Sustainability **2015**, *7*, 3984-4003; doi:10.3390/su7043984

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

A Novel Method for Simulating Urban Population Potential Based on Urban Patches: A Case Study in Jiangsu Province, China

Nan Dong [1,2], Xiaohuan Yang [1,3,*], Hongyan Cai [1] and Liming Wang [1]

[1] State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; E-Mails: dongn.14b@igsnrr.ac.cn (N.D.); caihy@lreis.ac.cn (H.C.); wanglm@igsnrr.ac.cn (L.W.)

[2] University of Chinese Academy of Sciences, Beijing 100049, China

[3] Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing 210023, China

* Author to whom correspondence should be addressed; E-Mail: yangxh@lreis.ac.cn; Tel.: +86-10-6488-8608.

Academic Editor: Marc A. Rosen

Received: 2 February 2015 / Accepted: 30 March 2015 / Published: 4 April 2015

Abstract: Urban population potential is a good measure of urban spatial interactions. However, previous studies often assigned population data to the administrative point of the government or the centroid of the region, such as the county, ward or village. In these cases, two problems exist: (1) the zone centroid problem and (2) the scale problem. To better deal with these problems, we proposed a novel method for simulating the urban population potential based on urban patches using Jiangsu Province as the study area. This study conducted research on a classification scheme based on area for urban patches and developed an urban population potential model on the basis of a potential model. The spatial simulation of the urban population potential at various urban scales and the comprehensive urban population potential of Jiangsu were determined. The spatial pattern is "southern Jiangsu high and north-central Jiangsu low", which is consistent with the "pole-axis" spatial system. This study also compared the simulations of the new method and a traditional method. Results revealed that the method based on urban patches was superior in simulating real spatial patterns of the urban population potential. Further improvements should focus on actual conditions, such as passable expressway entrances and exits and railway stations, and high-speed railway data should be employed when simulating the urban population potential across provinces and greater China.

Keywords: urban patches; spatial interaction; population potential; potential model; urban scale

1. Introduction

According to the National Bureau of Statistics of China [1], China has already reached an urbanization level of 53.7%, with an urban population of 731 million in 2013.The speed of China's urbanization has caused profound structural changes in the urban spatial interaction among Chinese cities. Furthermore, the assessment of urban spatial interactions has profound guiding significance for identifying the spatial structure differences in urban development and formulating regional sustainable development policies [2–4]. Therefore, it is necessary to adopt an appropriate method for predicting urban spatial interactions. Population potential is an effective quantitative indicator for measuring spatial interaction on the basis of a potential model [3,5], which is one of the most widely used types of spatial interaction models [6,7]. In this study, we used the urban population potential (UPP) to characterize urban spatial interactions. UPP is defined as the sum of the urban population in destination areas weighted by the distance necessary to get there [8].

Many researchers have used the potential model to calculate accessibility and population potential. Population data were assigned to the administrative point of the government or the centroid of the region, such as a county, ward or village [9–11]. Points represent zones for analysis when computing population potential. As noted by Heather Ann Eyre [12], this traditional method has disadvantages that may influence model performance: (1) the zone centroid problem, *i.e.*, the inaccuracy in model performance because the geographic centroid of the zone may be in a different location to the actual center of the zone (*i.e.*, UPP simulation patterns will be inaccurate due to different calculation of the centroid of a zone); and (2) the scale problem, *i.e.*, the uncertainty in model predictions because as the size of zone increases the modeling of intra-zonal trips becomes more inaccurate (*i.e.*, UPP simulation patterns could vary with the size of the zone changes). It is first necessary to determine what spatial units are most appropriate for models [13].

We thus designed a model for evaluating UPP based on urban patches. Instead of representing counties according to the administrative point of the county government, the new method uses independent urban patches as the basic spatial analysis units. The method alleviates the zone centroid problem by using the population-weighted centroid of each urban patch to represent the location of population. For the scale problem, urban patches are the smallest areal units, so there is no need to consider which spatial units (*i.e.*, city/county/town) is appropriate for better model performance. Moreover, note that most cities or counties are usually composed of a variety of mutually separated urban land-use patches, and these patches interact with each other within their urban precincts.

In terms of assessing model performance, there are some methods such as temporal and spatial comparison of the models or comparison of model and a null model developed from the same data [14–16]. In this work, due to the difficulty in measuring the actual UPP values, an approach based on the seat of the government was chosen for comparison in aspects of the number and spatial location of UPP zones. The objective of this study is to develop a new method for evaluating UPP based on urban patches. Jiangsu Province is selected as a case study. The new method and a traditional point-based method were compared. The results provide a new perspective of the spatial pattern of urban spatial interactions.

2. Study Area and Data Collection

2.1. Study Area

Jiangsu Province was selected as the study area. The province is located in Southeast China along the northern portion of the Yangtze River Delta (116°18′E to 121°57′E, 30°45′N to 35°20′N) (Figure 1). Jiangsu Province comprises 13 prefecture-level cities, 106 counties and districts, and a total area of approximately 102.6 × 10^3 km^2. According to China's Sixth National Population Census conducted in 2010, the total population of Jiangsu Province has reached 78.69 million. The province covers only 1.06% of the land area of the entire nation but contains 5.9% of the total national population. By 2010, Jiangsu's GDP reached $606.6 billion (exchange rate: 1 USD = 6.8275 CNY), accounting for 10.3% of the total national GDP. The per capita GDP reached $7739 and ranked second among all provinces [17,18].

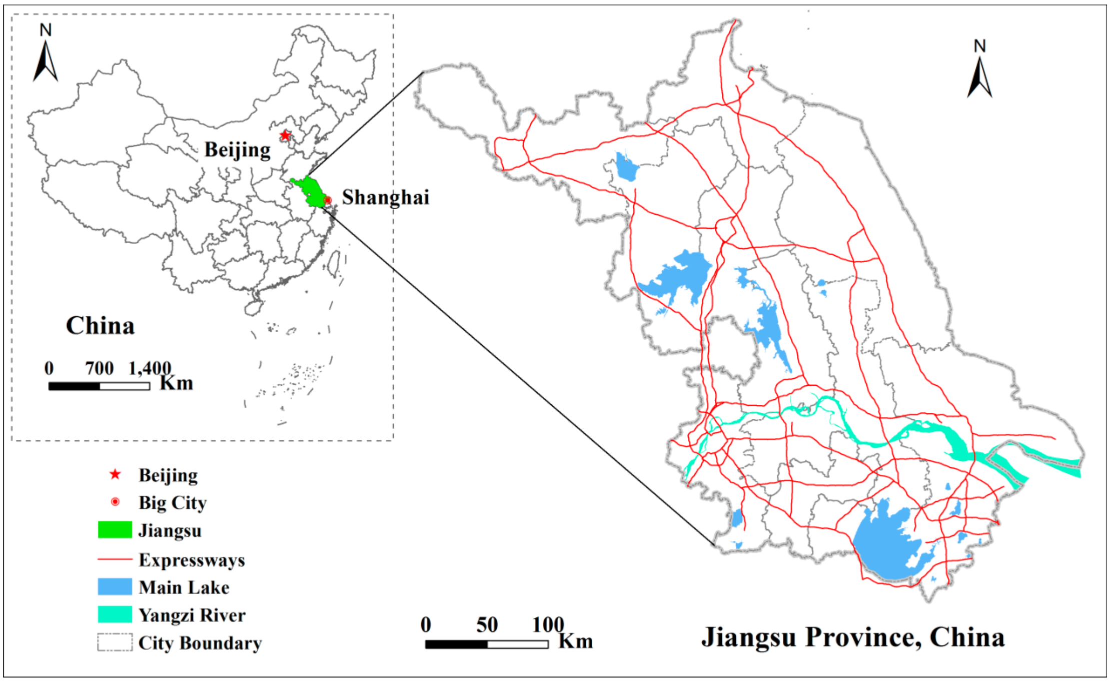

Figure 1. Location of the study area.

