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A GIS-based buffer gradient analysis on spatiotemporal dynamics of urban expansion in Shanghai and its major satellite cities

Xiaowen Li*, Lina Zhang, Chen Liang

State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, 100875

Abstract

A GIS-based gradient analysis is a useful tool for exploring spatiotemporal dynamics of urban land-use. Although some case studies have been conducted confirming the efficacy of this approach, the gradient analysis of large-scale regional urbanization has still been seldom documented, and the urbanization of satellite cities and their interactions with a central city in regional urbanization have also been poorly explored. In this study, a combination of remotely sensed data, urbanization metrics and GIS-based buffer gradient analysis is employed to analyze the overall spatiotemporal characteristics of urban expansion in the Shanghai region, China, and to explore the urbanization of its major satellite cities and their interactions. The results show the overall spatiotemporal changes in the urbanization gradient are largely influenced by the distance from the urban center, yet there are distinct spatial variations mainly resulting from the interactions of the urbanization of the central city with that of satellite cities. The urbanization within the urban-suburb transitional zones generally had a specific rhythm of intensity and weakness, which can function as the spatial signatures to analyze and demonstrate similar or other types of urbanization processes. The major satellite cities of the Shanghai region showed their distinct temporal-spatial characteristics in their urban expansion behaviors, and thus can be categorized as autonomous, passive, steady and irregular modes of urbanization.

Key words: Urban expansion; Spatiotemporal; Buffer analysis; Satellite city; Shanghai; China

1. Introduction

The transformations of cities reflect economic, environmental, technological, and social processes, yet all are in turn greatly driven by the evolving urban spatial structure itself. The strategies of smart growth and sustainable development of urban regions will depend upon improvements in our knowledge of the causes, chronology, and impacts of the process of urbanization and its driving forces (Potter and Unwin, 1995; Swenson and Franklin, 2000; Paul and Meyer, 2001; Mckinney, 2006; Weng, 2007). Hence, the morphology and evolution of cities due to urban

* Corresponding author. Tel.: +10-58802797; fax: +10-58802797.
E-mail address: xwli_bnu@163.com(X.W. Li)

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sprawl have long been hot topics in geographic research and urban planning to understand, represent and model the complex urban system (Friedmann, 1996; Douglass, 1998; Gaubatz, 1999; Antrop, 2004; Sudhira et al., 2004; Bryant, 2006).

Research in the fields of urban geography, ecosystems and modeling has been conducted for some time (Grimm et al., 2000; Zipperer et al., 2000; 2002; Yang et al., 2004), yet new sources of spatial data and innovative techniques offer the potential to significantly improve the analysis, understanding, presentation and modeling of urban dynamics. Based on remotely sensed data, combining landscape metrics with urban–rural gradient analysis is a technique commonly used to investigate how urbanization is changing the ecological patterns and processes across the landscape (McDonnell and Pickett, 1990; Medley et al., 1995; Luck and Wu, 2002; Zhang et al., 2004). By integrating ecological, social, and physical variables of different disciplines, the gradient paradigm has proved to be a useful tool for studying the urban morphology and ecological consequences of urbanization (McDonnell and Pickett, 1990; Medley et al., 1995; Foresman et al., 1997).

However, the transecting gradient paradigm also has a limitation in characterizing the complexity of urban morphology and the diversity of driving forces, especially in a metropolitan area where the regional urbanization process is not only determined by the urban growth of the central city but also shaped by the rural urbanization of satellite town. In addition, the transect selection of different partitions of the study area may generate varied results. To understand the overall mechanism driving regional urbanization, it is therefore necessary to explore urbanization in the satellite cities and the associated contribution to regional urbanization, but such research has seldom been documented so far.

China has experienced rapid development and quick urbanization over the last two decades, and together with economic development, the landscape has changed significantly (Yeung, 1998; Zhou and Ma, 2000; Liu et al., 2002). Large areas of agricultural land have been urbanized and the impacts of the landscape change on the environment have been significant (Zhou et al., 2004; Zhao et al., 2006). In China, research has been reported on the urbanization and consequential land cover change for mega-cities such as Beijing (Gu, 1999; Liu et al., 2000; Xie and Fan, 2003; He et al., 2002; Wu et al., 2006), Shanghai (Zhang et al., 2004; Zhu et al., 2006), Guangzhou (Seto et al., 2002; Weng, 2002; Yang et.al., 2004; Yu and Ng, 2007), the new and economically strong city of Shenzhen (Shi et al., 2000; Sui and Zeng, 2001), large cities in central and western China, such as Shijiazhuang and Chengdu (Xiao et al., 2006; Schneider et al., 2005) and the historic city of Lhasa (Zhang et al., 2000), as well as comparison research among them (Gaubatz, 1999).

As China's largest and wealthiest city, Shanghai has experienced rapid urban expansion over the past two decades. Shanghai's dynamic growth especially since the 1990s indicates the spatial form of new metropolitan expansion patterns. Its rapid urbanization is well suited to urban morphology, landscape ecology and other related research (Wang and Deng, 2001; Zhang et al., 2004; Zhu, 2006), and the ecological consequences of urban sprawl have been of considerable concern to scientists and policy makers (Ren et al., 2003; Zeng et al., 2005; Zhao et al., 2006). In recent research on Shanghai urbanization, transecting gradient analysis integrated with landscape pattern metrics has been used to quantitatively characterize the landscape and urbanization pattern and to study the impacts of road corridors on the urban landscape pattern (Zhang et al., 2004; Zhu et al., 2006). However, this transecting gradient research has not captured the full spatiotemporal patterns of urban change due to the focus being only on urbanization along some main transactions, and the research failed to address the urbanization interactions between the central city vs. satellite cities.

To fill the gaps in the previous studies, this study addresses urbanization in both spatial and temporal contexts, and explores urban expansion of the central city and satellite cities as well as their interactions in regional urbanization. Four sets of Landsat Thematic Mapper (TM) images were used and GIS-based buffer systems were established covering the central and the main satellite cities of Shanghai. Our research focuses on the overall spatiotemporal dynamics of urban morphology determined by urban expansion in both the central city and satellite cities. It addresses three questions: (1) What are the general spatiotemporal trends of urban expansion and the associated urbanization gradient across the entire Shanghai region? (2) What are the spatiotemporal trends of aeolotropic characteristics in regional urbanization across the entire Shanghai region? (3) What are the spatiotemporal characteristics of urban expansion for the major satellite cities and their urbanization interactions with the central city of Shanghai?

2. Study Area

Shanghai is one of the largest and most important industrial centers of China. It is located on the eastern coast of China with an administrative area of nearly 6400 km2. It is surrounded by the Yangtze River estuary to the north, the East Sea on the east, and Hangzhou Bay to the south. As the central city of the Yangtze Delta urban agglomeration, Shanghai occupies a special social and economic position in China. With the emergence of Pudong's Economic Development Zone, Shanghai has experienced China's most intensive urbanization in the past two decades, especially in the 1990s. For example, Shanghai’s urban area increased from 149.85 km2 in 1982 to 279.78 km2 in 1990, and climbed to 377.56 km2 in 2000. According to China’s latest census, Shanghai’s population was 16.74 million in 2000, which represented an increase of 3.4 million people since 1990. The average annual growth rate was 2.2% in the 1990s, and the total increase was 25.5% (Shanghai Municipal Statistics Bureau, 2004).

