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LETTER

The inhabited environment, infrastructure development and advanced urbanization in China's Yangtze River Delta Region

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Abstract

This paper analyzes the relationship among the inhabited environment, infrastructure development and environmental impacts in China's heavily urbanized Yangtze River Delta region. Using primary human environment data for the period 2006–2014, we examine factors affecting the inhabited environment and infrastructure development: urban population, GDP, built-up area, energy consumption, waste emission, transportation, real estate and urban greenery. Then we empirically investigate the impact of advanced urbanization with consideration of cities' differences. Results from this study show that the growth rate of the inhabited environment and infrastructure development is strongly influenced by regional development structure, functional orientations, traffic network and urban size and form. The effect of advanced urbanization is more significant in large and mid-size cities than huge and mega cities. Energy consumption, waste emission and real estate in large and mid-size cities developed at an unprecedented rate with the rapid increase of economy. However, urban development of huge and mega cities gradually tended to be saturated. The transition development in these cities improved the inhabited environment and ecological protection instead of the urban construction simply. To maintain a sustainable advanced urbanization process, policy implications included urban sprawl control polices, ecological development mechanisms and reforming the economic structure for huge and mega cities, and construct major cross-regional infrastructure, enhance the carrying capacity and improvement of energy efficiency and structure for large and mid-size cities.

1. Introduction

The United Nations Framework Convention on Climate Change explicitly mentions strategies to promote the inhabited development and control global average temperature increase to remain within 2 °C of pre-industrial levels. As the largest developed country, China will play an important role in the success of the agreements that emerged from the 2015 Paris Conference on Climate Protection. Under the Paris agreement, China announced that it aims for the country's carbon dioxide (CO_2) emissions to peak by approximately 2030 and to cut CO_2 emissions per unit of gross domestic product (GDP) by 60%–65% from the 2005 level. China's focus includes improving the living standards and promoting sustainable development.

Urbanization is taking place at an unprecedented rate around the world, particularly in China, with 70% of the world's population expected to live in cities by 2030. The Yangtze River Delta region is emblematic of China's rapid urbanization during the past decade

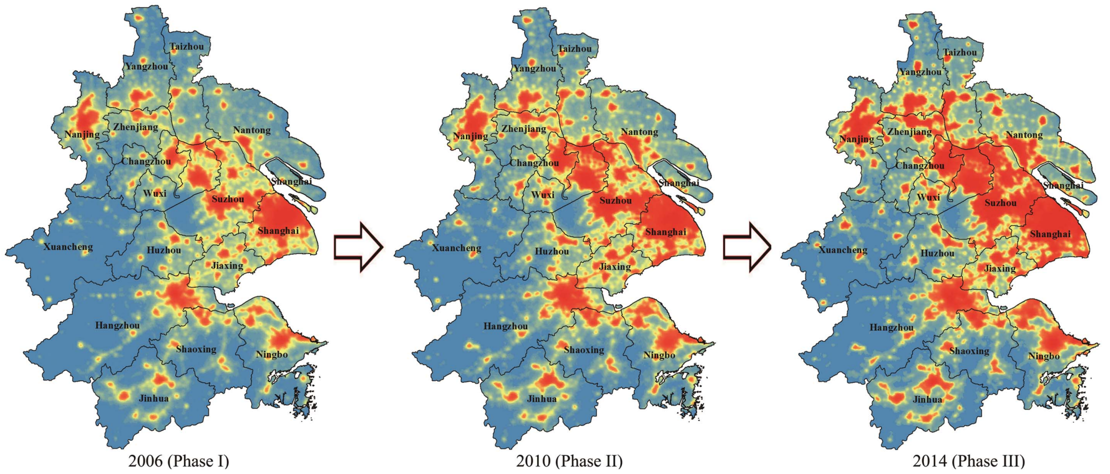


Figure 1. Evolution process of advanced urbanization in the Yangtze River Delta region. (Notes: the urbanization degree was presented by the intensity of the color, the deeper red color represents higher urbanization and lighter red color represents lower urbanization. The data comes from quick bird remote sense of Yangtze River Delta region in 2015.)

(Pan *et al* 2015). This 210 700 square-kilometer (km^2) region encompasses the triangular-shaped territory of Shanghai, southern Jiangsu province, and northern Zhejiang province. Occupying less than 2.2% of China's land area, it contributes more than 35.5% of total national imports and exports and almost a quarter of China's GDP.

One of the most prominent characteristics of urbanization is the rapid development of urban infrastructure. Our research team, which has focused on issues related to development of the Yangtze River Delta region since 1990, published a prior report (Gao *et al* 2004) analyzing the relationship between the inhabited environment and urbanization from 1990 to 2000. Due to the Eleventh Five-Year Plan (2006–2010), new trends and characteristics have emerged in the Yangtze River Delta's urban development. As seen in figure 1, extensive expansion in huge cities has given way to movement of populations into midsize and small cities. And the urban space structure had changed from various independent cities into metropolis from 2006–2014, which we define the period as advanced urbanization. Regional urban development has changed from extensive path to intensive path (Schwarz and Manceur 2014). There is also a significant change in the urban construction combined with energy consumption, waste emission and treatment. This shift is the reason for our study, which discusses the relationship between advanced urbanization, the inhabited environment and infrastructure development.

2. Literature review

As urbanization has advanced in China, cities have become not only the locations of economic growth and development but also the locations of increasing energy consumption and carbon emissions (Zhang and Qin 2013). York *et al* (2003) observed that rapid urbanization would significantly increase the infrastructure development but also had negative impact on the inhabited environment. In general, the construction and development of the urban infrastructure, including the construction of roads, bridges, buildings, sewage networks, etc, is associated with a high-energy input (Martinez-Zarzoso and Maruotti 2011). Also, usage and maintenance of the infrastructure, such as sewage networks, lighting, or water and waste treatment facilities, would diminish the inhabited environment (Vargo *et al* 2013). Focused on the problem, Astaraieimani *et al* (2012) discussed the atmospheric environment change resulting from urban development. In response, Wing and Eckaus (2007) have shown this negative impact can be decreased with the technical progress and industry structural changes, particularly in huge and mega cities. Additionally, Jiang and Lin (2012) observed that integrating urban development of regions would improve the infrastructure construction efficiency. Georgescu *et al* (2015) noted that the quality of the inhabited environment improved with attention to ecological amenities, especially urban landscape planning and sewage treatment.

Among the factors contributing the inhabited environmental impacts of urbanization, Poumanyvong and Kaneko (2010) identified per-capita GDP, total population, number of vehicles, economic structure, and average annual income as positive factors, and energy intensity in industry, length of transportation routes, and household energy intensity as negative factors. Liu (2009) analyzed in detail the factors that influenced infrastructure development and found that transportation and production of building materials exhibit the most significant relationship. Krey *et al* (2012) concluded factors affecting infrastructure deve- lopment associated with urbanization were dynamic. Similar results also were found by Fu *et al* (2013).

To increase the inhabited environment and infrastructure development and move toward sustainable cities, planners and organizations have been introducing low-carbon technologies. 'Smart growth' has also been proposed to manage expansion of cities, solve planning and design problems, and promote land use efficiency (Wey 2015). Compact, transit-oriented, bike-friendly land use as well as mixed-use development with a range of housing choices were also advocated (Harris 2012). Transit-oriented development has been particularly well implemented and documented in some developed countries such as Japan and Germany (Ni *et al* 2015). The concept of a compact city has also been suggested as an urban development model for sustainable growth (Martilli 2014). Compact cities have two major environmental benefits: reduced dependence on private cars and preservation of green space and arable land. Yu (2005) suggested an 'anti-planning' development path that emphasized the maintaining the integrity of the land and the authenticity of regional landscapes as the basis of urban development. In the new situation of urbanization, the concept of 'low-carbon towns' were proposed these years (Zheng *et al* 2012).

Although numerous studies have looked at the effect of urbanization on the inhabited environment and infrastructure development, there have been few quantitative analyses of what degree advanced urban development has affected them. This paper analyzes the relationship among the inhabited environment, infrastructure development as well as associated advanced urbanization in the Yangtze River Delta region between 2006 and 2014, with the goal of providing policy recommendations.