2.2. Data Sources and Preprocessing

(1) Data sources

The data used in this study are listed in Table 1.

Table 1. Data types and sources used in the present study.

Name	Type	Year	Scale or Resolution	Source
Land-use data	Raster	2010	1 km	Resources and Environmental Scientific Data Center (RESDC), Chinese Academy of Sciences (CAS)
Gridded population	Raster	2010	1 km	Resources and Environmental Scientific Data Center (RESDC), Chinese Academy of Sciences (CAS)
Time-consumptive grid surface	Raster	2010	1 km	Resources and Environmental Scientific Data Center (RESDC), Chinese Academy of Sciences (CAS)
Urban population, Jiangsu Province	Statistical data	2010	District or county level	Tabulation on the 2010 population census of Jiangsu Province
The seat of the government	Vector	2010	District or county level	National Geomatics Center of China
Boundary of districts or counties	Vector	2010	District or county level	National Geomatics Center of China

(2) Generating urban patches

Urban patches are the basic spatial analysis units in this study. The patches are defined as irregular and separate polygons that are converted from urban built-up land based on land-use data. Urban built-up land refers to a built-up area at the city, county, district or town level. Each grid of land-use data [19] records the percent area of one particular land-use type within 1 km^2. In this study, the grid is defined as a built-up land grid when the percent area of the built-up land is greater than 50%. Subsequently, 691 urban patches whose areas varied from 1 km^2 to 575 km^2 were generated using the "Extraction" and "Raster to Polygon" tools of ArcGIS (Figure 2a).

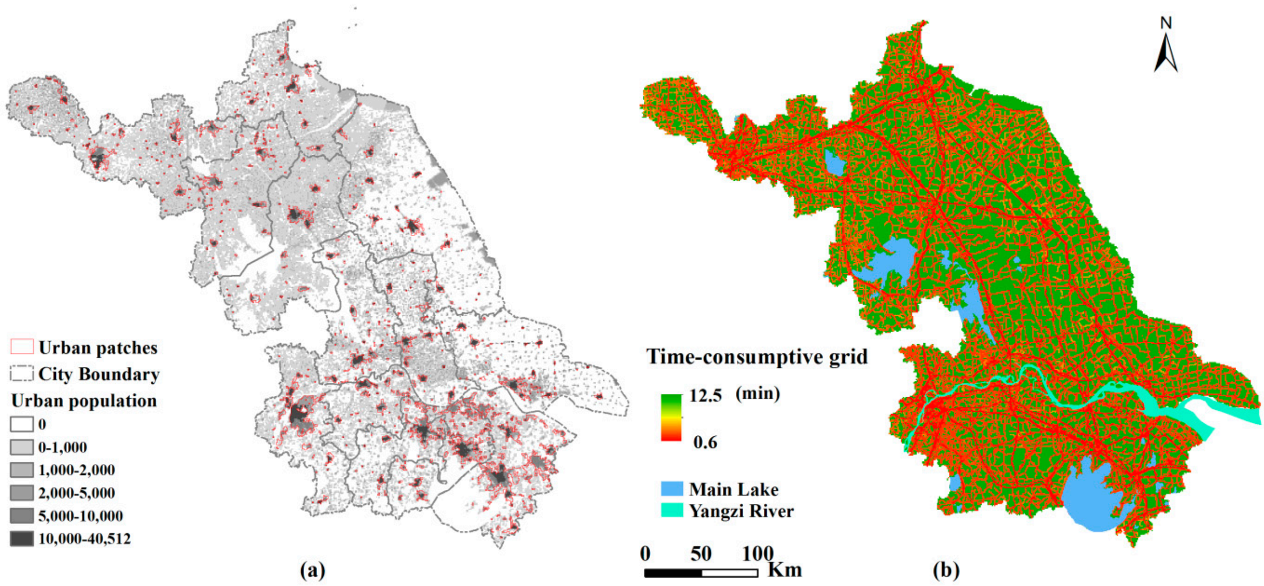

Figure 2. (**a**) Spatial distribution of urban patches and urban population in 2010; (**b**) Time-consumptive grid surface in 2010.

The definition of urban patches centroids is an important issue because it affects the calculation of the distance between zones. As the population is seldom distributed homogeneously, we used the population-weighted centroid of each urban patch to represent the location of population. Population-weighted centroid instead of the simple geographic centroid of an urban patch or the administrative point of the government represents the location of population more accurately [12,20].

(3) Generating the gridded urban population

The existing gridded population data was produced by the Spatial Population Updating System (SPUS). Population Spatialization Model (PSM) embedded in SPUS is used for generating 1 km by 1 km gridded population data in each population distribution region based on natural and socio-economic variables [21]. Here, urban population refers to persons living in a city or town, whereas the existing gridded population data is derived from populations of registered households (*hukou* in Chinese). Considering the data inconsistency between the urban population and household-registered population, we generated the gridded urban population, which is proportional to the existing gridded population data (Figure 2a).

(4) Defining the distance measurement

The distance variable is a function of the accessibility between the origin and destination zones. This measure of distance represents the factor that affects the level of interaction between origins and destinations. Therefore, the measure should consider the definition of the distance measurement [22]. Many "distances" may be used, including Euclidean distance, distance along the transportation network, travel time or cost in terms of time and money [12].

A measure of travel time can provide a realistic measure when modeling UPP because individuals who travel from an origin to a destination must use public transportation and road networks [10]. Time-consumptive grid surface data were considered, and each grid value records the time (minutes) through the grid via walking or transportation (Figure 2b). The dataset for roads and railways and the corresponding speed standards were used to generate a time-consumptive grid surface. The value of the grid in the region where transportation networks did not exist was assigned an average walking speed. The time through each grid can be influenced by the slope of the grid. In order to get a better time-consumptive grid surface, the speeds of walking and transportation are first corrected by slope, which is calculated by DEM data. Then, the travel time was calculated with the Costdistance Algorithm of ArcGIS.

3. Methodology

3.1. Urban-Scale Hierarchical Classification

In a region or country, because of different internal and external conditions, relatively distinct functional division has formed, which results in different scaled cities [23]. Urban-scale hierarchical classification means that cities can be divided into different scale levels according to some size indicators.

Based on central place theory, a higher urban-scale city results in a greater urban effect area and corresponds to a more complex urban function and stronger urban service capability. Inversely, a lower urban-scale city has a smaller urban effect area and weaker urban service capability. Therefore, when computing the UPP, it is necessary to account for different urban-scale level. Generally, the urban-scale hierarchical classification is the premise and foundation for simulating UPP.

To compare the new method based on urban patches, an approach based on the seat of county or district governments was designed. The main difference between the methods lies in the analytic units. Urban patches and the seat of the government are treated as the basic spatial units to simulate the UPP. Urban built-up area is a measurement index of city size [23]. Previous study also showed that China city size distribution in terms of urban built-up area perfectly accorded with rank-size rule [24]. Therefore, a classification scheme based on urban built-up area is proposed for urban patches. A classification based on population is adopted for the seat of the government.

3.1.1. A Classification Scheme Based on Area for Urban Patches

Statistical analysis was conducted for 691 urban patches with scatterplots. The rank by area decrease was the abscissa, and the urban patch area was the coordinate. The results show that the rank-size law is a good description of the distribution of the 691 urban patches; the coefficient of determination (R^2) was more than 0.96 (Figure 3). The fitting result can be expressed by a power function curve [24,25].

$$S_k = S_0 k^{-q} (q > 0) \tag{1}$$

where S_k is the area of the *k*th urban patch (km^2); S_0 is the theoretical area of the largest urban patch; *k* is the rank from the largest to the smallest urban patches by the area in the region (*k* = 1, 2, 3, . . .); and *q* is the Zipf dimension.

