Land -Use/Land- Cover Dynamics In Chiang Mai : Appraisal from Remote Sensing, GIS and Modelling Approaches

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ABSTRACT

Remotely-sensed images and Geographical Information Systems (GIS) data were integrated into the SLEUTH cellular automata (CA) model to analyze land –use/land- cover dynamics in Chiang Mai city and its surrounds. The land-use and land-cover statistics, obtained from GIS data base and satellite images from 1952, 1977, 1989 and 2000 revealed rapid increased in urbanization during these periods. To understand the underlying causes of land- use and land-cover dynamics, remote sensing, GIS and modeling techniques were applied. The SLEUTH model contains a characteristic that offers advantages in integrating with raster-based remote sensing data and in increasing the capability of GIS in modeling the spatial dynamics. The objectives of this research are (1) to systematically analyze remotely- sensed images of Chiang Mai area from available time series into major land-use-land -cover types and to identify the significant land- use/land- cover changes; (2) to apply a GIS for capturing the information on the temporal transportation layers, zones excluded from urbanization, and topographic layers such as slope and terrain hillshading in Chiang Mai; and (3) to test if the SLEUTH cellular automata model can be applied for simulating urban growth and land-use change in Chiang Mai. The study reveals that: (1) land –use/land -cover types in Chiang Mai can be classified based on the satellite images into Urban land, Agriculture, Forest, Water, and Miscellaneous; and the urban area increased from 13 km^2 in 1952 to 339 km^2 in 2000, with the tendency to increase over time; (2) the temporal transportation layers and slope developed by GIS served as the important variables for modeling urban growth by SLEUTH model; and (3) the urban development in Chiang Mai was best captured by Xmean and edge growth regression scores. In conclusion, the combination of remote sensing, GIS and SLEUTH model can be best applied to study urban growth and land -use change in Chiang Mai, if some adaptations for spatial accuracy and scale sensitivity are made.

Key words: Cellular automata; GIS; Remote sensing; SLEUTH, Scenario, Terrain hillshading, Urbanization; Chiang Mai; Model; Xmean

INTRODUCTION

Remotely -sensed data can be defined as data acquired from any sensor system, which includes those carried on aircraft, spacecraft and satellites. Deployment offers fast and accurate up-dating of spatial information about the Earth's surface. Remotely-sensed data have been applied to mapping problems and tasks in various fields of study, including forestry, agriculture, geology, oceanography, climatology and land resource inventory. Research on land -use/land- cover change in Chiang Mai has been conducted, based on remote sensing data on a regular basis so that up-to-date information can be obtained. Geographical Information Systems (GIS) have been defined as a tool for storing, analyzing, retrieving and manipulating digital spatial and thematic data in the most effective way. A GIS is capable of enhancing the positional accuracy of remote sensing data, whilst remote sensing data provide up-to-date information to the GIS data. Therefore, the combination of remote sensing and GIS has been extensively applied for obtaining the best accuracy of the result. The CA-SLEUTH model was developed by Clarke (1999) for simulating the urban growth and land cover change. This model examines urbanization and its impact on the natural environment (United States Environmental Protection Agency, 2000). The model has been applied to simulate and forecast urban growth and land use change in several developed -country settings. SLEUTH cellular automata model contains a characteristic that offers advantages for modelling land- use change and other physical dynamics. Rapid development of GIS helps foster the application of CA-SLEUTH model for studying urban development, land use change and other changes. Currently, only a few projects in Thailand used the combination of remote sensing, GIS and modeling for mapping the land -use/land- cover dynamics due to some problems such as the limitation of access to high- resolution data and the lack of technocrats. This research has three main objectives : (1) to systematically analyze remotely -sensed images of Chiang Mai area from available time series into major land- use/land-cover types and to identify the significant land -cover changes; (2) to apply a GIS for developing the land cover data base, as well as for creating the temporal transportation layers, zones excluded from urbanization, and topographic layers such as slope and terrain hillshading and (3) to test if the SLEUTH cellular automata model can be applied for simulating urban growth and land-use change in Chiang Mai. Coupling remote sensing, GIS and SLEUTH CA model is a challenging task and it may serve as an analytical tool to provide a flexible framework for the programming and running of dynamic spatial model in the rapid urbanization city like Chiang Mai.

