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Modelling Urban Land Use Change Using Geographically Weighted Regression and the Implications for Sustainable Environmental Planning

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Abstract: In this study we applied Geographically Weighted Regression (GWR) approach to model urban land use changes in Penang Island from 1990 to 2005, covering the period during which the Island has experienced tremendous urban growth due to in migration from adjacent areas. Land use change has potential impacts on the physical and social environment. We identified spatial variables describing environment, physical and socio-economic factors which are hypothesized to influence the change in the land use in the study area. An ordinary least squares regression (OLS) model is applied to the variables followed by a GWR model and the results are compared. The results show that the GWR outputs explained considerably more variance in the relationship of the explanatory factors compared to conventional OLS models and provided significantly better results. In addition, GWR also provided important insights on location where changes happen and what distance to the city center they appear. The information generated will give understanding of spatio-temporal dynamics of land use changes resulted from different land use policies and can serve as a basis for developing possible growth scenarios which are essential for sustainable urban planning and development. However, more comprehensive studies are needed to understand long term spatio-temporal patterns and complex inter-related challenges the urban areas of Penang Island facing presently.

Keywords: Urban Land Use Change, Sustainable Environmental Planning, Geographically Weighted Regression Modelling

1. INTRODUCTION

With recognition of the ecological, socio-economic, and cultural significance of urban areas and their sensitivity to rapid urbanization, greater emphasis is now placed on the issue of sustainability in urban development. Presently, urbanization has become one of the main factors of land degradation and resulting losses of non-urban land uses worldwide. Researchers emphasized that these changes of non-urban land uses however certainly provide many social and economic benefits, but have adverse effects on natural environment (Tang et al., 2005) including global carbon cycle, climate, biodiversity, and landscape ecology (Houghton et al., 1999; Luvall, 1997; Sala et al., 2000; Reid et al., 2000; Wickham et al., 2000). The urban areas are recognized as one of the complex and highly dynamic landscapes on earth surface which supports more than half of the global human population, as well as hubs of the worlds manufacturing and service industries (Kaplan et al., 2004). In spite of only 3% coverage of the Earth’s land surface, the urban areas are reported to exert marked effects on environmental conditions at both local and global scales (Grimm et al., 2000; Herold et al., 2003; Liu & Lathrop, 2002). In view of the fact that ecosystems in urban areas are strongly influenced by anthropogenic activities, considerably more attention is currently being directed towards monitoring urban land use changes (Stow & Chen, 2002). The spatially explicit modeling of land use changes is an important technique for describing processes of changes in quantitative terms and for testing our understanding of these processes...
Significance of these modeling techniques to understand the urban development process has been highlighted (Schneider and Gil Pontius Jr. 2001; Walsh and Crawford 2001). Moreover, urban land use change models can generate alternative landscape predictions on the basis of different land use policies and environmental constraints and predictions about future urbanization which are critical to the protection of ecosystems and the sustainability of communities (USGS, 2009). This necessitates the linking of the resulted changes to their driving factors for effective land use planning and sustainable management of resources. The driving factors (e.g. population or development), mediated by the socio-economic setting (e.g. market economy, resource institutions) and influenced by the existing environmental conditions or context, lead to changes in land use through the manipulation of the biophysical conditions of the land (Turner et al., 1995). Presently sustainable urban development became a widely recognized goal for human society and interest has burgeoned among urban planners and researchers to maintain sustainable urban environment and devise robust modeling techniques. The theoretical and mathematical models have for long been created for purposes of urban studies, aiming at clarifying processes of urban and regional change. However, currently a new wave of urban spatial modeling for understanding urban environment has come to the force and becoming an integral topic in current urban research agenda.