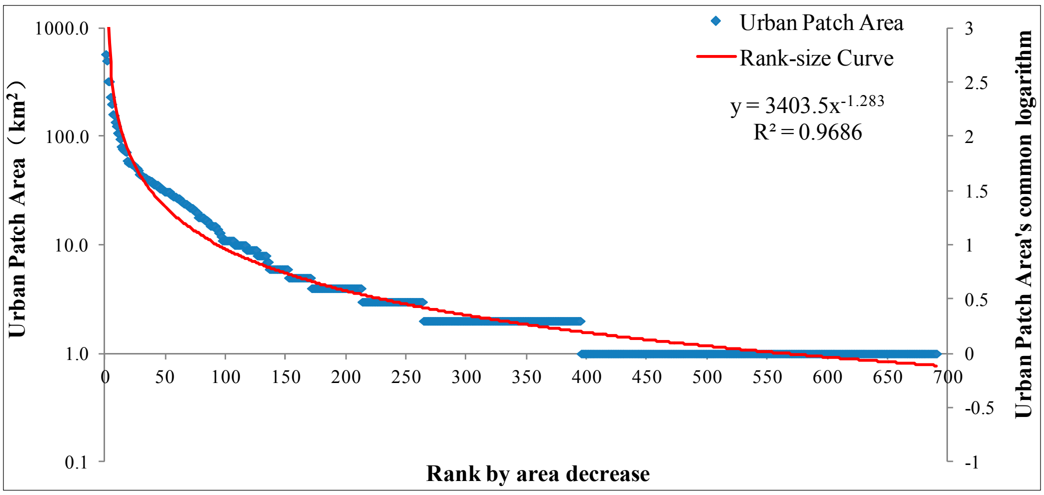

Figure 3. Rank-size curve of urban patch area.

The size of urban patches in Jiangsu Province is consistent with the rank-size law. Therefore, it is reasonable to believe that the urban scale can be expressed by the area of urban patches [26]. Meanwhile, the major and large urban patches are the main factors for simulating the UPP in Jiangsu Province.

According to the 2011 Jiangsu Yearbook [27], Jiangsu Province has 814 designated towns (*jianzhizhen* in Chinese), with an average built-up area of 3.19 km^2. The province also has 88 market towns (*jizhen* or *xiangzhen* in Chinese), with an average built-up area of 1.15 km^2. Organic towns and market towns are transitional settlements between urban and rural areas. Organic towns serve more important intermediary functions than market towns.

First, all urban patches can be classified into two categories with the threshold value 3.19 km^2: major and minor urban patches. Second, the major patches were further classified according to particular criteria. The criteria are (1) $\Delta S_k \geq 2$ km^2 (the approximate average of 3.19 and 1.15) and (2) R_k is the maximum value in the sequence from rank k to the end.

$$\Delta S_k = S_k - S_{k+1} \tag{2}$$

$$R_k = \frac{S_k - S_{k+1}}{S_k} \tag{3}$$

where ΔS_k is the area reduction from rank k to rank $k + 1$; R_k is the relative change rate of the area from rank k to rank $k + 1$.

Based on the above description and discussion, 691 urban patches in Jiangsu Province can be classified into 7 urban-scale levels (Table 2): the Nanjing-Suzhou level, the Wuxi-Changzhou level, the Xuzhou-Kunshan level, the city level (including the cities of Lianyungang, Suqian, Huai'an, Yancheng, Taizhou, Yangzhou, Zhenjiang, Nantong, Xinyi, Jiangyin, Zhangjiagang and Changshu), the important county and district level, the general county and district level and the town level.

Table 2. Hierarchical classification for urban patches.

Rank	Area of Urban Patches (S_k)/km^2	Area Reduction (ΔS_k)/km^2	The Relative Change Rate of Area (R_k)	Classify (Y/N)	Urban-Scale Level	Number of Urban Patches
1	575.0	-	-	-	I	2
		75.0	0.13	N (Do not meet the criteria 2)		
2	500.0					
		177.0	0.35	Y($\Delta S_k \geq 2$ km^2 and R_k is the max from rank 2 to rank 213)		
3	323.0				II	2
		1.0	0.00	N(Do not meet the criteria 1 and 2)		
4	322.0					
		90.0	0.28	Y($\Delta S_k \geq 2$ km^2 and R_k is the max from rank 4 to rank 213)		
5	232.0				III	2
		33.0	0.14	N(Do not meet the criteria 2)		
6	199.0					
		38.0	0.19	Y($\Delta S_k \geq 2$ km^2 and R_k is the max from rank 6 to rank 213)		
7	161.0				IV	12
～	～			N (Do not meet the criteria 1 or 2)		

Table 2. *Cont.*

Rank	Area of Urban Patches (S_k)/km^2	Area Reduction (ΔS_k)/km^2	The Relative Change Rate of Area (R_k)	Classify (Y/N)	Urban-Scale Level	Number of Urban Patches
18	72.0	12.0	0.17	Y($\Delta S_k \geq 2$ km^2 and R_k is the max from rank 18 to rank 213)		
19 ~ 77	60.0 ~ 20.0	…	…	N (Do not meet the criteria 1 or 2)	V	59
		2.0	0.10	Y ($\Delta S_k \geqslant 2$ km^2 and R_k is the max from rank 78 to rank 213)		
78 ~ 213	18.0 ~ 4.0	…	…	N (Do not meet the criteria 1 or 2)	VI	136
214 ~ 691	3.0 ~ 1.0	-	-	Y (According to the condition: $S_k < 3.19$ km^2)	VII	478
		…	…	N		

3.1.2. A Classification Based on Population for the Seat of the Government

It is difficult to obtain an actual and suitable reference database for comparison purposes because UPP characterization data are spatially influenced by the entire population, which is weighted by the travel time distance. Previous studies used points to represent zones for analysis when computing population potential. Therefore, a substitute approach based on the seat of the government was chosen for verification. The urban population data were assigned to the administrative points of the seat of county or district governments to calculate the UPP value.

According to the Scientific Development Evaluation System For Chinese Small and Medium Cities in China [28], a more reasonable criteria for classification is that cities can be classified into 5 levels according to the size of the urban resident population. It is important to note that small cities herein include not only municipal districts but also the counties and central town; 106 counties or districts of Jiangsu were classified into 5 levels (Table 3).

Table 3. Hierarchical classification for counties or districts.

City Hierarchy	Threshold Value of Classified Standard	Urban-Scale Level	Number	Counties or Districts
The mega city	10 million or more	1	0	-
The megalopolis	3–10 million	2	0	-
Large city	1,000,000–3,000,000	3	20	Jiangning, Peixian, Tongshan, Suining, Pizhou, Shuyang, Jiangdu, Xinghua, Taixing, Tongzhou…
Medium-sized city	500,000–1,000,000	4	58	Xuanwu, Baixia, Gulou, Pukou, Xixia, Liuhe, Quanshan, Fengxian, Xinyi, Xinpu…
Small city	500,000 or less	5	28	Qinhuai, Jianye, Xiaguan, Yuhuatai, Lishui, Gaochun, Yunlong, Gulou, Jiuli, Jiawang…

3.2. Urban Population Potential Modeling

The concept of population potential was developed by Stewart [29]. Population potential can be obtained on the basis of the potential model. A potential model, a variant of the gravity model, is a spatial interaction model based on Newton's law of gravitation [30,31].

