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Land-use suitability analysis for urban development in Beijing

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Abstract

On-going land-use suitability analyses are urgently needed for mega-cities as they experience rapid urban expansion and development. Noting the advantages of conventional methods concerning the independence and combination of assessment criteria, an Urban Development Land-use Suitability Mapping (UDLSM) approach is constructed herein based on opportunity and constraint criteria. Within this framework, two Multi-criteria Evaluation (MCE) methods, the Ideal Point Method (IPM) and Ordered Weighted Averaging (OWA), are used to generate the opportunity map. The protection map is obtained by means of constraint criteria utilizing the Boolean union operator. The suitability map is then generated by overlaying the opportunity and protection maps. By applying the UDLSM approach with the help of GIS tools, the urban development land-use suitability of Beijing, a mega-city and capital of China, is mapped and a sensitivity analysis undertaken to demonstrate the robustness of the new approach. Indirect validation is achieved by mutual comparisons of suitability maps resulting from the two MCE methods. Conflicting parcels of land are identified from the overlaying of the resultant map and two previous development blueprints for Beijing. The paper concludes by making some proposals aimed at improving the long-term urban development plans for Beijing.

Keywords: Urban Development, Land-use Suitability, Multi-criteria Evaluation, Ideal Point, Ordered Weighted Averaging, Beijing

1. Introduction

Land-use suitability analysis is a very important task faced by city planners and managers, the aim being to identify the most appropriate spatial pattern for future land use (Hopkins, 1977; Collins et al., 2001). In recent years, with the rapid development of GIS, land-use suitability analysis has been applied to a wide variety of planning situations including assessment of land suitable for agricultural activities (Feizizadeh & Blaschke, 2013), determination of land habitats for animal and plant species (Store & Kangas, 2001), landscape evaluation and planning (Girvetz et al., 2008), and regional planning and environmental impact assessment (Marull et al., 2007; Rojas et al., 2013). Researchers have carried out a large number of studies about land-use suitability and proposed many analysis methods, which can be categorized as follows: overlay mapping methods, Multi-criteria Evaluation (MCE) methods, and Artificial Intelligence (AI) methods (see Collins et al., 2001 and Malczewski, 2004).

Being easy to operate, the overlay mapping method is routinely applied in land-use suitability analysis (MacDougall, 1975; Steinitz et al., 1976; Tomlin, 1990). The core procedure involves overlay factors. Although overlay mapping developed as an enhanced version of the overlay factors method, it still has shortcomings such as inappropriate standardization of suitability maps and untested or unverified assumptions of independence among suitability criteria (Hopkins, 1977; Pereira & Duckstein, 1993). Therefore, the most popular approach is to use overlay mapping as a framework combined with other methods to analyze land-use suitability (McCloskey et al., 2011; Park et al., 2011).

Unlike overlay mapping, MCE methods take factors of independence and differences into consideration, leading to an incremental improvement in suitability analysis. MCE methods include Weighted Linear Combination (WLC) (Carver, 1991; Eastman, 1997), Weighted Potential-Constraint Method (Zong et al, 2007), Ideal Point Method (IPM) (Pereira & Duckstein, 1993; Jankowski, 1995), Analytic Hierarchy Process (Banai, 1993; Xiang & Whitley, 1994), Ordered Weighted Averaging (OWA) (Malczewski, 2006), Ecological Niche Suitability Model

(Ouyang & Wang, 1995) and so on. These methods incorporate many specific features, such as the use of Geographic Information Systems, rule-based algorithms, and data manipulation procedures. Multi-objective decisions are made by suitably combining geographic data and the preferences of experts and decision makers. Such methods are suitable for planning programs in ecology, landscaping, and land-use (Geneletti, 2005; Baja et al., 2007; Pourebrahim et al., 2011). However, MCE methods depend heavily on the input data which are assumed precise and accurate. Moreover, different standardization methods or different multi-criteria methods can lead to different land-use suitability patterns. With this in mind it has been suggested that two or more multi-criteria methods should be applied to dilute the effect of technique bias (Carver, 1991) and that a sensitivity study should be undertaken as part of any land-use suitability analysis (Lodwick et al., 1990).