The study area covers the major Shanghai metropolitan region. Because our research focuses on the dynamics of urban expansion in Shanghai, the target study area should focus on downtown Shanghai and include its major satellite cities. With central Shanghai as the nucleus, a fixed-window method was used, whereby fixed rectangular windows were superimposed over the most typical and concentrated areas of Shanghai's urbanization. Changes in land-use were observed within such areas for different time periods (Figure 1). The total area of the fixed windows was 5,250 km2 (75 km × 70 km), accounting for 80% of the jurisdiction of the Shanghai municipality except Congmin and some areas of Jinshan county..

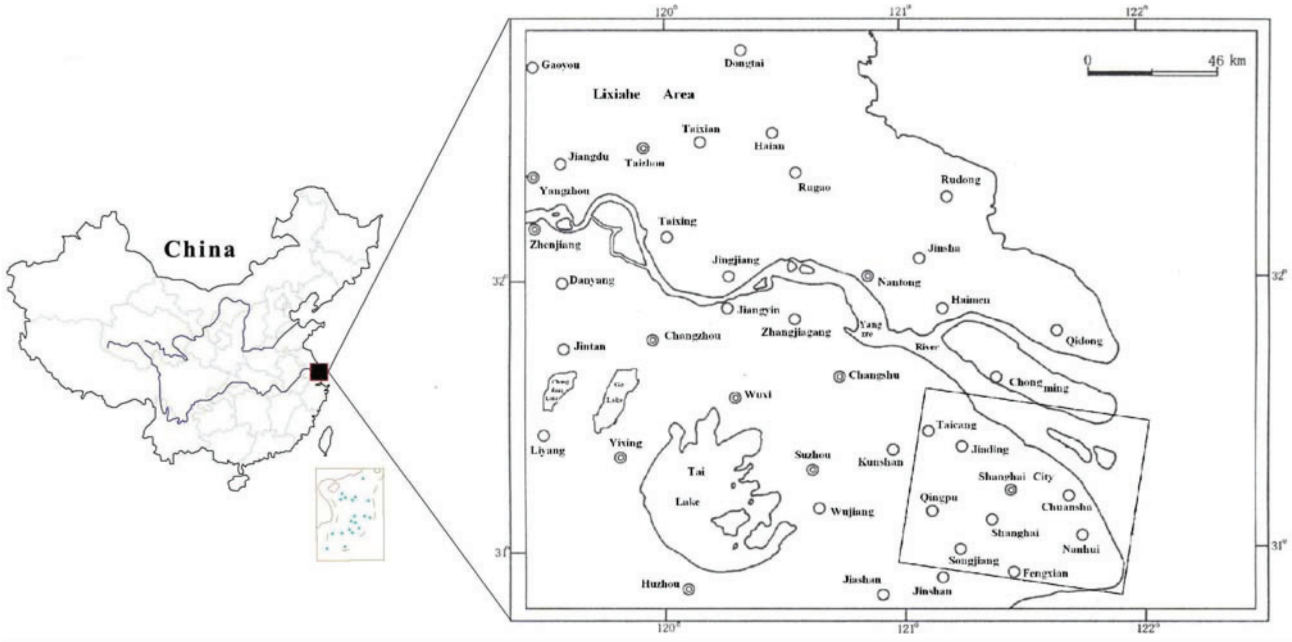

Fig. 1. Location of the Yangtze River Delta and study area. The study area is delineated by a fixed rectangular window covering an area of 5,250 km^2 (75 km × 70 km), accounting for 80% of administrative areas of Shanghai except some remote suburbs, i.e. Congmin and some areas of Jinshan county.

3. Data processing and methodology

Four sets of Landsat TM images were used in this study (1987/1990/1995/2000, resolution 30 m, seven bands). These images were processed with ERDAS IMAGINE software, which involves geometric correction, unsupervised and supervised classification, and GIS reclassification. The images were rectified to a Gauss-Krüger projection based on 1:50,000 scale topographic maps. A second order polynomial geometric model and cubic convolution algorithm were used during this process. The root mean squared errors for all four images were less than 1 pixel. Through the use of spectral classification, the urban area was extracted, which included high density residential areas and new development zones (generally in the form of industrial areas, but also new urban areas with relatively low building density). The results for the Shanghai urban area for 1987-2000 are shown in Figure 2.

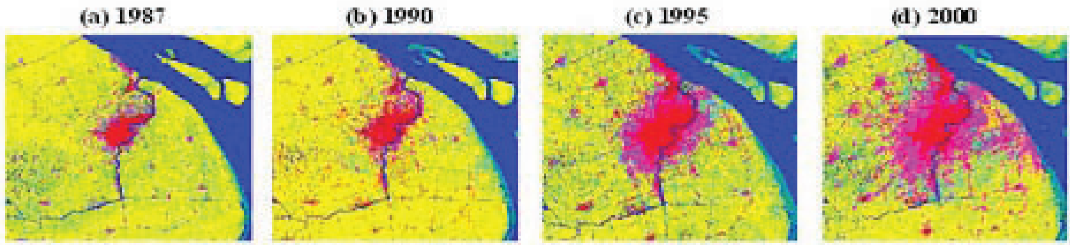

Fig.2 The urbanized area of Shanghai Metropolitan Region in 1987, 1990, 1995 and 2000 respectively.

To measure and quantify the magnitude and pace of urban growth, an urbanization proportional index (UPI) and urbanization intensity index (UII) were developed and employed (Liu, 2000), which are expressed as

$$UPI_{i,t\sim t+n} = (ULA_{i,t+n} - ULA_{i,t}) * 100 / TLA_i$$
$$UII_{i,t\sim t+n} = [(ULA_{i,t+n} - ULA_{i,t}) / n] * 100 / TLA_i$$

The variables $UPI_{i,t\sim t+n}$, $UII_{i,t\sim t+n}$, $ULA_{i,t+n}$ and $ULA_{i,t}$ are indices of the proportion of urbanization and the intensity of urbanization within a spatial unit *i* during a time period *t~t+n*, and the areas of urban land-use for years *t+n* and *t*, respectively. TLA_i is the total area of the spatial unit *i.* The UPI expresses the percentage of the total area occupied by urban expansion for a given spatial unit over the entire course of the study from 1987 to 2000, and it characterizes the total magnitude and spatial distribution patterns of such expansion throughout this period. The UII is used to compare the pace and intensity of urban expansion over various periods. Essentially, the UII calibrates the average annual urban expansion rates for each spatial unit, to ensure comparability of the pace of urban expansion for different periods of time.

