alone buildings for assessing the sustainability of urban design, so relevant researchers remain very interested in this line of research and contribute to providing effective methods. The widely recognized assessment tools described above have been used with mixed results at regional and international scales, with most allowing for a degree of multiplicity of interpretations of urban sustainability at local and global scales [22]. Concerns have been raised as to their effectiveness in considering: (a) the variations in the selection of indicators in the different context of development background, (b) the inconsistency of the statistical data standards and the degree of data disclosure between regions and countries, (c) the impact on its use and guidance effect due to the understandability or operability of the assessment method and (d) local variations in the decision-making process [17,22,23].

2.1.2.Chinese sustainability assessment tools and their limitation

China's urbanization path is considered unique because it is neither identical to that of developed economies nor does it duplicate the patterns of developing countries [7,24,25]. In recent decades, economists, planners, and geographers have painted a lot of ink for China's urbanization [26,27]. As in other countries of the world, research work in the field of sustainable urban development in China is increasing incredibly and dramatically. Considering that a reasonable and effective evaluation is a basic reference for operating target measures, most of the studies have focused on the establishment of evaluation indicator systems and the selection of evaluation methods.

After studying 14 existing reports on sustainable urban assessment tools formulated by the Chinese government and official scientific research institutions from 2000 to the present shown in Table 2-2, the focus, scoring methods and number of indicators of each evaluation system are different, and there is no uniform standard. Moreover, the indicators with higher frequency are sorted out in Fig. 2-2, excluding the indicators whose appearance frequency is less than 20%. And the indicator categories mostly focus on economic growth, human settlements, resource utilization, energy conservation, and environmental quality. The indicators with a higher frequency are sorted out in Figure 2, and indicators with a frequency of less than 20% are excluded. Among them, some indicators of resource utilization and the environment appear more frequently, such as "energy consumption", "water consumption", "wastewater discharged", etc. Followed by economic indicators such as "income", "GDP", etc., and then indicators related to urban infrastructure and urban characteristics. Some indicators have generally reached a high level, which means the difference between the data of each city is very small and there is currently no comparability, such as "waste treatment rate" and "sewage treatment rate", etc. Although compared with the aforementioned worldwide tools, subjective indicators appear more in China's assessment tools, but data collection is difficult with strong uncertain. Moreover, it is worth noting that indicators related to cultural or urban characteristics have been added recently to the proposed evaluation system, such as cultural investment and cultural consumption in the New-type Urbanization-Evaluation Index System of New Urbanization Quality City (trial version, 2020), cityscape protection and cultural tourism in Green and Low-carbon Cities Evaluation Indicators (trial version, 2011), and level of ecological culture in the National Ecological Civilization Pilot Policy Evaluation System (trial version, 2013). In addition, for scoring methods of assessment tools, the commonly used methods without assigning weights are (1) directly adding up the standardized values of the data, and (2) pre-determined scoring criteria for attainment and aggregate calculations based on indicator scores. Although these two methods are relatively simple, they do not reflect the importance of the indicators and make it difficult to delineate a convincing scoring criterion. The other is the weighted method of statistics, as shown in the table. As shown in Table 2-3, the commonly used weighting methods are AHP, Entropy, GRA, and PCA. each of them has different advantages and disadvantages. In comparison, the objective weighting method is used more often and convincingly.

Table 2-2 The general information list of 14 Chinese urban sustainability assessment tools.

No.	Assessment tools of city scale by Chinese authority agencies	Version year	Scoring methods	Indicator catigories	Number of Indicators
1	Ecological Counties, Ecological Cities Construction Evaluation	2003 (Trial	Summation of scores achieved	Economic development; Environmental protection; Social progress	219
2	China's Livable Cities Scientific Evaluation Standards	2007	Weighted standardlized values summation	Social civilization; Economic prosperity; Beautiful environment; Resource carrying; Convenience of life; Public safety	83
3	Low-carbon City Evaluation System of China	2011	Standardlized values summation	Economy; Energy; Infrastructure; Environment; Society	15
4	Green and Low-carbon Cities Evaluation Indicators	2011 (Trial version)	Summation of scores achieved	Social economy; Planning management; Construction land; Resources and environment; Energy conservation and emission reduction; Infrastructure and greening;	62
5	National Environmental Protection Model City Assessment Index and	2011	Summation of scores achieved	Economic society; Environmental quality; Environmental construction; Environmental management	24
6	National Ecological Civilization Pilot Policy Evaluation System	2013 (Trial	Summation of scores achieved	Economy; Natural Environment; Built environment; Regulations; Culture	30
7	Technical Criterion for Eco-environmental Status Evaluation	2015 (Draft)	Weighted standardlized values summation	Environmental quality; Pollution load; Ecological construction	18
8	Evaluation System for the Construction of National	2016 (Trial	Summation of scores achieved	Space; Economy; Environment; Life; Regulations; Culture	35
9	China Green Development Index System	2016	Weighted standardlized values summation	Resource utilization; Environmental governance; Environmental quality; Ecological protection; Growth quality; Green life; Public satisfaction	56
10	Evaluation System for Ecological Civilization Construction	2016	Summation of scores achieved	Resource utilization; Environmental protection; Annual evaluation results; Public satisfaction; Environmental incidents	23
11	Green City Evaluation Index System	2017 (Trial version)	Weighted standardlized values summation	Green production; Green life; environmental quality	67
12	Evaluation System of the Construction Target of the National Ecological Civilization Pilot Zone	2018	Summation of scores achieved	Economic quality; Resource and energy conservation and utilization; Ecological construction and environmental protection; Ecological culture cultivation; Mechanism	49
13	Indicators for City Services and Quality of Life	2019	Weighted standardlized values summation	Economy; Education; Energy; Environment; Finance; Fire and emergency response; Governance; Health; Leisure; Safety; Shelter; Solid waste; Communication and innovation; Transportation; Urban planning; Wastewater; water and sanitation	100
14	New-type Urbanization-Evaluation Index System of New Urbanization Quality City	2020 (Trial version)	Weighted standardlized values summation	Economic development; Social culture; Ecological environment; Public services; Residents' lives; Reward indicators	76

Despite the achievements of these evaluation methods through their implementation, there are still many limitations, taking into account that most of the evaluation systems are still in the experimental phase. The main reasons are as follows. (1) The existing evaluation standards in China are diverse and focused, and have not yet formed a universally recognized normative system. (2) Most of the existing evaluation systems are static evaluations of the construction level for the current situation, lacking continuous and dynamic comparable evaluation models. (3) There are more repetitive and subjective evaluation indicators, and the data sources are extensive and scattered, with low usability, easily disputing the validity of such indicators and is not conducive to the promotion and application.

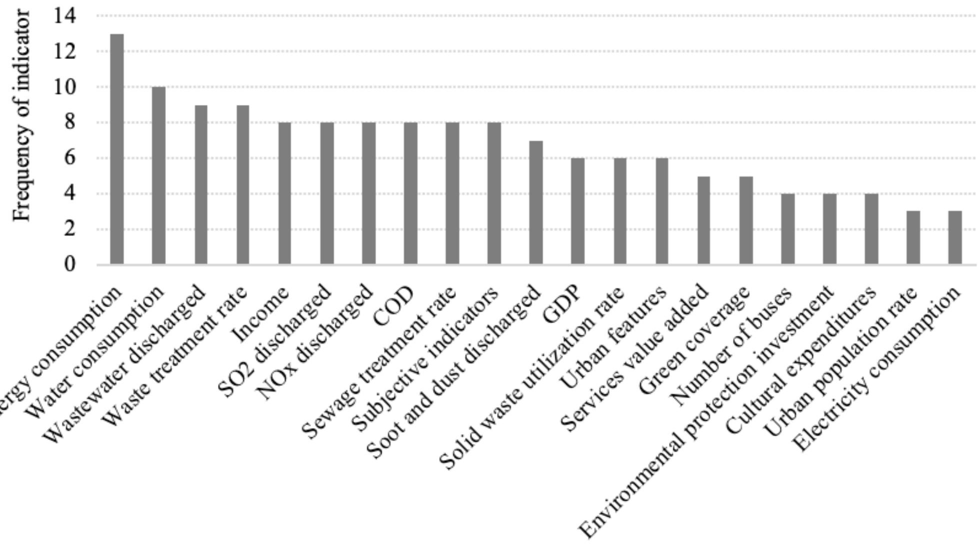

Fig. 2-2 The frequency of indicator extracted from 14 Chinese urban sustainability assessment tools .

Table 2-3 The commonly used weighting methods in 14 Chinese urban sustainability assessment tools.

Commonly used Weighted methods	**Advantages**	**Disadvantages**
AHP (Analytic hierachy Process)	Based on the actual experience of the decision makers	Strong subjectivity and uncertainty
Entropy	Based on the degree of numerical dispersion of the data	Ignore the physical and causal relationships between variables
GRA (Grey relation anaysis)	Based on the degree of fit between the data	Less data is easy to cause errors
PCA (Principal component analysis)	Based on the degree of influence of the data in the category	Available data need pass the KMO test

2.2.Urban Sustainability Assessment

2.2.1.Definition of urban sustainability assessment system

To intuitive express the two dimensions of urban sustainability, it needs to identify a simple and easy-to-understand measurement method. Inspired by the ratio model (input/output) originating from the X-efficiency theory of economics [28,29], the definition is extended as a new ratio model (quality/pressure) from the perspective of a big system of urban sustainable development shown in Fig. 2-3. On one hand, urban development activities are very complex and are the result of multi-factor interactions. On the other hand, sustainable development is a process of maintaining change in a homeostasis balanced environment. Thus, it is more suitable and comprehensive to treat it as a big system to consider the benefits and loads generated throughout the entire process of urban development.

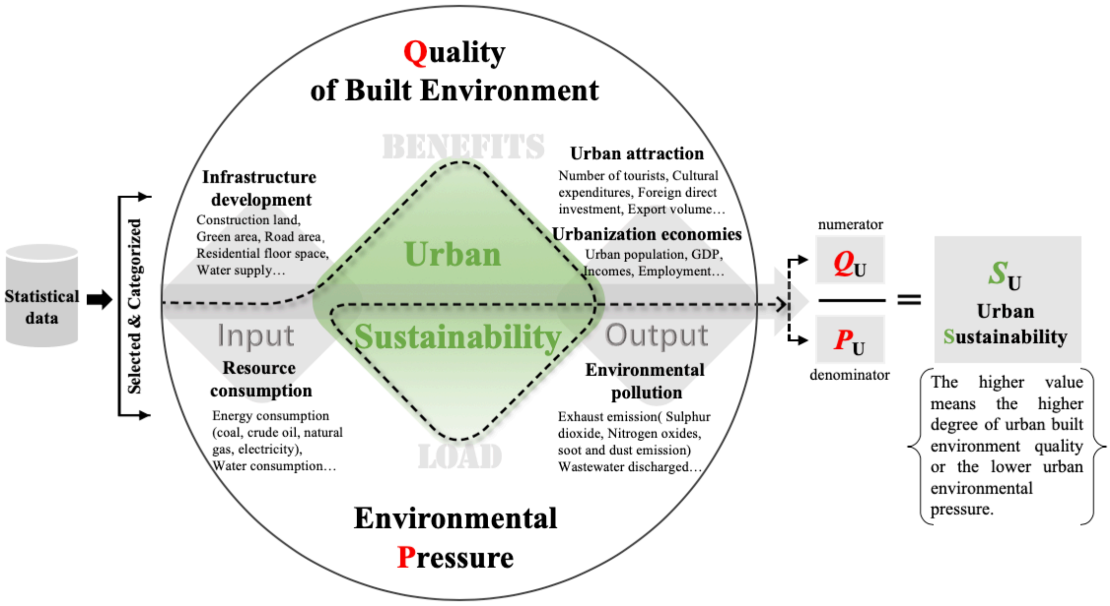

Fig. 2-3 The conceptual structure of the proposed evaluation system of urban sustainability (Su) measured from the quality of built environment (Qu) and environmental pressure (Pu).

Therefore, the two dimensions of the ratio model were named as "Quality of Built Environment" (Q_U) / "Environmental Pressure" (P_U), which is defined as "Urban Sustainability" (S_U) shown in Fig. 2-4 [30]. Among them, the S_U value is calculated from Q_U as the numerator and P_U as the two assessment dimensions. The higher the value, the stronger the ability of sustainable development, which means higher urban development quality or lower urban pressure. Among them, S_U values mean "the ability to maintain the sustainable state of the big system of urban development, improving the quality of the built environment while reducing environmental pressure as much as possible. Q_U values mean "the positive benefits of improving a better quality of human settlements and living environmental amenity for the urban inhabitant" by measuring the performance of urbanization economies, infrastructure development and urban attraction. P_U values mean "the load on the public environment, accompanying urban development" by measuring the performance of resource consumption and environmental pollution. The measurement formula of Su is as follows:

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

where Qui represents the total score value of indicator category i of the quality of built environment; Pui represents the score value of indicator category i of environmental pressure. When Su ≤ 1, the increasing pace of Pu is faster than the improved pace of Qu which means the city is in a barely or seriously unsustainable urbanization process; when Su ≥ 1, the increasing pace of Pu is slower than the improved pace of Qu which means the city is in a basic or highly sustainable urbanization process.

2.2.2.Indicator system

To accurately establish a relevant comprehensive indicator system, our indicator system of urban sustainability measurement model benefits from the public consensus on the SDGs, the critical literature review, our previously published studies [31,32] and experts' comments. Based on that, four key principles of setting the indicator system were summarized, some of which are also put forward by researchers [33–36]: (1) Sustainability-oriented: the set of indicator categories should be comprehensively and need to cover three-pillar fields of sustainable development, as well as the cultural fields that have received much attention recently; (2) Targeted: the selected indicators should match the evaluation targeted purpose, objects, and dimensions as well as the policy targets of urban development; (3) Effectiveness: the indicators should be relatively independent to avoid using duplicated measurement variables; (4) Availability: the data of indicators should be easily obtained from the open and reliable data platform.

Considering the actual situation and policy-driven urbanization trend in China, indicators were collected from the previously mentioned 14 existing indicator systems that were treated as valuable references. The subjective evaluative indicators, low-frequency indicators (the frequency of occurrence in references is less than 20%), and indicators with no statistically significant difference were excluded. Then, to make the indicator system is comprehensive, accessible, and widely reliable and used, all data of selected indicators are derived from the public China Statistical Yearbook, which is considered as the most comprehensive and authoritative dataset provided by the National Bureau of Statistics of China. Meanwhile, based on the measurement logic of the established S_U model, there should be interactive relationships between representative indicators of two dimensions of Q_U and P_U. Thus, the common statistical methods were used to analyze the correlation coefficient, and then combined them with the variance inflation factor method to test the multicollinearity of indicators. After multiple filtering out, there are 14 indicators categorized into four categories: urbanization economies, infrastructure development, resource consumption, and environmental pollution. In particular, it is necessary to respond to researchers' and policymakers' emphasis on the cultural field. The cultural field is valued because it is extremely helpful in shaping the unique 'magnetic force' of the city. Most the cities are engaging in enhancing that kind of 'power' to attract more resources so as to promote the quality of the urban environment. Hinch, 1996; Keum, 2010; SUI, 2019 [37–39] indicated that the boost of trade and tourism could also reflect both the bolstered 'hard power' and 'soft power' to a certain extent. Thus, the category was added of urban attraction to form the four representative indicators included to further improve our indicator system of the dimension of Q_U. Foreign direct investment and export volume of trade were selected as indicators to measure the benefits of social-economic attractiveness from the 'inward' and 'outward' perspectives. The number of tourists were selected to represent improvement directly or indirectly, reflecting on the comprehensive attractiveness of culture, and environment respectively. In addition, it needs to be explained that because more than 50% of the cities lack statistical data on the indicator of public cultural expenditures, which would be temporarily removed. Meanwhile, the empirical comparison of Shandong Peninsula data shows that the evaluation results before and after the index is eliminated after regression verification analysis r^2 is above 0.9, which means that the existing index system could hardly affect the evaluation results.

Against this background, an indicator system was established for urban sustainability to evaluate from two dimensions (Q_U and P_U) consisting of 17 relevant indicators shown in Table 1: (1) The dimension of Q_U, including urbanization economies infrastructure development and resource consumption, consisting of 9 represented indicators. (2) The dimension of P_U, including resource consumption and environmental pollution, consisting of 8 represented indicators.

2.2.3.Data source and processing

All data were collected from the authoritative China Statistical Yearbook Series (National Bureau of Statistics, n.d.) without further analysis, published available on government websites by the authoritative National Bureau of Statistics of China (2011-2019). This includes data released on official websites by relevant provinces or cities (2011-2019). The above data is only the original statistical information without any further analysis report attached. But some of the indicator values we chose were simply processed on the basis of statistical data, such as exchange rate conversion and per capita index conversion. Besides, the original data used in the calculation are the national average values of China from 2010 to 2018, so that our weighting criteria could be more universally used in China. Meanwhile, the units of data were eliminated to obtain their standardized value for the calculation by using the Min-Max feature scaling formula of the common normalization method. The equations are as follows:

Determining weighting criteria is important for scientific evaluation. Most scholars should prefer quantitative methods that assign weights after standardizing the statistical values of relevant indicators, which can avoid excessive influence or emphasize individual subjectivity. In addition, principal component analysis (PCA) has proven to be very effective and reasonable in some classic evaluation systems, such as the ecological footprint published by Wackernagel and Rees in 1992 [40], City

Development Index (published by UN-habitat in 1997), etc. [41] PCA method is mostly used as a statistical tool in exploratory data analysis and for making predictive models. It considers physical and causal relatedness and genetic distance among the variables by calculating the data covariance (or correlation) matrix. Factor analysis is calculated to work out the component score coefficient matrix (λ values) of all representative indicators in each category using SPSS (version 26). Then, the contribution rate of the component score in the corresponding category is determined as the weight coefficient of the indicator [42–44] (Table 2-4). In order to ensure that the data is suitable for PCA, the data set of each indicator category has passed the Kaiser-Meyer-Olkin (KMO) test (Table 2-5) with accepting values greater than 0.5 that recommended by Kaiser [45].

Table 2-4 The parameters of the weights coefficient of indicators using the PCA method.

Component		**λ values**	**∑ λ values**	**Weight (%)**	**Total**
Qu_1	p1	0.957	3.725	8.56	100%
	p2	0.952		8.52	
	p3	0.951		8.51	
	p4	0.865		7.74	
Qu_2	p5	0.968	3.469	9.30	
	p6	0.936		9.00	
	p7	0.938		9.01	
	p8	0.627		6.02	
Qu_3	p9	0.885	2.684	10.99	
	p10	0.813		10.09	
	p11	0.986		12.25	
Pu_1	q1	0.768	1.536	25.00	100%
	q2	0.768		25.00	
Pu_2	q3	0.646	3.083	10.47	
	q4	0.927		15.03	
	q5	0.589		9.56	
	q6	0.921		14.94	

Table 2-5 The parameters of the Kaiser-Meyer-Olkin (KMO) test.

Indicator Categories		Qu_1	Qu_2	Qu_3	Qu_4	Qu_5
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.70	0.64	0.74	0.61	0.62
Bartlett's Test of Sphericity	Approx. Chi-Square	115.45	114.76	169.23	0.86	106.47
	df	6	6	3	1	6
	Sig.	0.000	0.000	0.000	0.000	0.000

Through the results of weights in Table 2-6, it is found that the representative indicators that have the greatest impact on each category are the urbanization rate of Qu_1, construction land of Qu_2, foreign direct investment Qu_3, both energy and water consumption of Pu_1, and SO_2 discharged of Pu_2, that need to pay more attention to in the near future.

The standardized value of each indicators: $$u_{(p/q)i}' = \frac{u_i - \min(u_i)}{\max(u_i) - \min(u_i)} \quad (1)$$

The weight for each indicators: $$W_{(p/q)i} = \frac{|\lambda_{(p/q)i}|}{\sum_{i=1}^{n/m}|\lambda_{(p/q)i}|} \quad (2)$$

The weighted score for each indicators: $$Q_{Ui} = W_{(q)i} \cdot u_{(q)i}' \; ; \; P_{Ui} = W_{(p)i} \cdot u_{(p)i}' \quad (3)$$

Table 2-6 Indicator system and the weights of urban sustainability assessment.

Basic Dimensions	Indicator Categories	Weight (%)	Represented Indicators Description	Weight (%)
Quality of built environment (Q_U)	Urbanization economies (Qu_1)	33.33	q1: Urban population percentage (% of total population)	8.56
			q2: GDP per capita ($ / person)	8.52
			q3: Services value added (% of GDP)	8.51
			q4: Income per capita ($ / person)	7.74
	Infrastructure development (Qu_2)	33.33	q5: Construction land per capita (m^2 / person)	9.30
			q6: Residential area 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 (Qu_3)	33.33	q9: Number of tourists (1000 person)	10.99
			q10: Foreign direct investment (10^6 $)	10.09
			q11: Export volume of trade (10^6 $)	12.25
Environmental pressure (P_U)	Resource consumption (Pu_1)	50.00	p1: Energy consumption per capita (GJ / person)	25.00
			p2: Water consumption per capita (ton / person)	25.00
	Environmental pollution (Pu_2)	50.00	p3: Wastewater discharged per capita (ton / person)	10.47
			p4: SO_2 emission per capita (kg / person)	15.03
			p5: NOx emission per capita (kg / person)	9.56
			p6: Soot and dust discharged per capita (kg / person)	14.94

Notes: (1) Converting the Chinese currency (RMB) into U.S. Currency (USD) is calculated by multiplying with the annual average closing price of the exchange rate (USD/RMB). The annual data of exchange rates from 2010 to 2018 are 6.46, 6.31, 6.15, 6.16, 6.28, 6.65, 6.76 and 6.63 respectively, which is provided by Macrotrends for currency. (2) Income used the data of disposable income means the actual income at the disposal of residents for final consumption, other non-compulsory expenditure and savings. (3) Green area includes public parks, community parks and green areas nearby street. (4) Energy consumption includes coal, crude oil, natural gas and primary electricity and other energy. (5) Among the sub-indicators, q2, q4, q9-q11 and p1-p6 are annual values, and the others are cumulative values.

2.3.Spatio-temporal Methodologies based on Statistics and Geoinformatics

In statistics and econometrics, panel data are multi-dimensional data involving measurements over time. Panel data contain observations of multiple phenomena obtained over multiple time periods for the same variables [46]. Analysis methods based on panel data include correlation, regression, etc. However, most methods ignore the potential spatial effect between the variables. Moreover, in response to the decision-making needs of the ever-expanding megalopolises it is a more effective quantitative analysis method to fully recognize the dual change characteristics of the temporal and spatial dimensions of the urban environmental characteristics in the current period of time. [47–49]

2.3.1.Statistical data analysis using SPSS

Pearson correlation

The Pearson correlation coefficient is used to measure the degree of strength of linear association between two variables [50]. The magnitude of the correlation is evaluated by the Pearson correlation coefficient, which also refers to the Pearson's r. The Pearson's r value ranges from +1 to -1, where r = 1 indicates a perfectly positive correlation, r = -1 indicates a perfectly negative correlation, and r = 0 indicates no linear correlation. It is calculated as follows.

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}}$$

where r represents the correlation coefficient, X_i *or* Y_i represents the X-variable or Y-variable in a sample, $\bar{X}$ *or* $\bar{Y}$ represents the mean of the values of the X-variable or Y-variable.

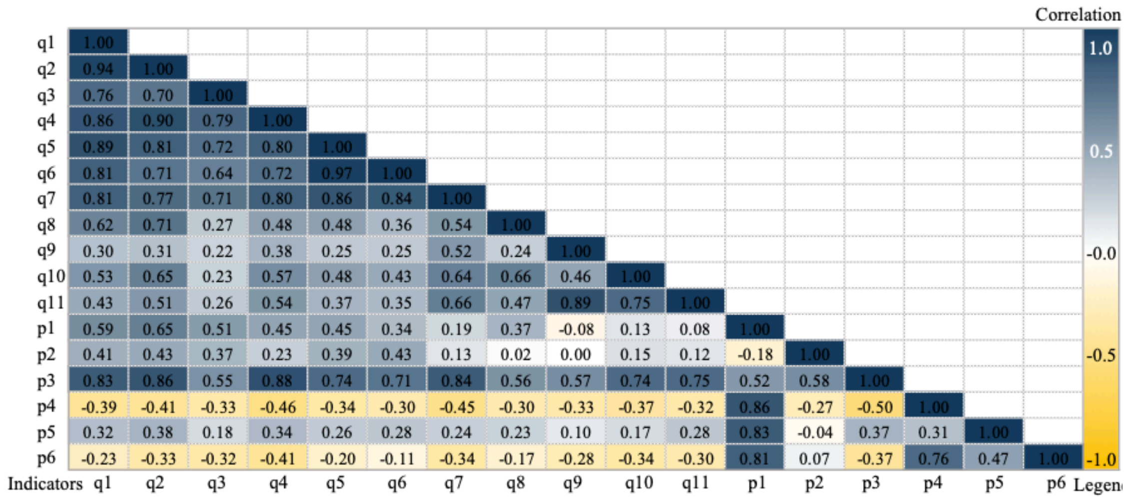

Fig. 2-4 Pearson correlation analysis of represented indicators.

It can be seen from Fig. 2-4 that there are obvious positive or negative interactions between representative indicators. Among them, the 11 indicators related to the quality of the built environment (Qu) show a positive promotion relationship. That is to say, each of the above indicators will drive the development of another indicator of the same dimension to a certain extent, which is useful for the overall improvement of urban environmental quality. But the relationship between the 6 indicators related to environmental pressure (Pu) is relatively complicated. Two-thirds of the indicators have a positive relationship with indicators of Qu, which means that as urban quality improves, it will increase the load of the natural environment. Although there are still two indicators (SO_2, and soot and dust discharged) of which performance is contrary to the above description, both of them have a significant promotion relationship with the p1 indicator of energy consumption. That means the environmental pressure is still a serious challenge worthy of attention in the process of urban development. Therefore, in view of the overly complex relationship above, it is very necessary to integrate the performance of all indicators for overall measurement so as to clearly quantify the sustainable development degree of the urban environment.

Curve Estimation Regression

In statistical modeling, regression analysis is a group of statistical processes used to evaluate the relationship between a dependent variable and one or more independent variables [51]. The most common form of regression analysis is linear regression, where a linear or more complex linear combination model is found that best fits the data based on specific mathematical criteria. However, it has some limitations as it cannot easily match any nonlinear data set. Therefore, curve estimation regression has been shown to be effective in modeling multiple correlated linear or nonlinear curves for regression models. The variance of the dependent variable distribution should be constant for all values of the independent variable, and all observations should be independent. The predictable regression model and interaction relationship (Fig. 2-5) are as follows:

$$\text{Linear model:}\quad y = b_0 + (X * t)$$

$$\text{Quadratic model:}\quad y = b_0 + (X * t) + (X * t^2)$$

$$\text{Cubic model:}\quad y = b_0 + (X * t) + (X * t^2) + (X * t^3)$$

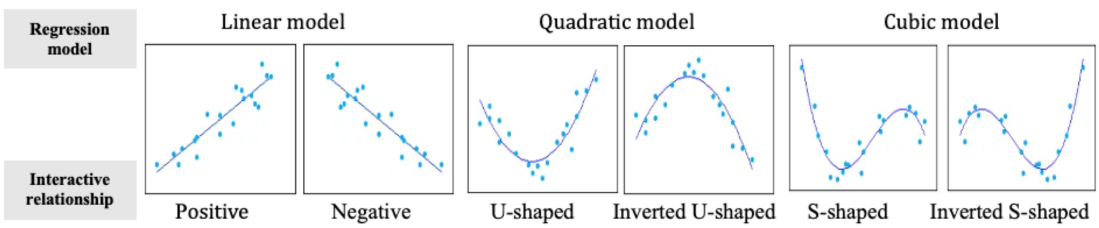

Fig. 2-5 Regression models and interaction relationships using Curve Estimation Regression

The information criterion for regression model selection is of great importance as well, and the fit and complexity of the model need to be fully considered. There are many commonly used information criteria, among which AIC (Akaike Information Criterion) [52] and the BIC (Bayesian Information Criterion) [53] are the most widely known [54–56]. Most researchers believe that AIC tries to select the model that best describes the unknown high-dimensional reality adequately, while BIC tries to find TRUE models among the set of candidates. [57,58] The lower of both values means that the model is considered closer to the truth. In general, it is preferable to use both AIC and BIC criteria for discriminating in model selection, but their results may be different. [59–61] Given the purpose of building the regression model and the estimation of the sample constants, together with the relative distance between the unknown true likelihood function of the data and the fitted likelihood function of the model, the choice of BIC was riskier. Therefore, AIC is used as the preferred standard and BIC is used for secondary cross-validation. In addition, the determination coefficient (R^2) is defined as a ratio of explained variance to the total variance of the dependent variable y and is used to represent the degree of fit between the predicted value and the actual value. R^2 is the square of the correlation coefficient and the value of R^2 is between 0 and 1, with values close to 1 indicating a good degree of fit. Generally speaking, if R^2 is greater than 0.5, it can be considered that the degree of fit of the prediction formula is reliable and meaningful. After using curve estimation regression, the prediction formula with the largest R^2 value as the preferred regression result of the variable. (Table 2-7)

In Chapters 4-7 of my research, the method of curve estimation regression is applied to analyze the interactive relationship between Qu and Pu. It is conducive to clarifying their logic of changes, the strength of the effect and predicting the future direction of urban development. the multiple regression model was chosen to fit scatter plots of the 9-year data set of each city into a single trend line, using the tool of SPSS Statistics V26 to realize the process of calculation and test. Among them, Qu is the independent variable, and Pu is the dependent variable. After the regression, an F test is required and the result with the p-value lower than 0.1 is considered to be statistically significant.

Table 2-7 The information criterion for regression model selection.

Criteria	Formula	Description
AIC	$2k + n\ln\left[\sum(y_i - \hat{y}_i)^2\right]$	The lower the value, the better the model.
BIC	$k\ln(n) + n\ln\left[\frac{\sum(y_i - \hat{y}_i)^2}{n}\right]$	
R^2	$1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y}_i)^2}$	The higher the value, the better the model.
Adjusted R^2	$\left\{1 - \left[\frac{(1 - R^2)(n - 1)}{(n - k - 1)}\right]\right\}$	

Hierarchical Clustering

Hierarchical clustering, also known as hierarchical cluster analysis, is an algorithm that groups similar objects into what are called clusters [62]. In theory, hierarchical clustering begins by treating each observation as a separate cluster. Each cluster is different from the others, and the objects in each cluster are roughly similar to each other. The clustering process iteratively performs the following two steps: (1) identifying the two closest clusters, and (2) merging the two most similar clusters. This iterative process continues until all clusters are merged together. Data for cluster analysis using SPSS should be prepared as follows: (1) Rows are observations (individuals) and columns are variables. (2) Any missing values in the data must be removed or estimated. (3) The data must be standardized to make the variables comparable. [63–65]

In Chapter 8, cluster analysis was used to classify 91 cities in the research area. The classification is based on the evaluation results (including Qu, Pu and Su) during the research period 2010-2018. Among the methods for combining clusters in a clustered manner, one called Ward's method was chosen. It is different from other methods. Instead of directly measuring the distance, it analyzes the variance of the clusters. The criteria for selecting the pair of clusters to be combined at each step are based on the optimal value of an objective function. This objective function can be "any function that reflects the investigator's purpose". Many standard clustering procedures are included in this very general category. To illustrate this procedure, Ward uses the example of the objective function being the sum of error squares, which is said to be one of the most appropriate methods for quantitative variables.

$$\Delta(A,B) = \sum_{i\in A\bigcup B} ||\vec{x_i} - \vec{m}_{A\bigcup B}||^2 - \sum_{i\in A} ||\vec{x_i} - \vec{m}_A||^2 - \sum_{i\in B} ||\vec{x_i} - \vec{m}_B||^2 = \frac{n_A n_B}{n_A + n_B} ||\vec{m}_A - \vec{m}_B||^2$$

where $\vec{m_j}$ is the center of cluster j, and n_j is the number of points. Δ is called the merging cost of combining the clusters of A and B. With hierarchical clustering, the sum of squares starts out at zero (because every point is in its own cluster) and then grows as the merge clusters. Ward’s method keeps this growth as small as possible.

2.3.2.Spatial relationships analysis using GIS model

Geographic distributions

Basic spatial statistics tools in Geographic distributions to calculate characteristic values of geographic data, such as the center, compactness, and orientation and observe shifting trends in these statistics over time. In Chapters 4-7, the methods of weighted mean center and standard deviational ellipse were used in the geographic distribution tools to explore the relationship between the spatial distribution characteristics of the urban sustainability results and the location offset of the geographic geometric center [66,67]. So as to measure whether the overall regional development is out of balance more intuitively and regard it as an important basis for formulating regional macro-planning strategies.

(1) Weighted mean center

The mean center is also referred to as the geographic center or the center of concentration of a set of characteristics. In mathematical terms, a centroid is the point where the sum of the squared distances of the population is likely to be the smallest [68]. For point features, the X and Y coordinates of each feature are used, and for polygons, the centroid of each feature represents the X and Y coordinates to be used. Mean centroids are generally used to track changes in feature distributions over time and can also be used to compare the distributions of multiple features, as defined, for example, by the U.S. Census Bureau.

In the study, the mean center calculated in geometric geographic coordinates is usually used as the reference geometric center. The metrics to be analyzed are overlapped as weights to obtain the weighted mean center, and then the displacement analysis is performed with the reference point. The weight needs to be a numerical attribute. The larger the numerical value, the higher the weight of the feature. It is very useful when calculating the theoretical expected results where each outcome has a different distribution advantage. The calculation process is as follows:

$$\text{The mean center:} \quad \bar{X}_{coord} = \frac{\sum_{i=1}^{n} X_i}{n}\ ;\ \bar{Y}_{coord} = \frac{\sum_{i=1}^{n} Y_i}{n} \tag{1}$$

$$\text{The weighted mean center:} \quad \bar{X}_W = \frac{\sum_{i=1}^{n} w_i X_i}{n}\ ;\ \bar{Y}_W = \frac{\sum_{i=1}^{n} w_i Y_i}{n}$$

Where $\bar{X}_{coord}$ and $\bar{Y}_{coord}$ are the coordinates of feature i, and n is equal to the total number of features.

(2) Standard deviational ellipse (or directional distribution)

The standard deviation is one of the classical statistics describing the dispersion of a univariate feature around its center. It evolves in two dimensions up to the standard deviation ellipse (SDE), which was first introduced by Lefever in 1926 [69,70]. Since then, SDE has long been used as a general-purpose GIS tool to delineate bivariate distribution features. It is commonly used to sketch the trend of the geographical distribution of the feature of interest, summarizing its dispersion and direction (Fig. 2-6). The results of the standard deviation ellipse give information on three parameters: (1) the rotation angle showing the direction of the distribution; (2) the dispersion along the major axis, which defines the direction of maximum dispersion of the distribution; and (3) the dispersion along the minor axis, perpendicular to it, which defines the minimum dispersion.

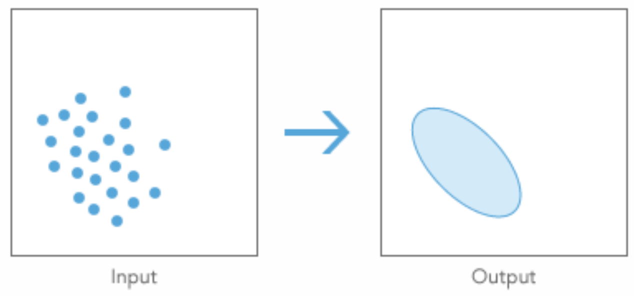

Fig. 2-6 The process diagram of standard deviational ellipse.

In theoretical terms, the trend of a set of points or regions is measured by calculating the standard distances in the x, y and z directions, respectively. These measures define the axis of an ellipse (or ellipsoid) that contains the distribution of features. The ellipse is called a standard deviation ellipse because the method calculates the standard deviation of the x and y coordinates from the mean center to define the axis of the ellipse. In 3D, the standard deviation of the z-coordinate from the mean center is also calculated, and the result is called a standard deviation ellipsoid. The ellipsoid or ellipsoid allows you to see if the distribution of features is stretched so that there is a specific direction. When working with one-dimensional data, the rule of three sigma is a common rule of thumb that conveys the percentage of data values that will fall within one, two and three standard deviations of the mean. In a normal distribution, this means that 68%, 95% and 99.7% of the data values will fall within one, two and three standard deviations, respectively. [69–71] In this study, the output standard deviation ellipse that is covered approximately 68% of the characteristics analyzed. The Standard Deviational Ellipse is given as:

$$C = \begin{pmatrix} var(x) & cov(x,y) \\ cov(y,x) & var(y) \end{pmatrix} = \frac{1}{n} \begin{pmatrix} \sum_{i=1}^{n} \tilde{x}_i^2 & \sum_{i=1}^{n} \tilde{x}_i \tilde{y}_i \\ \sum_{i=1}^{n} \tilde{x}_i \tilde{y}_i & \sum_{i=1}^{n} \tilde{y}_i^2 \end{pmatrix} \quad \text{where}$$

$$var(x) = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 = \frac{1}{n}\sum_{i=1}^{n}\tilde{x}_i^2$$

$$cov(x,y) = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y}) = \frac{1}{n}\sum_{i=1}^{n}\tilde{x}_i\tilde{y}_i$$

$$var(y) = \frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2 = \frac{1}{n}\sum_{i=1}^{n}\tilde{y}_i^2$$

Where x and y are the coordinates for feature i, $\{\bar{x}, \bar{y}\}$ represent the Mean Center for the features and n is equal to the total number of features.

Spatial autocorrelation

Traditional spatial statistics theory is based on the assumption of independent observations. However, in the real world, especially when it comes to spatial data, independent observations are not common in real life [72]. Geographical and economic behaviors between regions generally have a certain degree of spatial correlation or spatial effect. However, in actual analysis, many studies involving geospatial data ignore each other's influence, and incorrect model settings lead to deviations in the analysis results [74]. Spatial autocorrelation analysis is used to measure the basic attributes of geographic data: the degree of interdependence between data in one spatial location and data in other locations, which is considered the most important attribute of spatial effects, and so on. Fig. 2-7 shows the three types and samples of spatial autocorrelation. Generally speaking, there are three methods to examine the influence of spatial data, namely Moran's I, Geary's C and Getis index.

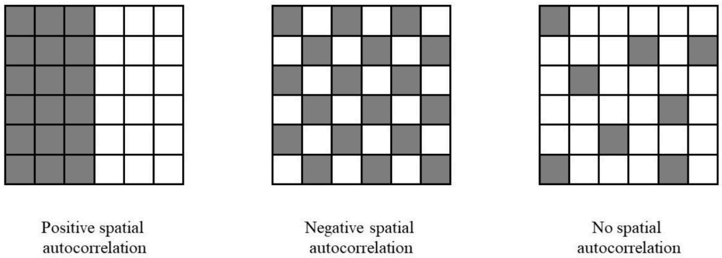

Fig. 2-7 Three spatial autocorrelation types and samples.

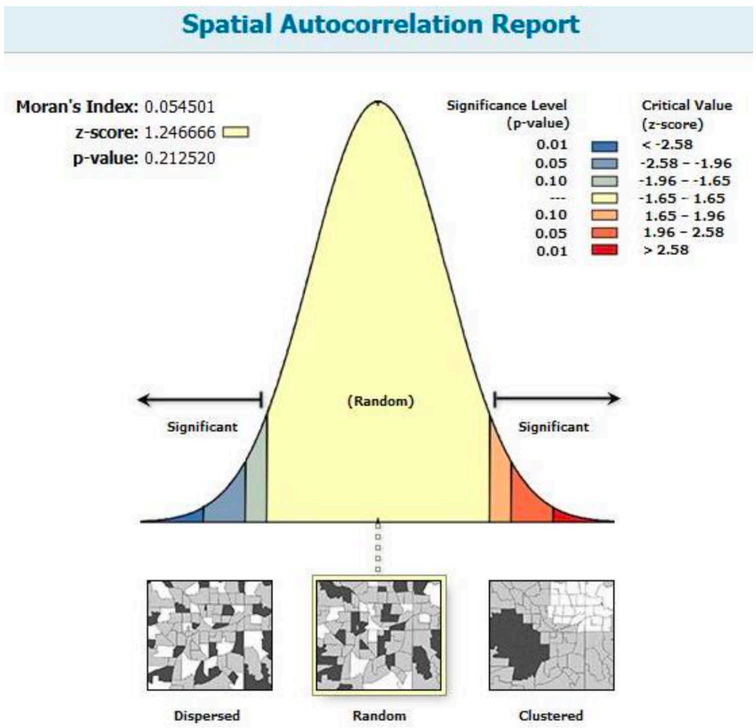

Fig. 2-8 Sample of autocorrelation analysis report in GIS.

In Chapter 8, a spatial autocorrelation analysis of the urban evaluation results was conducted to explore the temporal and spatial characteristics of its spatial effects. Therefore, Anselin (1995) suggests using local Moran statistics to determine the local spatial correlation index (LISA) [75] as a way to identify local clusters and local spatial outliers. Assessing significance in and of itself is not that useful for the Local Moran. The assessment of significance per se is not as useful for local Moran.

However, when the significance indication is combined with the location of each observation in the Moran scatter plot, a very powerful interpretation is possible. The combined information allows the classification of significant locations into high-high (HH) and low-low (LL) spatial clusters, as well as high-low (HL) and low-high (LH) spatial clusters. The references to High and Low are related to the mean value of the variables. In addition, a sample of autocorrelation analyses was reported as shown in Fig. 2-8. The Z-score and p-value are two key parameters used to measure the significance level of Moran's I-test. The Z-score was calculated by t-test. The local Moran's index (LMI) was calculated by the following formula.

$$LMI = \frac{(x_i - x^*)}{\frac{1}{n}\sum_{i=1}^{n}(x_i - x^*)} \sum_{i=1}^{n} \sum_{i \neq j}^{n} w_{ij} \frac{1}{n} \sum_{i=1}^{n} (x_i - x^*)$$

2.4.Summary

In this chapter, an assessment system for measuring the capacity of urban sustainable development was proposed in an easy-to-understand form and named "Urban Sustainability" (Su). It is based on reviewing the evaluation system related to urban sustainable development in domestic and worldwide research results, indicator selection, data collation, testing, and rigorous peer review. The necessity and significance of this assessment system are: (1) the worldwide sustainability assessment systems have certain limitations, and their general applicability needs to be proved. (2) China has not yet formed a highly authoritative and widely used sustainability assessment system, and related research is currently a hot topic, which would enrich the sustainable urbanization-oriented research works.

The main contribution include (1) identifying two key dimensions of urban sustainability in the context of China's urbanization: quality of built environment (Qu) and environment pressure (Pu); (2) establishing and defining a ratio (quality/pressure) model to quantify the capacity of sustainable development; (3) designing the indicator system of the model represented by urbanization economies, infrastructure development, urban attraction, resource consumption, and environmental pollution; and (4) determining the corresponding weighting criteria and detailed measurement method.

In addition, to comprehensively analyze the characteristics of the evaluation results and provide a basis for more targeted proposals for sustainable urbanization, effective analysis methods in the temporal and spatial dimensions have been summed up and introduced in this chapter: (1) statistical data analysis using SPSS, including the methods of Pearson correlation, Curve Estimation Regression, and Hierarchical Clustering. And (2) the analysis of the spatial relationships using the GIS model, including the methods of Geographic distributions and Spatial autocorrelation.

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Chapter 3. Overview of Urbanization and its Environment Investigation in China

3.1. Introduction

The urbanization process is quite complex, and some parts of the Chinese path are a significant deviation from the "standard" Western model. It is underpinned by China's economic strategy and administrative jurisdiction system. Scholars have argued that foreign theories of urbanization do not explain urbanization with Chinese characteristics, and therefore the study of Chinese urbanization should be more localized [1]. Although China has further increased its reform and opening up and urbanization, the level of urbanization still lags behind that of most developed countries. This is because urbanization is subject to too many constraints, such as urban housing supply, industrial structure, insufficient development of tertiary industry, scattered industrial distribution, lagging urban infrastructure, and increased environmental load and pollution. With the acceleration of urbanization since 2000, rapid economic growth and urban construction in China's administrative regions have been accompanied by enormous pressure of environmental resource consumption and severe pollution, etc. [2,3]. However, the superposition of various urban environmental problems is complex, and the distribution varies greatly between regions. Mainstream planning on metropolitan layout and environmental governance has become a focus of attention for governments and researchers in the promotion of urbanization. As a result, the development of coordinated planning for metropolitan clusters faces enormous challenges. Effective quantitative assessments are essential to find coping strategies in regions with complex urban environments like China.

In this chapter, to ensure the timeliness of the research results, we chose the time period with the most reference value for the future development of China's urbanization, that is, from 2010 (the year when China's urban population exceeds half) to 2018 (the most recent year with the complete database). All statistical data (2010-2018) were collected from the authoritative series of China Statistical Yearbooks, open-access published by the National Bureau of Statistics of China from 2011 to 2019. without further evaluative calculation. Besides, due to lack of data or the special governance modes, the data about the total or average of China mentioned in this chapter are limited to an overall range of China that excluding five autonomous administrative divisions, Hong Kong, Macao and Taiwan regions.

3.2. Investigation on urbanization and its environmental status from administrative divisions' perspective

3.2.1. An overview of urbanization in China

Since the 21st century, China's urbanization has maintained the highest growth rate of any country in the world. The urbanization rate has increased from 10.64% in 1949 to 59.58% in 2018, an average annual growth rate of more than 0.7% [4,5]. Although researchers do not reach agreement on the beginning and specific stages of China's urbanization process, most scholars agree that there were two turning points in the process, one with the adoption of the reform and opening-up policy and the other in the 1990s [6,7]. On the basis of urban population evolution and important policies or events, China's urbanization process has been divided into four stages. According to the typical "S-curve" of the Northam curve growth theory [8], the first two stages of China's urbanization process can be considered as the initial stage of urbanization, which reached 30% in 1996 [9]. And from the third stage to the present, it can be said to be a period of accelerated urbanization, but China's urbanization rate has not exceeded 70% so far and has not entered the end of urbanization [1]. The specific process of urbanization in China is as follows and shown in (Fig. 3-1):

(1) First stage (1949-1977): Since the founding of the People's Republic of China in 1949, the process of urbanization has fluctuated greatly, and the speed has been relatively slow. From 1964 to 1977, China's rural population grew faster than the urban population. The growth of urban population mainly occurs in small and medium-sized cities, while towns are underdeveloped, but the population of megacities has been well controlled [5,10].

(2) Second stage (1978-1995): Since China's reform and opening-up policy in 1978, the ups and downs of urbanization have largely ended and China has begun to experience a sustained rate of urban growth, averaging 4-5% per year, as the rural population has begun to decline. This growth is attributed to economic construction and net urban-rural migration and urban reclassification, which has greatly contributed to rapid urban development [9]. The State Council approved the Minutes of the National Conference on Urban Planning in 1980, which established the policy of "controlling the size of big cities, developing reasonably the middle cities, and promoting actively the growth of small cities" [11]. In 1994, China's Agenda 21 proposed new goals for urbanization, calling for moderate control of rapid population growth in large cities, development of satellite cities of large cities, active and moderate development of small and medium-sized cities, and vigorous promotion of the development of towns and cities [12,13].

(3) Third stage (1996-2009): After 1996, rapid urbanization was mainly driven by the tertiary sector, as a result of the joint efforts of the government and the market. After China joined the WTO in 2001, it entered a new era of further opening up [14,15]. In China, all levels of government play a decisive role, directly and indirectly, not only in many major aspects of the polity, but also in many major aspects of society and the economy, while providing "Chinese characteristics" to the urbanization process [1]. In additional, the reform and opening up greatly contributed to the construction of mega-city areas and the growth of urban space, and rational competitiveness and technological progress gathered in megacities in the context of economic globalization and regional economic integration. Since then, megacities have become the main form of urbanization development [16–18].

(4) Fourth stage (2010-now): Starting with the 12th Five-Year Plan in 2010, the urban population surpassed the rural population for the first time. China's urbanization rate increased from 50.05% in 2010 to 59.58% in 2018 [19], with an average annual growth rate of more than 1.2%. It is estimated that by 2050, the urban population will reach approximately 81.63% [20]. This means that China's

urbanization level will still grow by more than 20% until 2050. The new population is expected to exceed 200 million [21]. This will inevitably create significant urban challenges in terms of both quality of the built environment and environmental pressures. 2014 to date, China has made some success in transitioning from traditional industrial-led urbanization to a new type of urbanization aimed at building a competitive and livable urban environment [22–24]. However, there are still increasing environmental pressures that hinder substantial development [25–27]. The government began work aimed at vigorously promoting new urbanization development by establishing high-quality sustainable development.

From the spatial distribution of satellite-observed nightlights shown in Fig. 3-2, it can be clearly seen the geographical features of population evolution from 1978 to 2018. During nearly two decades after 1978, China realized continuous growth [28]. The regional focus of urbanization changed from growing faster in the east than in the center and west to growing faster in the south than in the north. However, the western and central regions are less populated. The population first gathered in the advanced cities. The position of smaller cities in the urban system then improved from 2010 onwards, and the actual population growth in advanced cities slowed down considerably. In addition, from 1980 to 1984, China launched Special Economic Zones (SEZs), which opened up 14 coastal cities and promoted the transformation of China's urbanization from inner to outer [29,30]. Since 1990s, China's urbanization has mainly occurred in the eastern coastal region, especially with the development of the Pearl River Delta, Yangtze River Delta and Shandong Peninsula, and the rise of China's megacities, but the polarization within cities has increased [31].

In addition to the ongoing discussion of population and region, a common focus of almost all scholars in the 21st century has been the concept of sustainable development. This has led them to study the characteristics of urbanization in China, such as continued rapid growth, extreme imbalances, dependence on economic growth, and resource conservation and destruction, etc. [32,33]

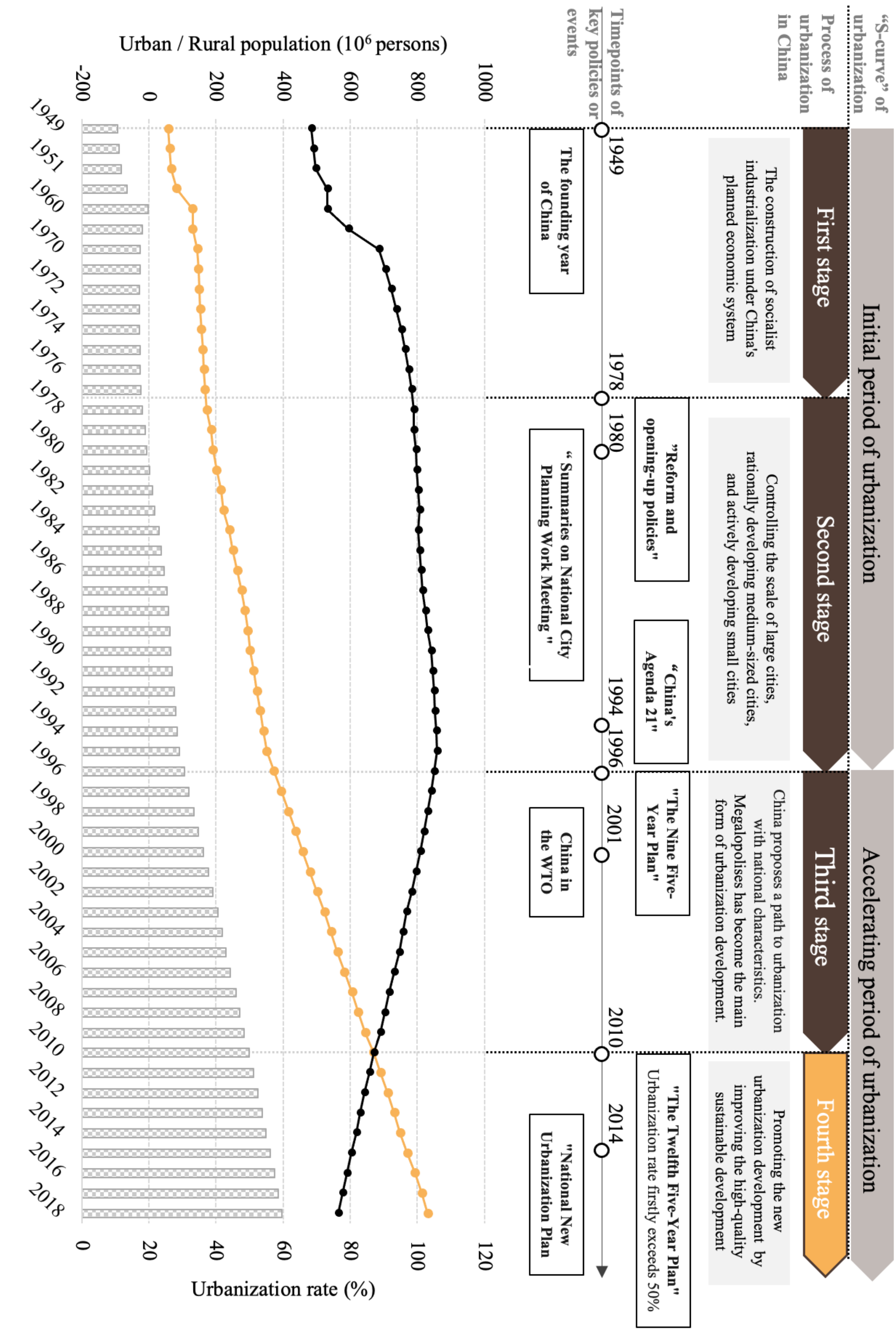


Fig. 3-1 The urbanization process and key timepoints of polices or events in China from 1949 to 2018.

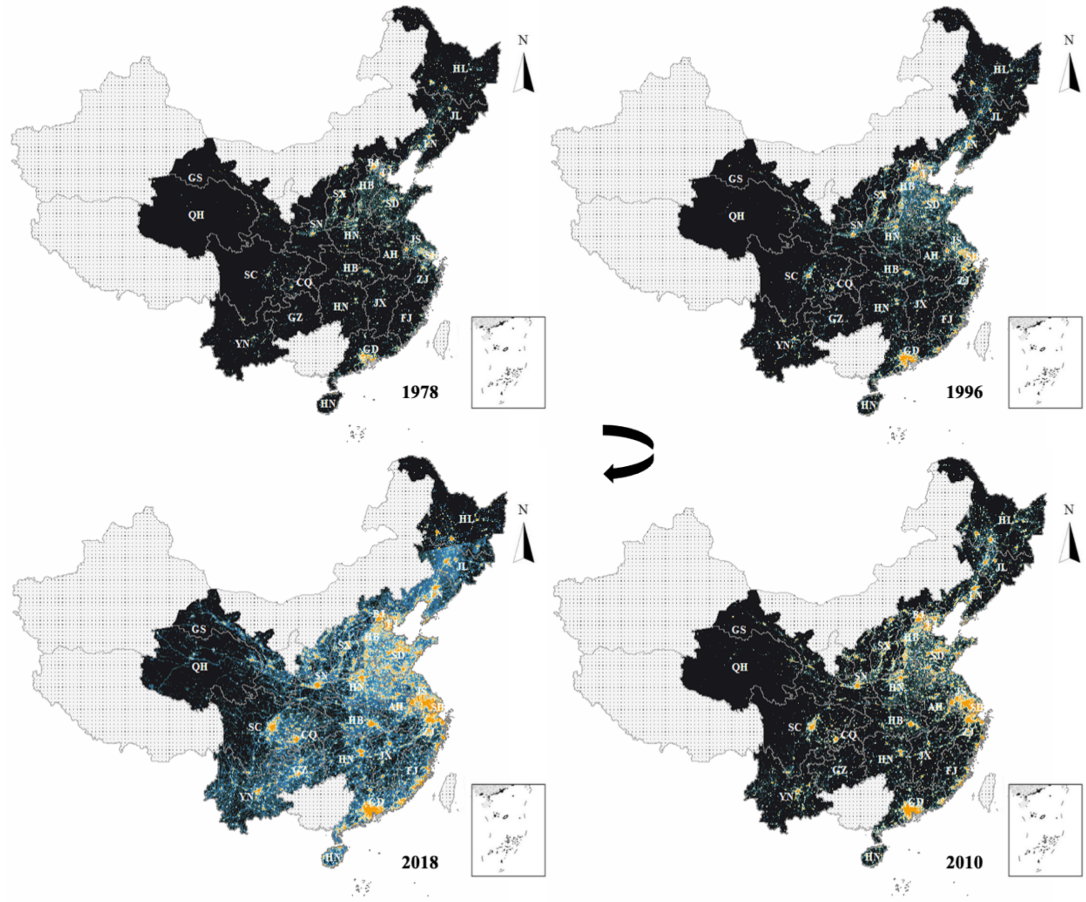


Fig. 3-2 The evolution of urbanization in China from 1978 to 2018.

