Applications of Remote Sensing and GIS to Monitoring of Urban Sprawl: A Case Study in *Wuxi* City, China

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Abstract
Built-up areas in *Wuxi* City, eastern China over the period of 1966-1998 were derived from a topographic map, a land use thematic map, and three multitemporal Landsat TM images using visual interpretation and automatic classification. The overlay of the five results revealed that the built-up area of the city expanded by more than tenfold from 11.6 to 136.1 km² during the 32-year period. The most drastic expansion occurred between 1977-1984 at a rate of 282.8%. Of the eight urban factors examined, total road length, urban population and per capita dwelling space are closely correlated with built-up area at a Pearson correlation coefficient of 0.95 or higher. Urban built-up area is most accurately modelled from per capita dwelling space, followed by total population and road length. If jointly modelled from the three variables, the modelling can be achieved at an accuracy of 99.84 percent.

I. INTRODUCTION

The Yangtze River Delta has traditionally been one of the most important industrial bases in China owing to its favourable natural, social, and cultural settings. Since the implementation of rural reform measures in the late 1970s, it has experienced phenomenal economic growth. Accompanied the economic development is rapid urbanisation. Urban planners require current and accurate information on urban land use and its change over time in order to properly manage urban sprawl, rationally layout urban infrastructure, and minimise the loss of valuable farmland in adjacent rural areas. Remote sensing has found wide applications in monitoring urban growth, its spatial patterns and temporal change for the Chinese cities of Beijing, Shanghai and Dongguan (Chen *et al*., 2000). As early as the 1980s, Jackson *et al*. (1980) studied the possibility of monitoring urban growth from Landsat imagery. Fahim *et al*. (1999) presented two cases of identifying urban expansion onto agricultural lands in the Nile River Delta in Egypt from SPOT images. In order to reduce the considerable over-estimation of land use change detected from multi-temporal images, Li and Yeh (1998) used principal component analysis of stacked multi-temporal images for the detection.

The detection of urban sprawl requires co-registration of multitemporal imagery, a task ideally achieved in a GIS that possesses a powerful analytical functionality. Bocco and Sanchez (1995) quantified changes in urban area that had been detected from remotely sensed images using GIS. De Brouwer *et al*. (1990) devised a method for the rapid assessment of urban growth using GIS. Yeh and Li (1997) integrated GIS and remote sensing for monitoring and evaluating urban land development in the Pearl River Delta. Pathan *et al*. (1993) analysed the trend of urban growth in the metropolitan region of Bombay from multi-date remote sensing data in Arc/Info.

In addition to identification and detection of urban areas, urban growth has also been simulated from various variables. Meaille and Wald (1990) simulated regional urban growth by combining GIS and satellite imagery with a numerical model. Yeh and Li (1998) developed a sustainable land development model using GIS for controlling urban sprawl in rapidly urbanising rural areas. Pathan *et al*. (1993) further attempted to relate the identified changes in urban areas to population and population density in different periods.

These studies focus on urban land use change over a limited number of time periods. Although the identified changes in urban extent were linked to other explanatory variables, they have not been explained from them. Thus, it remains unknown which socioeconomic factors are the most critical to urban sprawl and how to model its trend from these variables.

This paper attempts to identify the factors that can reliably predict and model urban sprawl in *Wuxi* City, *Jiangsu* province in the Yangtze River Delta. The specific objectives are: (1) to determine and analyze the spatial pattern of urban sprawl in the study area over the last 32 years; (2) to identify socioeconomic variables that are important to urban expansion; and (3) to model the expansion from the important explanatory variables.

II. STUDY AREA

The study area is *Wuxi* City situated in southeastern Jiangsu Province, about 128 km east of Shanghai (Figure 1). This area has been selected because its spatial extent has expanded drastically over the past few decades and because remote sensing data are available. The results obtained in this study can not only guide the proper planning of its expansion, but also be applicable to other urban areas of similar settings.