AI is a general term covering a number of methods which can aid the model description of complex systems for inference and decision making using modern computational techniques, such as fuzzy logic (Burrough & Mcdonnell, 1998), matter-element analysis (Gong et al., 2012), artificial neural networks (Sui, 1993; Zhou & Civco, 1996), evolutionary algorithms (Krzanowski & Raper, 2001), and cellular automata (Batty & Xie, 1994). The black box nature of AI methods makes them tolerant of imprecision, ambiguity, uncertainty, and partial truth; hence AI methods are especially useful in situations where there is a lack of information about the problem posed and are also helpful for evaluating solutions to a given complex problem (Porta et al., 2013). Unfortunately, also due to their very nature, black box approaches can often be unconvincing (O’Sullivan & Unwin, 2003).

Taking stock of the brief review above, an Urban Development Land-use Suitability Mapping

(UDLSM) approach is proposed herein which uses overlay mapping combined with Ideal Point Method (IPM) and Ordered Weighted Averaging (OWA) approaches to generate suitability maps that are then compared to generate the resultant maps. These two MCE methods are selected because the multi-criteria involved are reasonably combined, and the results are applicable and convincing (see Jiang & Eastman, 2000 and Malczewski, 2004). Beijing, the capital city of China, is taken as the study area because it is suffering increasingly adverse ecological consequences from rapid, relatively uncontrolled urban expansion. By 2010, the urban population of Beijing reached 86% of the total population, with more than 200 km^2 of Beijing's previous farmland (in 2000) changed into development land. Importantly, no comprehensive urban development land suitability analysis has previously been undertaken for the whole of Beijing city other than some brief restrictive zone analyses presented in the *Beijing City Master Plan (2004-2020)* (*Master Plan* for short) (BMPG, 2003) and *Beijing Development Priority Zones Planning* (*Priority Zones Planning* for short) (BMPG, 2012). Using the UDLSM approach, a complete land-use suitability map for urban development for the whole of Beijing is generated herein, and the resultant maps used to re-evaluate the *Master Plan* and *Priority Zones Planning*. Suggestions and guidance are then offered to support long-term urban development planning in Beijing.

2. Methodology and Materials

2.1. Principles for land-use suitability analysis

Land-use suitability was first recorded around 2,500 BC in ancient China (Meng, 2005). Such records were mainly concerned with identification of suitable land for agricultural crops (see FAO, 1976) which presents the classical agricultural land suitability analysis framework) until massive industrialization and urbanization began to occur in the 18th Century. The origins of ecological planning of expanded land suitability for urban and regional development are to be found in the late 19th and early 20th Centuries (Steiner et al., 1987). Charles Elliot and Warren Manning (Miller, 1993; Mcharg, 1996) are credited as pioneers who developed hand-drawn overlay techniques (i.e. firstly using **sun-print overlay**) for land suitability analysis. However, the early hand-drawn overlays omitted theoretical explanations for their rationale, and land suitability was addressed from an economic perspective rather than an environmental one (Collins et al., 2001). In the 1950s, Jacqueline Tyrwhitt (Steinitz et al., 1976) made a significant advance in land suitability analysis through the use of **transparent overlays** of four maps of relief, hydrology, rock type, and soil drainage. This was followed in the 1960s by the **ecological inventory process** of McHarg (1969) which combined natural and man-made attributes of the environment aimed at indicating the most suitable locations for various land uses such that they maximized economic benefits while minimizing environmental damage (Collins et al., 2001). This classical overlay procedure, called the McHargian method of ecological planning (Steiner et al., 1987) or simply McHarg's approach (Malczewski, 2004), is regarded as the precursor of **ecological suitability analysis** by Chinese researchers (Ouyang & Wang, 1995; Yang et al., 2009). In McHarg’s approach, the ecological factors addressed in land-use suitability analysis included forest values, scenic values, wildlife values, water values, recreation values, historic values, land values as well as physical factors (see McHarg, 1969). Few socio-economic factors were brought into land-use suitability analysis until "Land Evaluation and Site Assessment (LESA)" was proposed by the U.S. Department of Agriculture in 1980s (Meng, 2005). With advances in the scientific theories and methods concerning land evaluation, the ecological inventory process gradually extended from physical factors to cover ecological factors and economic-cultural factors (see Boyden, 1981 and McHarg, 1981). Regarding the criteria for land-use suitability for urban development, physical and ecological factors were selected for the analysis of State island (McHarg, 1969), proximity to road, proximity to main town, slope gradient, and distance from a wildlife reserve were addressed in evaluation of areas suitable for industrial development in Nakuru of Kenya (Jiang & Eastman, 2000), and topographic, geographic, and social factors were also used in mapping urban growth land suitability in South Korea (Park et al., 2011).