(Notes: the degree of urban population is represented by the change of color. The deeper yellow color represents higher urbanization, and the deeper blue color represents lower urbanization.)

3.2.2. The urbanization and its environmental distributions of provincial-level divisions

Chinese administrative hierarchy

Since 1949, China's urbanization with "Chinese characteristics" is different from the urbanization experience of many other developing countries. To a large extent, this is due to the fact that the underlying structures and policies are the result of government intervention through urban planning, which directly influences the spatial patterns of urbanization and the urban environment [5]. The command operates through a hierarchy of administrative-economic units, with power concentrated at the central level. This structure determines the basic configuration of China's urban system and the number of Chinese towns and cities. After the introduction of urban agglomerations as the main form of new urbanization in China in 2014, the government began to include the planning of megalopolises as an official work plan. As a result, China has long exercised management and control according to administrative levels [34].

Largely corresponding to the local governmental structure, there are basically five levels of urban administrative divisions, including provincial-level, prefectural-level, county-level, township-level, and basic-level autonomy. Excluding autonomous regions, Hong Kong, Macao and Taiwan regions, China has 26 provincial-level administrative divisions, including 22 provinces and four municipalities (Beijing, Tianjin, Shanghai and Chongqing) (Table 3-1).

Table 3-1 List of provincial-level administrative divisions in China

Provincial-level administrative divisions in China	Code name	Urbanization rate (%)	Total population (10^6 persons)	Land area (10^4 km^2)	Density (persons /km^2)	GDP ($ / person)	Length of coastline (km)
Shanghai[2]	SH	88	24	1	38	20335	213
Beijing[2]	BJ	87	22	2	13	21229	-
Tianjin[2]	TJ	83	16	1	13	18186	154
Guangdong	GD	71	113	18	6	13430	5291
Jiangsu	JS	70	81	11	8	17653	1071
Zhejiang	ZJ	69	57	11	5	14835	5287
Liaoning	LN	68	44	15	3	8760	2878
Fujian	FJ	66	39	12	3	13703	3752
Chongqing[2]	CQ	66	31	8	4	9901	-
Shandong	SD	61	100	16	6	11690	3561
Hubei	UB	60	59	19	3	10035	-
Heilongjiang	HL	60	38	45	1	6541	-
Hainan	HI	59	9	4	3	7803	1944
Shanxi	SX	58	37	16	2	6823	-
Shaanxi	SN	58	39	21	2	9539	-
Jilin	JL	58	27	19	1	8409	-
Hebei	HB	56	76	19	4	7047	487
Jiangxi	JX	56	46	17	3	7134	-
Hunan	UN	56	69	21	3	7964	-
Anhui	AH	55	63	14	5	7258	-
Qinghai	QH	54	6	72	0	7167	-
Sichuan	SC	52	83	49	2	7356	-
Henan	HN	52	96	17	6	7546	-
Yunnan	YN	48	48	39	1	5584	-
Gansu	GS	48	26	43	1	4717	-
Guizhou	GZ	48	36	18	2	6203	-
Total of China[1]	-	60.69	1287	524.11	2.46	10155.86	24425

Note: (1) Thel data of total of China does not include autonomous regions, autonomous regions, Hong Kong, Macao and Taiwan. (2) The marked cities are direct-administered municipalities of China.

General information of administrative population and land

The total population size of China's provinces varies greatly (Fig.3-3). In 2018, the gap between Guangdong Province, the most populous province, and Qinghai Province, the least populous province, exceeded 100 million people. There is no direct relationship between total population size and urbanization. The top three sectors with the highest urbanization levels are Shanghai, Beijing, and Tianjin, all of which are Chinese municipalities with urbanization rates over 80%, much higher than other provincial administrative regions. The least urbanized provincial administrations are Yunnan, Guizhou, and Gansu, all of which are located in western China and have urbanization rates below 50% [35].

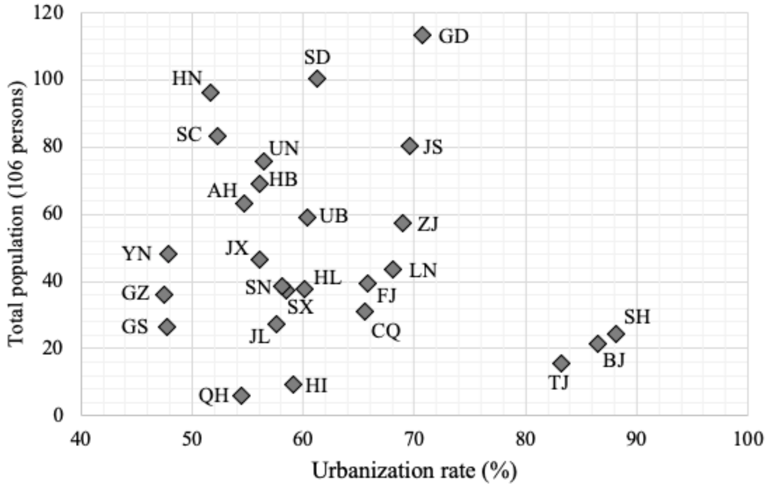


Fig. 3-3 General information of administrative population in China in 2018.

The distribution of population density in the provincial administrative regions in 2018 (Fig.3-4), the national average population density is 245.51 people/km^2, while the population density of municipalities Shanghai, Beijing and Tianjin exceeds 1,000 people/km^2. Among them, Shanghai is the highest region, with a population density of 3823 people/km^2. In addition, among the top ten divisions for population density, seven of them are coastal administrative regions.

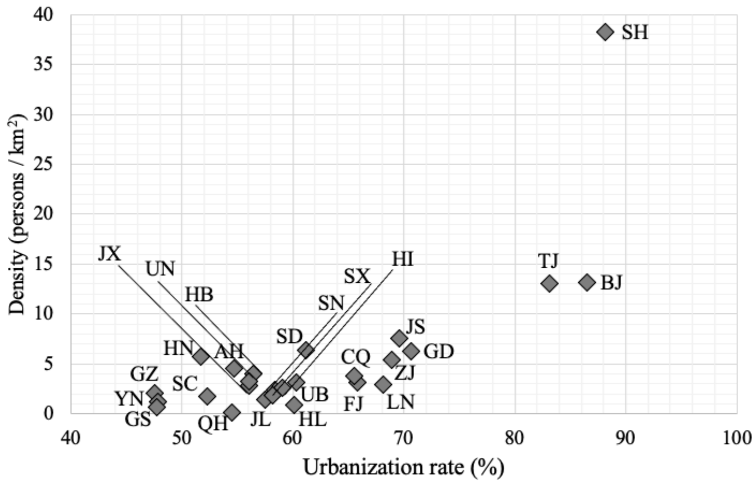


Fig. 3-4 General information of administrative population density in China in 2018.

The population density is directly related to the administrative area (Fig.3-5). China has a vast territory and rich topography and landforms. Taking the ‘Heihe-Tengchong Line’ as the boundary, about 90% of the population lives in the southeastern region, which accounts for about two-fifths of the country's land area, while the remaining population lives in the northwestern region, which accounts for about three-fifths of the country's land area. Thus, the administrative divisions located in the coastal area are generally smaller, and the inland divisions have larger jurisdiction. The difference between the largest Qinghai Province and the smallest Shanghai is more than 700,000 square kilometers. The administrative level of a municipality directly under the Central Government as equivalent to that of the province but the area is almost the same as that of a municipal administrative region, both of which are less than 100,000 square kilometers.

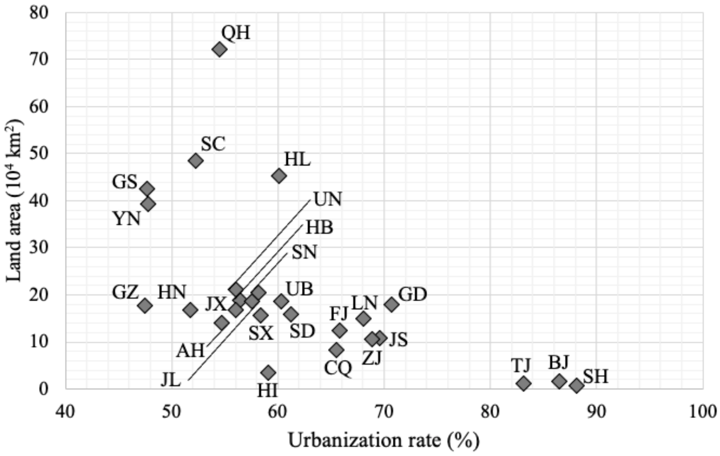
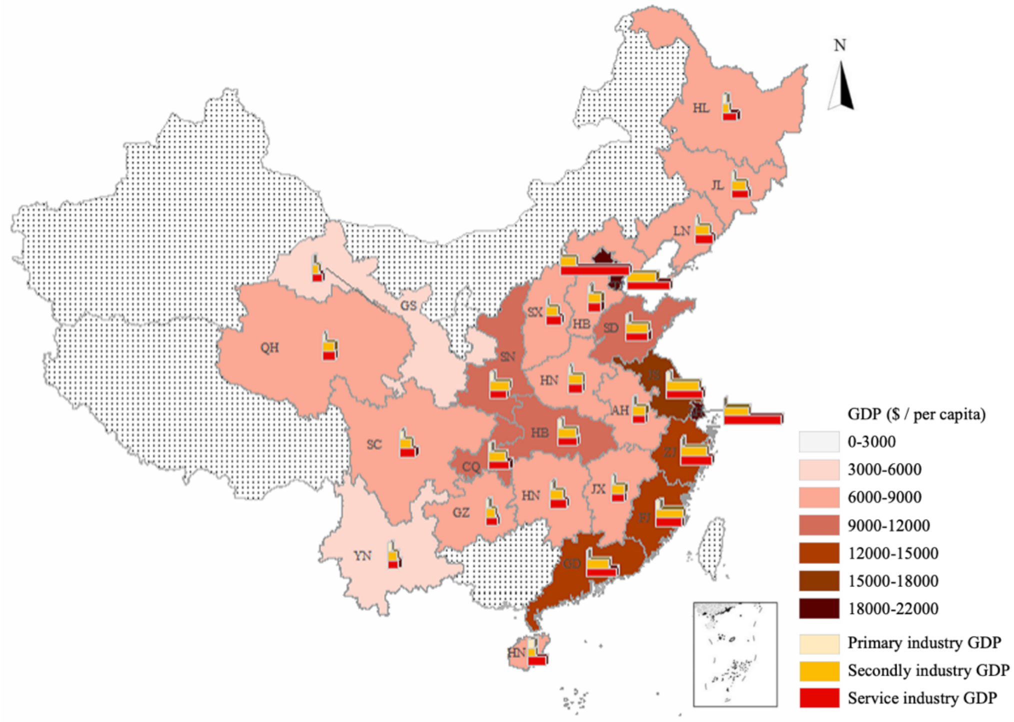


Fig. 3-5 General information of administrative land in China in 2018.

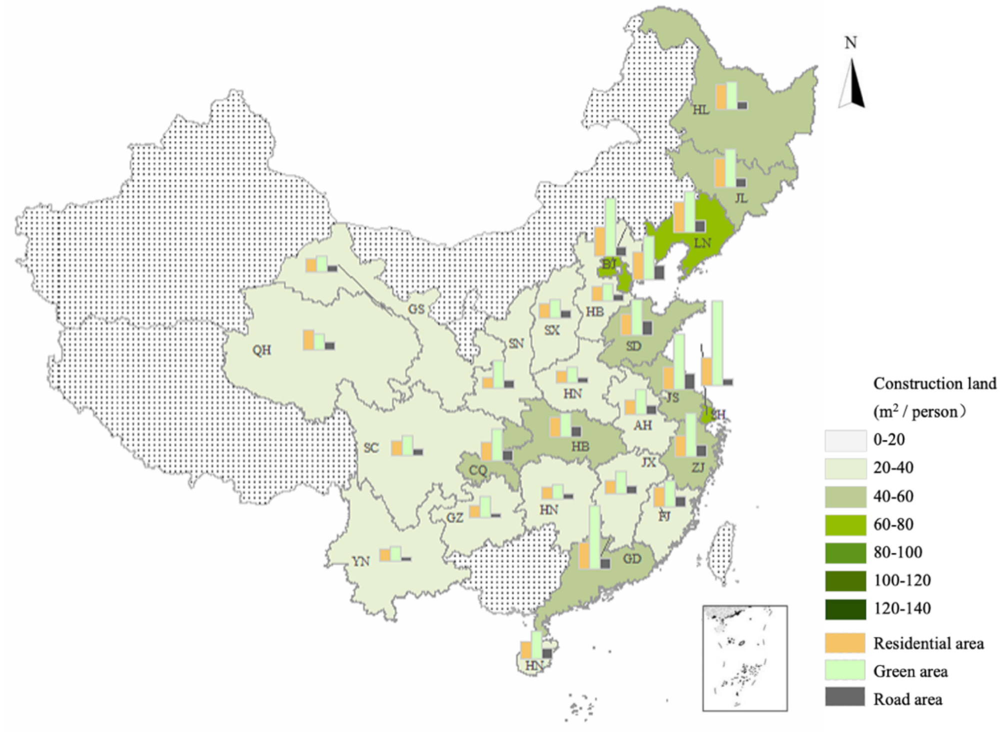
Spatial distributions of urban environment

In 2018, the annual gross domestic product (GDP) per capita in different provincial administrative regions of China ranges from approximately US$21,229 in Beijing to approximately US$4,717 in Gansu Province. The national GDP per capita exceeds the US$10,000 threshold, but the level of economic development varies greatly from region to region [36]. Four major geographic and economic regions can be discerned in China. The economically developed coastal regions in the east, the less developed regions in the center and northeast, and the developing regions in the west. This division has deep historical roots, reflecting the geography of each region and its political past and present. In addition, regional economic development is closely related to industrial structure, and the size of the service sector is closely related to the boundaries of the four major economic regions shown in Fig. 3-6(1).

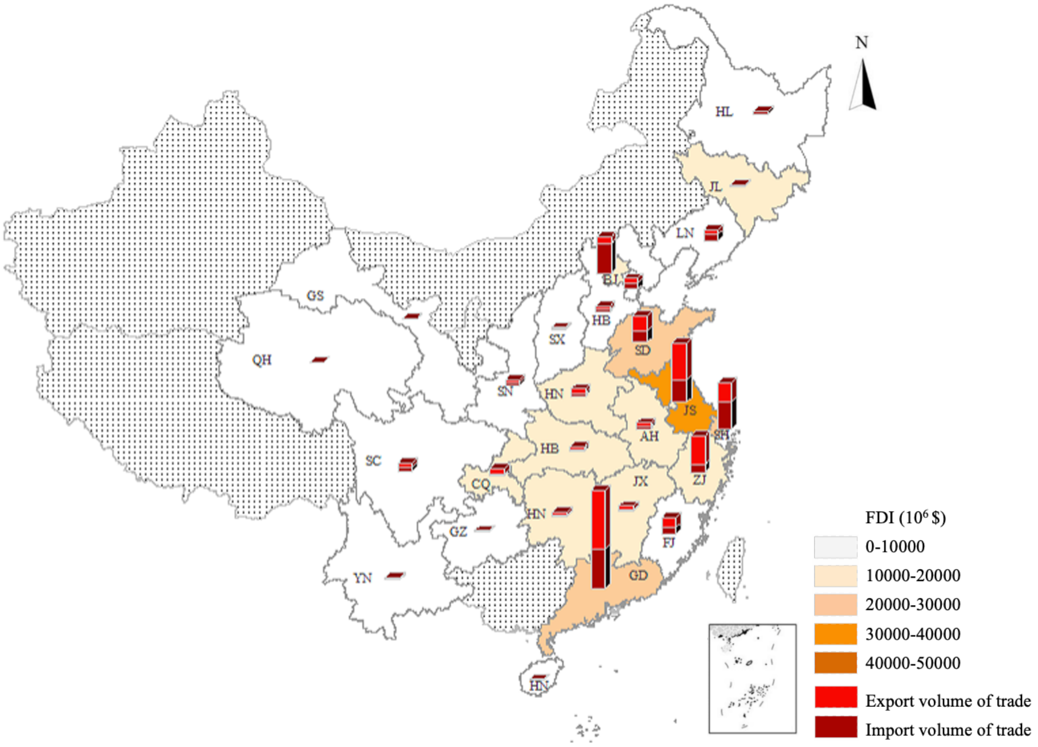
The infrastructure construction in the eastern coastal administrative divisions is significantly better than that in the central and western divisions. Among them, Beijing and Liaoning province in the northeast have the largest construction land area per capita. Besides, the northeastern region has the largest residential area, but the southern provinces are generally smaller. There is a large gap in the area of green land in various provinces, with more in coastal areas than inland areas. In particular, economically developed divisions have paid more attention to creating a green public environment. There is a small difference in the area of roads between administrative regions, and the distribution is similar to the construction land. (Fig. 3-6(2))



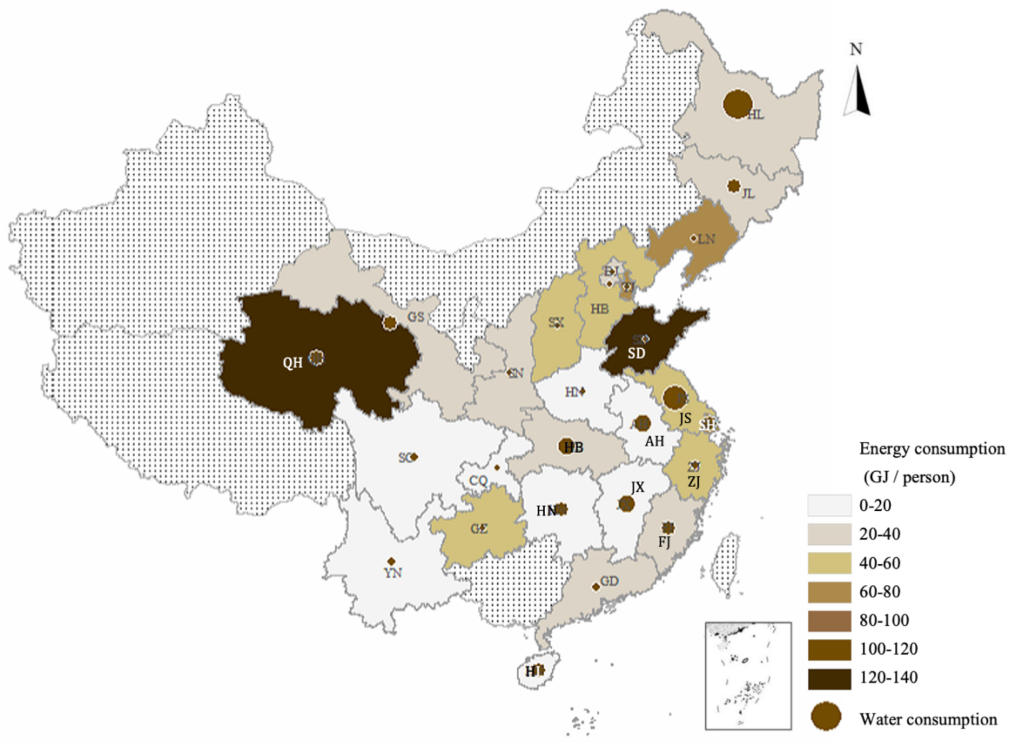
(1) Spatial distributions of urbanization economies



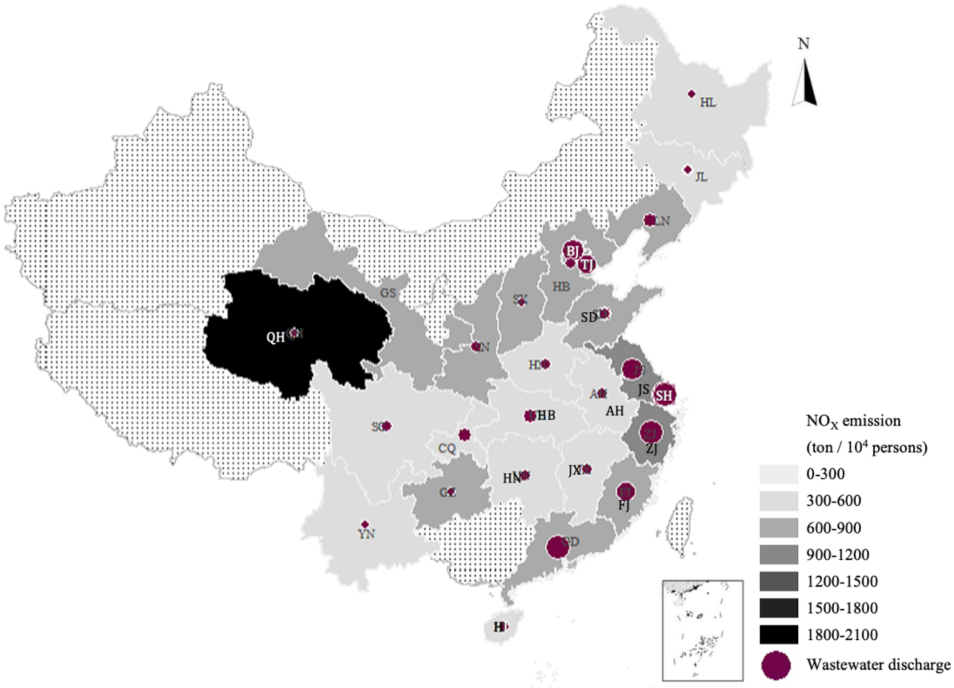
(2) Spatial distributions of infrastructure development



(3) Spatial distributions of urban attraction



(4) Spatial distributions of resource consumption



(5) Spatial distributions of environmental pollution

Fig. 3-6 Spatial distributions of urban environment in China by provincial-level administrative divisions in 2018.

The distribution of the foreign attractiveness of China's provinces is almost divided into two parts by the 'Heihe-Tengchong Line': the southeastern half of which the annual foreign direct investment exceeds 10 billion dollars, and the northwest half of which is less than this amount. Among them, Jiangsu province, Shanghai, Guangdong province and Shandong provinces have more attractive to Western economies [37]. This distribution characteristic can be supported by the evidence that the Chinese government planned on directing the FDI to special economic zones (SEZs) and areas geographically within the East of China [38]. Examples of incentives put in place include tax reductions on profits in Open coastal areas. Moreover, due to the advantages of ports and manufacturing, the regions with the most exports are concentrated in the eastern coastal areas, which are at a completely different level of magnitude from other regions. (Fig. 3-6(3))

China's total energy consumption ranked first in the world. In 2017, China's energy consumption required to create one dollar of GDP was about 2.5 times that of the United States and 4.1 times in Japan [14]. In particular, the Shandong province, Qinghai province and Liaoning are the largest energy consumption divisions in China due to energy-intensive heavy industry or large-scale resource extraction. Affected by the climate, the per capita energy consumption in the northern administrative region is also relatively high compared to the southern region. Conversely, the per capita consumption of water resources is higher in the southern region. But the per capita water consumption in Heilongjiang is very large, because it causes a lot of unnecessary waste both in transportation and living activities. (Fig. 3-6(4))

There is a certain relationship between environmental pollution and resource consumption, and their spatial distribution has some similarities. From the perspective of NOx emissions per capita in 2018, it can be clearly found two main pollution emission belts: one is the east-west distribution belt from Qinghai to Liaoning province, and the other one is the north-south distribution belt from Beijing to Guangdong province. And Guizhou is also facing the same environmental pressure of air pollution. The administrative divisions that discharge more wastewaters are mainly located in the distribution belt from Beijing to Guangdong, which would be closely related to intensive human activities. (Fig. 3-6(5))

3.3.Investigation on urbanization and its environmental development from megalopolises' perspective

3.3.1.The era of megalopolises in promoting urbanization

Since the 1980s, some scholars have explored the urban form of some cities and the combination pattern of different urban forms [39]. From urban agglomerations to urban clusters to megacities, these concepts reflect an evolving process of spatial studies of urbanization. It is usually believed that the emergence and development of megacities occur at a relatively high stage of urban development [40]. Li (1989) [41] was the first to study Gottman's theory of urban agglomeration and explored the conditions of formation, historical drivers of urban agglomeration, and was the first to focus on megacities in China. Wu (1990) [42] introduced the morphology and structure of hundreds of Chinese cities, the mechanisms of urban morphological evolution, and development trends from social, economic, cultural, and natural aspects, and proposed a reasonable model for the development of megacities [43]. Megalopolises are generally considered to be higher forms of urban agglomerations consisting of multiple metropolitan areas, and related studies are sponsored by the National Natural Science Foundation of China. The research experience from developed countries shows that a megacity area is a large population core, which in combination with the areas located in its vicinity, tends to integrate in both social and economic fields. Scholars believe that the era of China's megalopolises has arrived. And it is an important sign of a certain stage of economic development, which will surely be the mainstream for promoting high-quality urbanization and participating in international competition.

In 2006, the term "megalopolis" first appeared in Chinese government documents. The national "Eleventh Five-Year Plan" proposed to take megalopolises as the main form of urbanization. In 2007, the report of the 17th National Congress of the Communist Party of China pointed out that it was necessary to rely on large cities, form large radiating city clusters, and cultivate new economic growth poles [43,44]. In 2012, the report of the 18th National Congress of the Communist Party of China pointed out that it was necessary to continue to implement the overall strategy of regional development and scientifically plan the megacities The scale and layout of megalopolises. Since 2013, the central government has called for mega-cities as the main form of promoting the new type of urbanization in the country. The 2013 Central Urbanization Work Conference proposed to gradually develop and form a number of megalopolises with conditions in central and western China and northeast China by relying on market forces and national planning guidance. The 2014 National New Type Urbanization Plan (2014-2020) and the 13th Five-Year Plan" require the construction of optimized urbanization layout and form, the coordinated formulation and implementation of megalopolises' planning, and the clarification of the development goals, spatial structure and development direction of megalopolises [39]. Clarify the functional positioning and division of labor of each city, coordinate the layout of transportation infrastructure and information network, and accelerate the integration of urban clusters. 2017 report of the 19th National Congress of the Communist Party of China pointed out that the coordinated development of large, medium and small cities and towns should be built with urban clusters as the main body. 2018 Opinions of the CPC Central Committee and State Council on Establishing a New Mechanism for More Effective Regional Coordinated Development clearly states that urban clusters should promote the integration of national important regional strategies and establish a new model of regional development led by central cities for the development of megalopolises and driven by megalopolises. Promote the development of integration and interaction between regional segments [39,43,45].

Since 2015, China has approved 11 megalopolises' plans (Fig.3-7) , namely: Yangtze River Delta, Pearl River Delta, Shandong Peninsula, JingJinJi, West Side of the Straits, Guangzhou Plain, Liaozhongnan, Yangtze River Middle Reaches, Chengdu-Chongqing, Central Plains and Harbin-Changchun. These 11 megalopolises gather 60% of the population with 20% of the land and create 80% of GDP, of which the urban population accounts for 70%. At present, most megalopolises still need further development and cultivation. According to the “Ranking of China's Urban Development Potential: 2019” reported by the Evergrande Research Institute in April 2019, 96 of the top 100 cities with development potential are located in megalopolises. (Fig.3-8) In 2018, the per capita GDP of the Yangtze River Delta, the Pearl River Delta, the Shandong Peninsula, the JingJinJi region and the western region all exceeded 10,000, and their economic strength ranked among the top five with the largest increase in 9 years. In terms of urban population size, the five urbanization rates of the Yangtze River Delta, Liaoning Central and Southern, Pearl River Delta, West, JingJinJi and Shandong Peninsula have exceeded 60%, and the increase in Shandong Peninsula is much higher than other megalopolises. At present, the Shandong Peninsula has attracted more domestic and overseas attention both in terms of its international location relations and its own comprehensive strength. It is considered to be the fourth largest megalopolises with the most development potential after China's three major megalopolises (Yangtze River Delta, Pearl River Delta, JingJinJi). This is also the basis for choosing these top-four megalopolises as the research object in this study.

Recently, the study of China's megalopolises has shifted from rapid economic development to planning, layout, and environmental governance. This is because scholars have realized that the expansion of megalopolises has exacerbated the negative impacts of urbanization on the social environment, especially traffic congestion, housing shortage, environmental pollution, and ecological degradation, making the sustainable development of megalopolises a hot topic in the urbanization process. In addition, cities within the megalopolises compete with each other due to interest factors, and the coordination mechanism is not sound. There are also problems such as homogeneous competition and resource mismatch among megalopolises. These situations lead to increasing imbalance between different regions, which is an important issue to be addressed in the study of megalopolises in China.

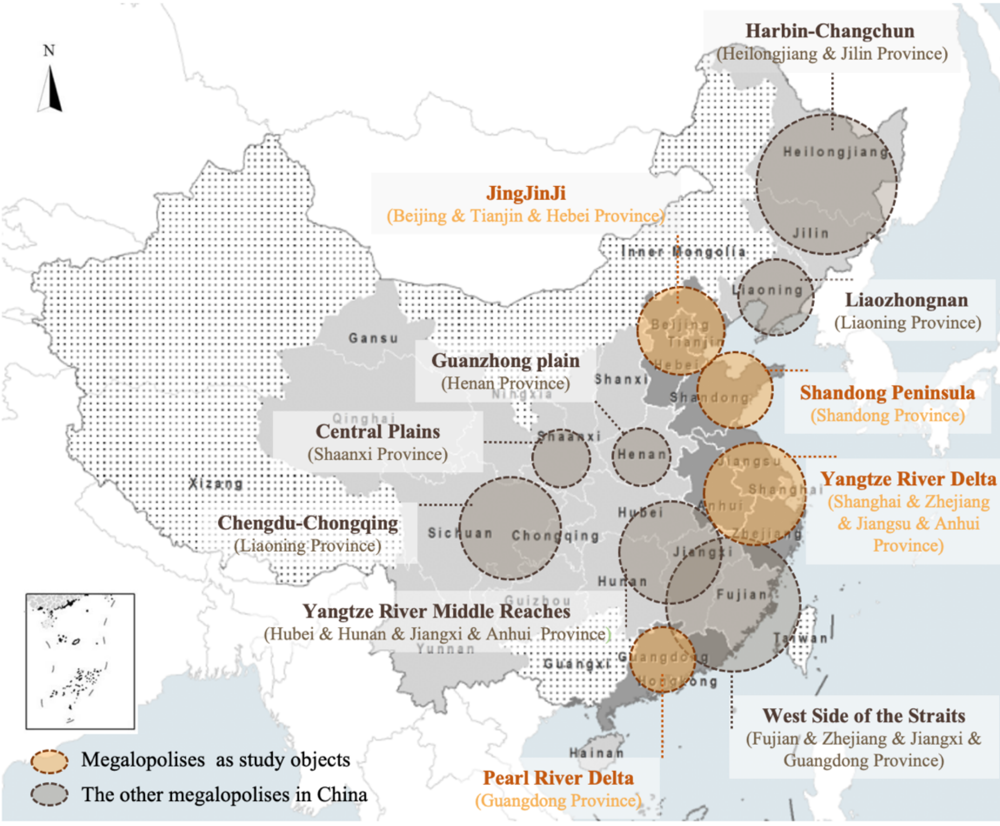


Fig. 3-7 Map of 11 megalopolises approved in China

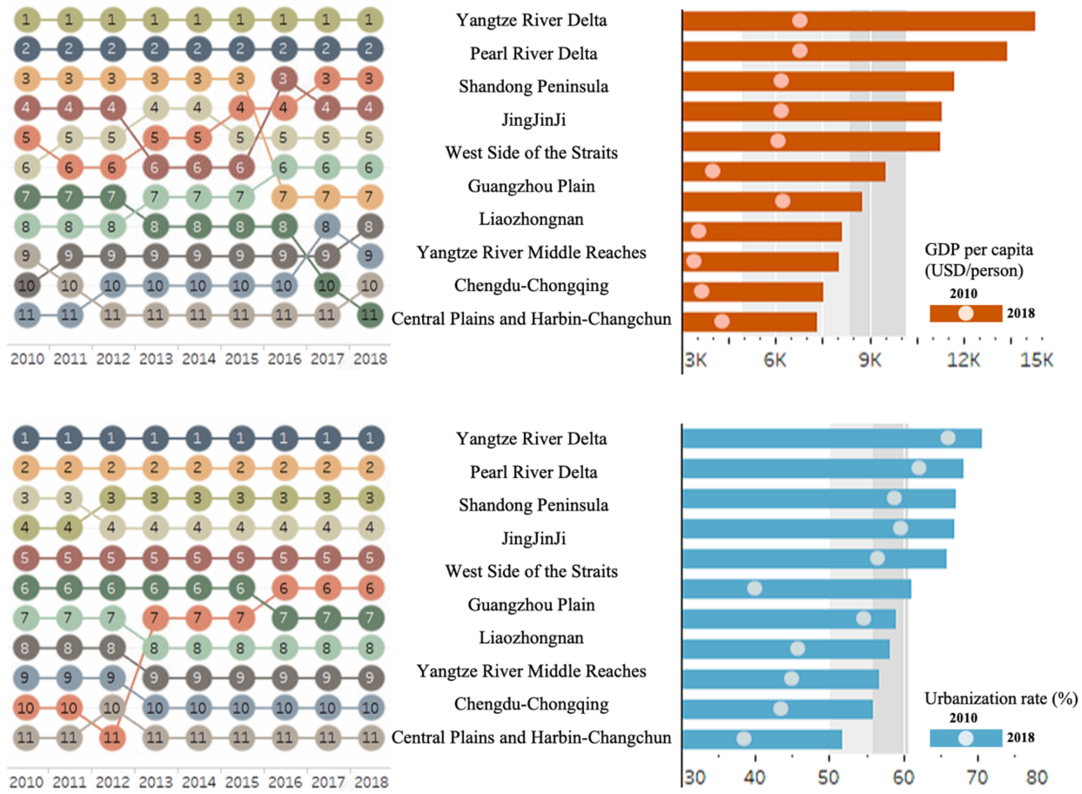


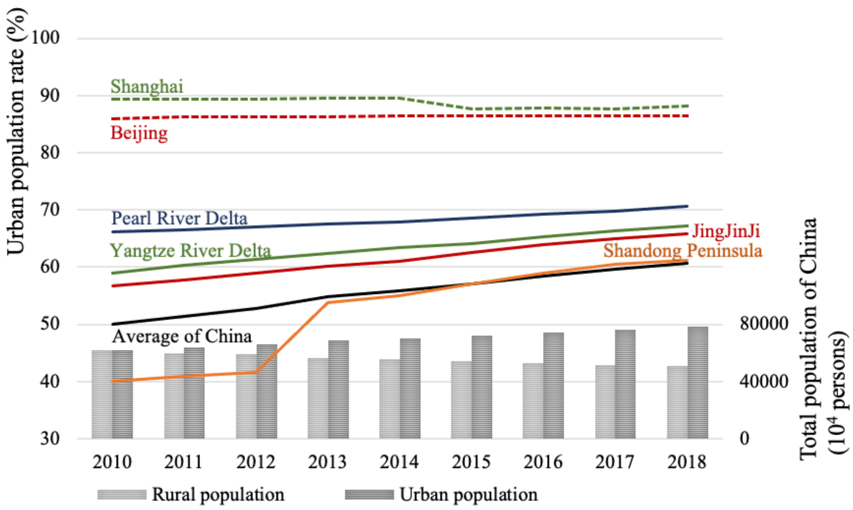
Fig. 3-8 Comparative analysis of GDP and Urbanization rate among 11 megalopolises in China.

3.3.2.Descriptive statistics analysis of urban environment indicators

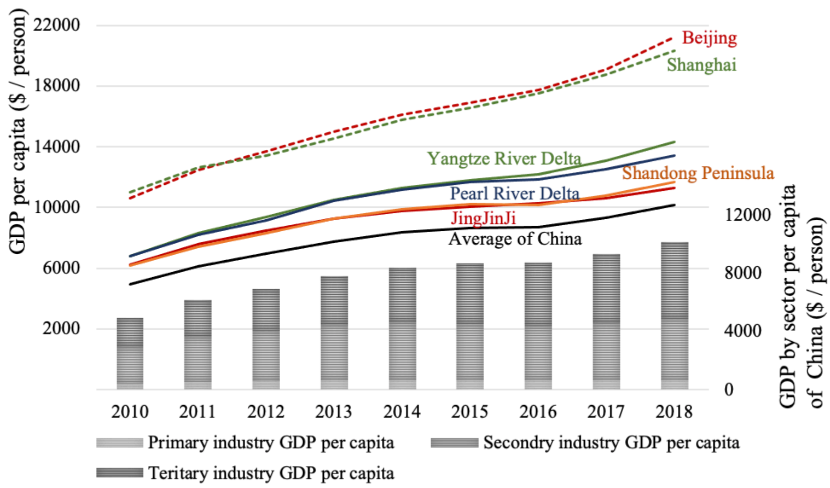
To overview understand the development of each urban environment indicators before assessment, the most important megalopolises (Yangtze River Delta, Pearl River Delta, JingJinJi and Shandong Peninsula) and the highest administrative level cities in China (Beijing and Shanghai) were extracted and analyzed together with China's average data (except autonomous regions). All data is national statistical data from 2010 to 2018, originally collected from the China Statistical Yearbook (20011-2019) publicly available on government websites.

Urbanization economies (Fig. 3-9)

Since the establishment of megalopolises in 2000, the Pearl River Delta, Yangtze River Delta and JingJinJi have grown rapidly and stepped into a steady urbanization process by 2010. This is the result of the guidance of the national authorities and the most developed first-tier cities, Beijing, Shanghai, Guangzhou and Shenzhen (commonly known as "North-South-Guangzhou-Shenzhen") [46,47]. They are large, densely populated urban metropolises with enormous economic, cultural and political influence in China. Although the development of the Shandong peninsula started far behind the other megacities, the growth of the urban population after the reform and opening up has been considerable. This is due to rapid urban construction and industrial transformation that contributed to the accelerated rate of urbanization in 2012. After the reform and opening up, the economy of non-agricultural industries developed rapidly. In particular, after 2006, China's GDP grew by an average of more than $1,000 every two years. in 2014, four metropolitan cities had a per capita GDP of more than $10,000, reaching the world's upper-middle income ranking [48,49]. The Yangtze River Delta and Pearl River Delta cities are in relatively good shape economically, with GDP per capita that has long been well above the national average. The Shandong Peninsula and JingJinJi have developed economically at roughly the same pace. The slowdown in the growth of the secondary industry and the decline in investment demand led to an overall slowdown in China's economic growth around 2015, followed by a return to rapid economic growth. In addition, although the share of tertiary industry in China has increased year by year to nearly 50%, it still lags behind the world average of 63.0% (statistical value in 2017). The unsatisfactory development of the service sector will cause a lag in the structural transformation of employment and low urbanization [50].



(1) Urban population and its proportion in the total population panel



(2) Total GDP and GDP by sector per capita

Fig. 3-9 The trend of urbanization economies in China from 2010 to 2018.

Infrastructure development (Fig. 3-10)

Over the past 30 years of reform and opening-up, China's infrastructure stock has ranked first in the world through moderately advanced large-scale infrastructure construction. In particular, the level of infrastructure development in four megalopolises is generally higher or nearly than China's average, but that in JingJinJi is relatively insufficient. However, there is a clear gap between per capita level and quality in China and in developed countries. The area of construction land per capita in China just exceeded the world average in 2014, but there is still a double gap with developed countries. With the influx of urban population in a short period of time, a series of problems have emerged, such as insufficient land supply, inadequate transport, and storage facilities, etc. Especially in the first-tier cities, there is a significant decline shown in the figure at about 2014. Moreover, the residential land area has basically not increased significantly in the past 9 years [51,52]. According to the 2010 census, the per capita housing area of 55% of Chinese households is less than 30m^2 [53]. The per capita housing area in the more developed areas of the southeast coast is relatively low, and the demand for housing improvement is stronger.

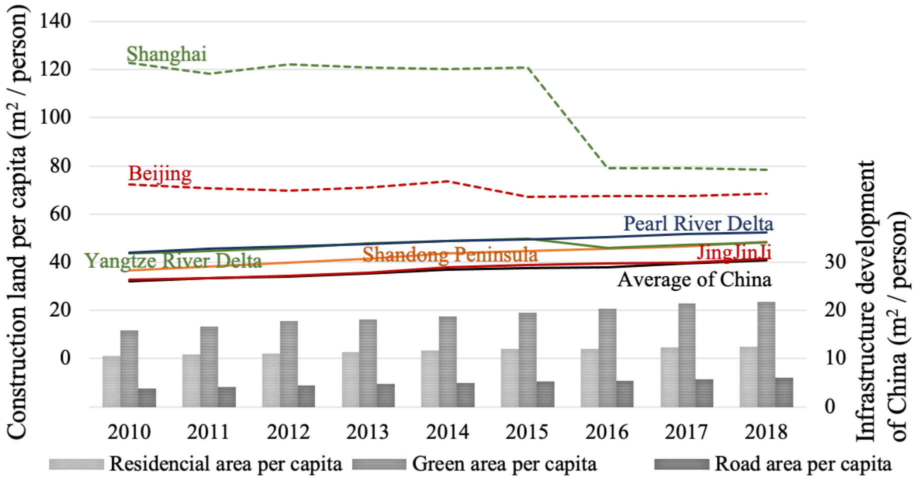


Fig. 3-10 The trend of infrastructure development in China from 2010 to 2018.

Urban attraction (Fig. 3-11)

Supported by the open-door policy, the four giant cities have taken advantage of convenient transportation, abundant labor force, low capital cost and large market size, and demand has attracted a large amount of foreign trade and foreign investment, exceeding the average level of China, especially in the Yangtze River Delta. However, in recent years, the level of growth has changed people's consumption habits and increased the pursuit of product quality and technological content [54]. Traditional labor-intensive products have gradually weakened due to their export advantages, while imports of high-tech products and higher-quality consumer goods for daily use, which help promote economic transformation and upgrading, have achieved counter-trend growth [55]. As a result, foreign trade growth has declined or grown slowly since 2015.In 2016, foreign-invested enterprises showed a rapid recovery driven by policy measures such as the reform of the commercial system and the reduction of the negative list of foreign investment access. However, they immediately fell back to in the JingJinJi and Shandong Peninsula regions, mainly due to low income and technological innovation industry trade protection. In addition, local governments in China see the development of and investment in tourism as a wise decision. With the 2008 Olympic Games in Beijing, the role of strategic pillar industries in the corresponding tourism industry began to emerge [56].

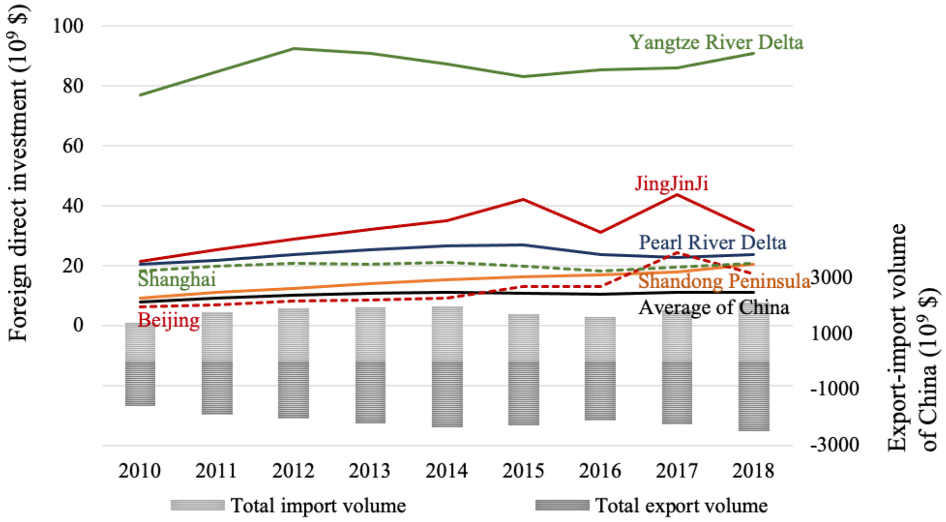
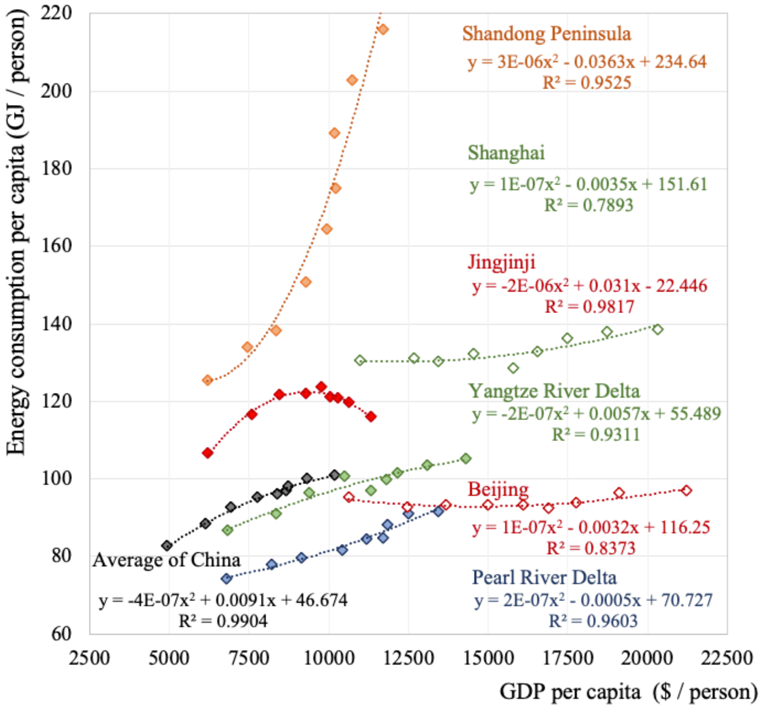


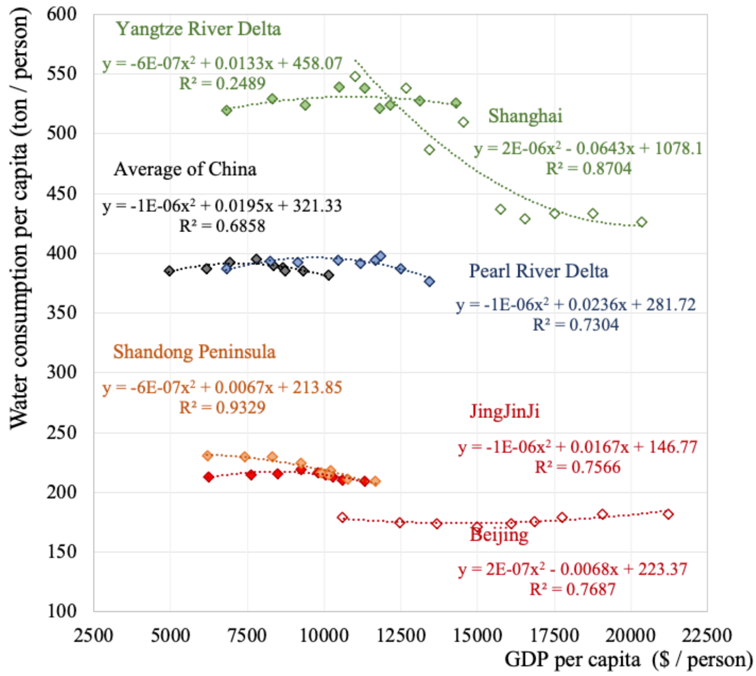
Fig. 3-11 The trend of urban attraction in China from 2010 to 2018.

Resource consumption (Fig. 3-12)

As Fig. 6-a shows, there is a clear linear relationship between energy consumption and GDP. The Shandong Peninsula is the largest resource consumption megalopolis in China. Its energy resource output accounts for a much larger share of the country than its reserves, and its energy extraction intensity far exceeds the national average. As a result, the rapid consumption of energy seriously threatens the sustainable use of resources. The energy intensity of JingJinJi, which follows closely behind, is also greater than the Chinese average, but already has been controlled into a declining phase. In addition, the national average curve shows that the value of energy consumption per capita starts to decline when the GDP per capita is 10,000 USD, as in the case of the environmental Kuznets curve [57]. The results of the third economic census in 2010 showed that the energy consumption intensity of the transportation, storage and postal industries was 1.35 tons of standard coal per 10,000 yuan, which has surpassed industry to become the sector with the highest energy consumption intensity [58]. Therefore, in the Yangtze River Delta and Pearl River Delta regions where these industries are advanced, causing their energy intensity continues to rise and even grow faster. In contrast, the pressure on water consumption has improved when the GDP reaches $7000-10000 per capita in both China and its four megalopolises. Moreover, except for the Yangtze River Delta, the intensity of water resources in the other three megalopolises is lower than or close to the national average.

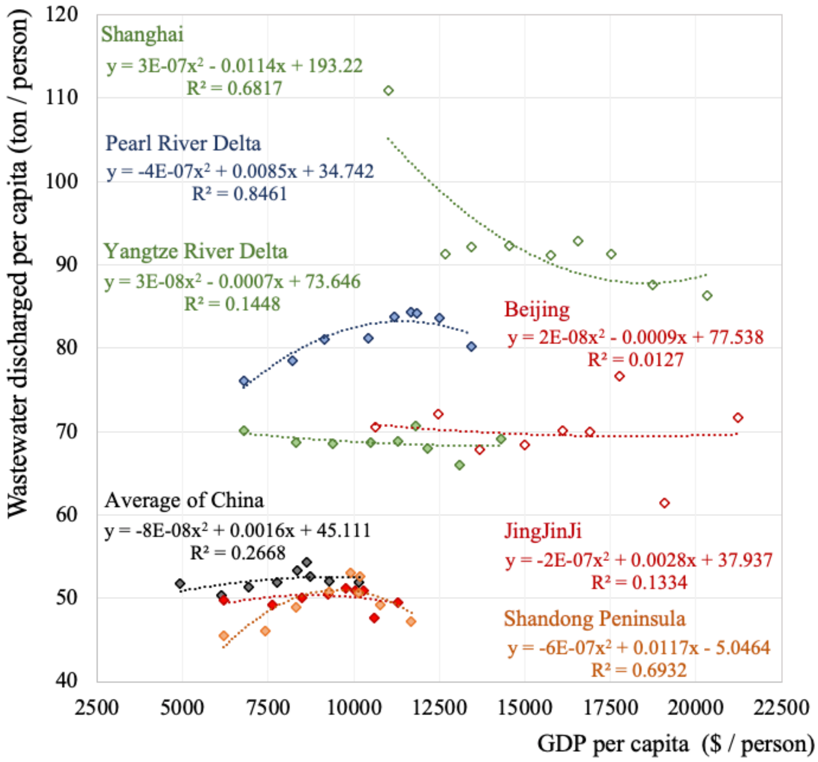


(1) Energy consumption per unit of GDP

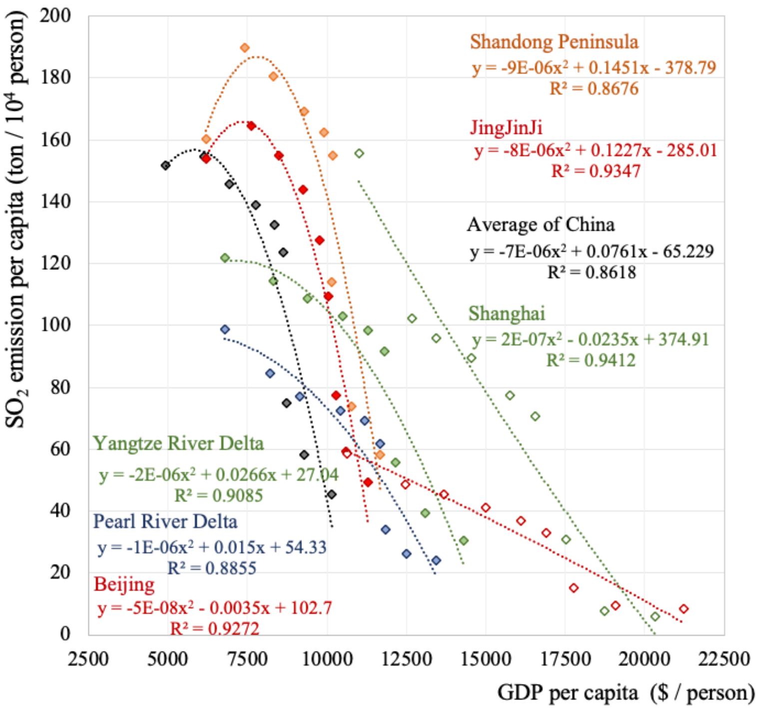


(2) Water consumption per unit of GDP.

Fig. 3-12 The trend of resource consumption in China (each point represents an average value of the variable for the cities in that group for each year in the data set from 2010 to 2018)



(1) Wastewater discharged per unit of GDP



(2) SO_2 emission per unit of GDP.

Fig. 3-13 The trend of environmental pollution in China (each point represents an average value of the variable for the cities in that group for each year in the data set from 2010 to 2018)

Environmental pollution (Fig. 3-13)

Rapid urbanization and unprecedentedly wide development of the built environment have caused serious pollution and a highly compromised associated environment. The Chinese government's policy to address water quality issues relies heavily on strengthening monitoring capacity and enforcement mechanisms. The Technical Policy Provisions for Water Pollution Prevention and Control were enacted as early as 1986, and the Water Pollution Law enacted in 2008 sought to improve the effectiveness of earlier legislation by increasing penalties [59]. When the GDP reaches about $10000 dollars per capita, wastewater discharge intensity begins to decline in most regions of China. Although the national average wastewater discharge intensity is low, the wastewater discharge intensity remains high in the Yangtze River Delta and the Pearl River Delta, especially in large coastal cities. The JingJinJi and Shandong Peninsula megalopolis with more inland cities have better sewage control than the national average. In addition, having the largest coal-fired power generation capacity in the world, China was the biggest emitter for SO_2 until about a decade ago. Thus, China has made tremendous efforts to control the emission of harmful substances such as SO_2, NOx, soot and dust, including the implementation of testing and strict management measures, and the installation of treatment facilities, etc. Especially in Yangtze River Delta and Pearl River Delta, the air pollution far lower than the domestic average. As the curve shows (Fig. 7-b), SO_2 emissions in China are in a stage of rapid decline. The peak emissions in almost all regions occurred when the GDP reached about $7,000 per capita. From the data released by Nasa in 2018 [60], out of the major emitters of SO_2, China and the United States of America have been able to reduce emissions rapidly, but China still remains the third largest emitter in the world.

3.4. Summary

Based on the statistical data from 2010 to 2018 published in the China Statistical Yearbooks, this chapter investigates the overview status and distributions of urbanization and its environment in China, which excluding five autonomous administrative divisions, Hong Kong, Macao, and Taiwan regions. This study uses descriptive statistics analysis methods and geographic distributions to preliminary understand the status of administrative population and land, and the distribution characteristics of the urban environment indicators. In particular, it focuses on the urbanization process with Chinese characteristics of governmental intervention, thus analyzing from the perspectives of both administrative divisions and megalopolises.

This research found that: (1) the urbanization process in China has evolved to the fourth stage and entered a period of accelerating urbanization from the national founding in 1949 till now, but still lag behind most developed countries. In this stage, the government started aiming at leading the work on greatly promoting the new urbanization development by improving the high-quality sustainable development. (2) The distribution of population changed from the east grew faster than the middle and the west to the south grew faster than the north of China, resulting in the polarization in many aspects within cities aggravated. (3) From the perspective of provincial-level administration divisions, the population and land size vary greatly. The population distribution in the coastal administrative regions is denser, while the land area in the inland administrative regions is larger. And (4) the rapid economic growth and urban construction in various regions of China coexist with tremendous pressure on environmental resources, which is not only complicated but also has significant distribution differences between regions.

Taking into account the above situation and constraints, all parties believe that (5) megalopolises should become the main platform for promoting urbanization and corresponding plans or policies began to study and formulate at this stage. From the perspective of approved 11 megalopolises by Chinese government, (6) The fourth largest megalopolises with the most development potential is the Yangtze River Delta, Pearl River Delta, Shandong Peninsula and JingJinJi megalopolis at present, which is the basis for choosing these top-four megalopolises as the cases of follow-up empirical studies. After a series of indicater analysis of statical data, the results show that (7) the performance of the four megalopolises in the aspects of urbanization economies, infrastructure development, and urban attractiveness is mostly higher than the national average, especially the Yangtze River Delta and Pearl River Delta. Moreover, (8) in terms of resource consumption and environmental pollution, different megalopolises are facing different environmental pressures. For example, the Shandong Peninsula and JingJinJi have higher energy intensity and severe air pollution, while the water use intensity and wastewater discharge in the Yangtze River Delta and Pearl River Delta are higher than the average level of China.