APPLICATIONS OF REMOTE SENSING AND GIS FOR LAND USE AND LAND COVER MAPPING IN CHIANG MAI STUDY AREA-

The Chiang Mai study area lies in the north of Thailand at approximately between 18° 32' and 19° 05' N latitude and between 98° 48'and 99° 22'E longitude. (see Figure 1). Itt encompasses the administrative districts of Muang, Mae Rim, Hang Dong, Saraphi, Sansai, Sankamphaeng and Doi Saket, which are included in the integrated town and city planning scheme. These districts are greatly influenced by urban sprawl. The size of the study area accounts for about 2, 415 km^2, which covers four 1:50000 scale topographic map sheets (4746 I-II and 4846 III-IV) of the Royal Thai Survey Department (1992).

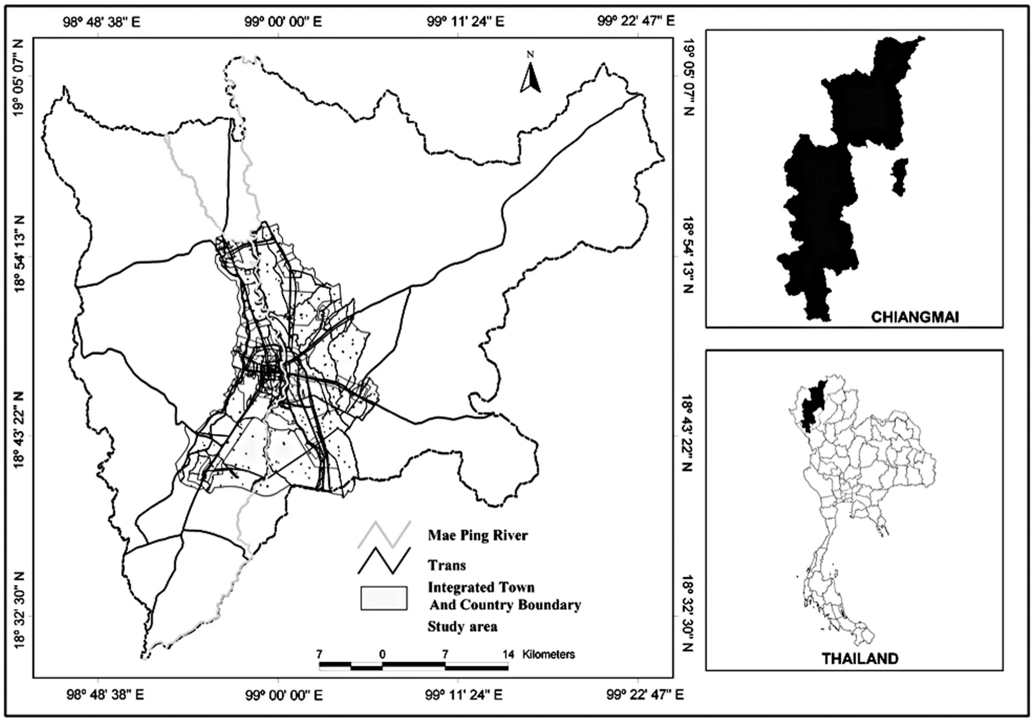

Figure 1. The Chiang Mai study area.

Earlier studies of land- use /land- cover change in the urban area of Chiang Mai were limited by high- resolution remote sensing data sources (Lebel et al., 2005), so that the whole part of Chiang Mai could not be mapped at once. Thus, Siripunya (1987) used aerial photographs (year 1979) to compare actual land-use with planning documents in eastern part of the Chiang Mai basin. Yarnasarn (1985) aggregated data from multi sources, including aerial photography and Landsat to document some of the broader changes in urban form. Wara-Asawapati (1991) applied Landsat MSS (Multispectral Scanner) to investigate the areas undergoing rapid change at the urban-rural fringe of Chiang Mai city and its environs between 1973 and 1985. The urban-rural land use transition in the Chiang Mai area has been found from agriculture to settlement areas. Sangawongse (1996) performed a change detection in the Chiang Mai area over 1,000 km^2 on Landsat-5 TM during the economic boom (1988–1991), using various techniques. A change matrix was created from the classified 1988 and 1991 data, which yielded 225 possible land -cover changes. The biggest change was found to be from disturbed forest land to low-density urban areas, accounting for about 10,422 hectares. The change from agricultural area to low- density built-up areas accounts for about 7,537 hectares.

Results from these studies can be used to document land -use/land -cover information in the past. However, planners need to know more about the trends of change in advance for regulating the effective land use planning. Current GIS techniques have limitations in modelling land use changes (Wagner, 1997), but the integration of GIS and CA model has demonstrated considerable potential (Itami, 1994; Li and Yeh, 2000). Linking remote sensing, GIS and the modeling techniques for mapping future land use changes could be one of the most effective approaches for this study.

