Modelling Land Use Changes at the Peri-Urban Areas Using Geographic Information Systems and Cellular Automata Model

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Abstract

In many cities, urban area expansion encroaches into agriculture area especially at the peri-urban region. While it helps to minimize commuting duration and distance between and in and out of cities, peri-urban area, however, experiences land loss due to housing needs, economic transformation from agricultural activities, environmental degradation, and decline of agricultural land without any replacement by alternative economic activity. Land use changes at peri-urban areas is a complex and dynamic process which involves both natural and human systems. In monitoring and evaluating these dynamic changes, GIS can effectively be used to detect trends of urban expansion and predict future growth pattern. This paper discusses the study undertaken in Seberang Perai region of Penang State which experience significant land use transformation since the 1970s. GIS was integrated with Markov Cellular Automata Model to evaluate land use changes and forecast land use pattern until the year 2020. It was found that significant changes have occurred since 1990s and the same urban growth pattern will continue. Major concentration of urban development will grow towards the southern districts. The constraint used, namely valuable paddy fields, manage to control urban development in the northern district. The findings provide invaluable information for planners and decision makers in managing and planning urban growth.

Keywords: Geographic Information System, Land Use Changes, Penang State, Peri-urban area, Penang State, Malaysia

1. Introduction

Statistics have shown that urbanization is a major concern of many world regions. For example, at present more than half of the world population is living in urban environment. It is estimated that urban population will double by 2050, where urban population will grow from 3.3 billion in 2007 to 6.4 billion in 2050 (United Nations, 2008). Ironically these new urban dwellers will concentrate in cities of developing nations (Ginkel, 2010).

Many cities in the developing nations have shifted from a mainly agriculture-based economy to one of industrialization in order to foster economic growth (McGee, 1971; Drakakis-Smith, 2000). Although this industrialization policy has succeeded in creating more jobs in non-agriculture sector, the investment has resulted in the proliferation of western technology, capital and values particularly into the largest towns (Herbert &

Thomas, 1990). This phenomenon has resulted in high population concentrations around a single city centre, causing economic imbalances among cities in the developing nations (Peterson et al., 1999). Table 1 below shows the size and projection of population growth in the developing nations between 1975 and 2025.

Malaysia experiences moderate population growth as compared to nations such as Brazil or Mexico. In 1975, Malaysian urban population constituted 37.6% of its total population of 12.3 million. By 2000, Malaysia population reached 22.3 million with more than 57% urban population. Furthermore, by 2020 the population is forecasted to reach 40.6 million, with 70% of them urban population (Department of Statistics, 1996; Department of Statistics, 2000; Ghani, 2000). Significant increase of urban population will result, over time, in transformation of the physical appearance of many cities in Malaysia (Petterson et al., 1999; Ghazali, 1999). Urban population tends to concentrate in major towns, creating for example, mega-urban region of Kuala Lumpur-Klang which accommodate more than 6 million people. Although mega-cities have become centre of economic and administrative activities, more attention should be allocated to the smaller cities (Hadi et al., 2009; Ginkel, 2010) since urban population will likely grow in smaller cities at the peri-urban areas. This is probably due to the improvement of infrastructure (road networks) which minimizes commuting duration and distance between and in-and-out of cities. Furthermore, the number of factories and residential areas developed at the urban fringe is growing. Therefore, more people will choose to live at the peri-urban area and yet work in the city (Simon et al., 2004).

Peri-urban area refers to a transition or interaction zone surrounding built-up area that is made up of built-up extension of the city, approximately 30-50 km beyond urban edge and its landscape features are subject to rapid transformation (Simon et al., 2004; McGee, 2009). Peri-urban area usually experiences intense urban development where agriculture, small-scale industry, industrial estates and suburban residential developments co-exist side by side (McGee, 2011). This area, therefore, has access to essential and complimentary linkages between urban and rural areas since income sources for the livelihood of its community come from the combination of agriculture and non-agriculture sectors (Tacoli, 1998; Koombe, 2005).