3. Materials and methods

3.1. Data source

Data used includes urban area from satellite remote-sensing images in 2006, 2010 and 2014 with the spatial resolution of 100 m. Urbanization degree, which proves to be an important indicator for urban development is then extracted and transformed into vector format in GIS for further analysis. We also collected population composition, primary energy consumption structure, economic conditions, waste emission and urban construction for the selected counties from China Statistical Yearbook (2006–2014). Since not all the indicators are available for all the counties in Yangtze River Delta region, we made regressions and predications to substitute the missing data.

3.2. Methods

3.2.1. Index system

To accurately evaluate the relationship between the inhabited environment, infrastructure development and advanced urbanization, this paper draws on the relevant research results when setting up the comprehensive index system. It particularly addresses the actual situation of the Yangtze River Delta region and constructs the evaluation index system based on objective scientific principles.

The index system of the advanced urbanization subsystem contains three basic indicators (urban population, built-up area and GDP), the inhabited environment subsystem contains five basic indicators (electricity consumption, fuel gas, water supply, exhaust emission and waste water) and infrastructure development contains three basic indicators (transportation, real estate and urban green area). Some important basic indicators would be described in detail in section 4. The interactive coercing relationship between the advanced urbanization subsystem, inhabited environment subsystem and infrastructure development subsystem is presented in section 5 (figure 2).

3.2.2. Weighting method

In processing the weights of the indicators, each weighting method has its limits. To reduce the differences brought by weighting methods, this paper chooses one type of objective weighting method: the entropy method (Hernandez *et al* 2012) to determine the weight of each indicator (W_i) as follows and then get the advanced urbanization index, the inhabited environment index and infrastructure development index:

$$E_i = -K\sum_{i=1}^{n} P_i \ln(P_i),$$

$$W_i = (1 - E_i) \Big/ \sum_{i=1}^{n} (1 - E_i),$$

where $K = 1/\ln(\mathrm{m})$, n denotes the number of data, P_i denotes the contribution degree of the ith data. When E_i tends to be 1, the contribution degree of the data tends to be uniform, which means the weight value tends to be 0.

3.2.3. Correlation analysis model

If linear combination of two or more non-stationary series is stationary, then this linear combination will be denoted by co-integrated equation, which can be used to depict the long-term stable equilibrium relationship of two or more series. The purpose of the study co-integration can be divided into two: one point is to judge whether there is a co-integration relationship between a group of non-stationary series, another point is to determine the rationality of the design of the linear regression equation by the co-integration test. The main idea and process of these two points are exactly the same.

Considering the complex form of the empirical model, it is necessary to determine if multi-collinearity exists before the regression. Therefore, a correlative

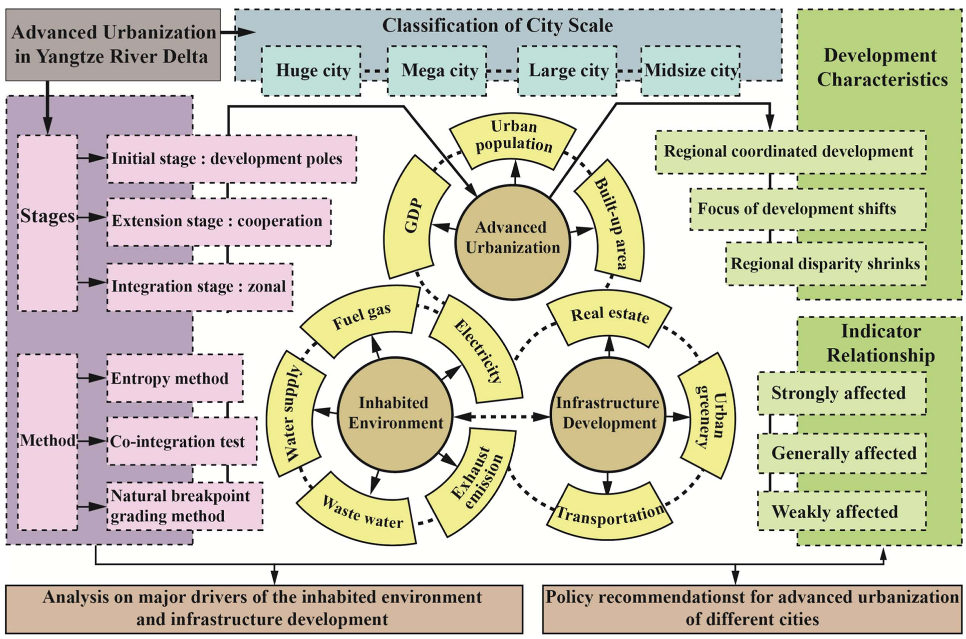


Figure 2. Analysis chart of relationship of the inhabited environment, infrastructure development and advanced urbanization. (Notes: the figure analyzes the method of investigate the impact of advanced urbanization on the inhabited environment and infrastructure development and showing the connection among elements).

analysis is undertaken on all of the independent variables in each of the final models for the Yangtze River Delta region. The test results indicate that there is significant correlativity between any two variables. In addition, to eliminate possible heteroscedasticity, all variables take a logarithmic form. So the empirical models are as follows:

$$\ln \text{IEI} = a_0 + a_1 \ln \text{AUI},$$

$$\ln \text{IDI} = a_2 + a_3 \ln \text{AUI},$$

where, AUI, IEI and IDI denotes advanced urbanization index, the inhabited environment index and infrastructure development index. a_0, a_2 are constants; a_1, a_3 are the coefficients of variables of 'In AUI'. They refer to the percentage change in the inhabited environment index and infrastructure development index caused by a 1% change in advanced urbanization index.

4. Data descriptive analysis

4.1. Advanced urbanization

Classification of city scale by urban population is common in China. To enable a contrastive analysis, we estimate the sample divided into four groups: huge cities (urban population > 10 million, Shanghai), mega cities (10 million > urban population > 5 million, including Hangzhou and Nanjing), large cities (5 million > urban population > 2.5 million, including Suzhou, Changzhou, Ningbo, Jinhua, Wuxi and Shaoxing), midsize cities (2.5 million > urban population, including Zhenjiang, Nantong, Yangzhou, Jiaxing, Huzhou and Jiangyin), taking China's fifth national population census into consideration.

Table 1 shows that Shanghai, Hangzhou, and Nanjing were the top three cities with the most urban population. The original cause of population concentrations in huge and mega cities was great economy scale, the GDP of which was all above 130 billion dollars. Excessive population agglomeration had a negative impact on the inhabited environment and led to the increase of energy and water consumption and waste emission. In contrast, Large and midsize cities could offer a better-quality natural environment, cheaper housing and more living space than densely populated cities. As a result, these cities attracted a large number of urban dwellers, and population grew more rapidly during 2006–2014. The population ratio among huge, mega, large, and midsize cities changed from 15:6:3:2 in 2006 to 12:7:4:3 in 2014. Advanced urbanization was characterized by a modest abandonment of the centers of metropolitan regions in favor of more peripheral locations. This relieved both overcrowding in huge and mega cities and excessive fragmentation of industrialization in large and midsize cities. Factors influencing this shift included:

(i) Facilities upgrades: new traffic infrastructure offered convenient passenger and freight transport and shortened the distance from central cities to satellite cities. Extension of traffic infrastructure from huge and mega cities to large and midsize cities promoted suburbanization.

(ii) Industrial shift: following the national government strategy of 'suppressing secondary industry

Table 1. Outline of 15 cities in Yangtze River Delta region. (The data come from the 2006–2014 China Statistical Yearbook National Bureau of Statistics NBS 2006–).