THE SLEUTH MODEL

SLEUTH is a modified cellular automaton model which consists of an urban growth sub model and a land cover change transition sub model (Clarke, 2002). The urban growth model is the main component of SLEUTH which is tightly coupled with the land cover change transition model. The SLEUTH urban growth sub- model is characterized by grids of homogeneous pixels, with a neighborhood of eight cells of two- cell states (e.g., urban/non urban), and five transition rules that act in sequential time steps (Silva and Clarke, 2002). SLEUTH simulates four types of urban land use dynamics: spontaneous growth, new spreading center growth, edge growth and road influenced growth (Clarke et al., 1997). The growth rules are applied sequentially during each cycle, and are controlled by five coefficients, namely: Diffusion, Breed, Spread, Slope Resistance and Road Gravity. Spontaneous growth simulates urbanized pixels by random and it is controlled by diffusion coefficient. New spreading center growth determines whether any of the new spontaneously- urbanized cells will become new urban spreading centers by the breed coefficient. Edge-growth simulates growth that stems from existing urban centers. It is controlled by the spread coefficient which influences the probability that a non-urban cell with at least three neighbors will become urbanized. Road-influenced growth simulates the influence of transportation network on growth patterns and it is controlled by the breed coefficient. The application of SLEUTH model, which is based on raster image form, has offered many advantages in modeling urban growth and land cover change, because of its cellular data structure, thereby making it possible to integrate with raster-based data from remote sensing (Jantz et al., 2003). Another advantage is that the future trajectory of urban morphology can be shown virtually during the simulation processes (Li and Yeh, 2000).

The model has been tried in several developed -country settings. Silva and Clarke applied the model to Porto and Lisbon metropolitan areas in Europe which are characterized by different spatial objects (Silva and Clarke 2002). Calibration result showed that the model adapted well to the European context as indicated by high regression scores which are close to the local characteristics. Candau applied the model to Santa Barbara in California to study urban growth (Candau, 2002). It was found that SLEUTH calibration was not scalable across image resolutions and data from the last 40 years proved more effective for calibration than including the entire historical profile available. Jantz and colleagues applied the SLEUTH model in Baltimore-Washington metropolitan area (23,700 km^2) in the United States, using a historic time series remote sensing imagery for assessing the impacts of alternative policy scenarios on declining of water quality in the Chesapeake Bay estuary (Jantz et al., 2003). In this application, future growth was projected to 2030 under three different policy scenarios (current trends, managed growth, ecologically sustainable growth). Result showed that SLEUTH has an ability to address many regional planning issues, but spatial accuracy and scale sensitivity must be considered for practical applications.

MATERIALS AND METHODS

1. Data sources

This study utilized data from various sources, including GIS digital data, satellite images, topographic maps and ortho-photo images. Table 1 summarizes the Chiang Mai spatial and temporal data, dating from 1952 to 2005. The satellite data for the Chiang Mai study area were supplied by Center of Geoinformatic and Technology, Huay Kaew Wtatershed Management Unit, and the Center for Global Change and Earth Observation, Tropical Rain Forest Information Center (TRFIC), at Michigan State University, USA.

Table 1. Spatiotemporal data used for developing land -use and land -cover data and GIS data.

Dates	Data types	Sources
1952 (2495)	Topographic Map 1:50,000 scale	Royal Thai Survey Department
1977 (2520)	Analog Land Use Map 1:100,000 scale	Department of land development Thailand
1985 (2518)	Landsat MSS	TRFIC, Center for Global Change and Earth Observation, USA
1989 (2532)	Landsat-5 TM P131/047	TRFIC, Center for Global Change and Earth Observation, USA
1989 (2532)	Digital vector GIS (ArcView)	Department of land development Thailand (DLD Program)
2000 (2543)	Landsat-7 ETM +	Center of Geoinformatic and Technology, Huay Kaew Wtatershed Management Unit, Chiang Mai
2000 (2543)	Digital vector GIS (ArcView)	Multiple Cropping Center, Chiang Mai University, Thailand (Landplan Program)
Feb. 22,2004	ASTER	USGS/EDC

From Table 1, topographic data in 1952 provided information on land use-land cover and road networks at 1: 50,000 scale. The analog land use map of 1977 provided information on land use-land cover in the study area at 1:100,000 scale. The Landsat data from1985 to 2000 were chosen for analyzing land use and land cover in the study area.