The Geographically Weighted Regression (GWR) approach of spatial modeling is an important part of these tools which provide technique to deal with spatial non-stationarity in multivariate regression and estimates regression coefficients locally using spatially dependent weights (Fotheringham et al., 1997). GWR is becoming a more commonly used technique in urban geographical and environmental studies as the important feature of GWR is its ability to generate parameter estimates for every regression point by using observations in a given neighborhood. The parameter estimates are characteristically mapped to highlight spatial variation (Mennis, 2006) and resulting maps are thought to be didactic aids for policymakers, and for summarizing the large amount of data generated by the procedure (Cho et al., 2009). More detail about GWR can be found in Fotheringham et al. (2002) and some other recent articles (e.g. Wang et al., 2005; Chang et al., 2008; Propastin et al., 2008). The GWR has been applied to investigate regional industrialization (Huang and Leung 2002), geographic diversity in urban and regional growth (Partridge et al. 2006), commuting patterns (Lloyd and Shuttleworth 2005), modeling urban spatial structure (Noresah and Rainis, 2009) and forecasts of regional employment (Li et al., 2009). Keeping the wide applications of GWR in background, this study aims at modeling urban land use changes using GWR approach over Penang Island, Malaysia. The spatial variable of relationship between the urban land use change and the proximate causes will give the idea of complexity and interconnections between the land use change and associated factors.

2. STUDY AREA

The Penang state is one of the most rapidly developing and industrializing states in Malaysia. It is located on the north-eastern region of Peninsular Malaysia (Figure 1) and consists of the Island of Penang and a coastal strip on the mainland known as Seberang Perai (or Prince Wellesley). The Penang Island is situated in the northern part of Malaysia and geographically situated between 5°12′ to 5°30′ North latitude and 100°09′ to 100°26′ East longitude. Being the most populated Island in the country; Penang Island has a population of about 745,000 in the year 2009 with 293 Km² coverage areas. The terrain of the Island is mainly represented by coastal plains, hills and mountains with much developed lowland areas. The coastal plains of the Island are narrow, the most extensive of which is in the northeast where the state capital Georgetown is situated. The elevation ranges from zero to 830m and the climate is equatorial humid type. The study area is located in the eastern part of Penang Island. This area is more densely populated, urbanized and industrialized as compared to most part of the Island.

3. DATA AND METHODOLOGY

Land use and population data used in this study are obtained from the Urban Planning Department of Malaysia.
The main data required for the model include location and amount of urban land use change from 1990-2005 (Figure 2), access factors (Figure 3), physical constraints (protected areas: forest, water body) (Figure 4) and social factors (population, education) (Figure 5), which are extracted and processed from primary and secondary sources. Urban land use change data is extracted from urban land use change map comprises of land that has been converted to residential, commercial, industrial, transportation and public institution uses for the period of 15 years. They are classified here as urban. Access factors include road networks, city centers/sub-center, employment centres, shopping centres and airport. Penang International Airport is located in the study area and is the only airport located on the northern region of Malaysia. Roads in Malaysia have been classified into hierarchy of expressway, highways, secondary, primary and residential roads. In this study, in order to reduce the uncertainty in classification, only expressway, highway and other roads are identified. The same classification applies to the city centers/sub-centers where the state capital, Georgetown is the major centre and other second order centres are minor centres. Forest or hilly areas takes major percentage of the Penang Island. Population data is available at sub-district level.

GWR incorporates the spatial structure of the data into the estimation of the regression model’s parameters and shows how those estimates vary across space. It also provides the researcher with an analytical tool to explore changes in the relationship between variables over space. In this present study, relationships between urban land use change as dependent variable and the independent variables are modeled using conventional ordinary least squares (OLS) and geographically weighted regression (GWR). Urban land use change model for the study area are developed using OLS and GWR tools. The amount of land use change between 1990 and 2005 is obtained by subtracting urban land area of 2005 to that of 1990. The urban land area of the study site has increased from 4958 hectares in 1990 to 6428 hectares in 2005, which shows an increase of 30 percent over the 15 year period. A total of 4584 square grids of 250m x 250m are generated covering the study area and a centroid of each grid is used as a reference point for spatial analysis and GWR modeling. The geographic location (i.e. x,y coordinates) of each grid centroid, information on urban change and independent variables are stored in an attribute table. Hypothesizing that proximity of the independent variables to the location of new growth influenced the change, GIS spatial analysis is carried out for each variable and stored as attribute in each grid. The land use change is mapped and intersected with the grid layer to calculate the amount of urban land use in each grid. Each grid is equivalent to 6.25 hectares. The proximity between geographic location of each grid and the spatial factors is calculated using Euclidean distance. GWR coefficients and local $R^2$ values are mapped to explore spatial variability of relationships between explanatory variables and the land use change. Finally, an F test is used to determine whether the GWR estimates are a significant improvement on the traditional globally estimated OLS and results are compared based on Akaike Information Criterion (AIC). Lower values of AIC indicate a closer fit to the data.
Figure 2. Variables used in the analysis: (a) Urban Growth from 1990 to 2000, (b) Access Factors, (c) Physical Constraints, and (d) Population Concentration 1990