Classification of city scale	City name	Total population (10 000 persons)	Urban population (10 000 persons)	Land area (km^2)	Density (persons/km^2)	GDP (billion US$)	Districts/ Towns
Huge city	Shanghai	2415	1432	6341	3809	348.01	16/220
Mega city	Hangzhou	884	624	16 596	533	135.06	8/110
	Nanjing	819	529	6582	1244	131.07	11/32
Large city	Wuxi	472	253	4627	1020	130.01	7/32
	Suzhou	654	333	8488	770	209.68	7/55
	Changzhou	366	316	4385	834	70.26	5/37
	Ningbo	580	493	9816	591	114.84	6/80
	Shaoxing	473	265	8279	572	63.90	3/79
	Jinhua	473	314	10 942	433	47.66	2/69
Midsize city	Zhenjiang	272	103	3847	706	47.16	3/63
	Nantong	767	212	8001	958	81.18	2/19
	Yangzhou	460	231	6591	698	52.39	3/70
	Huzhou	262	93	5818	451	29.05	2/44
	Jiaxing	345	158	3915	880	46.57	3/53
	Jiangyin	163	35	987	1652	43.60	0/12

and developing tertiary industry', many industries in huge and mega cities have shifted their bases to suburban areas. In large and midsize cities, collective industries represented by the 'Su Nan and Zhejiang models' have been fully developed, absorbing a large number of external laborers and enabling residents to work locally.

(iii) Policy support: as part of urban renewal, governments have implemented preferential policies to encourage urban residents to move to the suburbs (Chen *et al* 2008). The distribution of residential land has been rapidly expanded along transport routes to facilitate travel.

Urban population is one of the most important driving forces of demand for building stock (Huang *et al* 2013). Hence, such a large increase of the urban population in large and midsize cities would inevitably result in large-scale construction of residential building, commercial facilities and supporting infrastructure, which immediately translated into the pressure on the inhabited environment. Fortunately, the growth of population itself is not significant.

4.2. Inhabited environment

4.2.1. Electricity and fuel gas consumption

Despite energy shortages, the total annual energy consumption in the Yangtze River Delta region is considerable, accounting for almost 15% of national energy consumption. Total energy consumption and waste emissions have increased year by year (table 2). However, there are variations in the extent and nature of development, and the energy structure has been improved to be more efficient and less polluting.

Figure 3 shows the variation in per-capita annual electricity consumption in different cities. The effect of urbanization on energy consumption is as follows: (i) urbanization changes consumer needs and the lifestyles of private households. In particular, changes in consumer needs and behavior especially affect urban energy demand. Generally speaking, urban population is more dependent on commercial products and services than rural population (He *et al* 2009). As a consequence, the per-capita annual electricity consumption in large cities with the fastest rate of urbanization also have the fastest rate of electricity consumption. It increased from 6000 kilowatt-hours (kwh) d^{-1} in 2006 to 10 000 kwh d^{-1} in 2014. (ii) The traditional expanding pattern of industrial operations causes shortages and wastes resources (Gao *et al* 2007). Rapid expansion of private enterprises and manufacturing industries is estimated to consume more than 60% of large cities' total energy in the Yangtze River Delta region. Besides the rapid growth of economic size, significant changes are also witnessed in the economic structures of 15 cities, especially in Shanghai, Hangzhou and Nanjing. It is found that the increase rate of the tertiary industry in these cities was larger than other cities in recent years. According to statistics, energy consumption per unit of GDP caused by the tertiary industry was only 1/8–1/10 of the secondary industry. As a result, the per-capita electricity consumption of these cities was smaller than other large cities. (iii) Chinese government adjust its fiscal policies, such as the *Design Standard for Residential-Building Energy* and the *Green Building Action Program*, to support green construction, encourage real estate developers to engage in green construction and expand the scale of green buildings, which is to reduce the use of natural resources within one building by virtue of energy-efficient appliances and control systems. However, these regulations were difficult to enforce in

Table 2. Statistical data of the inhabited environment, infrastructure development of 15 cities. (The data come from 2006–2014 China Statistical Yearbook of 15 cities National Bureau of Statistics NBS 2006–).

		Item							
		Inhabited environment					Infrastructure development		
Year		Electricity (kwh)	Fuel gas (10^8 m^3)	Tap water (10^8 m^3)	Exhaust emission (10^8 m^3)	Waste water (10^8 m^3)	Road length (km)	Real estate (10^4 m^3)	Urban greenery (hectare)
Huge cities		1246.55	57.1	24.31	11 840	18.37	16 440	6191	15 729
I	2006	990.15	41.8	23.32	9428	15.57	14 619	6506	13 307
	2007	1072.38	45.1	23.95	9591	15.28	15 458	6090	13 899
	2008	1138.22	46.2	24.32	10 436	17.70	15 844	5723	14 777
II	2009	1153.38	45.5	24.11	10 059	17.26	16 071	5719	15 406
	2010	1295.87	55.5	24.43	12 969	18.97	16 687	6217	16 053
	2011	1339.62	62.3	24.30	13 692	19.33	16 792	5984	16 446
III	2012	1353.45	68.2	24.47	13 361	20.07	17 316	6476	16 848
	2013	1410.60	71.2	24.95	13 344	20.32	17 498	6274	17 142
	2014	1465.30	78.8	25.28	13 680	20.85	17 680	6735	17 685
Increase (%)		47.9	88.5	8.4	45.1	33.9	20.9	3.5	32.9
Mega cities		447.12	17.2	8.54	4702	5.94	4118	3380	3048
I	2006	318.25	15.1	8.32	4125	4.70	3593	2950	1729
	2007	355.93	15.9	7.72	4377	4.98	3633	2990	2064
	2008	370.48	14.3	8.09	4536	5.92	3694	3105	2110
II	2009	398.37	15.1	8.15	4620	5.90	3792	3230	2239
	2010	447.79	17.3	8.36	4839	5.66	3896	3585	2384
	2011	487.51	18.8	8.80	4855	6.32	4072	3652	3994
III	2012	508.33	18.5	8.89	4988	6.49	4536	3485	4003
	2013	550.60	19.9	9.22	4968	6.70	4810	3667	4321
	2014	586.89	20.7	9.37	5014	6.85	5038	3759	4587
Increase (%)		84.4	37.1	12.6	21.6	45.7	40.2	27.4	165.3
Large cities		471.74	10.53	4.18	4063	3.54	3660	2421	2824
I	2006	328.85	2.7	3.40	3225	2.08	2709	1577	1985
	2007	378.59	4.4	3.63	3452	2.54	2875	1620	2160
	2008	393.14	5.8	3.83	3590	2.95	2977	1850	2295
II	2009	411.54	7.2	4.29	3774	3.21	3771	2055	2974
	2010	475.21	10.6	4.48	3960	3.79	3903	2437	3029
	2011	522.37	13.8	4.51	4258	3.95	4022	2833	3069
III	2012	540.94	14.8	4.48	4563	4.17	4127	2965	3169
	2013	578.38	16.5	4.49	4772	4.47	4249	3120	3247
	2014	616.72	19.0	4.53	4981	4.75	4310	3335	3485
Increase (%)		87.5	603.7	33.2	54.4	128.6	59.1	111.5	75.6
Mid-size cities		203.27	4.8	2.10	2174	1.31	3372	1641	1115
I	2006	133.11	1.5	1.59	1282	0.76	2689	785	682
	2007	154.51	2.5	1.69	1465	0.92	2781	896	781
	2008	164.32	2.8	1.85	1652	1.05	3079	1024	861
II	2009	176.36	3.4	1.96	1830	1.19	3270	1435	985
	2010	202.44	4.7	2.17	2105	1.35	3433	1677	1098
	2011	225.17	5.4	2.11	2537	1.55	3552	1920	1240
III	2012	235.96	6.1	2.37	2680	1.63	3788	2130	1353
	2013	257.27	7.5	2.56	2902	1.67	3808	2400	1450
	2014	280.30	9.3	2.62	3118	1.72	3953	2506	1587
Increase (%)		111.5	520.0	64.8	143.2	126.3	47.0	219.2	132.7

(Notes: The indicator of transportation is evaluated by the road length).

