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Research Article

Sustainable land development model for rapid growth areas using GIS

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Abstract. There has been worldwide concern for sustainable development especially after the 1992's Rio's UN Conference on Environment and Development. Rapid encroachment of urban development on valuable agricultural land will have great influence on whether sustainable development can be achieved. A sustainable land development model is developed using GIS in an attempt to control urban sprawl under rapid rural urbanization. The objective of the model is to ensure that equity between generations and efficiency in land use can be achieved in land development so that development can be sustained in the future. The model is used to study the impacts of agricultural land loss in Dongguan in 1988–93, a rapidly growing area in the Pearl River Delta of China. The impact of unplanned urban growth is evaluated by comparing the actual development with optimal development derived from the sustainable land development model. Land use problems are identified in both spatial and time dimensions as some land conversions are found to occur at the 'wrong' time and locations. Future land development which can meet the objective of sustainable development is proposed using the model. By testing different development scenarios and land consumption parameters, planners and government officials can use the model as a decision support system for sustainable land development in areas in the world that are under great pressure of rapid urban growth.

1. Introduction

Rapid land use change has been witnessed in China since economic reform. A pressing problem is the substantial loss of fertile agricultural land in many coastal cities because of short-term economic considerations. China is among the nations with the lowest per capita land resource in the world (Chang and Kwok 1990). Severe agricultural land loss will bring about significant impacts on its further economic development and social stability.

The Rio United Nations Conference on Environment and Development in June 1992 was an important Earth summit that attracted delegates from 183 countries and regions. In July of 1992, shortly after the conference, the State Planning Commission and the State Science and Technology Commission of China began to organize all concerned government agencies to undertake the formulation and implementation of China's national strategies for sustainable development—China's Agenda 21 (Administrative Centre for China's Agenda 21 1993). One of the main concerns of China in achieving sustainable development is the rapid encroachment of urban development on the valuable agricultural land. This is most severe in southern China and the coastal areas where the economy is developing very rapidly

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and the conflict between the environment and economic development is most severe. Rational use of land resource is possible if urban expansion in China is guided by the concept of sustainable development with the assistance of remote sensing and GIS. Environmental information systems have been proposed for planning sustainable land use (Hallett *et al.* 1996). But, there is a general lack of operational models for implementing the concepts of sustainable development in GIS. The objective of this paper is to develop an operational sustainable land development model using GIS in an attempt to minimize the impacts of urban development on agricultural land loss through sustainable land allocation. The goal of the sustainable land allocation is to arrange land development and land conservation properly so that the needs of the present generation and future generations can both be satisfied. Dongguan, a fast growing city in southern China with a large amount of land loss in recent years, was used to test the GIS sustainable land development model.

2. Sustainable development and sustainable land use

The recent concept of sustainable development is a modified derivative of the concepts of the limit to growth (Meadows *et al.* 1972) and carrying capacity (Dasmann 1964, Edwards and Fowle 1955, US Department of Housing and Urban Development 1978). It does not only stress the importance of resource in limiting economic growth but also draws people's attention to the need of developing methods of how to grow in harmony with the environment, emphasizing the potential complementarity between growth and environmental improvement (Markandya and Richardson 1992). The essence of this idea is to restrain development in a way that will not damage our environment. In the *Brundtland Report*, sustainable development is defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development 1987). 'Sustainable development' is also considered as 'a process of social and economic betterment that satisfies the needs and values and of all interest groups, while maintaining future options and conserving natural resources and diversity' (International Union for the Conservation of Nature 1980, p. 2).

There are different components of sustainable development. In order to sustain development, the supply and quality of major consumables and inputs to our daily lives and economic production such as air, water, energy, food, raw materials, land, and natural environment need to be taken care of. Land is important because it is where our energy, food, and raw materials come from and it is also the habitat for wildlife and fauna. Similar to other resources, it is a scarce commodity. Some of the destruction of this natural resource is irreversible. For example, the conversion of agricultural land into urban land will remove the food production ability forever. The use of land unsuitable for development may bring harm to both the natural environment and human life. For example, housing development through land reclamation may destroy wetland which is a valuable natural habitat for some wildlife, and may lead to their extinction. It will also lead to the loss of property and human life in case of flooding. We have to make sure that land is used properly.

Sustainable land use can be defined as land use that satisfies the needs of the current generation and maintains the opportunities for the needs of future generations. The arrangement of land use should allow future generations to be at least as well off as we are. With respect to sustainable development, three operational criteria can be used: (1) to maintain equity between generations in consuming land resource; (2) to consume the amount of cultivated land as little as possible while maintaining a reasonable rate of economic growth; and (3) if a certain amount of cultivated land has to be sacrificed for the growth of economy, the land of less importance to agriculture should be selected first.

3. Sustainable land development model

The above operational criteria can be developed into a sustainable land development model that deals with the interaction of land demand and land supply. Integrated remote sensing and GIS is used in implementing the model. Land demand is estimated through population projection. The criterion of equity in land consumption per capita discussed in the following section can be used to enable each generation to consume land resources fairly. Remote sensing is used to provide an inventory of the amount of land that can be available for urban development. The land suitability of the land supply is computed by the use of GIS. After the amount of land consumption for each time period is decided and the suitability of the land supply known, GIS modelling is performed to allocate land supply to meet land demand according to the principles of sustainable development (figure 1).

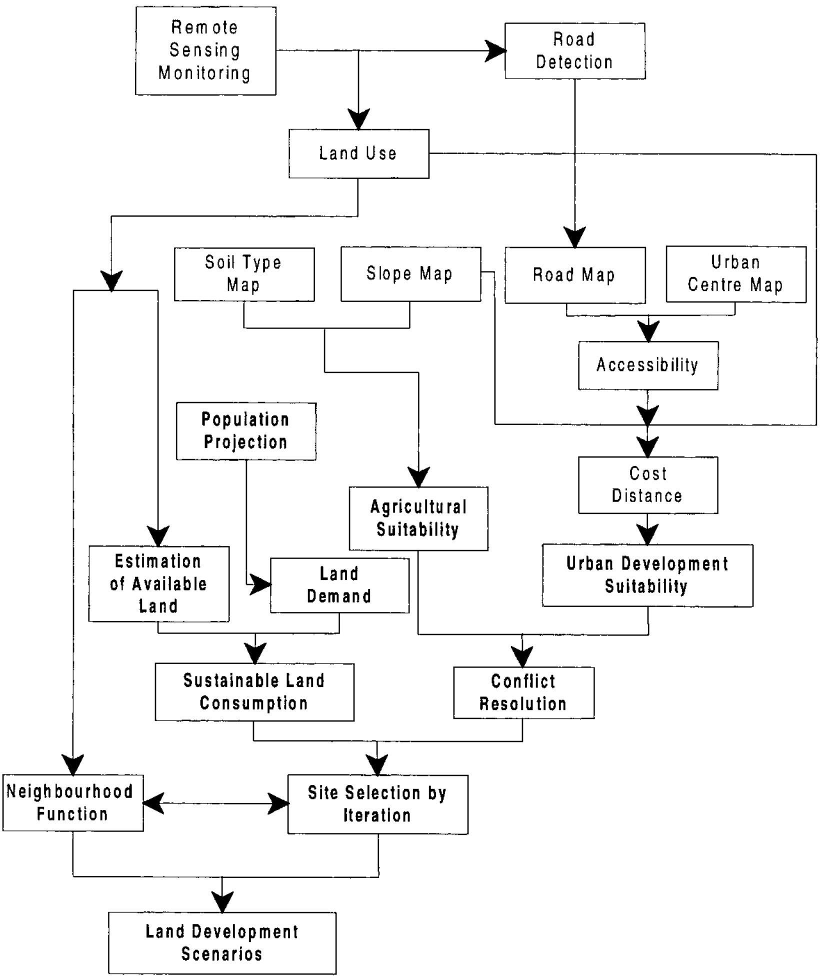

Figure 1. Sustainable land development modelling using remote sensing and GIS.