GIS-based buffer analysis was adopted in our research, which involved circular buffer zones surrounding the city center. Each buffer zone was employed as a basic spatial unit to characterize distance-dependent urban growth behavior with their UPI and UII values for a given time period. To achieve our research objectives, two different buffer systems were established, one was a buffer zone system with a width of 2 km covering the entire region designed to explore the overall urbanization process over the metropolitan area of Shanghai (comprising the Shanghai urban area and suburbs) (Figure 3). In addition, this buffer analysis system was then divided into eight average pie slice areas for aeolotropic (i.e. directional variation) analysis of urbanization, and calculations of the UPI and UII were made separately within these eight aeolotropic regions to explore aeolotropic trends in urbanization process. The division was (in clockwise order): west-northwest (WNW) or 0º to 45º, north-northwest (NNW) or 45º to 90º, north-northeast (NNE) or 90º to 135º, east-northeast (ENE) or 135º to 180º, east-southeast

(ESE) or 180º to 225º, south-southeast (SSE) or 225º to 270º, south-southwest (SSW) or 270º to 315º, and west-southwest (WSW) or 315º to 360º.

The other buffer system was established by delineating separate buffer zones to compare spatiotemporal characteristics of urban growth between the Shanghai urban center and the eight major satellite cites (except congming and Jinshan counties) in study area (Figure 4). In this analysis, the buffer zones covering the Shanghai urban center were defined as having a 1 km width, and thus 10 buffer zones were created outwards from the city center to incorporate the principal urban center of Shanghai. Given the much smaller urban areas, the buffer zones for those 8 satellite cities were 0.5 km in width, and 10 such buffer zones were enough to include the principal urban areas of each satellite city.

In both buffer analysis systems, urban areas of Shanghai indicated by Landsat MSS data from 1978 were extracted and used to represent the urban center as a baseline for creating buffer zones. Because the urban center of each satellite city was generally not obvious, the geometric center of each satellite city during the first time phase (1987) was used as the origin in creating the buffer zones.

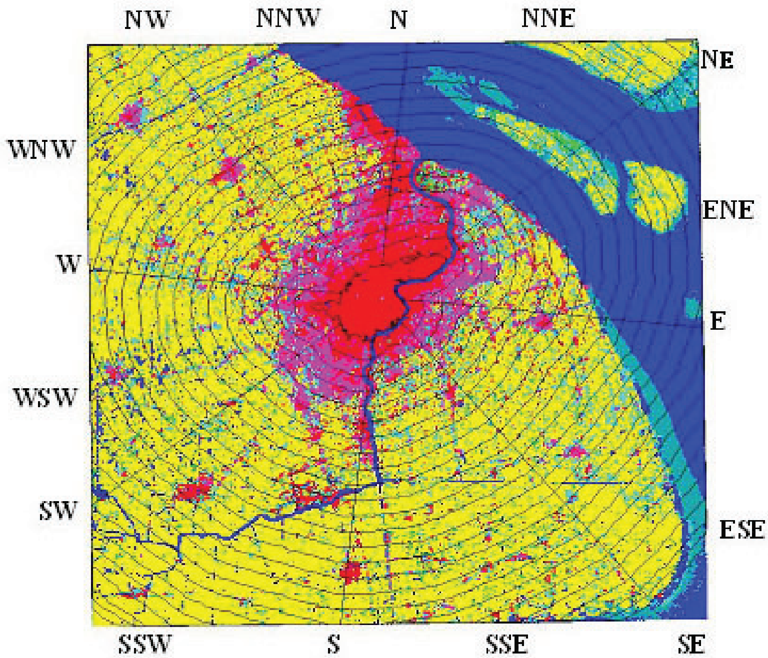

Fig. 3. A 2 km width buffer zone system established in measuring the overall spatiotemporal trends of urbanization gradients and associated spatial heterogeneity in the Shanghai region, which divided the study area into eight aeolotropic areas: ESE (east-southeast), SSE (south-southeast), SSW (south-southwest), WSW (west-southwest), WNW (west-northwest), NNW (north-northwest), NNE (north-northeast) and ENE (east-northeast).

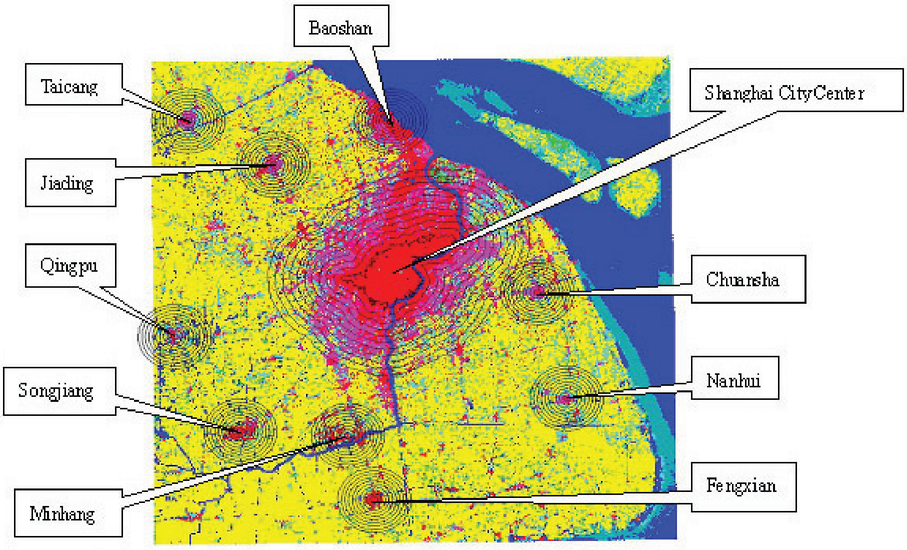

Fig. 4. Complex buffer zone system established by delineating separate buffer zones around the Shanghai city zone and its eight satellite cities to compare spatiotemporal characteristics of urban expansion between the Shanghai city zone and its major satellite cites. The width of the buffer zones covering the Shanghai city zone were defined as 1 km, while the buffer zones for the satellite cities were defined as 0.5 km in width. Besides urbanized areas extracted from Landsat MSS data in 1978 used as the urban center of the Shanghai city zone for creating buffer zones, the geometric center of each satellite city during the first time phase (1987) was used as the origin in creating the buffer zones.

4. Results and analysis

4.1. Spatiotemporal trends of UII based on buffer analysis during 1987~2000

Figure 5 displays the UII resulting from buffer zone analysis for the entire Shanghai region over each time interval. For the period 1987-1990, the UII showed a general and uniform decline, with equivalent initial and peak values, indicating that urbanization intensity was highest in the area (buffer zone) immediately surrounding the urban center. 20 km from the urban center, the curve has an obvious inflection point, indicating a rapid downtrend in the UII for the area within this distance from the urban center. Beyond the 20 km mark, the trend is a comparatively gentle decline, indicating that urbanization within an area of 20 km from the urban center is sensitive to the distance from the urban center. In addition, beyond 20 km from the urban center saw a gradual and smooth downtrend with relatively low UII value, demonstrating that the change in UII beyond such a distance may be largely related to the rural or local township urbanization rather than large-scale urbanization of Shanghai urban center. Therefore, we might conclude that 20 km from the original urban center constitutes the ambit of the effects of urbanization in the Shanghai municipal area from 1987-1990, forming a transitional band to the suburbs at the outskirts of metropolitan Shanghai. During this period, the transitional zone at the outskirts of the urban center swept north to the northwest section of Baoshan district (along a northerly axis of expansion) and extended south precisely to an area near Minhang district (along a southerly axis of expansion), presenting a north-south axis of expansion.