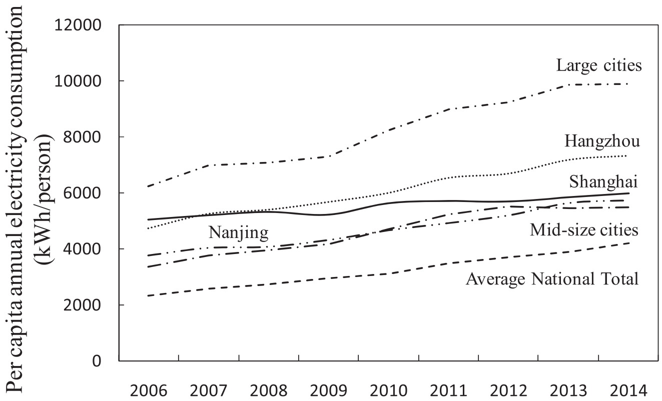


Figure 3. Per capita annual electricity consumption in the Yangtze River Delta region.

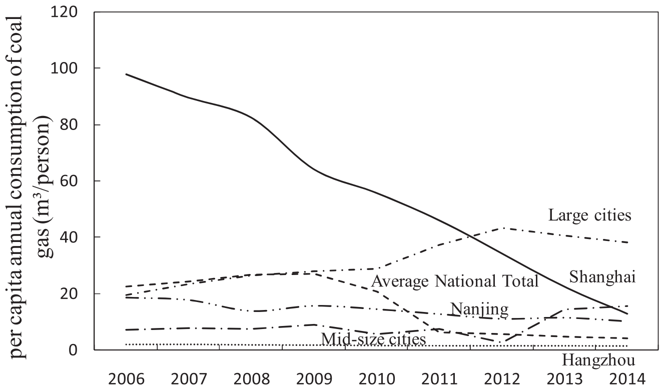


Figure 4. Per capita annual consumption of coal gas in the Yangtze River Delta region.

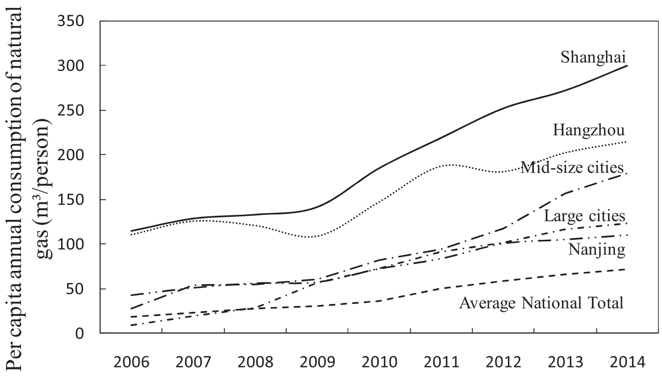


Figure 5. Per capita annual consumption of natural gas in the Yangtze River Delta region.

some large and midsize cities because of local protectionism and execution mechanism existed blemish.

Figures 4 and 5 show how the region's energy structure has changed over time. In 2004, the China's West-East natural gas transmission project was put into operation. It was the main force to increase the per-capita annual consumption in the Yangtze River Delta region In consequence, natural gas consumption has continued to grow at more than 150% in most of the region's cities while coal gas has shown the opposite trend except in large cities. By 2014, the Yangtze River Delta region had made great strides in shifting to a cleaner energy source than coal gas with natural gas representing 68% of the entire gas market. Two factors have influenced this shift. The societal need for low-carbon economy and energy conservation have promoted the gas industry's transformation, and the development of infrastructure and formulation of

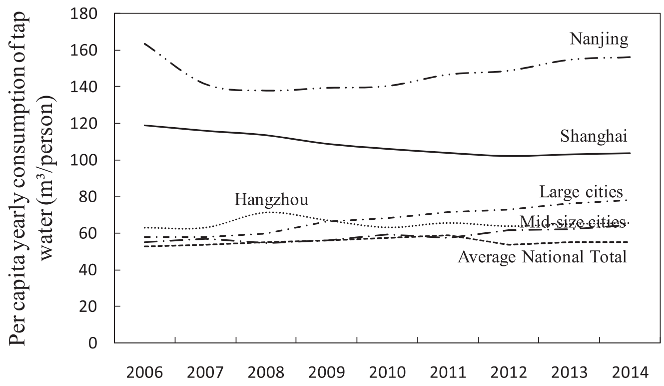


Figure 6. Per capita annual consumption of tap water in the Yangtze River Delta region.

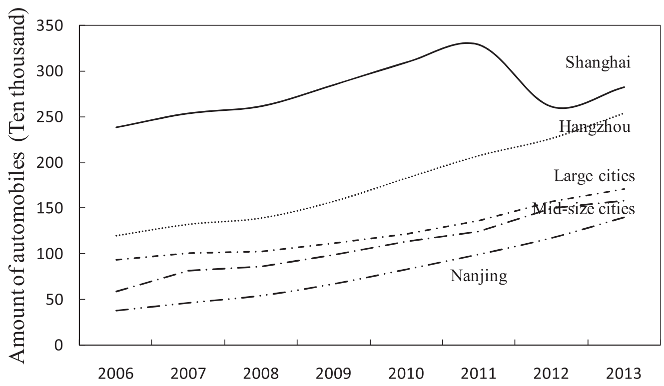


Figure 7. Number of automobiles in the Yangtze River Delta region.

national policies such as *Twelfth Five-Year Energy Development Plan* (2011–2015) (Xinhua net 2011) have created opportunities for development of the natural gas industry. Nonetheless, there was an increasing trend toward coal gas use in large cities; one reason might be population overgrowth without essential supporting energy infrastructure (Yuan *et al* 2014).

4.2.2. Water supply and treatment

Figure 6 shows per-capita yearly consumption of tap water in the region. The percentage of tap water consumption in the Yangtze River Delta region was apparently higher than the national average level. Since the *Twelfth Five-Year Plan*, a water-saving society has been a national policy goal. To ensure that total water consumption does not exceed the allowable maximum, huge and mega cities strictly control per-capita water consumption through the gradient charge; this is especially true in Shanghai and Nanjing. By the end of 2014, per-capita water consumption in those two cities had decreased by 12.6% and 5.7%, respectively, from peak values in 2006 (figure 6). However, in large and midsize cities, continuous population growth has resulted in an obvious increase in total water consumption. Totally, domestic and ecological water consumption has increased, but agricultural and industrial water consumption has decreased (Wang *et al* 2015).

The quality of water sources tends to deteriorate with rapid industrialization and urbanization. The level of domestic sewage treatment in the huge and mega cities has been gradually increasing, which benefited from the management and renovation of factories with inadequate wastewater treatment facilities. Sewage treatment is also inadequate in some small towns because of funding shortages, regulation lack and the complexity of constructing sewer system infrastructure. The lag in sewage treatment technologies in midsize cities means that nearly all of the effluent associated with the 28% of the water supply allotted to industry is discharged untreated into rivers.

4.3. Infrastructure development

4.3.1. Transportation

Since China joined the World Trade Organization in 2001, the Chinese automobile industry has expanded

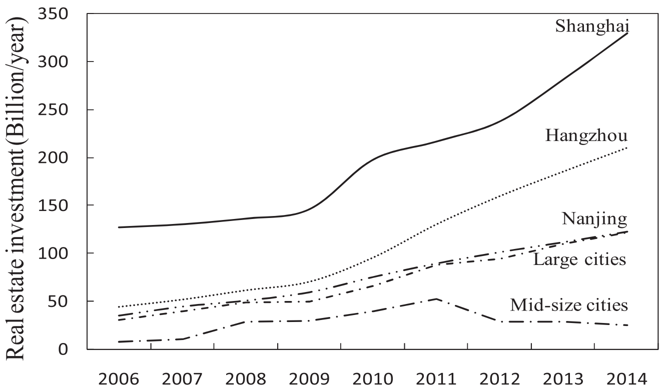


Figure 8. Real estate investment in the Yangtze River Delta region.