Land use changes at the peri-urban area is a complex and dynamic process that involves both natural and human systems (Xiao et al., 2006; Koomen & Stillwell, 2007). GIS can effectively be used to monitor and evaluate the dynamics changes of land use transformation (Batty et al., 1997; Harris & Batty, 2001). GIS can be integrated with dynamic simulation model such as Cellular Automata (CA) approach in order to capture and analyze spatial and temporal dynamics of urban spatial growth. At present, many studies have incorporated GIS and CA Model to simulate urban spatial growth in many parts of the world. Batty and Xie (1994), Batty et al. (1997), White and Engelen (2000) are among the pioneers to use integrated CA framework and GIS capability in modeling urban systems of European cities. In the United States, for example, Clarke et al. (1997) and Clarke and Gadyos (1998) used GIS and CA Model to simulate historical urban growth of San Francisco and Baltimore areas. The study by Wu and Webster (1998), Yeh and Xi (2001) were among the early studies of urban growth in Chinese cities. In other developing nations, however, not many studies have been undertaken to monitor and simulate urban spatial growth. The study by Samat (2002) employed GIS and CA Model to simulate urban spatial growth in the Seberang Perai region of Penang State, Malaysia intended to predict urban growth based on various planning scenarios. The study, however, linked physical accessibility of the site with other infrastructures as the main driver of land use transformation. Furthermore, it only predicted the spatial pattern of non built-up areas and built-up areas. Modeling multiple land use activities namely residential, commercial and public facilities, industrial and others activities proved to be more complicated and challenging.

The study by Sui and Zeng (2001), Xiao et al. (2006) and Long et al. (2011) also monitor land use changes, identify driving forces and map areas experiencing intense land use transformation. Based on driving forces of land use transformation, a dynamic simulation model was used to predict future land use activities (Harris & Batty, 2001; Klosterman, 2001; Samat, 2009). These studies then were used to effectively formulate various planning strategies to guide urban growth and development (Koomen & Stillwell, 2007). Although many studies have demonstrated the application of GIS and CA Model in modeling urban systems, the model was developed using complex mathematical formulation and required expertise in computing skills. This, therefore, limits the application of this model among planners and urban managers (Samat, 2002). The proposed study used CA-Markov Model readily available in IDRISI Software (Eastman, 2001) to model the spatial growth of multiple land use activities in the Seberang Perai region, Penang State, Malaysia.

2. Methodology

The study uses GIS to map the distribution of land use activities, monitor land use changes and predict future pattern of urban growth. Land use data of 1990, 2001 and 2007 data were obtained from Northern Zone Project

Office of Town and Country Planning Department and Town and Penang State Country Planning Department. Land value data was acquired from Asset and Evaluation Department (1990) while topographic information derived from topographic maps produced by Department of Survey and Mapping (1987).

In order to predict spatial pattern of urban growth, a GIS-based Cellular Automata Model was used. CA is one of the modeling approaches that has gained significant interest since it is claimed to be capable of generating complex systems based on a series of simple rules (Couclelis, 1985; Batty, 1997). This approach was originally developed by Ulam in the 1940s and became well known after Von Neumann used it to investigate the logical nature of self-reproducible systems (Batty & Xie, 1994). CA Model is an example of a model that requires simple rules but is potentially capable of generating very complex behaviour when the same rule is repeatedly applied at each iteration (Couclelis, 1985; Batty, 2010). The basic elements of a CA Model comprises of a series of cells, a set of local states, a neighbourhood and a transition rule (Couclelis, 1985).

The study area is divided into cells of 90m resolutions, the resolution that was previously proven to produce the best accuracy prediction and preserve the morphology of urban areas (Samat, 2006). Each cell has five different states representing land use activities in the study area. It is given by:

$$ {}^{t}LU_{i.j} = \begin{cases} 1 = \text{Residential} \\ 2 = \text{Commercial and public facilities} \\ 3 = \text{Industrial} \\ 4 = \text{Agricultural} \\ 5 = \text{Others} \end{cases} \tag{1} $$

A neighbourhood represents the cells immediately adjacent to a certain cell. Usually 3 x 3 cells or Extended Moore Neighborhood (5 x 5 cells) are used to capture the local interaction among cells (Couclelis, 1985; Batty, 1997). Transition rules determine the change of a cell’s state during a subsequent iteration. These can be deterministic or stochastic (Batty, 1997). In this study, CA-Markov currently available as an IDRISI module was used (Eastman, 2001).