Table 1. Variables used in present study

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent variable:</td>
<td></td>
</tr>
<tr>
<td>URB</td>
<td>Amount of urban land growth 1990-2000 (in hectare)</td>
</tr>
</tbody>
</table>

Independent variables:

- PExp: Proximity to nearest expressway
- PGtown: Proximity to Georgetown
- PMncity: Proximity to the nearest minor city centres
- PHway: Proximity to nearest highway
- PAirpt: Proximity to nearest airport
- PEduc: Proximity to educational institutions
- PMjrs: Proximity to nearest major road
- PFores: Proximity to nearest forest reserve
- PPopctr: Proximity to population concentration centres
- PCont120: Proximity to contour of 120 meters
- PAvln: Proximity to land available for development in 1990 (ha)
4. RESULTS

Results reveal that GWR models exhibited a significant improvement in explained variance as compared to the OLS regression models. The AIC score for GWR model decreased from 13586.1 to 13537.5 which reflect better goodness of fit than the global OLS (Table 1). AIC is a measure of spatial collinearity within the model data. The lower is the value of AIC; the better the fit is the model to observed data. This suggests that GWR model for Penang Island is better than the OLS model based on the AIC.

Table 2. Results of ANOVA test for GWR over the OLS urban land use change models

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLS Residuals</td>
<td>5169.7</td>
<td>12.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWR Improvement</td>
<td>285.9</td>
<td>103.09</td>
<td>2.7732</td>
<td>2.5375</td>
</tr>
<tr>
<td>GWR Residuals</td>
<td>4883.9</td>
<td>4468.91</td>
<td>1.0929</td>
<td></td>
</tr>
</tbody>
</table>

GWR Akaike Information Criterion: 13537.5 (OLS: 13586.1)

The summary results of the Global OLS and GWR models are presented (Table 3). The results of Global OLS models suggest that urban land use is positively related to predictor variables but the high amount of variation remains unexplained. Moreover, the low r-square (0.36) suggest that approximately 40% of variance of the urban land use growth in the study area can be explained by the explanatory variables whereas 60% of the variance still remains unexplained. The \( t \) statistics of the estimated parameters reveal that only 4 variables are statistically significant and explaining the variation in urban land use change. GWR models on the other hand explained about 60% of the variance and all the variables are statistically significant in explaining the change in the urban land change in the Penang Island. The Monte-Carlo test shows that all the predictor variables displayed significant non-stationarity and indicating spatial variation in the relationship between urban land use change and predictors variables. The intercept also showed significant non-stationarity in GWR model. Based on these results, it can be inferred that modelling this relationship with Global OLS regression attains with high amount of uncertainty.