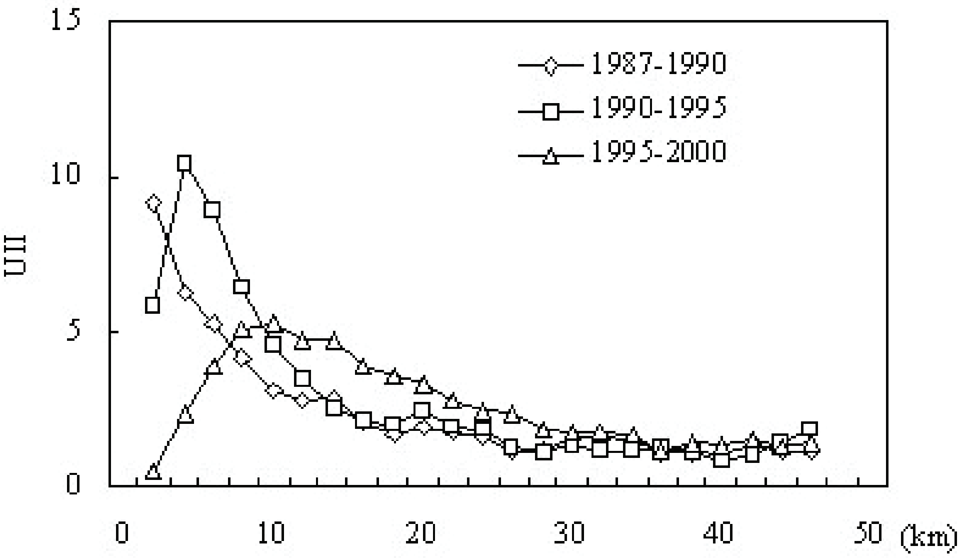

Fig. 5. Changes in the UII with distance to the urban center over the entire Shanghai region in different time periods from 1987 to 2000. The spatial signature reflected by trends in UII can be used in characterizing and comparing different urbanization types.

During 1990-1995, areas within 6 km of the urban center saw a sharp increase in UII with distance, with a rapid decline in the range from 6 to 20 km, and then a slow downtrend for the region beyond 20 km. The overall UII curve is unimodal, with a peak value 6 km from the urban center and higher than that of the previous time period, but having an initial value lower than that of the previous time period. The UII curve has several features: the most active region of the urban expansion zone has been pushed outward to 6 km from the urban center, the region 0 to 6 km from the urban center clearly had declining urban expansion, indicating a maturing of, and thus waning potential for, urbanization. In the range 4 to 16 km from the urban center, the UII values during 1990-1995 were noticeably higher than that previous, indicating clear intensification of urbanization within this band., In addition, the trends of UII change was nearly the same as that of the previous period for areas beyond 20 km from the urban center, with an inflection point 20 km from the urban center. This shows urbanization in Shanghai at that time was still primarily concentrated within 20 km of the urban center, with urban expansion along the north-south axis. Nonetheless, this region saw a marked increase in urbanization intensity, indicating an increased rural urbanization.

During the period 1995-2000, the UII curve again assumed a unimodal shape with an initial rise and subsequent decline, but its overall features and trends of change were quite different from those of 1990-1995. Firstly, the UII curve's initial value approached zero, becoming the curve's lowest value, whilst the peak value was considerably decreased to nearly half that of the previous period. The peak value was pushed out to 10 km from the urban center, indicating that the active urbanization circle during the previous period, immediately surrounding the urban center (within nearly 2km), had already completely urbanized and become a new part of the expanding urban center.

Within 10 km from the original urban center, the UII curve displayed a relatively rapid rise, but the values and rates of increase were much lower than that previous, showing that areas within 10 km from the urban center had a declining pace of urbanization. Secondly, the UII inflection point was further from the urban center at 30 km, with higher UII values in the buffer zones from 10 to 30 km compared to those previous. This implies the period 1995-2000 saw a decreased intensity of urbanization but an enlarged scope of expansion. The area affected by urbanization in Shanghai therefore expanded to 30 km from the urban center, breaking through the previous boundary delineated by the north-south axis of expansion, with advances into the areas of Qingpu, Songjiang, Fengxian and Nanhui. The wide-ranging, mid- and low-intensity urban expansion this period clearly indicates the ongoing large-scale development in eastern Shanghai (i.e Pudong New Development Area).

The UII curves for each period share certain common characteristics (Figure 5). For example, downtrends were comparatively smooth, without other prominent peak values, implying there were no other distinct centers of urbanization within the overall area except for the active urbanization circle around the Shanghai urban center. However, the ambiguous peak values emerged within 20 to 30 km from the urban center for 1987-1990 and 1990-1995, indicating the weak urbanization in these region. 20 km from the urban center roughly corresponds to the active urban expansion of outlying cities, such as Baoshan, Minhang, Jiading, Anting and other townships, while 30 km from the urban center reflects active exurb urbanization such as Qingpu, Songjiang, Fengxian and Nanhui. In addition, these ambiguous peak values disappeared with the higher and wider range of the UII curve over these zones for the period 1995-2000, indicating the regions between the suburbs and the central urban area underwent broad-scale urbanization, resulting in an overall uniform trend and intensity of urbanization.

4.2. Spatial aeolotropy of UII based on buffer analysis during 1987-2000

Figure 6 displays the results of the spatial aeolotropy analysis of the UII for Shanghai. During the period 1987-1990, all UII curves show peak values at initial points, followed by rapid declines and then gradual downtrends (except the NNE and ENE slices), indicating the areas immediately surrounding the urban center had a high intensity of urban growth in each direction. The SSW, WNW and NNE slices had high initial values above 10.0, implying they covered the key areas of urbanization. The SSW and NNE slices together have formed the north-south axis that is the main direction of Shanghai's expansion, whereas the WNW slice corresponded to the neighboring areas along the Shanghai-Jiading Highway.