2. Analysis Of Land Use/Land Cover Dynamics In The Study Area

There are several related challenges to applying remote-sensing technologies to the study and monitoring of urbanization in Chiang Mai. Early applications using satellite-based imagery were concerned primarily with identifying major land use /land cover types and deriving image classification algorithms. Currently, two methods are used for classifying satellite images into land -use and land-cover types: visual interpretations and image classification. Visual interpretation is the simplest way to obtain land -use/land -cover information from remotely -sensed images. However, the operators should have knowledge about patterns, orientation, color, texture and shadows that appear on the data before interpreting. Visual interpretation can be performed on aerial photograph, topographic maps and color composite satellite images. Image classification has been used for analyzing digital satellite images to obtain land use/land cover classes.

Time series geospatial data obtained from Table 1 were used for developing land use/land cover by remote sensing and GIS techniques. These satellite data were classified into several land cover types, based on the land use classification scheme (Anderson et al., 1976). Data for other periods were obtained from an existing land cover database, the earlier maps based primarily on aerial photography, which were populated into the same format using a GIS. Due to the inconsistency of land use data from various sources, much time and effort was spent. Procedures used for developing the spatio-temporal database included data acquisition, data management and manipulation, data conversion and reclassification.

The classification procedures were performed on ERDAS IMAGINE version 8.5, using the supervised and unsupervised classification methods in cooperation with ground truth data and available secondary data (Sangawongse, 1996, Sangawongse et al., 2005). The metadata and land use classification scheme used for classifying the land cover data of Chiang Mai were modified from the Department of Land Development of Thailand (1996). The output was a spatio-temporal land cover/land use maps for the Chiang Mai study area, spanning 1952 to 2000. The digital data base allowed the integration between historical land use data and the present land use data possible (Kuo, 2003), and can serve as an up-to-date land cover change information system. The classified images consist of five major types: (1) Agriculture, (2) Forest, (3) Urban and built-up land (4) Water body and (5) Miscellaneous land. Agriculture includes paddy field, field crops, orchards and swidden cultivation. Forest consists of hill evergreen, mixed deciduous, dipterocarp and forest plantations. Urban and built-up land consists of city/towns, rural residential land, institutional land, airport and recreational land. Miscellaneous land refers to grassland, barren land, salt pans and vacant land.

3. Data Preparation for the SLEUTH Model

Data preparation depends greatly on GIS and remote sensing techniques, for example, data conversion, reclassification and data import/export. The Chiang Mai spatio-temporal data consisted of 1952, 1977, 1989, 2000 and 2002. The land use data of 1952 and 1977 were digitized from topographic maps at 1:50,000 and analog land use map at 100,000 scales, respectively. The 1989 and 2000 data were acquired from Landsat-5 TM and Landsat-7 ETM+ at 30 meters resolution, respectively. The ASTER image acquired in February 2002 was used for producing the slope data.

The input data required by the SLEUTH model include Slope, Land use, Exclusion, Urban extent, Transportation and Hillshade (Figure 2). They were prepared at three resolutions to calibrate the SLEUTH model. The resolutions or cell sizes of 200m, 100m and 50m, which correspond to image rows and columns of 355 × 346, 670× 691 and 1340 ×1383 were used to cover the entire study area. The selection of these spatial resolutions was based on Candau (2002) and Dietzel (2003).

A slope map of the Chiang Mai area was created from a Digital Elevation Model (DEM) which was developed from an ASTER image by Geomatica software. The ASTER image contains topographic information derived from the along-track scan of the satellite orbit. The Hillshade layer for each study area was produced directly from a DEM, which was used as the background for model image output and for visualization purposes.

The land use data were developed from GIS and satellite images, which consisted of five major classes: Agriculture, Forest, Urban, Water and Miscellaneous. Land use with consistent classification for two time periods is needed for the model. It is noted that the land use data were not used in the model at this time due to the inconsistencies of some land cover types between dates.

Exclusion is defined as areas which are resistant to urbanization. Excluded areas chosen for this analysis are water bodies, public land, forestland, national park and the military area. These areas were mainly extracted from the classified land cover data. Pixel values for excluded areas range from 0-255, but areas available for urban development have a value of zero (http://www.ncgia.ucsb.edu/projects/gig).

The urban extent for this study includes city/towns, institutional land, airport, rural residential land and recreational land (Wara-Aswapati, 1991; Lo and Yang, 2002; Dietzel, 2003). Four urban time periods were used for calculating best-fit statistics of the model (Candau, 2002; Clarke, 2002; Jantz et al., 2003).