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Chapter 4. Measuring the Performance Urban Sustainability in Yangtze River Delta

4.1. Introduction

4.1.1.General information of urban environment in Yangtze River Delta

The Yangtze River Delta megapolis (geographic coordinates: 114°52′ E- 123°25′ longitude and 27°03’ N- 35°07′ N latitude), a key strategic developmental region, is considered as one of the world’s six largest megalopolises [1]. The total area is 358,000 km^2, located in the lower reaches of the Yangtze River in China, adjacent to the Yellow Sea and the East China Sea. The Yangtze River Delta urban agglomeration was gradually formed on the basis of the Shanghai Economic Zone established in 1982 [2,3] (Fig. 4-1). Expanded from 14 cities at the beginning of the implementation of the guiding policy to 41 cities in 2019, including Shanghai and all 11 cities Zhejiang Province, 13 cities in Jiangsu, and 16 cities in Anhui Province [4], which is the study area of this chapter (Table. 4-1). Many scholars who study the Yangtze River Delta continue to use the previous planning region [5–7], so that the research literature of urban agglomerations based on the latest scope of 41 cities is relatively lacking.

Shanghai, Zhejiang, Jiangsu, and Anhui in the Yangtze River Delta region each have their own advantageous industries and are relatively complementary, such as the financial economy in Shanghai, the manufacturing in Jiangsu Province, the service industry in Zhejiang Province, and traditional heavy industry in Anhui Province. For these reasons, the region has become the fastest-growing economies in China in recent years with a GDP of $13,089 per capita. It dominates the development of the domestic Yangtze River Economic Belt shown in Fig. 4-1. Besides, it can be seen as an international gateway on the eastern coast of China to connect with the Asia-Pacific region, which plays an important role with Japan and Korea for Yellow Sea Rim economic cooperation.

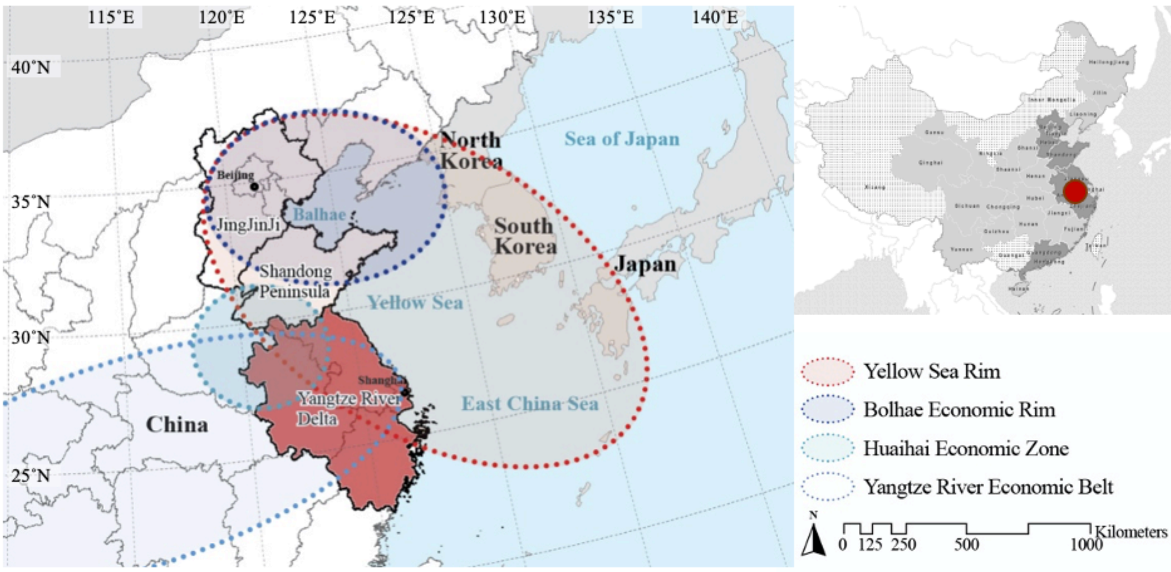


Fig. 4-1 Geography of the Yangtze River Delta megapolis

Table 4-1 Outline and classification of 41 cities in Yangtze River Delta in 2018

Provincial-level administrative divisions	**Cities in Yangtze River Delta**	**Urban population (10^4 persons)**	**Urbanization rate (%)**	**Total population (10^4 persons)**	**Land area (km^2)**	**Density (persons /km^2)**	**GDP ($ / person)**	**GDP (10^9 $)**	**Length of coastline (km)**
Shanghai	-	2135.54	88.10	2424.00	6341	3823	20334.53	492.91	213.05
Zhejiang Province	Hangzhou	758.98	77.40	980.60	16850	582	20778.90	203.76	20
	Ningbo	597.93	72.90	820.20	9816	836	19760.22	162.07	1562
	Jiaxing	311.92	66.00	472.60	12110	390	15548.85	73.48	121
	Huzhou	192.21	63.50	302.70	4223	717	13548.60	41.01	-
	Shaoxing	335.33	66.60	503.50	5820	865	16226.98	81.70	40
	Zhoushan	79.88	68.10	117.30	8279	142	16930.71	19.86	2444
	Wenzhou	647.50	70.00	925.00	10942	845	9793.58	90.59	355
	Jinhua	379.39	67.70	560.40	8845	634	11035.62	61.84	-
	Quzhou	128.12	58.00	220.90	1459	1514	10041.06	22.18	-
	Taizhou	386.76	63.00	613.90	10050	611	11976.61	73.52	745
	Lishui	134.77	61.29	219.90	17275	127	9566.05	21.04	-
Jiangsu Province	Nanjing	695.99	82.50	843.62	6587	1281	22921.40	193.37	-
	Wuxi	501.63	76.30	657.45	4627	1421	26242.03	172.53	-
	Xuzhou	573.01	65.10	880.20	11765	748	11575.65	101.89	-
	Changzhou	342.82	72.50	472.86	4372	1082	22488.46	106.34	-
	Suzhou	815.92	76.10	1072.17	8657	1239	26162.35	280.50	-
	Nantong	490.50	67.10	731.00	10549	693	17387.70	127.10	206
	Lianyungang	282.95	62.60	452.00	7615	594	9248.99	41.81	283
	Huai'an	307.32	62.40	492.50	10030	491	11028.93	54.32	-
	Yancheng	460.80	64.00	720.00	16931	425	11285.32	81.25	582
	Yangzhou	304.03	67.10	453.10	6591	687	18195.98	82.45	-
	Zhenjiang	227.58	71.20	319.64	3840	832	19110.87	61.09	-
	Taiizhou	330.06	71.20	463.57	5787	801	19110.87	88.59	-
	Suqian	295.55	60.00	492.59	8524	578	8422.62	41.49	-
Anhui Province	Hefei	606.31	74.97	808.74	11445	707	14589.68	117.99	-
	Huaibei	146.76	65.11	225.41	2741	822	6592.24	14.86	-
	Haozhou	214.78	41.01	523.72	8521	615	3678.26	19.26	-
	Suuzhou	242.82	42.74	568.14	9939	572	4327.90	24.59	-
	Bengbu	194.09	57.22	339.20	6026	563	7624.45	25.86	-
	Fuyang	355.29	43.29	820.72	10118	811	3233.60	26.54	-
	Huainan	223.71	64.11	348.95	5532	631	4898.60	17.09	-
	Chuzhou	219.78	53.42	411.42	13516	304	6605.35	27.18	-
	Liu'an	222.91	46.08	483.74	15451	313	4016.12	19.43	-
	Ma'anshan	159.51	68.25	233.71	4049	577	12378.85	28.93	-
	Wuhu	245.66	65.54	374.82	6026	622.00	13192.98	49.45	-
	Xuancheng	146.21	55.21	264.83	12313	215.09	7501.90	19.87	-
	Tongling	91.21	55.99	162.91	2923	557.41	11317.17	18.44	-

Chizhou	79.77	54.10	147.45	8399	175.56	7006.29	10.33	-
Anqing	230.91	49.22	469.13	13538	346.53	6165.23	28.92	-
Huangshan	72.41	51.46	140.71	9678	145.39	7266.64	10.22	-
Total of Yangtze River Delta	15168.65	67.31	22535	358100	629.30	14358.20	3235.66	6571.05
% of China (except autonomous and special administrative regions)	19.42	-	17.51	6.83	-	-	24.76	26.67

Although the Yangtze River Delta can be regarded as a model in all aspects of the quality of urban built environment, the extensive production methods and excessive consumption of resources and energy have made the environmental problems increasingly prominent, such as the expansion of urban acid rain, the deterioration of water quality in Yangtze River Basin, etc. (Liu et al., 2021; Wang et al., 2018; Zhang et al., 2021) Recently, relevant provinces and cities have formulated operable implementation plans and taken eco-environmental protection as one of the key contents. It provides reliable support for the overall coordination and ecological environmental protection in the Yangtze River Delta region. For example, the outline of the integrated regional development of the Yangtze River Delta issued in 2019 clarifies the requirements for the joint protection of the ecological environment.

4.1.2.The challenge of sustainable urbanization in Yangtze River Delta

The urbanization level of the Yangtze River Delta region was lower than the world average level before 2005 and then exceeded the world average level, showing a rapid growth trend. Researchers believe that during the period from 1989 to 2011, which entered the stage of rapid development, the opening up of cities drove the development of the entire regional economy. Large and medium-sized cities, especially the construction of new districts and the process of urbanization from top to bottom, are accelerating, and construction land is expanding rapidly.

Currently, the urbanization rate of that region reached 67.31% in 2018, and the population density reached 629.3 people per square kilometer [8]. There are 7 cities with net population inflows exceeding 1 million. It can be seen from the evolution of satellite images (Fig. 4-2) that the eastern coastal cities around Shanghai are densely populated. Due to the close ties between regions and the support of the integration policy, the population gradually gathered in the inland areas and formed dotted groups. Although the level of urbanization in the Yangtze River Delta is relatively high, there are still obvious problems of uneven regional economic development and excessive concentration of resource elements. Moreover, with the rapid urban development, the ecological environment of the Yangtze River Delta is seriously threatened. There are still large differences in economic and social conditions, natural resources, and climatic conditions among provinces and cities, which are with different abilities and levels of pollution prevention and control.

The Yangtze River Delta is still one of the regions with the most rapid urban development in China in the future because of the outstanding regional advantages, excellent natural endowment, and strong comprehensive economic strength. For a future period, the Chinese government gave it a development position for rapid economic growth and continued opening up. Therefore, whether regional cities can continue to develop sustainably is undoubtedly an unavoidable issue to consider. All cities in the Yangtze River Delta will face severe challenges in both urban construction and environmental protection in order to make the urbanization process sustainable.

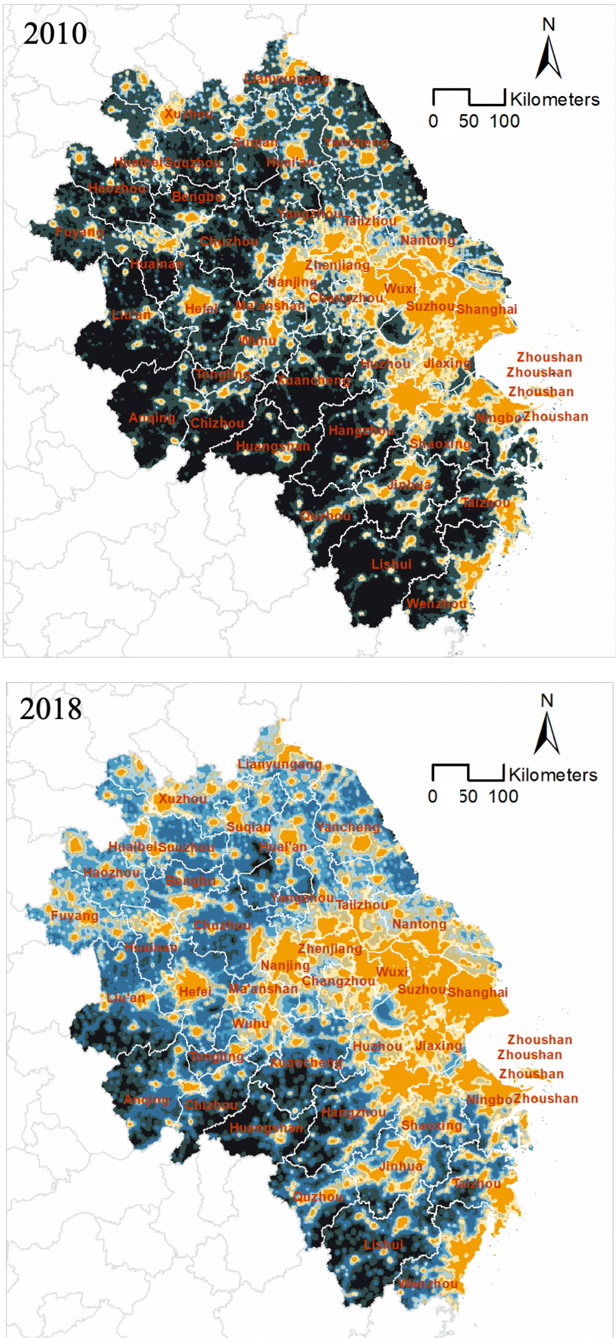


Fig. 4-2 The evolution of urbanization in Yangtze River Delta from 2010 to 2018. (Notes: the degree of urban population is represented by the change of color. The deeper yellow color represents higher urbanization, and the deeper blue color represents lower urbanization.)

4.2.Results presentation and interaction mechanism analysis in Yangtze River Delta

4.2.1.Overall results for each city

According to the urban sustainability assessment and calculation process provided above, all evaluation scores for 41 cities of the Yangtze River Delta in 2010-2018 were obtained. The box chart in Figures 4 respectively shows the ranges of the Qu, Pu, and Su values. The list of cities is arranged from left to right according to the level of urbanization from high to low. It can be roughly seen that (1) cities with a high urbanization rate have a relatively high quality of the built environment. (2) The environmental pressure gap between different cities is relatively obvious, but basically showing a trend opposite to the performance of the quality of built environment (3) the sustainable development level of each city in the region are different.

Specifically, from Fig. 4-3 (Qu), the index of Qu for the 41 cities ranged from 0.022 to 0.658. The compound annual growth rate (CAGR) in the past 9 years is between 0.61% and 19.14%. The city with the best performance but the least improvement was Shanghai, while Lu'an City had the lowest score in 2010, but the largest increase in the later period. Some backward cities such as Haozhou, Suzhou, Fuyang and Anqing have also changed significantly, with CAGR values exceeding 10%. The Fig. 4-3(Pu) shows that the index of Pu ranged from 0.020 to 0.743. These two values both appeared in 2010 and are the scores of Haozhou and Ma'anshan respectively, and they are still at the lowest and highest environmental pressure in the entire region. The range of CAGR is between -8.73% to 8.84% from 2010 to 2018. The growth rate of 19 cities is negative, which means that environmental pressure has eased. In addition to Haozhou, the cities with greater environmental improvement include Zhoushan, Tongling, Hangzhou. Those cities have been awarded "Chinese Garden Cities" for their rich natural heritage and outstanding contributions to environmental governance. But the environment of 22 cities has been adversely affected with CAGR values over 0. Especially Ma'anshan, Yancheng, Taiizhou and Lianyungang have serious environmental degradation mainly caused by the traditional heavy industries. From the comprehensive variation of Su in Fig. 4-3(Su), the lowest score is 0.259 that got by Ma’anshan City in 2010. And the highest level of sustainability is Zhoushan City with the value of 3.864 in 2018, which is also the city with the greatest degree of change in the whole region. In addition, Suuzhou, Hangzhou, and Wenzhou have also improved significantly. However, cities such as Ma'anshan, Yancheng, Tongling, Chizhou, Quzhou, and Wuhu are in a more serious state of unsustainability, and their situation have hardly changed in 9 years.

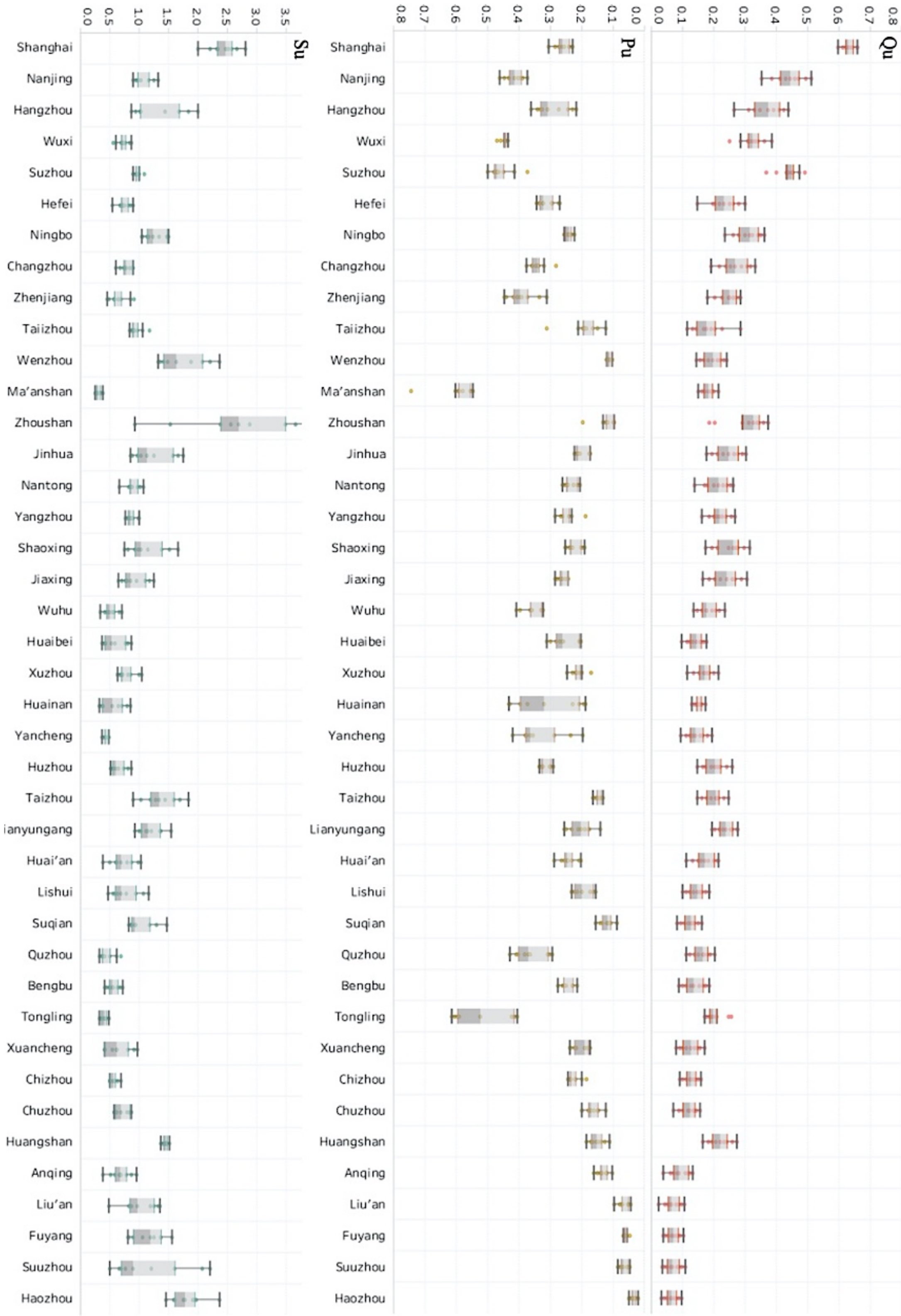
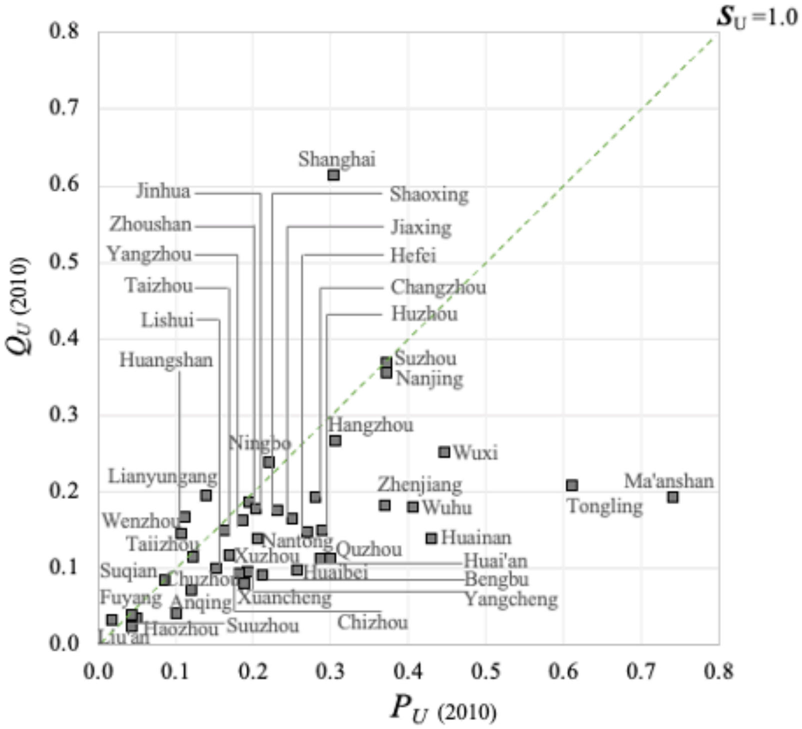


Fig. 4-3 The scores of Qu, Pu and Su of 41 cities in Yangtze River Delta from 2010 to 2018 measured by urban sustainability assessment system.

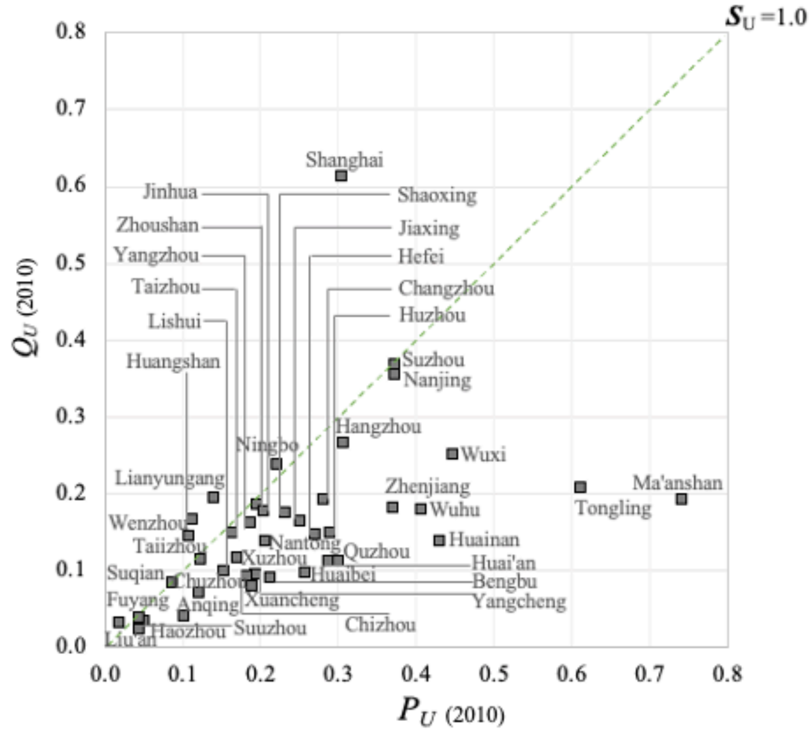
Fig. 4-4 presents the urban development states of 41 cities in the Yangtze River Delta from 2010 to 2018. It can be seen that: (1) The number of cities in the state of sustainable development increased from 6 cities in 2010 to 22 in 2018, with 19 cities remaining still in an unsustainable state of development. (2) The coastal cities in the Yangtze River Delta have better sustainability and showing significant geographic variation. Among them, in 2010, with the exception of Huangshan, the other 5 sustainable cities were all coastal cities. Then in 2018, among the 11 coastal cities in the Yangtze River Delta, only Yancheng has not yet reached a sustainable state because of large amount of industrial energy consumption. (3) From the perspective of city size, the sustainability level of mega cities (urban population ≧ 10 million) and large cities (10 million > urban population ≧ 5 million) is higher than that of small (urban population < 1 million) and medium-sized (5 million > urban population ≧ 1 million) cities. Only Huangshan, Haozhou and Lianyungang were the only small and medium-sized cities that reached a sustainable level in 2010. The remaining 32 cities of the same size have higher environmental pressure growth rates. In 2018, with the exception of Hefei and Wuxi, the remaining super-large cities, Shanghai and six large cities, all reached and mostly had a high degree of sustainability. (4) There are different development paths for cities to improve the level of sustainability, which can be roughly divided into three modes: a. priority to reduce Pu and control Qu: mainly cities with initial Pu scores greater than 0.5, such as Tongling and Ma'anshan; b. Prioritize to improvement Qu and control Pu: most of them are cities with an initial Qu scores of less than 0.2 and the Pu scores of less than 0.5, such as Nantong, Xuzhou, Changzhou, etc; and c) both improving city quality and reducing environmental pressure: mostly cities with initial Qu scores greater than 0.2 and Pu scores less than 0.5, such as Shanghai, Hangzhou, and Nanjing etc.



2010

Classification		Small-sized cities	Medium-sized cities	Large cities	Mega cities	Number of cities	
Su < 1.0 (Qu< Pu)	Coastal	Zhoushan	Taizhou, Shaoxing, Nantong, Jiaxing, Yancheng	Hangzhou	-	7	35
	Inland	Chizhou, Quzhou, Tongling, Ma'anshan	Suqian, Taiizhou, Yangzhou, Jinhua, Fuyang, Changzhou, Xuzhou, Lishui, Chuzhou, Wuxi, Hefei, Huzhou, Liu'an, Zhenjiang, Yancheng, Wuhu, Xuancheng, Bengbu, Huai'an, Anqing, Huaibei, Huainan	Suzhou, Nanjing	-	28	
Su ≥ 1.0 (Qu≥ Pu)	Coastal	-	Haozhou, Lianyungang	Wenzhou, Ningbo	Shanghai	5	6
	Inland	Huangshan	-	-	-	1	

(a) The regression result and the corrosponding city list of 2010



2010

Classification		Small-sized cities	Medium-sized cities	Large cities	Mega cities	Number of cities	
Su < 1.0 (Qu< Pu)	Coastal	Zhoushan	Taizhou, Shaoxing, Nantong, Jiaxing, Yancheng	Hangzhou	-	7	35
	Inland	Chizhou, Quzhou, Tongling, Ma'anshan	Suqian, Taiizhou, Yangzhou, Jinhua, Fuyang, Changzhou, Xuzhou, Lishui, Chuzhou, Wuxi, Hefei, Huzhou, Liu'an, Zhenjiang, Yancheng, Wuhu, Xuancheng, Bengbu, Huai'an, Anqing, Huaibei, Huainan	Suzhou, Nanjing	-	28	
Su ≥ 1.0 (Qu≥ Pu)	Coastal	-	Haozhou, Lianyungang	Wenzhou, Ningbo	Shanghai	5	6
	Inland	Huangshan	-	-	-	1	

(b) The regression result and the corrosponding city list of 2018

Fig. 4-4 The regression trends of different types of cities from 2010 to 2018

Note: (1) Su < 1.0 (Qu < Pu) means the city is in a barely or seriously unsustainable urbanization process. The increasing pace of urban environmental pressure (Pu) is faster than the improved pace of urban built environment quality (Qu). Su ≥ 1.0 (Qu ≥ Pu) means the city is in a basic or highly sustainable urbanization process. The increasing pace of urban environmental pressure (Pu) is slower than the improved pace of urban built environment quality (Qu). (2) Small cities (urban population < 1 million); Medium-sized cities (5 million > urban population ≧ 1 million); Large cities (10 million > urban population ≧ 5 million); Mega cities (urban population ≧ 10 million)

4.2.2.Coupling interaction mechanism between Qu and Pu

Many studies have shown that the quality of the urban built environment and environmental pressure have a certain mutual coupling mechanism. The relationship between the two dimensions (Qu and Pu) is conducive to clarifying their logic of changes, the strength of the effect and predicting the future direction of urban development. General linear regression is a commonly used tool, but it has certain limitations because it cannot easily match any nonlinear data set. In order to accurately find the relationship between Qu and Pu, we chose the multiple regression model to fit scatter plots of the 9-year data set of each city into a single trend line. Among them, Qu is the independent variable, and Pu is the dependent variable. After the regression, an F test is required and the result with the p-value lower than 0.1 is considered to be statistically significant.

Table 4-2 provides the estimation result with a regression equation for the 41 cities of the Yangtze River Delta region. 82.9% of the cities show a significant relationship between Qu and Pu, and only 7 cities (Shanghai, Wuxi, Ma'anshan, Huainan, Tongling and Xuancheng) show no significant relationship ($p \geqq 0.05$). Five different types of coupling relationships were explored as follows: (1) Inverted U-shaped relationship: The environmental pressure of 19 cities increased rapidly with the continuous improvement of Qu at first. Then, thanks to the implementation of key environmental protection policies and the introduction of technologies such as energy-saving and emission reduction, the pressure on the environment was controlled and even entered a benign state of gradual decline while improving quality. In some cities with a high level of urbanization or strong economic strength such as Hangzhou, Nanjing, Jiaxing, etc., the turning point of environmental change in these cities is usually in the mid-term of the "12th Five-Year Plan" around 2013. However, some small and medium-sized cities with relatively backward economies, such as Chizhou and Fuyang, have controlled their environmental problems to a certain extent in recent years. (2) Negative linear relationship: Zhoushan and Taizhou have made a lot of efforts in environmental governance and protection in the process of urban development so that environmental pressure has been continuously improved. (3) Inverted S-shaped relationship: This means that although these 7 cities (Ningbo, Xuzhou, Huzhou, Lianyungang, Lishui, Quzhou and Bengbu) have reduced their environmental load around 2013, they have shown a rebound trend in recent years. If environmental issues are ignored, the environment will deteriorate again as the city develops in the future. (4) Positive linear relationship: These four cities (Changzhou, Taiizhou, Huangshan and Liu'an) are particularly worthy of attention in the entire region. Environmental pressure continues to increase with the quality of urban development. It is very necessary to attach importance to environmental governance and take effective control measures Especially in Changzhou City, the slope value of the regression equation is relatively large. (5) U-shaped relationship: with urban construction, the environmental pressure first decreases and then increases. Therefore, Huai'an City also needs to further strengthen its attention to resource consumption and environmental pollution.

Table 4-2 The coupling interaction mechanism between *f*(Q) and *g*(P) by regression analysis of the 41 cities in Yangtze River Delta

Cities	AIC	BIC	R^2	Adjusted R^2	Std. error	F	p[1] value	Regression equation	Description	Inflection year
Zhenjiang	-39.077	-38.485	0.785	0.713	0.024	10.938	0.010**	$g(P) = -1.13+13.912 f(Q)-30.849 f(Q)2$	Inverted-U-shaped relationship	2013
Wenzhou	-75.603	-75.011	0.863	0.817	0.003	18.912	0.003**	$g(P) = -0.085+2.246 f(Q)-6.154 f(Q)2$		2013
Jinhua	-55.291	-54.700	0.840	0.786	0.010	15.725	0.004**	$g(P) = -0.107+3.047 f(Q)-7.107 f(Q)2$		2013
Nantong	-51.108	-50.516	0.745	0.660	0.012	8.768	0.017*	$g(P) = 0.045+1.443 f(Q)-2.485 f(Q)2$		2017
Yangzhou	-54.229	-53.638	0.893	0.858	0.010	25.163	0.001**	$g(P) = -0.518+6.59 f(Q)-13.763 f(Q)2$		2014
Shaoxing	-48.365	-47.773	0.699	0.599	0.014	6.973	0.027*	$g(P) = -0.086+2.981 f(Q)-6.718 f(Q)2$		2013
Jiaxing	-52.360	-51.768	0.599	0.466	0.012	4.488	0.044*	$g(P) = -0.01+2.514 f(Q)-5.581 f(Q)2$		2013
Huaibei	-42.313	-41.721	0.904	0.757	0.020	13.443	0.006**	$g(P) = -0283+9.281 f(Q)-37.470 f(Q)2$		2013
Yancheng	-40.940	-40.348	0.937	0.916	0.022	44.629	0.000***	$g(P) = -0.446+8.938 f(Q)-23.491 f(Q)2$		2018
Suqian	-54.112	-53.520	0.790	0.720	0.011	11.287	0.009**	$g(P) = -0.309+7.129 f(Q)-28.437 f(Q)2$		2014
Chizhou	-64.816	-64.224	0.938	0.917	0.006	45.452	0.000***	$g(P) = -0.191+5.991 f(Q)-20.86 f(Q)2$		2017
Chuzhou	-43.511	-42.920	0.575	0.433	0.019	4.059	0.047*	$g(P) = -0.047+3.27 f(Q)-11.773 f(Q)2$		2018
Anqing	-55.004	-54.412	0.768	0.690	0.010	9.911	0.013*	$g(P) = -0.047+3.27 f(Q)-11.773 f(Q)2$		2016
Fuyang	-78.426	-77.834	0.878	0.837	0.003	21.597	0.002**	$g(P) = 0.023+0.855 f(Q)-4.177 f(Q)2$		2017
Suuzhou	-54.545	-53.953	0.622	0.496	0.010	4.935	0.049*	$g(P) = 0.021+1.798 f(Q)-14.819 f(Q)2$		2013
Haozhou	-69.686	-69.095	0.837	0.782	0.004	15.386	0.004**	$g(P) = -0.005+0.907 f(Q)-4.048 f(Q)2$		2017
Nanjing	-43.393	-42.801	0.681	0.575	0.019	6.405	0.032*	$g(P) = -1.401+8.507 f(Q)-9.831 f(Q)2$		2014
Hangzhou	-38.921	-38.330	0.837	0.782	0.024	15.385	0.004**	$g(P) = -0.776+6.871 f(Q)-10.571 f(Q)2$		2013
Suzhou	-48.447	-47.855	0.896	0.861	0.014	25.812	0.001**	$g(P) = -2.708+14.088 f(Q)-15.577 f(Q)2$		2014
Zhoushan	-46.309	-45.915	0.744	0.707	0.017	20.295	0.003**	$g(P) = 0.244-0.399 f(Q)$	Negative linear relationship	-
Taizhou	-69.184	-68.789	0.834	0.811	0.005	35.271	0.001**	$g(P) = 0.209-0.310 f(Q)$		-
Ningbo	-62.032	-61.243	0.800	0.680	0.007	6.663	0.034*	$g(P) = -3.236+33.841 f(Q)-108.225 f(Q)2+113.959 f(Q)3$	Inverted S-shaped relationship	2013&2017
Xuzhou	-52.968	-52.179	0.832	0.731	0.011	8.248	0.022*	$g(P) = -1.023+19.972 f(Q)-103.313 f(Q)2+171.452 f(Q)3$		2013&2017
Huzhou	-58.312	-57.523	0.870	0.792	0.008	11.129	0.012*	$g(P) = -2.073+34.364 f(Q)-160.407 f(Q)2+243.486 f(Q)3$		2013&2017
Lianyungang	-41.630	-40.841	0.769	0.701	0.021	9.960	0.012*	$g(P) = -2.238+20.429 f(Q)-42.138 f(Q)2$		2014
Lishui	-51.305	-50.516	0.911	0.858	0.012	17.138	0.005**	$g(P) = -2.967+66.422 f(Q)-448.392 f(Q)2+977.046 f(Q)3$		2013&2017
Quzhou	-36.985	-36.196	0.824	0.718	0.027	7.800	0.025*	$g(P) = -1.674+32.227 f(Q)-153.237 f(Q)2+206.773 f(Q)3$		2013&2018
Bengbu	-58.866	-58.077	0.893	0.829	0.008	13.884	0.007**	$g(P) = 0.314+3.964 f(Q)-43.875 f(Q)2+130.881 f(Q)3$		2015&2018
Hefei	-45.696	-45.301	0.674	0.610	0.017	13.536	0.008**	$g(P) = 0.199+0.482 f(Q)$	Positive linear relationship	-
Changzhou	-43.048	-42.654	0.525	0.457	0.020	7.746	0.027*	$g(P) = 0.228+0.42 f(Q)$		-
Taiizhou	-41.206	-40.811	0.842	0.819	0.022	37.226	0.000***	$g(P) = 0.025+0.914 f(Q)$		-
Huangshan	-66.987	-66.593	0.954	0.954	0.005	145.194	0.000***	$g(P) = =0.012+0.639 f(Q)$		-
Liu'an	-51.935	-51.541	0.553	0.489	0.012	8.657	0.022*	$g(P) = 0.034+0.471 f(Q)$		-
Huai'an	-48.263	-47.671	0.777	0.703	0.015	10.479	0.011*	$g(P) = 0.447-1.811 f(Q)+3.471 f(Q)2$	U-shaped relationship	2017
Shanghai	-36.612	-36.020	0.079	-0.228	0.028	0.258	0.781	$g(P) = -6.08+20.314 f(Q)-16.251 f(Q)2$	No significant relationship	2012
Wuxi	-54.620	-53.831	0.437	0.098	0.010	1.291	0.373	$g(P) = -2.192+25.522 f(Q)-80.806 f(Q)2+83.898 f(Q)3$		2011&2017
Ma'anshan	-20.837	-20.246	0.041	-0.279	0.067	0.128	0.882	$g(P) = -0.292+10.043 f(Q)-28.085 f(Q)2$		2016
Wuhu	-37.896	-37.501	0.271	0.167	0.027	2.608	0.150	$g(P) = 0.446-0.472 f(Q)$		-
Huainan	-13.275	-12.684	0.273	0.031	0.102	1.127	0.384	$g(P) = -5.424-65.303 f(Q)+206.579 f(Q)2$		2017
Tongling	-17.763	-17.171	0.466	0.287	0.079	2.614	0.153	$g(P) = -2.293+25.064 f(Q)-54.496 f(Q)2$		2012
Xuancheng	-37.406	-36.617	0.418	0.068	0.026	1.195	0.401	$g(P) = -0.342+12.661 f(Q)-89.958 f(Q)2+195.255 f(Q)3$		2012&2017

4.3.Spatio-temporal characteristics of urban sustainability in Yangtze River Delta

4.3.1.Spatio-temporal variation patterns of results

To reveal the variation pattern of sustainability in the Yangtze River Delta, Arc-GIS 10.3 was applied to visualize spatio-temporal data of 41 cities in 2010, 2014 and 2018. Overall, the distribution of Qu, Pu and Su in this region is obviously unbalanced and shows the distinctly spatial different characteristics in geography.

As shown in Fig. 4-5(Qu), the areas with the better quality of urban built environment were initially concentrated around Shanghai with an advantageous location. Subsequently, the positive effects of radiation from the core city of Shanghai have gradually driven the improvement of the quality level in the eastern surrounding cities. But the western and northern inland cities are still lagging behind. This spatial distribution feature is consistent with the previous urbanization evolution process map to a certain extent. Shanghai's positioning as an international metropolis made it the first to gather more population and develop into the headquarters city of the region. After that, the region promoted policies such as industrial alliances and united Hangzhou and Nanjing, which are more economically powerful. As a result, the core areas of urbanization have shifted from coastal areas to inland areas, and the industrialization and infrastructure construction in these areas have also been developed simultaneously. At present, the spatial pattern of Nanjing-Shanghai-Hangzhou coordinated development was roughly formed. In the future, a coordinated strategy can be further implemented to develop Nanjing and Hefei as core cities to support the development of the western and northern regions. And Hangzhou can become a core city, combining Ningbo, Shaoxing and Jinhua to drive the highly integrated development of cities in the southern region.

Fig. 4-5(Pu) shows the distribution patten of urban environmental pressure. We found that the most severely affected areas were first distributed in the central (centered on Ma'anshan, Wuhu, and Tongling) and the southern inland areas (including Hangzhou and Quzhou). Cities in central area are particularly dependent on the growth of capital-intensive industries and the development of transportation to meet their geographic needs and industrial development goals. In addition, the construction of supporting facilities such as some large factories and industrial parks has also led to an increase in energy consumption and waste emissions. Due to the rapid urbanization of cities in the east, they have to rely on labor-intensive manufacturing to maintain population growth and meet economic and infrastructure needs. As a result, over-utilization of energy and serious pollution discharge have been caused. After that, environmental problems in the northern region began to emerge and the environmental pressure in the southern region eased. This is due to the implementation of targeted environmental improvement policies in the southern region around 2014, such as the remediation of heavily polluting and energy-intensive industries in Jinhua, air pollution prevention and control policy in Hangzhou, and drinking water source protection policy in Quzhou etc.

Environmental maintenance and governance in the northwest and southeast regions are better in the Yangtze River Delta.

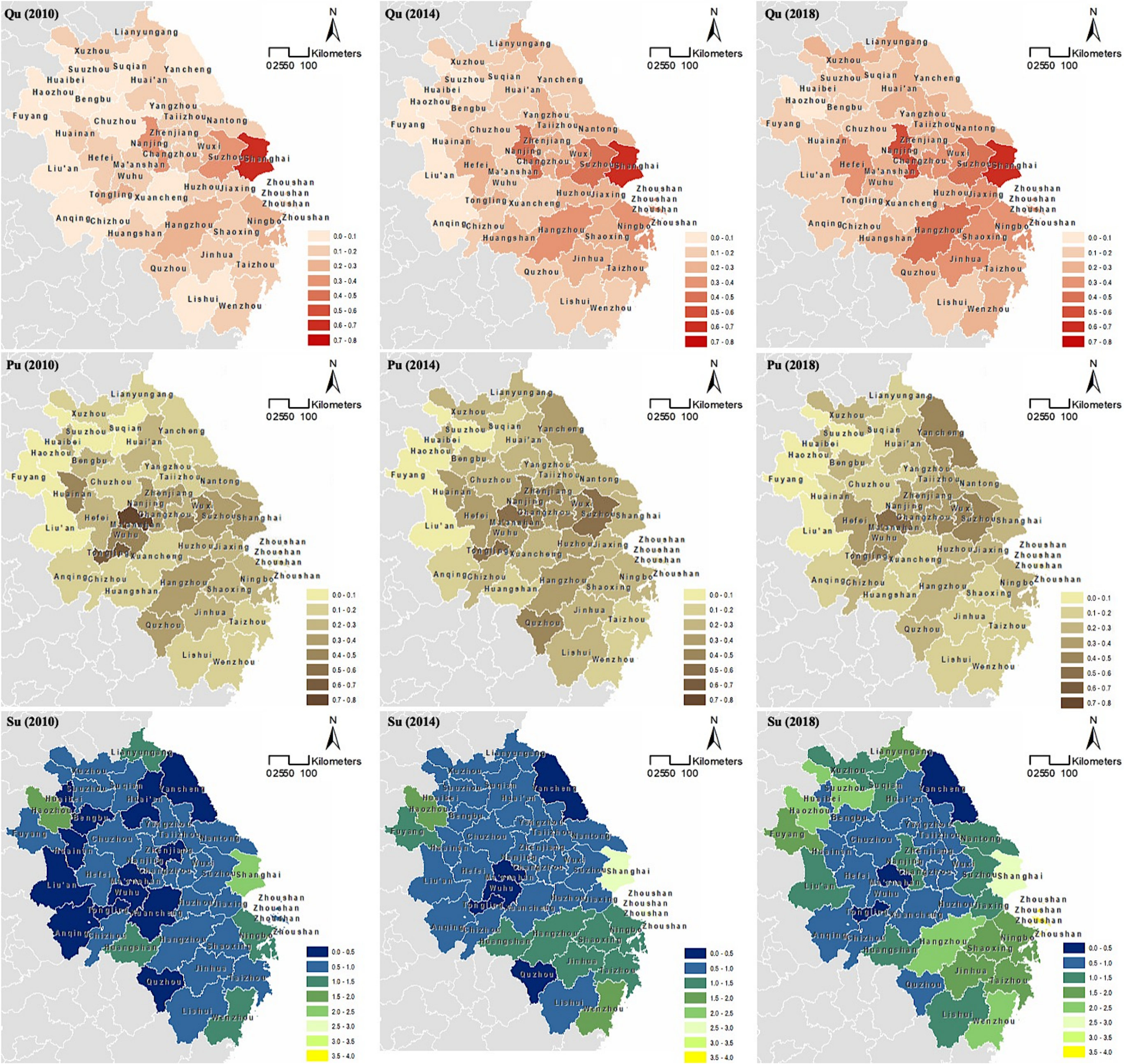


Fig. 4-5 The spatio-temporal variation pattern in the Yangtze River Delta from 2010 to 2018.

The spatial characteristics of the comprehensive evaluation results of urban sustainability are reflected in Fig. 4-5(Su). Generally speaking, the spatial distribution characteristics of sustainability in the northern Yangtze River Delta show a trend of developing from the periphery of the region to the inner cities. These sustainable cities are small and medium-sized cities with slow and steady growth. Although there is no high-quality urban construction environment, they have maintained a good urban environment. And the southern region is characterized by a gradual spatial evolution of sustainable development from the coast to the inland. These sustainable cities have made effective efforts in improving the quality of construction and establishing environmental maintenance mechanisms, compared with unsustainable cities in the north. At first, only a sporadic city located on the edge of the region entered a sustainable state in 2010. Then the development of cities in the southeast began to show a good momentum, forming a coordinated sustainable city group. In addition, the neighboring city of Haozhou in the northeastern region of Fuyang is the only sustainable urban group in the northern region. At present, most cities in the northern area are still in an unsustainable state, especially the cities partially surrounding Nanjing. Therefore, regional development policies need to be tilted towards these cities in the future in order to alleviate the negative impact of regional development imbalances.

4.3.2.Evolution track characteristics of regional patterns

The spatial track of the evolution of results (Fig.4-6, Table 4-3) in the Yangtze River Delta over the 9-year period was analyzed in this study, using the geographic distributions tool of weighted mean center and standard deviation ellipse, and the corresponding results are presented in Figure 2 and Table. On the whole, the mean centers of the evaluation results of Qu, Pu and Su have offset by different distances from the geographic center. It means that the regional development of the Yangtze River Delta is still in an unbalanced state. The mean center of Pu is located in Nanjing same as the geographic center, while the centers of Qu and Su are located in Changzhou City. The mean center of Qu moved closer to the geometric center but was 58.72km away from that and shortened 12.07km in 9 years. However, the mean centers of Pu and Su are far away from the geometric center with a distance of 20.04km and 39.46km respectively in 2018. And their increased distances during the period are 1.23km and 7.71km. It means that the regional imbalance is increasing.

From the shape of standard deviation ellipses, the main axis of all ellipses is basically the same, located in the southeast-northwest direction, but the changes of the ellipses are different. Although the angles of the three ellipses are approximately 135°, the major axis of the Qu and Su and the minor axis of Qu and Pu have been lengthened, indicating that heterogeneous spatial changes in the Yangtze River Delta region occurred over time. Moreover, the annual migration speeds are about the same that the mean center of Pu (V_P=1.87 km/year) has the fastest moving speed, followed by that of Su (V_S=1.77 km/year) and Qu (V_Q=1.51 km/year). It shows that the Yangtze River Delta region is developing towards an unbalanced state at a relatively fast speed. This is mainly due to the increasing environmental pressure of northern cities, which will lead to a gradual increase in the sustainability gap between northern and southern cities. Therefore, it is necessary to adopt more effective strategies to accelerate the realization of the balanced development of the whole region, especially to give priority to deal with the environmental problems in the northern cities.

Table 4-3 The detailed parameter of mean center and standard deviation ellipse

Weighted field	Year	Mean center		Standard Deviational Ellipse			
		Degree of longitude	Degree of latitude	Standard distance (km)	Angle of Rotation	Radius of major axis(km)	Radius of minor axis(km)
Geometric center	-	118.93	31.5	-	138.53	288.94	176.53
Quality of built environment (Qu)	2010	119.53	31.28	70.79	138.36	255.46	166.37
	2011	119.52	31.29	69.53	138.37	258.22	167.23
	2012	119.52	31.29	69.14	137.53	261.24	167.58
	2013	119.49	31.3	65.85	137.26	263.33	168.26
	2014	119.48	31.29	65.36	137.45	263.99	168.42
	2015	119.47	31.3	64.43	138.01	265.94	168.15
	2016	119.45	31.3	61.4	138.38	267.12	168.08
	2017	119.44	31.31	60.28	138.58	267.7	168.19
	2018	119.43	31.32	58.72	138.29	267.6	168.51
Environmental pressure (Pu)	2010	119.06	31.4	18.81	136.64	243.4	162.13
	2011	119.06	31.4	17.88	141.46	247.38	162.93
	2012	119.05	31.43	15.55	142.44	247.85	165.02
	2013	119.05	31.45	14.77	142.71	249.73	165.84
	2014	119.08	31.47	17.01	145.03	247.12	166.32
	2015	119.08	31.48	17.29	132.56	321.2	175.67
	2016	119.09	31.49	17.58	145.13	242.36	169.38
	2017	119.1	31.49	18.34	143.62	240.63	169.13
	2018	119.11	31.52	20.04	144.15	238.38	169.58
Urban sustainability (Su)	2010	119.21	31.44	31.75	138.46	310.82	179.21
	2011	119.27	31.37	40.27	134.49	308.57	182.26
	2012	119.3	31.34	45.07	131.56	314.37	180.72
	2013	119.26	31.34	41.26	131.56	314.37	180.72
	2014	119.28	31.29	45.57	131.17	319.19	177.79
	2015	119.3	31.3	46.61	132.56	321.2	175.67
	2016	119.3	31.27	48.02	133.04	320.79	175.75
	2017	119.26	31.31	42.68	133.86	322.85	175.75
	2018	119.23	31.31	39.46	133.58	326.71	175.41

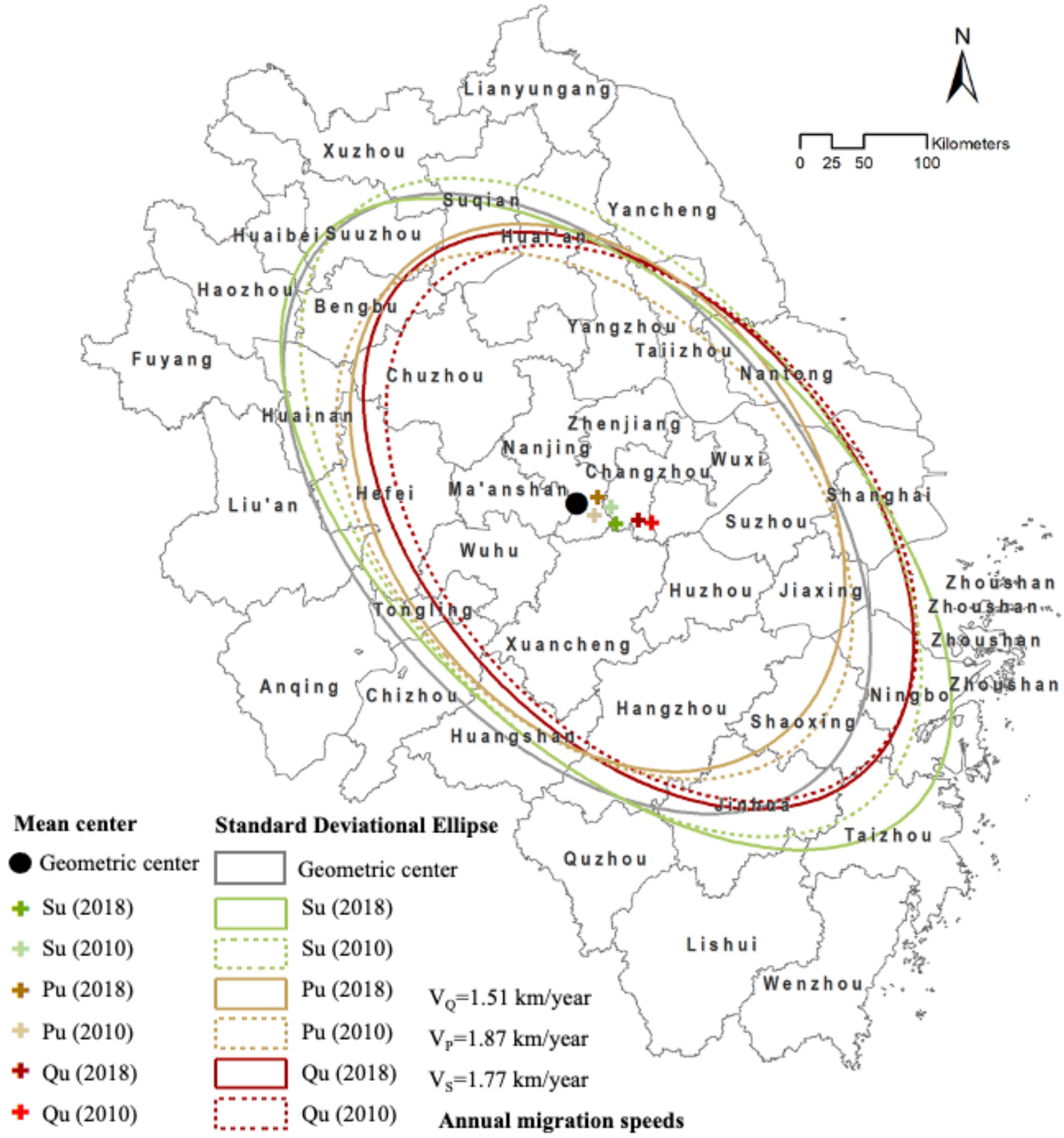


Fig. 4-6 Spatial dynamic map of Qu / Pu/ Su based on mean center and standard deviation ellipse during 2010–2018 across Yangtze River Delta

4.4. Discussions on countermeasures for cities in Yangtze River Delta

After understanding the spatio-temporal variation characteristics of urban sustainability of the 41 cities in the Yangtze River Delta during the recent period, we further obtained detailed diagnostic results of the performance of each indicator category. Then, by comparing the heat map of each original indicator statistical data, the key points that the city needs to be improved can be clearly diagnosed, so that more targeted urban development strategies can be proposed in the near future. The specific sub-item of sustainably characteristics and urban strategies of the city are discussed as follows (Fig. 4-7, 4-8).

4.4.1.Countermeasures of the quality of built environment

For urbanization economies: All 41 cities in this region have shown continuous positive changes in the economic performance of urbanization. The cities with outstanding achievements are Shanghai, Nanjing, Hangzhou, Wuxi, Suzhou, Ningbo, Changzhou and Zhoushan and these cities are the top 13 cities in terms of urbanization rate in 2018. Urbanization has rapidly brought the accumulation of talents, capital, technology and industrial resources to these cities, which has caused the region's GDP and per capita income to rise rapidly. Several cities with high levels of urbanization, represented by Hefei, Taiizhou, and Maanshan, lack economic strength. Industry has always been an important pillar for these cities to maintain stable economic development. But at the moment of transition to the stock era, it is necessary to optimize the configuration of the industrial structure. Although the overall level of Shaoxing, Jiaxing, Huzhou and Taizhou is relatively behind the above cities, they have improved rapidly in recent years. This is because the government has taken active countermeasures to increase the level of disposable income to attract talent inflow, thus effectively activating the urban economy. Other cities have been facing a backward situation in terms of economic urbanization. When formulating regional development plans, these cities should be priority given preferential treatment or support policies to stimulate their economic development

For infrastructural development: The development level of most cities in this area fluctuates significantly over time and varies greatly between regions. At present, Nanjing has a better overall performance in infrastructure construction, while other cities with better performance have obvious areas for improvement. The road area in Shanghai and Lianyungang is obviously insufficient, and the traffic congestion time increases during peak hours. In addition, Shanghai, as China's core city, has a dense population that has led to a decline in the per capita level of land for various infrastructures. While Zhoushan and Huangshan are famous for their natural scenery, there is ample green area, but other infrastructure land needs to be expanded as the permanent population increases. The scores of Ma'anshan, Wuhu, Huainan, and Tongling are lower than in 2010, which makes infrastructure facilities unable to meet the needs of local residents and deserves attention. The cities（Anqing, Liu’an, Fuyang , Suuzhou and Haozhou） with the lowest urbanization level in the region have experienced serious infrastructure shortages , which is closely related to economic backwardness. The cities with the lowest urbanization level in the region all have serious inadequate infrastructure, which is closely related to economic backwardness. Last year, Chinese government announced that it would increase macroeconomic adjustments [9], aiming to support infrastructure development through means such as special debt fundraising, and the above-mentioned cities should receive priority support from policies.