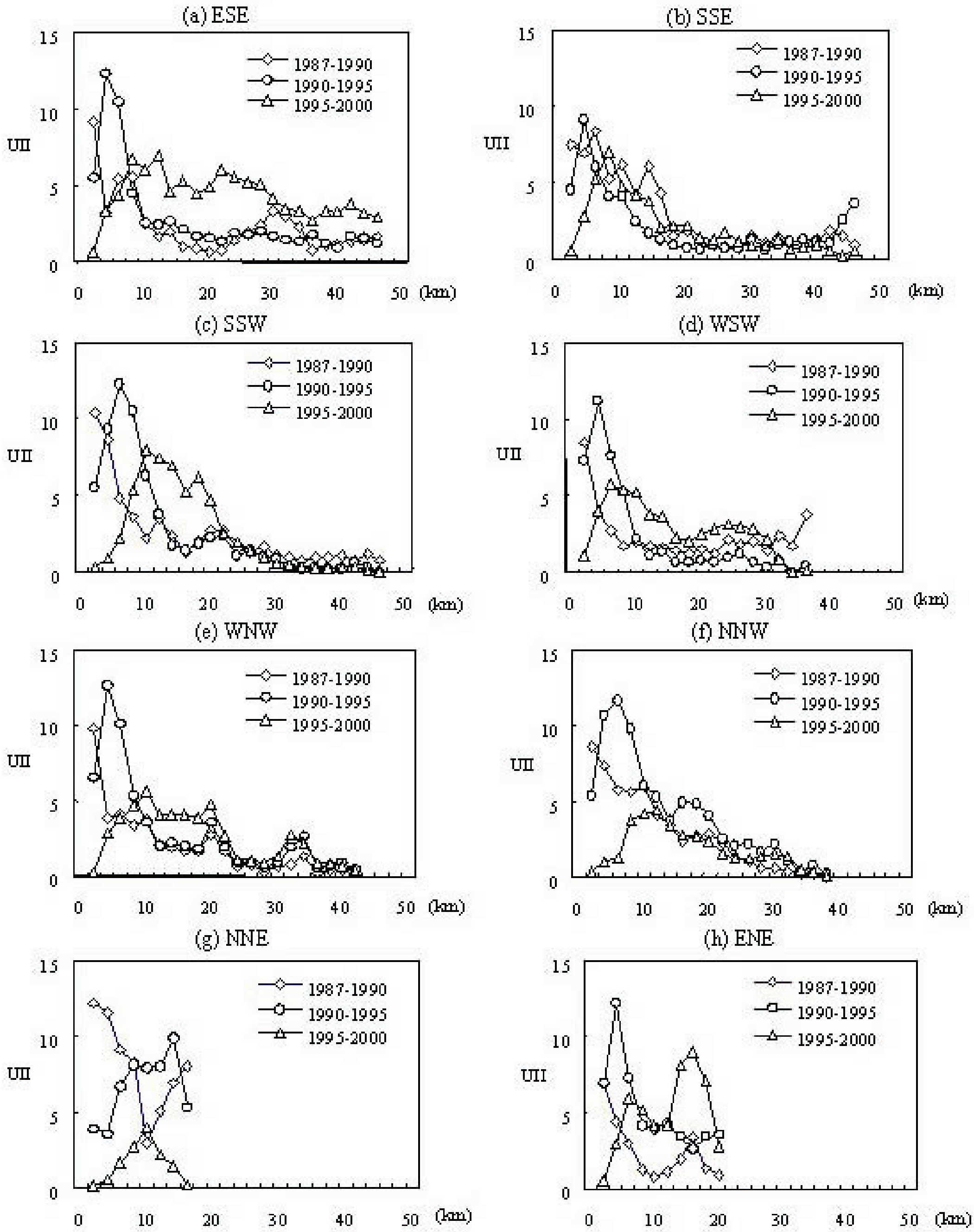

Fig. 6. Changes in the UII with distance to the urban center in different aeolotropic areas over the entire Shanghai region in

different time periods from 1987 to 2000. The aeolotropic areas are (a) ESE (east-southeast), (b) SSE (south-southeast), (c) SSW (south-southwest), (d) WSW (west-southwest), (e) WNW (west-northwest), (f) NNW (north-northwest), (g) NNE (north-northeast), and (h) ENE (east-northeast).

The differences in overall UII trends were as follows: the ESE (Chuansha and Nanhui), WNW (Jiading and Taicang), SSW (Minhang and Songjiang) and ENE (Pudong and Waigaoqiao) slices display several clear UII peaks with relatively wide wave crests at different distances. This demonstrates that several distinct expansion cores and associated concentrations of urbanization emerged at a local scale in each suburb during 1987-1990. These cores were surrounded by large non-urban areas and relatively isolated from the urbanization of Shanghai urban center. The ESE (Liuli, Yangsi, Chenhang, etc.) slice had a series of sharp peaks from 0 to 20 km, indicating it included several scattered, small-scale township expansion.

During the period 1990-1995, the UII curves had very similar trends to the overall UII change, with lower initial values than those of the previous period, rapid increases at the 6 km mark, a rapid tapering off to relatively low levels in the range 10-15 km, and a gradual decline thereafter. However, there were some differences in the directional changes in the UII, indicated by the extent of the decline as well as by the sizes and characteristics of peaks in each direction beyond 15 km from the urban center. These show the intensity and magnitude of urbanization in the suburbs involved a certain degree of directional variance. Moreover, the UII peak value and inflection point position for the SSE slice during this time period were obviously lower than those of the other slices, showing the intensity of urbanization was rather weak for both the central urban area and the suburbs in this direction. This can be explained by the fact that the SSE slice includes Shanghai's main agricultural areas with many rivers and canal networks, which acted as substantial physical barriers to the urbanization and infrastructural development.

For the period 1995-2000, although the UII curves remained similar to the overall trend, their peak values were lower, and the levels maintained after the peak values were higher, than those of the previous two time periods. However, the spatial aeolotropy of the UII was more prominent than that of the two previous periods. For example, the UII after each peak value remained higher for a relatively long distance in the ESE, ENE and SSW directional slices than was the case for the other directions. The ESE and ENE slices are precisely those containing the Pudong New Development Area, while the SSW slice includes Shanghai's southern axis of expansion. These results indicate how important the continued development of the Pudong Development Area and the region of south Shanghai were in contributing to heightened spatial aeolotropy in urbanization during this period. In comparison, the previously active northern axis of expansion in the NNW slice showed a dramatic reduction in UII. Increases in UII values for the other directions were also not apparent.

4.3. Spatiotemporal trends of UPI for downtown Shanghai and its main satellite cities

Figure 7 illustrates the UPI variation in Shanghai and its main suburbs as a function of distance from the urban center over the whole research period (1987-2000). The results show that downtown Shanghai had the dominant urban expansion compared with its major satellite cities, both in terms of magnitude and intensity. At the same time, downtown Shanghai's UPI curved downward gradually and maintained 60% of its maximum value 10 km from the margin of the old downtown area, indicating its urban expansion is still active in this area.

The UPI variations for the main satellite cities reveal that the decline in UPI is clearly much slower in Baoshan and Chuansha. With the exception of the innermost region, the UPI curves for these two satellite cities increase and level off significantly higher than do other satellite cities' UPI curves within most distance ranges. These two satellite cities also have relatively higher UPI levels within 5 km from the city center, demonstrating more robust expansion is maintained within this region, whereas within the same region, the UPIs of other satellite cities dramatically decline. This show that the degree of urbanization in Baoshan and Chuansha is markedly stronger than that of the other satellite cities over 1987~2000, and the expansion of these two satellite cities results in both the urban expansion axis in the northern parts of Shanghai and the development of the Pudong Development Area, respectively. In fact, these two satellite cities are closer to the central downtown area, their own "active" urbanization process and the "passive" urbanization process extending from downtown Shanghai interact in a distinct and mutually intensifying manner, markedly reinforcing these two suburbs' urbanization.