Transportation layers were derived from digitizing the historical topographic maps in 1952 and 1977. All the road layers were given weight in a GIS, based on their 'accessibility'. Highways were treated as the most accessible, with a weight of 100, provincial roads as second -most accessible at 50, and neighborhood streets as the least accessible with a weight of 25. Then, the weighted vector coverage was converted to a grid with the same resolution as other input data, giving the background a value of 0.

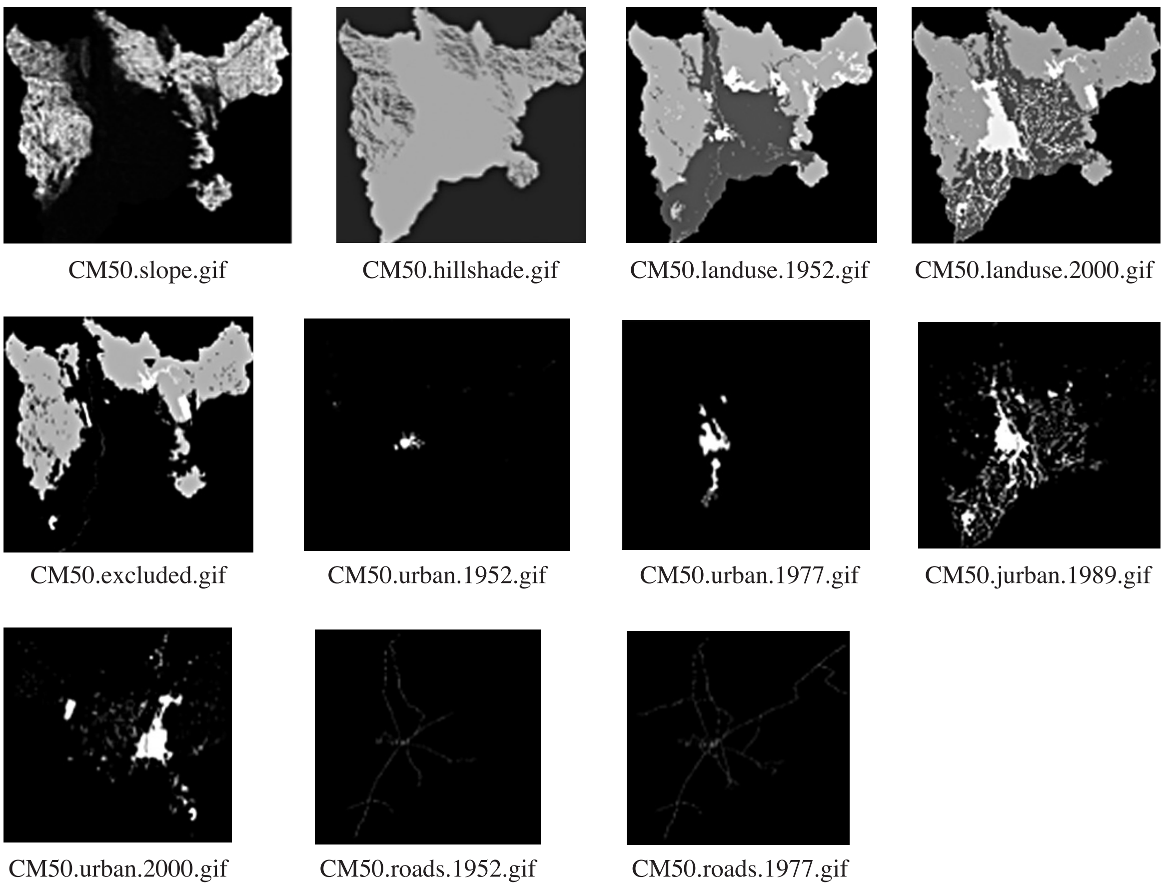

Figure 2: SLEUTH GIF images at 50m resolution of the Chiang Mai study area.

4. Brute -Force Calibration

The calibration procedure was based on SLEUTH version 3.0 beta program, which was downloaded from http://www.ncgia.ucsb.edu. The code is written in C programming language, and supports three modes: test, calibration and prediction. For this study, only test and calibration modes were used. The model was operated by a Linux Redhat version 9.0 on PC microcomputer at the Department of Geography, Chiang Mai University. All input grey scale gif images at three resolutions were verified in the SLEUTH test mode before use in the calibration as suggested by Silva and Clarke (2002). Brute-force calibration involved fitting the model to historical data on land use, transportation and urban extent. Three phases of calibration corresponding to progressively- higher spatial resolutions were carried out. As calibration proceeded to finer resolution, the range of parameters explored was narrowed around the best values obtained at the previous level, and the number of Monte Carlo simulations for coefficient combinations increased from previous to final calibration phases. The process of model fitting (or "calibration") is computationally very intensive, so only 4–8 simulations were done for each combination of parameters.