Although there appears to be no explicit definition of land suitability in the previous literature (to the knowledge of the present authors), its implications could be derived from researches and practices regarding to land suitability (McHarg, 1969; Hopkins, 1977; Steiner et al., 1987; Collins et al., 2001; Malczewski, 2004). Several points are pertinent concerning the principles of land-use suitability analysis. Firstly, land-use suitability is essentially the capacity or level of land suitable for prescribed uses (see Steiner et al., 2000; Collins et al., 2001; Marull et al., 2007). Secondly, the suitable land-use capacity or level involves collective physical, socio-economic, environmental, and ecological perspectives which are quantified through set criteria (see McHarg, 1981 and Collins et al., 2001). Land suitability analysis is therefore multi-disciplinary, involving physical science (e.g. geomorphology, geology, meteorology, hydrology, and soil mechanics), biophysical science (e.g. botany, and marine biology), social science (e.g. anthropology, economics, sociology, and politics) (McHarg, 1981), land science, ecology, and landscaping. Thirdly, the defined land uses can be categorized as developmental (namely urban, industrial, residential, extractive, transportation, circulation, etc.) (Marull et al., 2007) or non-developmental (i.e. agricultural, ecological, and geological) (Malczewski, 2004). In recent decades, growing attention has been paid to urban development land-use suitability owing to the severe environmental and ecological consequences worldwide of unabated urban sprawl. Lastly, suitability analysis or assessment is made according to specific requirements, preferences, or predictors of certain activities (Hopkins, 1977; Malczewski, 2004). Expert knowledge, the preferences of decision-makers, and public participation are represented in land suitability analysis by the scientific combination of real-world criteria.

2.2. Multi-criteria concerning urban development land suitability

Following the above principles, the land-use suitability analysis presented herein focuses on urban development. Criteria of land-use suitability for urban development are derived from multi-disciplinary scientific theories related to the physical, socio-economical, and ecological attributes. All criteria/factors for evaluation/analysis of land-use suitability fall within two categories, namely the opportunities and limitations/constraints of the environment (see Geddes, 1915; McHarg, 1969, 1981; Zong et al., 2007). The suitability analysis process essentially involves identification of opportunities and constraints for prescribed land-use(s) in a city or region or watershed. However, most physical and socio-economic factors have both permissive and restrictive features for a given land-use, which is determined by their spatial location (e.g. the factor slope, high gradient location restrictive and low gradient location permissive for urbanization). The resulting factor maps are used to reflect the degree of opportunity (or suitability) with rank values allocated to **all mapping units**. And then an ecological factor (e.g. forest value or historic value) is usually taken to represent the development constraint (or unsuitability) by means of rank values for **partial mapping units** in a specific area. The composite map of ecological factors has been variously called the suitability map for conservation (McHarg, 1969) or the protection map (McHarg, 1981).

Based on the principles behind suitability analysis and the present understanding of urban development suitability, two sets of criteria, i.e. opportunity criteria and constraint criteria, are utilized herein for urban development land-use suitability analysis. The set of opportunity criteria is structured using the physical and socio-economic factors listed in Fig.1. In considering the ecological impact, safety, and cost of urban development, the topography indicators comprise terrain elevation (S_1), slope (S_2), and geomorphological type (S_3), and the geology indicators are the engineering geological condition (S_4) and exposure to geological hazard (S_5). Socio-economic suitability is a composite of land use type (S_6), proximity to road (S_7) (city-level and country level), proximity to urban built-up area (S_8), population density (S_9), and air quality (S_{10}) (SO_2, NO_2, PM_{10}). Each indicator plays a different role in determining the degree of opportunity for urban development and so has a different weight. Rank values of all opportunity factors are combined with weights for each mapping unit. The set of constraint criteria is primarily concerned with conservation for which two levels of constraint are identified (namely, restrictive and prohibitive) for urban development. Surface water (C_1) (river, lake and reservoir), ground water (C_2), prime cropland preservation area (C_3), green belt (C_4), and piedmont ecological conservation area (C_5) are taken to be the restrictive factors for urban development. The prohibitive factors strictly protect against development and consist of world natural and cultural heritage (C_6), nature reserve (C_7), scenic resort and historic site (C_8), forest park (C_9), geopark (C_{10}), and source water protection area (C_{11}). These ecological constraint factors with negative rank values jointly represent protected or conservation areas by partial mapping unit (each constraint factor covers certain specific units rather than all units).