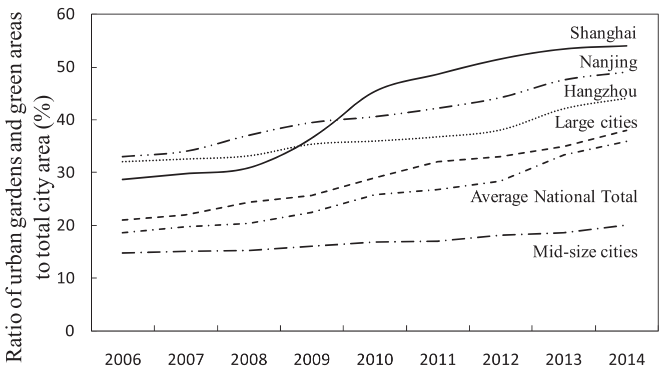


Figure 9. Ratio of urban greening in the Yangtze River Delta region.

significantly. During the 11th *Five-Year Plan* period (2006–2010), automobile sales increased by almost 25% annually in Yangtze River Delta region. In 2015, approximately 61 of every 1000 people in the region owned a private vehicle, compared with only 18 persons per 1000 in 2000.

To manage the growth in the number of vehicles and their associated environmental impacts, the city of Shanghai established policies that include lotteries for license plates and limitations on when vehicles can be operated (e.g., on odd or even dates only, depending on the last digit of the license plate). These policies have significantly reduced congestion and pollution. Figure 7 shows that growth in the number of motor vehicles in Shanghai was only 43.9% during 2006–2014, which was significantly lower than other cities. In addition, public transportation coverage, especially railways, has been significantly greater in huge and mega cities; convenient public transportation provided less-polluting and less-energy-consuming options for urban residents. Shanghai's rush-hour-peak congestion index has decreased by 8.4% and per-capita carbon emissions from vehicles have decreased by 12.6% since 2006 (Xinhua net 2015).

In contrast, large and midsize cities appeared to have a flat increasing rate associated with increasing traffic pressure and exhaust gas emissions (Lin *et al* 2015). Under conditions of continuous city growth and rural–urban migration, private transport is increasing substantially. Urbanization increases also inner-city private transport, because of commuter traffic, often over great distances. This tends to result in an increasing level of motorized individual transport that implies increasing the construction of road infrastructure.

4.3.2. Real estate investment

The real estate and building industry has a significant impact on the infrastructure development. Since 2006, the real estate market has developed rapidly in huge and mega cities with the rapid development of the national economy, consumer demand, and urban construction. Real estate investment in Shanghai have reached 330 billion yuan, almost 3–5 times of that in large and midsize cities, suggesting the huge property market (figure 8). In large and midsize cities, represented by Wuxi, Haining, Jinhua, Yangzhou and Changzhou, real estate development maintained relatively stable growth. By contrast, these cities tended to have more capacity for growth in the real estate market than huge and mega cities (Zhang 2015). Several factors for this phenomenon included population influx from central cities, modifications and updates of existing units in older cities, abundant land resources for real estate development. In addition, the gradual transfer of private capital and massive investment by multinational enterprises from huge and mega cities will boost the building economy sustainably. However, real estate development would consume a significant quantity of raw materials as well as social and labor resources, and the manufacture, construction, and transportation of building materials produce significant greenhouse gas emissions (Li and Colombier 2009). It would have negative effects on the inhabited environment.

4.3.3. Urban greenery

Urban greenery contributes to a healthy natural environment for city residents. Figure 9 shows the ratio of urban greenery in the Yangtze River Delta region from 2006 to 2014. Shanghai previously had very little urban greenery but has made rapid progress during the past nine years, from 29.7% green space in 2006 to 52.2% in 2014. Reasons for the increase include preparations for the city's hosting of the World Expo in 2010. Since 2006, Shanghai has built 27 parks, including Century Park and Quyang Park, bringing the city's total to 125 parks and per-capita green space to 13.6 m^2. However, Shanghai still has much less per-capita green space than Britain (36.8 m^2 per capita) and Japan (33.5 m^2 per capita) where laws regulate the amount of green space. By comparison to the ratio in huge and mega cities in the Yangtze River Delta region, the ratio of green space in large and midsize cities is lower. One reason is that these cities are currently more focused on economic development than environmental concerns.

The current problems related to urban green space in the Yangtze Delta Region include: (i) the percentage of urban green space is low in small towns, much lower than the regional average. (ii) There is little investment in construction of green space and a tendency toward the development approach of 'pollute first, clean up later'. (iii) Green space professional and management capacity are lacking; this has resulted in poor management and maintenance of the trees that have been planted as well as lack of long-term planning. (iv) For the green space that has been constructed, there has been a tendency to focus on appearance rather than the ecological benefits and functions it can provide.

The ecological crisis that will result from industrial development in this region will create pressure to develop green space in large and midsize cities. To respond to the demand for more green space, environmental policies have been established that promote gradual adoption of urban greening technologies and practices to support development of green space, such as roof greening technique, metope greening system, artificial soil, greening precast slab and other technologies, etc.

5. Empirical results

5.1. Correlation analysis

This study divides the panel data of 15 cities in the Yangtze River Delta region during 2006–2014 into four groups for respective regression in order to investigate the relationship between advanced urbanization, the inhabited environment and infrastructure development with considering different-scale cities. After collecting the statistical data of 15 cities, we use entropy method to determine the weight of each indicator (W_i) and then get the ln AUI, ln IEI and ln IDI (table 3), then we get 8 empirical models through the co-integration test.

Model 1–8 and table 4 provides the estimation result for the Yangtze River Delta region. It can be seen that except for model 1, the regression results of regional variables are statistically significant at the 0.1 level or lower. The adjust R square of model 1 is 12.9%, which means the impact of advanced urbanization on the inhabited environment in huge cities seems not significant as others. We find the coefficient of advanced urbanization index is 0.334, 0.554 and 0.839 in model 3, 5 and 7, indicating that a 1% increase in advanced urbanization index would lead to a 0.334%, 0.554% and 0.839% increase of the inhabited environment index in mega, large and midsize cities, respectively. This finding means that advanced urbanization exerts a greater effect to the inhabited environment, which means more energy consumption and waste emission, in midsize cities than mega and large cities when other elements remain constant. As for the infrastructure development, model 2, 4, 6 and 8 show that 1% growth in advanced urbanization index would promote the infrastructure development index by 0.303%, 0.392%, 0.529% and 0.933%, respectively. It reveals that advanced urbanization in mega and midsize cities has greater impact on the infrastructure development, and it plays a relatively weak role to the infrastructure development in huge cities.

The estimate result conforms to the research results from Qiang W *et al* (2016), who thought that the impact of advanced urbanization on energy use, urban construction and emissions and wastes was greater in large and midsize cities. Factually, as many cities in China have already gone through the upsurge of city construction, particularly in huge and mega cities, lower elasticity is unlikely to be the result of scale for the infrastructure development, thus it has less

Table 3. Advanced urbanization index, inhabited environment index and infrastructure development index of 15 cities in the Yangtze River Delta region.