These five land use categories represent main land use activities in the study area. The evolution of cells from time t to $t+1$ is determined by a function of its state, its neighborhood space and a set of transition rule. It is given by equation 2 below.

$$ {}^{t+1}LU_{i,j} = f(({}^{t}LU_{i,j}) \cdot ({}^{t}S_{i,j}) \cdot ({}^{t}P_{x,y,i,j}).({}^{t}N_{i,j})) \tag{2} $$

where

${}^{t+1}LU_{i,j}$ = the potential of cell i,j to change at time $t+1$,

${}^{t}LU_{i,j}$: = states of cell i,j at time t,

${}^{t}S_{i,j}$: = suitability indexes of cell i,j at time t,

${}^{t}P_{x,y,i,j}$: = probability of cell i,j to change from state x to state y at time t, and;

${}^{t}N_{i,j}$: = neighborhood index of cell i,j.

The transition rule is formulated based on suitability indexes, transition probabilities and neighborhood indexes. The Multi-Criteria Evaluation (MCE) suitability index maps were generated based on weighted linear combination approach shown in equation 3 below. This approach is simple and can easily be implemented using Weighted Linear Combination Approach in IDRISI GIS software (Eastman, 2001).

$$ {}^{t}S_{i,j} = \sum_{m=1}^{M} {}^{t}x_{i,j} \cdot w_m \cdot c_m \tag{3} $$

where

${}^{t}S_{i,j}$: = suitability indexes for cell i,j at time t ,

${}^{t}x_{i,j}$: = score of criteria m at cell i,j at time t,

w_m = weight for criterion m, and;

c_{m}. = Boolean value for constraints.

The score for each criterion is standardized using fuzzy approach since it allows determination of varying degrees of set membership. In this study, we used two types of criteria, *factors* and *constraints*, where a factor signifies a continuous degree of fuzzy membership (in the range of 0±255), and constraints to limit the alternatives altogether (i.e. fuzzy membership is either 0 or 1) (Jiang and Eastman, 2000). In addition to suitability index, transition rule is calculated on the basis of transition potential of each cell. This study involves two different periods, as given below.

$$^{t}P_{x,y,i,j} = P\{X_t = a_y \mid X_{t-1} = a_x\} \tag{4}$$

$^{t}P_{x,y,i,j}$ represents the probability of cell *i,j* to change from activity a_x to activity a_y

$$^{t}N_{i,j} = \sum {}^{t}N_{i,j} / 24 \tag{5}$$

Finally, the transition rule is calculated on the basis of number of developed neighbors as given below.
The value for $^{t}N_{i,j}$ is calculated on the basis of Extended Moore Neighborhood or 5 x 5 cells. This size of neighborhood is used since it allows the influence of surrounding cells on central cell to be taken into consideration. This uniform transition rules are repeatedly applied in order to simulate land use changes from 1981 to 1998. This period is chosen mainly due to data availability. Although present land use data is available, they possess compatibility conflict. The model is then applied onto the Seberang Perai region. Schematic diagram of the proposed model is shown in Figure 1 below. The study evaluated land use change between 1981 and 1991.

In order to develop the suitability index map, factors influencing urban spatial growth were determined. These factors were analyzed using MCE. These maps and also transition potential maps were combined in CA-Markov Model. Assessment was conducted to evaluate the accuracy of the model. Finally, the model was used to make future prediction.

3. Study Area and Data

Seberang Perai, which is a part of Penang State was chosen as the study area. This area is located in the northwest of Peninsular Malaysia, centered at 5° 20′ N and 100° 25′ E with an area approximately 738.4km^2. Figure 2 shows the location of the study area. Seberang Perai is relatively flat with only 5% of its area has the elevation of more than 50 feet. There are two reasons for selecting Seberang Perai. First, this area is particularly important for the development of Peninsular Malaysia, since it is one of a few cases where rapid urban development of a small town has occurred, primarily as a result of industrialisation (Goh, 1991). Furthermore, various infrastructures have been developed here in order to cater for spill over demand from Penang Island. This area is linked with the other states via North-South and Butterworth-Kulim Expressways. This area is located within the Northern Corridor Economic Region (NCER) which aims to become a world-class economic region by the year 2025. As such, this area stands out as a potential local centre for population growth and economic development for the northern region of Peninsular Malaysia. Future population projections and related planning policies suggest that this area will undergo significant urban development. For example, Seberang Perai is expected to experience a 60% population increase by 2010, from a 1991 figure of 545,688 (Department of Statistics, 1991). Such increment is expected to take up a further 16% (≈120km^2) of the land area of Seberang Perai (SPMC, 1998).