Fig.1 Physical and socio-economic factors in terms of opportunity for urban development

2.3. Urban development land suitability mapping

Using the opportunity and constraint criteria, the capacity of land suitable for urban development is mapped by an overlay of the opportunity map and the protection map. The former is generated using the preselected IPM or OWA approach. And a Boolean union operator is used to combine all the constraint factors into a protection map. All mappings are carried out using GIS tools.

2.3.1. Opportunity mapping

(1) Ideal Point Method (IPM)

The IPM (Zeleny, 1982) orders a set of alternatives on the basis of their separation from an ideal point. This point represents a hypothetical alternative that consists of the most desirable levels of each criterion across the alternatives under consideration. The alternative which is closest to the ideal point is the best alternative. Here, we use a method based on the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to choose the best alternative, aided by GIS tools (Hwang et al., 1993). TOPSIS is a very popular approach among MCE methods, and is widely used in land siting, and land-use analysis (Ekmekçioğlu et al., 2010; Soltanmohammadi et al., 2010).

The estimated impacts of alternatives on every criterion for every unit are organized into a decision matrix **D** and associated weight vector **w** given by:

$$\mathbf{D} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \qquad \mathbf{w} = \begin{bmatrix} w_1 & w_2 & \cdots, & w_n \end{bmatrix}^{\mathrm{T}} \tag{3}$$

where x_{ij} is the criteria value, i represents the grid cell of each criterion raster layer in Arcgis, j

represents criteria, and w_j represents each criterion's weight. There are a total of m grid cells and n criteria. In this case, the weights are determined by Delphi and AHP methods. Then the criterion values are aggregated in the following standardized format,

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{bmatrix} \text{ in which } p_{ij} = \frac{x_{ij}}{\overline{x}_j} w_j \tag{4}$$

where $\overline{x}_j$ is the mean value of column vector j, where j=1, 2…, n. Hence, $\overline{x}_j$ is the mean value of the raster map of criterion j. For each criterion j, an ideal point M_{1j} and a negative ideal point M_{2j} are defined according to the nature of the criterion and its impact on urban development land-use. Using the Euclid norm as a distance measure, the distance between criterion value and M_{1j} / M_{2j} can be calculated as follows,

$$S_{1_i} = \sqrt{\sum_{j=1}^{n} (p_{ij} - M_{1j})^2}\,, \quad S_{2_i} = \sqrt{\sum_{j=1}^{n} (p_{ij} - M_{2j})^2} \quad (i = 1, 2\ldots, m) \tag{5}$$

Then the similarity is given by,

$$T_i = \frac{S_{2_i}}{S_{1_i} + S_{2_i}} \quad (i = 1, 2\ldots, m) \tag{6}$$

$T_i \in [0,1]$. All the calculations are undertaken using Arcgis. After transforming all criteria data into raster format with level values ranging from 1 to 5, the raster layers are further standardized and overlaid with each other using raster calculator tools. The opportunity degree is ranked according to T-values, such that the larger the T-value, the higher the opportunity degree.

(2) Ordered Weighted Averaging (OWA) approach

Yager (1988) proposed OWA as a parameterized family of combination operators. OWA involves two sets of weights: criterion weights and order weights. Herein, the OWA formula is defined as follows:

$$\text{Opportunity Degree} = \sum_{j=1}^{n} \left(\frac{u_j v_j}{\sum_{j=1}^{n} u_j v_j} \right) Z_{ij} \qquad (7)$$

where Z_{ij} is the value of grid cell i corresponding to criterion j, u_j is the weight of criterion j, assigned according to the relationship between criterion j and urban development land suitability given the preferences of the decision-maker(s), indicating the relative importance of criterion j in the set of criteria under consideration and the way different criteria compensate for each other. The set of u is the same as the set of criteria weights w used in the ideal point method. v_j is the order weight which is assigned to an attribute value at a particular location after application of the criterion weights in decreasing order without considering from which attribute the value originates. The order weight is central to the OWA combination procedure. It controls the position of the aggregation operator on a continuum between the extremes of MIN and MAX, as well as a incorporating a trade-off measure indicating the degree of compensation between criteria (Jiang & Eastman, 2000). With different sets of order weights, one can generate a wide range of decision strategies, in terms of risk and tradeoff (Malczewski et al., 2003).