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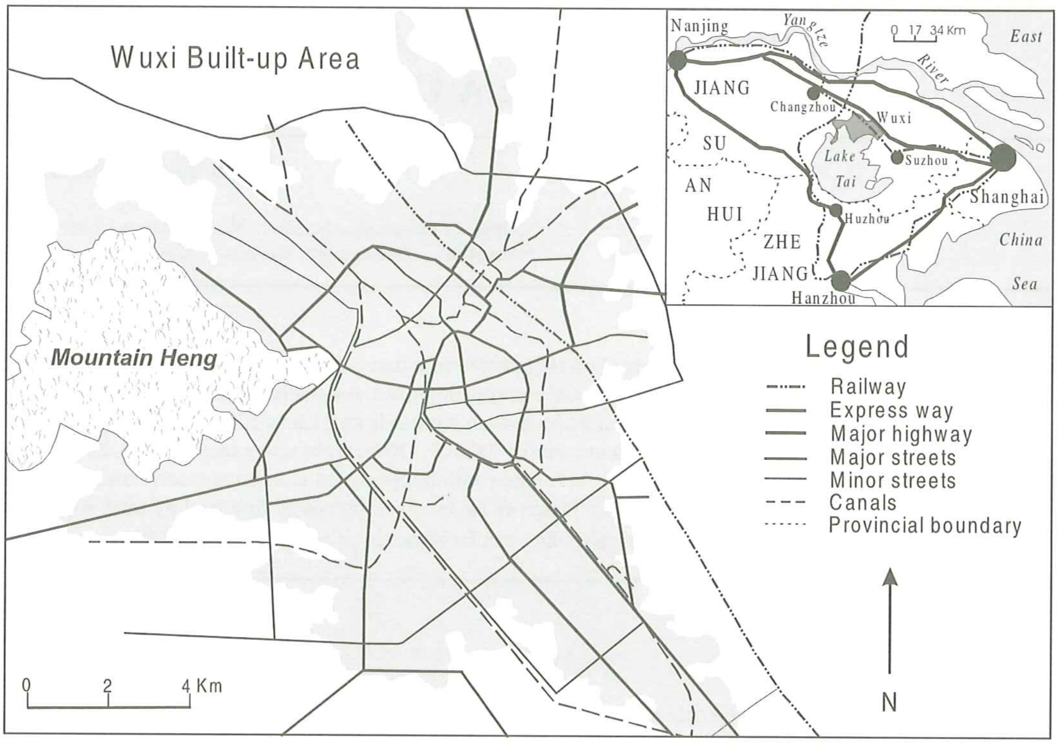

Figure 1. Extent of built-up area (1984) in Wuxi City and its location in the Yangtze River Delta.

Located in the lower reaches of the Yangtze River Delta, *Wuxi* City has a flat terrain that is only 1-5 m above sea level. Residual hills sporadically dot throughout the city bound. The topography is gently sloped from the west to the east. As a transport pivot, it is well served by rail and highway. The main land covers found in *Wuxi* are built-up areas, farmland, woodland, canals and lakes. Water features exemplified by the Grand Canal are abundant throughout the city. Formally founded over 50 years ago, *Wuxi* has become one of the most important industrial bases in the Yangtze River Delta. By 1998 the total territory under its jurisdiction (including rural areas) had grown to 517 km² with a total population of 1.1 million. The proper management of the land resource requires accurate and current information in order to avoid expensive mistakes in urban planning. It is very important to monitor the sprawl of *Wuxi* built-up areas so that limited land resources can be rationally allocated for balanced uses and investment in urban infrastructure can be minimised. The layout of different suburbans and urban subzones can be spatially organised.

III. RESEARCH METHOD

Two types of data were collected in this study, socioeconomic data and remotely sensed data. The former comes chiefly from Statistical Yearbook of *Wuxi* (Anon, 1999). The latter includes satellite imagery and thematic maps. In total, three TM scenes were collected (August 4 of 1984, November 19 of 1991 and August 11 of 1998). A 1970 topographic and a 1984 thematic maps were acquired as well. The topographic map has a scale of 1:100,000 with the Gauss-Kroger projection. It was generated from aerial photographs taken in 1966. It shows general land covers, including urban areas and transportation features. Published in 1984 at 1:50,000, the thematic map of land use distribution shows the extent of built-up areas in 1977. No maps published before 1970 were collected because the urban built-up area did not undergo noticeable outward expansion prior to then.