Seberang Perai is undergoing rapid urbanization resulting from the spill-over demand from Penang Island for residential areas and other developments. This area will also experience a significant increase in population where it is estimated that by the year 2015 and 2020, more than 990,000 and 1.1 million people will populate this region respectively (SPMC, 1998; JPBD, 2007). Such an increase will indeed require a significant amount of land to accommodate the need for housing areas and other facilities. For example, between 2000-2005 and 2006-2010 additional 35,877 and 30,033 housing units were required respectively and it was projected that between 2011 and 2015 another 32,930 units are necessary to meet the population growth demand (JPBD, 2007). Although the demand for housing area is known, the locations of these housing units have yet to be determined. Unplanned residential development can cause traffic congestion, inefficient use of space and insufficient public utilities to cater for the growing numbers of dwellers (Simon et al., 2004; McGee, 2011).

Another reason for selecting the Seberang Perai is due to data availability. Data availability is an important issue in monitoring land use changes since data input and database creation is time consuming and costly (Klosterman, 1995; Samat, 2006). In Malaysia, like many developing nations, a limited number of useful spatial modelling data sets exist in digital format (Yaakup & Healey, 1994; Samat, 2009). Datasets used for this project were acquired over a prolonged period for Seberang Perai. These include digital datasets of roads (at 1:50,000), sub-districts (at 1:75,000), slope (at 1:50,000), and land use (at 1:75,000) of 1990, 2001 and 2007 obtained from Northern Zone Project Office of Town and Country Planning Department, and Penang State Town and Country Planning. Other data such as road network and public facilities were digitized from topographic maps (Department of Survey and Mapping, 1986).

4. Urban Expansion in Seberang Perai region and Factors Influencing Urban Development

In identifying factors influencing urban spatial growth, the study calculated the 1990-2007 Annual Urban Intensity Index (AUII) for Seberang Perai. Grid of 1km x 1km was used to identify areas experiencing high speed urban expansion. Figure 3 below shows the speed of urban expansion between 1990 and 2001, and 2001-2007 respectively. From Figure 3, high speed expansion is detected in South Seberang Perai where some cells experience more than 70% intensity index between 1990 and 2001. Only a few cells in Central District experience a similar speed of urban development. Majority of the cells in the north experience slow speed growth. On the other hand, from 2001 to 2007, many cells in North Seberang Perai experience high speed urban growth. This was due to the development of residential areas and education hub in Kepala Batas-Bertam area. Urban growth did occur at the rest of the regions, but at a slower rate. Based on the trend of urban growth, it was found that infrastructure such as roads and public facilities played significant role in attracting urban development. This is partly due to the government-driven infrastructure establishment that promotes and directs urban growth towards specific regions. In this study, post 1990s period saw investment on transportation network such as North-South Expressway and Butterworth-Kulim Expressway increased the accessibility between this region and other parts of Peninsular Malaysia.

Between 1990 and 2007, significant increase of built-up areas was detected in Seberang Perai. In 1990, built-up area stood at 30,452.4 acres, eleven years later it reached 39,247.5 acres and finally 51,333.8 acres in 2007 (see Table 2). The expansion was probably due to the development of education institutions especially in the northern district. In addition, a new pattern of urban growth can be detected in this area, such as the development of Bertam township which houses many education institutions and residential areas.

Based on the trend of urban expansion in Seberang Perai region, this study categorizes urban growth influencing factors into three: physical, socio-economic and environmental. Five physical factors describing spatial relationship between sites and others facilities located within the study areas were identified. Socio-economic factor was limited to the availability of land value data which was interpolated from Property Evaluation Report (Valuation and Property Service Department, 1999). Finally, environmental factors considered in this model were flood-prone areas and valuable paddy field areas, which were utilized as constraints towards urban development.

Weights were determined based on the interviews conducted, involving five local planners who were directly involved in land use planning in the study area (Samat, 2009). Different sets of weight were derived for different land use activities namely residential, commercial and public facilities, and industry. Table 3 below shows the weights used for the three respective major land use activities. The weights were held constant throughout the simulation, changes in weights might produce significant influence on urban spatial growth (Samat, 2006). These weights were used to generate suitability index maps as shown in Figure 4, showing that potential sites for urban development were clustered around existing urban development corridors. 1981 land use data was used as initial state of the model. The output produced was validated using actual data of 1991 and 2000. Then, the model was used to simulate urban spatial growth until 2020.