RESULTS AND DISCUSSION

Image classification result yielded five major land cover types: (1) Agriculture, (2) Forest, (3) Urban and built-up land (4) Water body and (5) Miscellaneous land (Table 2). Agriculture includes paddy field, field crops, orchards and swidden cultivation. Forest consists of hill evergreen, mixed deciduous, dipterocarp and forest plantations. Urban and built-up land consists of city/towns, rural residential land, institutional land, airport and recreational land. Miscellaneous land refers to grassland, barren land and others. Based on the change detection analysis, the urban area of Chiang Mai increased from 15 km^2 in 1952 to 339 km^2 in 2000, with a tendency to increase over time (Figure 3). It is noted that the urban area in 1977 was slightly underestimated, because most of village areas did not appear on the 1:100,000 land use map. The significant change was found from agriculture to urban land. It is difficult to obtain the accurate classification result for the study area, because of the heterogeneity of the surface cover, the topographic effect and the limited resolution of the satellite image being used (Sangawongse, 1996; Lebel et al., 2005). The success of image classification depends on many factors such as the quality of the image data and the selection of the optimum image channels to classify (Sangawongse, 1996).

Table 2. Land Use /Land Cover Change in the Study Area Between 1952–2000.

Years	1952		1977		1989		2000	
Land cover types	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	%
1. Agriculture	909.5	37.66	971.5	40.23	972.73	40.28	819.69	33.94
2. Forest	1378.4	57.08	1365.3	56.54	1122.24	46.47	1222.35	50.62
3.Miscellaneous	102.6	4.25	13.3	0.55	14.72	0.61	6.94	0.29
4.Urban/Built-up	15.0	0.62	64.7	2.7	291.35	12.06	339.47	14.06
5. Water	9.5	0.39	0.2	0.01	13.85	0.57	26.46	1.10
Total area	2414.9	100	2414.9	100	2414.9	100	2414.9	100

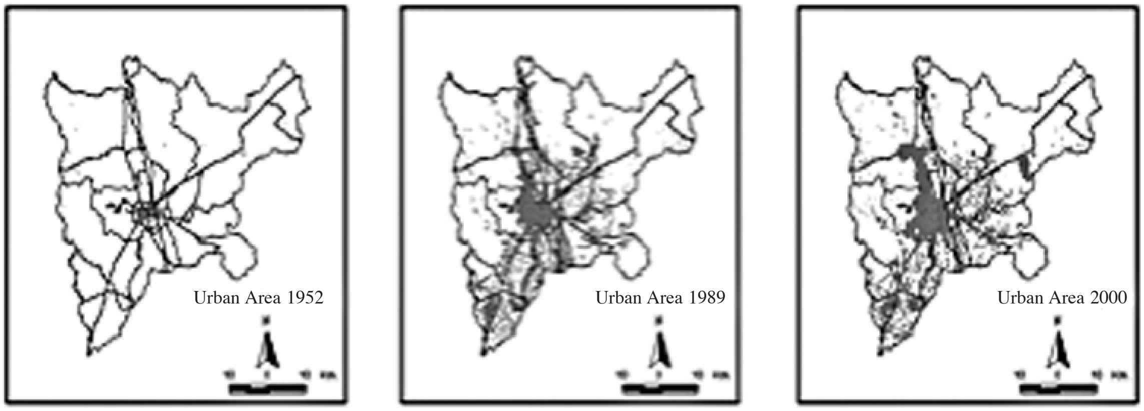

Figure 3: Urban expansion in the study area (1952–1977–1989–2000).

GIS proved to be the effective tool for developing the land use/land cover data base, as well as for manipulating input data for the SLEUTH model. The use of an existing GIS data base is often limited by the inconsistency of the data. For example, the elevation data of the study area contained many digitizing errors (e.g., disconnected lines and sliver polygons) that have led to the poor quality of the slope layer and other products. It is recommended to edit and manipulate both spatial and attribute data before use.

The result from calibration of SLEUTH model produced 13 least- square regression metrics, such as population (number of urban pixels), cluster (urban cluster edge pixels), edges (urban perimeter), average slope, Xmean (average longitude) and Lee Sallee (a shape index) metric. Each metric represents the comparison between the simulated growth and the actual growth for the control years. To avoid difficulties in isolating and describing the factors that influence a regression score, only a subset of significant metrics were selected to explain the growth characteristics of Chiang Mai city (Dietzel and Clarke, 2004). These metrics included Compare, Cluster, Cluster Size, Edges, Xmean, and Lee Sallee. Table 3 shows only six metrics from the sorted- top five highest- scoring results, with their associated growth parameters that control the behavior of the system at a different phase of calibration.