All data processing were carried out in ER Mapper® 6.0, MapInfo® (version 4.0) and Geomedia® (3.0). The maps were input into the computer via scanning. In ER-Mapper® the TM images and maps were geometrically rectified using ground control obtained from the 1970 topographic map. After geometric rectification, the 1970 map was automatically classified. Since the urban area was marked with dark ink, its separation from other covers was relatively easy to achieve. The urban area in 1977 was delineated from the land use thematic map manually on screen. Urban built-up area was also automatically extracted from the multi-temporal TM images of bands 4 and 5 using Normalised Difference Vegetation Index (NDVI), namely,

$$NDVI = (Band\ 5 - Band\ 4) / (Band\ 5 + Band\ 4) \quad (1)$$

This index allows urban area to be separated from other covers present within the study area (e.g., farmland, forest, and water). The accuracy of separation was enhanced through two steps of processing: binary encoding and median filtering with a window of 11 by 11 pixels. This window size was adopted because the resultant boundaries matched the actual outline of the city quite closely. The binary-encoded image of 0 and 1 was subsequently rank-filtered. All the mapped results in the raster format were vectorized in MapInfo® before they were exported to Geomedia® for overlay analysis. This analysis revealed the expanded areas in different times. The derived area figures were exported to MS Excel for correlation analysis and regressional analysis.

IV. RESULTS

Spatial extent and shape of *Wuxi*

In total, five sets of results separated at a rough interval of seven years were obtained (Figure 2). The urban built-up of *Wuxi* was only 11.6 km² in size in 1966. Thirty-two years later this figure increased to 136.1 km², or by more than tenfold. In addition to size, urban sprawl has also drastically altered the city's shape. In 1966 it was elongated with the longer axis oriented southeast-northwest at a length of 8.4 km. The shorter axis perpendicular to it was only 4.3 km long, or about half of the longer one. This shape was formed by urban growth along the Grand Canal initially, and the railway and the highway later. From 1966 to 1977 the urban area expanded outward only negligibly. Nearly all the expansion took place around the 1966 perimeter. So the overall shape of the urban area did not change noticeably. During the next seven years, the city experienced drastic expansion by a rate of 282.8% thanks to economic boom. Due to the lack of planning, the expansion occurred in all directions, had radically modified the city's shape. The diameter in the southeast-norhtwest grew to 14 km, and to 10 km in the northeast-southwest direction, making the urban area star-shaped. From 1984 to 1991 the spatial expansion of built-up area was restricted to the east, northwest and southwest directions. In the southwest a scenic area was developed while an industrial area was established in the northwest. By comparison, little expansion occurred in the southeast direction because one of the suburbs was upgraded to the city status and became excluded from the city limit. Between 1991-1998, the urban area experienced another wave of massive expansion at a rate of 56.98%, the second highest. The outward expansion occurred in directions opposite to the previous ones. For instance, in the southeast a high-tech industrial park was developed. Due to these changes, the shape of the city was more circular with an approximate radius of about 15 – 18 km.

Significant variables

The dynamic nature of urban sprawl is explored through the correlation relationship between expanded area and relevant socioeconomic factors. Eight urban parameters collected from the Statistical Yearbook of *Wuxi* (Anon, 1999) were correlated with the detected urban built-up areas. Five variables (total urban population, total road length, total floor areas of building construction, total floor areas of residential buildings, per capita dwelling space, and population density of urban areas) have a Pearson correlation coefficient of over 0.94 (Table 1). These variables are thus considered significant to prediction of urban sprawl. By comparison, investment in urban infrastructure and housing investment are less closely correlated with the detected urban areas at a coefficient of