5. Results and Discussion

As shown in Figure 2, built-up areas occur around existing urban areas of Butterworth and Bukit Mertajam and these areas tend to grow linearly along major road network. Urban development seems to move towards the south of Seberang Perai. The restriction imposed on developing paddy field areas manage to curb urban development at the fringe of urban areas (Samat, 2002). It should be noted that a significant portion of areas in the northern district were classified as urban areas in 2000 mainly due to misclassification of paddy field areas during harvesting season as built-up area. Therefore, the data obtained from satellite images is only used to study the trend of urban growth. Based on the pattern of urban growth, it can be classified as compact type of growth and linear urban growth. This study however, only simulated urban growth pattern using a compact type of growth.

In terms of urban growth speed, Figure 3 shows that the southern district experienced high speed of urban expansion between 1991 and 2000, where some of the cells experienced more than 70% annual urban intensity index. In comparison, only a few cells in central district experience the same speed. Majority of the cells in the north experienced slow urban growth speed. On the other hand, between 2001 and 2007, many cells in the north experienced high speed of urban growth. This was due to the development of residential areas and a few higher learning institutions such as Universiti Sains Malaysia's Advance Dental and Medical Institute, secondary schools and Industrial Training Institute in Bertam. Other areas experienced slow pace of urban growth.

With 1981 land use data used as the initial stage of the CA-Markov Model, uniform rule was applied repeatedly to simulate pattern of urban growth for 1991 and 2000, and predict urban spatial pattern for 2010 and 2020. The model was validated using 1991 and 2000 land use data. The accuracy of the model is shown in Table 4 below. Kappa Index calculated for prediction of 1991 and 2000 was satisfactory. The result shows that prediction accuracy of 1991 land use data exceeded 80%. Unfortunately, the 2000 prediction accuracy for commercial and public, and industrial categories was poor. As shown by previous study conducted by Samat (2002) in the same area, prediction accuracy of the model decreases when the model tried to predict for a longer period of time. It should be noted that since the uniform transition rule was used throughout the simulation period, the dynamic changes of infrastructures and policy were not incorporated into the model. Improvement in road networks, newly developed areas and population growth provided significant influence on growth of the surrounding regions. This should be dynamically included in the model during simulation period.

Although the model accuracy was slight lower for 2007 (81%), it was used to predict spatial pattern of land use activities for 2010 and 2020. Figure 5 shows spatial pattern of land use distribution prediction. The model was used to predict compact type of growth scenario. The model also can be parameterized to predict sprawl type of growth, where in this case, the constraint used to control urban development from encroaching into agricultural land should be omitted. In addition, other growth scenarios could be tested by assigning more weight value on factors influencing urban development.

Despite the regulation to impede urban growth from encroaching into valuable paddy field areas, it continues to occur at the urban fringe. As a result, the boundary between urban and rural areas becomes less distinctive. Such is a common phenomenon in Malaysia since improvement in infrastructure causes more people to opt to live at the fringe and commute daily to urban centre to work (Simon et al., 2004; McGee, 2009).

6. Limitation of the Study

The study attempted to simulate urban spatial pattern using CA-Markov model of IDRISI GIS software. The framework of the model relies heavily on the capability of the software used; however, the output generated becomes useful for planners and decision makers with limited computing skills, in anticipating the resulted spatial pattern of urban growth.

The model was designed to capture compact type of urban growth since Malaysian National Urbanization Policy intends to ensure this type of urban growth pattern (Town and Country Planning Department, 2010). Uniform rule was applied to capture land use transition throughout the study area. The model, therefore, was unable to capture linear and leap-frog types of growth which were quite common in the peri-urban areas. This limitation is probably related to the capability of the CA model framework where users are unable to stop the iteration and insert changes in the model.

7. Conclusions

The study demonstrates the application of GIS in mapping the distribution of urban expansion, the speed of urban growth and the future spatial pattern of urban expansion. The approaches used in this study was simple and can easily be implement to foresee the future spatial pattern of urban growth using different policy approach. Although this study only demonstrates the prediction if urban spatial pattern using one planning scenario (compact type of growth), this model can be implemented to predict urban spatial pattern using urban sprawl scenario.

Various strategies have been devised to control and direct urban growth towards specific locations. However, in spite of plan reviews urban development still encroach into valuable agricultural land. It is timely, therefore, to think about limiting urban growth using urban growth boundary, for example, to control and quantify urban growth in a sustainable manner. Such a boundary will be useful for planning and land allocation in order to satisfy demands of the future generation and at the same time safeguarding the environment.