There are many approaches to obtain v_j. Noting the present research focus and the applicability of the foregoing approaches, a min-max disparity approach is used to obtain order weights (Wang & Parkan, 2005). The model is described as follows:

$$\text{Minimize } \{ \underset{j \in \{1,\ldots,n-1\}}{Max} \left| v_j - v_{j+1} \right| \}, \qquad (8)$$

$$\text{subject to } \alpha = \frac{1}{n-1} \sum_{j=1}^{n} (n-j) v_j \text{ , } 0 \le \alpha \le 1 \quad ,$$

$$\sum_{j=1}^{n} v_j = 1,\ 0 \le v_j \le 1,$$

in which α reflects the degree of ANDness and ORness. When $\alpha = 1$, ANDness = 1 and ORness = 0; $\alpha = 0$, then ANDness = 0 and ORness = 1. Besides,

$$\text{TRADEOFF} = 1 - \sqrt{\frac{n\sum(w_j - 1/n)^2}{n-1}} \tag{9}$$

Therefore, the value of α controls the position of the aggregation operator on a continuum between the extremes of MIN and MAX, as well as the degree of trade-off.

The calculation of order weights is undertaken using an Excel solver with an appropriate model. After loading the obtained order weights, criterion weights and criteria layers in raster format, the information is processed and transformed by Arcgis and IDRISI, using the OWA procedure of IDRISI decision support module. There the rank and calculation are undertaken automatically. When the result is generated, it is then loaded to Arcgis and further transformation and classification undertaken accordingly.

2.3.2. Protection mapping

To highlight ecological sensitivity, instead of carrying out a weighted analysis, we adopt a Boolean union operator in GIS tools to generate the protection map, which is confirmed by Liebig's law (von Liebig, 1840) in ecology. Since a higher restrictive level is represented by a more negative value, when undertaking the overlaying process, each unit retains the most negative value among all constraint factor layers as the final value. Areas with no restriction are assigned the value 0. In this way, the aggregated protection map is generated.

2.3.3. Suitability mapping

Comprehensive urban development land suitability values are determined by combining the opportunity and protection maps. In order for decision makers to be able to rank the results, the resultant map is classified into 5 levels as follows: *not suitable*, *marginally suitable*, *moderately suitable*, *suitable* and *highly suitable*. The k-means clustering tool in SPSS is used to classify the suitability levels, because once the number of levels is fixed, k-means clustering produces a result which ensures that data classified at different levels would have significant differences. This conforms to the present definition of suitability level.

2.4. Study area and materials

2.4.1. Study area

Beijing, the capital city of China, is situated at the northern extremity of the North China Plain and has an area of about 16,411 km^2. The geography of Beijing is characterized by alluvial plains in the south and east, and hills and mountains in the north, northwest and west. Over the past decade, the population of Beijing has increased from 13.9 million to 19.6 million, of which about 86 % is urban. During the same period, the GDP per capita surged from 17,900 to 71,900 Yuan. These increases are linked to rapid urbanization and the associated expansion of development land. By 2010, development land taken from farmland occupied an area greater than 200 km^2, approximately 21% of the total area of Beijing. Meanwhile, Beijing has been experiencing severe ecological degradation. For example, the area of wetlands in Beijing reduced from 4.07 % to 1.86 % from 1978 to 2005. Even though countermeasures have been implemented, such as the 3023 km^2 of land protected against exploitation following *Priority Zones Planning*, there nevertheless remains an intense conflict of interest between urban expansion and ecological protection. Rational land-use planning is urgently required in order to keep up with the pace of urban development, as well as to minimize negative ecological impacts.

2.4.2. Data sources

Table 1 summarizes the data sources used to evaluate each criterion. Fig. 2 depicts the maps obtained for each opportunity factor, compiled using Arcgis 9.3. The terrain elevation and slope data are derived from a 30 m x 30 m DEM of Beijing using a surface analysis process. The engineering geological condition and geological hazard exposure maps are digitized from hard copy maps. Data on proximity to road and proximity to urban built-up area are obtained from the Beijing road map and the 2008 Beijing land-use map respectively, using the buffer wizard in Arcgis 9.3. The population density is mapped using statistical census data from a digital administrative map also derived from the 2008 Beijing land-use map. Air quality data are collected for each administrative district on a digital administrative map derived from the 2008 Beijing land-use map. Restrictive factor maps and prohibitive factor maps are digitized from hard copies, and presented in a composite map of constraint factors (see Fig. 3).