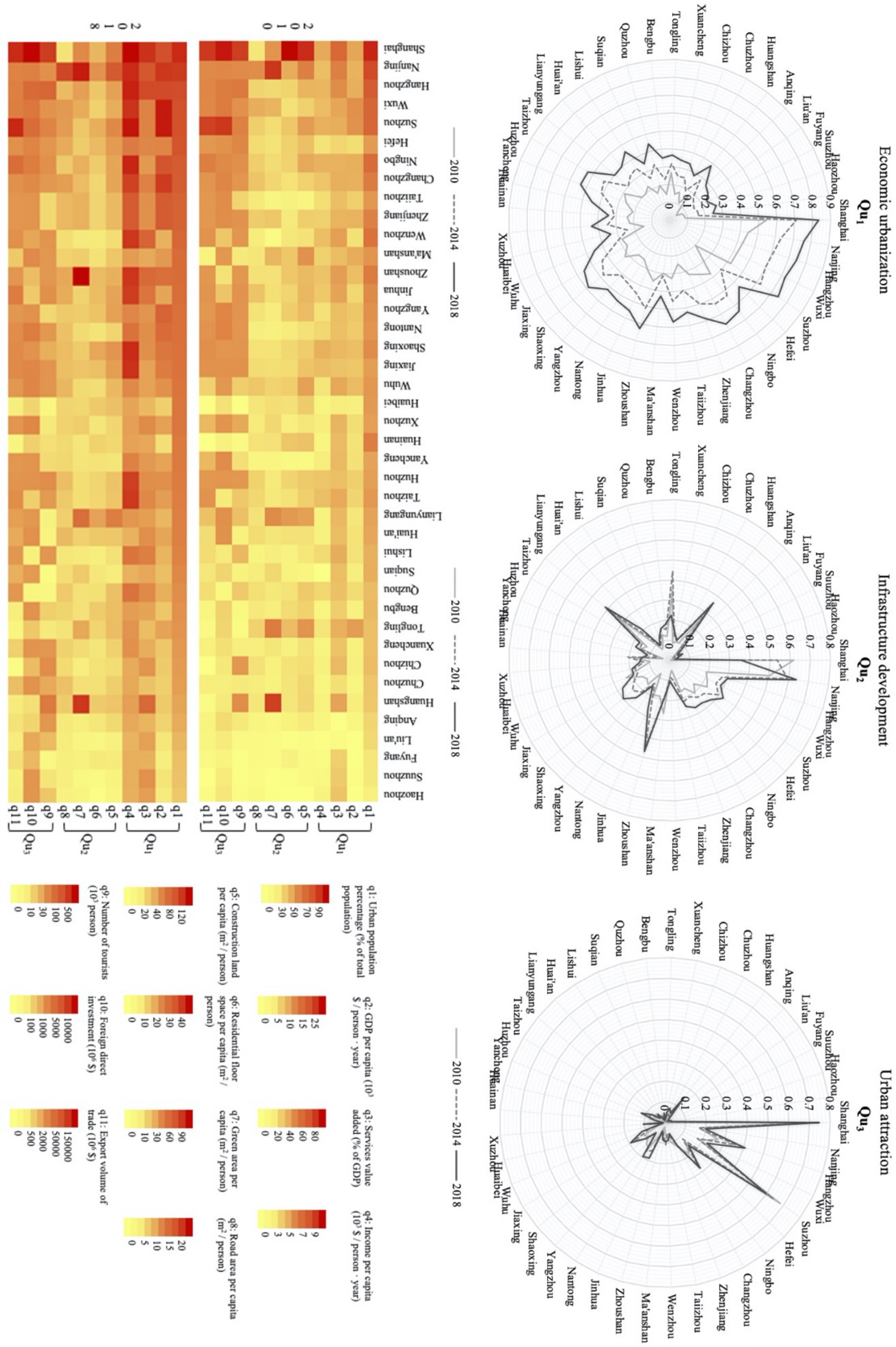


Fig. 4-7 The performance of each of the indicator categories of Qu in Yangtze River Delta

For urban attraction: The attraction of the entire Yangtze River Delta is concentrated in a few cities, and most cities need to be strengthened to create competitive urban features. The most attractive cities are Shanghai and Suzhou, which score significantly higher than other cities, followed by Hangzhou, Ningbo, Nantong, Jiaxing, Jinhua, Huangshan and Huzhou . These cities have some strategies worth learning from: (1) obtain the opportunity to host international events by creating a high-quality urban environment, thereby increasing visibility. For example, Shanghai has hosted the World Expo, Jiaxing hosted the Boao Forum for Asia, the annual meeting of the Summer Davos Forum, etc. [10] (2) Strengthen the protection and open use of local tangible and intangible cultural heritage to attract tourists. Such as the double heritage of world culture and nature Huangshan, Suzhou embroidery and Nantong kite artwork. (3) Enhance the comprehensive development strength of the city, form a good mid-to-long-term development prospect, and inject capital into the domestic bond market to gain the favor of foreign capital. Taiizhou, Zhoushan, Yangzhou, Huainan, Suqian, Tongling, Liu'an, Fuyang, Suuzhou and Haozhou with lower scores than the other cities, need to find out the unique charm of one's own city, enhance the soft power of culture and the hard power of the built and natural environment from many aspects, so as to achieve the goal of comprehensively enhancing the urban attractiveness.

4.4.2.Countermeasures of the environmental pressure

For resource consumption： In the Yangtze River Delta region, the resource consumption of more than half of the cities has increased compared with 2010, which means that the environmental pressure of these cities has increased. The main reasons for the excessive consumption of resources are as follows: (1) A large number of industrial production activities have caused an increase in energy consumption. The Shanghai-Nanjing-Hangzhou Industrial Base, one of China's four major industrial bases, is located in the research area. Among the cities covered by the base, only Shanghai and Hangzhou are the first to use advanced energy technologies to improve energy efficiency and reduce consumption. Other cities such as Suzhou, Wuxi, Changzhou, Ningbo, Nantong and other related cities have seen significant increases in consumption. (2) Urban development aims at excessively pursuing the speed of urbanization, which has caused adverse environmental effects. The transformation of energy consumption structure in some cities has been slow, but it still promotes the urbanization process at the cost of high consumption, thereby increasing the environmental load, especially Nanjing, Wuxi, Hefei, Zhenjiang and Ma’anshan. (3) Some economically underdeveloped cities have insufficient funds for equipment upgrades and technology iterations, and still need to rely on a large amount of high-energy-consuming traditional industrial production to maintain urban development. (4) The citizens have poor awareness of water saving and the mechanism for regulating water consumption is not sound, which causes serious waste of water resources. Therefore, it is necessary to support and manage the city in terms of funds, energy-saving technology and environmental awareness.

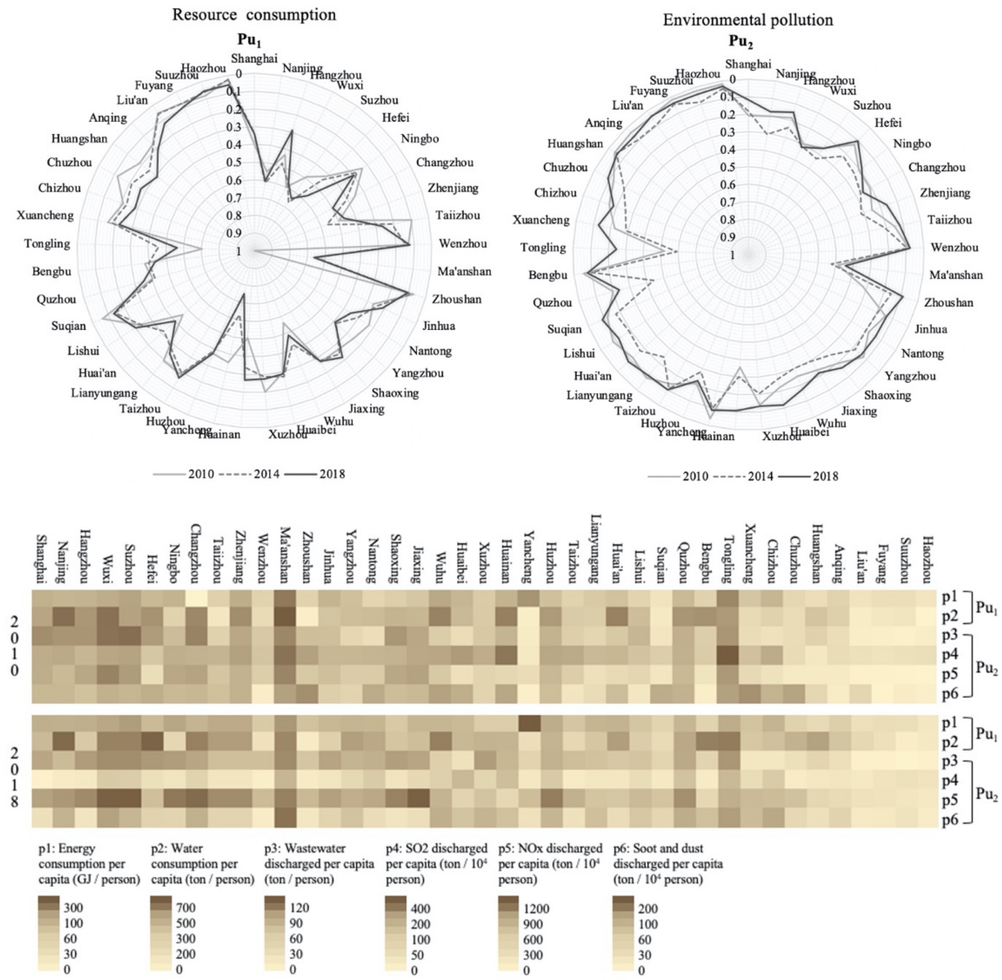


Fig. 4-8 The performance of each of the indicator categories of Pu in Yangtze River Delta

For environmental pollution: Compared with resource consumption, the gap in the environmental pollution scores of cities is small, and the pollution level of most cities has decreased compared with 2010. It can be seen that the environmental quality of cities with low urbanization rate is relatively good, but there are still some cities such as Chizhou, Tongling, Quzhou, and Yancheng that have serious pollution. On the one hand, excessive energy consumption in local chemical and other industries and backward processing equipment technology have caused large emissions of pollutants, especially nitrogen oxides. On the other hand, the urban ecological environment system is inherently fragile, or was damaged by serious pollution incidents such as Chizhou in the early period. The environmental problems of Ma'anshan and Wuxi, the cities with the lowest pollution scores in the region, are most in need of vigilance and control as soon as possible. Both cities were once pillared by heavy industries and are still in the process of transformation and upgrading. Solid waste emissions and nitrogen oxide emissions are the pollution sources that Ma’anshan and Wuxi should take the lead in reducing pollution. Moreover, Nanjing, Changzhou, Zhenjiang, Jiaxing, Shaoxing and Wuhu have relatively large pollution, and it is necessary to take targeted measures based on the diagnosis results.

4.5. Summary

The main conclusions of the empirical analysis of 41 cities in the Yangtze River Delta megapolis from 2010 to 2018 can be summarized as follows:

During the past 9 years, (1) the quality of the built environment in the study area has generally shown an upward trend, while the environmental pressure has shown a deteriorating trend. The main reason is that rapid urbanization has brought about large-scale construction and maintenance of economic strength, which has increased resource consumption and intensified pollution problems. From the performance of evaluation scores, (2) the Qu index scores range from 0.022 to 0.658 and the Pu index scores range from 0.020 to 0.743. The composite Su score has a minimum value of 0.259 and a maximum value of 3.86, indicating that there is a significant development gap between cities in the region of Yangtze River Delta. And (3) the number of cities in a sustainable state increased from 6 in 2010 to 22 in 2018, but there are still 19 cities in an unsustainable state of development. Generalizing the basic conditions of cities reveals that coastal cities or cities with larger urban populations have better sustainability development, especially the mega cities have high levels of sustainability. Using the curve estimation regression model, it was further found that (4) 82.9% of cities showed a significant relationship between Qu and Pu, and only 7 cities show no significant relationship ($p \geqq 0.05$). There are five different types of interaction mechanisms. Among them, 19 cities showed an inverted U-shape and 2 cities with a negative linear relationship, which indicates that the negative impact on environmental stress is diminishing in improving the quality of the built environment. However, (5) there are 7 cities showing an inverted S-shape, 4 cities with a U-shape, and one city with a positive linear mechanism, which means that there are adverse urban development trends due to mutual inhibition and 29.3% of cities should especially worthy of attention to environmental management.

In terms of spatio-temporal characteristics of evolution results, it can be intuitively found that (6) the sustainability of the urban environment in this area shows high degree of urban differences and spatial heterogeneity. In Yangtze River Delta, the distribution characteristics of sustainability in the northern region show a trend of developing from the periphery of the region to the inner city, while the sustainability of coastal cities is higher than that of inland cities in the southern region. Future regional development policies should take as the primary goal alleviating the adverse effects of regional development imbalances. Specifically, (7) the mean center of Qu moves closer to the geometric center at a rate of 1.51 km/year to the southwest but remains 58.72 km away from the geometric center. But (8) the mean centers of Pu and Su are moving to the north, with 20.04 km and 39.46 km away from the geometric center, at a rate of 1.87 km/year and 1.77 km/year respectively.

The movement trajectories of both deviate from the geometric center, indicating that the gap between the unbalanced development of southern and northern cities in the Yangtze River Delta region is increasing rapidly.

Therefore, at the level of macro-regional coordinated development, (9) it is necessary to adopt more effective strategies to alleviate the environmental pressure problems of northern cities as a priority. At the micro level of city-specific development, (10) the results of each city's sub-assessment scores can be combined with a heat map of indicator statistics for a case-by-case diagnosis. Broadly speaking, (11) for the countermeasures of the quality of built environment, the cities recommended to prioritize responses of urbanization economies are Hefei, Ma’anshan, Jiaxing, Wuhu, Bengbu, Xuancheng, Chizhou, Huangshan, Anqing and Fuyang; the cities that need to give priority to improve infrastructure development are Shanghai, Hangzhou, Wuxi, Suzhou, Ningbo, Taiizhou, Wenzhou, Jinhua, Yangzhou, Xuzhou, Yancheng, Huzhou, Taizhou, Lishui, Liu’an, Suuzhou and Haozhou; and the cities that need to particularly strengthen their urban attractiveness are Nanjing, Changzhou, Zhenjiang, Zhoushan, Nantong, Shaoxing, Huaibei, Huainan, Lianyungang, Huai’an, Suqian, Quzhou and Tongling. (12) For the countermeasures of the environmental pressure, the cities recommended to prioritize responses to reduce resource consumption are Shanghai, Nanjing, Suzhou, Hefei, Taiizhou, Nantong, Yangzhou, Wuhu, Huaibei, Yancheng, Huai’an, Bengbu, Chuzhou, Huangshan, Anqing, Liu’an, Fuyang and Haozhou, while the other cities urgently need to prioritize deal with the severe environmental pollution issues.

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Chapter 5. Measuring the Performance Urban Sustainability in Pearl River Delta

5.1. Introduction

5.1.1.General information of urban environment in Pearl River Delta

The Pearl River Delta megalopolis (geographic coordinates: 112° 57' E-114° 30' E longitude and 22° 26' N-23° 56' N latitude), has been one of the most economically dynamic regions since the launch of China's reform program in 1979 (Fig. 5-1). The total area is 179,800 km^2 located in South China on the north shore of the South China Sea. The megalopolis was developed from the Pearl River Delta Economic Open Zone established in 1985 [1]. In 1994, in order to take the lead in modernization, a portion of nine cities in Guangdong Province was designated as the Pearl River Delta megalopolis. It was then expanded to include the entire group of 9 cities in 2008 [2]. Based on the development experience of the other three megalopolises in the thesis, it is believed that in the future, the entire Guangdong Province of 21 cities is likely to be the planning scope of the Pearl River Delta megalopolis, which is the study area of this chapter (Table. 5-1).

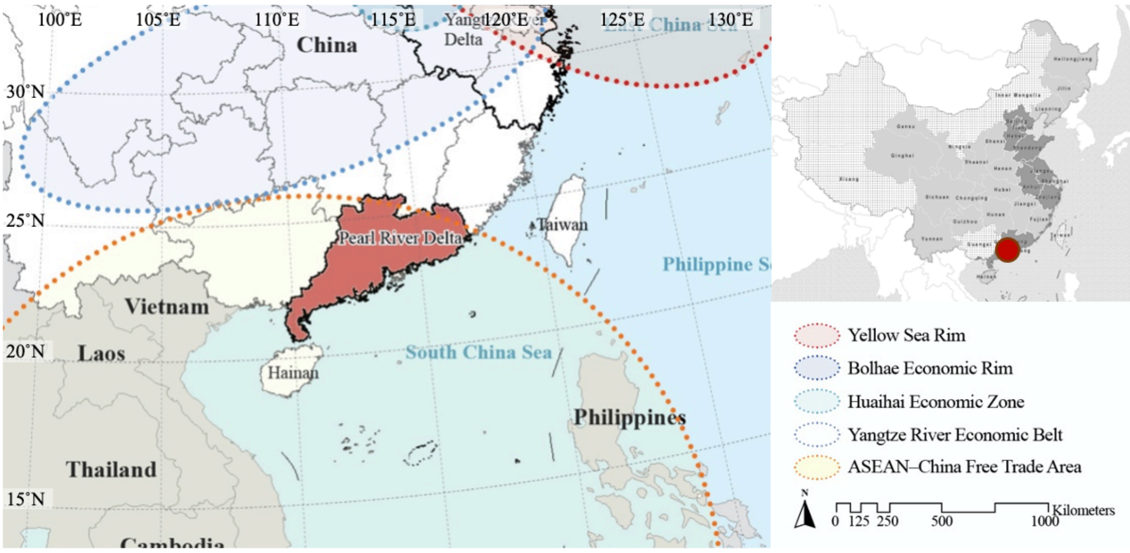


Fig. 5-1 Geography of the Pearl River Delta megalopolis

The Pearl River Delta is the heart of high technology, manufacturing and foreign trade. It is now the richest region in southern China and, along with the Yangtze River Delta in eastern China and JingJinJi in northern China, is one of the wealthiest regions in the entire country. Its economy is larger than any other province in the country and is the fourth largest sub-national economy in the world, with a GDP of US$1.53 trillion in 2019 (US$12,318 per capita). The PRD's favorable geographic location and low-cost labor supply quickly attracted significant investment from Hong Kong, Macau and abroad, stimulating both regional urbanization rates and the development of low value-added labor-intensive industries, particularly manufacturing. In 2008, the ASEAN Secretariat invited the PRD to enter into an agreement to develop cooperation and activities of mutual interest in the ASEAN-China Free Trade Area. Today, the boom in labor-intensive and capital-intensive industries has made the region the "factory of the world" and representative of the Chinese economy almost overnight. [3].

However, the resulting 30 years of industrialization and urbanization have witnessed an accelerated deterioration of the natural environment in the Pearl River Delta. In addition, population growth accompanying the urbanization of the region has increased the demand for energy resources, a trend that poses a serious challenge to the future development of the region. At the same time, investment in environmental management has been relatively slow. Inevitably, urbanization has had a significant impact on the environment and the urban environment is in poor condition. This will place greater demands on sustainable urban development in the Pearl River Delta.

Table 5-1 Outline and classification of 21 cities in Pearl River Delta in 2018

Cities in Pearl River Delta (belonging to the Guangzhou Province）	**Urban population (10^4 persons)**	**Urbanization rate （%）**	**Total population (10^4 persons)**	**Land area (km^2)**	**Density (persons /km^2)**	**GDP ($ / person)**	**GDP (10^9 $)**	**Length of coastline (km)**
Shenzhen	1302.66	100.00	1302.66	1997	6521.55	28045.62	365.34	261
Foshan	750.88	94.98	790.57	3798	2081.70	18956.25	149.86	-
Dongguan	763.86	91.02	839.22	2460	3411.35	14878.77	124.87	112
Zhuhai	170.35	90.08	189.11	1736	1089.05	23247.25	43.96	604
Zhongshan	292.44	88.35	331.00	1784	1855.72	16553.44	54.79	57
Guangzhou	1287.44	86.38	1490.44	7249	2055.99	23133.21	344.79	157
Huizhou	341.77	70.76	483.00	11347	425.65	12812.88	61.89	281
Shantou	397.01	70.41	563.85	2199	2563.95	6719.73	37.89	218
Jiangmen	305.78	66.50	459.82	9507	483.67	9513.88	43.75	329
Chaozhou	173.48	65.30	265.66	3146	844.41	6059.48	16.10	136
Shaoguan	169.33	56.49	299.76	18413	162.80	6762.17	20.27	-
Shanwei	165.10	55.15	299.36	4865	615.33	4636.93	13.88	455
Yangjiang	134.45	52.61	255.56	7956	321.22	7969.47	20.37	342
Qingyuan	201.45	52.00	387.40	19036	203.51	6093.93	23.61	-
Jieyang	311.66	51.18	608.94	5266	1156.40	5331.47	32.47	68
Meizhou	221.09	50.49	437.88	15865	276.01	3824.16	16.75	-
Zhaoqing	198.29	47.76	415.17	14891	278.80	7999.04	33.21	-
Heyuan	140.00	45.25	309.39	15654	197.65	4904.35	15.17	-
Zhanjiang	315.35	43.01	733.20	13263	552.82	6188.67	45.38	2024
Maoming	271.47	43.00	631.32	11428	552.45	7387.56	46.64	248
Yunfu	106.74	42.24	252.69	7785	324.58	5068.41	12.81	-
Total of Pearl River Delta	8020.57	70.69	11346	179644	631.58	13430.02	1523.77	5291
% of China (except autonomous and special administrative regions)	10.27	-	8.82	3.43	-	-	11.66	21.47

5.1.2.The challenge of sustainable urbanization in Pearl River Delta

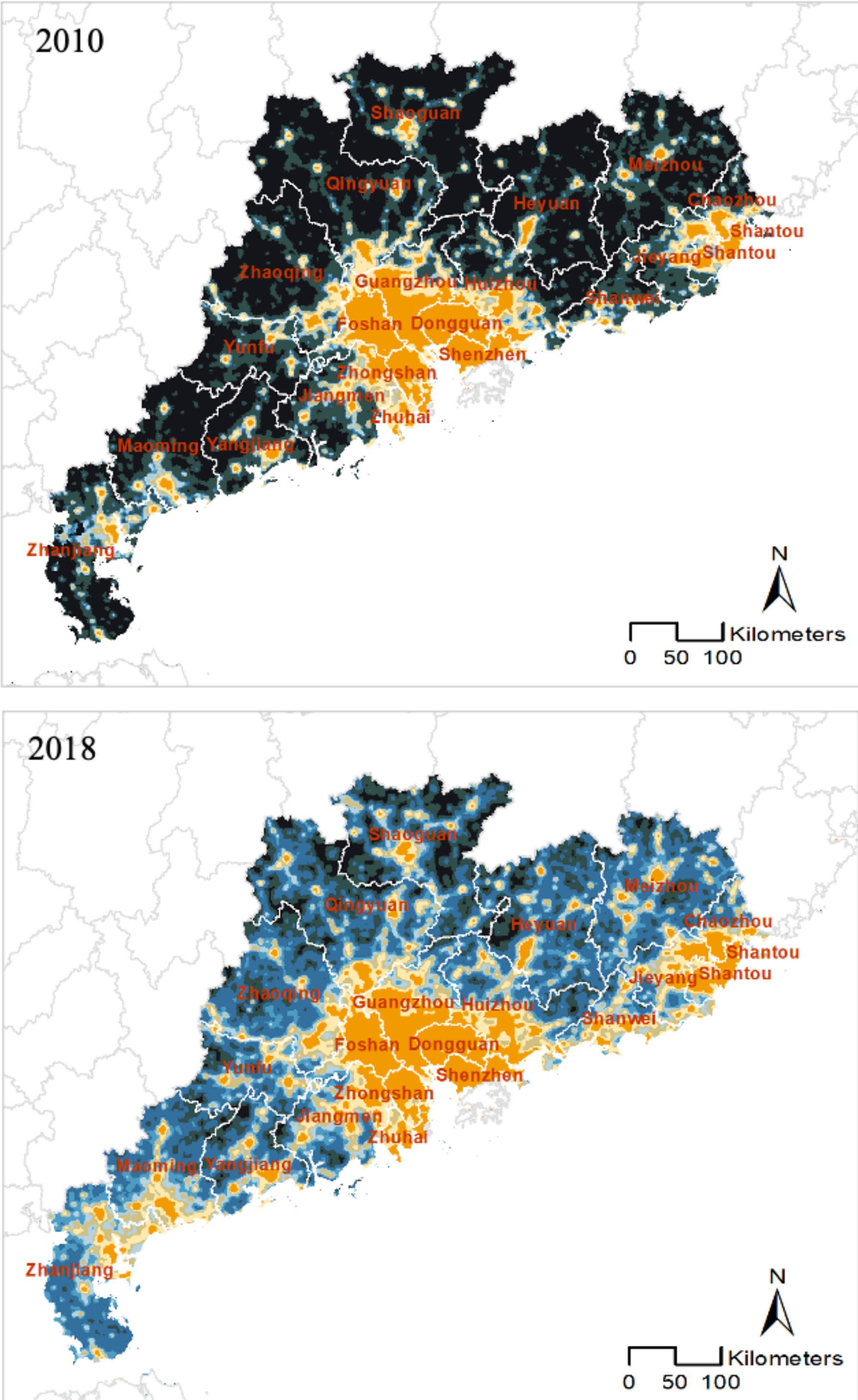


Fig. 5-2 The evolution of urbanization in Pearl River Delta from 2010 to 2018. (Notes: the degree of urban population is represented by the change of color. The deeper yellow color represents higher urbanization, and the deeper blue color represents lower urbanization.)

The Pearl River Delta is the most populous megalopolis of China and one of the most densely urbanized regions in the world. It can be seen in Fig. 5-2 that the urban population is mostly concentrated in the southeast coastal area. Among them, the central coastal areas around Guangdong and Shenzhen are the most densely populated, followed by the eastern area surrounding Shantou, and the intersection of Zhanjiang and Maoming in the south. The population of inland cities is significantly less than that of coastal cities.

In the 1980s, the Pearl River Delta, which was dominated by farmland and small rural areas, has experienced rapid economic development, population growth, and urban expansion over the past 40 years. The urbanization rate rose from 16.3% in 1978 to 55.65% in 2000 [4]. Then, during a sustained phase of accelerated urbanization from 2000 to 2010, the proportion of urban population increased by 10.52%, or an average of 1.05% per year. By 2018, the level of urbanization in the Pearl River Delta increased to 70.69%, with eight cities having reached 70% or more (National Bureau of Statistics, 2019). As a result, the urban density was as high as 632 persons/km2 in 2017, ranking second among China's metropolitan areas. According to Northam's three-stage theory of urbanization development, urbanization in the Pearl River Delta has entered the terminal development stage, which will last for about one or two decades after 2018.

The report "Territorial Spatial Planning (2020-2035)" predicts that the resident population of the Pearl River Delta will reach 130 million by 2035, with an average annual growth rate of about 1.15 million [5]. The level of urbanization will advance toward the predicted goal of 80%. At the same time, the economic development of the Pearl River Delta region is presented as a national strategy. As a result, regional urban development will face a greater challenge of balancing the quality of the built environment with its environmental pressures. On the one hand, the development of regional coastal and inland cities is not coordinated; on the other hand, population and economic growth will have a negative impact on energy consumption and environmental pollution.

5.2. Results presentation and interaction mechanism analysis in Pearl River Delta

5.2.1.Overall results for each city

The box charts of Fig. 5-3 show the ranges of the Qu, Pu and Su evaluation scores of 21 cities in the Pearl River Delta region from 2010 to 2018, using the urban sustainability assessment tool. It can be roughly seen that: (1) Cities with higher urbanization rates have a high quality of the built environment, but the trend is not obvious. And the quality gap of cities with lower urbanization is smaller. (2) The cities are relatively little difference in the dimension of environmental pressures, but individual cities have obvious environmental problems with a significant range of score changes. The trend of Pu scores is basically opposite to that of the urbanization levels of cities. (3) The degree of urban sustainability roughly follows the trend of the urbanization rate. Some cities with relatively low levels of urbanization have greater changes in sustainability.

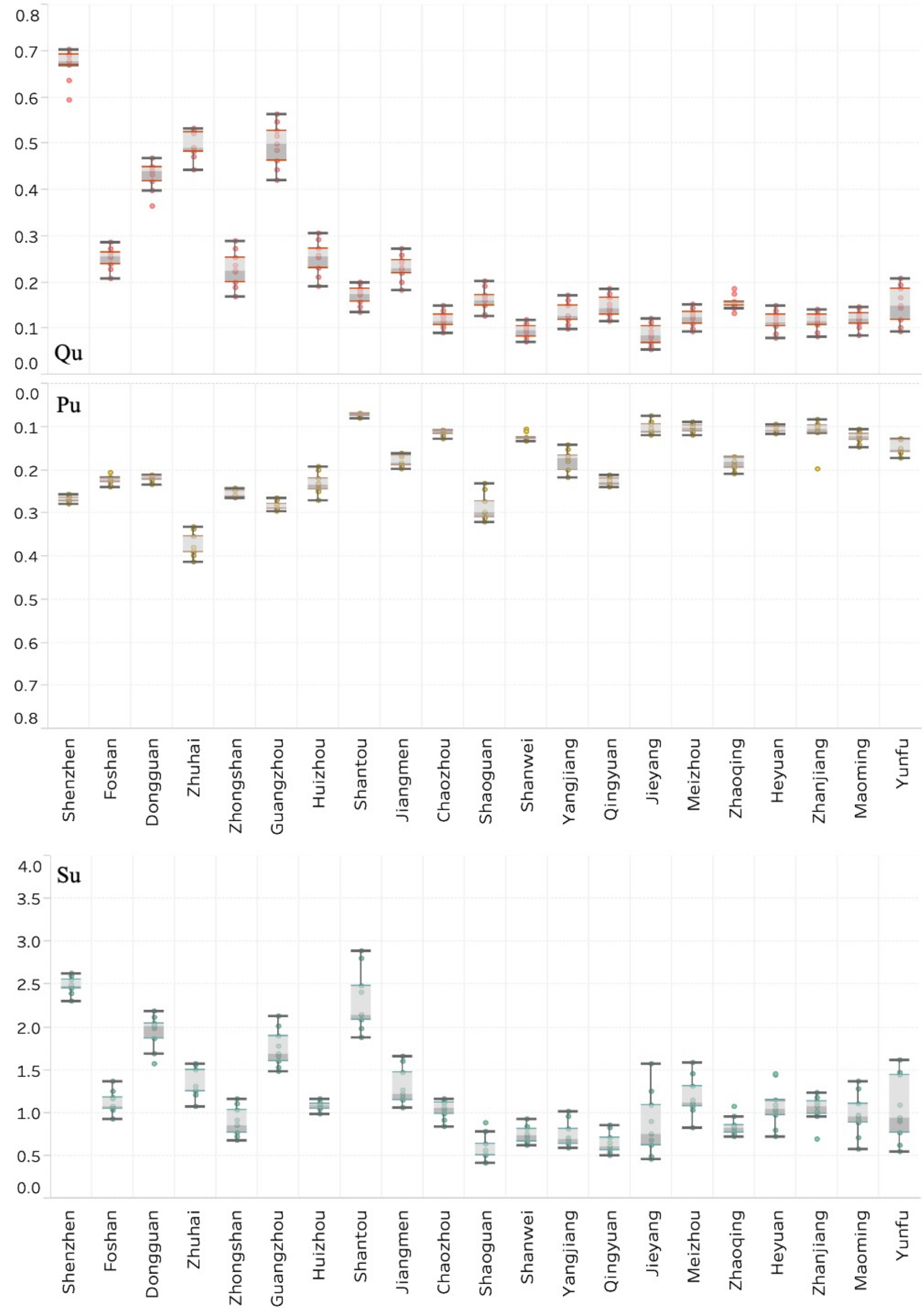


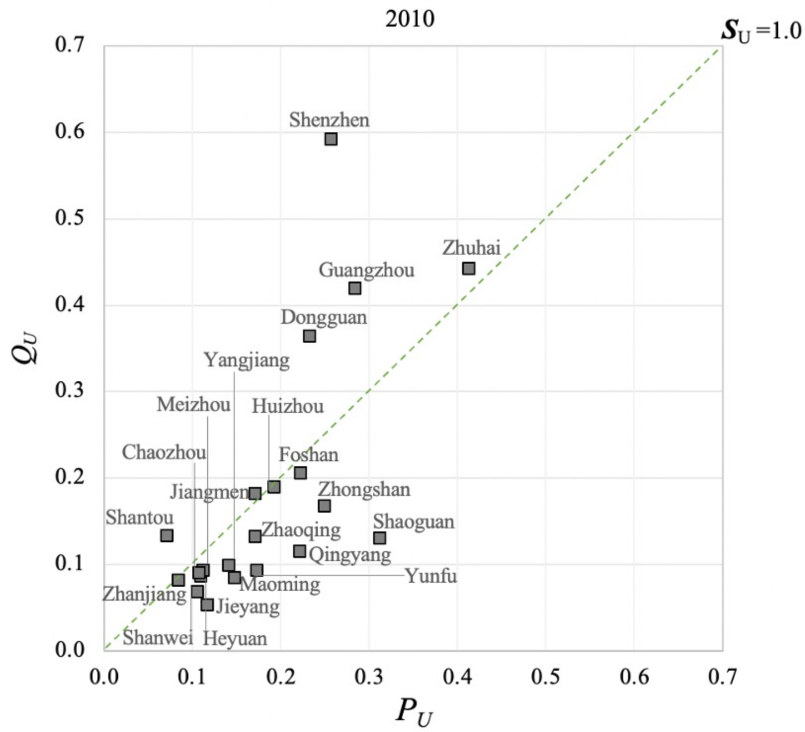
Fig. 5-3 The scores of Qu, Pu and Su of 21 cities in Pearl River Delta from 2010 to 2018 measured by urban sustainability assessment system.

Specifically, from Fig. 5-3(Qu), the index of Qu for the 21 cities ranged from 0.054 in 2010 to 0.702 in 2013. The compound annual growth rate (CAGR) in the past 9 years is between 1.71% and 9.38%. From the median point of view, cities can be divided into three categories: (1) the performance of

Shenzhen has been in a leading position in this dimension followed by Donguan, Zhuhai and Guangzhou, with the median points of Qu over 0.4. These cities are all economically affluent cities in the region with the GDP has reached more than 10,000 USD per capita in 2018. (2) The median of cities of Foshan, Zhongshan, Huizhou and Jiangmen are more than 0.2 in the dimension of Qu. These cities rank among the top nine in terms of urbanization rate, and they have had competitive advantages in labor-intensive manufacturing over the past few years. (3) More than 60% of the cities have a median of less than 0.2. The disparity between the rich and the poor among regional cities is also a problem that has always been a concern in the Pearl River Delta. Then, the index of Pu ranged from 0.069 to 0.413 shown in Fig. 5-3(Pu). These two are the scores of Shantou in 2018 and Zhuhai in 2010, and the environmental pressure in Zhuhai has been at the highest level. Mainly because of the unreasonable industrial structure with the ratio of the above light and heavy industries is about 1:2. And air pollution has always been serious, so related governance regulations were promulgated in 2017. The annual CAGR ranges from -4.62% to 3.91%. Only 7 out of 21 cities have a positive growth rate, which means that most cities in the Pearl River Delta have made efforts to alleviate environmental pressures in 9 years. However, nine cities have a median value of Pu higher than 0.2, and seven of the top ten cities in urbanization are included. That reflects the urban populations interact with and adversely affects their environment.

From the comprehensive variation of Su in Fig. 5-3(Su), the lowest score is 0.404 that got by Shaoguan City in 2011. And the highest score is 2.879, which is Shantou's score in 2018. The annual CAGR ranges from 1.41% to 14.69%. There are 9 cities that have a median point of Su scores exceeds 1.0. The urbanization level of these cities is among the top ten in the region. It indicates that the increasing sustainability has maintained the continuous development of these cities towards a high level of urbanization. Although the gap is obvious, the sustainability of other backward cities has improved greatly. Especially Jieyang, Maoming and Yunfu have an annual CAGR of more than 10%.

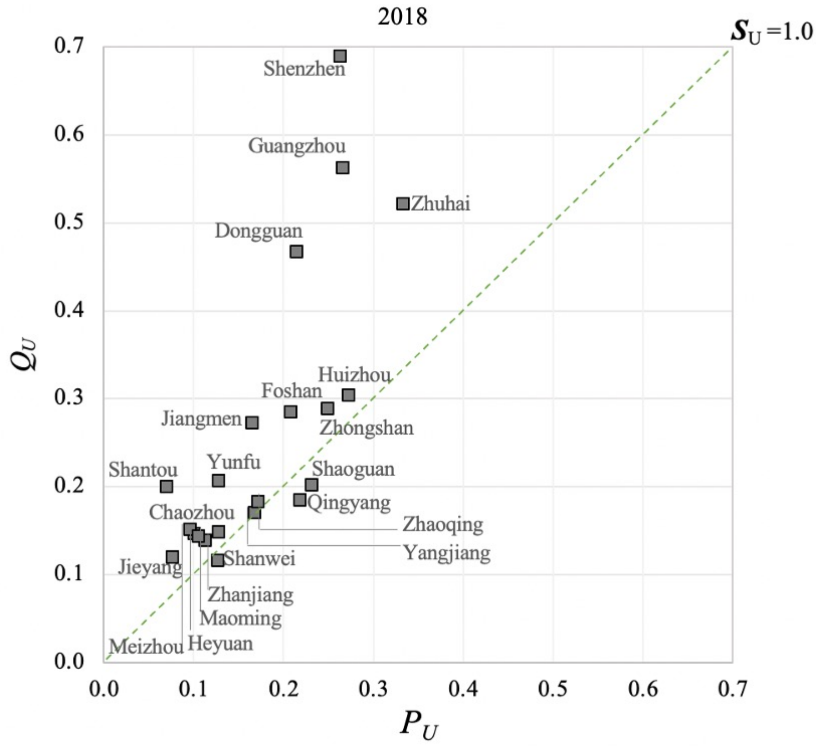
In addition, the urban development states of 21 cities in Pearl River Delta from 2010 to 2018 could be presented from Fig. 5-4 and found that: (1) The number of cities in a state of sustainable development increased from 6 cities in 2010 to 18 in 2018. (2) Since 2010, all sustainable cities are coastal cities and are the first to be included in the planning scope of this urban agglomeration. In addition to the geographical advantages of coastal resources and foreign-oriented economy, the early megalopolis policy support is also an important reason. (3) Since 2012, the Pearl River Delta has entered a stage of high-quality development driven by innovation in the economy, which has further promoted the development of regional cities. But there are still three 3 of the cities are still in an unsustainable state of development. (3) By 2018, most cities will achieve basic sustainable development by improving urban quality, but the environmental load of individual cities such as Chaozhou and Huizhou increased accordingly. (4) The three unsustainable cities of Shanwei, Shaoguan and Qingyuan have made efforts to balance urban quality and environmental pressure control in the past nine years. In particular, the environment of Shaoguan City has changed drastically, and as a result, it was recognized by the state as a city with significantly improved environmental quality in 2019.



2010

Classification		Small cities	Medium-sized cities	Large cities	Mega cities	Number of cities	
Su < 1.0 (Qu< Pu)	Coastal	-	Huizhou, Zhanjiang, Chaozhou, Yangjiang, Zhongshan, Shanwei, Maoming, Jieyang	-	-	8	15
	Inland	Yunfu	Meizhou, Heyuan, Zhaoqing, Qingyuan, Shaoguan	Foshan	-	7	
Su ≥ 1.0 (Qu≥ Pu)	Coastal	-	Shantou, Zhuhai, Jiangmen	Dongguan	Shenzhen, Guangzhou	6	6
	Inland	-	-	-	-	0	

(a) The regression result and the corrosponding city list of 2010



2018

Classification		Small cities	Medium-sized cities	Large cities	Mega cities	Number of cities	
Su < 1.0 (Qu< Pu)	Coastal	-	Shanwei	-	-	1	3
	Inland	-	Shaoguan, Qingyuan	-	-	2	
Su ≥ 1.0 (Qu≥ Pu)	Coastal	-	Shantou, Jiangmen, Jieyang, Zhuhai, Maoming, Zhanjiang, Chaozhou, Zhongshan, Huizhou, Yangjiang	Dongguan	Shenzhen, Guangzhou	13	18
	Inland	Yunfu	Meizhou, Heyuan Zhaoqing	Foshan	-	5	

(b) The regression result and the corrosponding city list of 2018

Fig. 5-4 The regression trends of different types of cities from 2010 to 2018

Note: (1) Su < 1.0 (Qu < Pu) means the city is in a barely or seriously unsustainable urbanization process. The increasing pace of urban environmental pressure (Pu) is faster than the improved pace of urban built environment quality (Qu). Su ≥ 1.0 (Qu ≥ Pu) means the city is in a basic or highly sustainable urbanization process. The increasing pace of urban environmental pressure (Pu) is slower than the improved pace of urban built environment quality (Qu). (2) Small cities (urban population < 1 million); Medium-sized cities (5 million > urban population ≧ 1 million); Large cities (10 million > urban population ≧ 5 million); Mega cities (urban population ≧ 10 million)

5.2.2.Coupling interaction mechanism between Qu and Pu

The relationship between Qu and Pu of 21 cities in the Pearl River Delta is obtained through the method of curve estimation and regression in Table 5-2, so as to further understand the development trend of the city. The estimation list shows that except for the 4 cities of Shenzhen, Qingyuan, Meizhou and Heyuan, the performance of these two aspects of the other 17 cities has a significant coupling relationship, with the p values lower than 0.5. Five types of mechanisms have been found as follows：

(1) Negative linear relationship: the four cities with this situation are Dongguan, Zhuhai, Maoming and Yunfu. The advanced manufacturing development policy put forward during the national "Twelfth Five-Year Plan" period took the lead in achieving success in the manufacturing industry in the Pearl River Delta. In addition, the city took the lead in establishing a joint prevention and control mechanism for air pollution, which continued to alleviate the environmental pressure of these manufacturing-oriented cities.

(2) Inverted U-shaped relationship: the environmental pressure of 5 cities first increased and then decreased with the improvement of the quality of the built environment. Most inflection points appeared around 2013, due to the implementation of the second phase (2013-2015) air quality continuous improvement implementation plan, in the context of maintaining rapid economic development.

(3) Inverted S-shaped relationship: There were five cities that had a benign transition around 2013, and the cities began to develop in a well-controlled environment. However, in recent years, there has been a trend of reversal. The rise of high-quality cities has begun to become an important layout strategy of the government, so environmental problems have reappeared.

(4) U-shaped relationship: Chaozhou City has continued to increase its environmental load following the development of urban quality after 2013. This is mainly due to the non-compliance of pollution control in the building materials industry and inadequate departmental supervision, especially the frequent environmental violations in the heavy-polluting industries in the Fengjiang River Basin.

(5) Positive linear relationship: Huizhou and Zhanjiang have the most unfavorable relationship for sustainable urban development, which deserves special attention. It is necessary to quickly transform the urban development model that consumes resources excessively and pursues rapid economic growth.

Table 5-2 The coupling interaction mechanism between f(Q) and g(P) by regression analysis of the 21 cities in Pearl River Delta

Cities	AIC	BIC	R^2	Adjusted R^2	Std. error	F	p[1] value	Regression equation	Description	Inflection year
Dongguan	-69.335	-68.940	0.706	0.664	0.005	16.806	0.005**	*g(P) =0.313-0.214 f(Q)*		-
Zhuhai	-42.309	-41.915	0.511	0.441	0.021	7.309	0.030*	*g(P) =0.704-0.658 f(Q)*	Negative linear relationship	-
Maoming	-65.138	-64.743	0.832	0.808	0.006	34.717	0.001***	*g(P) =0.201-0.632 f(Q)*		-
Yunfu	-61.069	-60.675	0.826	0.801	0.007	33.294	0.001***	*g(P) =0.205-0.371 f(Q)*		-
Foshan	-62.978	-62.386	0.665	0.553	0.006	5.943	0.038*	*g(P) =-0.456+5.744 f(Q)-11.979 f(Q)2*		2013
Guangzhou	-73.093	-72.501	0.951	0.872	0.004	28.250	0.001***	*g(P) =-0.552+3.569 f(Q)-3.764 f(Q)2*		2014
Shantou	-81.106	-80.515	0.765	0.687	0.002	9.760	0.013*	*g(P) =-0.14+2.646 f(Q)-8.021 f(Q)2*	Inverted U-shaped relationship	2013
Jiangmen	-55.473	-54.881	0.613	0.484	0.010	4.276	0.048*	*g(P) =-0.365+5.057 f(Q)-11.535 f(Q)2*		2013
Jieyang	-73.037	-72.446	0.951	0.935	0.004	58.39	0.000***	g(P) =*0.09+0.992 f(Q)-9.051 f(Q)2*		2012
Zhaoqing	-51.306	-50.714	0.516	0.354	0.012	4.194	0.049*	g(P) =*-0.894+13.772 f(Q)-43.464 f(Q)2*		2016
Zhongshan	-69.092	-68.303	0.811	0.698	0.004	7.170	0.029*	*g(P) =-1.059+17.45 f(Q)-75.307 f(Q)2+105.853 f(Q)3*		2012&2017
Shaoguan	-50.054	-49.265	0.899	0.839	0.013	14.915	0.006**	*g(P) =-1.442+31.359 f(Q)-178.951 f(Q)2+319.895 f(Q)3*	Inverted S-shaped relationship	2013&2018
Shanwei	-74.518	-73.729	0.929	0.886	0.003	21.665	0.003**	*g(P) =-0.831+28.783 f(Q)-283.929 f(Q)2+922.554 f(Q)3*		2013&2017
Yangjiang	-48.993	-48.204	0.799	0.679	0.014	6.629	0.034*	g(P) =*-1.952+43.598 f(Q)-289.175 f(Q)2+623.129 f(Q)3*		2014&2017
Huizhou	-70.028	-69.634	0.971	0.967	0.004	234.767	0.000***	*g(P) =0.066+0.664 f(Q)*	Positive linear relationship	-
Zhanjiang	-61.630	-61.236	0.611	0.555	0.007	10.988	0.013*	*g(P) =0.049+0.466 f(Q)*		-
Chaozhou	-77.386	-76.794	0.889	0.852	0.003	24.045	0.001**	*g(P) =0.201-1.84 f(Q)+9.141 f(Q)2*	U-shaped relationship	2013
Shenzhen	-64.633	-64.041	0.454	0.312	0.006	2.811	0.138	*g(P) =-0.298+1.609 f(Q)-1.136 f(Q)2*		2017
Qingyuan	-57.430	-56.839	0.428	0.238	0.009	2.249	0.187	*g(P) =-0.028+2.941 f(Q)-10.448 f(Q)2*	No significant relationship	2015
Meizhou	-54.617	-54.026	0.244	-0.008	0.010	0.967	0.433	*g(P) =-0.094+3.394 f(Q)-14.154 f(Q)2*		2014
Heyuan	-58.406	-57.814	0.155	-0.127	0.008	0.549	0.604	*g(P) =0.055+1.053 f(Q)-5.063 f(Q)2*		2014

5.3.Spatio-temporal characteristics of urban sustainability in Pearl River Delta

5.3.1.Spatio-temporal variation patterns of results

As shown in Fig. 5-5(Qu), cities with better urban built environment quality are distributed in the central to northern area. It is mainly based on that the advanced cities of Guangzhou, Shenzhen and Zhuhai contribute to the surrounding areas by promoting the improvement of the quality level of cities along the Northwest horizontal axis. Cities at the two ends of the region are still lagging behind, and this distribution feature is closely related to the planning policies that give priority to supporting the Special Economic Zones proximity to Hongkong and Macau. At present, this region has further formed a high integration and the structure of the Yunfu-Shenzhen-Shaoguan, a U-shaped pattern of urban spatial development in the integration urbanization stage. To a great extent, the cities on the growth pattern can provide radiant power for the development of the surrounding area more conveniently by sharing economy and industries cooperation, etc.

The distribution pattern of Pu results Fig. 5-5(Pu) is slightly different from Qu's. The cities with the greatest environmental pressure in the Pearl River Delta have always been concentrated in the central area. And the environmental performance of cities in the southwest is better in the begging, but the urban environment of cities in the northeast improved significantly by 2018. Especially in Meizhou and Jieyang, it meets the characteristics of the interaction mechanism summarized above. Therefore, the central region is the region that needs the most priority for governance. On the one hand, this area is a gathering place for many export-oriented high value-added manufacturing factories, and energy consumption and pollution are bound to be high [6]. On the other hand, the rapid economic development of these cities has attracted a large influx of population, daily consumption and increased car ownership, which has led to increasingly prominent regional complex and cumulative environmental problems.

The distribution pattern of the comprehensive Su results is shown in Fig. 5-5(Su). The spatial distribution characteristics of urban sustainability in the Pearl River Delta present a development pattern that gradually spreads in both directions from the middle to the two ends of the region. By 2018, a sustainable urban belt near the sea will be formed and the central cities have the highest degree of sustainability. But the cities of Shaoguan and Qingyuan in the north and the only city of Shanwei in the south are still in an unsustainable state of development. In the latest guidance document for regional land and space planning (2020-2015), the planning concept of "one belt, one core and one district" is proposed, which is consistent with the distribution results of Su. And that directly proves that the urban sustainability assessment system is effectiveness. The above plan calls for strengthening the advantages of the coastal city belt, using the central core cities to drive the development of the surrounding backward cities, and improving the quality of the ecological environment in the northern region.

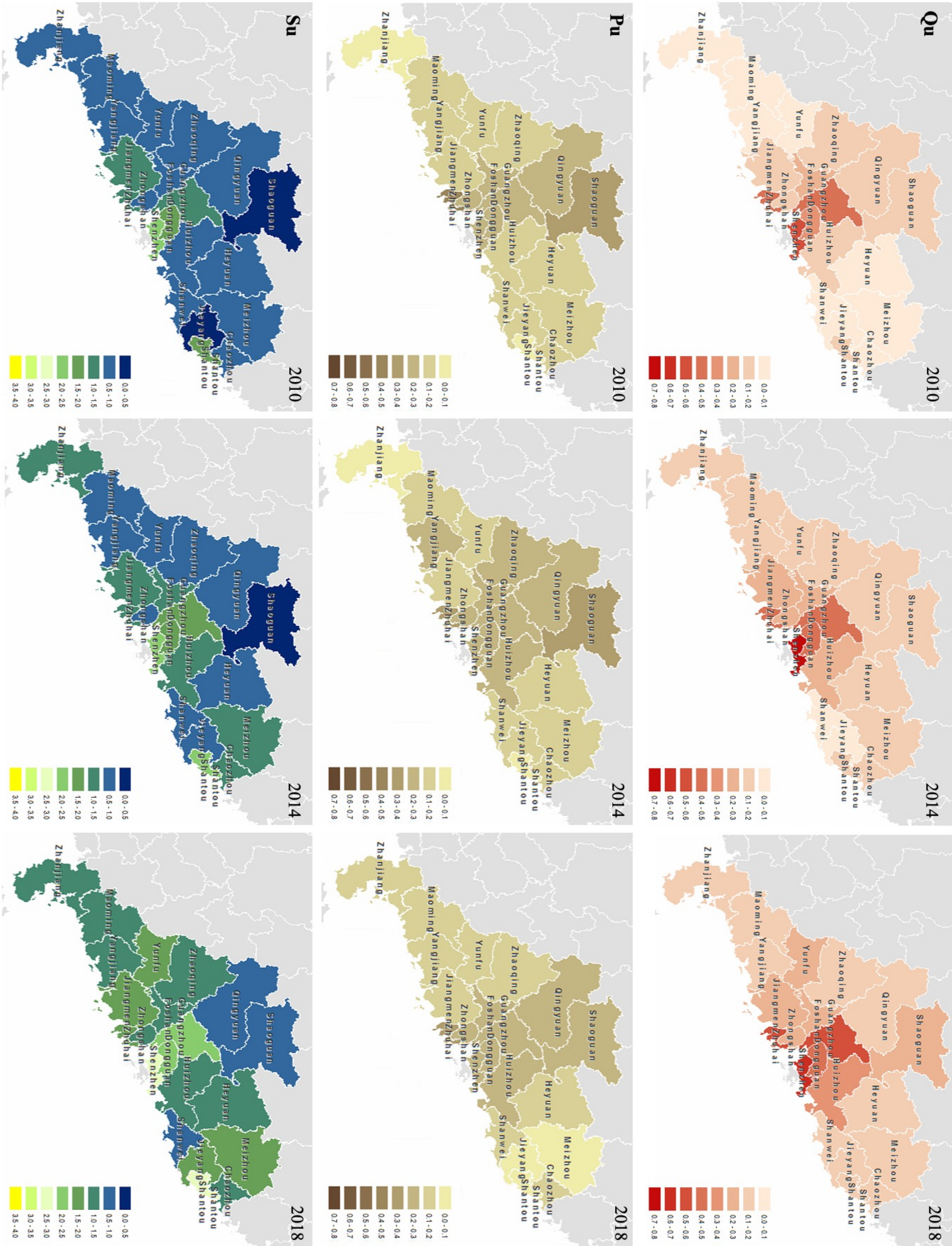


Fig. 5-5 The spatio-temporal variation pattern in the Pearl River Delta from 2010 to 2018.

5.3.2.Evolution track characteristics of regional patterns

The evolution track of evaluation results from the regional pattern of the Pearl River Delta from 2010 to 2018, and the corresponding results are shown in Fig. 5-6 and detailed parameters in Table 5-3. On the whole, the mean centers of the evaluation results of Qu, Pu and Su are slightly offset in different directions relative to the geographic center, which means that the regional development of the Pearl River Delta is still slightly unbalanced. All the mean centers are located in Dongguan City, and gradually approaching the geographic center. The mean center of Qu located in the south direction of the geometric center, that of Pu is in the southwest direction, and of Su is in the southeast direction. And the distance from each mean center of Qu, Pu and Su to the geographic center is 11.59km, 15.26km and 18.81km in 2018 and shortened by 2.41km, 1.84km and 1.38km respectively in 9 years. From the shape of standard deviation ellipses, the main axis of all ellipses is basically the same, located in the southwest-northeast direction, but the changes of the ellipses are different. The ellipses of Qu and Su tend to increase in the major and minor axis directions, which means that the regional performance gap in quality and sustainability is gradually decreasing. The size of Pu's ellipse is basically unchanged. The major axis of the Pu ellipse increases, and the minor axis decreases slightly, indicating that heterogeneous spatial changes in the dimension of environmental pressure occurred over time.

Although the angles of the three ellipses are approximately 63°, the major axis of Su is significantly longer than that of Qu or Pu. That means the sustainability gap between the cities in the southwest to the northeast is small, and the gap between these cities and the city in the northwest is large. Moreover, the annual migration speeds are about the same that the mean center of Su (V_S=0.60 km/year) has the fastest moving speed, followed by that of Pu (V_P=0.48 km/year) and Qu (V_Q=0.42 km/year). It shows that the Pearl River Delta region is recovering regional balanced development with a positive trend. Although the quality of urban development has improved at the same speed as environmental protection, the progress of the two is still slow. Therefore, it is necessary to adopt more effective strategies to accelerate the realization of the sustainable urbanization of the whole region, especially to give priority to the northwestern cities.