3.1. Land demand

The growth of urban population and economy creates urban land demand. More urban land will be needed to satisfy further growth of urban population and economy in the future. It is important to differentiate two types of land demand—present land demand and future land demand. Future land demand cannot be compromised in order to satisfy present land demand because future generations also need additional land resource as present generation needs it now. The criterion of between-generation equity is needed to justify whether a land demand is reasonable to all generations. It is argued that the equity between generations in land consumption should be implemented so that future generations can get access to a fair amount of land resource.

3.1.1. Per capita equity

The growth of population in a region will be expected to stabilize after the population comes close to or reaches its maximum limit. There are many factors that restrict the growth of population beyond the maximum limit. These factors may include water supply, housing provision, transport, pollution and available land. Urban planners need to arrange the quota of land consumption in the future years according to the growth of population. A simple way to realize equity between generations is to ensure that land consumption per capita is equal between years. Assuming that the total quantity of available land for development is Q_n and the total additional population is P_{na} in the whole period, under the per capita equity criteria, land consumption per capita should be Q_n/P_{na}. Therefore, land consumption Q_t in period t should be:

$$Q_t = P_{ta} Q_n / P_{na} \tag{1}$$

where Q_t is the planned land consumption and P_{ta} is the projected additional population in period t.

3.1.2. Tietenberg's equity

In environmental economics, demand and supply curve are considered to be influenced by price. It is assumed that the quantity demanded Q_d falls and quantity supplied Q_s increases as price P rises. The search for efficient allocation begins by establishing the marginal benefit and marginal cost functions. Given the ideal conditions, the demand function for a commodity is equal to the marginal benefit function for that commodity, and the supply function is equal to the marginal cost function for that commodity (Common 1988). Total benefit is simply the sum of the marginal benefit, and total cost is the sum of the marginal cost. Efficient allocation is to maximize the net benefit which equals the total benefit minus total cost. It is easy to show that the net benefit is maximized when the marginal benefit is equal to the marginal cost. The intersection of the marginal benefit (demand) and the marginal cost (supply) gives the output Q_0, at which the net benefit is maximized (figure 2).

Based on the theory of environmental economics, Tietenberg (1992) proposes a dynamic efficient allocation model which can be used to realize efficient resource allocation and maintain the equity between generations in different time periods. The model allows that a depletable, non-recyclable resource can be allocated using dynamic efficiency criteria. He considers that dynamic efficiency assumes that society's objective is to balance the current and subsequent uses of the resource by maximizing the present value of the net benefit derived from the use of the resource.

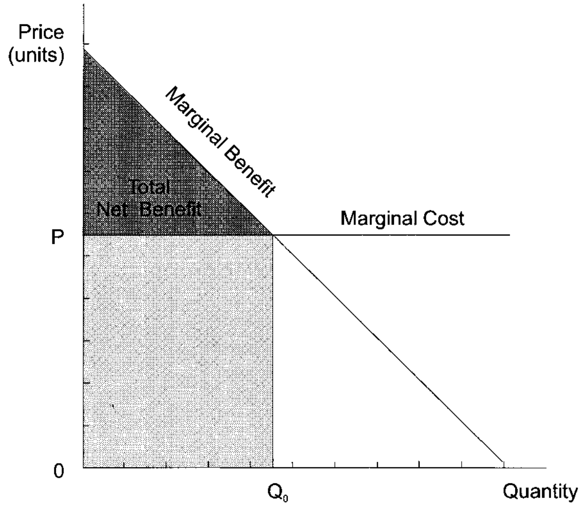

Figure 2. Maximizing total net benefit.

The time value of money is incorporated in the model. For example, a dollar today invested at a 10% interest rate will yield \$1·10 a year from now. Thus, the present value of a net benefit B_n received n years later is

$$B_n/(1+r)^n \tag{2}$$

where r is the interest rate.

The question is how to arrange the amount of resource used in different periods so that the total net benefit can be maximized, given the supply is fixed. Tietenberg assumes that the demand curve for a depletable resource is linear and stable over time. Thus, the inverse demand curve in year t can be written as:

$$P_t = a - bq_t \tag{3}$$

Then the total benefit TB from extracting an amount q_t in year t is the integral of equation (3):

$$\begin{aligned} TB &= \int (a - bq_t)\,dq_t \\ &= aq_t - bq_t^2/2 \end{aligned} \tag{4}$$

The marginal cost of extracting that resource is further assumed to be a constant c. The total cost TC of extracting the amount q_t is:

$$TC = cq_t \tag{5}$$

Then the dynamic efficient allocation of a resource over n years should satisfy the following maximization condition:

$$\underset{q_t}{\mathrm{Max}} \sum_{t=1}^{n} (aq_t - bq_t^2/2 - cq_t)/(1+r)^{t-1} + \lambda \left(Q - \sum_{t=1}^{n} q_t \right) \tag{6}$$

where Q is the total available amount of the resource supplied. Maximization can be achieved by solving the following equations:

$$(a - bq_t - c)/(1 + r)^{t-1} - \lambda = 0 \quad t = 1, \ldots, n \tag{6a}$$

$$Q - \sum_{t=1}^{n} q_t = 0 \tag{6b}$$

The solution of equation (6) yields a stream of q_t which is the proposed amount of resource consumed in each time period t. The summation of all q_t is equal to Q. A simple calculation can show that the model provides a solution for efficient allocation of resource. For example, assuming that the parameter values needed for the calculation are: $a = 100$, $b = 1$, $c = 20$, $r = 0{\cdot}10$, $Q = 50$, and the amount of resource supplied ($Q = 50$ units) needs to be allocated into only two separate periods, the results are: $q_1 = 27{\cdot}62$ and $q_2 = 22{\cdot}38$ units. It can be seen that more resource is allocated to the first period because of the existence of interest rate r. The total net benefit is 3228·14 from the two periods. One may believe that it will be fairer to allocate an average half of the resource for each period. However, the total net benefit is 3221·59 which is lower than that of the dynamic efficient allocation. Under very extraordinary circumstances, one may prefer to use all the resource in the first period, contrary to the concept of sustainable development. The net benefit is only 2750. It indicates that the consumption of all resource to satisfy the need of the current generation is inefficient in using the resource in the long run. Even the net benefit from the 'average' consumption is much better than that from the extraordinary consumption.