Table 1 Information on the data used in the present research

Fig.2 Maps of topographic, geologic and socio-economic factors used as opportunity factors in this study. (a) S_1, (b) S_2, (c) S_3, (d) S_4, (e) S_5, (f) S_6 and S_8, (g) S_7, (h) S_9, (i) S_{10}

Fig.3 Composite map of constraint factors

2.4.3. Data standardization

All factor maps are normalized onto 100 m x 100 m grid layers. From the above multi-criteria database for all mapping units (grid), values are derived and standardized for the opportunity and constraint factors before combining these non-commensurate criteria. Unlike conventional standardization methods, such as linear transformation, a scoring and ranking system is used to quantify the opportunity and constraint levels which are from 1 to 5 (see Table 2 (a)) and -1 and

-0.6 (see Table 2 (b)) respectively. The scoring system is built according to relevant regulations and standards of Beijing (See Table 2) with a proper understanding of each factor's intrinsic properties and its impact on land suitability for urban development. Here, a higher score indicates higher degree of opportunity or lower degree of constraint. Of particular note is that, in the ideal point method, standardization is preferred to quantitative factors such as elevation, slope, air quality and population density.

Table 2(a) Ranking and scoring system of opportunity factors for urban development

Table 2(b) Ranking and scoring system of constraint factors for urban development

3. Results

3.1. The map resulting from IPM

Weights of opportunity factors are obtained by AHP and Delphi methods. The weights are based on a survey of the views of 9 experts in research fields of urban ecology, environmental planning, and environmental assessment. The information obtained from the survey is further processed by group decision-making and the comparison matrix established accordingly. Table 3 lists the final weights by which the synthesized opportunity map is overlaid. By overlaying the opportunity map with the protection map and reclassifying the result by k-means clustering method, the urban development land-use suitability distribution is generated, as shown in Fig. 4. The distribution indicates that the land-use suitability level decreases from central Beijing to the periphery, and decreases from the central, eastern and southern plains to mountainous regions to the west and north. The region of highest suitability is located at the central part of the city, whereas the region of lowest suitability roughly corresponds to areas where exploitation is prohibited by *Priority Zones Planning* including the Miyun, Guanting, and Huairou Reservoirs, and the Jinhai lake scenic area. *Suitable* and *highly suitable* areas for urban development occupy 890 km^2, i.e. 5.5 %, of the total area. *Marginally suitable* and *not suitable* areas cover 11669 km^2, i.e. 71 % of the total area of Beijing. The remaining 3842 km^2 area is *moderately suitable* for development.

Table 3 Opportunity factor weights

Fig.4 Land-use suitability generated by the ideal point method

3.2. The map resulting from OWA

The OWA approach provides various scenarios by altering the value of α. Since the present goal is to provide an urban development land-use suitability decision support system for Beijing that meets the requirements of many factors, takes into account the independence of each factor, and ensures the results are representative and applicable, a scenario is selected with the order weights calculated with $\alpha = 0.8$ as a reference case for further assessment and analysis. The choice of $\alpha = 0.8$ reflects a relatively strict standpoint that a region is only included provided most factors meet their thresholds (ANDness = 0.8). The trade-off degree is 0.68, which indicates a moderate trade-off effect between the factors. Table 3 and Table 4 list the criterion weights and order weights respectively. Fig. 5 shows the final urban development land-use suitability map. Fig.4 and Fig.5 exhibit almost the same distributions of degree of suitability. *Marginally suitable* and *not suitable* areas cover 11844 km^2, i.e. 72 % of the total area. The remaining 5567 km^2 area is suitable for urban development.

Table 4 the OWA order weights generated by the min-max disparity approach with α=0.8

Fig.5 Land-use suitability map generated by OWA approach

4. Discussion

A sensitivity analysis has been undertaken by altering the weights of the ten opportunity factors which directly affect the suitability result. However, altering the weights does not necessarily change the resultant suitability map. Taking the suitability map resulting from OWA, Table 5 indicates the map's sensitivity to a 20% increase in the initial weight assigned to each of the ten opportunity factors (when one is increased by 20%, the other nine are equally decreased by (20/9)% to keep the weight sum equal to 1). The high consistency (see Table 5, generated by a kappa analysis) indicates that the suitability map remains almost unchanged even though the absolute values of the degree of suitability change with the increased weight. Similar findings are obtained for a 20% increase of weights in the suitability map resulting from IPM and for a 20% decrease of weights in both of the maps. It may thus be concluded that the urban development land-use suitability map is stable despite small changes in the weights utilized by both methods.