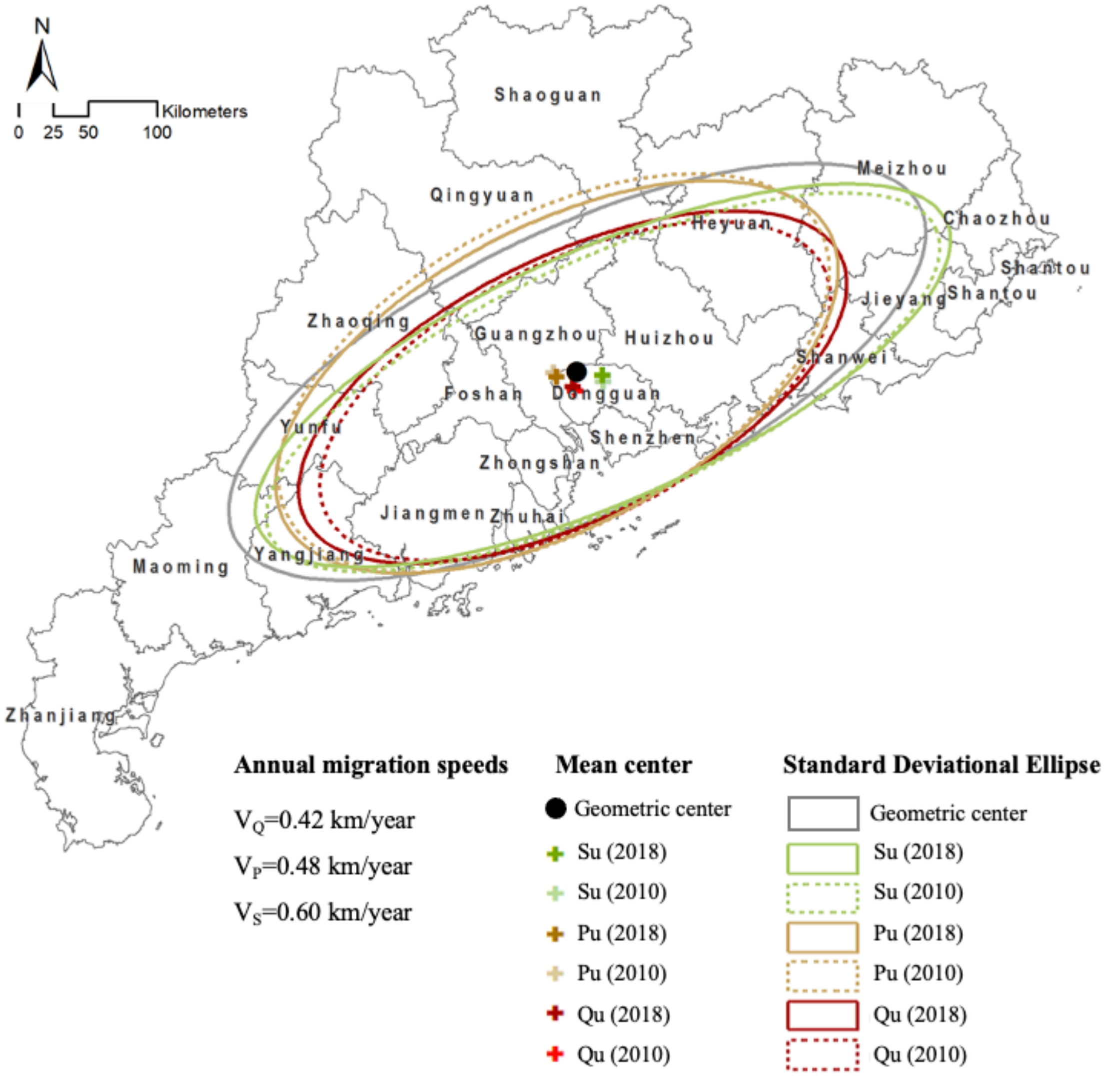


Fig. 5-6 Spatial dynamic map of Qu / Pu/ Su based on mean center and standard deviation ellipse during 2010–2018 across Pearl River Delta

Table 5-3 The detailed parameter of mean center and standard deviation ellipse

Weighted field	Year	Mean center: Degree of longitude	Mean center: Degree of latitude	Standard Deviational Ellipse: Standard distance (km)	Angle of Rotation	Radius of major axis(km)	Radius of minor axis(km)
Geometric center	-	113.70	23.09	-	64.46	276.73	103.07
Quality of built environment (Qu)	2010	113.68	22.96	14.00	63.69	201.84	94.24
	2011	113.67	22.95	15.83	64.08	203.38	92.49
	2012	113.67	22.96	14.91	63.68	207.06	93.45
	2013	113.68	22.97	13.75	63.94	208.96	93.22

	2014	113.67	22.97	13.71	63.93	209.99	93.31
	2015	113.66	22.96	14.49	63.69	213.60	93.90
	2016	113.67	22.97	13.15	64.04	213.20	94.27
	2017	113.66	22.98	12.22	64.05	215.65	95.10
	2018	113.66	22.99	11.59	64.03	216.93	95.32
Environmental pressure (Pu)	2010	113.54	23.09	17.10	61.49	219.69	113.05
	2011	113.52	23.09	18.42	61.53	219.25	113.53
	2012	113.53	23.07	18.18	61.57	220.55	112.49
	2013	113.53	23.08	17.60	61.68	221.81	112.28
	2014	113.52	23.09	18.47	61.38	221.16	112.40
	2015	113.43	23.03	28.70	59.96	235.30	111.24
	2016	113.54	23.08	16.39	61.70	223.82	111.55
	2017	113.55	23.07	15.94	62.11	224.96	109.48
	2018	113.56	23.06	15.26	62.06	224.33	108.85
Urban sustainability (Su)	2010	113.88	23.00	20.19	65.34	266.64	88.55
	2011	113.89	23.01	21.44	65.43	267.67	86.92
	2012	113.89	23.02	20.38	65.29	268.74	88.00
	2013	113.87	23.01	19.47	65.29	269.31	87.63
	2014	113.88	23.01	19.95	65.39	272.20	87.30
	2015	113.99	23.06	29.28	66.85	260.83	87.34
	2016	113.88	23.03	19.03	65.95	270.92	88.45
	2017	113.88	23.04	19.12	65.94	272.36	90.70
	2018	113.88	23.05	18.81	66.00	273.89	91.06

5.4. Discussions on countermeasures for cities in Pearl River Delta

Based on the radar charts of indicator categories, the specific performance of each city in the Pearl River Delta can be found by comparison. Then combining the heat map of each original indicator statistical data, the key points that the city needs to be improved can be clearly diagnosed. So that more targeted urban development strategies can be proposed in the near future. The specific subitems of sustainable characteristics and urban strategies of the city are discussed as follows (Fig. 5-7, 5-8).

5.4.1.Countermeasures of the quality of built environment

For urbanization economies (Figure 5), the economic performance of all 21 cities has shown an increasing trend as urbanization increases in the Pearl River Delta. The top six cities in urbanization level performed well, with scores higher than 0.6. The performance of GDP and income per capita are both high, but more reasonable adjustments to the industrial structure are needed. That is to increase the economic benefits of the industry by expanding the scale of the services industry. Taking the development plan of the Guangdong-Hong Kong-Macao Greater Bay Area as an opportunity and combining the advantages of ports will help these cities cooperate and develop rapidly in areas such as finance, software, real estate, and logistics. However, other cities scored below 0.5, showing a large economic gap. At present, the government the strategies of reducing the cost of manufacturing enterprises to support the development of the local real economy is improving economic returns. And it is better to implement the policies for attracting labor inflows at the same time. In particular, it is necessary to give priority to support for the economic growth of cities such as Shanwei, Jieyang, Heyuan, Zhanjiang, Maoming and Yunfu, which scored less than 0.2 and had a small increase in 9 years.

For infrastructure development (Figure 5), the differences between cities are still significant. Currently, Shenzhen, Dongguan, Zhuhai, and Guangzhou are performing better in this regard, with a score higher than 0.4. But the level of infrastructure in Shenzhen and Zhuhai has decreased due to insufficient land for construction, residential land and roads per capita. That is mainly because a high percentage of people's activity was concentrated in the core district of these cities leading to traffic pressure and high housing prices [7], so the supply and demand contradiction of land was highlighted. It can be adjusted appropriately by adopting purchase restriction policies. Some cities, such as Foshan, Zhongshan, Chaozhou, Shanwei, Jieyang, and Zhanjiang, are almost in a backward state in infrastructure indicators and need to focus on strengthening investment and construction. Coastal and inland cities can use the efficient strategies in Zhuhai and Yunfu as examples, such as the overall layout of urban and rural construction land, priority ensuring the land demand in dense districts, and the construction of a "water, land, air, and rail" multi-dimensional transportation network, etc. In addition, most cities with low levels of urbanization need to increase the per capita green area and road area to improve the quality of the human settlement environment.

For urban attraction (Figure 5), Guangzhou and Shenzhen, as provincial capital cities and sub-provincial cities respectively, exhibited absolute attractive advantages in all aspects, followed by Dongguan, Zhuhai, Huizhou and Jiangmen. Almost all of these cities' attractiveness indicators are basically in good condition, but there is still potential for improvement. Approximately two-thirds of the cities need to make great efforts in this area, with a score of less than 0.1. Six of them, Shaoguan, Shanwei, Yangjiang, Jieyang, Heyuan and Maoming, need to increase their attractiveness to tourists. These cities are rich in natural resources, ethnic minorities gather, and the conditions for the development of natural scenery and cultural tourism with ethnic characteristics are unique. In addition, Shaoguan, Shanwei, Yangjiang, Meizhou, Maoming and Yunfu can support the free development of export-oriented enterprises by providing flexible systems and reducing environmental restrictions. Most cities need to increase the attractiveness of foreign investment. Along with globalization and the international division of labor, foreign investors mostly are concentrated in regions with a comparative advantage in the manufacturing sector. Therefore, it is necessary for the government to work hard to reduce system barriers to improve the manufacturers environment, and to adopt more market-oriented policies to attract the inflow of foreign capital.

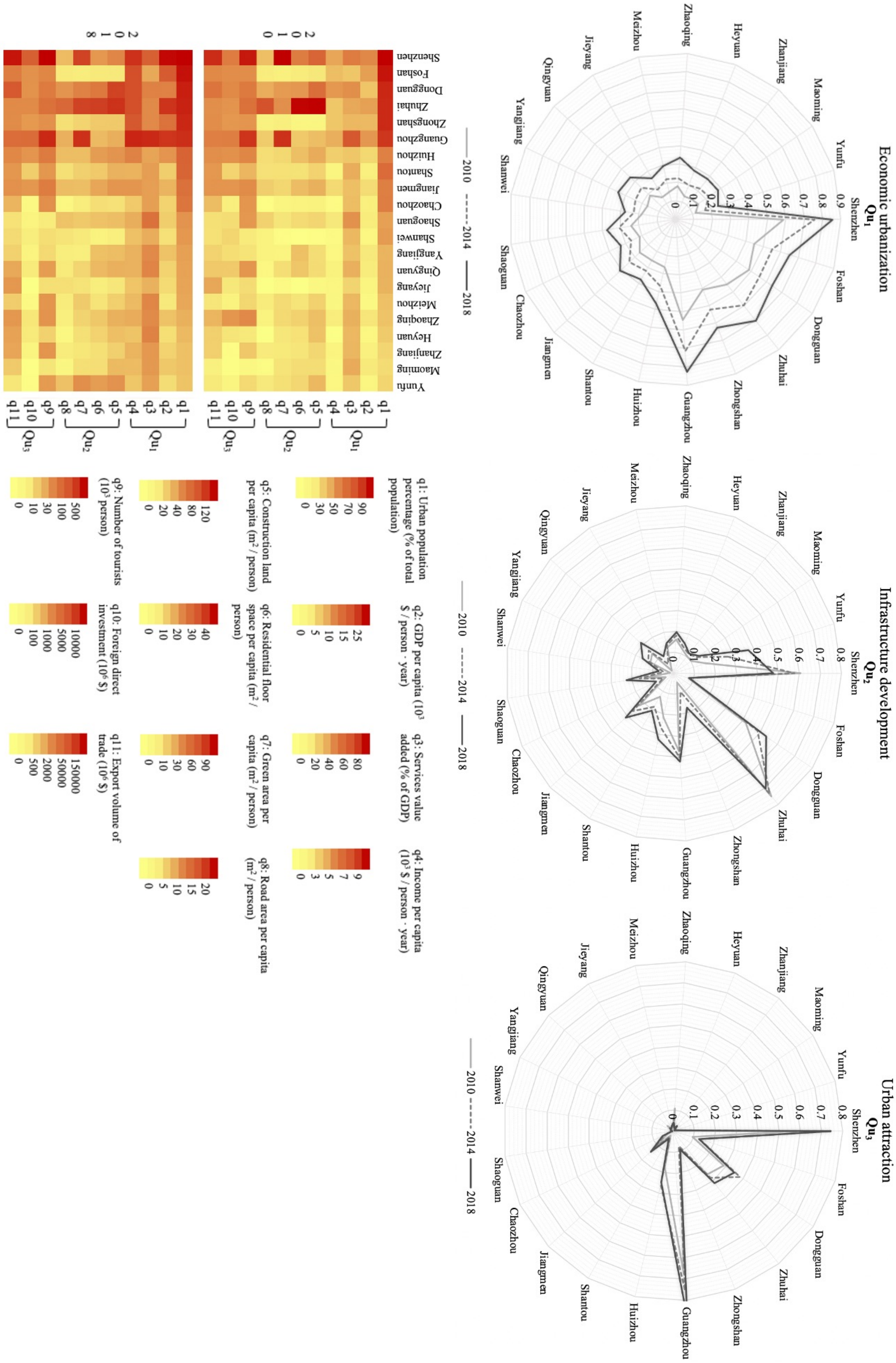


Fig. 5-7 The performance of each of the indicator categories of Qu in Pearl River Delta

5.4.2.Countermeasures of the environmental pressure

For resource Consumption, ten cities have eased the pressure in this regard, but consumption in 11 cities has increased from 2010 to 2018. Among them, Shantou performed the best, with a score below 0.1, benefiting from the development of low energy consumption industries. Since it was identified as the first batch of circular economy pilot cities in 2006, it has accelerated the development of low energy consumption and circular industries based on the principles of reduction, reuse, and recycling, and has achieved positive results. There are 11 cities have slightly pressure with the scores are between 0.1-0.2. Among them, the coastal cities of Jiangmen, Chaozhou, Yangjiang, Maoming, and Yunfu that have well-developed manufacturing industries need to control energy consumption, while Shanwei, Jieyang, Zhaoqing, Meizhou, Heyuan, and Zhanjiang need to give priority to reducing water consumption. Foshan and Dongguan Zhongshan, Huizhou, Qingyuan, and Shaoguan are at moderate pressure levels, with scores between 0.2-0.4. These six cities have more energy-intensive industries and have a higher level of urbanization than the above-mentioned cities. It is necessary to control industrial energy consumption and domestic water consumption. Zhuhai and Guangzhou scored above 0.4, reflecting that excessive resource consumption in cities has led to environmental pressure. These three cities have been listed as the highest warning level for urgent control of regional energy intensity for many years. Focus will need to be placed upon improving energy efficiency and upgrading green low-carbon technology during the coming period. In addition, water-saving measures in Zhuhai and Guangzhou are also top priorities.

For environmental pollution, the pollution level of most cities has been reduced from 2010 to 2018, and some of them have increased first and then decreased. At present, the environmental pollution scores of all 21 cities Pearl River Delta are less than 0.2, and the difference between cities is small. It shows that the quality of the atmosphere and water environment in the province continues to improve. According to the 2018 report, the air quality in the Pearl River Delta region has fully and stably reached the national air quality level II standard, and the water quality compliance rate of provincial-controlled rivers, lakes and reservoirs has reached more than 90%, thanks to a series of effective regional pollution prevention and control mechanisms implemented during the 12th Five-Year Plan [8]. However, there are still 4 cities of Dongguan, Shanwei, Qingyuan, Zhanjiang that have not returned to the level of 2010 or even worse, and still need further improvement. It can be found that the high rate of urbanization has a degrading effect on urban per capita pollution emissions in terms of wastewater and NOx emissions. Studies have shown that there is a positive correlation between household income and residential wastewater production in China [9]. So, with the rapid growth of urban population and income, it is better to optimize the current system for wastewater treatment. Moreover, the demand for car purchases in these cities has increased rapidly, and according to statistics, the number of cars in the region ranks second in the country. Therefore, cities urgently need to focus on the promotion and application of clean energy technologies. For example, the government can increase subsidies for the purchase of new energy vehicles and the corresponding supporting charging infrastructure at the same time. Additionally, awareness campaigns regarding environmental protection of recycling are also helpful for urban wastewater management.

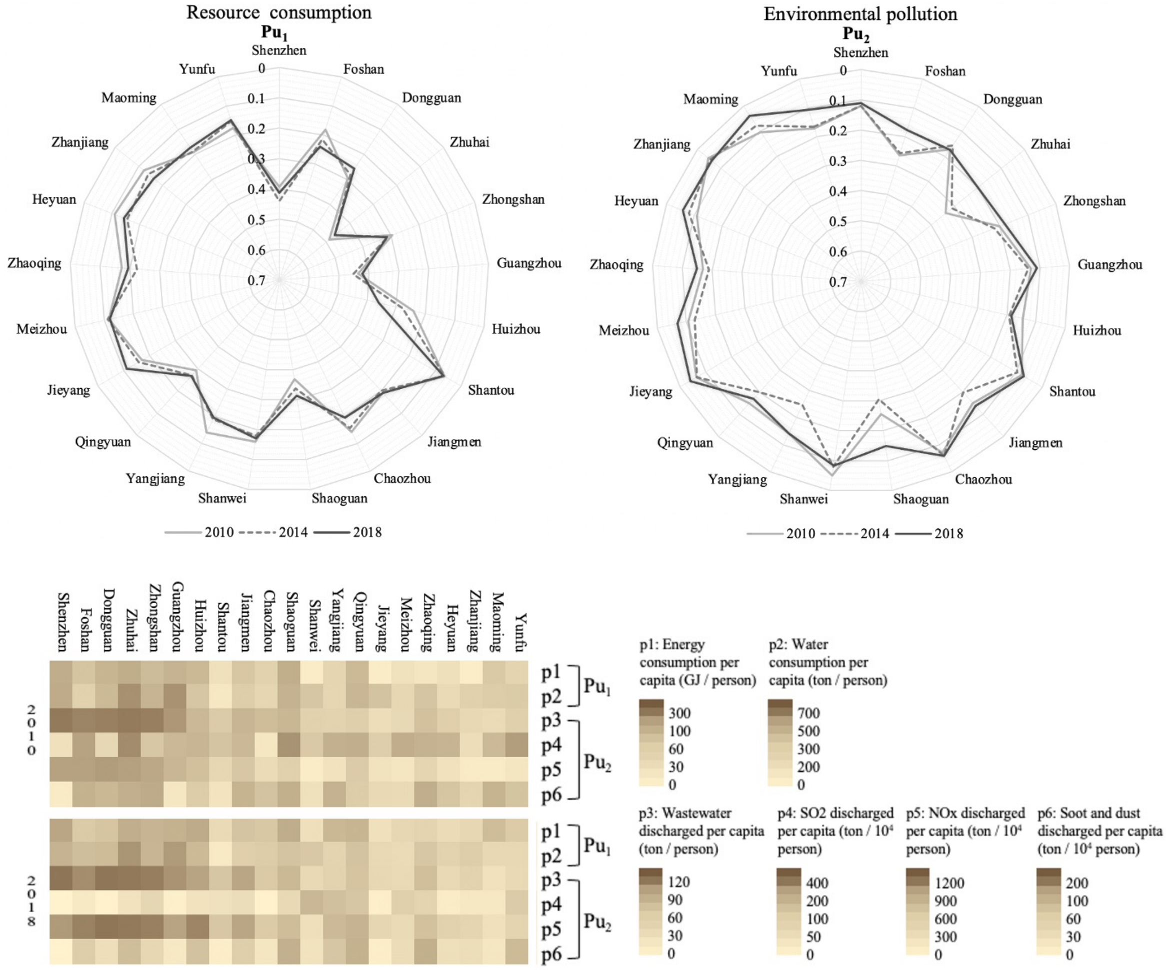


Fig. 5-8 The performance of each of the indicator categories of Pu in Pearl River Delta

5.5.Summary

The main conclusions of the empirical analysis of 21 cities in the Pearl River Delta megalopolis from 2010 to 2018 can be summarized as follows:

During the past 9 years, (1) the quality of the built environment in the study area has generally shown an upward trend, while the environmental pressure has changed slightly but eased. The main reason is labor-intensive and capital-intensive industries increased resource consumption and untimely environmental management investment. From the performance of evaluation scores, (2) the Qu index scores range from 0.054 to 0.702 and the Pu index scores range from 0.069 to 0.413. The composite Su score has a minimum value of 0.404 and a maximum value of 2.879, indicating that there is a significant development gap between cities in the region of Pearl River Delta. And (3) the number of cities in a sustainable state increased from 3 in 2010 to 18 in 2018, but there are still 3 cities in an unsustainable state of development, and all are medium-sized cities. Generalizing the basic conditions of cities reveals that Coastal cities typically reach sustainability earlier than inland cities. Most cities then achieve basic sustainability by improving the quality of the built environment but resulting in constant or even increased urban environmental loads. Using the curve estimation regression model, it was further found that (4) 81.0% of cities showed a significant relationship between Qu and Pu, and only 4 cities did not have significant interactions between Qu and Pu ($p \geqq 0.05$). There are five different types of interaction mechanisms. Among them, 6 cities showed an inverted U-shape and 4 cities with a negative linear relationship, which indicates that the negative impact on environmental stress is diminishing in improving the quality of the built environment. However, (5) there are 4 cities showing an inverted S-shape, one city with a U-shape, and 2 cities with a positive linear mechanism, means that there are adverse urban development trends due to mutual inhibition and 38.1% of cities should especially worthy of attention to environmental management.

In terms of spatio-temporal characteristics of evolution results, it can be intuitively found that (6) the sustainability of the urban environment in this area shows slightly urban differences and spatial heterogeneity. In Pearl River Delta, the spatial patterns of urban sustainability show a development pattern that gradually spreads from the central part to the two ends. A sustainable urban belt along the coast was formed in 2018, with the cities located in the central part having the highest sustainable development level. Specifically, (7) the mean centers of Qu, Pu and Su all move closer to the geometric center respectively at a migration speed of 0.42 km/year to the north, 0.48km/year to the east and 0.60 km/year to the west. But the distances from each of the above mean centers to the geographic center are 11.59 km, 15.26 km and 18.81 km. That reveals the gap between the unbalanced development of west and east cities in the Pearl River Delta region is gradually diminishing.

Therefore, at the level of macro-regional coordinated development, (9) it is necessary to strengthen the advantages of the coastal city belt to drive the high-quality development of the backward cities in the north, and simultaneously alleviate the environmental pressure on these cities. At the micro level of city-specific development, (10) the results of each city's sub-assessment scores can be combined with a heat map of indicator statistics for a case-by-case diagnosis. Broadly speaking, (11) for the countermeasures of the quality of built environment, the cities recommended to prioritize responses of urbanization economies are Dongguan, Huzhou, Jiangmen, Jieyang, Zhaoqing, Heyuan, Zhanjiang and Yunfu; the cities that need to give priority to improve infrastructure development are Shenzhen, Foshan, Zhongshan, Guangzhou, Chaozhou, Shanwei, Meizhou; and the cities that need to particularly strengthen their urban attractiveness are Zhuhai, Shantou, Shanwei and Meizhou. (12) For the countermeasures of the environmental pressure, the cities recommended to prioritize responses to reduce resource consumption are Shenzhen, Zhuhai, Guangzhou, Chaozhou, Shaoguan, Heyuan, Zhanjiang and Maoming, while the other cities urgently need to prioritize deal with the severe environmental pollution issues.

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Chapter 6. Measuring the Performance Urban Sustainability in Shandong Peninsula

6.1. Introduction

6.1.1.General information of urban environment in Shandong Peninsula

The Shandong Peninsula megalopolis (geographic coordinates: 114.48° 48' E-122° 42' E longitude and 34° 23' N-38° 24' N latitude) , as a national priority planning area of 16 cities, has played a major role in eastern China (Fig. 6-1). The total area is 157,754.94 km^2 located in the lower reaches of the Yellow River and extends out to sea as a typical peninsula region (between the Bohai Sea to the north and the Yellow Sea to the south) [1]. The region of the Shandong Peninsula megalopolis was first delineated in the early master planning guidebook (2006-2020), including 8 cities. Later, in the new urbanization planning guidebook (2014-2020), it was expanded to 14 cities. At present, 16 cities in the province have been covered in the Shandong Peninsula in the latest regional development plan (2016-2030), which is the study area of this chapter (Table. 6-1).

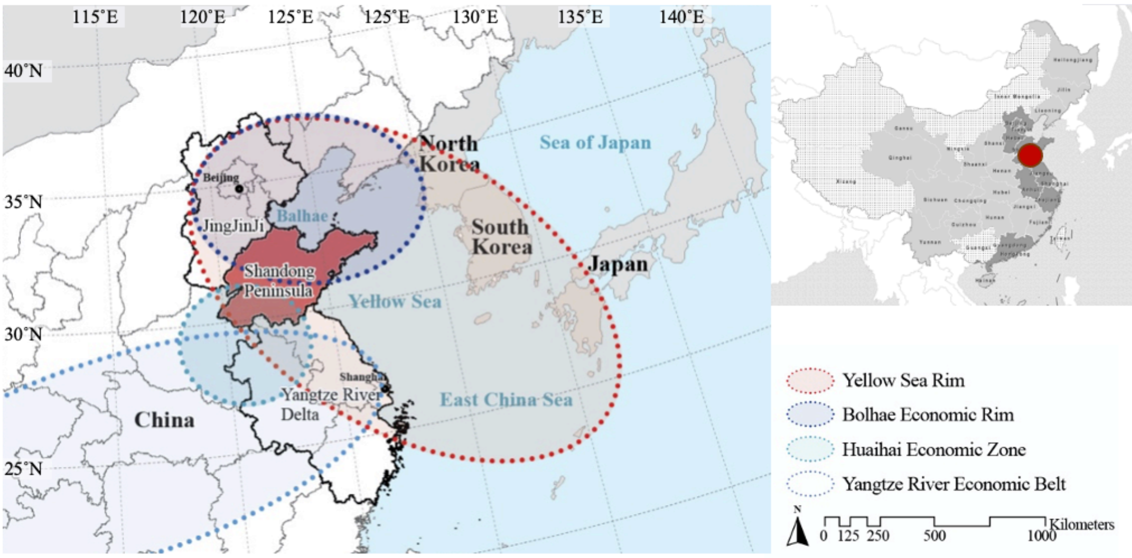


Fig. 6-1 Geography of the Shandong Peninsula megalopolis

With the absolute advantages of resource-rich and labor-abundant, it has become the biggest China's industrial producer and one of the top manufacturing areas. It is also one of China's most important energy providers with 50,000 km^2 of coalfields. For these reasons, Shandong has strong economic potential after the opening-up. In 2017, Shandong had a GDP of $10,720 per capita, ranked third in the Chinese megalopolises. However, this rapid economic growth has caused excessive energy consumption and pollution, resulting in tremendous pressure on the environment and creating a huge obstacle to the sustainable urban development of the Shandong Peninsula region.

Compared with other three important regions in China, the Shandong Peninsula region has more geographical advantages, which is expected to lead the way in high-quality trade in the Northeast Asian region. From an international side, it with neighboring Japan and South Korea countries has very convenient transportation, and a number of international cooperation agreements have been reached. From the domestic side, it is easy to internal cooperation with advanced adjacent areas of JingJinJi, Yangtze River Delta, and the Yellow River Economic Belt.

Table 6-1 Outline and classification of 16 cities in Shandong Peninsula in 2018

Cities in Shandong Peninsula (belonging to the Shandong Province)	Urban population (10^4 persons)	Urbanization rate (%)	Total population (10^4 persons)	Land area (km^2)	Density (persons $/km^2$)	GDP ($ / person)	GDP (10^9 $)	Length of coastline (km)
Qingdao	692.15	73.67	939.48	11175	840.68	19267.94	181.02	863
Zibo	336.15	71.49	470.18	5965	788.21	16258.82	76.45	-
Jinan	625.80	70.80	883.94	10244	862.89	15121.88	133.67	-
Dongying	149.97	69.04	217.21	7923	274.14	28834.55	62.63	350
Weihai	191.91	67.81	283.00	5797	488.19	19407.87	54.92	986
Yantai	463.45	65.07	712.18	13746	518.08	16588.29	118.14	909
Tai'an	348.97	61.87	564.00	7762	726.63	9765.22	55.08	-
Weifang	579.28	61.80	937.30	16143	580.62	9907.44	92.86	113
Rizhao	176.85	60.35	293.03	5348	547.93	11335.10	33.22	100
Zaozhuang	231.25	58.88	392.73	4563	860.64	9226.44	36.23	-
Jining	491.19	58.85	834.59	11187	746.04	8910.69	74.37	-
Binzhou	226.11	57.64	392.25	9445	415.31	10153.43	39.83	240
Dezhou	331.25	57.01	581.00	10356	561.01	8775.37	50.98	-
Liaocheng	314.50	51.77	607.45	8715	697.05	7826.77	47.54	-
Linyi	547.59	51.54	1062.40	17191	617.99	6697.89	71.16	-
Heze	440.48	50.25	876.50	12194	718.80	5298.02	46.44	-
Total of Shandong Peninsula	6146.90	61.18	10047.24	157754.94	636.89	11690.12	1174.53	3561
% of China (except autonomous and special administrative regions)	7.87	-	7.81	3.01	-	-	8.99	14.45

6.1.2.The challenge of sustainable urbanization in Shandong Peninsula

Shandong Peninsula is China's second most populous region and is experiencing its fastest urbanization development period in history [2]. Since the urban population surpassed the rural population in 2012, the annual urbanization growth rate has been greater than 1%, and about 1 million people migrate to its urban areas each year (Fig. 6-2). As a result, the urban density in 2017 was as high as 637 persons/km^2.

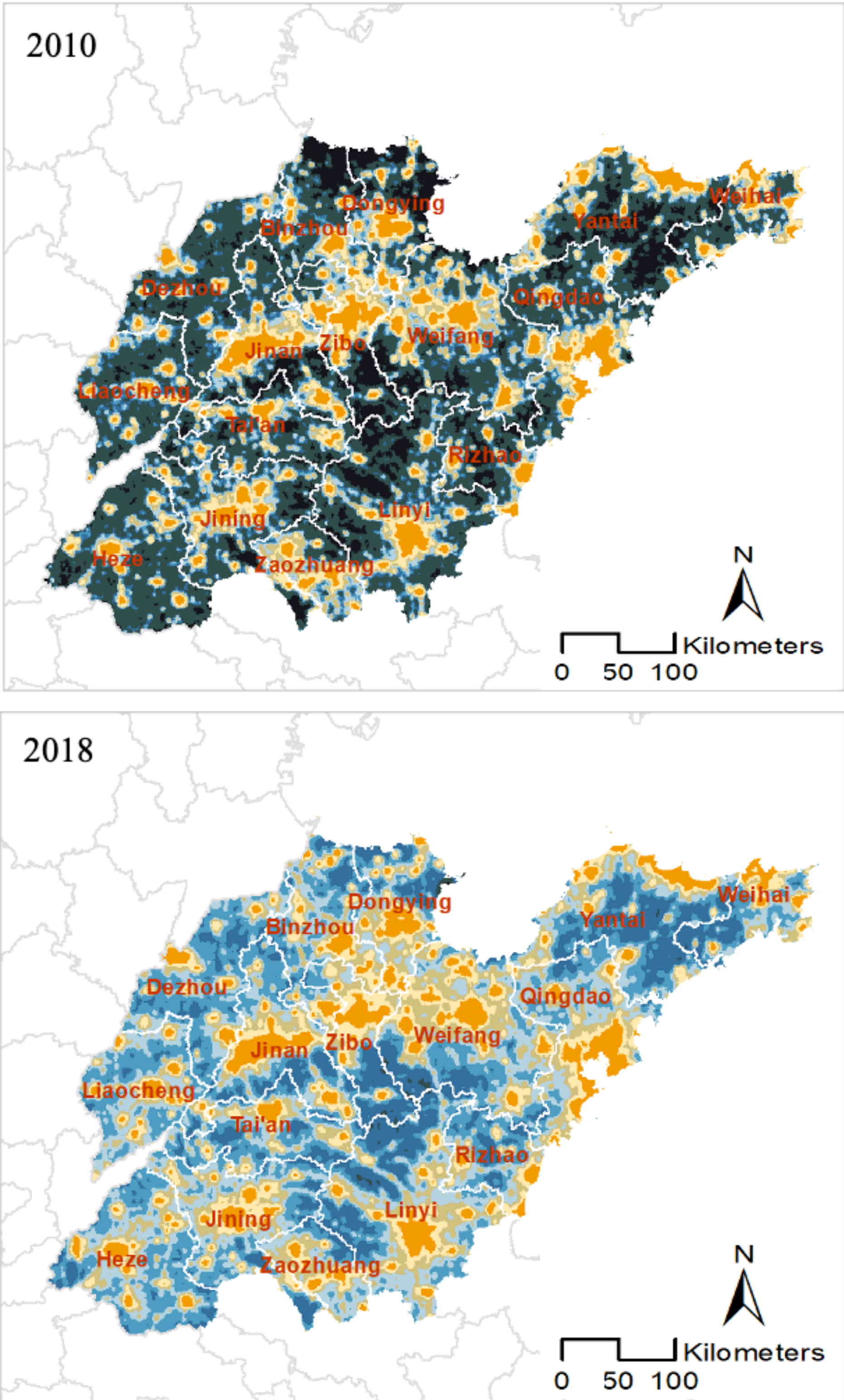


Fig. 6-2 The evolution of urbanization in Shandong Peninsula from 2010 to 2018. (Notes: the degree of urban population is represented by the change of color. The deeper yellow color represents higher urbanization, and the deeper blue color represents lower urbanization.)

Since the reform and opening up policy implementation, the urbanization development in Shandong Peninsula can be divided into four phases. The first phase lasted from 1978 to 1986 when the urbanization rate increased from 13.6% to 23%. In this period, the development of secondary and tertiary industry absorbed large amount of surplus rural labor force, waking up the urbanization process from the stagnating planned economy. The second phase (1987-1998) is the phase of the initial stage when urbanization rate had reached 35% in 1998. The output value ratio of the tertiary industry ascended significantly. The third accelerated phase lasted from 1999 to 2009 when the rate increased from 36.58% to 48.32%, with an increasing speed of even over 1.5% per year. And the lack of infrastructure and environmental problems are becoming increasingly significant, that have become key bottlenecks restricting regional development [3].

In the fourth stage of urbanization starting in 2010, it is predicted that Shandong Peninsula will continue to go on rapid urbanizing during next one or two decades. It is estimated that by 2030, the urban population of Shandong Peninsula will be about 80 million, and the urbanization level will reach about 75% [4]. That means the sustainable development of cities will face severe challenges. On the one hand, the current infrastructure construction speed is relatively backward. Failure to meet the growing needs of the population will result in a reduction in the quality of life of the citizens, which will affect the willingness to live in. On the other hand, the local transmission industry has many layouts and slow upgrades. Consumption and pollution are likely to increase the environmental pressure of the city, especially in the winter heating season.

6.2. Results presentation and interaction mechanism analysis in Shandong Peninsula

6.2.1.Overall results for each city

After calculation of the urban sustainability assessment, all evaluation scores for 16 cities of the Shandong Peninsula in 2010-2018 were obtained. The ranges of the Qu, Pu and Su values is shown in the box charts of Fig. 6-3 respectively. It can be roughly seen that: (1) Cities with higher urbanization rates have the high quality of the built environment, with little difference in the magnitude of change. (2) Environmental pressure is clearly divided into two different situations. Most of the cities with relatively small environmental pressures, but individual cities have obvious environmental problems with a significant range of score changes. (3) The degree of urban sustainability roughly follows the trend of urbanization rate, but some cities with higher urbanization rates have a significant lagging gap.

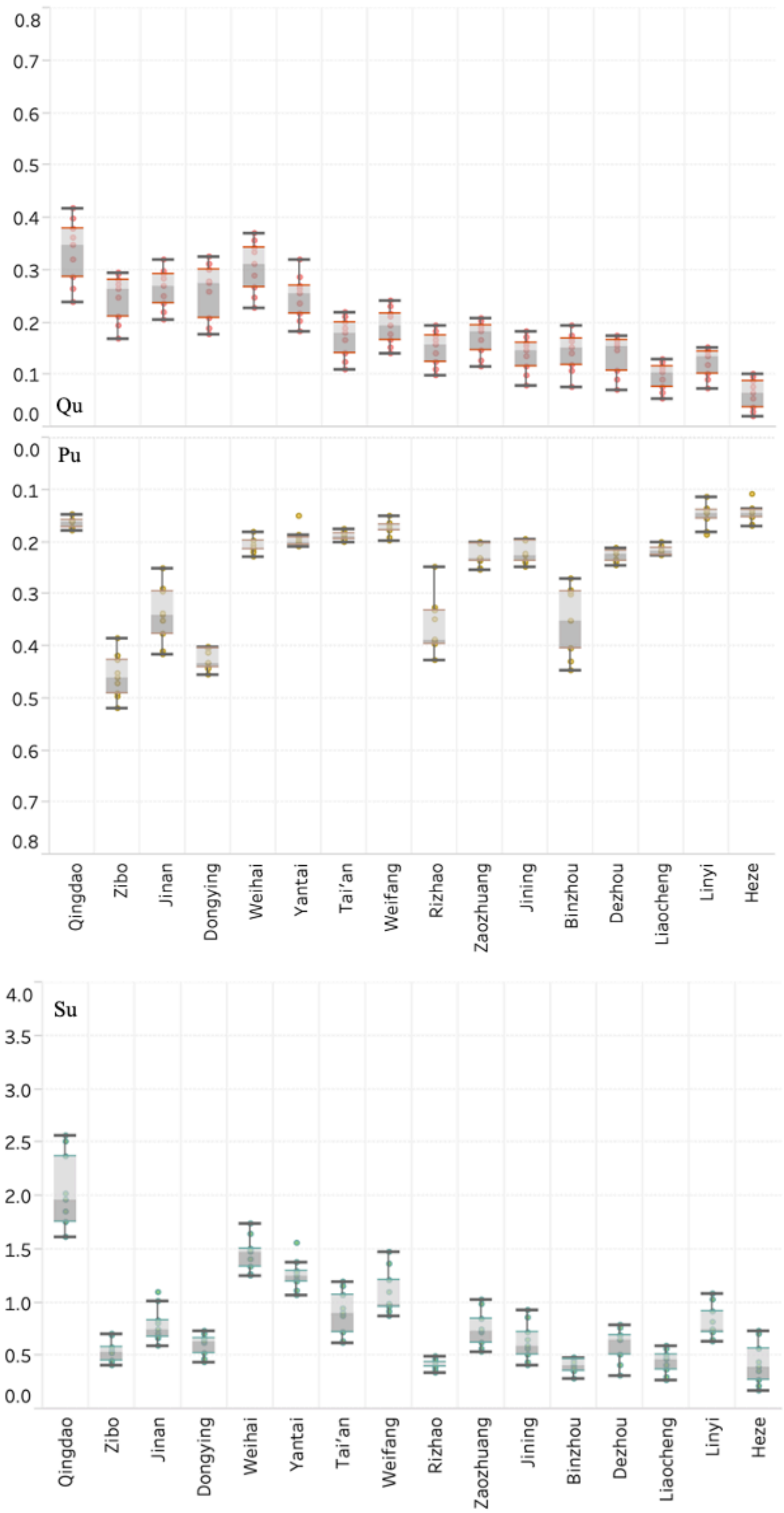
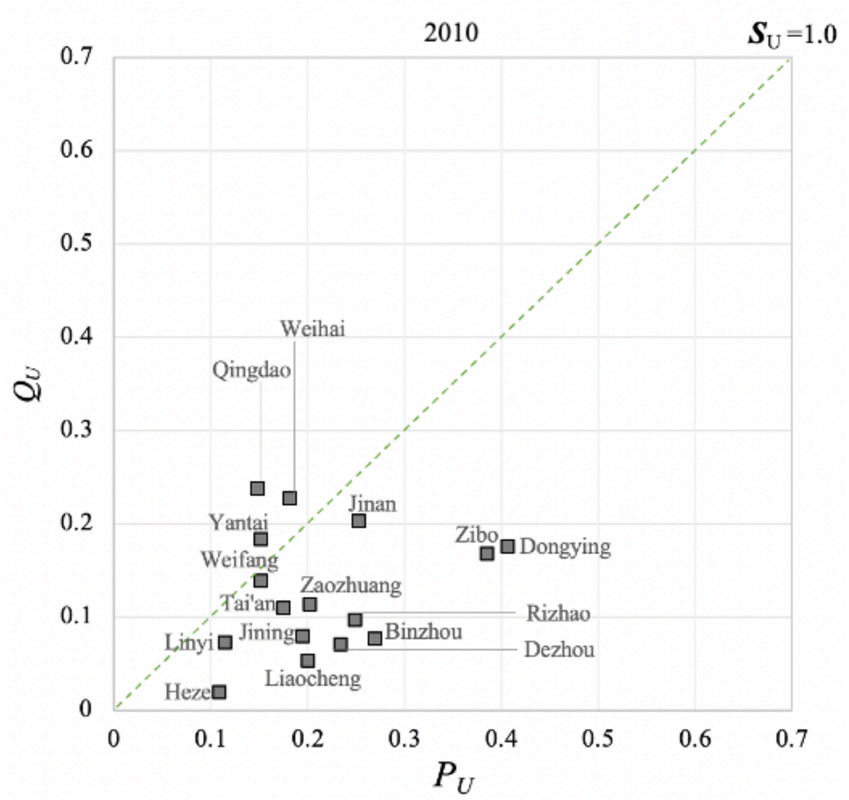


Fig. 6-3 The scores of Qu, Pu and Su of 16 cities in Shandong Peninsula from 2010 to 2018 measured by urban sustainability assessment system.

Specifically, from Fig. 6-3(Qu), the index of Qu for the 16 cities ranged from 0.019 to 0.417. The compound annual growth rate (CAGR) in the past 9 years is between 5.14% and 20.71%. From 2010 to 2018, The performance of Qingdao has been in a leading position in this dimension. But even if Heze has the highest growth rate, its score is still the lowest. Other backward cities such as Liaocheng and Binzhou have also changed significantly, with CAGR values exceeding 10%. Except for some historical reasons, the underdeveloped secondary and tertiary industries and the priority policy of supporting coastal areas are the main reasons for these cities' backwardness. Then, the index of Pu ranged from 0.109 to 0.499 shown in Fig. 6-3(Pu) These two are the scores of Heze in 2010 and Zibo in 2014, and the environmental pressure in Dongying is currently in the highest level. The range of CAGR is between -0.72% to 5.05% per year. Only one city has a negative growth rate, which means that the pressure on cities in Shandong Peninsula is increasing throughout the region. And it can be clearly seen that the scores of several heavy industrial cities (Zibo, Jinan, Dongying, Rizhao and Binzhou) are generally higher, which is the result of the consumption of resources and the high environmental load in pursuit of economic growth. The adverse environmental effects would restrict the sustainable development of cities in the long run. On the contrary, the environmental pressure of other cities, especially coastal cities, has been well controlled during urbanization. This resulted from targeted planning policies like the "Shandong Peninsula Urban Agglomeration Master Plan (2006-2020).” It provided guidance and encouragement in green construction and clean energy use, etc.

From the comprehensive variation of Su in Fig. 6-3(Su), the lowest score is 0.172 that got by Heze City in 2010. And the highest score is 2.565, which is Qingdao's score in 2018. From the median point of view, the cities with Su scores more than 1.0 (Qingdao, Weihai, Yantai and Weifang) are the first coastal cities to be included in the Shandong Peninsula, and the rate of improvement is relatively fast. This proves that the previous overall planning policy has had a certain improvement effect on the development of these cities. However, some cities are in a severely unsustainable state, with a median value of less than 0.5. These cities also have the smallest increase in the entire region and are facing a very severe adverse situation.

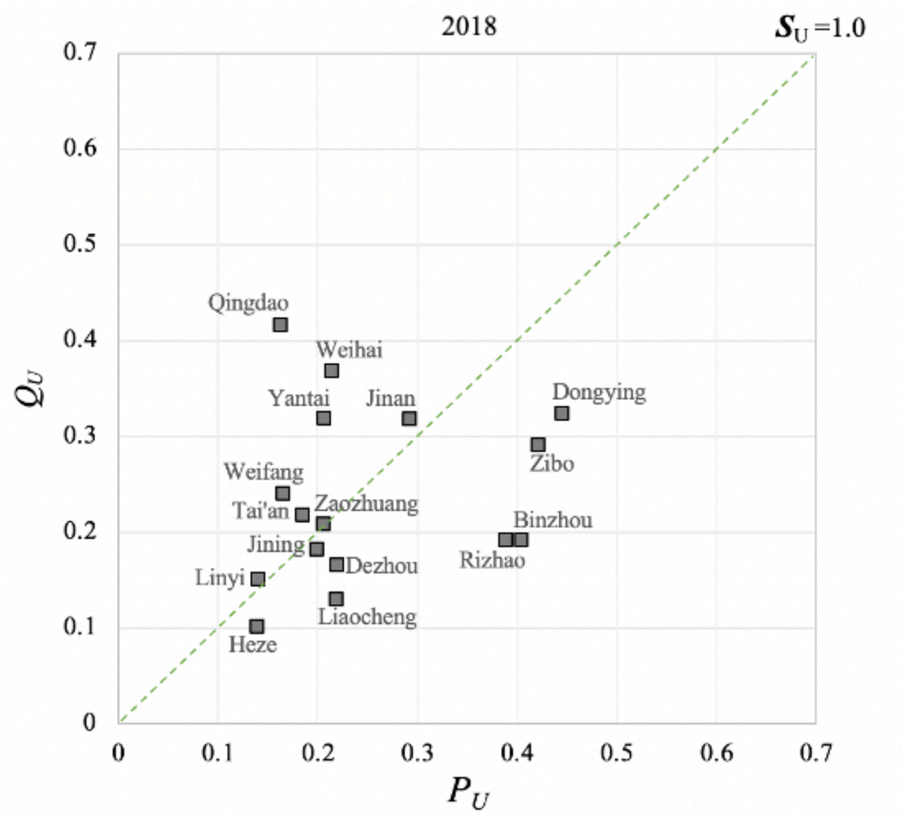
In addition, the urban development states of 16 cities in Shandong Peninsula from 2010 to 2018 could be presented from Figure 3 and found that: (1) The number of cities in a state of sustainable development increased from 3 cities in 2010 to 8 in 2018, half of the cities are still in an unsustainable state of development. （2）At the beginning, the sustainability of coastal cities is better, while the improvement of inland cities is relatively large. This is related to the expansion of the coverage of regional planning policies. （3）In the Shandong Peninsula, all large cities have reached a state of sustainable development. It can be considered that a larger city scale is helpful to quickly improve the level of sustainable development, which is achieved by a development model that keeps the environmental load unchanged while improving the quality of the city. (4) The development path of medium-sized cities is divided into two modes: a few cities (Dezhou and Tai'an) can increase Qu while further reducing the pressure on the environment. Due to the limitation of population size, the strategy adopted by most cities (such as Dongying, Heze, Rizhao, etc.) is to prioritize human resources and other resources to improve Qu. Although it has a certain positive effect, it more or less aggravated impact on the environment inevitably. That also the main reason for the slow improvement of the sustainable level of medium-sized cities.



2010

Classification		Small cities	Medium-sized cities	Large cities	Mega cities	Number of cities	
Su < 1.0 (Qu< Pu)	Coastal	-	Weifang, Dongying, Rizhao, Binzhou	-	-	4	13
	Inland	-	Tai'an, Zaozhuang, Zibo, Jining, Dezhou, Liaocheng, Heze	Jinan, Linyi	-	9	
Su ≥ 1.0 (Qu≥ Pu)	Coastal	-	Weihai, Yantai	Qingdao	-	3	3
	Inland	-	-	-	-	0	

(a) The regression result and the corrosponding city list of 2010



2018

Classification		Small cities	Medium-sized cities	Large cities	Mega cities	Number of cities	
Su < 1.0 (Qu< Pu)	Coastal	-	Dongying, Rizhao, Binzhou	-	-	3	8
	Inland	-	Jining, Dezhou, Heze, Zibo, Liaocheng	-	-	5	
Su ≥ 1.0 (Qu≥ Pu)	Coastal	-	Weihai, Yantai, Weifang	Qingdao	-	4	8
	Inland	-	Tai'an, Zaozhuang	Jinan, Linyi	-	4	

(b) The regression result and the corrosponding city list of 2018

Fig. 6-4 The regression trends of different types of cities from 2010 to 2018

Note: (1) Su < 1.0 (Qu < Pu) means the city is in a barely or seriously unsustainable urbanization process. The increasing pace of urban environmental pressure (Pu) is faster than the improved pace of urban built environment quality (Qu). Su ≥ 1.0 (Qu ≥ Pu) means the city is in a basic or highly sustainable urbanization process. The increasing pace of urban environmental pressure (Pu) is slower than the improved pace of urban built environment quality (Qu). (2) Small cities (urban population < 1 million); Medium-sized cities (5 million > urban population ≧ 1 million); Large cities (10 million > urban population ≧ 5 million); Mega cities (urban population ≧ 10 million)

6.2.2.Coupling interaction mechanism between Qu and Pu

The relationship between Qu and Pu of 16 cities in Shandong Peninsula is obtained through the method of curve estimation and regression in Table 6-2, so as to further understand the development trend of the city. The estimation list shows that except for Dezhou, the performance of these two aspects of other 15 cities has a significant coupling relationship, with the p values lower than 0.5. Three types of mechanisms have been found as follows：

(1) Inverted U-shaped relationship: 10 of the cities have developed significantly during the rapid urbanization stage, but environmental problems have intensified. Most inflection points appeared around 2014 or 2016 due to the changes in development planning strategies in recent years, indicating the introduction of a well-coordinated development trend. Among them, cities with relatively high environmental pressure have paid attention to environmental issues ahead of time, so the transition period appears early, such as Weifang and Zaozhuang. And Qingdao and Jinan are more valued because of their priority city status.

(2)Inverted S-shaped relationship (3 cities): the three cities with this situation are Zibo, Jining and Heze. They all made their first benign turning point in 2014 thanks to related environmental protection strategies, which reduced the environmental pressure. However, these cities have always been eager to improve the level of urbanization, while ignoring the coordinated development of Qu and Pu. As a result, the three cities have been in an unsustainable state of development. And the opposite trend appeared in 2017, which indicates that environmental problems are at risk of worsening again in the future.

(3)Positive linear relationship (2 cites): The relationship between Qu and Pu in Dongying and Binzhou is the most unfavorable situation for the sustainable development of cities in the entire Shandong Peninsula. The continuous improvement of urban quality is accompanied by a continuous increase in environmental load. Although the development of Qu of the two is relatively fast, they have already caused serious environmental problems to the urban environment, such as large areas of soil, water pollution, and high intensity of sand and dust weather, which require long-term recovery.

Table 6-2 The coupling interaction mechanism between *f*(Q) and *g*(P) by regression analysis of the 16 cities in Shandong Peninsula

Cities	AIC	BIC	R^2	Adjusted R^2	Std. error	F	p[1] value	Regression equation	Description	Inflection year
Qingdao	-62.774	-62.183	0.676	0.568	0.006	6.268	0.034*	*g(P) =-0.108+1.671 f(Q)-2.484 f(Q)2*		2013
Jinan	-28.964	-28.372	0.556	0.408	0.042	4.755	0.048*	*g(P) =-1.829+16.923 f(Q)-32.341 f(Q)2*		2014
Weihai	-64.861	-64.270	0.878	0.838	0.006	21.621	0.002**	*g(P) =-0.187+2.821 f(Q)-5.01 f(Q)2*		2016
Yantai	-61.389	-60.798	0.886	0.848	0.007	23.401	0.001**	*g(P) =-0.109+1.912 f(Q)-2.788 f(Q)2*		2016
Tai'an	-63.968	-63.377	0.618	0.491	0.006	4.853	0.049*	*g(P) =0.039+1.936 f(Q)-5.89 f(Q)2*	Inverted U-shaped relationship	2013
Weifang	-62.322	-61.730	0.825	0.767	0.007	14.163	0.005**	*g(P) =-0.264+4.696 f(Q)-12.147 f(Q)2*		2014
Rizhao	-44.263	-43.671	0.914	0.886	0.018	32.056	0.001***	*g(P) =-0.328+8.41 f(Q)-24.27 f(Q)2*		2017
Zaozhuang	-50.183	-49.591	0.662	0.549	0.013	5.879	0.039*	*g(P) =-0.259+6.309 f(Q)-19.579 f(Q)2*		2014
Liaocheng	-69.938	-69.346	0.838	0.784	0.004	15.480	0.004**	*g(P) =0.13+1.738 f(Q)-7.984 f(Q)2*		2016
Linyi	-45.221	-44.630	0.585	0.446	0.017	4.224	0.049*	*g(P) =-0.153+5.061 f(Q)-20.196 f(Q)2*		2016
Zibo	-32.464	-31.675	0.603	0.364	0.034	4.194	0.049*	*g(P) =0.643+7.972 f(Q)-57.427 f(Q)2+111.264 f(Q)3*		2014&2017
Jining	-54.445	-53.656	0.838	0.740	0.010	8.607	0.020*	*g(P) =0.003+2.991 f(Q)-4.401 f(Q)2+34.774 f(Q)3*	Inverted S-shaped relationship	2013&2017
Heze	-59.046	-58.257	0.893	0.829	0.008	13.935	0.007**	*g(P) =0.057+3.429 f(Q)-28.537 f(Q)2+21.831 f(Q)3*		2014&2017
Dongying	-56.747	-56.352	0.819	0.793	0.009	31.569	0.001***	*g(P) =0.339+0.343 f(Q)*	Positive linear relationship	-
Binzhou	-30.013	-29.619	0.668	0.668	0.041	14.111	0.007**	*g(P) =0.142+1.493 f(Q)*		-
Dezhou	-50.512	-49.920	0.130	-0.160	0.013	0.447	0.659	*g(P) =0.276-0.956 f(Q)-4.136 f(Q)2*	No significant relationship	2013

6.3. Spatio-temporal characteristics of urban sustainability in Shandong Peninsula

6.3.1.Spatio-temporal variation patterns of results

As shown in Fig. 6-5(Qu), cities with better urban built environment quality are distributed in the central to eastern coastal areas. It is mainly based on that the advanced cities of Jinan, Qingdao and Weihai have a positive effect on the surrounding areas through promoting the improvement of the quality level of cities along the east-west horizontal axis. Other inland cities are still lagging behind, and this distribution feature is closely related to the planning policies that give priority to supporting the development of coastal cities. At present, the gap between these cities and the advanced cities is becoming more and more obvious in the cities that run through the horizontal axis in the east-west direction. It is possible to consider increasing the construction of the transportation network to make the cooperation between coastal and inland cities closer and the sharing of resources such as talents and technology more convenient. In addition, it can be considered to take the lead in supporting cities with development potential in the southern region, such as Zaozhuang, and to promote the development of cities along the north-south line along with Dongying and Jinan, and then gradually support other relatively backward inland cities in the west.

The distribution pattern of Pu results of Fig. 6-5(Pu) is different from Qu's. The areas with greatest environmental pressure on the Shandong Peninsula were initially concentrated in the northwest part adjacent to the JingJinJi region, and then the environment in the south and east also deteriorated. By 2018, the environmental pressure of several cities in the south has eased, and cities in the northwest still have serious environmental problems. This is closely related to Shandong's position on heavy industry, Especially the traditional industries such as petrochemical, steel and coal, which account for about 68% of total industrial output value [5]. And these heavy industry and energy mining bases are located in the northwestern region, so energy consumption and pollution emissions are one of the causes of environmental degradation. Another reason is that the urbanization process has increased the energy consumption of daily life and transportation in the urban area. Therefore, due to untimely environmental countermeasures and other reasons, some cities with higher urban standards are also facing greater environmental pressures, such as Yantai and Weihai. , Tai'an and so on.