The population potential at a given point may be identified as a measure of the influence of the entire population weighted by the distance of people to that point [3,32]. A general formulation of the population potential model can then be formulated as [33,34]:

$$P_i = \sum_{j=1}^{n} \frac{M_j}{C_{ij}^{\alpha}} \tag{4}$$

where P_i is the population potential at any given point *i* in space; M_j is the population size of zone *j*; C_{ij} is the travel time between point *i* and zone *j*; *α* is the distance frication coefficient; and *n* is the total number of zones in the study area.

It is assumed that C_{ii} = min(C_{id}) (cf. [2]). C_{id} is the travel time between point *i* and point *d* (*d* = 1, 2, …,8). Point *d* is the center-point of 8 neighborhoods' grid of point *i.* As a result, the self-potential of the point *i* is equal to the max potential within one urban patch.

In previous studies, empirical values of *α* vary from 0.9 to 2.29 [35–37]. The most often cited measures of *α* vary between 1.5 and 2 [38] and range from 1.0 to 2.2 [20]. The value is often set to 1 [3,9] and 2 [39,40]. The population potential model is a type of gravity model borrowed by geographers from the physical sciences (e.g., Newton's laws of gravitation) [5,41]. Therefore, in this study, the coefficient *α* is set to 2, according to the accepted value and that the coefficient of Newton's laws of gravitation is 2.

Based on central place theory, different urban-scale cities have different service area. A higher urban-scale city results in a greater urban effect area and a lower urban-scale city has a smaller urban effect area. The service area of cities at high urban-scale level covers that of cities at low urban-scale level. The service area of cities at the same urban-scale level is not overlapping. To an extent, the same urban-scale cities have competitive relationships with each other in terms of urban spatial interactions. The different urban-scale cities have complementary relationships in urban spatial interactions.

As a result, we advise to use the maximum value model for taking consideration of competitive relationships when simulating the UPP at the same urban-scale level:

$$UPP_{il} = \max\left(\frac{M_1}{C_{i1}^2}, \frac{M_2}{C_{i2}^2}, \cdots, \frac{M_n}{C_{in}^2}\right) \tag{5}$$

where UPP_{il} is the UPP value at any given point *i* at the urban-scale level *l*; M_n is the urban population of urban patch *n*; C_{in} is the travel time between point *i* and urban patch *n*; *n* is the total number of urban patches at the urban-scale level *l*.

We advise to use the addition model for taking complementary relationships into account when simulating UPP at the different urban-scale levels:

$$UPP_i = \sum_{j=1}^{L} UPP_{ij} \tag{6}$$

where UPP_i is the UPP value at any given point *i* in space; *L* is the total number of urban-scale levels.

4. Results

4.1. Urban Population Potential at Different Urban-Scale Levels

Using Equations (4) and (5), the UPP values (10,000 individuals/min^2) at different urban levels were calculated. Figure 4a–g shows the spatial distribution of UPP at each urban-scale level. For illustration purposes, the red zones on the map (Figure 4) are defined as high-value zones (HVZs). The maps show that a point has a higher UPP when it is closer to the center of the HVZ. The UPP values decrease with increasing travel time. Moreover, the UPP value decreases faster when the distance increases. Thus, the places that are close to urban areas have a stronger influence than other places far from urban areas.

Another interesting finding is that the intensity of HVZs decreases or diminishes when the urban-scale level degrades. To facilitate a quantitative analysis, the highest UPP value was used. The highest UPP value at each level is 232.769, 121.645, 79.518, 74.959, 22.760, 15.780 and 9.565. However, the numbers of HVZs increase when the urban-scale level degrades. For example, Figure 4a–c have only two patches. Figure 4d–g have 12, 59, 136 and 478 patches. The larger patches are concentrated in prefecture-level cities (Figure 4a–d). The medium patches are concentrated in the important counties and districts (Figure 4e). The smaller ones are distributed mainly in the general counties and towns (Figure 4f,g).

4.2. Urban Population Potential of Jiangsu Province

A comprehensive UPP was obtained using Equation (6) and results of Equations (4) and (5) (Figure 4a–g), as shown in Figure 5. The results of this study are shown as a raster map (1-km cell size) for Jiangsu Province in 2010. Clearly, the prefecture-level cities (Nanjing, Changzhou, Wuxi and so on) have large-scale scopes and high-capacity UPPs. Compared with major cities, counties and towns have lower capacities for UPP. The UPP intensity of the southern region is stronger than that in the northern region of the Yangtze River. There are many linear high-potential features along highways and main roads besides many HVZs. For instance, the Shanghai-Nanjing expressway links Nanjing HVZ, Changzhou HVZ, Wuxi HVZ and Suzhou HVZ (Figure 6). These HVZs and linear high-potential features form a complex network-connecting spatial structure.

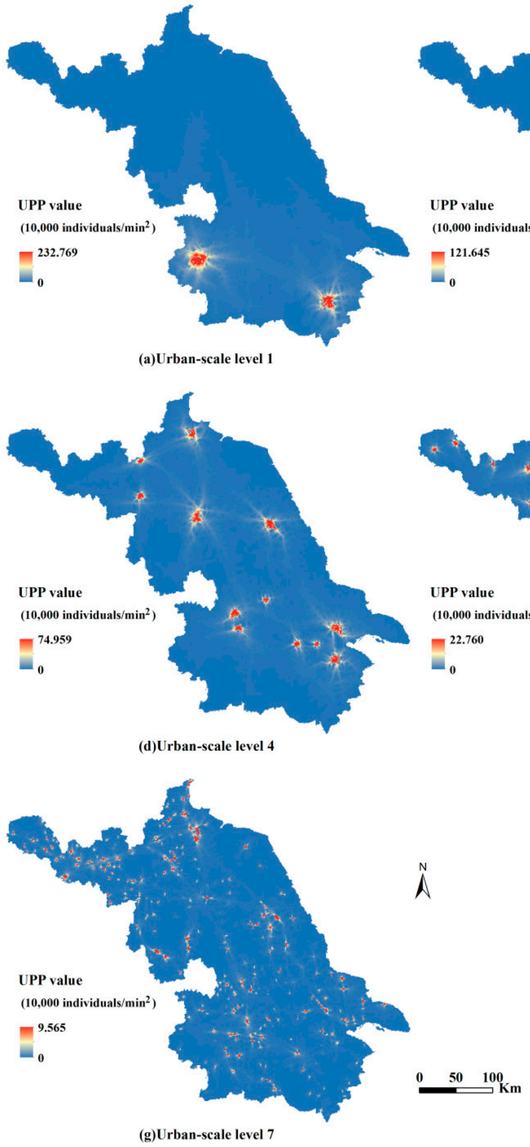

Figure 4. Spatial distribution of urban population potential (UPP) at each urban-scale level.

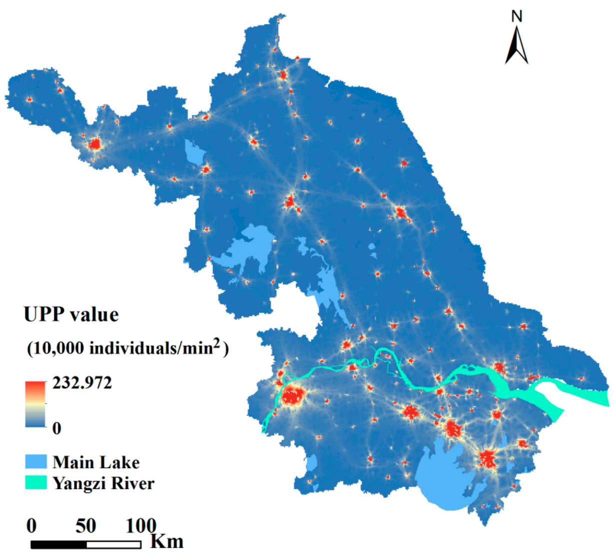

Figure 5. Spatial distribution of urban population potential in Jiangsu Province.