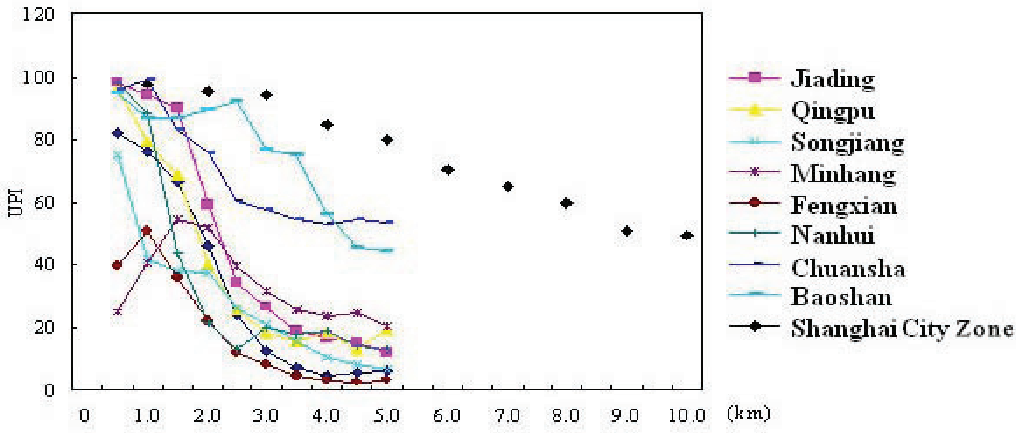

Fig. 7 Comparing trends of Urbanization Proportional Index (UPI) between downtown Shanghai and its major satellite cities with the distance to the urban centers over 1987~2000, the eight major satellite cities are Jiading, Qingpu, Songjiang, Minhang, Fengxian, Nanhui, Chuansha, and Baoshan.

In contrast, the UPI trends of other satellite cities are more uniform. The general features of these similar curves are relatively high values within the innermost areas followed by a rapid decline with distance, as well as a constant lower level at the 5 km mark. This indicates those satellite cities far from downtown Shanghai have not themselves distinct urban expansion zones and have a much smaller scale of urban expansion, for which higher UPI values were seen in Minhang (part of the expansion axis in the southern part of the city) and Jiading (part of the area adjacent to the Shanghai-Jiading Highway).

4.4.Spatiotemporal characteristics of UII for the major satellite cities

Figure 8 presents the trends in the UII with distance from each satellite city center. During each time period, each city's UII curve has a distinct association with the overall trend of downtown Shanghai, yet the strength of this association and the intensity variations for various time periods have clear individual differences. This shows that, on the one hand, the urbanization of these satellite cities cannot avoid being influenced and shaped by Shanghai's urbanization, yet on the other hand, they also have their own relatively independent expansion processes. The interaction between the "passive" and "active" aspects of urbanization results in the diversity and complexity of suburban or rural urbanization. Based on the spatial characteristics shown by the UII curves in Figure 8, urban expansion and characteristics of Shanghai's major satellite cities can be categorized as detailed in the following section.

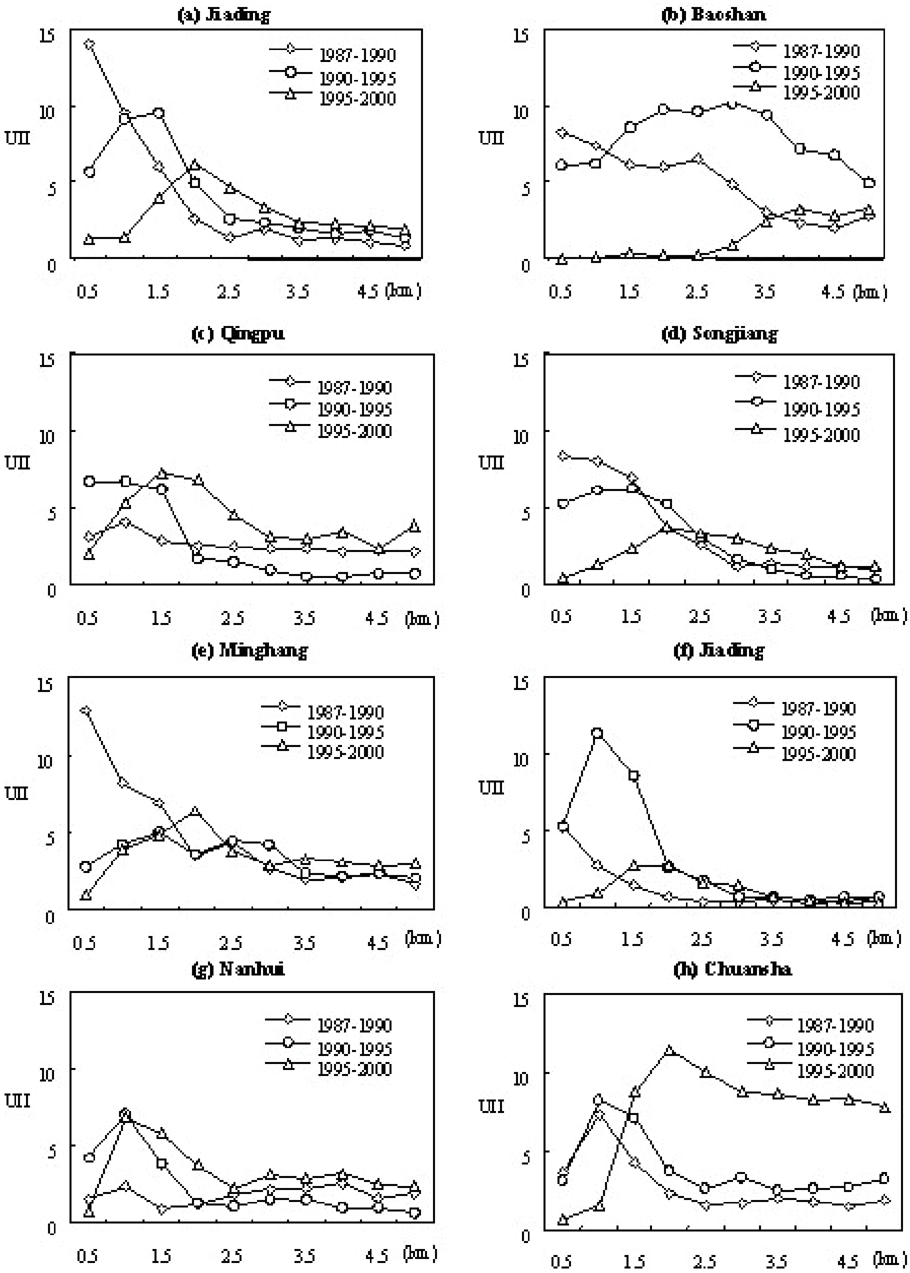

Fig. 8 Comparing the trends of the UII with distance to the urban center among the eight major satellite cities in the Shanghai region during different time periods from 1987 to 2000.