The distribution pattern of the comprehensive Su results is shown in Fig. 6-5(Su). The spatial distribution characteristics of urban sustainability in the Shandong Peninsula present a trend of gradual improvement from the coastal cities in the east to the cities in the central and southern areas. The three eastern cities have reached a basic level of sustainability since 2010, which shows that the advantages of beautiful coastal environment, marine economy and resource have been fully utilized for urban development. Several neighboring cities in the central and southern regions showed good momentum and all reached a sustainable state in 2018. This trend is consistent with the urban development structure chart in the Shandong Peninsula Urban Agglomeration Development Plan (2016-2030)

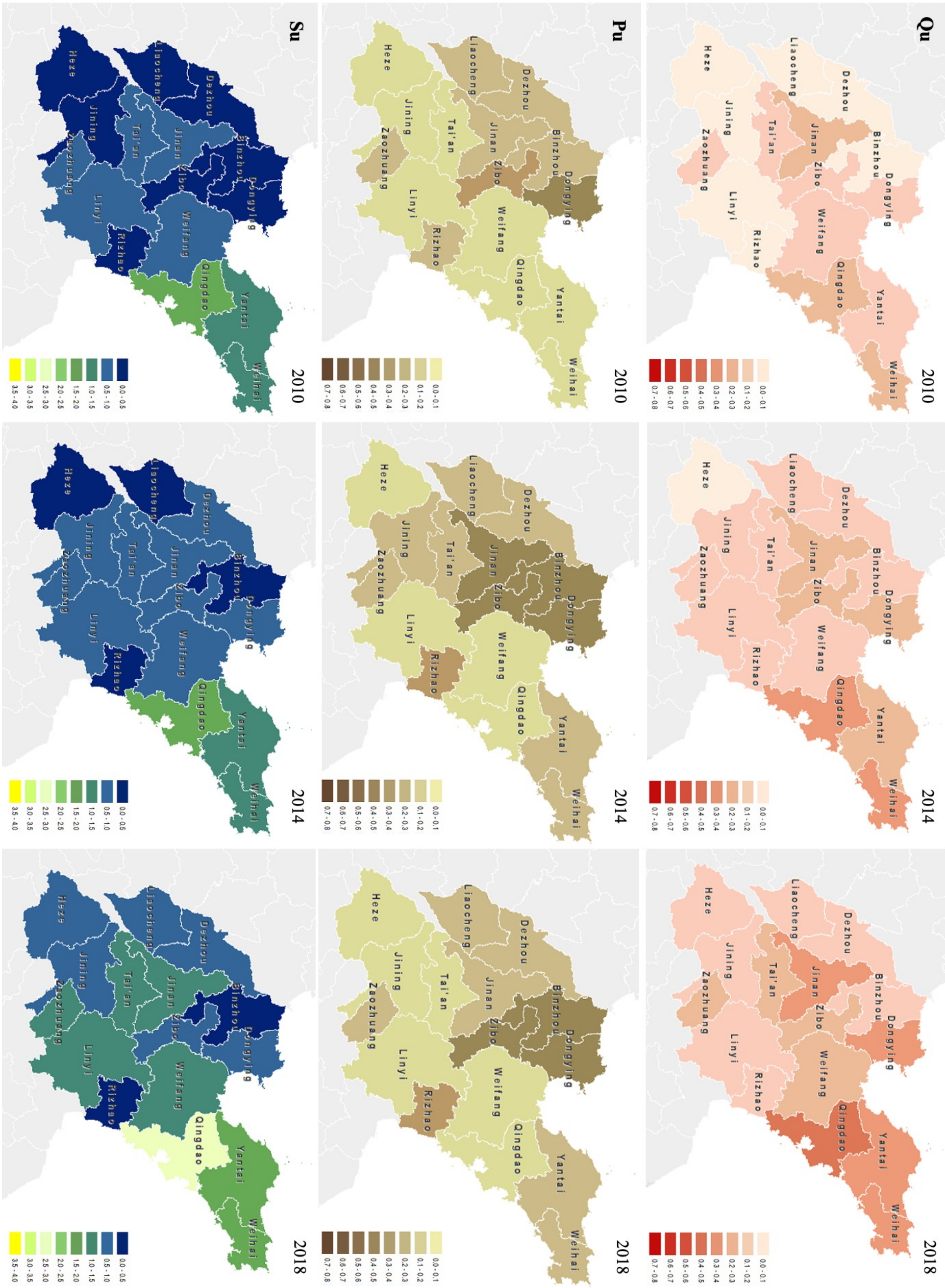


Fig. 6-5 The spatio-temporal variation pattern in the Shandong Peninsula from 2010 to 2018.

report [6]. In other words, planning policies play a vital role in the development of cities, and can guide the strengthening of connections between cities, so as to provide help for backward cities to achieve integrated development. However, most cities in the northern and western regions are still in an unsustainable state of development. In addition, Rizhao City, near the sea, is the only unsustainable city in the southeast. Like Binzhou City, the Su scores of these two cities have still lower than 0.5 during the past 9 years, which is very worthy of priority attention in the future.

6.3.2.Evolution track characteristics of regional patterns

Fig. 6-6 and Table 6-3 shows the results of the evolution track analysis of the Shandong Peninsula year by year and the corresponding detailed parameters list. On the whole, the mean centers of the evaluation results of Qu, Pu and Su have different degrees of deviation from the geographic center, reflects that the regional development of the Shandong Peninsula is still in an unbalanced state. Seen separately, the mean centers of Qu and Su are located in Weifang City, moving from northeast to southwest and gradually approaching the geographic center. Among them, the distance from the mean center of Qu and Su to the geographic center is 56.25km and 60.38km in 2018 and shortened by 19.67km and 33.99km respectively in 9 years. The mean center of Pu is slight to the north but still located in Zibo City same with the geometric center, and the evolution trace has moved a small distance eastward. The shapes of standard deviation ellipses of three values are barely unchanged, with the minor axis increased a little. The distance from the mean center of Pu to the geographic center has been extended from 17.2km to 18.54km. It indicates that slightly heterogeneous regional pattern changes have occurred over time to a certain extent in the Shandong Peninsula.

Although the angles of the three ellipses are approximately 65°, the major axis of Pu is significantly shorter than that of Qu or Su, which means that cities in the northwest-southeast of Shandong Peninsula have relatively lower development quality and greater environmental pressure. Therefore, there is a greater gap in sustainability from cities in the opposite direction and regional policies should focus more on supporting cities in the northwest-southeast direction. From the annual migration speeds, the mean center of Su (V_S=4.30 km/year) has the fastest moving speed, followed by that of Qu (V_Q=2.47 km/year) and Pu (V_P=1.00 km/year). It shows that the sustainable development of the Shandong Peninsula is changing from an imbalance to a gradually balanced situation at a relatively rapid rate. In order to maintain this positive trend, development policies at the regional level are preferred to prioritize improving the quality of the built environment of southwestern cities and solve environmental problems in southern cities.

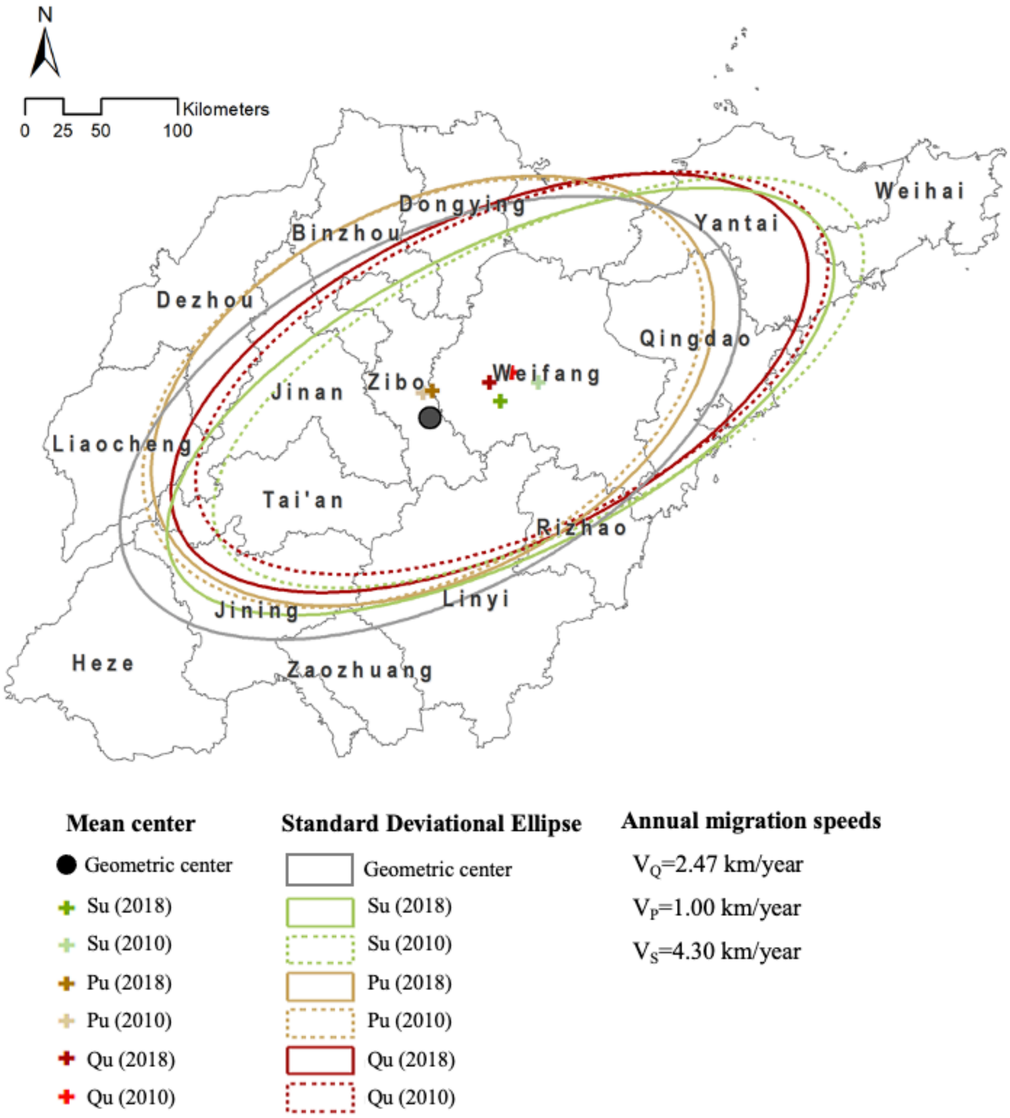


Fig. 6-6 Spatial dynamic map of Qu / Pu/ Su based on mean center and standard deviation ellipse during 2010–2018 across Shandong Peninsula

Table 6-3 The detailed parameter of mean center and standard deviation ellipse

Weighted field	Year	Mean center: Degree of longitude	Mean center: Degree of latitude	Standard Deviational Ellipse: Standard distance (km)	Angle of Rotation	Radius of major axis(km)	Radius of minor axis(km)
Geometric center	-	118.14	36.37	-	62.62	219.78	116.23
Quality of built environment (Qu)	2010	118.79	36.57	75.92	65.70	221.37	103.67
	2011	118.74	36.56	69.65	65.63	221.36	105.30

	2012	118.69	36.55	64.57	65.44	221.96	106.34
	2013	118.64	36.55	58.66	65.38	221.03	108.39
	2014	118.62	36.54	56.64	65.19	221.64	108.66
	2015	118.63	36.53	56.88	65.17	222.93	108.11
	2016	118.61	36.53	55.13	65.04	222.91	108.40
	2017	118.61	36.53	54.57	64.99	223.39	108.24
	2018	118.62	36.53	56.25	64.73	224.21	107.75
Environmental pressure (Pu)	2010	118.12	36.53	17.20	62.50	196.51	119.81
	2011	118.12	36.48	12.54	62.10	194.79	118.09
	2012	118.14	36.48	11.56	61.89	196.55	118.45
	2013	118.14	36.47	11.01	61.98	198.38	118.59
	2014	118.11	36.49	12.89	61.79	192.05	120.49
	2015	118.14	36.47	10.67	62.45	193.63	119.84
	2016	118.16	36.53	17.06	62.62	194.56	121.00
	2017	118.19	36.53	18.44	63.34	195.84	121.65
	2018	118.19	36.53	18.54	63.11	196.22	121.54
Urban sustainability (Su)	2010	118.98	36.49	94.37	63.80	231.75	96.23
	2011	118.94	36.50	89.82	64.36	234.16	99.63
	2012	118.86	36.48	81.03	64.57	234.61	101.01
	2013	118.77	36.48	70.73	64.71	234.37	103.84
	2014	118.81	36.47	74.81	64.45	239.03	101.19
	2015	118.78	36.47	72.37	64.31	239.04	101.21
	2016	118.72	36.42	64.58	63.93	236.91	100.36
	2017	118.67	36.41	58.91	63.64	237.66	100.64
	2018	118.68	36.41	60.38	63.39	238.26	100.07

6.4. Discussions on countermeasures for cities in Shandong Peninsula

Based on the radar charts of indicator categories, the specific performance of each city in the Shandong Peninsula can be found by comparison. Then combining the heat map of each original indicator statistical data, the key points that the city needs to be improved can be clearly diagnosed. So that more targeted urban development strategies can be proposed in the near future. The specific subitems of sustainable characteristics and urban strategies of the city are discussed as follows (Fig. 6-7, 6-8).

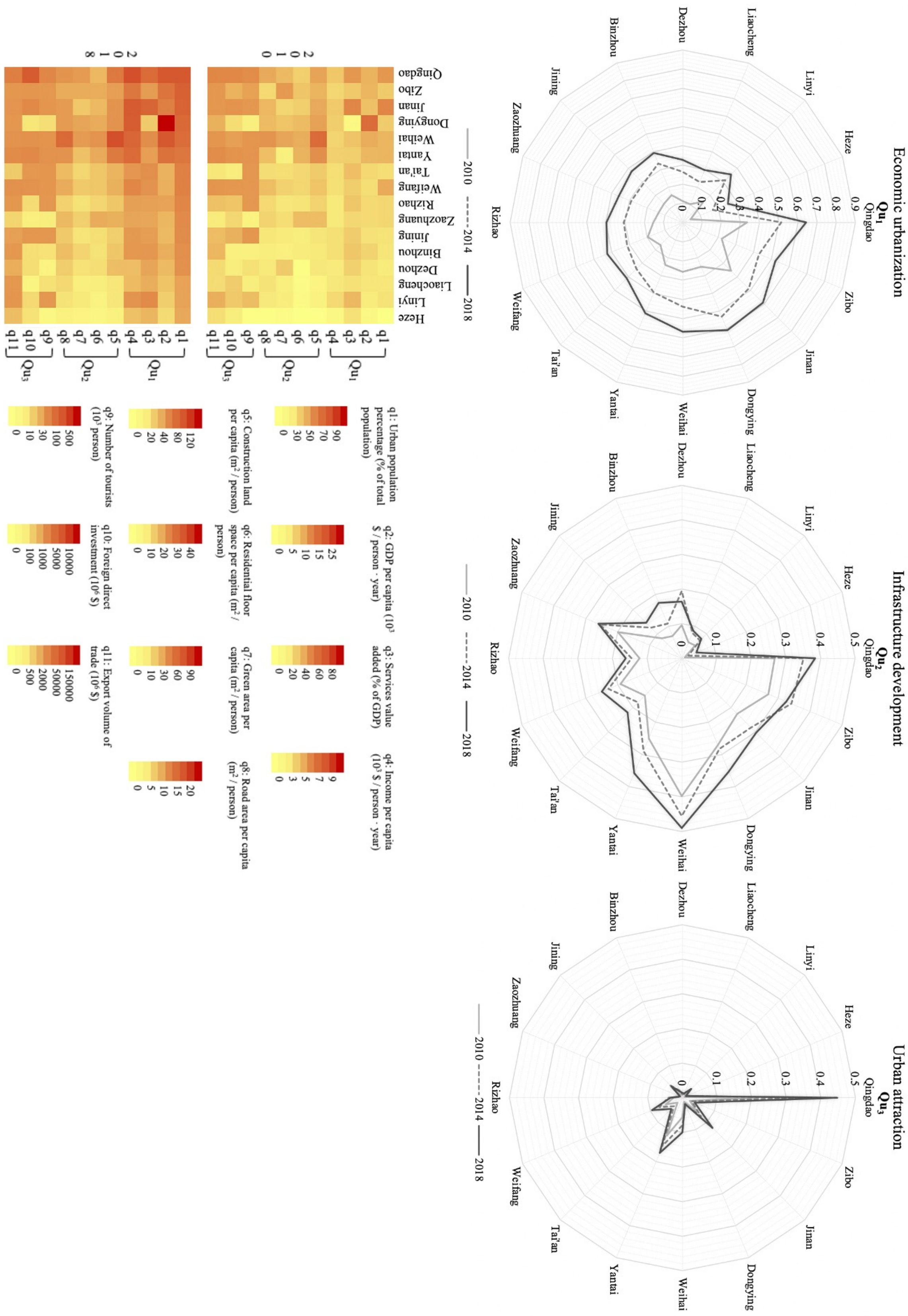


Fig. 6-7 The performance of each of the indicator of Qu in Shandong Peninsula

6.4.1.Countermeasures of the quality of built environment

For urbanization economies, studies have shown that urbanization and economic development usually go hand in hand. The economic performance of all 16 cities has shown an increasing trend as urbanization increases in the Shandong Peninsula. Coastal cities are performing better than inland cities, especially Qingdao, Dongying and Weihai, which have seen significant increases in their scores in the past 9 years. These cities not only benefit from the local advantages of a distinctive seaside economy and the government's prioritized support, but also from the fact that they have gathered a large number of talented occupants through attractive policies. The main reason for the backward cities with a score of Qu less than 0.5 is the lower per capita GDP. Among them, Dezhou, Liaocheng and Heze have further impacts on people's income levels due to economic backwardness. These cities can adopt industrial promotion policies to develop competitive local industries. In addition, Zibo and Dongying, the cities with heavy industry as the pillar, urgently need to optimize the industrial structure, and the important direction of future adjustments should be to increase the proportion of the service industry. Such as encouraging fixed asset investment in the tertiary industry, combining the advantages of local traditional industrial manufacturing to develop environmental protection industries such as new materials and technologies, etc.

For infrastructure development, with the rapid growth of the urban population, most cities in the Shandong Peninsula are still showing a lack of supporting infrastructures, making some areas unable to meet the needs of all their citizens. There are readily apparent differences in the level of infrastructural development between such cities. Reasons for this lag are mainly an underdeveloped economy or a rapid period of urbanization, resulting in insufficient of construction land area (like Liaocheng and Heze), residential area (like Linyi and Binzhou) and green area (like Jinan and Rizhao), road area (like Jining and Binzhou). Not only do these cities need to get financial support from the state, but they must also consider proposing phased, high-quality infrastructural plans for their local needs. Although Qingdao and Jinan have relatively high scores for infrastructure development, the unequal distribution of urban infrastructure investment has led to a large number of people migrating to specific areas, and the high housing prices and income mismatch has brought economic burdens to all of the citizens. In this regard, the Weihai Municipal Government continues to provide support for the infrastructure that the people are concerned about and put forward the principle of "early planning, early approval, and early construction", which is worth learning from [7].

For urban attraction, the gap between city attractiveness is very significant. Qingdao alone scored dramatically higher than the other cities. After Qingdao, the most attractive cities are Yantai, Jinan, Jining, Weifang, Weihai and Tai'an. These cities have some beautification strategies worth mentioning: 1) Increased investment in the construction of scenic areas and maintenance of natural and cultural heritage, such as Mountain Tai's World Cultural and Natural Double Heritage Scenic Area. 2) Shaping of the influence of local culture by holding international events such as the Olympic Games and the International Beer Festival in Qingdao. 3) Strengthening of unique local industries and improvement of product competitiveness, such as Weifang's textile industry. 4) Provision of preferential tariff policies to attract foreign investment, such as the bonded areas in Qingdao, Weifang, Jinan, Yantai, and the China-Korea Free Trade Zone in Weihai. Although all of the cities have their own historical culture, unique scenery and local industry, they have neglected to take care and make use of these powerful urban properties. Among them, Dongying, Zaozhuang, Binzhou, Dezhou, Liaocheng and Heze need to explore tourism resources to attract more tourists. Some cities such as Dongying, Rizhao, Zaozhuang and Liaocheng can focus on improving preferential foreign investment policies. Yantai, Zaozhuang and Heze also need to increase the competitiveness of local products in terms of export marketing.

6.4.2.Countermeasures of the environmental pressure

For resource Consumption, almost all 16 cities in the Shandong Peninsula have gradually increased their resource consumption and have ranked first in the country for many years in this regard, shown in the decreasing trend of scores from 2010 to 2018. This is closely related to Shandong’s position on heavy industry, emphasizing traditional industries such as chemical, steel and coal, which account for about 68% of total industrial output value. Shandong has thus ranked second in China in industrial output for many years [1]. Excessive consumption of resources largely comes from the heavy industry-intensive cities such as Zibo, Dongying, Rizhao, Binzhou and Liaocheng. Although the "Comprehensive Plan for Energy Conservation and Emission Reduction" was uniformly implemented nationwide in 2007 [3], improvement has not been significant. For one, the economic structure of Shandong Province is too dependent on industry and the equipment is seriously worn out. In pursuit of stable economic growth, most cities will choose to maintain production and upgrade at a slow rate. Secondly, high costs of upgrading, lack of financial funds, loose supervision of use, and weak awareness of energy conservation are difficult to solve. Therefore, considering that these resources cannot be used sustainably, there is an urgent need to strengthen policies of financial support for environmental improvement, accelerate the progress of energy-saving technology, give full play to the guiding role of government, improve subsidies, and enhance citizens' environmental awareness. Compared with energy consumption, the control of water consumption is relatively good, but individual cities such as Binzhou, Dongying and Dezhou still need to raise awareness of water conservation.

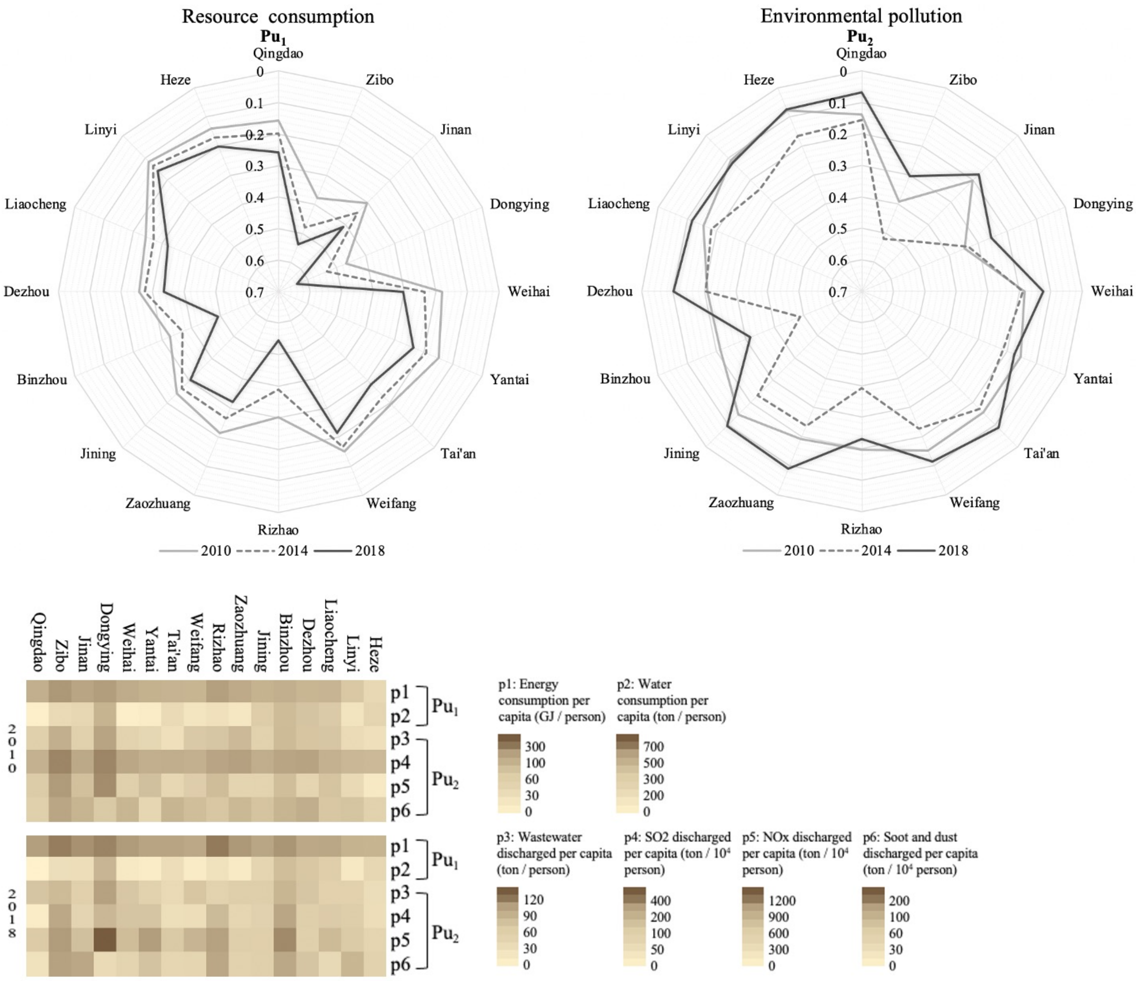


Fig. 6-8 The performance of each of the indicator categories of Pu in Shandong Peninsula

For environmental pollution, most cities have relatively minor differences, with a few exceptions. From 2010 to 2018, although almost all cities have experienced the mitigation of environmental pollution intensified, there are still five cities that have not returned to the level of 2010 or even worse. Among them, Binzhou has relatively significant deterioration, followed by Rizhao, Yantai, and Linyi. In these cities, the main pollution sources are NOx and soot and dust due to the rapid migration of a large number of people to these cities, resulting in an uptick in the number of private cars and exhaust emissions. It is necessary to raise citizens' environmental awareness, encourage the masses to ride or walk more often or promote the purchase of small-displacement cars and the use of clean energy or less polluting fuels through incentive mechanisms [8]. Fortunately, from 2014 to 2017, the scores of all cities in the Shandong Peninsula increased. This is attributed to the concept of conversion between old and new kinetic energy proposed in 2015, which has heightened government focus on the control of environmental pollution. Shandong's government has put forward requirements for accelerating the conversion of low-capacity and high-polluting enterprises into green industries focused on technological innovation. This is true especially in the heavy industrial cities of Zibo, Rizhao and Zaozhuang, which have tried to reduce pollution emissions while increasing resource consumption. This indicates that effective government intervention can have positive effects on improving the environment with regards to urbanization. In addition, some cities, such as Qingdao, Zibo, Dongying and Binzhou, need to make efforts on water pollution. They must not only increase citizens' awareness of water conservation but also appropriately increase or optimize sewage treatment and water recycling equipment.

6.5. Summary

The main conclusions of the empirical analysis of 16 cities in the Shandong Peninsula megalopolis from 2010 to 2018 can be summarized as follows:

During the past 9 years, (1) the quality of the built environment in the study area has generally shown an upward trend, while the environmental pressure experienced an upward and then a downward trend but was more severe compared to 2010. The main reason is the excessive energy consumption and pollution caused by the massive energy extraction and the concentration of heavy industries. From the performance of evaluation scores, (2) the Qu index scores range from 0.019 to 0.417 and the Pu index scores range from 0.109 to 0.499. The composite Su score has a minimum value of 0.172 and a maximum value of 2.565, indicating that there is a significant development gap between cities in the region of Shandong Peninsula And (3) the number of cities in a sustainable state increased from 3 in 2010 to 8 in 2018, but there are still 8 cities in an unsustainable state of development. Generalizing the basic conditions of cities reveals that coastal cities are more sustainable than inland cities and their larger size facilitates rapid improvements in sustainability. Using the curve estimation regression model, it was further found that (4) 93.8% of cities showed a significant relationship between Qu and Pu, and only one city did not have significant interactions between Qu and Pu ($p \geqq 0.05$). There are three different types of interaction mechanisms. Among them, 10 cities showed an inverted U-shape relationship, which indicates that the negative impact on environmental stress is diminishing in improving the quality of the built environment. However, (5) there are 3 cities showing an inverted S-shape, 2 cities with a positive linear mechanism, which means that there are adverse urban development trends due to mutual inhibition and 31.3% of cities should especially worthy of attention to environmental management.

In terms of spatio-temporal characteristics of evolution results, it can be intuitively found that (6) the sustainability of the urban environment in this area shows high degree of urban differences and spatial heterogeneity. In Shandong Peninsula, the distribution characteristics of sustainability in the northern region show a trend of gradual improvement from the coastal cities in the east to the cities in

the central and southern areas. But most cities in the northern and western regions are still in an unsustainable state of development. Specifically, (7) the mean center of Qu and Su move closer to the geometric center at a rate of 2.47 km/year and 4.30 km/year to the southwest but remains 56.25 km and 60.38 km away from the geometric center respectively. But (8) the mean center of Pu is moving to the east, with 18.54 km away from the geometric center at a rate of 1.00 km/year. That indicates the gap between the unbalanced development of western and eastern cities in the Shandong Peninsula region is narrowing at a relatively rapid rate.

Therefore, at the level of macro-regional coordinated development, (9) the preferred development policy is to prioritize the improvement of the quality of the built environment in the southwestern cities and to address the environmental problems of the north and east cities. At the micro level of city-specific development, (10) the results of each city's sub-assessment scores can be combined with a heat map of indicator statistics for a case-by-case diagnosis. Broadly speaking, (11) for the countermeasures of the quality of built environment, the cities recommended to prioritize responses of urbanization economies are Yantai, Dezhou, Liaocheng and Heze; the cities that need to give priority to improve infrastructure development are Qingdao, Jinan, Tai’an, Weifang, Rizhao, Jining and Linyi; and the cities that need to particularly strengthen their urban attractiveness are Zibo, Weihai, Yantai, Zaozhuang and Binzhou. (12) For the countermeasures of the environmental pressure, the cities recommended to prioritize responses to reduce environmental pollution are Zibo. Weihai, Yantai, Weifang, Dezhou and Linyi, while the other cities urgently need to prioritize decrease the resource consumption.

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Chapter 7. Measuring the Performance Urban Sustainability in JingJinJi

7.1. Introduction

7.1.1. General information of urban environment in JingJinJi

The JingJinJi megalopolis (geographic coordinates: 113° 27' E-119° 50' E longitude and 36° 05' N-42° 40' N latitude) is the National Capital Region of China (Fig. 7-1). The total area is 217,156 km^2, 1.9% of China's territory [1], and located Northern area as the vibrant center of political, cultural, and economic. The administrative hierarchy of the JingJinJi is quite complete and there are cities of different sizes. It includes eleven prefecture-level cities surrounding two municipalities of Beijing and Tianjin, along the coast of the Bohai Sea, and all 13 cities have different development characteristics (Table. 7-1).

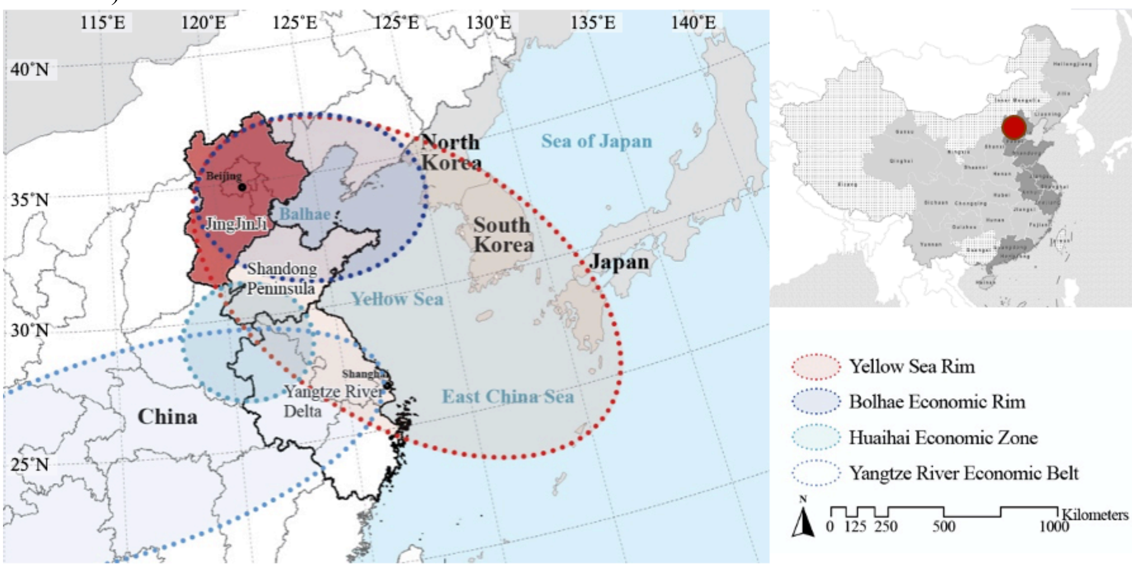


Fig. 7-1 Geography of the JingJinJi megalopolis

The biggest advantage of JingJinJi is that it can have a more coordinated development and better environmental plan over a wider area, attracted much attention all over the world. As an important international link for China, it has established close coordinated development cooperation relations with neighboring countries in finance, trade, and investment, especially Japan, South Korea and North Korea [2]. It had a GDP of 11,299.36 dollars per capita in 2018, contributing to 9.75% to China's (except autonomous and special administrative regions) GDP in 2014 and ranked fourth in the Chinese megalopolises.

JingJinJi has traditionally been involved in heavy industries and manufacturing, and now is becoming a significant growth cluster for the automobile, electronics, petrochemical sectors, automotive industry, software and aircraft, also attracting foreign investments in manufacturing and health services. Beijing complements this economic activity with strong petrochemical, tourism and R&D industries. Tianjin and Hebei, surrounding Beijing, have become China's workshop and a major manufacturing base for items such as oil, steel, cement, electronics, and a range of other heavy industrial products [3]. Therefore, this region is one of the most polluted areas in China. Statistics showed that among the top-twenty most polluted Chinese cities, eleven cities are from the JingJinJi region, with eight cities being listed in the top-ten most polluted cities.

Table 7-1 Outline and classification of 13 cities in JingJinJi in 2018

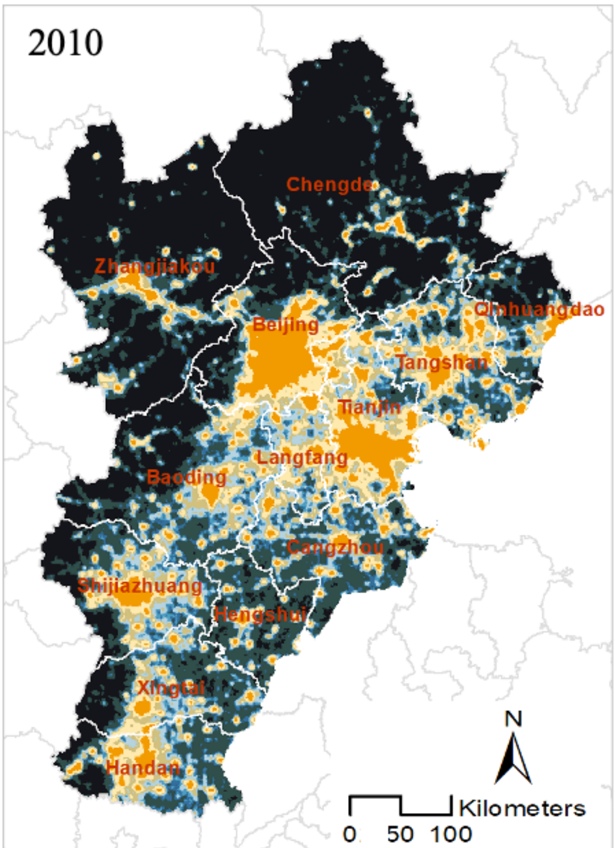
Provincial-level administrative divisions	Cities in JingJinJi	Urban population (10^4 persons)	Urbanization rate (%)	Total population (10^4 persons)	Land area (km^2)	Density (persons /km^2)	GDP ($ / person)	GDP (10^9 $)	Length of coastline (km)
Beijing	-	1863.40	86.50	2154.20	16400	1313.54	21228.99	457.31	-
Hebei Province	Tianjin	1297.14	83.15	1560.00	11966	1303.64	18186.22	283.70	154
	Tangshan	501.07	63.14	793.58	14151	560.78	12734.22	101.06	196
	Shijiazhuang	658.02	60.08	1095.16	14060	778.91	8780.01	96.16	-
	Langfang	290.24	60.01	483.66	6419	753.44	9458.77	45.75	-
	Qinhuangdao	186.23	59.42	313.42	7803	401.67	7735.08	24.24	163
	Zhangjiakou	253.78	57.24	443.36	36797	120.49	5202.59	23.07	-
	Handan	541.86	56.87	952.81	12065	789.70	5475.94	52.18	-
	Cangzhou	406.91	53.64	758.60	14304	530.33	7489.64	56.82	128
	Xingtai	390.18	52.91	737.44	12433	593.12	4392.47	32.39	-
	Baoding	616.37	52.54	1173.14	22185	528.80	4534.13	53.19	-
	Chengde	186.35	52.07	357.89	39490	90.63	6220.85	22.26	-
Total of JingJinJi		7424.39	65.87	11271	216911	519.59	11299.36	1273.49	641
% of China (except autonomous and special administrative regions)		9.51	-	8.76	4.14	-	-	9.75	2.60

7.1.2. The challenge of sustainable urbanization in JingJinJi

JingJinJi are the top five most populous regions in China, with an urbanization rate of 65.87% in 2018. And the total urban population is 74.24 million, contributing 9.51% to China (excluding autonomous regions and special administrative regions). From the urban luminosity map, most of the population of JingJinJi is concentrated in the central-east to south-west, with Beijing, Tianjin and Shijiazhuang as the gathering points. The coastal areas and the southern areas adjacent to other cities show a significant increase in population (Fig. 7-2).

After the founding of the People's Republic of China, the urbanization of the JingJinJi megalopolis has undergone a tortuous process. At first, the development was slow, and by 1980, the proportion of urban population was only 25.79%. After the reform and opening up, the urbanization process in the JingJinJi has accelerated significantly. In particular, Beijing and Tianjin have now entered a highly urbanized stage. From 2000 to 2010, the average urban population growth rate of the JingJinJi urban agglomeration was 3.51%, higher than the national average growth rate of 3.15% [4]. Among them, Beijing and Tianjin have entered a higher level of urbanization with an urbanization rate of over 80%, but other cities are still at a lower level of urbanization. Over the past nine years, urbanization has grown at an annual rate of more than 1.5%. As a result, the urban density in 2017 was as high as 520 persons/km^2, which is higher than many of the world's metropolises.

By 2050, the Chinese government is planning the JingJinJi megalopolis as home to 130 million people over the equivalent area. And the Chinese government gives much attention to the region of JingJinJi and sets the newly implemented national policy “to build a world-class agglomeration of cities with the capital as the core” [2]. However, due to rapid urbanization and economic development, there is a serious conflict between economic development and environmental sustainability [5]. At the same time, the development of regional integration is constrained by the administrative system. The imbalance between the three regions is obvious. Beijing is the capital, while Tianjin and Hebei depend on it in terms of resource allocation and administrative coordination. And this affects the integration and cooperation in the JingJinJi megalopolis. Therefore, sustainable urbanization in the JingJinJi faces great challenges in the future.



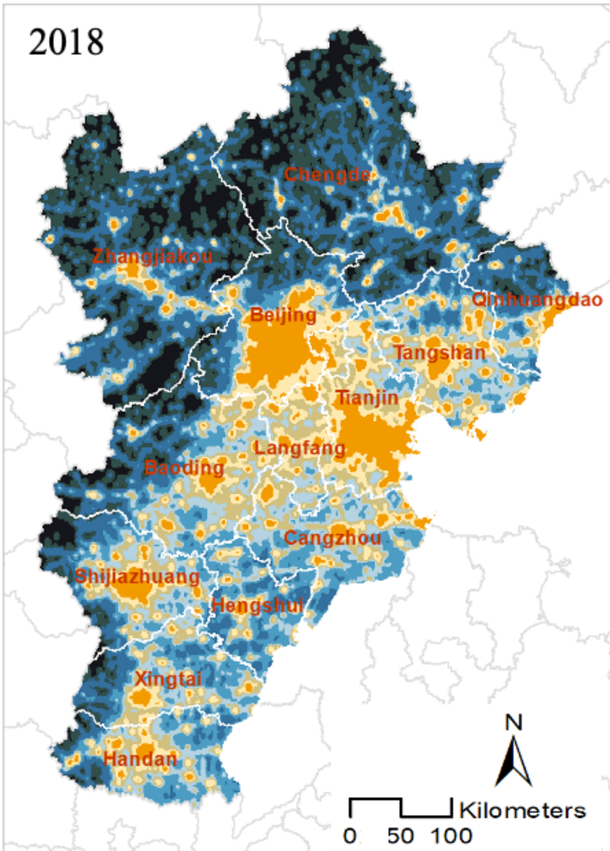


Fig. 7-2 The evolution of urbanization in JingJinJi from 2010 to 2018. (Notes: the degree of urban population is represented by the change of color. The deeper yellow color represents higher urbanization, and the deeper blue color represents lower urbanization.)

7.2. Results presentation and interaction mechanism analysis in JingJinJi

7.2.1. Overall results for each city

The box charts of Fig. 7-3 show the ranges of the Qu, Pu and Su evaluation scores of 13 cities in the JingJinJi region from 2010 to 2018, using the urban sustainability assessment tool. It can be roughly seen that: (1) With the improvement of the level of urbanization, the performance of cities in quality of the built environment is relatively high. But the performance gap between cities with lower urbanization rates is small differences in this respect. (2) The performance of environmental pressure between cities has significantly different characteristics, and the gap is large. The trend of Pu scores is slightly opposite to that of the urbanization levels of cities. (3) The degree of urban sustainability roughly follows the trend of the urbanization rate. Some cities with relatively low levels of urbanization have shown greater improvement in sustainability.

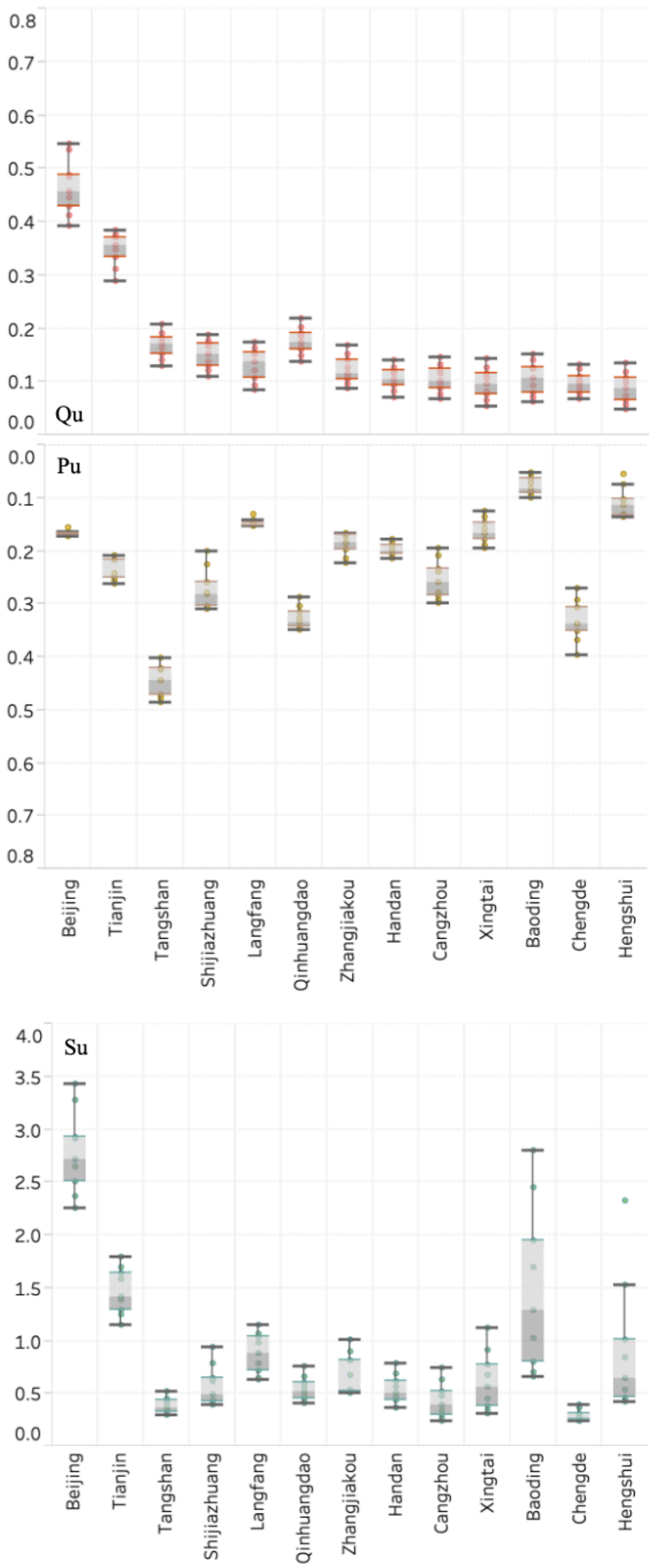
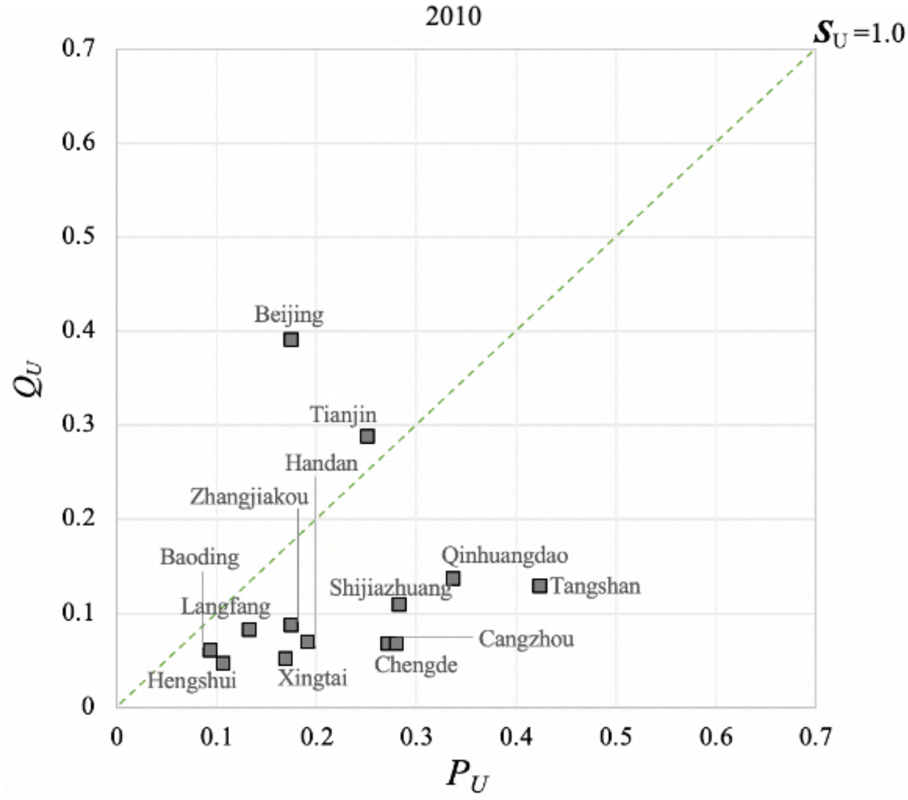


Fig. 7-3 The scores of Qu, Pu and Su of 13 cities in JingJinJi from 2010 to 2018 measured by urban sustainability assessment system.

Specifically, from Fig. 7-3(Qu), the index of Qu for the 13 cities ranged from 0.047 of Hengshui in 2010 to 0.545 of Beijing in 2018. The compound annual growth rate (CAGR) in the past 9 years is between 2.33% and 12.26%. From the median point of view, cities can be divided into two categories: (1) the performance of Beijing has been in a leading position in this dimension followed by Tianjin, with the median points of Qu over 0.3. (2) The median of the other 11 cities in JingJinJi is less than 0.3 in the dimension of Qu. Among them, Langfang performs better than other cities, but the gap between these cities and advanced cities above is very prominent. Then, the index of Pu ranged from 0.053 to 0.487 shown in Fig. 7-3(Pu). These two are the scores of Baoding in 2018 and Tangshan in 2010. The annual CAGR ranges from -6.64% to 2.52%. The two cities of Langfang and Chengde have a positive growth rate, which means that their urban environmental problems have deteriorated in 9 years. The other 13 cities have shown environmental improvement trends. But Tianjin, Shijiazhuang, Cangzhou and Chengde have a median score of less than 0.2, which is also a city worthy of attention. Moreover, the environmental pressure in Tangshan has always been at the highest level with a median score of Pu below 0.4. It was hailed as China's "cradle of industrialization". Even today, Tangshan is a hub of steel, energy, chemical, and ceramics production.

From the comprehensive variation of Su in Fig. 7-3(Su), the lowest score is 0.238 that got by Chengde City in 2011. And the highest score is 3.424 obtained by Beijing in 2017. The annual CAGR ranges from 4.28% to 20.24%. There are only 3 cities of Beijing, Tianjin and Baoding that have a median point of Su scores exceed 1.0. Baoding has the largest increase, and the current level of urban sustainability ranks second in the region. As a prefecture-level city in central Hebei province, it has convenient geographical advantages, abundant natural resources, and great industrial-economic potential. Therefore, in 2017, the Xiongan New District in Baoding's jurisdiction was positioned as a sub-provincial city in China, and the state invested a lot of manpower and related resources in the construction of This area in advance. Besides, Beijing, Hengshui, Xingtai and Tianjin have also seen relatively large improvements. The median sustainability scores of Tangshan, Shijiazhuang, Cangzhou, and Chengde are less than 0.5, which needs to be further improved.

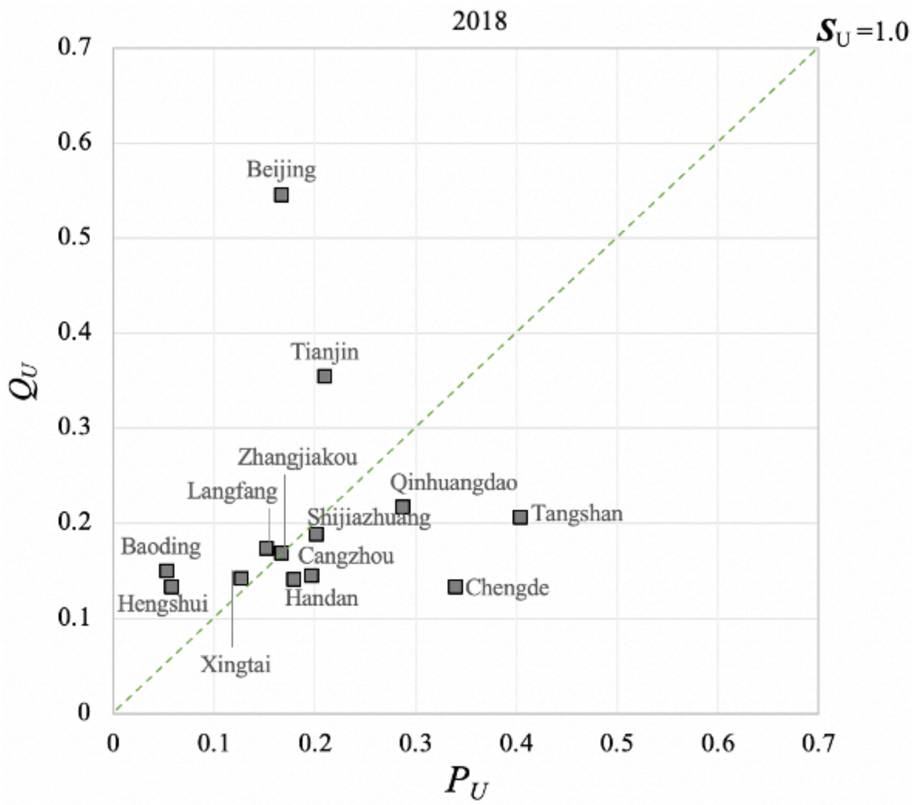
In addition, the urban development states of 13 cities in JingJinJi from 2010 to 2018 could be presented from Fig. 7-4 and found that: (1) The number of cities in a state of sustainable development increased from 2 cities in 2010 to 7 in 2018. (2) In 2010, only two megacities, Beijing and Tianjin, were in a sustainable state. Because of their special political statuses are the capital and municipality of China respectively. So, the economy of these cities is particularly developed with the largest improvement in the quality of the built environment. (3) There are two types of development paths of cities that have entered a state of sustainable development for 9 years. Baoding, Hengshui, and Xingtai have chosen a development path that not only improves the quality of the built environment but also strives to reduce environmental pressure. However, Langfang and Zhangjiakou have taken priority to ensure the improvement of Qu and try to keep the environmental pressure from increasing. As a result, the degree of sustainability improvement of these two cities is less than that of the above cities.



2010

Classification		Small cities	Medium-sized cities	Large cities	Mega cities	Number of cities	
Su < 1.0 (Qu< Pu)	Coastal	-	Qinhuangdao	Baoding, Shijiazhuang	-	3	11
	Inland	-	Langfang, Zhangjiakou, Hengshui, Handan, Xingtai, Tangshan, Chengde, Cangzhou	-	-	8	
Su ≥ 1.0 (Qu≥ Pu)	Coastal	-	-	-	Tianjin	1	2
	Inland	-	-	-	Beijing	1	

(a) The regression result and the corrosponding city list of 2010



2018

Classification		Small cities	Medium-sized cities	Large cities	Mega cities	Number of cities	
Su < 1.0 (Qu< Pu)	**Coastal**	-	Qinhuangdao	Shijiazhuang	-	2	6
	Inland	-	Handan, Cangzhou, Tangshan, Chengde	-	-	4	
Su ≥ 1.0 (Qu≥ Pu)	**Coastal**	-	-	Baoding	Tianjin	2	7
	Inland	-	Hengshui, Langfang, Xingtai, Zhangjiakou	-	Beijing	5	

(b) The regression result and the corrosponding city list of 2018

Fig. 7-4 The regression trends of different types of cities from 2010 to 2018

Note: (1) Su < 1.0 (Qu < Pu) means the city is in a barely or seriously unsustainable urbanization process. The increasing pace of urban environmental pressure (Pu) is faster than the improved pace of urban built environment quality (Qu). Su ≥ 1.0 (Qu ≥ Pu) means the city is in a basic or highly sustainable urbanization process. The increasing pace of urban environmental pressure (Pu) is slower than the improved pace of urban built environment quality (Qu). (2) Small cities (urban population < 1 million); Medium-sized cities (5 million > urban population ≧ 1 million); Large cities (10 million > urban population ≧ 5 million); Mega cities (urban population ≧ 10 million)

7.2.2. Coupling interaction mechanism between Qu and Pu

The relationship between Qu and Pu of 13 cities in JingJinJi is obtained through the method of curve estimation and regression in Table 7-2, so as to further understand the development trend of the city. The estimation list shows that except for Tianjin, the performance of these two aspects of the other 12 cities has a significant coupling relationship, with the p values lower than 0.5. three types of mechanisms have been found as follows：

Table 7-2 The coupling interaction mechanism between f(Q) and g(P) by regression analysis of the 13 cities in JingJinJi

Cities	AIC	BIC	R^2	Adjusted R^2	Std. error	F	p[1] value	Regression equation	Description	Inflection year
Beijing	-76.386	-75.992	0.697	0.653	0.003	16.084	0.005**	g(P)=0.207-0.085 f(Q)	Negative linear relationship	-
Baoding	-66.014	-65.619	0.914	0.901	0.006	74.013	0.000***	g(P)=0.136-0.54 f(Q)		-
Shijiazhuang	-49.745	-49.153	0.910	0.881	0.013	30.507	0.001***	g(P)=-0.415+10.734 f(Q)-39.711 f(Q)2	Inverted U-shaped relationship	2013
Langfang	-76.533	-75.941	0.864	0.819	0.003	19.085	0.003**	g(P)=0.046+1.524 f(Q)-5.333 f(Q)2		2014
Handan	-62.568	-61.977	0.797	0.729	0.007	11.746	0.008**	g(P)=0.061+3.127 f(Q)-16.52 f(Q)2		2013
Xingtai	-55.110	-54.519	0.860	0.814	0.010	18.474	0.003**	g(P)=0.146+1.158 f(Q)-9.512 f(Q)2		2012
Hengshui	-58.224	-57.632	0.933	0.910	0.008	41.573	0.000***	g(P)=0.009+3.381 f(Q)-23.128 f(Q)2		2013
Tangshan	-58.624	-57.835	0.956	0.930	0.008	36.199	0.001**	g(P)=-5.936+112.081 f(Q)-641.328 f(Q)2+1197.175 f(Q)3	Inverted S-shaped relationship	2013&2018
Qinhuangdao	-75.603	-74.814	0.987	0.979	0.003	123.719	0.000***	g(P)=-1.703+34.493 f(Q)-188.264 f(Q)2+329.967 f(Q)3		2012&2018
Zhangjiakou	-52.304	-51.515	0.807	0.691	0.011	6.964	0.031*	g(P)=-1.675+44.538 f(Q)-342.864 f(Q)2+851.229 f(Q)3		2014&2017
Cangzhou	-60.441	-59.652	0.977	0.963	0.007	70.808	0.000***	g(P)=-0.555+25.799 f(Q)-248.061 f(Q)2+730.738 f(Q)3		2012&2018
Chengde	-42.346	-41.557	0.835	0.736	0.020	8.426	0.021*	g(P)=-1.047+35.994 f(Q)-297.38 f(Q)2+788.159 f(Q)3		2014&2017
Tianjin	-40.563	-39.972	0.143	-0.143	0.022	0.500	0.630	g(P)=0.515-1.39 f(Q)+1.697 f(Q)2	No significant relationship	2017

(1) Negative linear relationship: in this type of interaction shown by Beijing and Baoding, the urban environment and the natural environment are quite coordinated, which is the reason for the large increase in urban sustainability of the two cities. It is undeniable that political factors played an important role.

(2) Inverted U-shaped relationship: the environmental pressure of 5 cities of Shijiazhuang, Langfang, Handan, Xingtai and Hengshui first increased and then decreased with the improvement of the quality of the built environment. Most inflection points appeared around 2013. This benefited from the comprehensive implementation of the grid environment supervision system and the supporting plan implementation plan during the same period.