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Table 1. Urbanization trends, size and growth of urban areas 1975–2025 of selected developing nations

Country	1975		2000		2025	
	Total in thousands (000)	% urban Dwellers	Total in thousands (000)	% urban dwellers	Total in thousands (000)	% urban dwellers
Argentina	21029	80.73	32762	89.94	43083	93.39
Brazil	66065	61.65	141979	81.21	204791	88.94
Indonesia	26259	19.36	85819	40.34	167393	60.74
Malaysia	4616	37.65	12820	57.49	22942	72.65
Mexico	36948	62.76	79580	77.71	117222	85.82
Philippines	15294	35.56	44005	59.01	77622	74.26
South Africa	12314	47.97	24550	53.12	48673	68.60
Thailand	6244	15.10	13555	21.90	28756	60.74

Source: UNCHS, 1996.

Table 2. Land use changes from non-urban to urban between 1990 and 2007

Year	Built-up (acres)	Non Built-up (acres)
1990	30,452.4	146,875.2
2001	39,247.5	138,080.2
2007	51,333.8	125,970.1

Table 3. Weights used for three major land use activities modeled in the study

Criteria Used	Residential	Commercial and Public Facilities	Industrial
Proximity to employment centers	0.14	0.00	0.00
Proximity to major roads	0.08	0.26	0.73
Proximity to public facility	0.05	0.00	0.00
Proximity to population centers	0.28	0.64	0.08
Land Value	0.44	0.11	0.19
Consistency Ratio	0.08	0.03	0.06

Table 4. The validation of the proposed model for the simulation of urban development between 2001 and 2007

Land Use Categories	Kappa Index (x 100) 2001	Kappa Index (x 100) 2007
Residential	83.7	70.9
Commercial and public facilities	80.7	40.5
Industrial	84.1	51.9
Agricultural	86.1	85.3
Others	83.0	44.8
Overall accuracy	90.29	81.04