Table 3. Summary results of the Global OLS and GWR model

<table>
<thead>
<tr>
<th>Variables</th>
<th>( \beta )</th>
<th>( t )</th>
<th>p-value *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.20</td>
<td>0.86</td>
<td>0.00***</td>
</tr>
<tr>
<td>PUrb90</td>
<td>-0.00</td>
<td>-0.36</td>
<td>0.00***</td>
</tr>
<tr>
<td>PForest</td>
<td>0.00</td>
<td>1.42</td>
<td>0.00***</td>
</tr>
<tr>
<td>PGtown</td>
<td>0.00</td>
<td>2.24***</td>
<td>0.00***</td>
</tr>
<tr>
<td>PMnrcity</td>
<td>-0.00</td>
<td>-1.83</td>
<td>0.00***</td>
</tr>
<tr>
<td>PExp</td>
<td>-0.00</td>
<td>-1.90</td>
<td>0.00***</td>
</tr>
<tr>
<td>PHway</td>
<td>0.19</td>
<td>-2.23***</td>
<td>0.00***</td>
</tr>
<tr>
<td>PAirpt</td>
<td>-0.00</td>
<td>1.07</td>
<td>0.00***</td>
</tr>
<tr>
<td>PPopct</td>
<td>-0.00</td>
<td>-2.85***</td>
<td>0.00***</td>
</tr>
<tr>
<td>P Educ</td>
<td>-0.00</td>
<td>-1.52</td>
<td>0.00***</td>
</tr>
<tr>
<td>PAvland</td>
<td>-0.00</td>
<td>-3.95***</td>
<td>0.00***</td>
</tr>
<tr>
<td>PCont120</td>
<td>-0.00</td>
<td>-1.50</td>
<td>0.00***</td>
</tr>
<tr>
<td>N</td>
<td>4584</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted r-squared</td>
<td>0.36</td>
<td></td>
<td>0.68</td>
</tr>
</tbody>
</table>

*** = significant at .1% level

* Results of Monte Carlo test for spatial non-stationarity (Fotheringham, 2002)
Figure 3 shows the spatial distribution of the intercept and all the parameters of the GWR model. Intercept term or constant parameter determines the basic level of urban land use change without the effects of all the factors across the study area (Huang and Leung, 2002). Local estimates of intercept coefficient ($\beta_0$) range from a minimum of -27.32 to a maximum of 20.13 with a median of 1.36 instead of a constant (0.20) for the global

Figure 3 (a-k). Spatial variation of the parameter estimates of GWR model
regression. The result appears to show an apparent spatial variation in the constant parameter. All parameters are significant for GWR model and the parameter estimates are mapped to show the spatial variation. Figure 6 shows the spatial variation of the parameter estimates that are hypothesized to have influenced the change in the urban land use in Penang Island. Higher parameter estimate means that the effect of the variable is higher in that region as compared to other parts of the region (Huang and Leung, 2002). The darker is the shaded area the higher is the parameter estimates.

5. CONCLUSIONS AND RECOMMENDATIONS

The Penang Island has experienced tremendous urban growth since the opening of the Penang Bridge in 1989. This has resulted in-migration from the adjacent areas and the spatial structure of urban areas has changed with respect to diverse populace, morphology and their relationship to the core city. In order to improve our understanding of mechanism of these changes, in this present study we examined relationship between urban land use change and its driving forces. This relationship is tested using regression modelling approach by taking eastern region of Penang Island as a target study area because this area is densely populated, urbanized and industrialized as compared to most part of the Penang Island. The OLS and GWR models are developed to study the relationship between urban land use change and determinant factors. Results reveals that GWR models performed better and provide significant improvement over the global regression models. The global OLS models explained only about 40 percent of the variance in the urban land use change as compared to the GWR models which explained about 60 percent of the variance. This is because the GWR method has the advantage of providing local parameters estimates and reveals interesting pattern of spatial variation or non-stationarity of parameters. The spatial distribution of all parameters shows significant spatial variation with higher parameters in some parts of the region.

From sustainable spatial planning of view the present study is particularly important because the spatial characteristics of land use change are useful for understanding various impacts of human activity on the overall ecological condition of the urban environment (Yeh & Li, 1999). It has been widely accepted that the understanding of urbanization pattern and process at local scale is essential in guiding sustainable urban development. In Penang Island (target area) as per population demographic trends, the urbanization process is rapid and may undergo a high spatial restructuring process; therefore focus should be achieving sustainable urban landscapes by establishing sustainable equilibrium between ecological, social and economic functions of urban ecosystems. In order to accommodate growing urban population in a planned and sustainable manner, investigation of urban structure and morphology for planning proper infrastructure facilities becomes crucial. Using GWR approach there is a need of identification and spatio-temporal analysis of suburban areas as their connections with the core city is considered to be important. The spatial information of urban land use change is largely lacking for study area therefore the results of the present study can be utilized to develop urban growth scenario for forecasting possible future changes which may leads towards sustainable urban land use planning. However, further studies with large number of data would require for more reliable predictions about urban land use changes in the region.

REFERENCES