Table 3: Calibration result of Chiang Mai city.

Least squares regression metrics	Resolution (meter)		
	200	100	50
1. Compare	0.99	0.99	0.99
2. Cluster	0.91	0.99	0.99
3. Cluster Size	1	0.99	0.99
4. Edges	1	0.97	0.99
5. Lee Sallee	0.16	0.18	0.26
6. Xmean	0.99	1	1

Five growth parameters			
Diffusion	3	10	33
Breed	71	66	46
Spread	16	38	60
Slope	38	50	43
Roads	36	30	47

Source: Sangawongse et al., 2005

Calibration output was explored by using the statistical methods (e.g., sort descending) to select the best-fit values. It was found that Cluster-Size, Edges and Xmean scores were best captured for Chiang Mai as indicated by scores of 1, 1 and 0.99, respectively. It is observed that Lee Sallee that measures spatial fit by taking the ratio of intersection and the union of the simulated and actual urban growth (Candau, 2002) did not yield a high score (around 0.26 in the coarse calibration phase). A perfect spatial match is 1. It is hard to obtain high values of the shape match for Chiang Mai due to scattered expansion of the city (Lebel et al., 2005), making it hard for the model to fit the actual shape exactly.

Increased spatial resolution and narrowed down the ranges of parameters have improved the calibration. For example, the initial Diffusion and Spread values of 33 and 60 in Chiang Mai were narrowed down to 3 and 16. Figures 4 reflects the behavior of urban Chiang Mai to the different growth coefficients values.

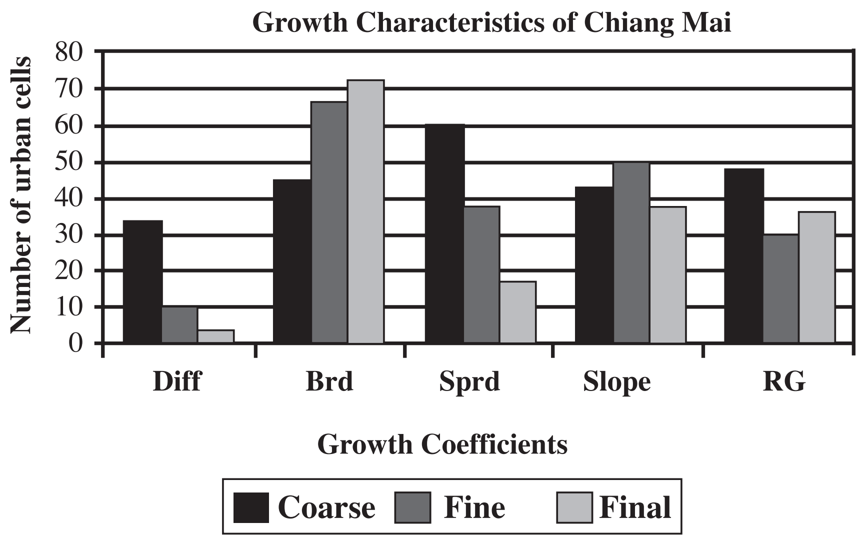

Figure 4. Behavior of Chiang Mai to the growth coefficients.

Different characteristics of Chiang Mai city were captured in the set of final coefficients that describe the areas under investigation. The starting parameter values in 1952 are: Diffusion = 1, Breed = 1, Spread = 3, Slope = 29, Roads = 40. These numbers can be used to predict future growth in the prediction mode of the SLEUTH model. The quality of the input data and the selection of optimal parameter ranges should be considered carefully to improve the calibration result. Since the calibration of SLEUTH is computer- intensive, it should be implemented on a super computer or to be run on a parallel processing and high-performance computing methods (e.g., cluster computer) in order to obtain the result in a timely manner.

In conclusion, applying the SLEUTH model to Asian countries has just started, there is still a need for modelers to explore in more aspects of using this model. This calibration experience has provided us some insights to SLEUTH model and more understandings on how the CA adapted to the urban environment in Asian countries.