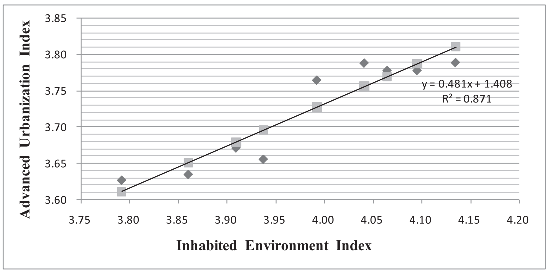
Cities	Year	Advanced urbanization index	Inhabited environment index	Infrastructure development index	ln AUI	ln IEI	ln IDI
Huge cities	2006	6198.8700	4237.0044	12 287.815	3.79	3.63	4.09
	2007	7257.3191	4316.2707	12 741.382	3.86	3.64	4.11
	2008	8126.6123	4693.6156	13 256.865	3.91	3.67	4.12
	2009	8666.5111	4529.0694	13 665.053	3.94	3.66	4.14
	2010	9834.0922	5821.7518	14 275.372	3.99	3.77	4.15
	2011	11 000.1836	6144.7468	14 476.332	4.04	3.79	4.16
	2012	11 614.4757	6002.2785	14 925.311	4.06	3.78	4.17
	2013	12 466.8498	6000.4434	15 095.072	4.10	3.78	4.18
	2014	13 652.5488	6154.6747	15 535.233	4.14	3.79	4.19
Mega cities	2006	2507.9984	435.5218	1982.121	3.40	2.64	3.30
	2007	2961.9153	470.2350	2271.744	3.47	2.67	3.36
	2008	3408.2759	487.8367	2322.873	3.53	2.69	3.37
	2009	3687.5340	506.3644	2448.516	3.57	2.70	3.39
	2010	4324.4911	544.1979	2600.325	3.64	2.74	3.42
	2011	5179.5864	563.5943	3984.051	3.71	2.75	3.60
	2012	5900.8310	582.2234	4030.067	3.77	2.77	3.61
	2013	6434.1790	600.1089	4336.491	3.81	2.78	3.64
	2014	6811.5113	619.7936	4589.539	3.83	2.79	3.66
Large cities	2006	1702.7013	485.0084	1918.973	3.23	2.69	3.28
	2007	2153.4845	521.1500	2021.483	3.33	2.72	3.31
	2008	2681.6084	542.5325	2200.355	3.43	2.73	3.34
	2009	3037.1865	570.7027	2650.016	3.48	2.76	3.42
	2010	3728.5634	602.2699	2896.093	3.57	2.78	3.46
	2011	4491.6709	648.9723	3143.132	3.65	2.81	3.50
	2012	5076.2197	694.4951	3261.266	3.71	2.84	3.51
	2013	5541.2237	727.3492	3389.697	3.74	2.86	3.53
	2014	5807.6061	760.5302	3578.191	3.76	2.88	3.55
	2006	605.6483	501.1792	887.742	2.78	2.70	2.95
Mid-sizecities	2007	719.289 43	573.0347	993.714	2.86	2.76	3.00
	2008	854.6246	645.6852	1118.966	2.93	2.81	3.05
	2009	947.0677	715.0504	1426.261	2.98	2.85	3.15
	2010	1125.3442	822.6576	1623.051	3.05	2.92	3.21
	2011	1317.5727	990.4553	1826.268	3.12	3.00	3.26
	2012	1462.7570	1046.2816	2008.301	3.17	3.02	3.30
	2013	1610.3870	1133.2171	2207.503	3.21	3.05	3.34
	2014	1815.3780	1218.0189	2325.780	3.26	3.09	3.37

Table 4. Estimation results: advanced urbanization model for entire sample, 2006–2014.

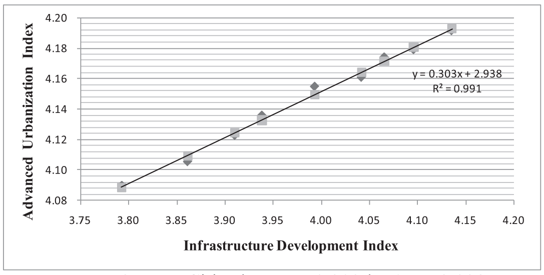
Indicators	Cities	Coefficients	Standard errors	*R* square
ln IEI	Huge	0.481	0.084	0.871
	Mega	0.334	0.013	0.989**
	Large	0.554	0.023	0.972**
	Midsize	0.839	0.020	0.996***
ln IDI	Huge	0.303	0.010	0.991***
	Mega	0.392	0.085	0.941*
	Large	0.529	0.033	0.972**
	Midsize	0.933	0.045	0.983**

(Notes: *,** and *** is significance level at 0.1, 0.05 and 0.01 respectively).

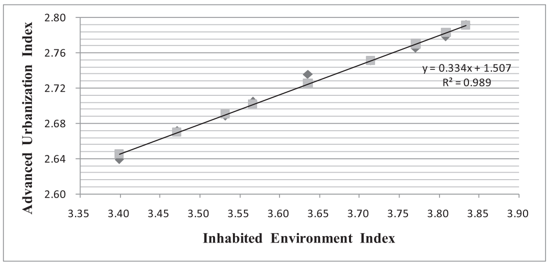
impact on the inhabited environment. In the past 9 years, rapid development of tertiary industry, transfer of labor force, policy formulation and so on, which lead to relatively few resource consumption and urban construction, have played an increasing important role in the growth of advanced urbanization in huge and mega cities. The limited living space and vulnerable environments would also be unable to sustain another round of growth of extensive urbanization. Rather, it could possibly be significant improvement in the inhabited environment quality and infrastructure service during the rapid advanced urbanization process in large and midsize cities. Although the advanced urbanization kept growing at a certain rate, its influence and contribution on the inhabited environment and infrastructure development was rather outstanding. The urgent demand of economic development requires a mass amount of infrastructure construction combined with great resource consumption. Meanwhile, the transfer of talents, investment and investment had the greatest positive impact on the increase of them.



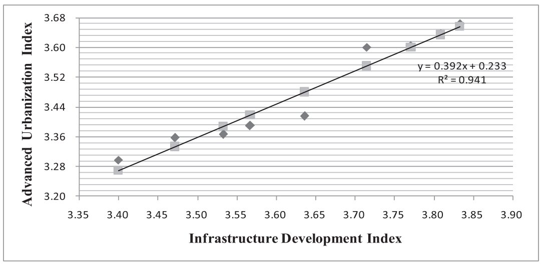
Model 1 Huge Cities ln *IEI* = 0.481 ln *AUI* +1.408



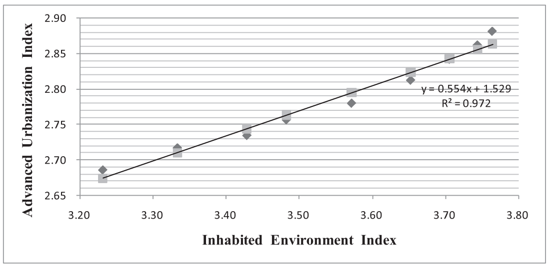
Model 2 Huge Cities ln *IDI* = 0.303 ln *AUI* +2.938



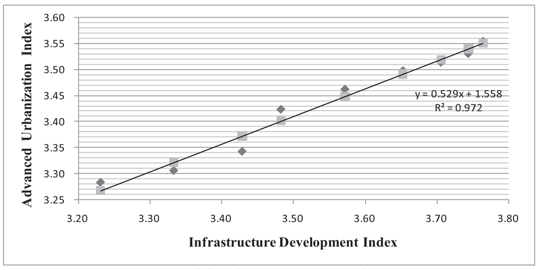
Model 3 Mega Cities ln *IEI* = 0.334 ln *AUI* +1.507



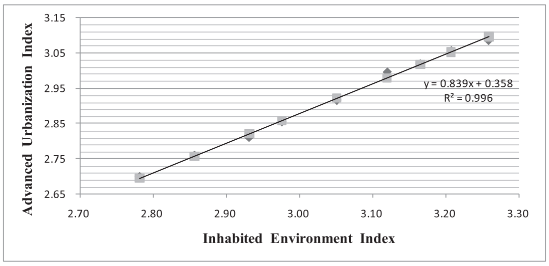
Model 4 Mega Cities ln *IDI* = 0.392 ln *AUI* +0.233



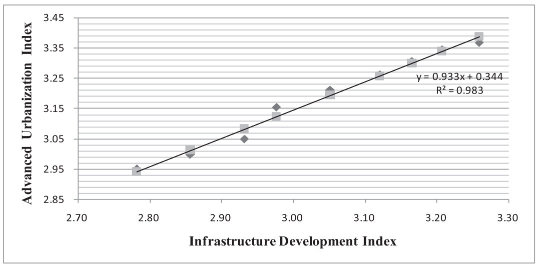
Model 5 Large Cities ln *IEI* = 0.554 ln *AUI* +1.529



Model 6 Large Cities ln *IDI* = 0.529 ln *AUI* +1.558



Model 7 Midsize Cities ln *IEI* = 0.839 ln *AUI* +0.358



Model 8 Midsize Cities ln *IDI* = 0.933 ln *AUI* +0.344

(**Notes:** ▲ represents actual values ■ represents predicted values)