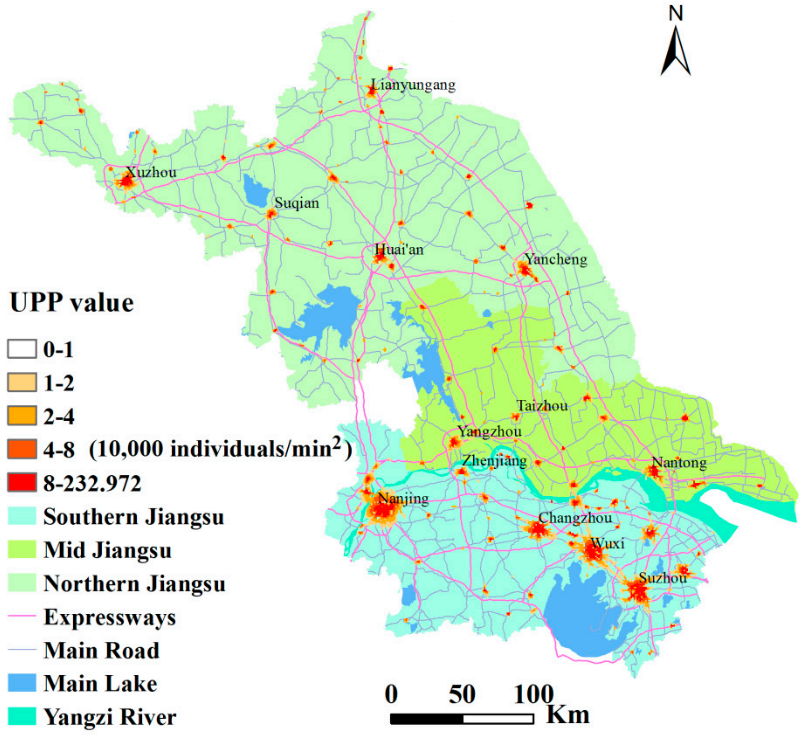

Figure 6. Distribution of urban population potential in Jiangsu Province.

5. Discussion

5.1. Distribution of Urban Population Potential

The map in Figure 5 uses a stretched color scheme to represent UPP and to illustrate the spatial distributions of UPP. From the perspective of the spatial distribution of UPP, Jiangsu Province can be divided into three sub-regions: southern Jiangsu sub-region (including the cities of Nanjing, Suzhou, Wuxi, Changzhou, and Zhenjiang), middle Jiangsu sub-region (including the cities of Yangzhou, Taizhou, and Nantong), and northern Jiangsu sub-region (including the cities of Xuzhou, Yancheng, Lianyungang, Huai'an and Suqian), as shown in Figure 6.

Spatial divisions among different sub-regions are obvious. The developed sub-regions, such as southern Jiangsu, have large-scale scopes and high-capacity UPPs. However, the less-developed sub-regions, such as middle Jiangsu and northern Jiangsu, are weak. In general, the UPP of the sub-regions shows a "southern Jiangsu high and north-central Jiangsu low" spatial pattern.

The concentration of the population in big cities may partly explain these patterns. For example, Nanjing, the capital of Jiangsu Province, is one of the National Primary Central Cities with a total urban population of 6.23 million. The urban population density (UPD) of Nanjing has reached 947 individuals/km^2, and it ranked second among all prefecture-level cities. The UPD of Suzhou, Wuxi, Changzhou and Zhenjiang ranked in the top six (Table 4). The patterns may also be explained by the traffic development. For instance, the expressway density of Nanjing, Suzhou, Wuxi and Changzhou in southern Jiangsu ranked in the top four. Thus, the traffic development in southern Jiangsu is ranked number one. As a result, southern Jiangsu has a high-capacity UPP.

Table 4. Urban population and expressway statistical data in 2010 *.

Prefecture-Level City	Urban Population (Individuals)	Urban Population Density(Individuals/km^2)	Length of Expressways(km)	Expressway Density(km/km^2)
Nanjing	6,238,186	947	435	0.066
Suzhou	7,329,514	864	535	0.063
Wuxi	4,481,903	969	273	0.059
Changzhou	2,900,970	664	221	0.051
Lianyungang	2,273,872	303	336	0.045
Taizhou	2,570,087	444	244	0.042
Yangzhou	2,530,918	384	267	0.041
Zhenjiang	1,929,892	502	152	0.040
Huai'an	2,438,667	242	377	0.037
Xuzhou	4,561,500	405	412	0.037
Nantong	4,064,388	508	277	0.035
Suqian	2,278,812	266	207	0.024
Yancheng	3,772,779	222	322	0.019

* Data from the China Statistical Yearbook for Regional Economy 2011 [42] and Jiangsu Statistical Yearbook 2011 [17].

The three UPP sub-regions in the study are consistent with the three economic zones. From the beginning of the "10th Five-Year Plan" of Jiangsu, the entire province was divided into three economic zones [43,44]: the southern, middle and northern Jiangsu economic zones. To an extent, this finding may support spatial divisions of UPP. There are pronounced links between the population distribution and the economic development in Jiangsu Province. For example, southern Jiangsu is located in the northern wing of the Yangtze River Delta area, which is the sixth largest urban agglomeration in the world [45]. The economic development speed in the area is the fastest in China. The strongest UPP sub-region may benefit the most.

Another spatial characteristic is that HVZs and linear high-potential features compose the spatial pattern of the UPP. When HVZs are recognized as "poles" and linear high-potential features are recognizes as "axes", the different scaled "poles" and "axes" form the spatial structure of a point-axis. This result reveals that the spatial pattern of UPP in Jiangsu Province is consistent with the "pole-axis" spatial system, which is a famous theory by Lu Dadao [46].

5.2. Comparison with Results of the Method Based on the Seat of the Government

To guarantee the comparability of the results, calculations based on the seat of the government were executed by using the same data: the urban population and time-consumptive grid surface. The UPP based on the seat of the government was obtained using Equations (4)–(6), as shown in Figure 7a. A key difference between Figures 5 and 7a is that Figure 5 shows there are visually many small HVZs around large HVZs (Figure 7b). These small HVZs are basically situated in designated towns (*jianzhizhen* in Chinese).