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REFERENCES

Anderson, J., E. Hardy, J. Roach, and R. Witmer. 1976. A land use and land cover classification system for use with remote sensor data. U.S. Geological Survey, Professional Paper 964, 28. http://landcover.usgs.gov/pdf/anderson.pdf

Candau, J. 2000. Calibrating a cellular automaton model urban growth in a timely manner. In Proceedings of the 4th International Conference on Integrating Geographic Information Systems and Environmental Modeling. (Bolder: University of Colorado)

Candau, J. 2002. Temporal calibration sensitivity of the SLEUTH urban growth model M.S. Thesis. University of California (Santa Barbara), California, USA.

Clarke, K. C., S. Hoppen, and L. Gaydos. 1996. Methods and techniques for rigorous calibration of a Cellular Automaton model of urban growth. Proceedings, Third International Conference/Workshop on Integrating Geographic Information Systems and Environmental Modeling, January 21-25th, Santa Fe, NM.

Clarke, K. C., S. Hoppen, and L. Gaydos.. 1997. A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area' Environment and Planning B: Planning and Design 24: 247-261.

Clarke, K. C., and L. Gaydos 1998. Loose coupling a Cellular Automaton model and GIS: Long-term growth prediction for San Francisco and Washington/Baltimore, International Journal of Geographical Information Science 12 (7): 699-714.

Clarke, K. C. 2002. Land Use Change Modeling Using SLEUTH. Proceedings LUCC training workshop. National Taiwan University, Taiwan. 15-19 December 2002

Dietzel, C. 2003. Forecasting California's farmland loss under stable and unstable conditions. Department of Geography, University of California (Santa Barbara), California, USA.

Dietzel, C.K., and K. C. Clarke 2004. Determination of Optimal Calibration Metrics through the use of Self-Organizing Maps, Institute for Environmental Studies, Amsterdam, Integrated Assessment of Land System Workshop, October 28-30,2004.

Environmental Protection Agency 2000. Projecting land use change: A summary of models for assessing the effects of community growth and change on land use pattern, http://www.epa.gov/cbep/tools/reportfinal3.pdf, access: April 2001.

Jantz, C. A., S. J. Goetz, and M. K. Shelley. 2003. Using the SLEUTH urban growth model to simulate the impacts of future policy scenarios on urban land use in the Baltimore/Washington metropolitan area. Environment and Planning B. 31: 251-271.

Itami, R. M. 1994, Simulating spatial dynamics: cellular automata theory. Landscape and Urban Planning 30: 24-47.

Kuo, Chun-Lin 2003. Towards better understandings of land use change in Taiwan by using historical GIS. URISA conference paper page 1-7.

Lebel, L., D. Thaitakoo, S. Sangawongse, and D. Huaisai. (in press). Views of Chiang Mai: the contributions of remote sensing to urban governance and sustainability. Prepared as a chapter in M. Netzband, C. Redman, and W. Stefanov. (Ed). Applied Remote Sensing for Urban Planning, Governance and Sustainability. Springer-Verlag (Expected late 2005).

Li, X., and GAR-ON. Yeh A. 2000. Modeling sustainable urban development by the integration of constrained cellular automata and GIS. International Journal of Geographical Information Science 14 (2): 131-152.

Lo, C. P., and X. J. Yang,. 2002. Drivers of land-use/land-cover changes and dynamic modeling for the Atlanta, Georgia Metropolitan Area, Photogrammetric Engineering and Remote Sensing 68 (10): 1073-1082.

Sangawongse, S. 1996. Land use/Land cover Change Detection in the Chiang Mai Basin: Appraisal from Remote Sensing, GIS and Cartographic Data Developed for Monitoring Applications. Ph. D. Dissertation. Monash University, Victoria, Australia.

Sangawongse, S., C. H. Sun, and B. W. Tsai. 2005. Urban growth and land cover change in Chiang Mai and Taipei: results from the SLEUTH model. Proceedings of MODSIM 2005, the International Congress on Modeling and Simulation on Australia and New Zealand, Melbourne, Australia.

Silva, E. A., and K. C. Clarke 2002. Calibration of the SLEUTH urban growth model for Lisbon and Porto. Computers, Environment and Urban System 26: 525–552

Siripunya, U. 1987. A comparative study of land use on the eastern part of the Chiang Mai basin with the land use plan using physical characteristics as the criteria. M. S. Thesis. Chiang Mai University, Thailand.

Wagner, D. F. (1997). Cellular automata and geographic information systems, Environment and Planning B: Planning and Design 24: 219–234.

Wara-Aswapatti, P.1991. Image processing technique for urban and rural land use monitoring in northern Thailand. Journal of Thai Geosciences 1: 59–63.

Yarnasarn, S. 1985. Land-use patterns and land-use changes in Chiang Mai, northern Thailand. Ph. D. Dissertation, Columbia University, USA.