5.2. Distribution pattern

The evolution of advanced urbanization in Yangtze River Delta region has taken place in three stages: initial stage (urbanization rate <60%), extension stage (urbanization rate between 60% and 70%), and integration stage (urbanization rate >70%). Each stage has its own characteristics of economic scale, industry layout, population distribution, energy structure and infrastructure construction (figure 10). During the initial urbanization stage, huge and mega cities was still the focus of regional development as usual. Nanjing, Shanghai, Hangzhou, and Ningbo have become the development poles and played an increasing important role in regional urban development (Gao *et al* 2007). Meanwhile, the level of urbanization of large and midsize cities were still at a relatively low level. When it comes to the extension urbanization stage, industry cluster and population agglomeration in huge and mega cities was weakened and devolved out gradually. Therefore, a few large and midsize cities developed quickly under the action of polarization effect of huge and mega cities (Pan *et al* 2015). Eventually, what had been several independent cities had merged into a single metropolis with the current zonal, continuous development pattern. It can be seen from the figure 10, a Z-shaped urban growth belt has been forming in Yangtze River Delta region in the integration urbanization stage. Many dynamic, transitory, and multiplex features contributed to the evolution of region's current integration urban configuration.

According to the advanced urbanization on the inhabited environment and infrastructure development, 15 cities can be divided into three grades: weakly affected, generally affected, and strongly affected. The natural breakpoint grading method in the ArcGIS technology platform is used for the type classification of 15 cities in Yangtze River Delta region.

As shown in figure 10, the strongly affected areas, distributed throughout the northern (including Yangzhou, Zhenjiang, Nantong and Jiangyin) and central region (including Jiaxing and Huzhou). Over

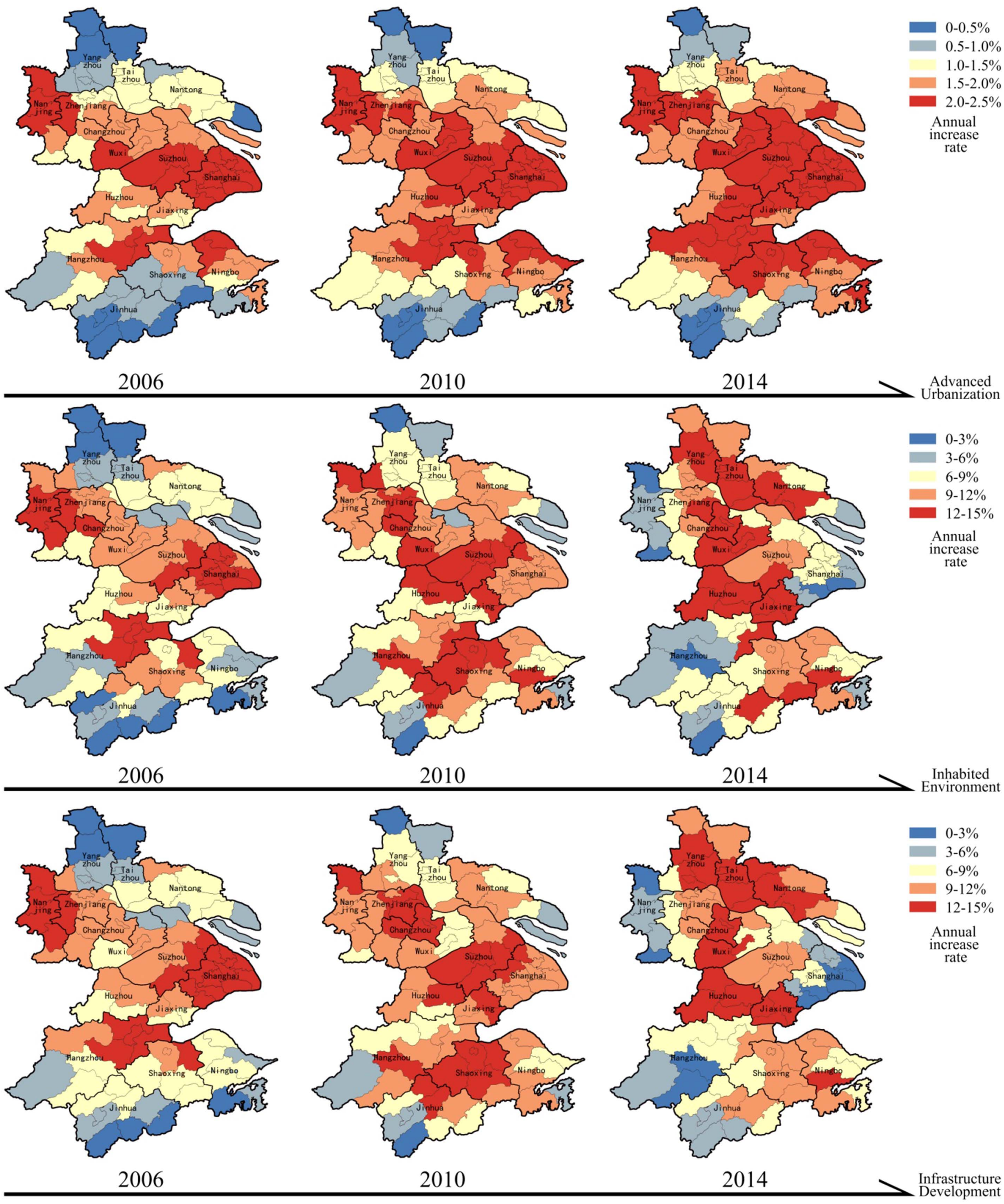


Figure 10. Distribution pattern of advanced urbanization, the inhabited environment and infrastructure development.

the past 9 years, they were on the half way through industrialization, which relied on labor-intensive manufacturing industries for economic growth due to its abundance of urban development capacity. They all maintained high growth rates of urban population, energy consumption, waste emission, real estate development and car ownership. These factors have played an important role in increasing the inhabited environment and infrastructure development. Especially in Jiaxing and Huzhou, whose location was closer to huge and mega cities, the impact of advanced urbanization was even stronger.

The generally affected areas are distributed throughout the rapidly industrializing central region (Suzhou, Changzhou and Wuxi), the private enterprise base in the southern regions (Jinhua, Shaoxing and Ningbo). The inhabited environment improvement and infrastructure development in Suzhou, Changzhou and Wuxi relied on the capital-intensive industry growth and transportation development to their location and industrial development demand. The completion of massive industrial parks would absolutely lead to the increase of energy consumption and waste emission. As for Jinhua, Shaoxing and Ningbo, the gradual rise of private enterprise, particularly the e-commerce market growth, caused positive influence on the inhabited environment improvement and infrastructure development. Among them,

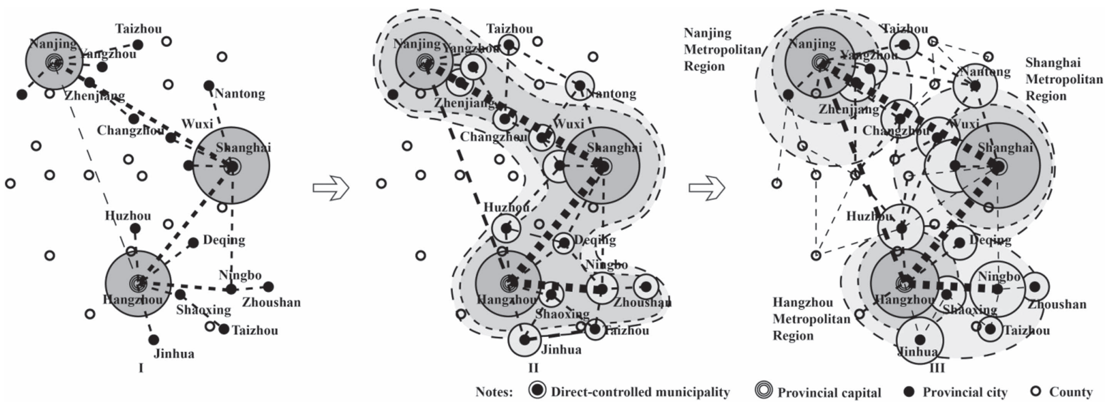


Figure 11. Schematic diagram of Yangtze River Delta region's development.

industry alliance, regional coordination and favorable governmental policies were main factors.