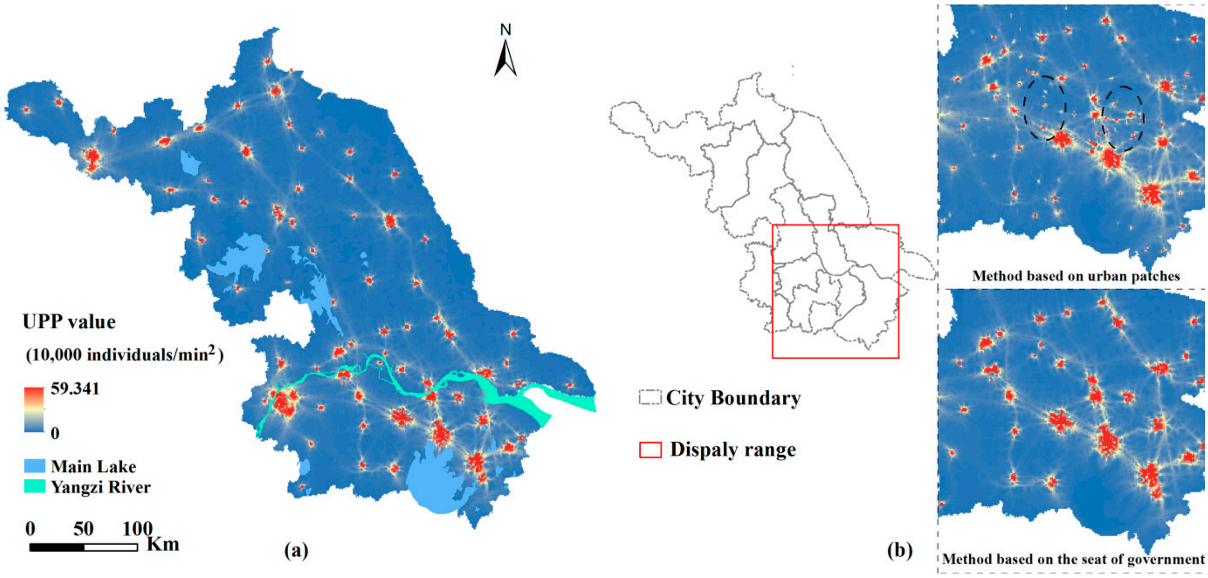

Figure 7. (**a**) Spatial distribution of urban population potential based on the seat of the government in Jiangsu Province; (**b**) A partial comparison chart between Figures 5 and 7a.

Comparing the two simulation results is a problem because of the spatial characteristics of the UPP. This study emphasizes the comparison between two methods based on the number and spatial locations of the UPP zones. (1) A higher number corresponds to a stronger ability to detect UPP; and (2) a more dispersed spatial distribution may provide a more satisfactory reason for a high capacity to disclose the UPP at small scales, such as the county level or town level. For the purposes of illustration, this study uses the centroids of UPP zones to represent the locations of UPP zones. The method of obtaining UPP zones and their centroids at four thresholds (8, 4, 2 and 1) should first be elaborated.

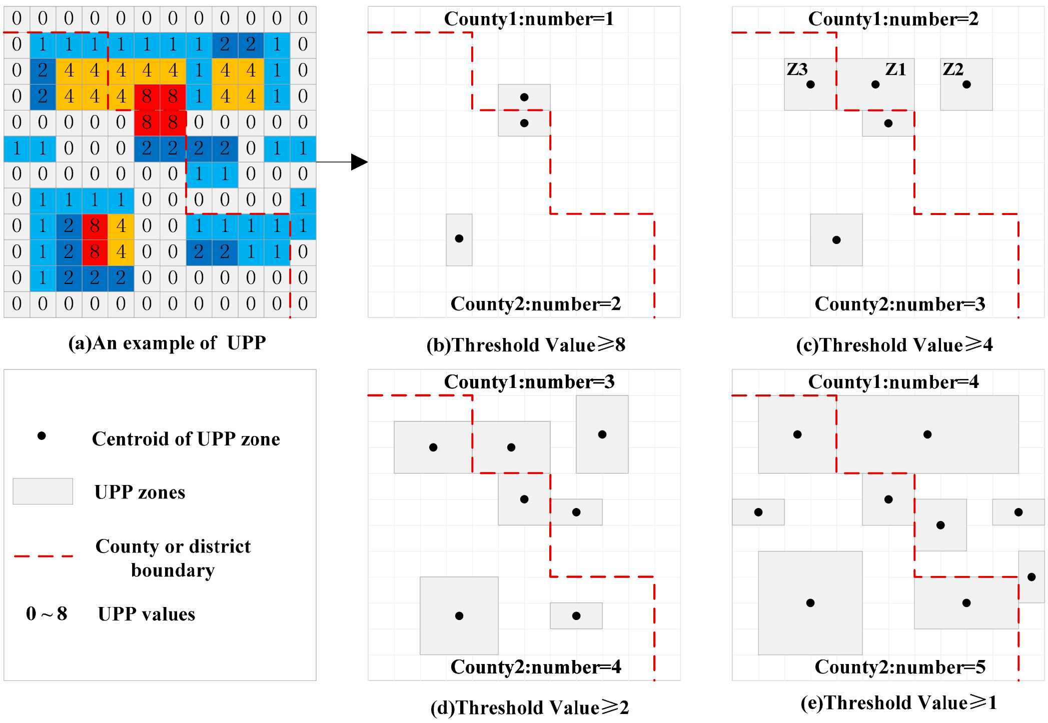

Figure 8. Illustration of obtaining UPP zones and their centroids at four threshold values.

A UPP zone is composed of many grid cells whose values are greater than or equal to the threshold value. These cells should meet the following requirements: (1) the cells are connected with one another in geographical space; and (2) the UPP zone is separated by county or district boundaries in geographical space. Using the threshold value ≥4 as an example, for county1, two cells whose value (value = 1) is less than 4 result in two disconnected parts: UPP zones Z1 and Z2. For county1 and county2, the boundary leads to two separate parts: UPP zones Z1 and Z3. Centroids can be obtained from UPP zones by using the ArcGIS tool "Feature to Point" (Figure 8c). UPP zones and their centroids in 106 counties or districts at four threshold values can be obtained this way, as mentioned above (Figure 8).

5.2.1. Comparison of the Number of UPP Zones

The number of UPP zones was summarized in units of the prefecture-level city. The number of UPP zones based on the seat of the government experiences slight changes with a decreasing threshold. In contrast, the number of UPP zones based on urban patches varies greatly, particularly in Xuzhou (10 to 36).

The number change, which is calculated by the number of UPP zones based on urban patches minus the number based on the seat of the government at different threshold values, is shown in Figure 9. The average number change is 1, 5, 7 and 9 when threshold value is greater than or equal to 8, 4, 2 and 1, respectively. The gap in the numbers between the two methods increases as the threshold decreases. This rule is particularly demonstrated by the figures for nine prefecture-level cities (*i.e.*, Xuzhou, Suzhou, Nantong, Huai'an, Yancheng, Yangzhou, Zhenjiang, Taizhou and Suqian). To an extent, the figures from Nanjing, Wuxi and Lianyungang also follow this rule. It can be concluded that the method based on urban patches detects more UPP zones than the method based on the seat of the government, particularly when the threshold value is greater than or equal to 1.

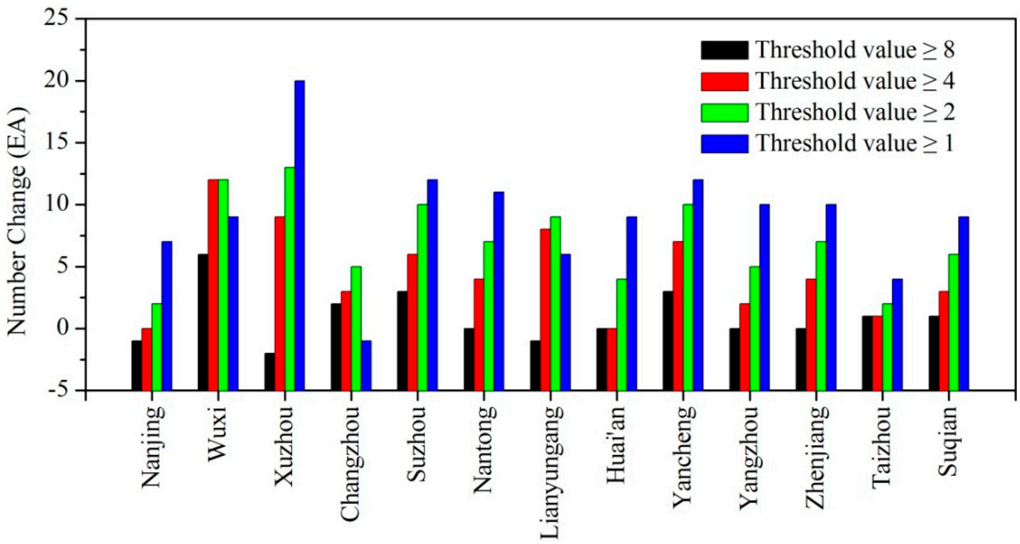

Figure 9. Number change in the UPP zones at various threshold values.