(3) Inverted S-shaped relationship: There were five cities of Tangshan, Qinhuangdao, Zhangjiakou, Cangzhou and Chengde that had a benign transition around 2013, and the cities began to develop in a well-controlled environment. However, in the year 2017 or 2018, there has been a trend of reversal. It indicates that if do not take effective countermeasures and blindly develop the urban built environment, environmental problems will emerge again. Although local governments have recently proposed implementing the "Regulations on Ecological Environment Protection" to further protect and improve the ecological environment and prevent pollution and other public hazards, the pressure these cities will face has not yet received sufficient attention.

7.3. Spatio-temporal characteristics of urban sustainability in JingJinJi

7.3.1. Spatio-temporal variation patterns of results

As shown in Fig. 7-5(Qu), cities with better urban built environment quality have been concentrated in Beijing and the adjacent eastern coastal areas from 2010 to 2018. The main reason is that (1) Beijing has superior economic strength which has played an important role in supporting the economic growth of neighboring cities. And (2) they have greater geographical advantages of coastal ports and strong competitiveness in modern industry. In 2010, only the provincial capital Shijiazhuang in southern area of JingJinJi had better quality of built environment. Subsequently, other cities in the central area that bordered advanced cities gradually developed, while cities at the north and south ends of the JingJinJi region were still in a backward state except Handan. By 2018, Beijing and the eastern coastal cities still have obvious advantages in the dimension of Qu, and there is almost no gap in the development level of the other cities.

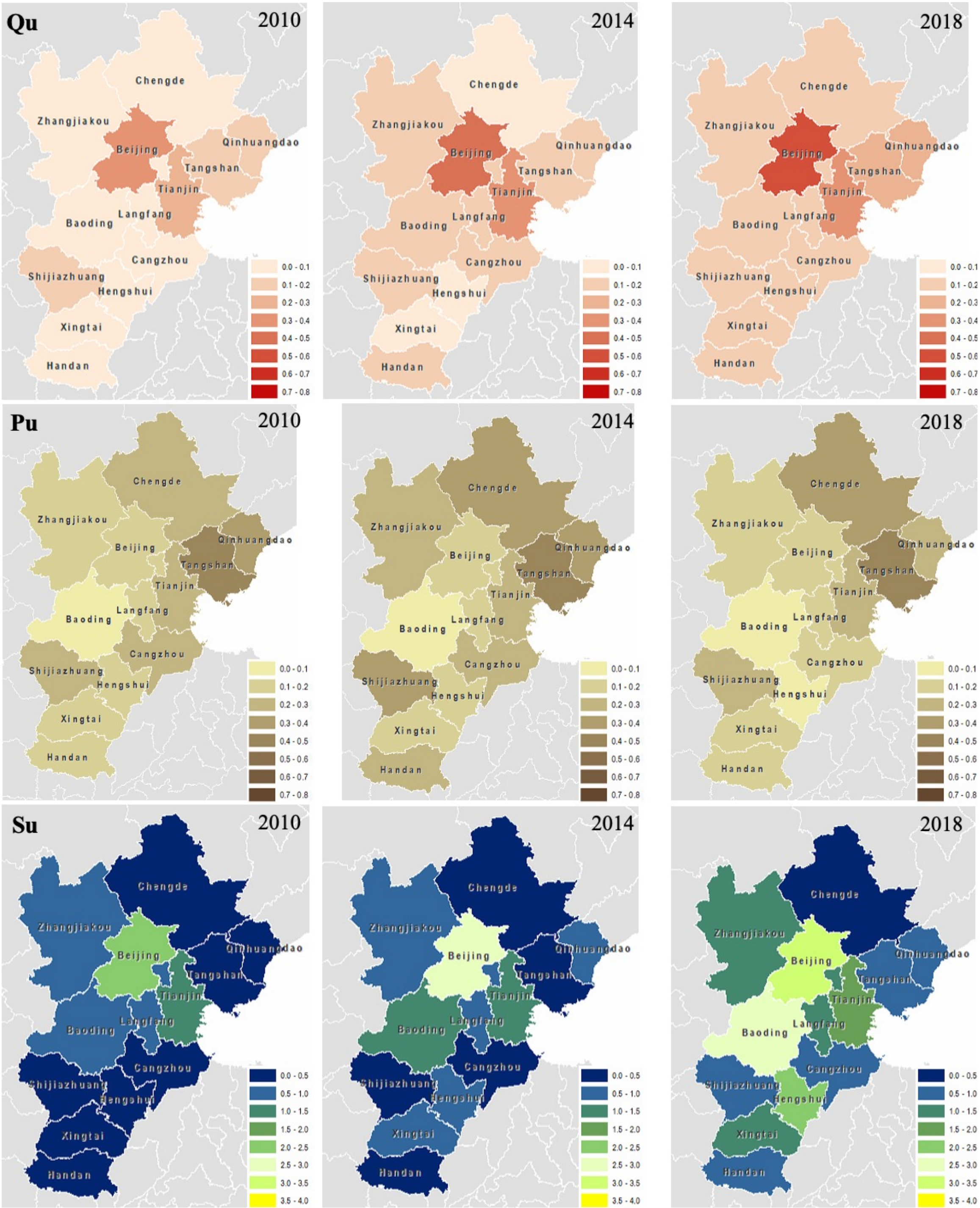


Fig. 7-5 The spatio-temporal variation pattern in the JingJinJi from 2010 to 2018.

From the distribution pattern of Pu results in Fig. 7-5(Pu), there are roughly two characteristics: (1) the environmental load of coastal cities in the JingJinJi region has been greater than that of inland cities from 2010 to 2018. (2) The pressure of urban environment of the western and southern areas are less than that of the northeast and northern areas. At first, a C-shaped distribution pattern with "Chengde-Tangshan-Shijiazhuang" as the endpoint was formed in 2010, and then the environmental pressure of cities in this pattern and surrounding cities increased. Due to the relatively high energy consumption of heating in winter, urban pollutants in northwestern cities follow the prevailing wind direction from northwest and has adversely affected the environment of the capital Beijing [6]. For this reason, related improvement policies including factory relocation were adopted around 2015, so that the environmental pressure of the northwestern cities was controlled or even eased. But at present, the coastal area from Chengde to Tianjin in the northeast and Shijiazhuang in the south are still facing daunting environmental challenges.

From the distribution pattern of the comprehensive Su results in Fig. 7-5(Su), the spatial distribution characteristics of the sustainable development of cities in JingJinJi present a progressive development pattern from the center to the south. Since 2010, the urban sustainability of the central region centered on Beijing has been higher than that of other cities, and then the sustainability of the southern and eastern cities has gradually improved. By 2018, the central and western cities and individual cities in the south are already at a basic level of sustainable development, but the gap between regional cities is obvious. The concentration of unsustainable cities in the northeastern region is an area that needs key remediation in the future.

7.3.2. Evolution track characteristics of regional patterns

In Fig. 7-6 and Table 7-3, the evolution track characteristics of the JingJinJi regional pattern from 2010 to 2018 are visually displayed through the geographic distribution methods mentioned above. On the whole, the mean centers of the evaluation results of Qu, Pu and Su are offset in different directions relative to the geographic center, indicates that the JingJinJi regional development is still unbalanced. The mean centers of Qu and Pu are located in Langfang same as the geographic center, while the centers of Su are located in Baoding City. Among them, the mean center of Qu moved closer to the geometric center but was 32.84km away from that and shortened 21.91km in 9 years. However, the mean centers of Pu are far away from the geometric center with a distance of 65.29km respectively in 2018 and increased distances of 19.46km during the period. It means that the regional imbalance increasing due to the greater pressure of the environment in the northern area of JingJinJi. Therefore, the mean center of Su pattern shows the trend to approach the geometric center first, and then move away from the geometric center to the south, with the current distance from that is 24.79km.

From the shape of standard deviation ellipses, the main axis of all ellipses is basically the same, located in the southwest-northeast direction with the angles of the three ellipses are approximately 30°. But the changes of the ellipses are different. The minor axis of Su shortened while the others became longer, indicating that heterogeneous spatial changes in the JingJinJi region occurred over time.

Moreover, the mean center of Su (V_S=5.96 km/year) has the fastest moving speed per year, followed by that of Pu (V_P=2.78 km/year) and Qu (V_Q=2.77 km/year). It shows that the JingJinJi region is developing towards an unbalanced state at a relatively fast speed. This is mainly due to the increasing environmental pressure of northern cities, which will lead to a gradual increase in the sustainability gap between northwest and southeast cities. Therefore, it is necessary to adopt more effective strategies to accelerate the realization of the balanced development of the whole region, especially to give priority to deal with the environmental problems in the northeast cities.

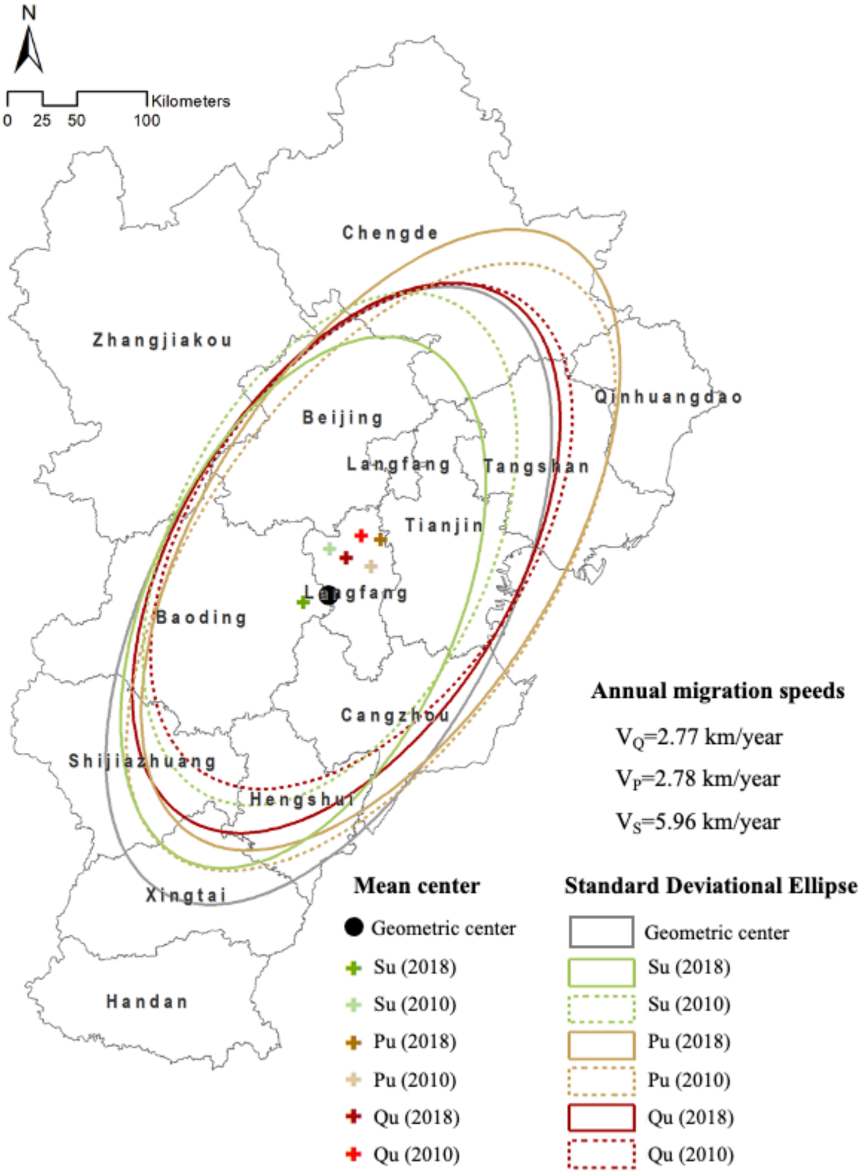


Fig. 7-6 Spatial dynamic map of Qu / Pu/ Su based on mean center and standard deviation ellipse during 2010–2018 across JingJinJi

Table 7-3 The detailed parameter of mean center and standard deviation ellipse

Weighted field	Year	Mean center		Standard Deviational Ellipse			
		Degree of longitude	Degree of latitude	Standard distance (km)	Angle of Rotation	Radius of major axis(km)	Radius of minor axis(km)
Geometric center	-	116.29	39.06	-	29.07	243.86	123.29
Quality of built environment (Qu)	2010	116.63	39.43	54.75	34.57	204.12	118.47
	2011	116.61	39.40	50.74	34.31	206.66	118.51
	2012	116.59	39.37	47.42	33.70	209.50	118.15
	2013	116.58	39.36	46.03	33.54	209.59	117.90
	2014	116.56	39.33	41.71	33.27	211.34	116.97
	2015	116.53	39.31	37.60	33.17	213.08	117.07
	2016	116.51	39.31	36.40	32.30	215.46	118.61
	2017	116.50	39.32	36.27	31.86	215.49	118.63
	2018	116.48	39.30	32.84	31.53	219.17	119.96
Environmental pressure (Pu)	2010	116.68	39.22	45.83	34.82	250.78	123.74
	2011	116.66	39.19	42.73	34.53	253.30	123.07
	2012	116.66	39.20	43.17	34.24	252.33	124.13
	2013	116.67	39.25	46.64	33.76	251.61	126.59
	2014	116.68	39.31	50.58	32.68	252.82	127.42
	2015	116.71	39.30	53.05	32.91	254.17	125.27
	2016	116.72	39.30	54.20	32.30	215.46	118.61
	2017	116.77	39.35	61.23	32.96	253.08	125.85
	2018	116.79	39.39	65.29	32.44	251.01	126.64
Urban sustainability (Su)	2010	116.35	39.37	34.24	26.60	197.33	113.07
	2011	116.35	39.37	34.85	26.78	195.29	113.04
	2012	116.33	39.34	30.99	26.71	198.34	111.62
	2013	116.31	39.30	26.51	27.08	198.44	109.69
	2014	116.26	39.24	20.39	27.46	199.06	108.61
	2015	116.21	39.21	19.03	27.03	198.92	110.02
	2016	116.18	39.19	19.00	26.32	200.18	111.45
	2017	116.13	39.14	20.01	25.27	200.01	109.62
	2018	116.07	39.04	24.79	24.61	203.26	110.04

7.4. Discussions on countermeasures for cities in JingJinJi

Based on the radar charts of indicator categories, the specific performance of each city in the JingJinJi can be found by comparison. Then combining the heat map of each original indicator statistical data, the key points that the city needs to be improved can be clearly diagnosed. So that more targeted urban development strategies can be proposed in the near future. At present, the

"JingJinJi Integration" plan proposed in 2014 provides development ideas but lacks detailed implementation strategies [1,7]. Therefore, the following discusses the characteristics of urban sustainable development and specific sub-projects of urban strategies to provide guidance. (Fig. 6-7, 6-8)

7.4.1.Countermeasures of the quality of built environment

For urbanization economies, the performance of all 13 cities has shown a large increasing trend in the JingJinJi. The top six cities in terms of urbanization level perform well. Among them, Beijing's score far exceeds other cities, greater than 0.8. As the capital of China, Beijing was ranked as having the 7th most competitive financial center in the world and fifth most competitive in Asia (after Shanghai) in the 2020 Global Financial Centers Index. Tianjin's score is between 0.6-0.7, and the gap with Beijing can be narrowed by optimizing the industrial structure and increasing income. The other four cities scored between 0.4-0.5 mainly because of the low per capita GDP. In addition, Tangshan City, which is based on heavy industry, with a ratio of 16:1 to the light industry in 2017, urgently needs to vigorously develop the tertiary industry. The remaining 7 cities with a score of less than 0.4 are also facing the same challenges. For example, dispersing non-capital functions of Beijing and adjust economic structure and spatial structure to let industries and resources within the region be rebalanced more optimally, including from industries where there is overcapacity.

For infrastructure development, the basic conditions for realizing the integrated development plan of the JingJinJi region lie in the infrastructure construction. Judging from the scoring results, Beijing scored the highest, followed by Tianjin and Qinhuangdao, with a score above 0.2. Five cities including Shijiazhuang have scores between 0.1 and 0.2, and five cities including Langfang have scores below 0.1. So, it can be seen that the existing infrastructure in JingJinJi is inadequate to meet the present demand, such the insufficient construction land area (like Langfang, Handan), residential area (like Shijiazhuang, and Chengde), green area (like Baoding and Tianjin), and road area (like Beijing and Cangzhou). With the growth of population and economy, the JingJinJi megalopolis has entered a stage of accelerated development. It is expected that nearly 100 billion RMB will be invested in infrastructure planning and construction in the next few years. Therefore, decision-makers can focus on the above-mentioned needs, and at the same time consider optimizing traffic patterns, adjusting network layout, and introducing corresponding mechanisms, etc.

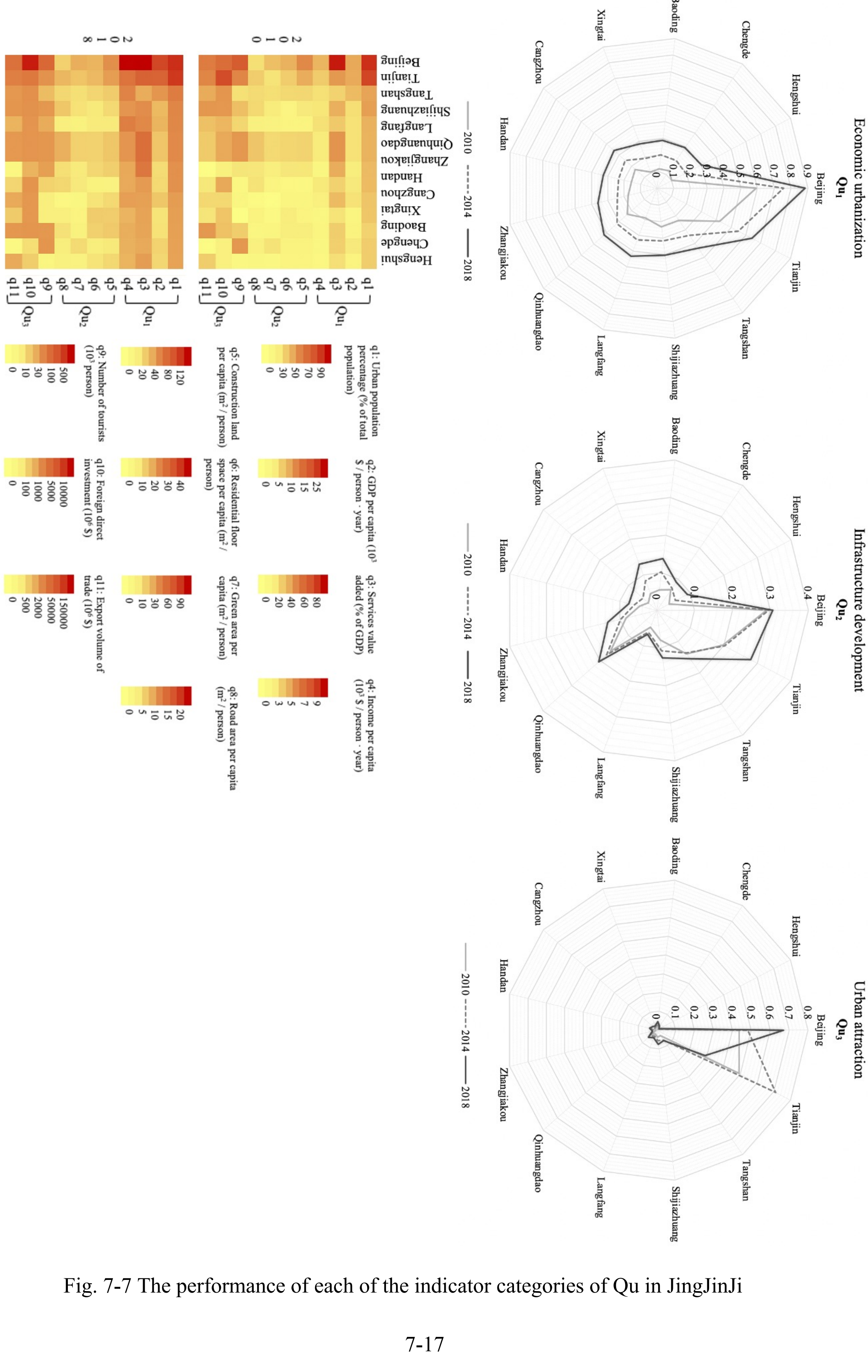


Fig. 7-7 The performance of each of the indicator categories of Qu in JingJinJi

For urban attraction, Beijing and Tianjin, as the capital city and municipality respectively, exhibited absolute attractive advantages in many aspects. However, Tianjin's urban attractiveness has rapidly weakened from 2010 to 2018 due to the decrease in foreign investment and the number of tourists. Other cities in Henan Province have almost no competitiveness in this regard, but individual cities such as Shijiazhuang, Qinhuangdao, Handan and Baoding have improved their performance in all relevant indicators in recent years. Therefore, in future development, the siphoning effect of Beijing and Tianjin on surrounding cities should be weakened to activate the competitiveness of backward cities. It is recommended to prioritize measures for disadvantaged indicators: (1) Give priority to strengthening the competitiveness of Tangshan, Handan, Cangzhou, form and Hengshui culture and environmental characteristics to attract foreign tourists; (2) Give priority to increasing the foreign investment attraction of Handan, the city and Hengshui (3) Priority will be given to improving the competitiveness of the export products and trade markets of Langfang, Zhangjiakou, Handan, Form and Chengde.

7.4.2.Countermeasures of the environmental pressure

The resource consumption of 8 of the 13 cities in JingJinJi shows the increasing trend from 2010 to 2018. Especially Tangshan, Langfang, Qinhuangdao, Zhangjiakou and Chengde which are the bigger consumers of industrial products and contributors to the energy consumption of fossil fuel, metallic minerals, and biomass. Although the pressure on resource consumption has eased in other cities, the magnitude of change is relatively small. Economic activity had the strongest influence on the change in the total energy consumption during the study period, accounting for about 80% of the total increase. Moreover, the population effect had the second-strongest influence on the growth of consumption. For example, the total energy consumption of freight and passenger transportation is increasing fast. In contrast, most cities have less pressure on water resources, but cities in Qinhuangdao, Zhangjiakou, Chengde, Tangshan and Cangzhou still need to pay attention to water conservation. The material-use efficiency is a means to reduce consumption on national [8,9] and regional scales [10]. Thus, the JingJinJi cities should seek to continue increasing their consumption efficiency to move toward greater resource sustainability in the process of regional integrated and coordinated development.

For environmental pollution, except for Handan and Chengde, pollution levels in other cities have declined from 2010 to 2018. Some of these cities have increased first and then decreased, and the pressure levels in cities are different at present. Hengshui and Baoding performed best in urban pollution control, with scores less than 0.1, that mainly because the discharge of SO_2 and soot and dust have been significantly reduced. It is not only benefited from the construction of the Xiong'an Demonstration Zone, but also due to the slowdown of urbanization in order to give priority to environmental protection. The cities with the most serious environmental problems are Tangshan and

Chengde, due to excessive resource consumption and outdated pollution treatment technologies. In addition, soot and dust emissions are still an environmental problem that has plagued the JingJinJi region for many years, eight of China's ten most polluted cities are in the region ranked by the WHO's database in 2016 [11]. Moreover, it was reported that the amount of smoke and dust emissions in 2018 was as high as 6 times the national average, resulting in a high rate of severely polluted days of air quality in most cities. Although the government has been committed to the campaign against air pollution, it still needs to continue its efforts. It can be considered to increase R&D or introduce investment in environmental protection technology and advanced cleaning products.

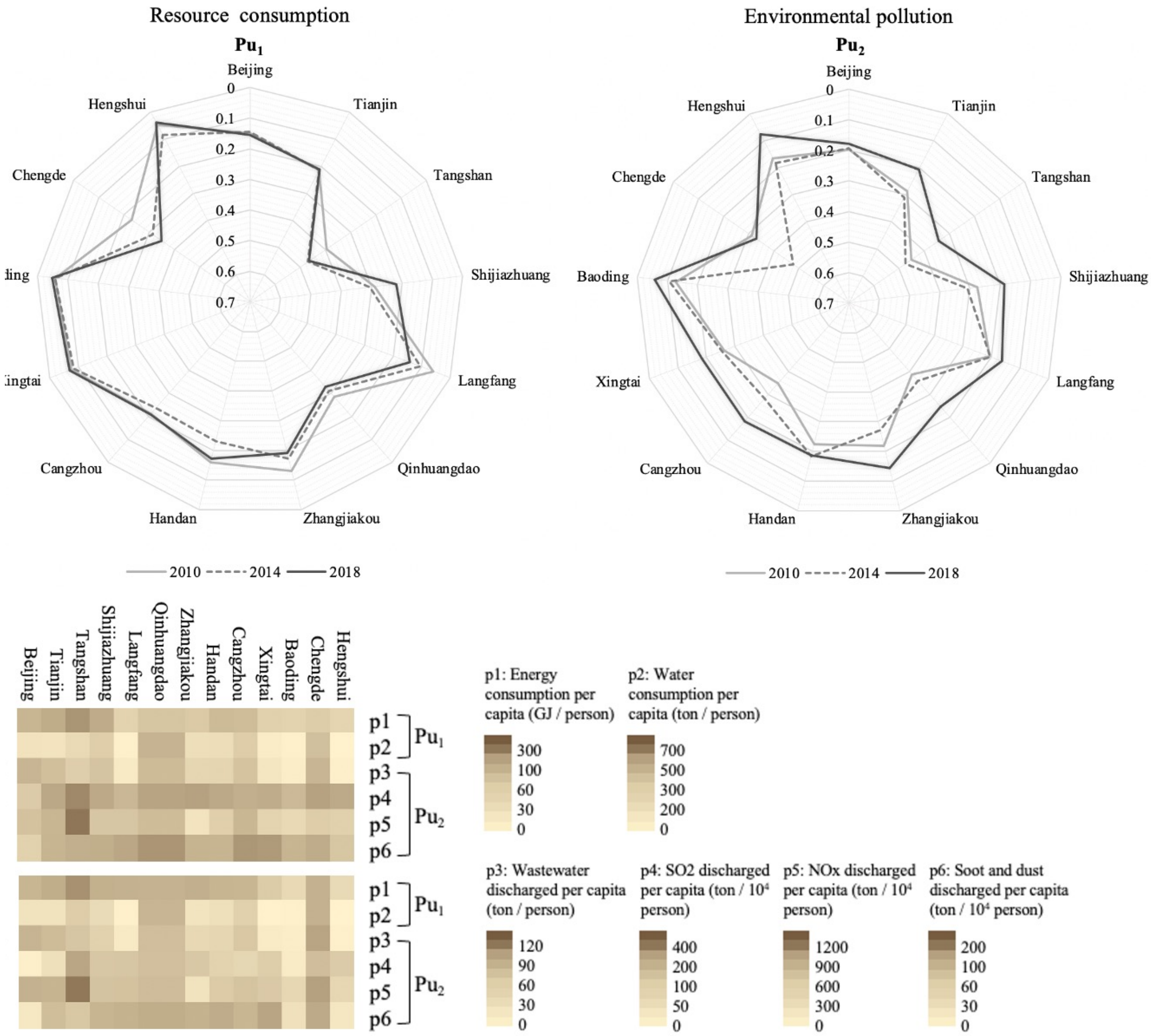


Fig. 7-8 The performance of each of the indicator categories of Pu in JingJinJi

7.5.Summary

The main conclusions of the empirical analysis of 13 cities in the JingJinJi megalopolis from 2010 to 2018 can be summarized as follows:

During the past 9 years, (1) the quality of the built environment in the study area has generally shown an upward trend, while the environmental pressure experienced an upward and then a downward trend. The main reason is heavy industry and manufacturing and the environmental pressures that accompany their industrial transformation process, as well as geopolitical factors. From the performance of evaluation scores, (2) the Qu index scores range from 0.047 to 0.0.545 and the Pu index scores range from 0.053 to 0.487. The composite Su score has a minimum value of 0.238 and a maximum value of 3.424, indicating that there is a significant development gap between cities in the region of JingJinJi. And (3) the number of cities in a sustainable state increased from 2 in 2010 to 7 in 2018, but there are still 6 cities in an unsustainable state of development. In this process, 3/5 cities have chosen a sustainable development path that both improves the quality of the built environment and strives to reduce environmental stress, while others have prioritized ensuring urban quality improvements. Using the curve estimation regression model, it was further found that (4) 92.3% of cities showed a significant relationship between Qu and Pu, and only one city did not have significant interactions between Qu and Pu ($p \geqq 0.05$). There are three different types of interaction mechanisms. Among them, 5 cities showed an inverted U-shape and 2 cities with a negative linear relationship, which indicates that the negative impact on environmental stress is diminishing in improving the quality of the built environment. However, (5) there are 5 cities showing an inverted S-shape relationship. This kind of reversal trend suggests that environmental problems are bound to occur if the environment is ignored, and the focus is only on promoting the quality of the urban built environment.

In terms of spatio-temporal characteristics of evolution results, it can be intuitively found that (6) the sustainability of the urban environment in this area shows obvious urban differences and spatial heterogeneity. In JingJinJi, the spatial patterns of urban sustainability present a progressive development pattern from the center to the south. Midwestern cities and individual cities in the South have reached the basic level of sustainable at present. Specifically, (7) the mean center of Qu moves closer to the geometric center at a rate of 2.77 km/year to the southwest but remains 32.84 km away from the geometric center. But (8) the mean centers of Pu and Su are moving to the Northeast and southwest, 65.29 km and 39.04 km away from the geometric center, at 2.78 km/year and 5.96 km/year respectively. The movement trajectories of both deviate from the geometric center, indicating that the gap between the unbalanced development of southwest and northeast cities in the JingJinJi region is increasing rapidly.

Therefore, at the level of macro-regional coordinated development, (9) it is necessary to prioritize effective strategies to focus on environmental issues in cities in the Northeast. At the micro level of city-specific development, (10) the results of each city's sub-assessment scores can be combined with a heat map of indicator statistics for a case-by-case diagnosis. Broadly speaking, (11) for the countermeasures of the quality of built environment, the cities recommended to prioritize responses of urbanization economies are Xingtai, Baoding and Chengde; the cities that need to give priority to improve infrastructure development are Beijing, Shijiazhuang, Langfang, Handan and Cangzhou; and the cities that need to particularly strengthen their urban attractiveness are Tianjin, Tangshan, Qinhuangdao, Zhangjiakou and Hengshui. (12) For the countermeasures of the environmental pressure, the cities recommended to prioritize responses to reduce environmental pollution are Tianjin, Handan, Xingtai and Hengshui, while the other cities urgently need to prioritize decrease the resource consumption.

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Chapter 8. Comparative study and classification discussion among four megalopolises

8.1. Introduction

Sustainable urbanization not only emphasizes the dynamic balance of the quality of the built environment and its environmental pressure in the course of urbanization. It goes beyond the narrow scope of urban areas into individual sustainable cities—and beyond the development of each megalopolis. It is to bring about the harmonious development of different regions in the whole country. China's large population base, its high speed of economic growth, its energy shortage and fragile environment are all critical factors to be considered in establishing a pattern of sustainable urbanization with Chinese local characteristics. It is clear that sustainable urbanization must adhere to the basic national policy based on the coordinated development of all parties in China. Therefore, on the basis of a detailed understanding of the sustainable development of the four major megalopolises, it is possible to find the universal development characteristics of cities throughout the country through comparison and discussion. So as to achieve the ultimate goal of providing a basis for decision makers to plan the national sustainable urbanization path.

When well-planned and managed, cities create value, which is the totality of the economic, social, environmental, and intangible conditions outcomes that have the potential to improve the quality of life of residents in meaningful and tangible ways. As is increasingly understood by policymakers at all levels of government, planned urbanization leads to positive development outcomes that can be leveraged for improved quality of life and overall prosperity. For this to happen, all parties must create an enabling environment for cities to thrive, and local authorities must seize the opportunities given to them to flourish and develop. Urbanization should not be at the expense of the natural environment. In fact, both should be symbiotic and mutually enhancing. The policies or investments should priority support the backward areas based on the local situation of urban development.

At present, 60.4% of the cities are basically in a state of sustainable development, but the phenomenon of imbalanced regional development is obvious. From the empirical results of 9-year data of 91 samples, the evaluation data of all dimensions show significant positive correlative relationships with urbanization level (R^2>0.5) (see Fig. 8-1). In other words, improving the qualities of both urban built environment and natural environment are conducive to maintaining sustainable urbanization. But the most effective way to maintain the process of urbanization is to balance the relationship between the above two dimensions to improve the level of urban sustainability. At the same time, it further proves that the evaluation method proposed in this study can provide effective guidance for China's sustainable urbanization.

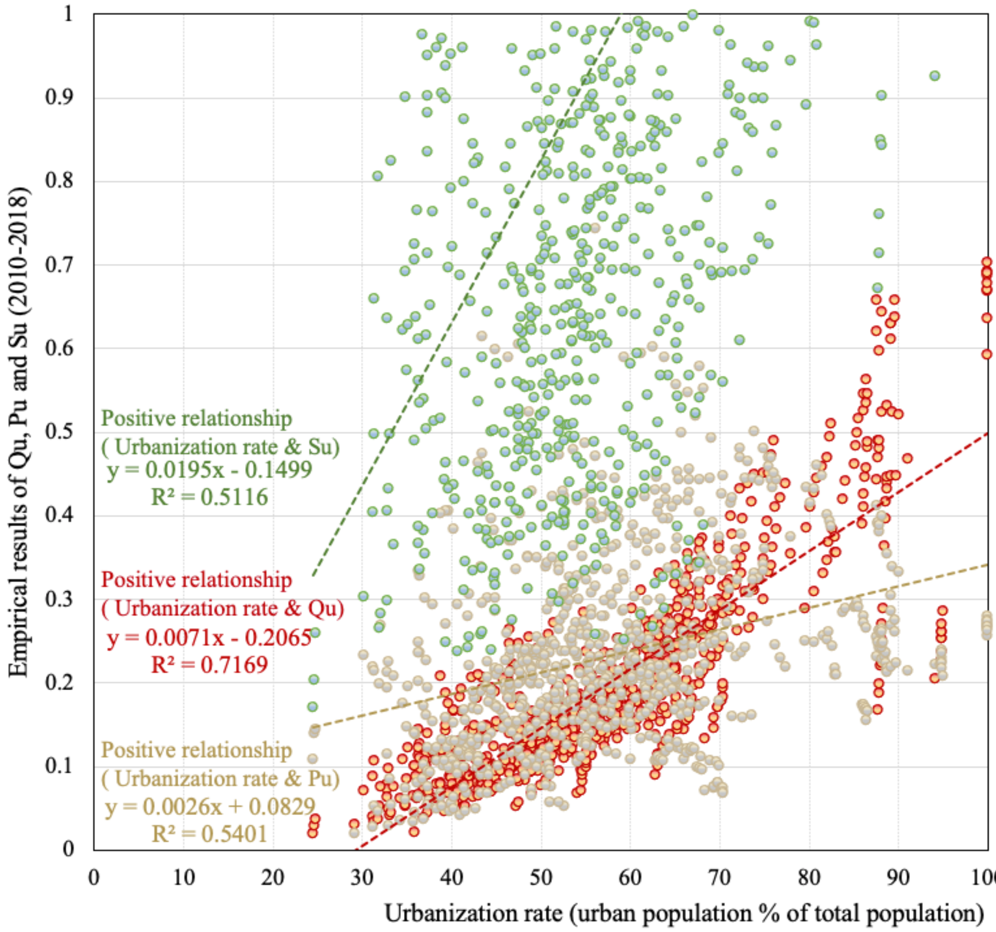


Fig. 8-1 The interaction mechanisms between values of Qu / Pu / Su and urbanization rate

The study of this chapter compared the results from urban sustainability assessment among four studied megalopolises and discuss the characteristics and implications of urban sustainability based on city classification. Firstly, to visually compare and understand the current sustainable development situation, interactive mechanism, and trend judgments of the four studied megalopolises, a series of statistical analyses were carried out that based on the assessment panel data of Qu, Pu and Su from 2010 to 2018. Then, using the spatial autocorrelation method of geographic information system to analyze the different clustering of urban sustainable features from a spatial perspective. In order to further explore the universal characteristics of China's urban development and explore the corresponding countermeasures, 91 studied cities were classified and discussed according to three characteristics of geographic location, urban population size, and sustainability performance clustering. It is recommended that decision-makers establish an inter-city complementary system through regional planning to build an active cooperative relationship and achieve sustainable urbanization throughout the entire country.

8.2.Comparative analysis of urban sustainability among four megalopolises

8.2.1. Data comparative analysis among four megalopolises

Rapid urbanization makes rapid economic growth in emerging economies and cities play crucial roles in driving megalopolises' development. In terms of the quality of the built environment (Fig.8-2 & Table 8-1), all four megalopolises show the continuously positive trends from 2010 to 2018 with a steady growth rate. The Qu score in Pearl River Delta was 0.182 in 2010 and 0.262 in 2018 which always in a leading position. It followed by that in the Yangtze River Delta, Shandong Peninsula, and JingJinJi. Although the ranking of cities has not changed in 9 years, the growth rate of the Shandong Peninsula and the Yangtze River Delta is relatively fast seen from the slopes of the regression lines, and their CAGR reached 7.31% and 6.04%, respectively. That is to say, the gap between the top three megalopolises is getting smaller, but the gap between them and the fourth-place JingJinJi is increasing accordingly. Geographically, the urban divide between China's prospering southern regions and lagging northern areas will continue to widen in the coming years. The southern regions benefit from export dependence and active economic activities, while resource-rich northern regions were dragged down by slower fixed investment, falling commodity prices, or population migration. Therefore, it is still necessary to deal coping with horizontal disparities in domestic regions, with huge implications for sustainable growth and corresponding policymaking.

From the comparison figure of Pu (Fig.8-2 & Table 8-1), the current environmental pressure of the Pearl River Delta megalopolis is the smallest and is significantly better than other megalopolises, followed by JingJinJi, Yangtze River Delta and the Shandong Peninsula in 2018. And the U-shaped regression characteristic indicates that the environmental pressures of four megalopolises increase with time at the initial of the study period, but later these pressures diminish started before 2016. Among them, the change of the JingJinJi and Pearl River Delta regions occurred earlier, probably around 2012. But the Yangtze River Delta and the Shandong Peninsula are relatively late, making the gap of the state of the environment with the above two regions became more significant. From the perspective of environmental pressure alleviation trends, JingJinJi has seen the fastest environmental improvement, with an average annual compound decline rate of 1.4%. And other regions are less than 1%. The established regional linkage mechanism in JingJinJi proved to be an efficient governance model for the protection and restoration of ecosystems and the prevention and control of pollution. However, the environmental load of the Shandong Peninsula, which is relied on heavy industry, has increased compared to 2018. And the ranking of the Shandong Peninsula has changed from third to first according to the Pu scores in nine years, indicating that its urban environmental problems have become increasingly prominent.

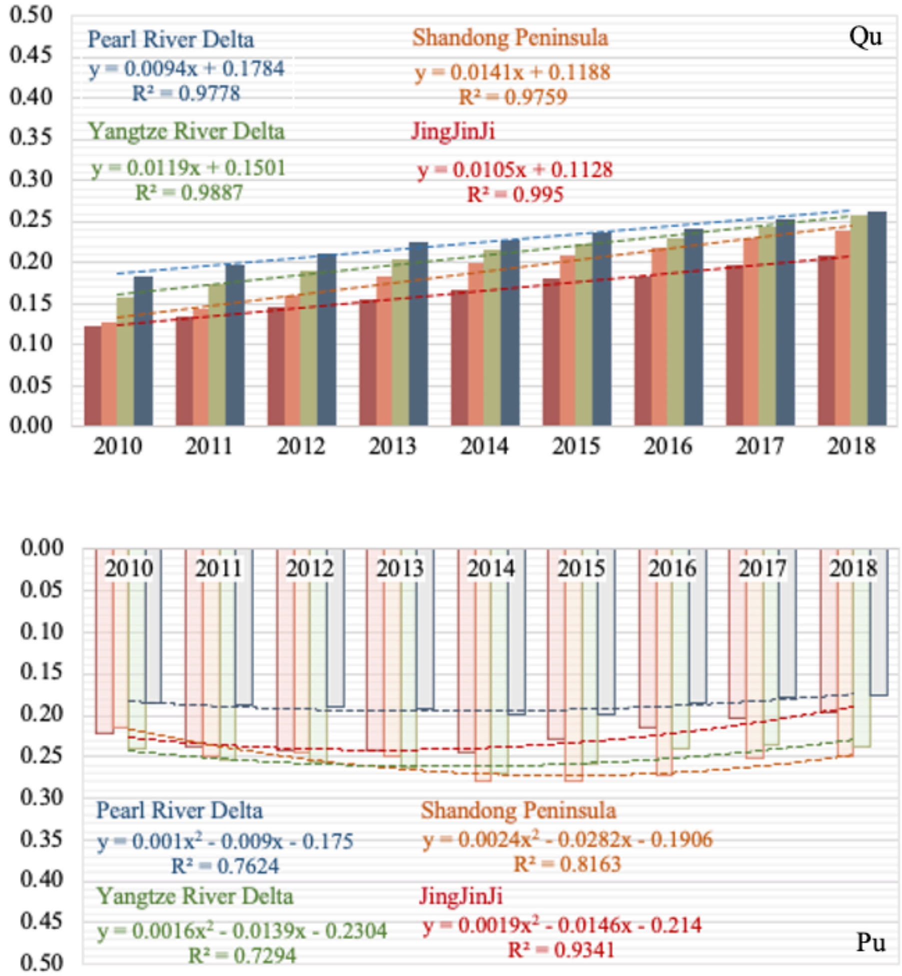


Fig. 8-2 Data comparative analysis of Qu and Pu among four megalopolises

Table 8-1 Data comparative analysis among four megalopolises

	Yangtze River Delta	Pearl River Delta	Shandong Peninsula	JingJinJi
Qu (2010)	0.157	0.182	0.127	0.122
Ranking	2	1	3	4
Qu (2018)	0.257	0.262	0.239	0.208
Ranking	2	1	3	4
Mean	0.21	0.23	0.19	0.17
CAGR (%)	5.62	4.12	7.31	6.04
Pu (2010)	0.240	0.185	0.214	0.222
Ranking	1	4	3	2
Pu (2018)	0.238	0.176	0.250	0.195

Ranking	2	4	1	3
Mean	0.25	0.19	0.25	0.23
CAGR (%)	-0.08	-0.57	1.74	-1.40
Su (2010)	0.741	0.953	0.643	0.607
Ranking	2	1	3	4
Su (2018)	1.283	1.495	1.067	1.345
Ranking	3	1	4	2
Mean	0.97	1.19	0.82	0.89
CAGR (%)	6.29	5.12	5.79	9.24

Note: CAGR = Compound annual growth rate.

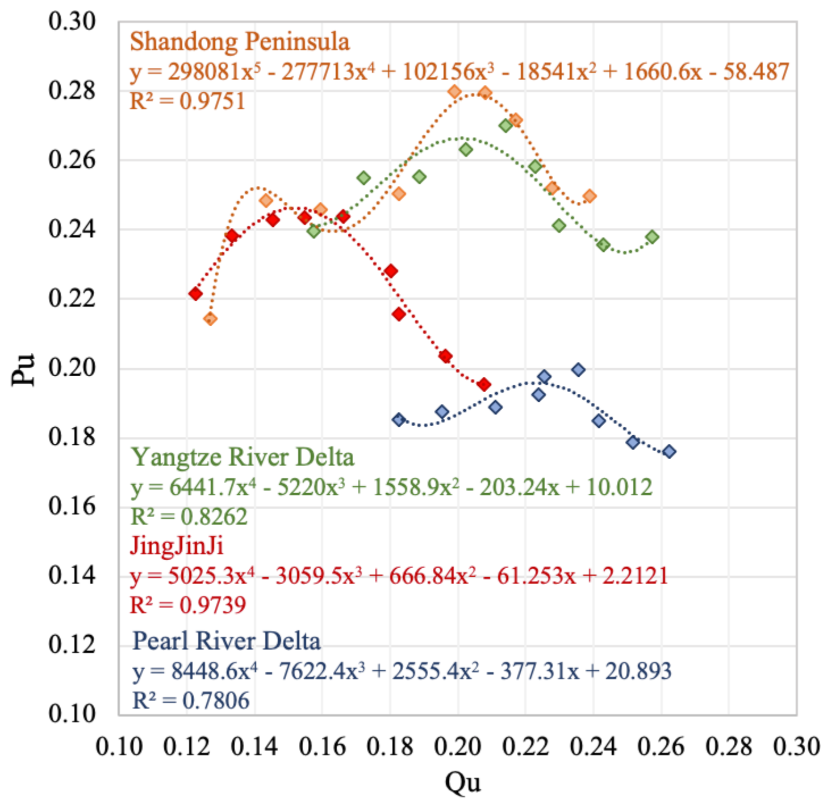


Fig. 8-3 The mechanism curve between Qu and Pu among four megalopolises

As represented by the mechanism curve between Qu and Pu (Fig. 8-3), all trends of megalopolises are experiencing a fluctuating process. The R^2 value of all fitted curves is greater than 0.7, and it can be judged that the fitting is valid. Although all urban agglomerations seem to have passed the peak of environmental pressure, the Yangtze River Delta and the Shandong Peninsula have shown a negative trend of pressure rebound with the continuous improvement of urban quality. Normally, rapidly growing cities in the low-quality stage of the urban built environment, the scale effect, which increases pollution and other degradation, overwhelms the time effect. Then in the higher quality stage, cities' growth is slower and pollution reduction efforts can overcome the scale effect. And the demand for a cleaner environment will increase making the environment will improve. Though it proved that the pollution problems are being addressed in developing economies, the Jevons' effect [1,2] sometimes occurs when technological progress or government policy increases the efficiency. That is improved efficiency increases real incomes and accelerates economic growth, but when the effect from increased demand predominates, and improved efficiency increases the speed at which resources are used and increasing the consumption of that resource [3]. This is the reason why the city develops at any time but causes the rebound effect that need to be considered in the formulation of planning strategies.

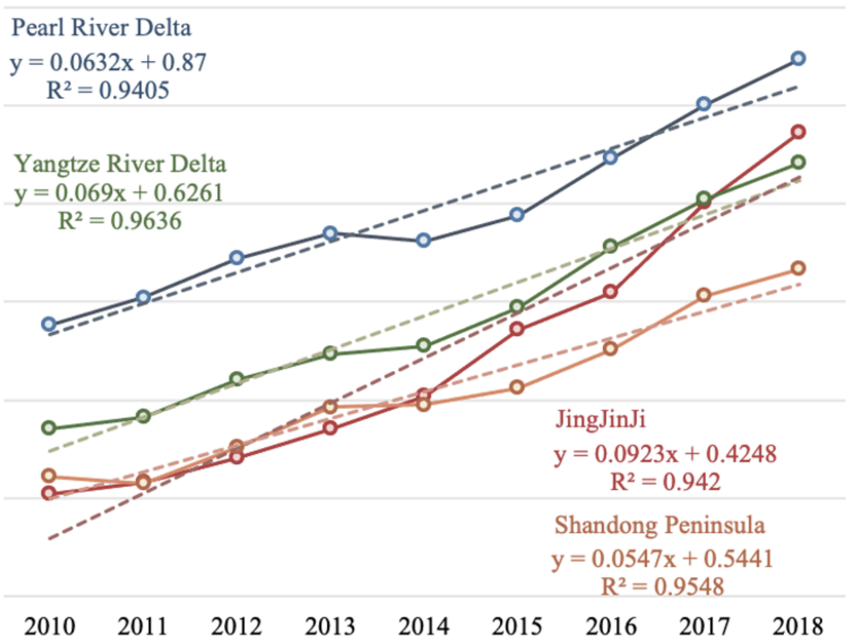


Fig. 8-4 Data comparative analysis of Su among four megalopolises

From a comprehensive point of view, among the four megalopolises (Fig.8-4), the Pearl River Delta megalopolis has the highest level of sustainability and has been among the best for 9 years. And followed by JingJinJi, Yangtze River Delta and the Shandong Peninsula in 2018. The average Su scores of all cities in corresponding agglomerations separately exceeded 1.0 in 2011, 2016, 2015, and 2017. It reveals that the four megalopolises are basically in a state of sustainable development. In terms of the slope of the regression line, the sustainable urbanization process of JingJinJi is relatively fast, and the score surpassed the Yangtze River Delta region in 2017. Followed by the Pearl River Delta, the Yangtze River Delta and the Shandong Peninsula. Therefore, the results can be concluded that (1) the sustainability of each megalopolises is showing a positive trend of improvement (2) but due to the different speed of improvement, the gap between the urban agglomerations would have a tendency to widen, which may cause imbalanced development of the entire country and is not conducive to the coordinated development in the future.

8.2.2. Spatial autocorrelation analysis among four megalopolises

Fig shows the Local indicators of Spatial Association (LISA) cluster map of the evaluation results of Qu, Pu and Su. That divides the 91 cities into four types, namely, high- high cluster areas (HH), high-low cluster areas (HL), low-high cluster areas (LH), and low-low clustering areas (LL), to reflect the spatial correlative pattern of the urban sustainability performance of megalopolises in China. Over time, the number and spatial distribution of the agglomeration areas showed constant dynamic change. And there are obvious, different and even imbalanced spatial agglomeration distribution characteristics in the 91 cities of four studied megalopolis from 2010 to 2018. In general, the clustering distribution of cities in the Qu map is relatively concentrated compared with that in Pu map. Comprehensively, the sustainable and unsustainable cities are clustered but separated from each other in the whole study area. (Fig.8-5 - 8-8)

In the cluster maps of Qu values (Fig.8-6), the HH cluster areas are all distributed in the eastern coastal area of megalopolises. This kind of agglomeration especially in the economic urbanization field can easily generate positive externalities because the proximity enhances the interaction of both economic activities and the diversity on innovation or diffusion of technologies. So, the number of cities in HH areas showed an increasing trend over time. There are mega or large advanced cities in or around this kind of areas, such as Shanghai, Guangzhou, Shenzhen and Qingdao. It is these cities that have played an active role in the radiation effect on the surrounding cities. On the contrary, LL clusters appear in the fringe areas at the junction of megalopolises, mostly are inland areas. Although the areas of the LL cluster have decreased compared to 2010, those are still the key focus areas for urban quality improvement. The JingJinJi and Yangtze River Delta regions still have several clustered areas with LH or HL phenomenon, indicating that the gap between neighboring cities in that areas is too large. That means the ring of lagging cities has not only become a cold economic growth pole but has also been constrained by peripheral development for a substantial period. These backward cities are generally constrained by neighboring cities with higher administrative levels (such as Beijing, Tianjin, and Hefei). Thus, the priority socioeconomic trend toward localized authority is one of the reasons for the unbalanced development of some regions.

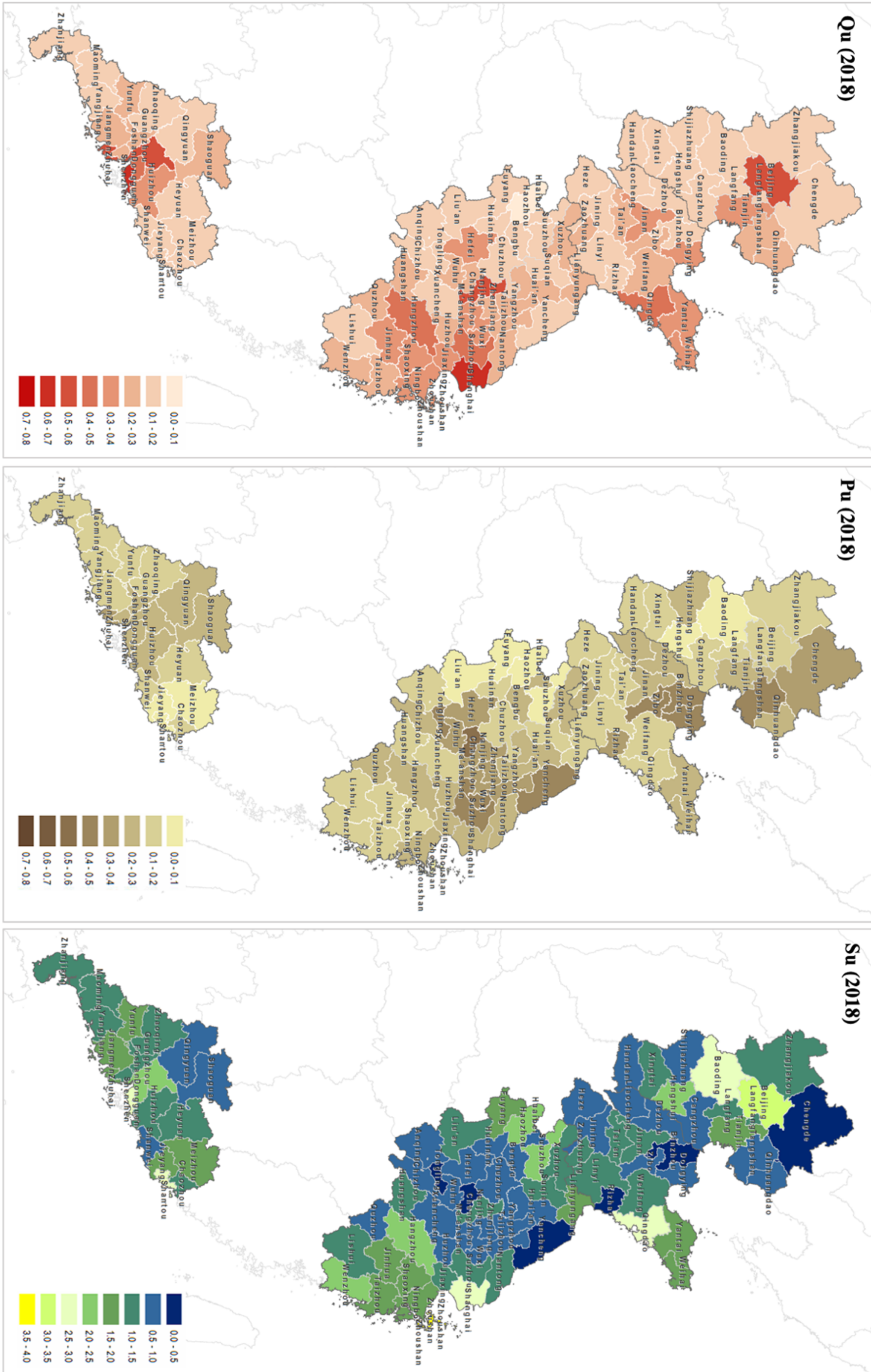


Fig. 8-5 Maps of the evaluation results of Qu, Pu and Su among four studied megalopolises in 2018

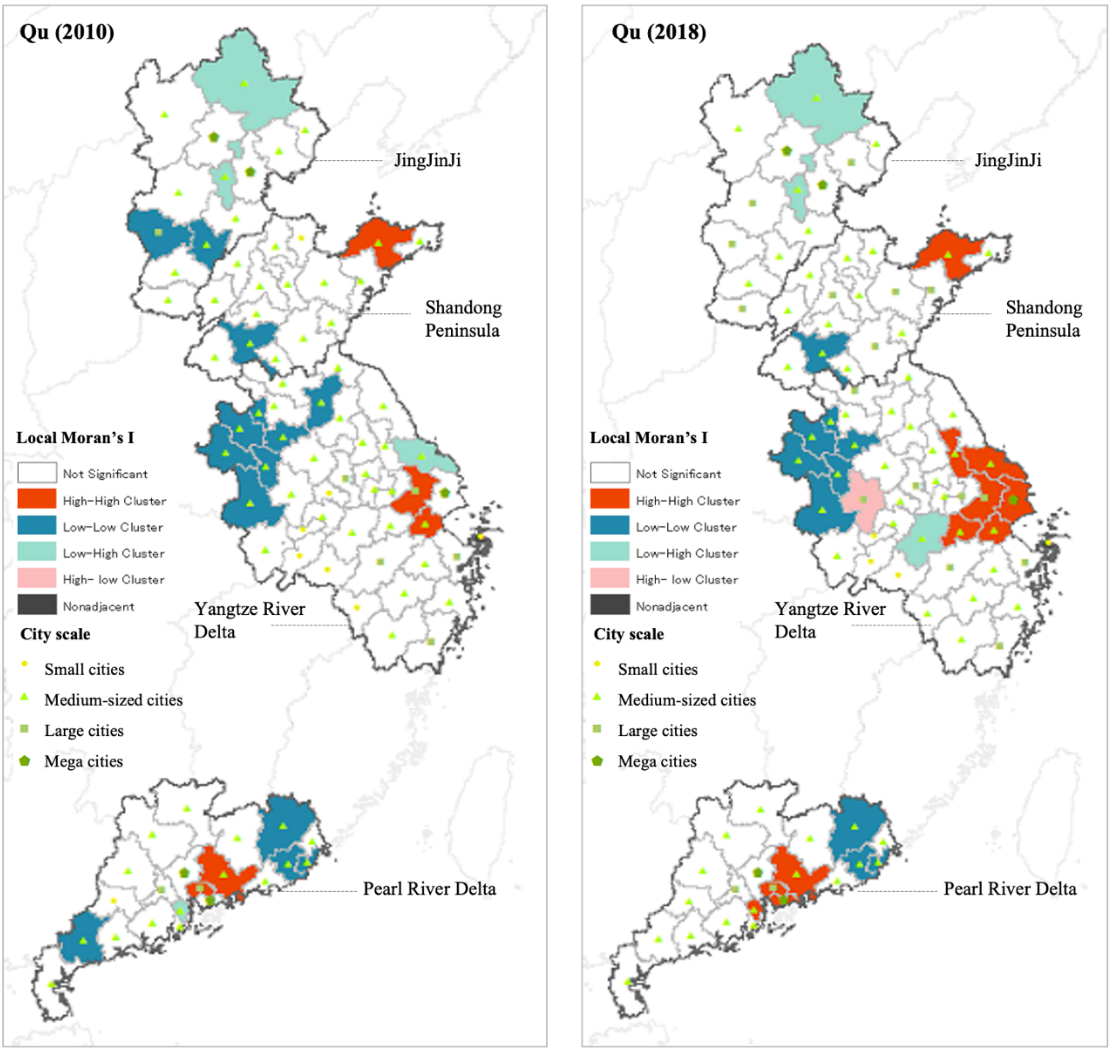


Fig. 8-6 Spatial Association (LISA) cluster map of the evaluation results of Qu in 2010 and 2018

In terms of spatial distribution of Pu values (Fig.8-7), the maps show a scattered cluster distribution, but the environmental pressures affect more northern than in the southern region of China. It is worth noting that the HH cluster areas located in the JingJinJi and the Yangtze River Delta have expanded compared to 2010. That means the adverse effects of urban environmental pressure spread between neighboring cities. And the environmental governance of the corresponding area has not received much attention. In contrast, Xuancheng City in Yangtze River Delta has maintained a better environmental quality under the surrounding of these high environmental pressure cities seen from LH clusters feature, which is worthy of emulation by those cities. Moreover, the number of cities in LL clusters areas has increased, showing a positive trend of environmental improvement especially the medium-sized cities. In addition, under the agglomeration effect of low environmental pressure cities, the high environmental pressure of individual cities (such as Huainan, Huaibei and Huai'an), has been relieved. Both environmental pressures and environmental policies clearly affect different groups within them unequally. These differences are essential to take into account in the design of more targeted and more equitable countermeasures.