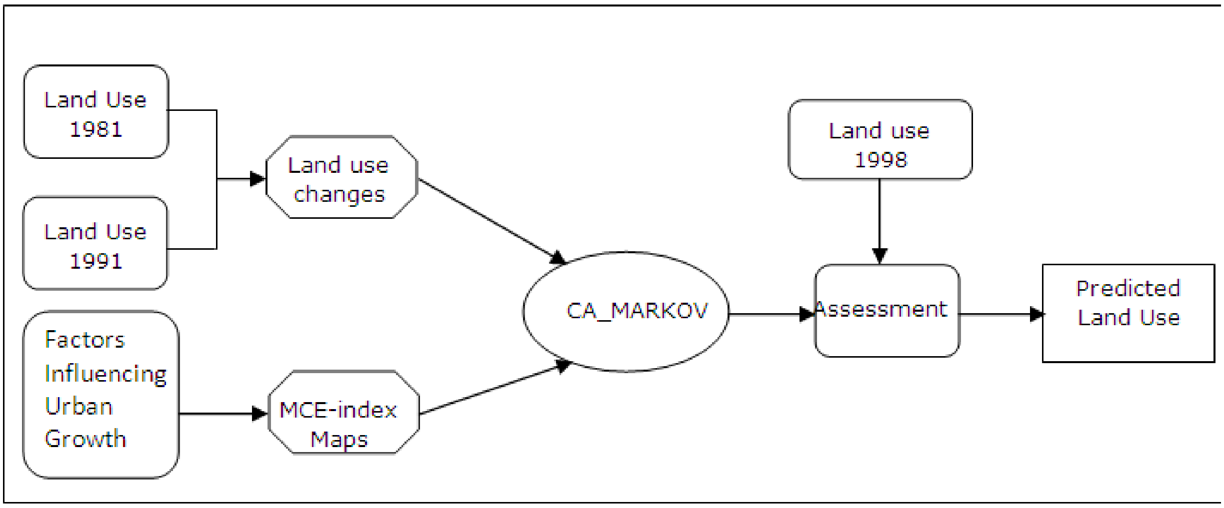


Figure 1. The schematic diagram of the proposed model

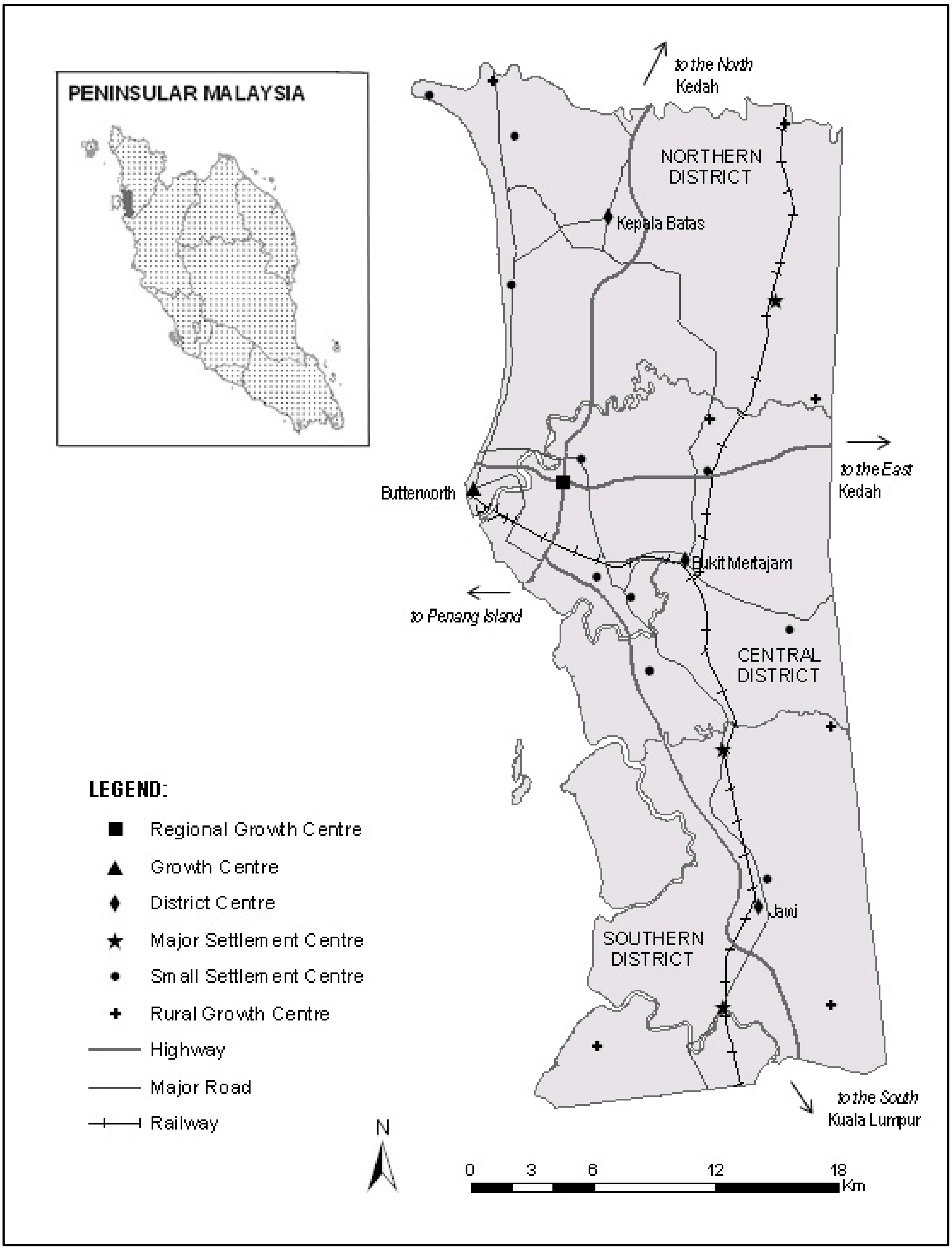
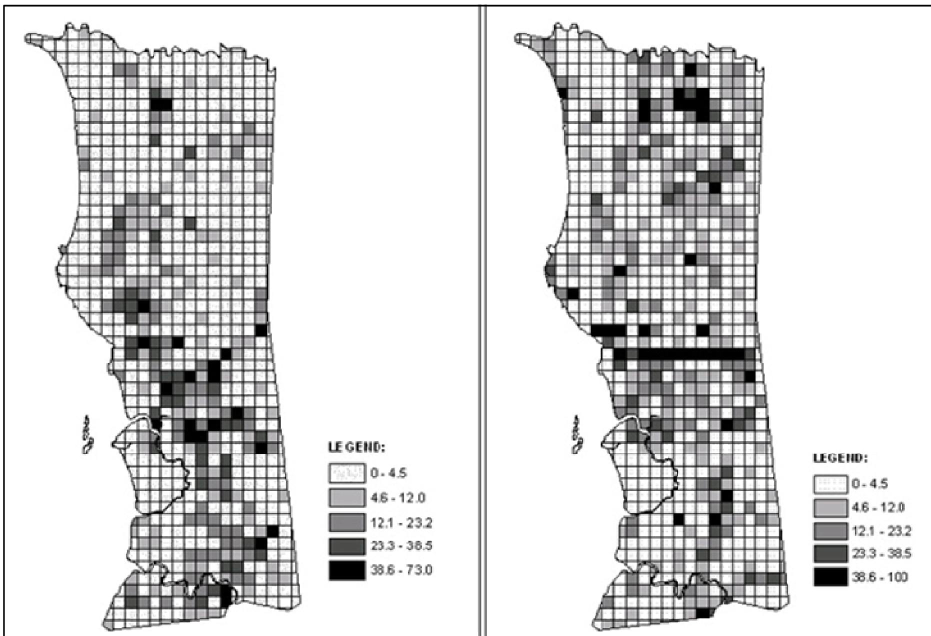