5. Conclusion and Discussion

5.1. Synoptic spatiotemporal characteristics of urban expansion in the Shanghai region

Our study has demonstrated that the overall spatiotemporal pattern of regional urbanization can be quantified using a combination of spatial metrics measuring the pace of urbanization and GIS-based buffer analysis. The results from our study can adequately address the research questions outlined in the introduction. Based on the results of the buffer zone analysis, Shanghai's urban expansion can be divided into the following three phases:.

Initial rapid urbanization phase (1987-1990): Outskirts of the city that are immediately adjacent to the urban center usually have the highest expansion intensities. There is a rapid and uniform decrease in intensity with increasing distance from the urban center in the urban-suburb transition zone. The urban expansion zone has formed but is still small, and the urban expansion intensity decreases as the expansion zone moves outward. During this period, the most active urbanization occurred at Baoshan and Minhang, which constituted the polar areas of North-to-South axis.

High speed urbanization phase (1990-1995): Due to large-scale urban expansion, the urbanization intensity increases as a whole, and there is a large increase in the active urban expansion zone. Because the inner urban expansion zone immediately surrounding the urban center has completely urbanized and partly transformed into a new urban center, the urban expansion zone rapidly moves outward, with a drastic increase in diameter and area. On both the inner and outer sides of the urban expansion zone, the urban expansion intensity decreases. However, the inner area's potential for further urbanization is almost exhausted and its urban expansion has continued to weaken until it essentially halts. In contrast, the potential of the outer area's urbanization increases with distance from the city center and urbanization is apparent. These areas become part of the active urban expansion zone as it moves outward. Spatial variations in urban expansion intensity are most distinct during this phase.

Extensive and diffusive urbanization phase (1995-2000): Urban expansion has already caused considerable growth of the urban area, as well as outward expansion of the urban-suburb transition zone. The extent of the urban expansion zone also continues to increase, and the peak values of UII are at points farther from the original urban center but with lower values. Because key large-scale construction projects within the urban-suburb transition zone have essentially been completed, urbanization has begun a transformation from being localized, high-intensity, and highly uniform to being region-wide, scattered, complementary, and less intensive. Therefore, UII peak values are lower than those in the previous phase, and the urban expansion zone is regionally extensive and diffusive, leading indistinct borders between the urban area and the suburbs, and the suburbs are already under the influence of the large-scale regional urbanization .

Urbanization within the urban-suburb transition zone has a rhythm of intensification and weakening as its specific spatial signature. The aforementioned spatiotemporal pattern for urbanization, while describing the various stages of urban development for one particular city (i.e. Shanghai), is applicable also as a model of similar urbanizations. The analysis scheme can be used to analyze and compare the differences in urban expansions of various cities.

5.2. Spatiotemporal aeolotropic characteristics in Shanghai urbanization

Based on the results of buffer zone analysis, the spatial aeolotropic characteristics of Shanghai's urban land-use expansion can be summarized as follows: Within 10 km of the urban center, the main feature of the spatial aeolotropy is the expansion of downtown Shanghai, which is mainly characterized by different rates of expansion along the north-to-south expansion axis during different time periods, as well as the development of the areas adjacent to the Shanghai-Jiading Highway and the Pudong New District to the west and east, respectively. Farther than 10 km from the urban center, the aeolotropy of urban expansion is instead due to the spatial distribution of satellite cities and their different expansion rates over various time periods. The areas of higher expansion intensities in the satellite cities mainly concentrated at two boundaries: one approximately 20 km from the urban center corresponding to the north-south expansion axis (used as the diameter), and the other approximately 30 km from the urban center corresponding to the urbanization of exurban towns. Pudong's large-scale development and construction is another major cause of the increase in spatial aeolotropy of urban expansion in the last decades.

Besides the physical differentiation caused by the land and the sea, no large-scale geomorphic variation exists in the Shanghai region, and geomorphic factors are not significant contributors in the spatial aeolotropy of the urban expansion. The intensity, direction, and pattern of urban expansion are mainly determined by the location (especially the distance from the urban center), and associated socioeconomic factors (land price, transportation convenience, urban planning policy, etc.). However, as physical constraints on urbanization, the layout of the river, canal system, and other small-scale topographical and geomorphic features have an influence on the small scale aeologropy of regional urbanization.

5.3. Spatiotemporal characteristics of urban expansion of the major satellite cities and their interactions with downtown Shanghai

The urbanization of Shanghai's major satellite cities is clearly influenced by their distance from the urban center. The major satellite cities are generally spread out in concentric circles surrounding central downtown Shanghai. The expansion of urban land-use under downtown Shanghai's influence (within 10-15 km from the urban center) is based on having the shortest distance to the urban center, and thereby leads to the urban expansion zone having a relatively high degree of spatial aggregation. This zone pushes outward continually as the urban center expands. In areas beyond the direct influence of downtown Shanghai, the expansion of the satellite cites is simultaneously influenced by the centripetal attraction of downtown Shanghai and the centrifugal attraction of surrounding towns (i.e. satellite cities), consequently reinforcing the trend of scattered urban land-use expansion in these areas.

Despite being strongly influenced and shaped by central downtown Shanghai, the expansions of urbanization in the major satellite cities still exhibit relatively marked individual differences, owing to the influence of their location-dependent conditions and historical socioeconomic factors. Based on their spatial signature reflected by the UII curves, they can be categorized into four modes of urbanization.

Autonomous expansion mode (standard mode): Jiading is the most typical example of this mode. Jiading's UII curve is similar to that of downtown Shanghai, revealing the urban center is continually growing (not evident in 1990; in 1995 the urban center radius is about 1-1.5 km; in 2000 the radius is about 2-2.5 km). Accompanying the expansion of the urban center, a continually outward-pushing urban expansion zone is formed. With increasing distance from the urban center, the UII rapidly decreases, and linearly decreases after a certain distance (3.5 km). Therefore this type of town also has its own urban-suburb transition zone, with similar urbanization expansion characteristics to those of downtown Shanghai, thus showing the relatively integrated structure and mature urban development configuration of this type of satellite city.

Passive expansion mode: The urban expansion is strongly influenced by the central city's or the whole region's urban expansion. This type of urban formation and expansion is mainly due to economic factors external to the area (such as industrial development zones) instead of internal factors such as population growth. Therefore, the pace of urban expansion often clearly exceeds the pace of population growth. Baoshan and Chuansha are most typical of this mode. During 1987-1990 and 1990-1995, Baoshan experienced rapid urban expansion. During 1990-1995, the whole buffer zone saw high-intensity, large-scale urban expansion, which was clearly linked with the large-scale construction activities of Baoshan Steel Company during this period. In fact, Baoshan's existence and development rely mainly on this enormous steel conglomerate. Initially, population growth and urban development were largely dependent on the development of the steel manufacturing industry. Baoshan's urban structure is relatively imperfect and its urban function is relatively unitary. Because of its closeness to downtown Shanghai, Baoshan's expansion interacts the most with the expansion of the Shanghai downtown area. As a result, Baoshan has no independent urban expansion zone.