Specifically, we find that the weakly affected areas are concentrated in the central region (including Shanghai, Hangzhou and Nanjing), which have the highest level of urbanization. Due to their large economies, the growth in real estate, car ownership, road construction and the population scale have tended to be saturated. In contrast, rural development, technological innovation of industry and the quality of urbanization became the main urban development strategy over last 9 years. The increase in the inhabited environment and infrastructure development is mainly driven by the development of the rural economy, especially the rise of tourism and its related industries. Therefore, it presents the relatively slow growth of the inhabited environment and infrastructure development compared with the large and midsize cities. In general, the migration patterns has changed as the core areas of advanced urbanization trickled down from the coast to the inland regions, and more industrialization and infrastructure development was seen in these regions.

6. Conclusion and discussion

In this paper, we have discussed the inhabited environment, infrastructure development and advanced urbanization in Yangtze River Delta region, considering cities differences and characteristics of regional development, and we find several interesting phenomena from the data description.

Comparing the results of 15 cities in Yangtze River Delta region from 2006 to 2015, the indicator value shows the distinctly spatial differentiation. The location of Shanghai is advantageous in Yangtze River Delta region. As the headquarter of the region (figure 11(I)), a high percentage of people's activity was concentrated in the core city, and the concentration decreased from the center to the outside of the city (Ewing and Rong 2008), so the supply and demand contradiction of land and other resources in Shanghai was highlighted. Among all the cities, the completeness of infrastructure construction and resource consumption in Shanghai has been the highest. Especially the number of motor vehicles and real estate investment are almost 3–5 times of that in other cities. To ease traffic pressure and housing price, Shanghai has established limited purchasing order and initiative results were obtained. The negative correlation between the inhabited environment and the advanced urban economic development was obvious. It shows the strong dependency on the trend of population and resource gathering to the metropolis, while other cities or towns in urban agglomeration lagged behind to a great extent.

Because of the rapid development of globalization and information, the polycentric urban system in Yangtze River Delta region networking structure has been further improving gradually, and the region tended to be mixed-use and coordinated development (Talen 2012). Mega cities including Hangzhou and Nanjing have often been used as core cities (Gu *et al* 2007). Hangzhou, an important economic center in the region and an international tourist city, focused on developing comprehensive functions, including technological innovations, e-commerce, information, and tourism to strengthen its central position. Nanjing has solid foundation and a strong potential of industry development, which is suitable for developing electronic information, auto machinery and petrochemical industries. Accompanied with the opening of Hangzhou Bay Bridge in 2008 and the 2010 Shanghai World Expo, this region has further formed a high integration and the structure of the Shanghai-Nanjing-Hangzhou, a Z-shaped pattern of urban spatial development. To a great extent, it has promoted the mage cities to gather a mass of population and industries (figure 11(II)). Therefore, it resulted in the relatively high increase of resource consumption and infrastructure development. The house price in Hangzhou and Nanjing was kept tremendously costly and the traffic jam in cities became more and more serious. Surprisingly, the increment of exhaust emission in mega cities was the lowest and urban greenery was the highest, which reveals that these cities paid more attention to environmental protection and sustainable growth rather than economy development blindly.

Back then, whole-sale markets of consumer goods, industrial products, and subsidiary agricultural products emerged in middle and small towns of Yangtze River Delta region. The new market towns include Keqiao Textile Market zoing in Shaoxing, Shengze Silk Market zoing in Wujiang, Leather Market zoing in Haining. Being a crucial place to attract the labor force, the whole-sale markets accelerated the advanced urbanization process by transforming surplus labor force. At the same time, the booming growth of e-commerce promoted the radiating capacity of regional commodity markets improved greatly. The urban railway also developed rapidly, it constructed the most convenient transportation channel, strengthening urban functions, and promoting the urban development for the huge and mid-size cities (Kuo and Miller-Hooks 2012). Gradually, some new towns in the suburbs had higher agglomerations of activity than did those on the border of the central urban area. These characteristics were observed in huge and mega cities, such as Nanjing and Hangzhou. Therefore, three metropolitan areas in Yangtze River Delta region began to emerge, namely the Shanghai metropolitan, Nanjing metropolitan and Hangzhou metropolitan areas, a result supported by several empirical studies. Additionally, Suzhou, Wuxi, Jiaxing, and Ningbo have been found to have more connections with other cities to promote spatial homogenization (figure 11(III)). According to the analysis, although the inhabited environment and infrastructure development in huge and mid-size cities were still at a relatively low level, the increment of were obviously higher than huge and mega cities. For instance, the growth rate of fuel gas consumption in huge and mid-size cities was even 8–15 times of that in huge and mega cities. However, natural gas has become the region's dominant energy source, replacing coal gas and thus reducing pollutant emissions. At the same time, the environmental harm caused by advanced urbanization in huge and mid-size cities also was apparent, which can be seen from the growth rate of exhaust emission and waste water.

Then co-integration test shows that significant differences exist among cities in terms of the impact of advanced urbanization on the inhabited environment and infrastructure development, which is worth noting by policymakers. Surprisingly, it reveals that advanced urbanization in mega and midsize cities has greater impact on the infrastructure development, and it plays a relatively weak role to the infrastructure development in huge cities. Weakly affected areas are distributed in highly urbanized areas that have entered the post-urbanization stage (such as Shanghai and Nanjing). The tendency to switch the industrial structure toward tertiary industries along with a serious of unfavorable policies significantly curbed the increase in the inhabited environment and infrastructure development. Strongly affected areas are concentrated in northern and central undeveloped region. During the late-middle period of urbanization, the key point of urban development in these cities was real estate, road construction, population agglomeration and industry improvement.

The dynamic factors and mechanism of advanced urban development of each city is unbalanced. The developed cities such as Shanghai, Hangzhou and Nanjing faced the higher ecological pressure. They generally had the urgent need to improve the inhabited environment instead of the simple economic growth. However, the huge and mid-size cities else still paid more attention to the rapid increase of economy. Different purposes lead to the oriented contradiction of the policy and strategy of the development (Chen *et al* 2008). It was in dire need of close coordination and cooperation to break the departments' limit to establish the regional system. The urban association proposed by the 15 cities in Yangtze River Delta region was in the implementation process.

As management policies, more actions should be taken to control the acceleration of urban sprawl since several studies have confirmed that these areas will consume more energy and resources and emit more greenhouse gases (Gouldson *et al* 2014). In future urban development, intensive use of urban built-up land instead of extensive urban sprawl should be advocated in the decision making process. However, it also have the urgent need to construct major cross-regional infrastructure to strengthen the relationship between the cities in the region. As economic strategies, the existing industry-dominated and carbon-intensive economic structure, especially in huge and mega cities, does not match with advanced development demands. These cities shall take the lead to push forward the ecological development mechanisms. The mechanisms will ensure to control the balance between advanced urbanization and inhabited development and relieve the ecological pressure. As environmental strategies, large and mid-size cities needs to adopt policies to enhance the carrying capacity matching growing urbanization rates in the long-run. With the concentration of various industries in these cities, improvement of energy efficiency and usage of renewable energy in those industries are also important.

In the foreseeable future, advanced urbanization will become a development engine for Yangtze River Delta region's economic growth and inhabited environment. This indicates numerous studies need to be done exploring the relationship between advanced urbanization, inhabited environment and infrastructure development, assessing eco-environmental plan's effects on urbanization quality, and analyzing the interactive effects between system structure and system function. Our empirical study for the Yangtze River Delta region demonstrated that the proposed advanced urbanization quality assessment model is a powerful tool to highlight the implications of the important links among advanced urbanization system structure, function and quality.

Acknowledgments

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