Table 5 Sensitivity of suitability map to 20% increase in weights

The criteria system has been established according to the characteristics and requirements of urban development. Each criterion plays a unique and important role in determining the final suitability according to the criterion's intrinsic nature and relationship to land-use suitability for urban development (Section 2.2). The opportunity factors and constraint factors are derived scientifically from relevant disciplines including geology, geomorphology, hydrology, ecology, sociology, and economics. Moreover, the database for mapping criteria is collected from trusted primary sources, and the process by which criteria values are ranked is also strictly based on existing local regulations and standards (Table 2).

The MCE methods used herein to generate the opportunity map are particularly well suited to ensuring independence and combination of multi-criteria. The core of IPM involves assessing land on the basis of its separation from the best and the worst situations generated by the combinations of each factor with the most suitable and unsuitable values (set according to relevant standards and guidelines). The IPM generates complete sets of weights and ranks for each attribute, thus overcoming some of the disadvantages arising from lack of independence among attributes that affect conventional MCE methods. Multi-criteria are combined using calculations of their Euclidean distances from an ideal point. Hence, there is no need to impose a specific relationship between the factors and degree of opportunity; an advantage given that such relationships are still unclear and not necessarily linear (as assumed in other MCE methods). For the OWA approach, the introduction of criteria and order weights means that the results reflect not only the influence of each particular criterion and the interactions of the different criteria with each other, but also the attitudes of the decision makers. In addition to these advantages over conventional methods, the OWA functions also provide control of the degree of compensation among criteria. The choice of $\alpha = 0.8$ corresponds to strict decision making, and its 0.68 trade-off indicates moderate compensation among the factors, which maintains the independence of each criterion. Hence we conclude that the OWA approach provides more accurate results given its rational basis, and so is useful for providing practical decisions.

Table 6 lists the results obtained from a comparison between the suitability maps generated using the IMP and OWA approaches whereby the statistics of overall agreement were determined using spatial analysis and the contingency coefficients calculated using kappa analysis. Overall agreement is presented by the area that has the same degree of suitability as that of the total sum. The statistics of overall agreement and kappa are 70 % and 0.57 under a strict comparison of two maps involving five suitability levels, which indicate high agreement and moderate contingency according to Landis & Koch (1977). For a comparison involving two suitability levels (grouping *not suitable* and *marginally suitable* as *not suitable*, and the others as *suitable*), the overall agreement is as high as 91 % and the kappa coefficient is 0.78. In short, the IMP and OWA maps provide very similar spatial distributions of land-use suitability.

Table 6 Comparison of suitability maps between IMP and OWA

Using the suitability map, the *Master Plan* and *Priority Zones Planning* were evaluated in terms of the ecological fit between their spatial patterns. Fig.6 shows the OWA-derived suitability map overlain by urban development regions in the *Master Plan* and four functional zones from *Priority Zones Planning*. With regard to the *Master Plan*, most of the planned urban development regions are in accordance with areas classified as *moderately suitable*, *suitable*, and *highly suitable*, which confirms the *Master Plan* has a good ecological fit to the suitability map. There are four categories of function zones in *Priority Zones Planning*, namely the capital function core zone, the urban function expansion zone, the new urban development zone, and the ecological conservation zone (see Fig. 6). The first three zones are primarily related to development and roughly correspond to areas in the suitability map classified as *moderately suitable*, *suitable*, and *highly suitable*. The ecological conservation zone is consistent with areas that are *marginally suitable* and *not suitable* where most of the 63 protected areas named in *Priority Zones Planning* are situated, including world natural and cultural heritage sites, nature reserves, scenic resorts and historic sites, forest parks, geo-parks, and source water protection areas. The overlay map again indicates satisfactory ecological fit between the sustainability map and *Priority Zones Planning*.

However, there are a few specific land parcels earmarked for urban development that are located in areas classified as *marginally suitable* or *not suitable* which should be reconsidered by urban planners and decision makers. For example, the land parcels set aside for urban development in northwestern Daxing (A1 zone) and southern Tongzhou (A2 zone) are located in *marginally suitable* or *not suitable* areas (see Fig. 6). The main reason for these constraints is that the A1 zone occupies both green belt and groundwater source recharge areas, and the A2 zone is sited in an area of poor engineering geological condition containing some prime cropland. Both zones are affected negatively by a concentration of PM_{10} that is above the local air quality standard. The following suggestions are made to address these issues regarding the lack of ecological fit between the planning documents for Beijing and the suitability map. The A1 zone should be used for recreation or urban open space instead of residential, commercial, or industrial development. Where urban development is inevitable, the percentage of land used for such development should be limited to within 20 % of the total land area (in accordance with the local regulations concerning green belt areas). And countermeasures must be taken to prevent the pollution of groundwater sources, such as the use of perfect wastewater collection and drainage systems, operations that do not involve the digging of trenches, and the prohibition of heavily polluting industries. For the A2 zone, it is suggested that the priority should be to relocate urban development elsewhere in a more suitable area. Otherwise, should development of A2 be inevitable, then countermeasures should be implemented, perhaps by substituting the prime cropland that would be lost from A2 by the cropland elsewhere of the same quality and quantity, by paying reclamation fees, and improving the engineering geological conditions.