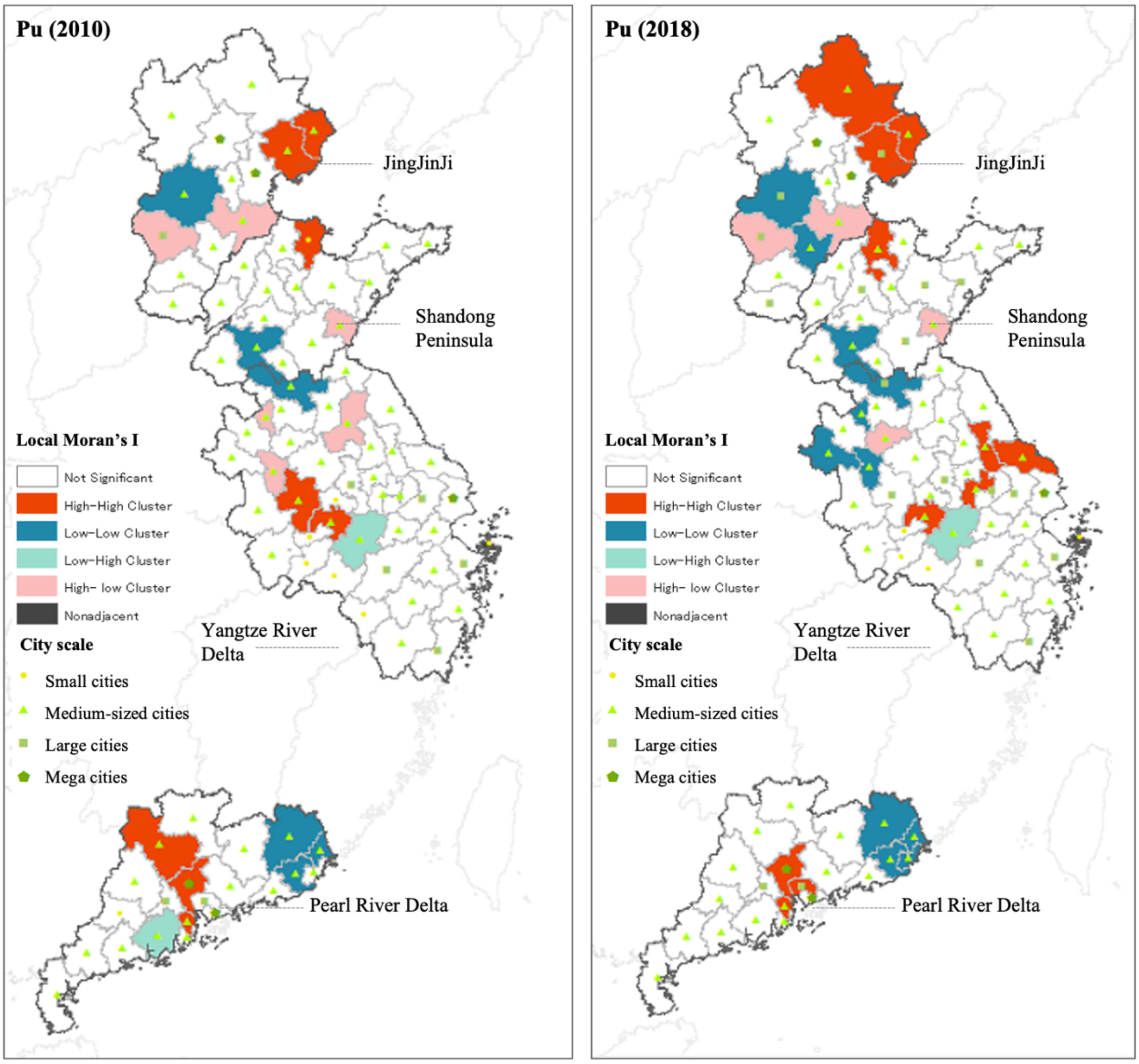


Fig. 8-7 Spatial Association (LISA) cluster map of the evaluation results of Pu in 2010 and 2018

Judging from the clustering characteristics of the entire range (Fig.8-8), the sustainable development of the Pearl River Delta region is more balanced, compared with the other three megalopolises. Each urban agglomeration has an HH cluster area at a high level of sustainability. Most HH cluster areas are along the sea with a large-sized urban population gathered. The variation of distribution from 2010 to 2018 shows that that under the planning concept of regional integrated development, the collective effect of these cities has been further strengthened and played a positive role in promoting the development of surrounding cities, especially in the Yangtze River Delta. However, in order to avoid further unfavorable consequences of widening internal gaps, the premise of strengthening the agglomeration effect of advanced cities is to give priority to supporting cities in LL cluster areas and LH agglomeration areas, especially the JingJinJi and Yangtze River Delta urban agglomerations. In addition, cities of HL cluster have the potential to become central cities to coordinate the development of surrounding area, such as Jinan and Nanjing. These areas happen to complement each other with high-gathering areas, which is conducive to the realization of the integrated development goal of the entire urban megalopolises.

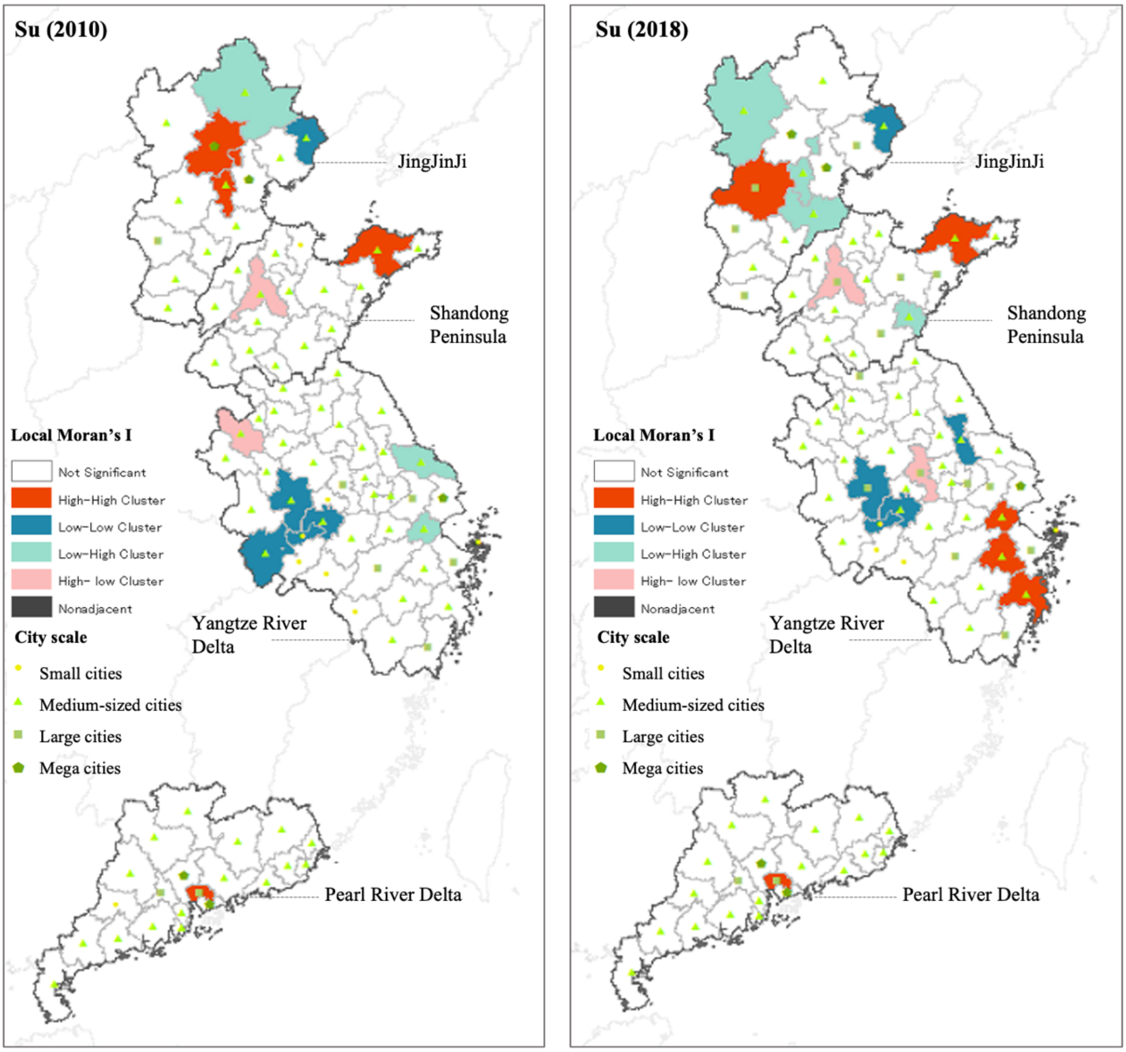


Fig. 8-8 Spatial Association (LISA) cluster map of the evaluation results of Su in 2010 and 2018

8.3. Characteristics and implications of urban sustainability based on city classification

To further explore the general urban development characteristics and provide extensive guidance for many cities as possible, classification is used as a common data analysis method for comparative study. That is the process of finding a model that describes and distinguishes data classes and concepts. Based on sufficient research sample data, the characteristics and development implications of various cities were explored by classifying them according to different standards of geographic location, urban population size, and sustainability performance clustering. The detailed discussion is as follows:

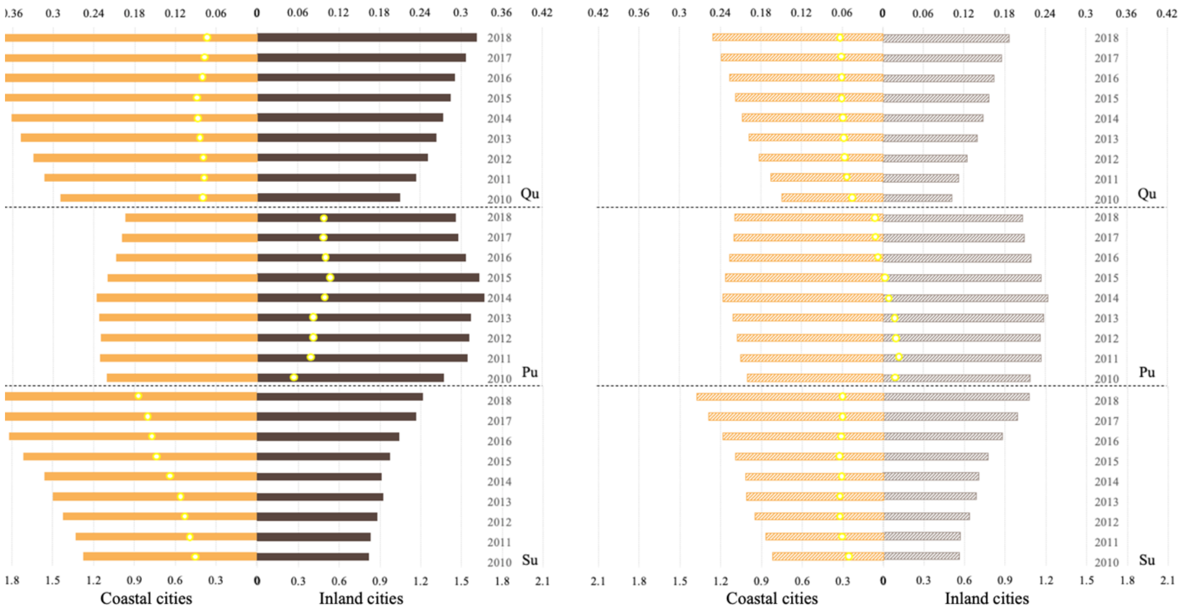
8.3.1.Discussion by geographic location and urban population classification

According to geographical location, 91 sample cities are divided into two groups: coastal cities and inland cities, including 36 and 55 cities respectively (Table 8-2). Through analyzing the mean scores of the urban sustainability performance of these two groups (Fig.8-9 and 8-10), it can be seen that (1) there are obvious differences in most assessment categories between coastal cities and inland cities, but the gap is gradually increasing. (2) The sustainability performance of coastal cities is generally better than that of inland cities especially in urbanization and its quality of built environment. And (3) The environmental pressure of inland cities is generally greater than that of coastal cities of the same population size. The main reasons are as follows: (a) Transportation layout: there are 2076 berths of 10,000 tons arranged along the national coastal line with a transportation production capacity of 13.951 billion tons in 2019 [4]. These trade activities have brought huge economic benefits boosting a great economic benefit. But the inland cities only rely on land transportation, and the cost of corresponding facility construction and frequent transportation is a large amount of consumption and pollution emissions. (b) Marine industries development: the great importance is attached to develop marine industries in promoting the creation of ocean-economy value, such as marine chemistry, biomedicine, ocean power, engineering and tourism etc. There's an energy associated with large bodies of water that just cannot be found in inland cities, but a large part of China's inland cities is vast in land and rich in resources. (c) Policy orientation effects: the national government has established open economic zones, special economic zones and open coastal cities in coastal area to encourage trade businesses by implementing financial incentives like preferential tax regimes. But China's inland cities are asserting themselves to rise through a unique blend of state intervention and pro-developmental reform [5–7].

Table 8-2 List of cities by geographic location and urban population classification.

City classification	Small cities	Medium-sized cities	Large cities	Mega cities	Total
Coastal	Zhoushan (**1**)	Jiaxing, Shaoxing, Taizhou, Nantong, Lianyungang, Yancheng, Zhuhai, Shantou, Huizhou, Shanwei, Zhongshan, Jiangmen, Yangjiang, Zhanjiang, Maoming, Chaozhou, Jieyang, Qinhuangdao, Dongying, Yantai, Weihai, Rizhao and Binzhou (**23**)	Hangzhou, Ningbo, Wenzhou, Dongguan, Baoding, Shijiazhuang, Qingdao, Weifang (**8**)	Shanghai, Guangzhou, Shenzhen, Tianjin (**4**)	**36**
Inland	Tongling, Chizhou and Huangshan (**3**)	Huzhou, Jinhua, Quzhou, Lishui, Changzhou, Huai'an, Yangzhou, Taiizhou, Suqian, Huaibei and other 31 cities (**41**)	Nanjing, Wuxi, Xuzhou, Suzhou, Hefei, Foshan, Tangshan, Handan, Jinan, Linyi (**10**)	Beijing (**1**)	**55**
Total	**4**	**64**	**18**	**5**	**91**

In terms of urban population size classification, it can be divided into four categories according to the reports by United Nations: small cities (urban population < 1 million), medium-sized cities (5 million > urban population ≧ 1 million), large cities (10 million > urban population ≧ 5 million) and mega cities(urban population ≧ 10 million). Due to the insufficient number of samples of the current studied cities, all 91 cities are merged into two groups for discussion, namely, medium-small cities (including 64 medium-sized cities and 4 small cities and) and mega-large cities (including 5 mega cities and 18 large cities) (Table 8-2). In general, there is significant gap between medium-small and mega-large cities in the same geographical conditions as follows (Fig.8-9 and 8-10): (1) though the development gap between cities of different scales in inland areas in the urban sustainability is shrinking, that of coastal areas shows an increasing trend. (2) The environmental quality of large cities is better than that of medium-small cities. But (3) the environmental pressure of those cities is greater than that of medium-small cities, especially in inland areas. That is mainly because the (a) facilities upgrades: the construction of traffic infrastructure offered passenger and freight transport and shortened the distance to advanced cities. Extension of traffic infrastructure from mega cities to large cities promoted urban development, but it has still not been conveniently connected to medium-small cities till now. And (b) industrial shift: following the national government strategy of 'suppressing secondary industry and developing tertiary industry'. In mega and large cities, the collective industries have been fully developed, absorbing a large number of external laborers and enabling residents to work locally but causing large consumption and pollution.



(1) Comparison of panel data in **Mega-large cities** (2) Comparison of panel data in **medium-small cities**

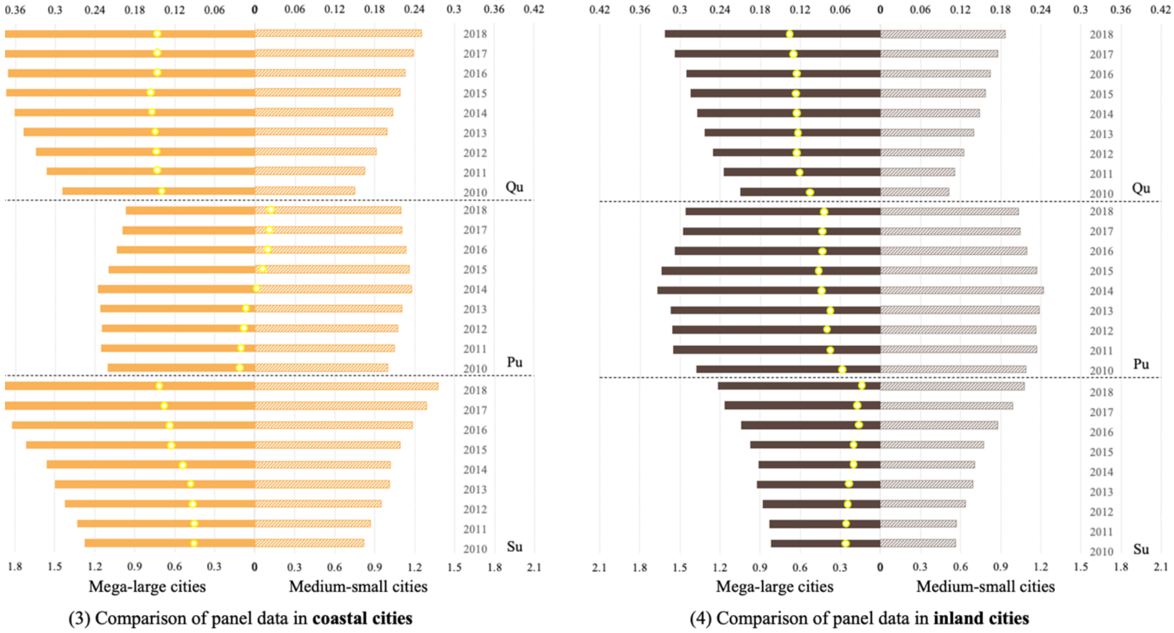


Fig. 8-9 Comparison of evaluation scores of Qu, Pu and Su in cities by geographic location and urban population classification from 2010 to 2018

(Notes: (1) All evaluation data uses the mean value of a sample of cities in the corresponding group. (2) Yellow points mark the difference between the two numbers.)

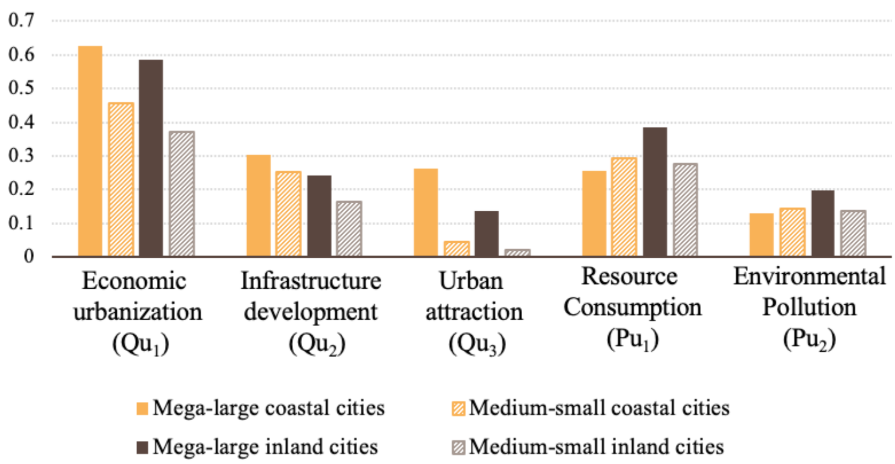


Fig. 8-10 Comparison of the mean evaluation scores of each indicator categories among four types of cities in 2018

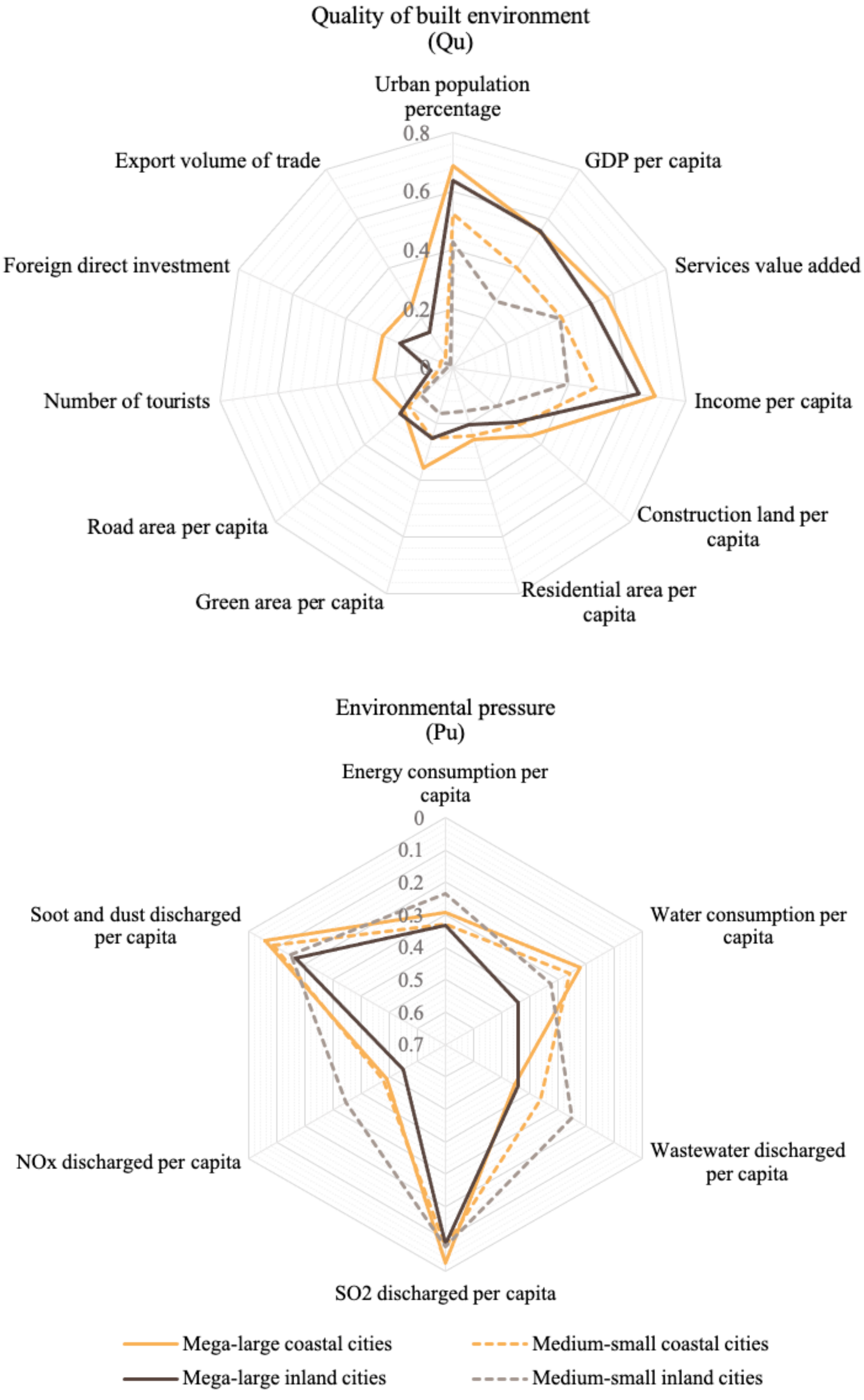


Fig. 8-11 The performance of each of the indicator of Qu and Pu by city classification in 2018

Combined with the analysis results (Fig.8-9, 8-10 and 8-11), the comprehensive characteristics and specific development implications of different types of cities can be understand based on the above classification standard:

(1) For mega-large coastal cities, all values of representative indicators for the dimension of the urban built environment are greatest compared to other cities. During the past decade, large coastal cities have seen the fastest improvement in economic urbanization and urban attraction. In particular, rapid urban population agglomeration and industrial upgrading have driven GDP growth. At the same time, the investment promotion policy and strengthening the characteristics of coastal cities, it has attracted large amounts of foreign investment to promote urban development. But roads and residential areas are insufficient due to land shortage and overload housing prices. Besides, the sustainability values are greater than 1.0 and increase year by year, surpassing other types of cities. This means that the improvement of urban quality is less than the degree of environmental pressure caused, showing a good trend of sustainable development. Higher-income economic gains are used for investment in industrial upgrading, energy efficiency improvement, and emission control, without causing too much load on the environment. However, improving environmental quality is the most important aspect for the future development of large coastal cities.

(2) For mega-large inland cities, although a certain speed of urban development has been maintained under the urgent needs of the economy, a lot of resource consumption has been generated during the construction process. However, efforts are still needed to enhance urban residential construction, as well as the urban attractiveness in tourism and export trade. Coupled with the lack of pollution control capabilities, much of the environmental performance has declined over the past decade. Environmental pollution indicators' values have significantly decreased, mainly due to the discharge of wastewater and nitrogen oxides. Nitrogen oxide emissions are related to public power generation and road transportation and the construction of infrastructure facilities is usually better in larger cities. Thus, the load transportation in inland areas is frequent, and the proportion of vehicles is high, which requires strict control of emission standards. These cities shall take the lead to push forward the ecological development mechanisms. The mechanisms will ensure to control the balance between urbanization and inhabited development and relieve the ecological pressure. With the concentration of various industries in these cities, improvement of energy efficiency and usage of renewable energy in those industries are also important.

(3) For medium-small coastal cities, the rapid urbanization process in the past decade has brought about a rapid transformation of the industrial structure. The better use of ports and the advantages of resources and policies have led to a substantial increase in GDP. The supporting

infrastructure has also been gradually built to improve the city's comprehensive carrying capacity, but the urban public service facilities are still in short supply. Despite the coastal scenery, the city needs to be improved in the construction of natural and cultural characteristics. Compared with the increase in data consumption, there are fewer changes in pollution because of better emission control measures. Due to the seafront, in order to protect the marine ecological environment, the government has tightened water pollution control in coastal cities and issued corresponding water environment policies [8]. Although the overall level of sustainable development is relatively high, similar to mega-large inland cities, their resource consumption is still large, causing damage to the environment. For example, excessive Oil and gas drilling has serious consequences for our wildlands. As urban infrastructure construction and attractiveness increase, these cities need to adopt policies to enhance the carrying capacity and pay attention to the impact on the environment accordingly, so as to match growing urbanization rates in the long run.

(4) For medium-small inland cities, due to limited living space and the environment of vulnerable groups, they gained the lowest evaluation values in measuring the quality of the built environment. Urban development mainly depends on the growth of urbanization economic indicators, especially the urbanization rate. However, the lower level of construction of infrastructural facilities has not met the needs of the growing urban population for production and life. Moreover, the external competitiveness is insufficient, especially the low investment value of its own city cannot attract more external investment. Although the urban environment has been well maintained or even improved, urban sustainable efficiency is extremely low. In the face of the current government's urgent desire to promote large-scale construction of infrastructure, if the corresponding environmental protection policy is not implemented separately, both human activity and natural processes will inevitably generate serious impacts on the urban environment. These actions have to priority prevent the urban atmospheric environment from deteriorating in medium-small inland cities, especially the control of SO2 and soot and dust emissions.

8.3.2.Discussion by the sustainability performance clustering classification

According to sustainability performance analysis, 91 sample cities are forming into 6 clusters by using hierarchical clustering of Ward Linkage Method. From the dendrogram, it begins to appear different characteristics of these 6 clusters of cities, which we could summarized into 6 different Types (Table 8-3 and Fig.8-12). Furthermore, when looks into the sustainability performance on Fig.8-13, it can be seen that:

(1) Advanced positive type: there are 7 cities in this type, include Shanghai, Beijing, Shenzhen, Guangzhou, Dongguan, Qingdao and Hangzhou. Those cities are advanced economic cities with high urbanization and high-level administrative division. It obviously has the highest Qu points among all these 6 types, and the Pu points are relatively much lower, therefore, the difference value between Qu and Pu is significant and the sustainability performance is remarkable. The reason is there are most China's mega cities included in this Type, like Beijing, Shanghai and Shenzhen, the urban population, GDP and Income are incredible high compared to other cities, and the control of SO2 discharge, soot and dust discharge, water and energy consumption is doing efficiently well, which made those supper cities growth in a good manner. These cities in this type are on the right track and would predict to high performance continuously in the near future. Cities like Beijing, Shanghai and Shenzhen, they are already recognized as international mega cities, their city infrastructure are at world leading level, the urban attraction are also outstanding, also their mega cities aggregation effect would attracts young talents continuously pour in, which would further improve the GDP and incomes, etc. but also should be aware that the residential area, green area and infrastructure requirements would facing more challenges, and need to be carefully deal with in the future. For cities like Hangzhou, Qingdao and Dongguan, industrial upgrading would be the priority, how to keep and enhance their GDP, incomes and efficiently control their NOx, wastewater discharge is the problem they must facing in the future.

(2) Coordinated positive type: there are 17 cites in this type, which Wenzhou, Zhoushan, Shantou, Liu'an, Maoming, Heyuan and Weifang could be represented. These cities are in a well-coordinated but relatively backward position in terms of urban quality and environment. It simply keeps lowest Pu value among all 6 types, even though its Qu value is not high as well, but the differences is supper positive and sustainability performance is also remarkable. Most cities in this Type are small cities, some of them are even sub-cities of those mega cities, the function of these cities is quite simple and clear, there is not much pressure from the political aspects even the GDP value is low, and on the other hand the SO2 discharge, soot and dust discharge is controlling well, therefore, their sustainability performance is significant. Although the value of Quality of built environment is not high, but the value of environment pressure is

controlled very well, that makes their sustainability performance also very outstanding. Cities like Weifang, Baoding and Wenzhou, they are all non-heavy industry based, such as modern agriculture industry for Weifang, world famous small commodity trading market for Wenzhou, etc. Their reasonable industrial structures made them even more sustainable than most of those larger cities. Other cities in this type are middle or small cities, although their population, GDP and incomes are quite low, but once they keep their industry structure, keeps control the environmental pressure, they would keep the high performance of sustainability.

(3) Smart positive type: there are 31 cities in this type, which includes the largest number of cities among all types, Haozhou, Jinhua, Shaoxing, Ningbo, Weihai, Tianjin, Jiaxing, Tai'an, etc. could be represented. In the type's cities have the middle range of both Qu and Pu values, however, the differences are subtlety kept, made these types of cities' sustainability performance still positive. The cities in this type are steady improvement with joint implementation of urban construction and environmental control strategies. Mostly of them are the majority middle cities of China, although their statistics are variously different, the urban population, GDP, services value and incomes are enough high, while the SO2 discharge, soot and dust, energy consumption etc. are controlled well enough, made this type of cities still sustainability performance well. For these cities, their statue is sensitive, the value of environmental pressure is actually already a bit higher than mega cities, but their population, GDP and incomes, etc. are much lower, city like Tai'an and Huangshan should make full use of its tourist resources to develop non-heavy industries, to reduce the environmental pressure, other city like Xuzhou, Foshan, Ningbo and Linyi need to focus on the control of environmental pressure, some of their heavy industry such as Linyi's building material board industry need to be upgrading into more greenery industries, same as Ningbo's petroleum processing and coking industry. Their subtle statue needs to be carefully handled to keep more positive sustainability performances.

(4) Transitional negative type: there are 10 cities in this type, include Nanjing, Suzhou, Changzhou, Hefei, Jinan, Wuxi, Zibo, Dongying etc. Those cities are in the process of industrial transformation and upgrading but relatively developed. It obviously has very high Qu values, but at same time has significant high value of Pu, the absolute value of Qu is not enough to cover the Pu value, which makes its sustainability performance low. Most of the cities in this type are heavy industry city, such as Suzhou, Zibo, Dongying, etc. although they create significant value of GDP and the urban population, incomes, road infrastructures are doing well, however, their environmental pollutions due to the heavy industry, such as NOx discharge, energy consumption are so high, made those cities with mega Pu than its mega Qu. For this type of cities, heavy industry is becoming double-edged sword for their sustainability

performance, on one hand their industry indeed creates more GDP incomes and job opportunities, making the city have higher Qu values, but more important on the other hand, their huge resource consumption and pollutions made even higher negative efforts. Based on this statue, the priority of actions should be focus on the control of environmental pressure, to reduce the negative impact, such as Zibo, Dongying need to be industry upgrade, reduce, or even remove their petroleum industry to significant throw down their negative impact on the sustainability performances.

(5) Lagging negative type: there are19 cities in this type, which Shaoguan, Shijiazhuang, Huaibei, Heze, Xingtai etc. could be represented. It simply has a lowest level of Qu values, and has a tiny higher level of Pu values, which made it subtle negative difference between Pu and Qu value, thus made this type of cities sustainability performance low. The cities of this type are mostly small or middle cities, which are long-terms multi-dimensional lagged behand with inadequate environmental governance capacity. They don't have much urban attractions and lack of infrastructure development, although the urban population, GDP and incomes are at the middle range, but the NOx discharge, energy consumption etc. environmental pressures are also higher, made this type of cities sustainability performance subtle lower. For this type of cities such as Shijiazhuang and Handan are facing the similar situations with some mega negative cities, they are also heavy industry-based economy, and the ideal solution for these cities should also be upgrading their industry structures. Cities with middle size of urban development, they are sharing the similar situation of Qu values with subtle positive cities, but not well control enough for the Pu values that makes their sustainability performance somehow negative. The suggested solution would be making proper policy for their city's industry development, to conducting more greener industry, for example Dezhou is trying to develop the largest solar energy industry of the country recent years, which would be good tend to transfer the negative performance to positive in the near future.

(6) Purely negative type: there are 7 cities in this type, include Tongling, Tangshan, Ma'anshan, Rizhao, Binzhou, Yancheng and Chengde. It obviously has the highest Pu value among all these 6 types, and the Qu value are relatively much lower, therefore, the difference value between Pu and Qu is obvious and the sustainability performance is negative. It can be easily found that most of these cities are heavy industrial cities with high energy consumption and high pollution, such as Tongling, Tangshan, Ma'anshan, to produce higher GDP, urban population and incomes, they consume significant amount of energy, much higher NOx discharge, and so on. The excessive environmental pressure made this type of cities sustainability performance worst among all types. For the cities in this type, most of them in the situation of heavy-industry and natural resource consumption mode, such as Tangshan, Ma'anshan and Binzhou, coal industry

and petroleum industry are their main support, and which already going to the resource depletion statue. So, upgrading industry, enhance strict control of environmental pressures are the proper solutions. That would definitely take years step by step to transfer into a positive sustainability performance.

Table 8-3 List of cities by sustainability performance clustering classification.

No.	City classification	Common characteristics description	Level of urban sustainability	List of cities	Total
I	**Advanced positive type**	Advanced economic cities with high urbanization and high-level administrative division	High sustainability with high quality	Shanghai, Beijing, Shenzhen, Guangzhou, Dongguan, Qingdao, Hangzhou	7
II	**Coordinated positive type**	Urban quality and environment are in a well-coordinated but relatively backward cities	Moderate sustainability with low pressure	Wenzhou, Zhoushan, Jieyang, Yunfu, Zhanjiang, Chaozhou, Fuyang, Meizhou, Suqian, Weifang, Heyuan, Maoming, Liu'an, Suuzhou, Hengshui, Baoding, Shantou	17
III	**Smart positive type**	Steady improvement cities with joint implementation of urban construction and environmental control strategies.	Basic sustainability with low quality	Tianjin, Xuzhou, Foshan, Ningbo, Linyi, Langfang, Tai'an, Jiaxing, Zhongshan, Nantong, Yangzhou, Taizhou, Zaozhuang, Lishui, Huai'an, Chuzhou, Shanwei, Anqing, Zhaoqing, Yangliang, Weihai, Huangshan, Zhuhai, Huizhou, Lianyungang, Yantai, Jiangmen, Taizhou, Shaoxing, Jinhua, Haozhou	31
IV	**Transitional negative type**	In the process of industrial transformation and upgrading but relatively developed cities	Slight unsustainability with high quality	Nanjing, Suzhou, Hefei, Jinan, Wuxi, Changzhou, Zibo, Dongying, Huzhou, Zhenjiang	10
V	**Lagging negative type**	Long-terms multi-dimensional lagged behand cities with inadequate environmental governance capacity	Intermediate unsustainability with low quality	Shijiazhuang, Handan, Chizhou, Shaoguan, Huaibei, Huainan, Wuhu, Qinhuangdao, Quzhou, Cangzhou, Liaocheng, Heze, Bengbu, Dezhou, Qingyuan, Jining, Xuancheng, Zhangjiakou, Xingtai	19
VI	**Purely negative type**	Heavy industrial cities with high energy consumption and high pollution	Severe unsustainability with high pressure	Tangshan, Tongling, Ma'anshan, Yancheng, Rizhao, Binzhou, Chengde	7

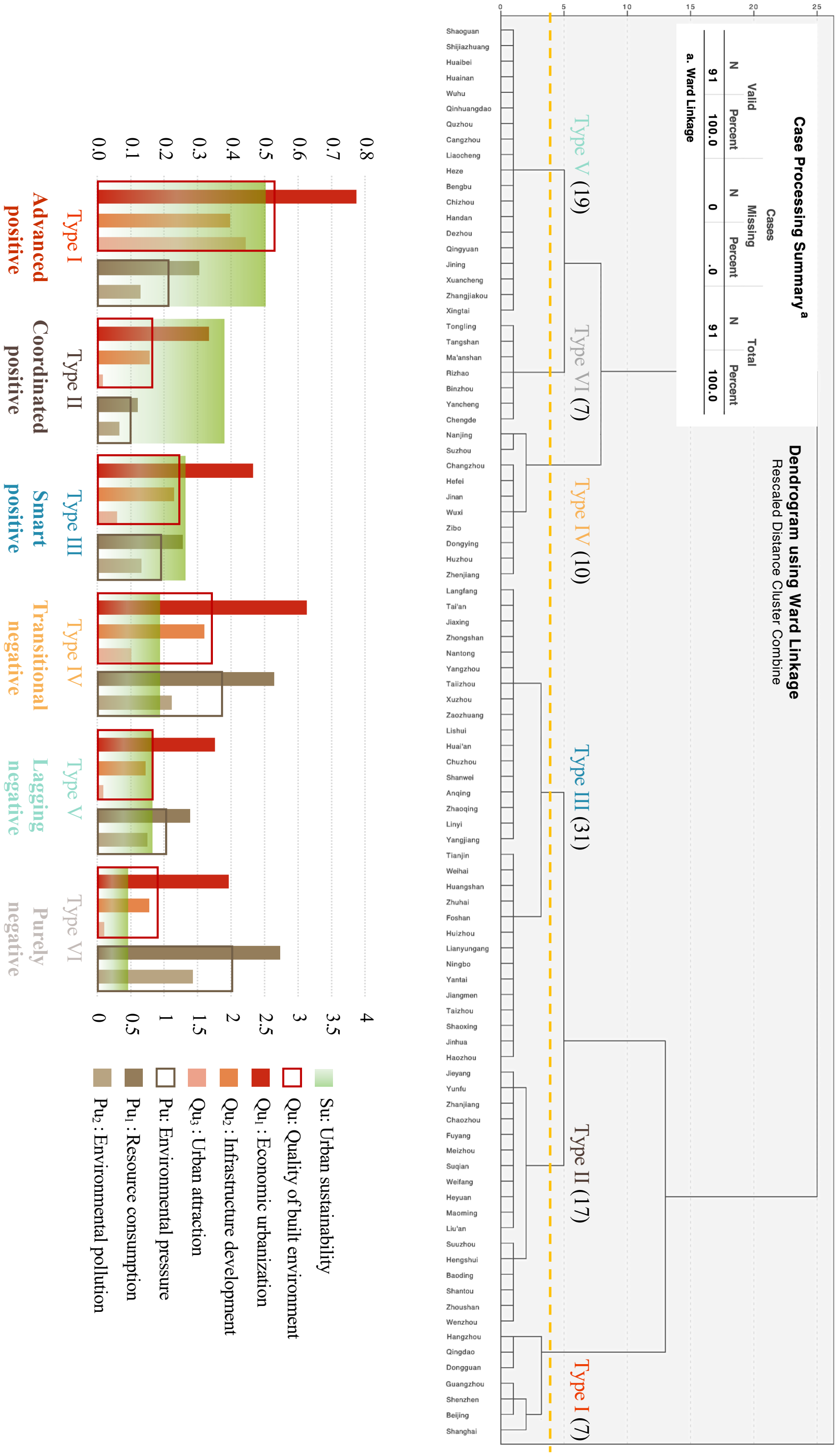
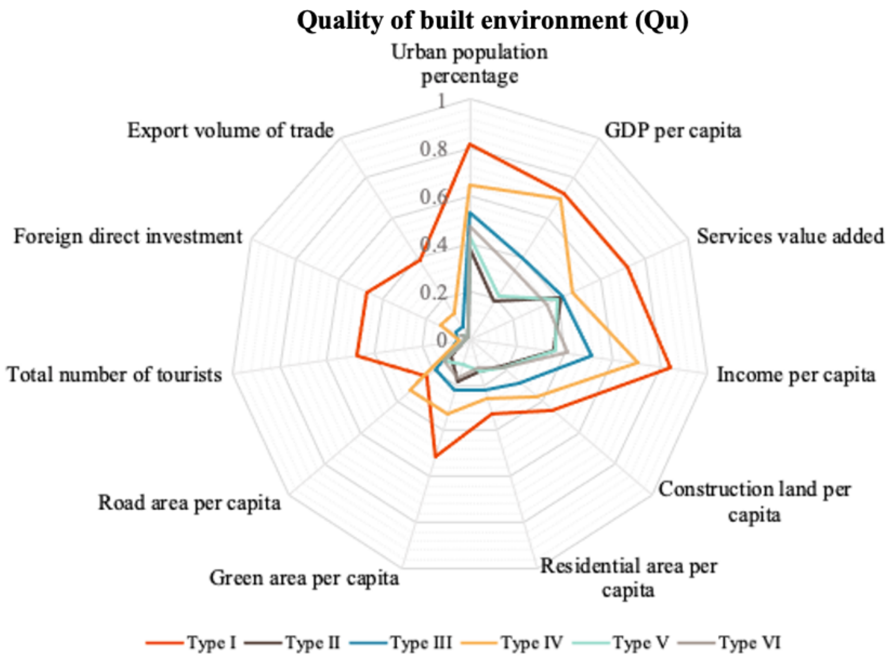
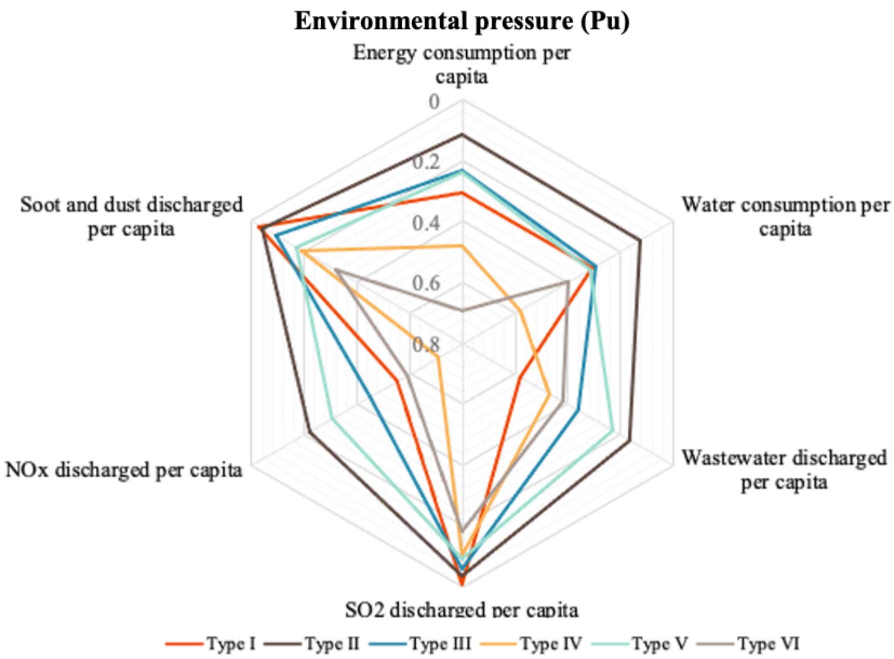


Fig. 8-12 Result of hierarchical Clustering and comparison of the mean evaluation scores of each indicator categories among 6 types of cities in 2018



(1) The mean evaluation scores of Qu among 6 types of cities in 2018



(2) The mean evaluation scores of Pu among 6 types of cities in 2018

Fig. 8-13 Comparison of the mean evaluation scores among 6 types of cities in 2018

8.4.Summary

By comparing the sustainability performance results of four major Chinese megacities, the following main conclusions are obtained:

From data comparative analysis from 2010 to 2018, (1) all four megalopolises show the continuously positive trends in terms of the quality of the built environment with a steady growth rate. The Pearl River Delta has the highest Qu score, followed by the Yangtze River Delta, Shandong Peninsula and JingJinJi. (2) The environmental pressure experienced an upward and then a downward trend. And the Pearl River Delta megalopolis has the least environmental pressure, followed by JingJinJi, Yangtze River Delta and the Shandong Peninsula in 2018. Comprehensively, (3) the Pearl River Delta has the highest level of sustainable development, ranking top for nine consecutive years, followed by JingJinJi, Yangtze River Delta and Shandong Peninsula. In particular, the JingJinJi megalopolis has the fastest improvement of urban sustainability. In general, (1) the sustainability of each megalopolises is showing a positive trend of improvement (2) but due to the different speed of improvement, the gap between the urban agglomerations would have a tendency to widen, which may cause imbalanced development of the entire country and is not conducive to the coordinated development in the future.

The LISA cluster maps present that: (1) the HH cluster areas of Qu scores are all distributed in the eastern coastal areas surrounding by larger cities. But LL clusters appear most in the fringe areas at the junction of megalopolises. (2) The number of HH / HL / LH cluster areas of Pu is significantly greater in northern China's megalopolises than in the south, which indicates that the northern region is facing greater environmental challenges and that the adverse effects of environmental problems are spreading between neighboring cities. (3) Each megalopolis region has a HH cluster area with a high level of sustainable development. While strengthening the agglomeration effect of advanced cities, the development of backward cities in LL, LH and HL cluster areas can be supported as a priority.

In order to provide guidance for as many cities as possible, some general urban development characteristics were further analyzed through classification discussions of the 91 samples of cities: Analysis by geographic location and urban population classification reveals that: (1) though the gap in urban sustainability between cities of different sizes in inland areas is narrowing, the gap in coastal areas is on the rise. (2) The quality of the built environment in larger cities is generally better than that in smaller cities. But these cities are under greater environmental pressure, especially in inland areas. Moreover, corresponding characteristics analysis and implications are also discussed for four types of mega-large coastal cities, mega-large inland cities, medium-small coastal cities and medium-small inland cities. Then, analyzed through the classification of sustainability performance, 91 sample cities are forming into 6 different types. For each different types, accordingly suggestions are made to improve their sustainability performances.

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Chapter 9. Conclusion

9.1. Conclusion

Sustainability is a global consensus and an arduous challenge for urban development and most of its difficulty lies in dealing with risks related to the quality of built environment and its environmental pressure, especially for developing countries in the context of rapid urbanization. Currently, China is in the accelerated process of urbanization, which has a positive impact on improving the development of urban construction but has brought more pressure and more cost to the natural environment. Sustainability assessments are a tool that can be used to better conceptualize and define urban sustainability and are increasingly seen as the indispensable basis for informed decision-making.

With the above motivation, the key contributions of this study include: (1) an evaluation system for measuring the capacity of urban sustainable development is proposed in an easy-to-understand form and named “Urban Sustainability” (S_U). And (2) a comprehensive assessment of the urban sustainable development performance of China's four major urban agglomerations was conducted in the spatial and temporal dimensions, which has uniquely enriched the sustainability-oriented research works. However, the urban sustainability assessment system established in this study has many shortcomings that need to be improved, including the need for the indicator system to be screened and updated according to urban development trends, the establishment of more efficient data collection links with national publishing platforms, and the time period and allocation method for weight judgment to be further discussed. The main conclusions in each chapter can be summarized as follows:

In Chapter 1, *BACKGROUND AND PURPOSE OF THE STUDY*, research background and significance of the sustainability performance of urbanization and its environment is demonstrated. Then the purpose of the study is proposed. In order to maintain a sustainable increase in urbanization rates and to prevent these developing countries from prematurely entering a state of urban shrinkage due to environmental concerns, this study is potentially practical relevance for promoting sustainable urbanization.

In Chapter 2, *URBAN SUSTAINABILITY ASSESSMENT AND RESEARCH METHODOLOGIES*, the urban sustainability assessment system for measuring the capacity of urban sustainable development was proposed, including: (1) identifying two key dimensions of urban sustainability in the context of China's urbanization: quality of built environment (Qu) and environment pressure (Pu); (2) establishing and defining a ratio (quality/pressure) model to quantify the capacity of sustainable development; (3) designing the indicator system of the model represented by urbanization economies, infrastructure development, urban attraction, resource consumption, and environmental pollution; and (4) determining the corresponding weighting criteria and detailed measurement method. Besides, other used spatio-temporal methodologies of Statistics and Geoinformatics used in the article to support the analysis are also introduced.

In Chapter 3, *OVERVIEW OF URBANIZATION AND ITS ENVIRONMENT INVESTIGATION IN CHINA,* through investigating the urbanization and its environmental status from the perspective of provincial administrative divisions and megalopolises, respectively, the research found that: Although China's has entered the stage of rapid urbanization, the rapid economic growth and urban construction in various regions of China coexist with tremendous pressure on environmental resources, which is not only complicated but also has significant distribution differences between regions. And megalopolis has been regarded as the mainstream for promoting high-quality urbanization and corresponding plans or policies began to study and formulate at this stage. On this basis, this study identifies the four most important megalopolises as the empirical cases, as well as the time period of the study.

In Chapter 4-7, *MEASURING THE PERFORMANCE OF URBAN SUSTAINABLITY IN YANGTZE RIVER DELTA / PEARL RIVER DELT / SHANDONG PENINSULA / JINGJINJI*, the four megalopolises as empirical objects are analyzed and interpreted one by one in each chapter for their evaluation results from 2010 to 2018. In general, (1) from 2010 to 2018, the quality of the built environment in four megapolises have generally shown an upward trend, while the environmental pressure experienced an upward and then a downward trend, but the degree of change and the main reasons are different among four megalopolises. And (2) the sustainability of the urban environment in all megapolises shows varying degrees of urban differences and spatial heterogeneity, thus effective policies or planning need to be tilted towards backward cities in order to alleviate the negative impact of regional development imbalances. Until 2018, (3) there is a total of 60% of cities reached a sustainable state, including 22 (of 41) cities in the Yangtze River Delta, 18 (of 21) cities in Pearl River Delta, 8 (of 16) cities in Pearl River Delta, 7 (of 13) cities in JingJinJi megalopolis.

The main results of the analysis in terms of spatio-temporal distribution characteristics are: (1) in Yangtze River Delta, the distribution characteristics of sustainability in the northern region show a trend of developing from the periphery of the region to the inner city, while the sustainability of coastal cities is higher than that of inland cities in the southern region. And the first priority for countermeasures should be to relieve the environmental pressure on northern cities. (2) In Pearl River Delta, the spatial patterns of urban sustainability show a development pattern that gradually spreads from the central part to the two ends. It is necessary to strengthen the advantages of the coastal city belt to drive the high-quality development of the backward cities in the north, and simultaneously alleviate the environmental pressure on these cities. (3) In Shandong Peninsula, the distribution characteristics of sustainability in the northern region show a trend of gradual improvement from the coastal cities in the east to the cities in the central and southern areas. And the preferred development policy is to prioritize the improvement of the quality of the built environment in the southwestern cities and to address the environmental problems of the southern cities. And in JingJinJi, the spatial patterns of urban sustainability present a progressive development pattern from the center to the south. Midwestern cities and individual cities in the South have reached the basic level of sustainable at present. It is recommended that the corresponding strategy prioritizes solving environmental problems in cities in the Northeast. At the same time, at the micro-level of future development responses for each city, combined with detailed diagnosis results, recommendations for sustainable urbanization were also be targeted provided.

In Chapter 8, *COMPARATIVE STUDY AND CLASSIFICATION DISCUSSION AMONG FOUR MEGALOPOLISES,* the sustainability performance results of four major Chinese megacities are compared and found that (1) the Pearl River Delta has the highest level of sustainable development, followed by JingJinJi, Yangtze River Delta and Shandong Peninsula. (2) Although each megalopolis region has a HH cluster area with a high level of sustainable development. While strengthening the agglomeration effect of advanced cities, the development of backward cities in LL, LH and HL cluster areas can be supported as a priority. In addition, combining the results of comprehensive analysis, the corresponding characteristics and specific development implications were further analyzed through classification discussions of the 91 samples of cities: (3) by geographic location and urban population, coastal cities or large cities have better urban sustainability than inland cities or small cities. (4) Based on the sustainability performance clustering, cities can be classified into six types. For each different types, accordingly suggestions are made to improve their sustainability performances. (5) Based on the sustainability performance clustering, cities can be classified into six types. The cities of advanced positive, coordinated positive and smart positive type have positive sustainability performance. While the remaining three types of transitional negative, lagging negative and purely negative type have negative sustainability performance with different degrees of environmental pressure. (6) Corresponding characteristics and implications of the different types of cities mentioned above are summarized in order to provide a reference for cities in similar situations, which can be informed by indicators that need to pay more attention and to avoid unsustainable risks.

In Chapter 9, *CONCLUSION*, the whole summary of each chapter has been presented.

Sustainable urbanization will become the focus of China's development in the foreseeable future. There is an urgent need to further expand the scope of research to gradually cover all the megapolises or even all regions in China. By doing so, the results can not only provide a basis for macroscopic top-level planning in China but can even optimize and adjust the layout of city clusters, for example, by establishing interconnections between cities based on their complementarity. A visual diagnostic and evaluation system can also be established for each city to facilitate real-time self-examination and provide decision aids for cities, all of which are prospects for future research.