Furthermore, Tietenberg also demonstrates that the dynamic efficient allocation can be perfectly consistent with sustainability, providing that the gains are shared appropriately among generations. Some part of the extra gains should be saved for future generations. Because of the influence of the interest rate, future generations may get more benefit through inheriting the savings than the 'average' consumption. The essential process of the allocation is to achieve the greatest net benefit while maintaining the possibility with which future generations can be at least as well off as the current generation.

Tietenberg's equity can be modified to allocate land consumption in each period. In period t, the additional population P_t can be regarded as fixed. Thus, the marginal benefit falls as land consumption q_t or land consumption per capita q_t/P_{ta} increases (figure 3). The total net benefit in consuming a fixed quantity Q of land resource over n periods can be maximized to achieve efficient land use. Thus, the allocation of the land consumption q_t in each period t is obtained by the above maximization solution. There are the following equations:

$$(a - bq_t/P_{ta} - c)/(1 + r)^{t-1} - \lambda = 0 \quad t = 1, \ldots, n \tag{7a}$$

$$Q - \sum_{t=1}^{n} q_t = 0 \tag{7b}$$

where P_{ta} is the projected additional population in period t. When the discounting rate r is zero, this becomes:

$$q_1/P_{1a} = q_2/P_{2a} = q_3/P_{3a} = \cdots = q_n/P_{na} \tag{8}$$

This shows that when there is no discounting ($r = 0$), the modified Tietenberg's equity becomes a strict per capita equity.

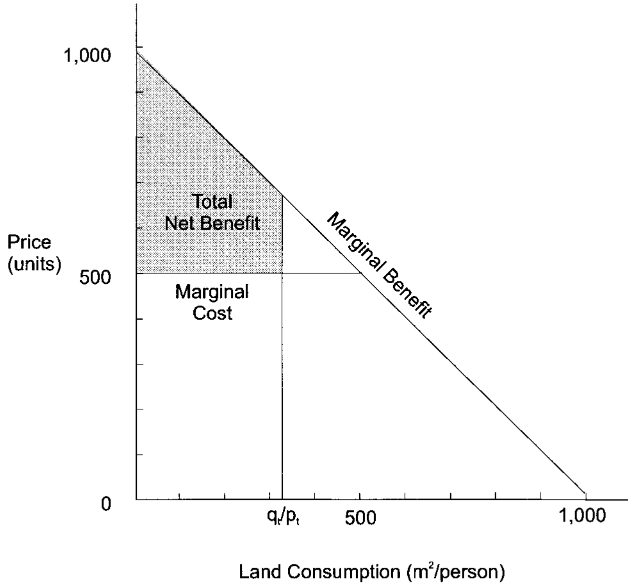

Figure 3. Marginal benefit and cost for land consumption per capita.

3.2. *Land supply and land suitability*

Land supply is related to two aspects—the amount and quality of land. The total amount of land supply is fixed because the area of a state or a city will not change, in most situations. The conversion of agricultural land into urban land is an irreversible process. It is apparent that the total available land for the conversion is decreasing. The quality of land can be assessed through land evaluation by producing suitability maps for various types of land uses. Land has two major attributes—geographical location and physical properties. These two attributes are important in deciding whether a piece of land is suitable for agricultural production or urban development.

3.2.1. *Geographical location*

The location of a piece of land has its meaning usually by its relative distance from an urban centre. Such distance can often decide the land value for this piece of land. Platt (1972) stresses the importance of location as a determinant of land use. Agricultural activities arrange themselves in space according to distance to the market and transport costs (Chisholm 1964).

3.2.2. *Physical properties*

The physical properties of land consist of soil properties, water condition, topography and size. Agricultural production heavily depends on the quality of land which is highly influenced by soil properties. Some types of soil may not be suitable for growing some particular types of vegetation. Everything being equal, soil fertilities will determine the yield of the agricultural production. The water condition is a crucial factor in deciding land suitability for agricultural production. The construction of irrigation systems can resolve the problem of water shortage and thus improve production capability. Topography is also important in the evaluation of land suitability, especially in areas with complicated geomorphological features. Uneven relief deters both urban development and agricultural activities. Ratings for topography are used to evaluate its suitability for different land uses. The size of a piece of land is a parameter that needs to be considered for land development. Planners need to aggregate land uses so that the fragmentation of land uses can be avoided.

3.2.3. *Land suitability*

There are two major types of land suitability—urban development suitability and agricultural suitability. Urban development suitability is more related to locational factors, transport conditions and topographic features. A piece of land will be favourable for urban development if it is close to an urban centre or connected to an urban centre by an efficient highway. However, agricultural suitability is more related to soil types and topographic features. It is more productive to grow crops in flat land with high fertility. There are often conflicts between urban development suitability and agricultural suitability because a piece of land can be suitable to both types of land use. There is a need to resolve such conflicts of land uses.

3.3. *Modelling spatial efficiency in GIS for sustainable development*

The above discussion mainly focuses on the allocation of land resource at the right time. Spatial efficiency, on the other hand, addresses the issue of the allocation of land use at the right place. It can be achieved if the following conditions can be met: (1) the best agricultural land can be conserved; (2) land with the best location for development can be converted to urban uses to meet necessary demand; (3) the conflict of land use can be resolved properly; and (4) land development should not be carried out in a fragmented pattern.

Under no constraints, the criterion of spatial efficiency means that land with higher scores of the suitability for a specific land use should be selected first for that land use. More benefits may be generated if each type of land use is allocated to the most suitable land. However, there is often competition in the use of the same piece of land for different land uses. There is a need to tackle the problem of competing land use. Furthermore, the selection procedure should be subject to the constraint of spatial integrity to prevent fragmentation of land use. Fragmentation of land use can result in wasteful use of land resource because more facilities and other services have to be provided.

It is very complicated or even impossible to realize the above spatial efficiency with conventional methods because data needed for the decision are huge. In addition, the decision itself is rather complicated due to the involvement of multi-criteria. For instance, there are obvious conflicts in the allocation of land for either agricultural or urban use. Furthermore, uncertainties which are well acknowledged in urban planning require land use planning to be prepared using a scenario-approach.