Figure 8 indicates the most intensive period of Chuansha's urban expansion was 1995-2000, corresponding to the large-scale construction of the Wangqiao and Zhangjiang high-tech industrial zones in the same region and time period. Obviously, Chuansha's urban expansion was driven by the large-scale construction of the Pudong Development Zone instead of its own urban population growth or economic development during 1995-2000. Chuansha's urban expansion has no typical expansion zone (its UII curve sharply declines both sides of its peak values). The UII curve has a peak value at 2.0 km from the urban center and then slowly decreases before remaining high after the turning point. This reveals the momentum of urbanization due to the intensive and extensive expansion of development zones. It is evident that this kind of urban expansion, driven mainly by development zones, is not associated with the development of Chuansha itself and is more to do with the overall regional development of the Pudong New Development Area.

Steady expansion mode: This urban expansion is characterized by a relatively steady rhythm of intensity variations over all time periods, as well as UII curves having lower peak values for all periods and there being less fluctuation with distance from the urban center. Qingpu and Nanhui are most typical of this mode. These suburbs have historically functioned as Shanghai's most important bases of agriculture and aquaculture. Therefore, urban expansion, mainly due to internal factors such as population growth, relates to the expansion of residential land-use. A moderate increase in industrial land-use has mainly been due to the evolution of small-scale development zones and rural and township enterprises. Because there is no large-scale development zone, the intensity of urban expansion is relatively stable over all periods. There is also no distinct urban expansion zone for this type. However, since Nanhui is closer to Pudong, during 1990-1995 and 1995-2000 it was more influenced by the development of Pudong and had larger urban expansion intensity variations than did Qingpu. This is indicated by more notable peaks, increases, and decreases on the UII curve.

Irregular expansion mode: This mode includes three satellite cities, e.g. Minhang, Songjiang, and Fengxian. Even though these three suburbs have traditionally given priority to agriculture, as major components of the southern suburban cluster of Shanghai, their industrial development has also progressed quite rapidly, constituting a substantial proportion of urban expansion. However, this expansion of industrial land-use is mainly the result of rural and township enterprises, together with some medium and small-scale development zones, sometimes with a high-intensity expansion (e.g. Fengxian). As the distribution of development zones and other industrial land-use areas are more scattered, the distribution and trends of peak values of urban expansion intensities become more irregular.

5.4. Desakota pattern of Shanghai urbanization

Desakota is characterized by an intensive mixture of agriculture and non-agricultural activities and the ‘‘interlocking’’ of urban and rural settlements (McGee, 1991; Zhou, 1991; Lin, 2001). Desakota patterns are neither urban nor rural, but demonstrate features of both, indicating large-scale extensive metropolitan urban sprawl and rural urbanization (Ginsburg et al., 1991; McGee, 1991). Desakota dynamics show distinct spatial patterns, new growth of large and specialized urban districts dominant in the vicinity of large cities and incremental expansion of existing urban places in small cities and rural areas (Medley et al., 1995; McDonnell et al., 1997). In reality, desakota is a complex socioeconomic physical entity, which is characterized by high population densities, rapid growth of non-agricultural activities, labor mobility, occupational fluidity, and intensely mixed land uses. The physical characteristic is the outer appearance of internal economic, policy and social forces.

Physical evidence of the desakota pattern is very distinct and prominent in China, especially in those metropolitan areas experiencing rapid regional urbanization in the southeast coastal region. The desakota pattern has been explored, quantified and modeled in Shenzhen (located in the Peal River Delta, Guangdong Province) and Suzhou (locate in the Yangtze River Delta, Jiangsu Province) (Sui and Zeng, 2002; Xie et al., 2006). In addition, Guangzhou also shows desakota features with diffusion-coalescent urban sprawl with a multi-nucleated urban pattern (Yu and Ng, 2007). Some scholars argue that bottom-up forces (e.g. overall urban planning) and local interactions (township or rural level industrialization and urbanization) begin to play more and more important roles in forming this new urban pattern, and have resulted in the complexity of centrifugal and centripetal driving forces in shaping the desakota pattern (Seto and Fragkias, 2005). Thus, analyses of both top-down (constraining) and bottom-up (locally interacting) mechanisms are essential for characterizing the complex, dynamic, multidimensional configuration of urban patterns.

Our study demonstrated that the urbanization interactions between downtown Shanghai and its major satellite cities were generally much intensified following ongoing regional urbanization, and the active urbanization zone (i.e. urban-suburb/rural transitional zone) became much more intensive in UII and then extensive in sprawling area across the urbanizing zone, suburban and rural areas. This intensive and extensive urbanization has homogenized and mitigated variations in the urban/suburb/rural gradient and resulted in a desakota phenomenon through the Shanghai region. Based on our research, we assumed the desakota pattern of Shanghai has mainly been driven by the reinforced interactions between top-down large-scale urban expansion from the central city and bottom-up small-scale township or rural urbanization, and as a result, the distinction in landscape patterns between urban and rural areas has become blurred.

The desakota pattern of Shanghai was most prominent in 2000 after more than 10 years of rapid regional urbanization; however this urban sprawl seems to have been further developed in line with the prevailing urban planning policy of the Shanghai Government, which focused on transferring transition from the urban-rural separation to coordinated urban-rural development by removing the existing dual urban-rural socioeconomic structure, ensuring farmers shared in the benefits of urbanization by integrating urban and rural resources, and speeding up rural urbanization and suburbanization by extending infrastructure and public services from the central city to satellite towns and rural areas.

As an emerging urbanization pattern in China, understanding rural–urban nexus and its new landscape patterns is a key to understanding China's tremendous social and economic transformation (Tang and Chung, 2000). Somehow the patterns are representative of China's economic vitality and provide clues to its continuing social and political stability in the face of great economic upheavals (Lieberthal, 1995). However, the large-scale urban sprawl would bring about tremendous negative ecological consequence, and the pace of urbanization and the size of desakota regions must be controlled for there to be sustainable co-development between urban and rural areas. Therefore, how to coordinate and integrate urban and rural urbanizations with the least ecological and environment costs is a great challenge in urban and regional planning especially for metropolitan areas.

Our study demonstrates the overall spatiotemporal dynamics of urban expansion can be determined by examining variations in the urbanization gradient extending from the city center, through the suburbs, to the rural outskirts or urban fringes, and combining temporal data with GIS-buffer gradient analysis can server this purpose well. Comparing with transect based gradient analysis, buffer gradient analysis can give additional insights into regional urbanization dynamics by revealing urbanization dynamics of both the central city and associated satellite cities, and specifically addressing how urbanization interactions between the central and satellites cities shape overall urbanization patterns.

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