5.2.2. Comparison of the Spatial Distribution of UPP Zones

The spatial distribution of UPP zone centroids based on the two methods at various threshold values is shown in Figure 10. The centroids of UPP zones based on urban patches become scattered, and most become increasingly far from the county or district seat of the government as the threshold value decreases. In contrast, the centroids of the UPP zones based on the seat of the government are basically clustered and near the county or district seat of the government. Therefore, the method based on urban patches has the ability to disclose UPP zones particularly below the county scale. Considering the analysis of Section 5.2.1, it is clear that the method based on urban patches detects more UPP zones, which are distributed mainly in towns. Many people live in towns in China, and the main towns are the local economic centers. As a result, below the county scale, there are actually many UPP zones. Generally, compared with the method based on the seat of the government, the method based on urban patches is superior in simulating real spatial patterns of the UPP.

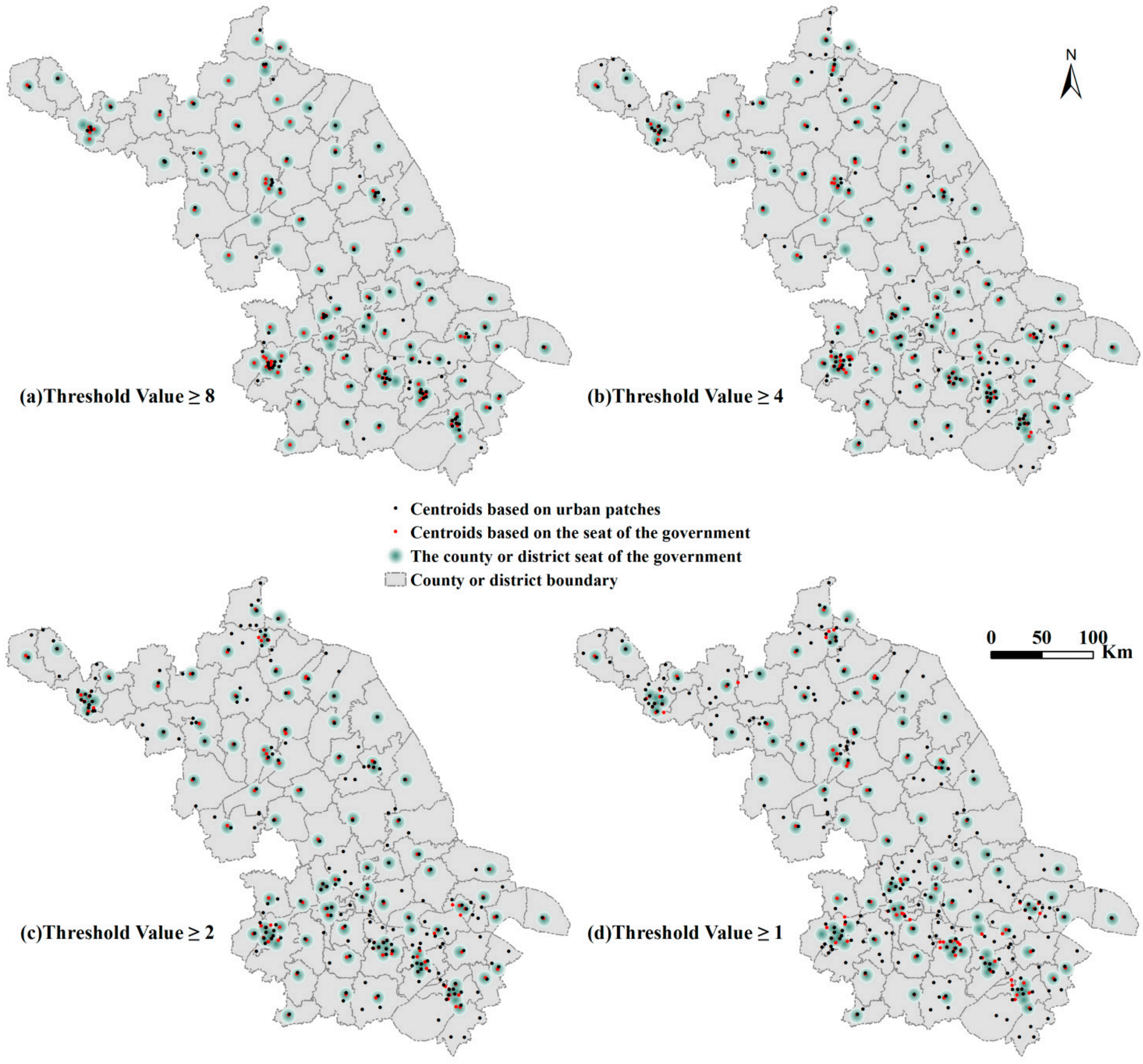

Figure 10. Spatial distribution of UPP zones centroids at different threshold values.

6. Conclusions

In summary, by using gridded population data, land-use data and a potential model, this study proposed a novel method in which urban patches are treated as the basic spatial units for simulating the UPP. Jiangsu Province was selected as the case study.

Our results using the new method revealed a UPP spatial pattern of "southern Jiangsu high and north-central Jiangsu low". The spatial pattern is consistent with the "pole-axis" spatial system. Based on this preliminary case study, we recommend the urban patches method for improving the performance of urban spatial interactions because it is free of administrative boundaries and it overcomes limitations of the zone centroid and scale problem. The method provides a realistic simulation of UPP and satisfies the refinement requirements. The urban patches method could provide a new perspective on the patterns of urban spatial interactions.

The method uses travel times to measure spatial distance assuming that any railways and expressways are passable. Further improvements would be to focus on the actual passable conditions of expressway entrances and exits and railway stations. Moreover, high-speed railway data should be taken into consideration when simulating the UPP across provinces and greater China.

Acknowledgments

This research was jointly supported by the National Research Programs (2012BAI32B06, 2012BAI32B07), and the Project of the National Natural Science Foundation of China (41271173, 41301155). We would like to thank Jingying Fu, Na Zhao, the editor and all the reviewers for their helpful suggestions and comments on this paper.

Author Contributions

Nan Dong analyzed the data and wrote the paper; Xiaohuan Yang, Hongyan Cai and Liming Wang modified the paper.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. National Bureau of Statistics of China. Statistical communique of the People's Republic of China on the 2013 national economic and social development. Available online: http://www.stats.gov.cn/tjsj/zxfb/201402/t20140224_514970.html (accessed on 24 February 2014). (In Chinese)
2. Czyz, T. Application of the population potential model in the structural regionalisation of Poland. *Geogr. Pol.* **1995**, *66*, 13–31.
3. Faíña, A.; López-Rodríguez, J. European union enlargement, european spatial development perspective and regional policy: Lessons from population potentials. *Investig. Reg.* **2006**, *9*, 3–21.