GIS can help in selecting land with higher scores of urban development suitability for land conversion. Unfortunately, it has been shown in another study that the best location for urban development often falls on the best agricultural land (Yeh and Li 1996). It means that the solution to land allocation is faced with competing objectives. Eastman *et al.* (1993) offer a heuristic solution to the problem of multi-objective land allocation under the conditions of conflicting objectives such that large raster data sets may be handled using procedures that have an immediate intuitive appeal. The logic of this intuitive solution is illustrated by the diagrams in figure 4. The suitability map of each objective is created and put as an axis in a multi-dimensional space. In an extreme case which is to find the best land for an objective, just move

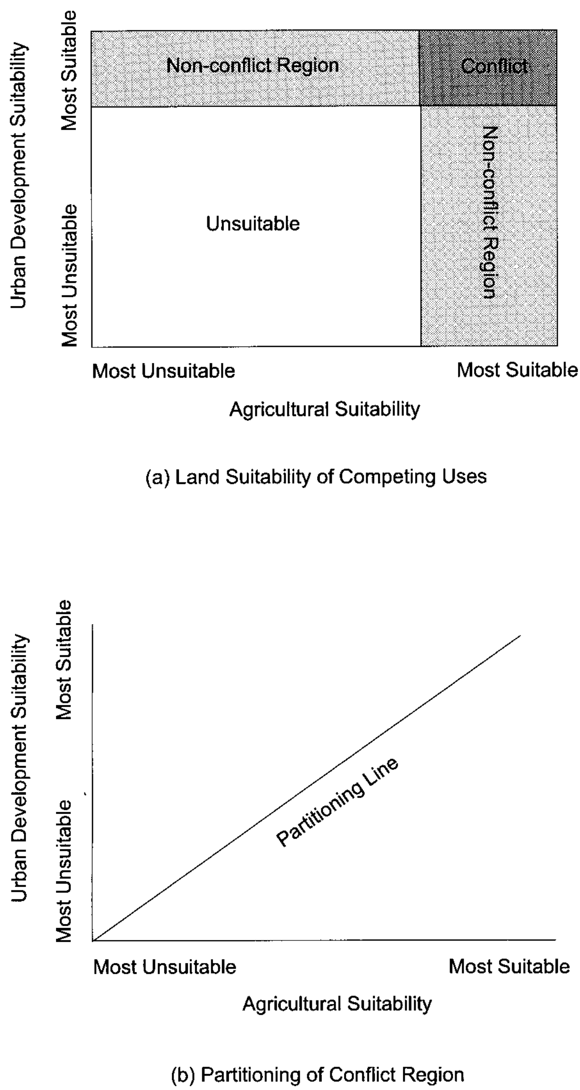

Figure 4. Competing land uses (*a*) and solution (*b*) (Eastman *et al.* 1993).

the decision line down from the top to a lower value until enough of the best land is located. The conflict is found in the area best for both objective 1 and objective 2. A simple partitioning of the affected cells can be used to resolve the conflict (figure 4). The decision space is partitioned into two regions so that cells are allocated to their closest ideal point. A 45° line between a pair of objectives assumes that they are given equal weight in the resolution of the conflict. The angle of the decision line can be altered by assigning different weights to competing uses.

Land allocation simply based on land suitability will lead to a fragmented pattern of land use because land is heterogeneous. Fragmentation is in conflict with the criteria of spatial efficiency because the cost will be higher for either urban development or resource conservation. A neighbourhood function using GIS is proposed to reduce the fragmentation in land allocation through the influence of neighbourhood land uses. A proposed land use will be given a higher possibility if the land use is compatible to its neighbouring land uses. The land suitability at a location (n) will be affected by the land uses in its neighbours. A gain in the suitability for land use W_i will be added to a location if the land use is also predominant amongst its neighbourhood. For example, cell A should have a gain in urban development suitability score because it is surrounded with many cells of urban land use (figure 5). In contrast, cell B should be assigned a negative gain because its neighbourhood cells are dominated by agricultural land use.

The influence of neighbourhood is exerted by multiplying the original suitability $S_n(W_i)$ with a neighbourhood function $Q_n(W_i)$ in each iteration of land allocation. The new set of suitability becomes:

$$S_n(W_i) = S_n(W_i) \times Q_n(W_i) \tag{9}$$

where $S_n(W_i)$ is the suitability of land use W_i in location (cell) n, and $Q_n(W_i)$ is the neighbourhood function. The neighbourhood function $Q_n(W_i)$ for a location (cell) n is devised to indicate the contribution from neighbourhood m to the suitability in a location n. A moving window will be used to calculate the proportion of W_j in the neighbourhood m of the location n:

$$P_m(W_j) = A_m(W_j)/A_m \quad m \in \Omega \tag{10}$$

where $A_m(W_j)$ is the area of land use W_j in the neighbourhood m, A_m is the total area of the neighbourhood, and Ω is a rectangular neighbourhood containing $k \times k$ pixels. Modification is made by the multiplication of the proportion $P_m(W_j)$ and the compatibility coefficient $p_{nm}(W_i | W_j)$. The coefficient $p_{nm}(W_i | W_j)$ is the probability that a location n will be in land use W_i if its neighbourhood is in land use W_j. Since all land use types from neighbourhood m have influence on location n, the total modification will be the sum of the contribution from all land use types. It is expressed as:

$$Q_n(W_i) = \sum_j p_{nm}(W_i | W_j) A_m(W_j)/A_m \tag{11}$$

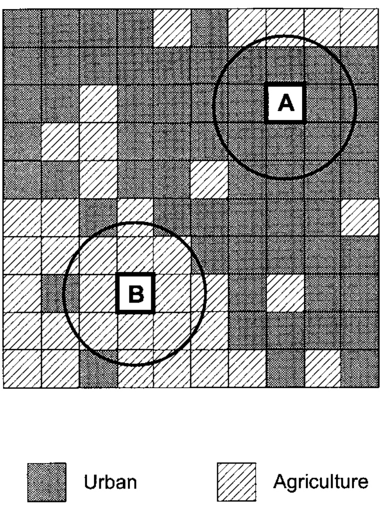

Figure 5. Neighbourhood influences on land suitability.

The sum of the full set of $p_{nm}(W_i|W_j)$ is equal to 1:

$$\sum_j p_{nm}(W_i|W_j) = 1 \tag{12}$$

Equation (9) can be written as an explicit iteration formula:

$$S_n^{k+1}(W_i) = S_n^k(W_i) \times Q_n(W_i) \tag{13}$$

The above formula enables GIS modelling to insert a neighbourhood function in each iteration of land allocation. n iterations can be defined to reduce the fragmentation of land uses. In each iteration of the dynamic land allocation, land suitabilities in each cell are modified according to previous land allocation. It encourages compatible land use patterns through the modification of land suitabilities.