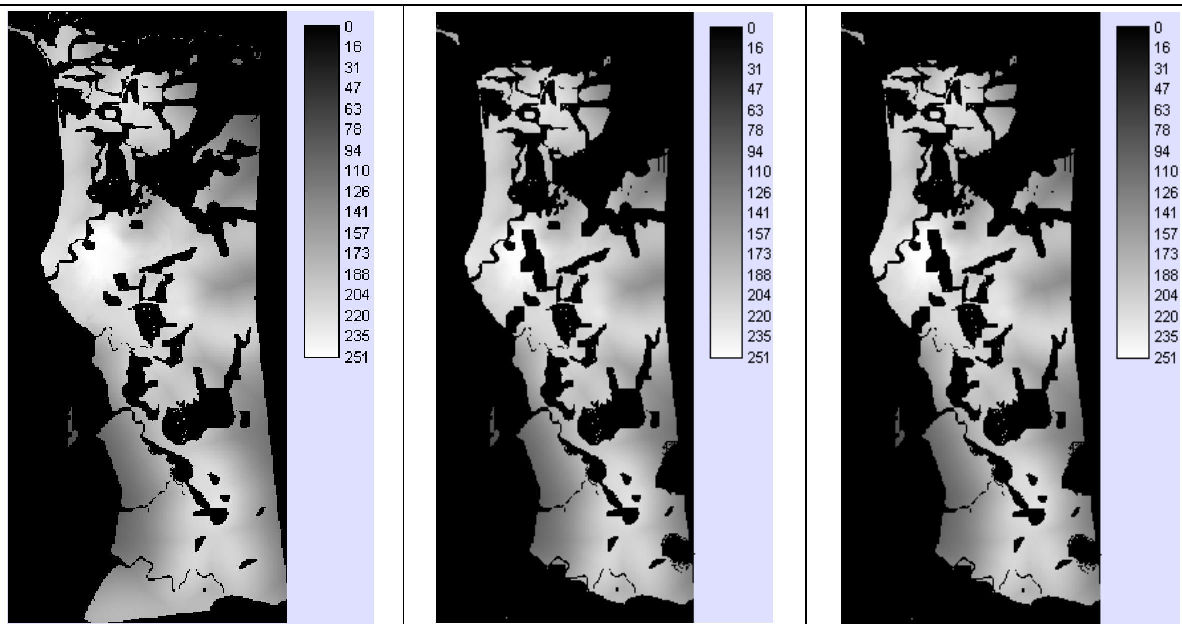
Figure 2. The study area



(a) Speed of urban expansion between 1990 and 2001

(b) Speed of urban expansion between 2001 and 2007

Figure 3. Speed of urban expansion between 1990 and 2001 and between 2001 and 2007



(a) MCE-suitability index map produced for residential activity.

(b) MCE-suitability index map produced for commercial and public facilities.

(c) MCE-suitability index map produced for industrial activity.

Figure 4. MCE-suitability index maps produced for three major land use activities modeled in this study

Figure 5. Urban spatial pattern 2010 (left) and 2020 (right) produced using GIS and CA-Markov Model