4. Wu, W.; Zhang, W.; Jin, F.; Deng, Y. Spatio-temporal analysis of urban spatial interaction in globalizing China—A case study of Beijing-Shanghai corridor. *Chin. Geogr. Sci.* **2009**, *19*, 126–134.
5. Pueyo, A.; Zuniga, M.; Jover, J.A.; Calvo, J.L. Supranational study of population potential: Spain and France. *J. Maps* **2013**, *9*, 29–35.
6. Alonso, W. A theory of movements. In *Human Settlement Systems: International Perspectives on Structure,Change and Public Policy*; Hansen, N.M., Ed.; Ballinger Publishing Company: Cambridge, MA, USA, 1978; pp. 197–212.
7. Fotheringham, A.S.; O'Kelly, M.E. *Spatial Interaction Models: Formulations and Applications*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1989.
8. Biosca, O.; Spiekermann, K.; Stępniak, M. Transport accessibility at regional scale. *Europa XXI* **2013**, *24*, 5–17.
9. Middleton, N.; Gunnell, D.; Frankel, S.; Whitley, E.; Dorling, D. Urban–rural differences in suicide trends in young adults: England and Wales, 1981–1998. *Soc. Sci. Med.* **2003**, *57*, 1183–1194.
10. Verburg, P.H.; Overmars, K.P.; Witte, N. Accessibility and land-use patterns at the forest fringe in the northeastern part of the Philippines. *Geogr. J.* **2004**, *170*, 238–255.
11. Xiao, Y. Local economic impacts of natural disasters. *J. Reg. Sci.* **2011**, *51*, 804–820.
12. Eyre, H.A. Measuring the Performance of Spatial Interaction Models in Practice. Ph.D. Thesis, The University of Leeds, Leeds, UK, January 1999.
13. Tayyebi, A.; Pekin, B.K.; Pijanowski, B.C.; Plourde, J.D.; Doucette, J.S.; Braun, D. Hierarchical modeling of urban growth across the conterminous USA: Developing meso-scale quantity drivers for the land transformation model. *J. Land Use Sci.* **2013**, *8*, 422–442.
14. Tayyebi, A.; Perry, P.C.; Tayyebi, A.H. Predicting the expansion of an urban boundary using spatial logistic regression and hybrid raster–vector routines with remote sensing and GIS. *Int. J. Geogr. Inf. Sci.***2014**, *28*, 639–659.
15. Tayyebi, A.; Pijanowski, B.C.; Linderman, M.; Gratton, C. Comparing three global parametric and local non-parametric models to simulate land use change in diverse areas of the world. *Environ. Model. Softw.***2014**, *59*, 202–221.
16. Tayyebi, A.; Pijanowski, B.C.; Pekin, B. Two rule-based urban growth boundary models applied to the tehran metropolitan area, Iran. *Appl. Geogr.***2011**, *31*, 908–918.
17. Jiangsu Provincial Statistics Bureau. *Jiangsu Statistical Yearbook, 2011*; China Statistics Press: Beijing, China, 2012.
18. National Bureau of Statistics of China. *China Statistical Yearbook, 2011*; China Statistics Press: Beijing, China, 2012.
19. Liu, J.; Kuang, W.; Zhang, Z.; Xu, X. Spatiotemporal characteristics, patterns and causes of land use changes in China since the late 1980s. *Acta Geogr. Sin.* **2014**, *69*, 3–14.
20. Luo, W.; Wang, F. Measures of spatial accessibility to health care in a GIS environment: Synthesis and a case study in the Chicago region. *Environ. Plan. B* **2003**, *30*, 865–884.
21. Yang, X.; Huang, Y.; Dong, P.; Jiang, D.; Liu, H. An updating system for the gridded population database of China based on remote sensing, GIS and spatial database technologies. *Sensors* **2009**, *9*, 1128–1140.

22. Apparicio, P.; Abdelmajid, M.; Riva, M.; Shearmur, R. Comparing alternative approaches to measuring the geographical accessibility of urban health services: Distance types and aggregation-error issues. *Int. J. Health Geogr.* **2008**, doi:10.1186/1476–072X-7-7.
23. Zhou, Y. *Urban Geography*; The Commercial Press: Beijing, China, 1995; pp. 254–255.
24. Tan, M.; Lu, C. Distribution of China city size expressed by urban built-up area. *Acta Geogr. Sin.* **2003**, *58*, 285–293.
25. Chen, Y. The rank-size scaling law and entropy-maximizing principle. *Phys. A: Statist. Mech. Appl.* **2012**, *391*, 767–778.
26. Schweitzer, F.; Steinbrink, J. Estimation of megacity growth: Simple rules *vs.* complex phenomena. *Appl. Geogr.***1998**, *18*, 69–81.
27. Jiangsu Yearbook Magazine. *Jiangsu Yearbook, 2011*; Jiangsu Yearbook Magazine: Jiangsu, China, 2012.
28. CSMC. Research outputs of the scientific development evaluation system for chinese small and medium cities. Available online:http://www.csmcity.com/luntan/bbs2011/pjbg.html (accessed on 17 September 2011). (In Chinese)
29. Stewart, J.Q. An inverse distance variation for certain social influences. *Science* **1941**, *93*, 89–90.
30. Salze, P.; Banos, A.; Oppert, J.-M.; Charreire, H.; Casey, R.; Simon, C.; Chaix, B.; Badariotti, D.; Weber, C. Estimating spatial accessibility to facilities on the regional scale: An extended commuting-based interaction potential model. *Int. J. Health Geogr.***2011**, doi:10.1186/ 1476-072X-10-2.
31. Hansen, W.G. How accessibility shapes land use. *J. Am. Inst. Plann.* **1959**, *25*, 73–76.
32. Deichmann, U. A review of spatial population database design and modeling. Available online: http://www.ncgia.ucsb.edu/Publications/Tech_Reports/96/96–3.PDF(accessed on 28 March 1996).
33. Fotheringham, A.S. Spatial competition and agglomeration in urban modelling. *Environ. Plan. A* **1985**, *17*, 213–230.
34. Rich, D.C. Population potential, potential transportation cost and industrial location. *Area* **1978**, *10*, 222–226.
35. Love, R.; Morris, J. Mathematical models of road travel distances. *Manag. Sci.* **1979**, *25*, 130–139.
36. Berens, W.; Körling, F. Estimating road distances by mathematical functions. *Eur. J. Oper. Res.* **1985**, *21*, 54–56.
37. Brimberg, J.; Love, R. General considerations on the use of the weighted lp norm as an empirical distance measure. *Transp. Sci.* **1993**, *27*, 341–349.
38. Peeters, D.; Thomas, I. Distance predicting functions and applied location-allocation models. *J. Geogr. Syst.* **2000**, *2*, 167–184.
39. Grübler, A.; O'Neill, B.; Riahi, K.; Chirkov, V.; Goujon, A.; Kolp, P.; Prommer, I.; Scherbov, S.; Slentoe, E. Regional, national, and spatially explicit scenarios of demographic and economic change based on sres. *Technol. Forec. Soc. Change* **2007**, *74*, 980–1029.
40. Arbia, G.; Petrarca, F. Effects of scale in spatial interaction models. *J. Geogr. Syst.* **2013**, *15*, 249–264.
41. Jones, B.; O'Neill, B.C. Historically grounded spatial population projections for the continental United States. *Environ. Res. Lett.* **2013**, *8*, 044021.

42. Department of Comprehensive Statistics of National Bureau of Statistics. *China Statistical Yearbook for the Regional Economy, 2011*; China Statistics Press: Beijing, China, 2012.
43. Duan, Q.; Mao, J. On economic regionalization in provincial scope based on the gravity model and 0–1 programming model: A case study of Jiangsu province. *Econ. Geogr.* **2011**, *31*, 1239–1245.
44. Shen, S.; An, Y.; Dai, X. A review and preview on the regional economic study in Jiangsu since 1980s. *Econ. Geogr.* **2005**, *25*, 302–306.
45. Gottman, J. Megalopolitan systems around the world. *Ekist. Probl. Sci. Hum. Settl.* **1976**, *41*, 109–113.
46. Lu, D. Formation and dynamics of the"pole-axis" spatial system. *Sci. Geogr. Sin.* **2002**, *22*, 1–6.