4. Sustainable land development modelling using GIS—a case study of Dongguan, China

4.1. *The study area—Dongguan*

Dongguan is located north of Hong Kong and Shenzhen and south of Guangzhou at the eastern side of the Pearl River Delta (figure 6). It is a new city that was upgraded from a county to a city in 1985. In the past, it was mainly an agricultural area. Since 1985, the growth of industries has been more rapid than agricultural development. The average annual industrial growth rate was 37% in 1985–92, with some years over 45%, compared with 8·5% in agriculture. Concomitant to economic development was rapid urban development and the encroachment of urban development on the valuable agricultural land. Land development was especially rapid after

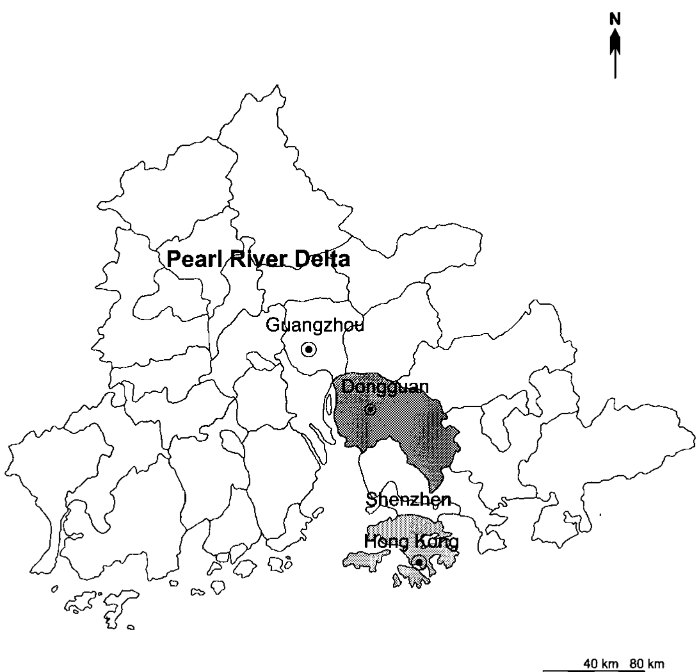

Figure 6. Location of Dongguan in the Pearl River Delta.

1990 because of the sudden property boom in the Pearl River Delta fuelled by the property boom in Hong Kong.

Dongguan has a total area of 2465 km^2. It consists of a city proper and 29 towns. The total permanent population in 1993 was 1·39 million and there were many temporary workers from other parts of Guangdong and China working in Dongguan. Significant land use change and loss of agricultural land can be observed in the whole city, but the magnitude of the loss has not been estimated and there is a lack of a plan to reconcile economic development with the loss of the valuable agricultural land. The integration of remote sensing and GIS provides an efficient way to help planners and decision makers to monitor land use changes and formulate sustainable development strategy to guide future urban growth (Yeh and Li 1997).

The major land use problem in Dongguan is to control encroachment on the best agricultural land. The integration of remote sensing and GIS was used to achieve sustainable land use allocation. The allocation of land may be considered to be optimal when the aggregate social returns from its various uses are maximized (Lopez *et al.* 1994). The sustainable land development model attempts to allocate land in both the time and spatial dimensions. The amount of land to be converted to urban use for each time period was based on the criterion of the equity between generations. Efficiency in spatial allocation was realized by reducing agricultural suitability loss and ensuring compact development.

4.2. *Amount of land supply and land consumption*

The city can support a maximum population of 4–5 million with regard to its water supply (Zeng *et al.* 1994). The growth of the population in the future was estimated according to the historical trend of the growth. The population of the city was 1 267 605 and 1 389 232 respectively in 1988 and 1993. The annual increase rate of the population was 1·9% during the period. By natural increase, the city needs about 72 years to reach its carrying capacity. It also needs to take floating population into account in land use planning. In China, planning authorities allow floating population to be considered in land use planning with 50% discount. It means that a floating population of 100 million are equal to 50 million registered population in land use planning. Assuming that the discounted additional floating population is equal to the additional registered population by the worst scenario of migration, the city needs about 40 years from 1988 to reach its maximum population.

The total available amount of land for future land development is estimated using remote sensing. Two Landsat–TM images dated 10 December 1988 and 22 November 1993 were used in the study (Yeh and Li 1996). In 1988, the city had 140 524·8 ha of agricultural land according to remote sensing data. It is assumed that only 30% of the total, or 42 157·4 ha of agricultural land, will be allowed for urban conversion because too much land loss will cause severe environmental impacts.

The modified Tietenberg's model was used to decide on the optimal allocation of the quantity of land consumption (42 157·4 ha) in the time period under study (40 years). It is assumed that the marginal benefit falls from 1000 to 0 units when land consumption per capita increases from 0 to 1000 m^2 per capita and that the marginal cost is constant as 500 units (figure 3). Under no discounting, each generation should obtain an equal quota of land consumption per capita. However, actual land development cannot disregard the influence of discounting which reflects economic growth, inflation and economic policy. Table 1 shows the result of the allocation of land consumption in each period based on the model with the

Table 1. Optimal allocation of land consumption with various discounting rates (r) in Dongguan for different time periods.

Years	Land consumption (in (hectares)		
	$r=0{\cdot}0$	$r=0{\cdot}1$	$r=0{\cdot}2$
1988–1993	3741·0	6527·1	8400·2
1994–1998	4100·0	6535·7	8381·5
1999–2003	4493·4	6418·2	8101·2
2004–2008	4924·5	6136·4	7452·1
2009–2013	5397·0	5643·0	6291·2
2014–2018	5914·8	4879·9	3531·2
2019–2023	6482·4	3775·4	0·0
2024–2028	7104·4	2241·7	0·0
Total	42 157·4	42 157·4	42 157·4

discounting rate $r=0$, 0·1 and 0·2 respectively. The results clearly demonstrate that a higher discounting rate will result in the depletion of land resource at an earlier stage. For example, when $r=0{\cdot}20$, the land resource will be depleted before 2018 based on the model.

The optimal quantities of land consumption in 1988–1993 and 1994–2005 were obtained when $r=0$ and $r=0{\cdot}1$. When $r=0$ (absolute equity), the optimal quantities of land consumption are 3741·0 and 10 563·1 ha respectively for 1988–1993 and 1994–2005. When $r=0{\cdot}1$ (discounting equity), the optimal quantities of land consumption are 6527·1 and 15 408·4 ha respectively for the two periods.

4.3. *Land suitability*

For a given amount of land provision, optimal spatial land allocation was performed to find the best sites for land development using GIS modelling. Before the allocation, urban suitability and agricultural suitability maps were created. Two variables, soil type and slope, were used for land suitability analysis. The 1:50 000 soil map of the 'comprehensive soil survey' in the 1980s was digitized. The contours of the relief map (1:50 000) were digitized and then converted into a digital terrain model (DTM). The TIN function in Arc/Info was used to create the slope map. In assessing land suitability for agriculture, two variables, soil types and slope, were given scores according to their suitability for agriculture. The rating was carried out according to experiences or field investigation. The rating may be adjusted so that the evaluation result can reflect the real situation. The criteria for the rating is to grade the land according to its likely yield, and various soil and site properties that influence yield are combined in a mathematical formula (McRae and Burnham 1981). The procedure began by rating soil types and slope degrees respectively on a continuous score. Table 2 provides a corresponding simplified 7-level ranked categories: 1—extremely unsuitable, 2—unsuitable, 3—less suitable, 4—suitable, 5—more suitable, 6—very suitable, 7—extremely suitable, according to the suitability for agriculture. Then a final score was obtained by adding the numerical continuous rating from the following formula:

$$AG\_SU = 0{\cdot}5S_{\text{soil}} + 0{\cdot}5S_{\text{slope}} \tag{14}$$

where S_{soil} and S_{slope} are the scores for soil and slope, and AG_SU is the agricultural suitability score.

Table 2. Rating scheme using the variables of soil types and slope for agricultural suitability.