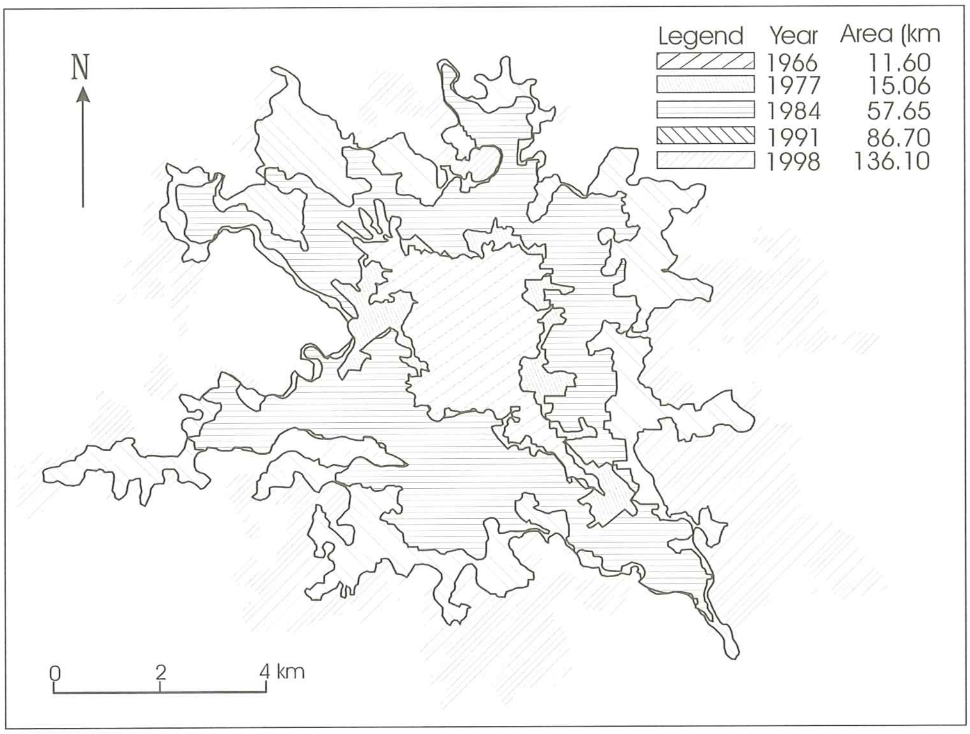

Figure 2. Detected expansion in built-up areas and their distribution (the area figure includes those areas encompassed by the shaded boundary).

Table 1. Pearson correlation coefficient between detected urban areas and socioeconomic variables.

Variable	Per-capita dwelling space	Residential building area	Building construction area	Population	Road length	Population density	Housing investment	Infrastructure investment
Coefficient	0.9981	0.9966	0.9911	0.9892	0.9698	0.9403	0.7406	0.7406

around 74%. Hence, they will not be the focus of this study any more.

Regressional relationship

The detected urban areas were regressed linearly against the above variables that have an R^2 value of 0.95 or above with urban build-up area. Although there are five of them, some of them are not totally independent of one another. For instance, per capita dwelling space is derivable from total floor areas of residential buildings and total population. Total floor areas of building construction is closely correlated with per capita dwelling space. Therefore, only three variables are regarded essentially critical to urban sprawl: total population (x1), total road length (x2) and per capita dwelling space (x3). They were regressed against the detected urban built-up area. If regressed individually, both total population and road length can predict urban built-up area at an accuracy of 94.3% or higher. However, per capita dwelling space allows urban area to be most accurately modelled at an R^2 value of 99.62% (Table 2). Caution must be exercised in interpreting this close relationship. At the early stage of urban development, the spatial expansion is driven by the need to build more residential buildings to upgrade the living conditions of existing population, as well as to provide accommodation for the influx of migrant population. Once the per capita dwelling space reaches certain equilibrium, the relationship may disappear altogether. Instead, population and total road length are more reliable predictors of urban sprawl. In this case, they can predict the urban built-up area at an accuracy of 99.19%. If modelled from all three variables jointly, the accuracy increases slightly to 99.84%. The specific model is presented in equation (2).

$$\text{Area} = -91.309 - 0.47501 * x1 - 0.05986 * x2 + 35.236 * x3 \quad (R^2=99.84\%) \qquad (2)$$

V. CONCLUSIONS

The urban built-up area of *Wuxi* City increased by more than tenfold between 1966 and 1998. The fastest growing period was 1977-1984 when the built-up area increased its spatial extent by a rate of 282.8%. The spatial expansion did not take place equally in all directions. The outward sprawl in the southwest-northeast direction outpaced that in other directions. This pattern of growth has drastically altered the shape of the city that has evolved from elongated to star-shaped. Of the eight socioeconomic variables examined, six have a Pearson correlation coefficient of 0.90 or higher with urban built-up area. Among these variables, three independent ones (per capita dwelling space, total urban population and road length) are critical to prediction of urban sprawl. If built-up area is modelled from the variables individually, per capita dwelling space is the most reliable factor, followed by total population and road length. If jointly modelled from all three variables, the accuracy of modelling can be as high as 99.84 percent.

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Table 2. Regressional relationship between expanded urban areas and important parameters.

Independent variable(s)	Interception	Slope	R^2 (%)
Population	-131.903	2.3721	97.86
Road length	12.8275	0.1622	94.3
Per capita dwelling space	-73.8207	22.7605	99.62
Population	-85.564	1.5915	99.19
Road length		0.0577	
Population		-0.475	
Road length	-91.309	-0.0599	99.84
Per capita dwelling space		35.236	

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