Soil types		Slope (degree)	Score	Class
1. Paddy soil types	(1) No. 23, 27, 25, 26, 21 (Yield $>9000\ \mathrm{kg\ ha^{-1}}$)	0–2·5	150–120	7
	(2) No. 29, 17, 15, 42, 11, 22, 19, 2, 41 4, 8, 10, 24, 20 (Yield $=7500$–$9000\ \mathrm{kg\ ha^{-1}}$)	2·5–5	120–100	6
	(3) No. 13, 30, 7, 18, 37, 40, 33, 28, 38, 31, 12, 9, 3, 35, 36, 14 (Yield $=6000$–$7500\ \mathrm{kg\ ha^{-1}}$)	5–7·5	100–70	5
	(4) No. 32, 34, 6, 1, 39, 5, 16 (Yield $=4500$–$6000\ \mathrm{kg\ ha^{-1}}$)	7·5–10	70–60	4
2. Dry cultivated soil types	(1) No. 45, 46, 47, 48, 49, 52, 55, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64	10–15	60–25	3
3. Mountain soil types	(1) No. 44, 50, 51	15–30	25–15	2
	(2) No. 43, 65	>30	15–0	1

Land suitability was calculated by using GRID in Arc/Info. The final map was created by generalizing the final score into 7 categories. Thus, land which is rated 1 and 2 cannot be used for agricultural activities and land which is rated above 2 is suitable, and rated 7 is most suitable for agriculture.

Urban development suitability indicates the potential suitability of land for urban uses. The suitability is decided by two factors, distance (location) and slope. A site with close distance to an urban (town) centre is regarded to be of high value for urban development suitability. Cost-distance rather than Euclidean distance is used to measure the influence of transport condition and other costs. Instead of calculating the actual distance from one point to another, the cost-distance calculates the shortest accumulated cost of each cell to the closest target cell. The cost-distance reflects the 'true distance' better than Euclidean distance because other factors influencing distance can be considered in the cost-distance.

In the calculation, each normal cell was assigned a cost value of 1. The cells of various types of roads were assigned cost values of less than 1 because automobiles make the distance 'shorter' when running on a road. A cost value higher than 1 was thus assigned to the cells of water because crossing water will be more difficult than crossing land. The cost values for various types of cells are listed in table 3.

The COSTDISTANCE command in GRID of Arc/Info was used to calculate the cost distance for each cell:

$$\mathrm{CO\_D} = \mathrm{COSTDISTANCE(PTWN, COST)} \tag{15}$$

Table 3. Cost values used for various types of cells.

Cell types	Cost values
Normal cells	1·0
Water	3·0
Railway and express way	0·1
Main road	0·2
Other roads	0·3

where CO_D is the cost distance grid, PTWN is the grid with urban (town) centres and COST is the cost grid. The cost distance and the slope of each cell decides the urban development suitability of the cell. A cell with the higher values of the cost distance and slope will have a lower urban development score. The cost distance and the slope were rated respectively on a continuous score (table 4). Table 4 provides a correspondent simplified 7-level ranked categories: 1— extremely unsuitable, 2—unsuitable, 3—less suitable, 4—suitable, 5—more suitable, 6—very suitable, 7—extremely suitable, according to the suitability of urban development.

Then the final score of urban development suitability was obtained by adding the numerical continuous rating in (16) where S_CO_D and S_SLOPE are the rating values of the cost distance and slope with respect to urban development suitability, and SU_UR is the final rating of urban development suitability.

$$\mathrm{SU\_UR} = 0{\cdot}6\,\mathrm{S\_CO\_D} + 0{\cdot}4\,\mathrm{S\_SLOPE} \tag{16}$$

4.4. *Modelling spatial efficiency in GIS for sustainable development*

Given the total amount of land consumption, GIS modelling can be used to allocate agricultural land for urban development based on the criterion of spatial efficiency. There are five scenarios of the land consumption in Dongguan in the study period:

1988–1993 (past)

(1) the amount of land provided is the same as that of the actual land loss (21 285·7 ha) in 1988–93;
(2) the amount of land provided is 3741·0 ha when $r=0$;
(3) the amount of land provided is 6527·1 ha when $r=0{\cdot}1$;

1994–2005 (future)

(4) the amount of land provided is 10 563·1 ha when $r=0$; and
(5) the amount of land provided is 15 408·4 ha when $r=0{\cdot}1$.

Without constraints, the most efficient allocation is to allocate sites with higher scores of urban development suitability for urban development. Land development according to this allocation can generate higher economic benefits. However, it is argued that agricultural suitability should be involved in the model because there is a need to conserve the best agricultural land. The conflict between the two objectives was resolved using the partitioning method discussed above (Eastman *et al.* 1993). The partitioning line is 0·6SU_UR − 0·4SU_AG. A slightly higher weight is given to ‘urban’ objective because more emphasis is given to urban development.

Table 4. Rating scheme using variables of cost distance and slope for urban development suitability.

Cost distance	Slope	Score	Suitability class
0–1000	0–5	150–120	7
1000–2000	5–10	120–100	6
2000–3000	10–12	100–70	5
3000–4000	12–15	70–60	4
4000–5000	15–17	60–25	3
5000–10 000	17–25	25–15	2
>10 000	>25	15–0	1

Spatial integrity needs to be implemented during the modelling using the neighbourhood function. The allocation was performed with iterations so that the neighbourhood effect function was integrated in the allocation model to increase spatial efficiency. During each iteration of the spatial dynamic allocation, urban development suitability was modified according to the previous step of land use allocation. For example, if a cell is surrounded by many cells which have been selected as urban area in previous iterations, an increase of urban development suitability for the cell is created through the influence of the neighbourhood function. Three major land use types, urban use, crop, and orchard in the neighbourhood of a cell are considered to be important to influence the urban development suitability of the cell. Other land use types, e.g., water and forest, are considered as incompatible to urban use. The existence of the large proportion of these land use types in the neighbourhood should reduce urban development suitability. The compatibility coefficients are listed as follows:

$$p_{nm}(\text{urban}|\text{urban}) = 0{\cdot}5$$

$$p_{nm}(\text{urban}|\text{crop}) = 0{\cdot}3$$

$$p_{nm}(\text{urban}|\text{orchard}) = 0{\cdot}2$$

$$p_{nm}(\text{urban}|\text{others}) = 0$$

An AML program in Arc/Info GRID was developed for the detailed implementation of the sustainable land allocation. The program enables the sustainable land development model to improve spatial efficiency by taking land suitability and spatial integrity into considerations.

4.5. *Results of sustainable land development modelling using GIS*

The modified Tietenberg's equity will achieve more efficiency in using land resource through maximizing the total net benefit. The per capita equity guarantees that the same amount of per capita consumption is reserved for all generations. The emphasis on the equity between generations is useful for the better allocation of land resource. Apart from helping decision-makers and planners to allocate land for future development based on the principle of sustainable development, the model can also be used to evaluate past land consumption to see how far the actual land development deviates from the rational land development generated by the model.

Urban expansion and rural urbanization are proceeding at an astonishing rate with a significant amount of agricultural land loss each year in Dongguan (Yeh and Li 1997). The fast spread of the urban areas across the city can be clearly identified in the satellite images. If there is no measure to guide the land use pattern towards the direction of sustainable development, it is very questionable whether future generations can accept the cost of land loss. Under the trend of such land conversion, agricultural land in Dongguan will be depleted very soon, leading to other environmental problems.

The sustainable land development model was used to generate the optimal land allocation for 1988–1993 and 1994–2005. Figure 7 shows the actual land loss and the optimal land conversion generated by the model with the same amount of land consumption of 21 285·7 ha. Figure 8 shows the results of the optimal allocation of land development for 1994–2005 to achieve the best efficiency both in spatial and time dimensions according to the modified Tietenberg's equity when $r = 0{\cdot}1$ (discounting). It allows 15 408·4 ha of land loss for land development in this period (1994–2005).

(a)

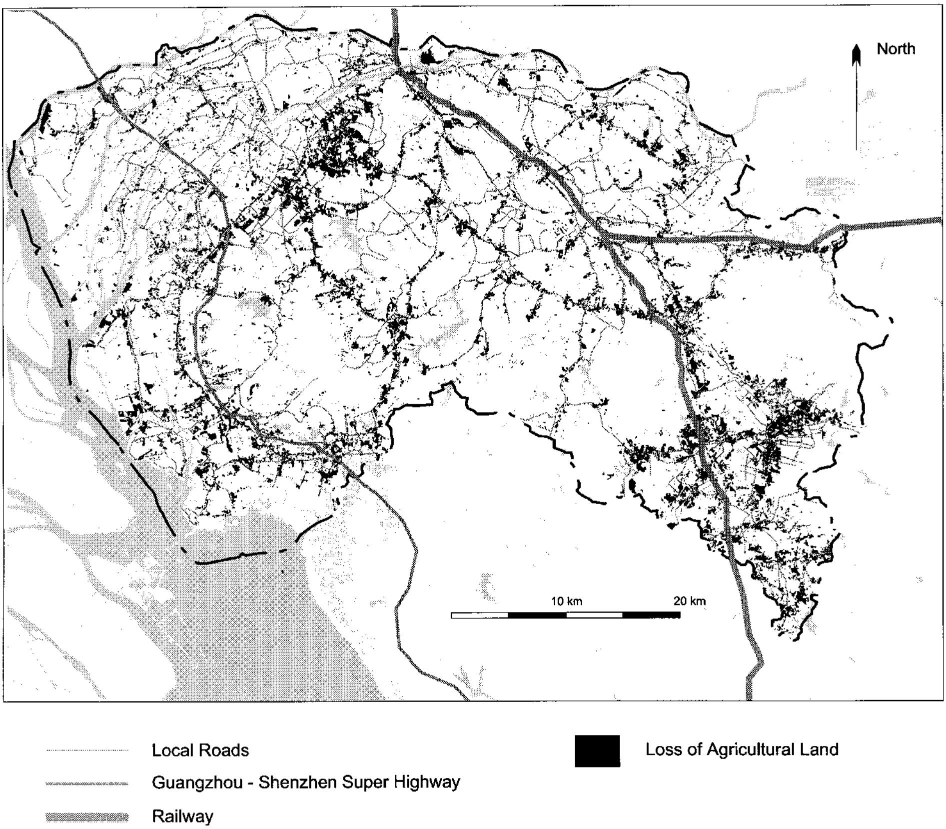

Figure 7. Comparison between actual (*a*) and optimal (*b*) land loss with the same amount of total land consumption in 1988–1993.

The comparison between the actual land loss pattern and the optimal land loss pattern (based on the modified Tietenberg's equity) was used to examine the land use problems in Dongguan in 1988–1993. It is found that the quantity of actual land loss in Dongguan in 1988–1993 exceeds the expected proportion which is calculated with the criteria of between-generation equity. The quantity of the actual land loss is as high as 21 285·7 ha while the expected should be 9687·4 ha and 2488·2 ha respectively based on the modified Tietenberg's equity and per capita equity. In both cases, the actual agricultural land consumption is much higher than the expected—about 2 to 9 times the expected. Therefore, the city should keep strict control on land development and reduce the amount of land loss with regard to the interest of future generations.

Even with the same amount of actual land loss in 1988–1993, better efficiency could be achieved if land development had proceeded based on spatial efficiency criteria. It is found that the actual development pattern lacks proper land use planning and the cost is greater than it should be. The comparison between the actual land loss pattern and the optimal development pattern highlights these land use problems (figure 7). Two simple indices, compactness (Ebdon 1985) and agricultural suitability loss S_{loss} can be used to evaluate the efficiency between the two

(b)

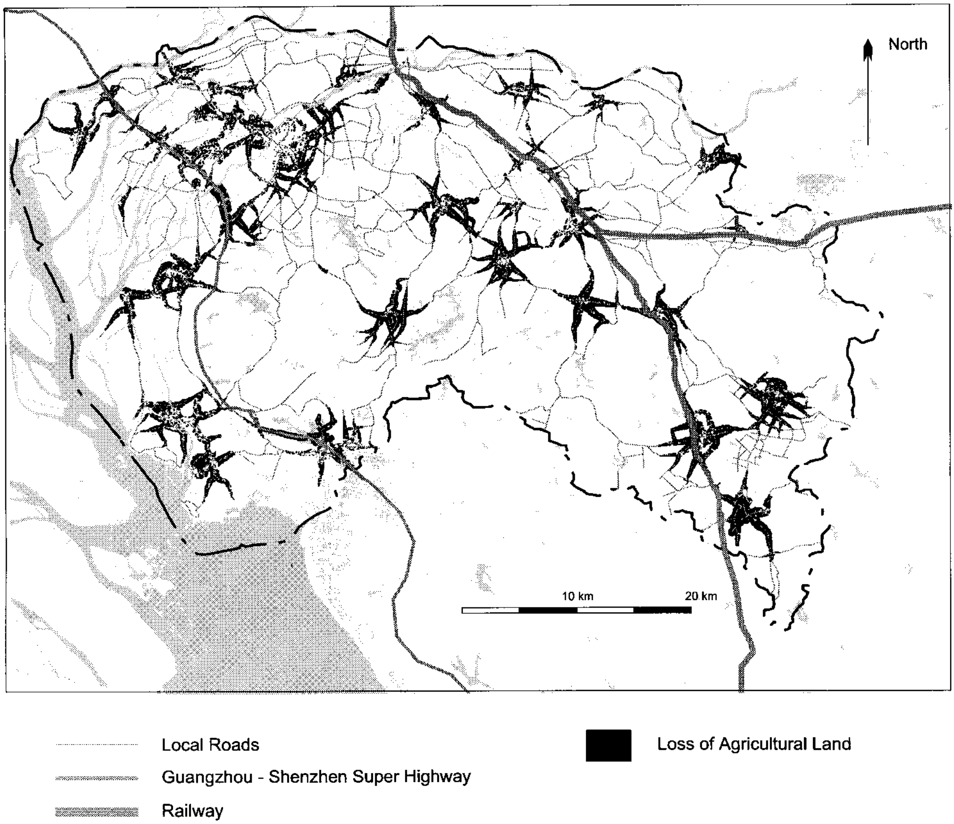

Figure 7. (*Continued*)

patterns. Given the same amount of land consumption, it is expected that the efficient land allocation should be in a pattern of more compact land uses and less agricultural suitability loss. The compactness index CI is:

$$\mathrm{CI} = \mathrm{Area}/\mathrm{Perimeter} \tag{17}$$

CI was calculated using Arc/Info GRID commands. The larger the value of CI, the more compact is the development.

Loss of good quality agricultural land is another aspect of land loss. As different land has different suitabilities to agriculture, the impact of land loss varies according to its agricultural land suitability. If a town has a large proportion of its land loss on the most fertile land, it will cause greater cost to agriculture than a town which is using less fertile land. Therefore, it is more appropriate to use agricultural suitability loss instead of area loss in the evaluation of land loss. The total loss of the agricultural suitability is:

$$S_{\mathrm{loss}} = \sum_{i} \sum_{j} S(i, j) \tag{18}$$

where S_{loss} is the total suitability loss, $S(i, j)$ is the suitability for agricultural type j

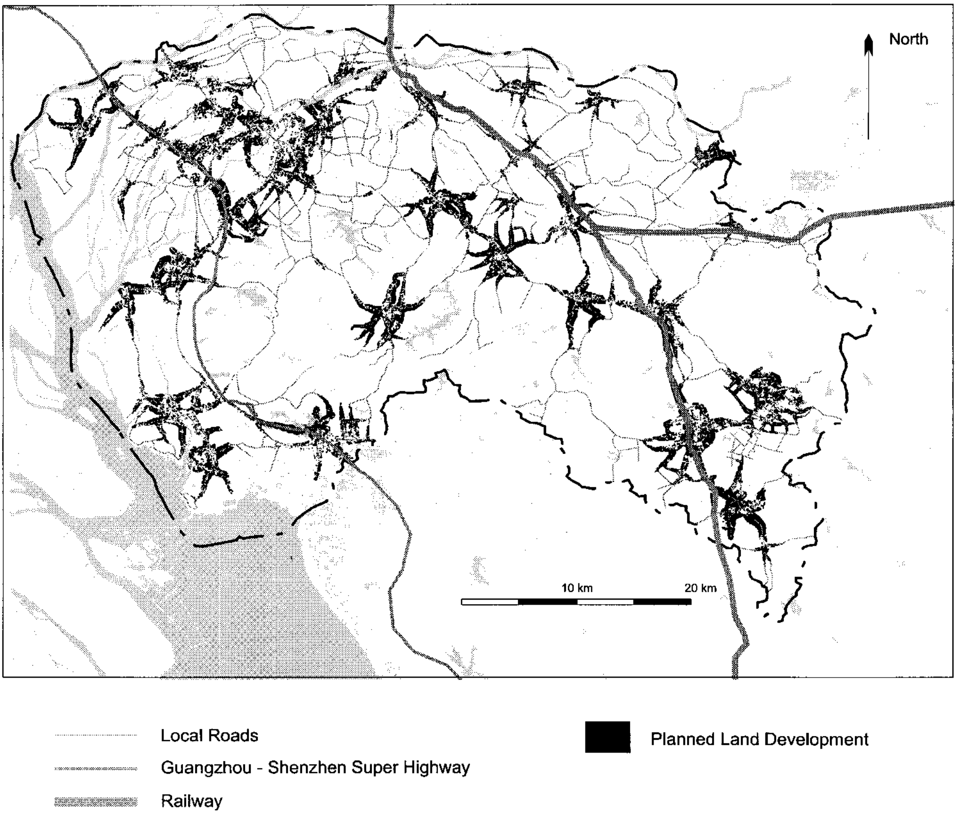

Figure 8. Optimal land development in 1994–2005 by the sustainable land development model (discounting $r = 0{\cdot}1$).

Table 5. Comparison of the efficiency between actual and optimal land loss with the same amount of land consumption in 1988–1993.

	Compactness index (CI)	Suitability loss (S_{loss})
Actual development	9·4	9·26E+06
Optimal development	23·5	8·90E+06

in location i where the land loss occurs. S_{loss} was calculated using Arc/Info GRID commands. The higher the value of S_{loss}, the more valuable agricultural land is lost.

Table 5 shows that the actual land loss is highly fragmented because its compactness index is less than half of that of the optimal model. There is also a decrease of suitability loss if the optimal land development model is used.

A further comparison of the concurrence of the actual land conversion and the optimal land conversion was carried out using the Summary function of GIS Analysis in ERDAS IMAGINE. Table 6 indicates that only about one fifth of the actual land conversion occurs on the exact locations expected by the optimal model. It means that a large proportion (80·1%) of the actual land conversion falls outside the optimal locations. The cost is unnecessarily high for the development pattern because it is not a spatially efficient development.

Table 6. Concurrence matrix of actual and optimal agricultural land loss with the same amount of land consumption in 1988–1993 (in ha).

Optimal development	Actual development		
	Converted	Not converted	Total
Should be converted	4098·7 (19·3%)	17 187·0 (9·4%)	21 285·7
Should not be converted	17 187·0 (80·7%)	204 882·5 (90·6%)	222 069·5
Total	21 258·7 (100·0%)	222 069·5 (100·0%)	

5. Conclusions

There has been worldwide concern for sustainable development especially after the 1992's Rio UN Conference on Environment and Development. Many countries have prepared Agenda 21 for the formulation and implementation of strategies for sustainable development. GIS is a useful tool for the formulation and implementation of sustainable development strategies, especially for those which are land and resource related. The sustainable land development model developed in this paper can provide an operational model for the implementation of the concepts of sustainable development. It allocates urban land use by minimizing the use of valuable agricultural land for urban development for the benefit of the future generation and the prevention of urban sprawl.

The main emphasis of the present study is the conservation of agricultural land because it is the most valuable resource in China for supporting its large population. Because of this, agricultural land suitability is the main input to the sustainable land development model. But, the sustainable land development model does not have to be confined to agricultural land use. It can be extended for the consideration of other environmental areas, such as forest and wetlands, by replacing agricultural land suitability with environmental suitability.

The sustainable land allocation scenarios can provide some guidelines for Dongguan's future land development. The result can help the city to avoid the chaotic and wasteful allocation of land resource if the model is accepted. Land allocation cannot be determined just by demand side, otherwise excessive land loss will happen. This was witnessed in Dongguan in 1988–1993. Future land development should consider the constraint of the available land resource from the supply side carefully in order to achieve sustainable development for the city.

By testing different development scenarios and land consumption parameters, planners and government officials can use the GIS sustainable land development model as a decision support system for sustainable land development in areas in the world that are under great pressure of rapid urban growth. The model will be able to suggest areas where future urban development should take place. Planners could use this as a guide in developing their strategic plans to meet the objectives of sustainable development.

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