Fig.6 Suitability map of OWA overlaid with spatial patterns from the Beijing *Master Plan* and *Priority Zones Planning*

5. Conclusions

A UDLSM approach has been proposed for urban development land-use suitability analysis. The approach presents a criteria system of opportunities and constraints based on new principles for urban development suitability mapping. The Ideal Point Method (IPM) and Ordered Weighted Averaging (OWA) approach were introduced to generate the opportunity map, and a Boolean union operator was used for the composite constraint map. The two maps have been generated and converted into a resultant suitability map for Beijing using the UDLSM approach which divides the area of Beijing into five degrees of land-use suitability, namely *not suitable*, *marginally suitable*, *moderately suitable*, *suitable* and *highly suitable*. Around 28 % of the total land area is found to be suitable for urban development, mainly located in the plain, with the remaining land that is not suitable for further urban development occupying the majority of the 63 protected zones in Beijing. The resultant maps obtained using IPM and OWA methods exhibit very similar patterns of suitability degree; the overall agreement of 91 % and kappa coefficient of 0.78 indirectly validate the UDLSM approach. A sensitivity analysis shows that the UDLSM approach gives stable results when subjected to a uniform 20 % change in the weighting values. In general, the *Master plan* and *Priority Zones Planning* blueprints appear to have taken ecological fitness properly into consideration, although the present analysis indicates that there are a few land parcels whose planned use conflicts with the suitability map and where future countermeasures may be required.

Acknowledgments

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Figure captions:

Fig.1 Physical and socio-economic factors in terms of opportunity for urban development

Fig.2 Maps of topographic, geologic and socio-economic factors used as opportunity factors in this study. (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, (f) S6 and S8, (g) S7, (h) S9, (i) S10

Fig.3 Composite map of constraint factors

Fig.4 Land-use suitability generated by the ideal point method

Fig.5 Land-use suitability map generated by OWA approach

Fig.6 Suitability map of OWA overlaid with spatial patterns from the *Beijing Master Plan* and *Priority Zones Planning*

Figure 1

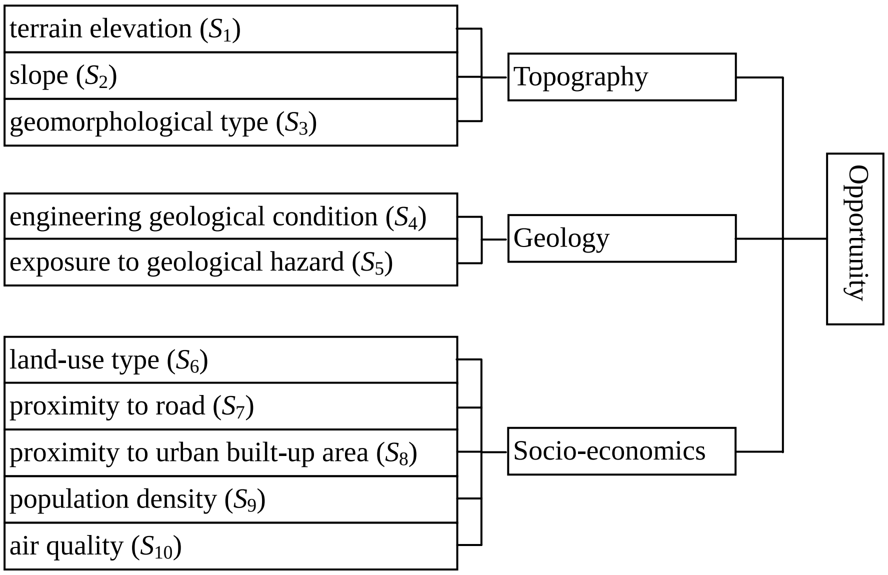

Fig.1 Physical and socio-economic factors in terms of opportunity for urban development

Figure 2

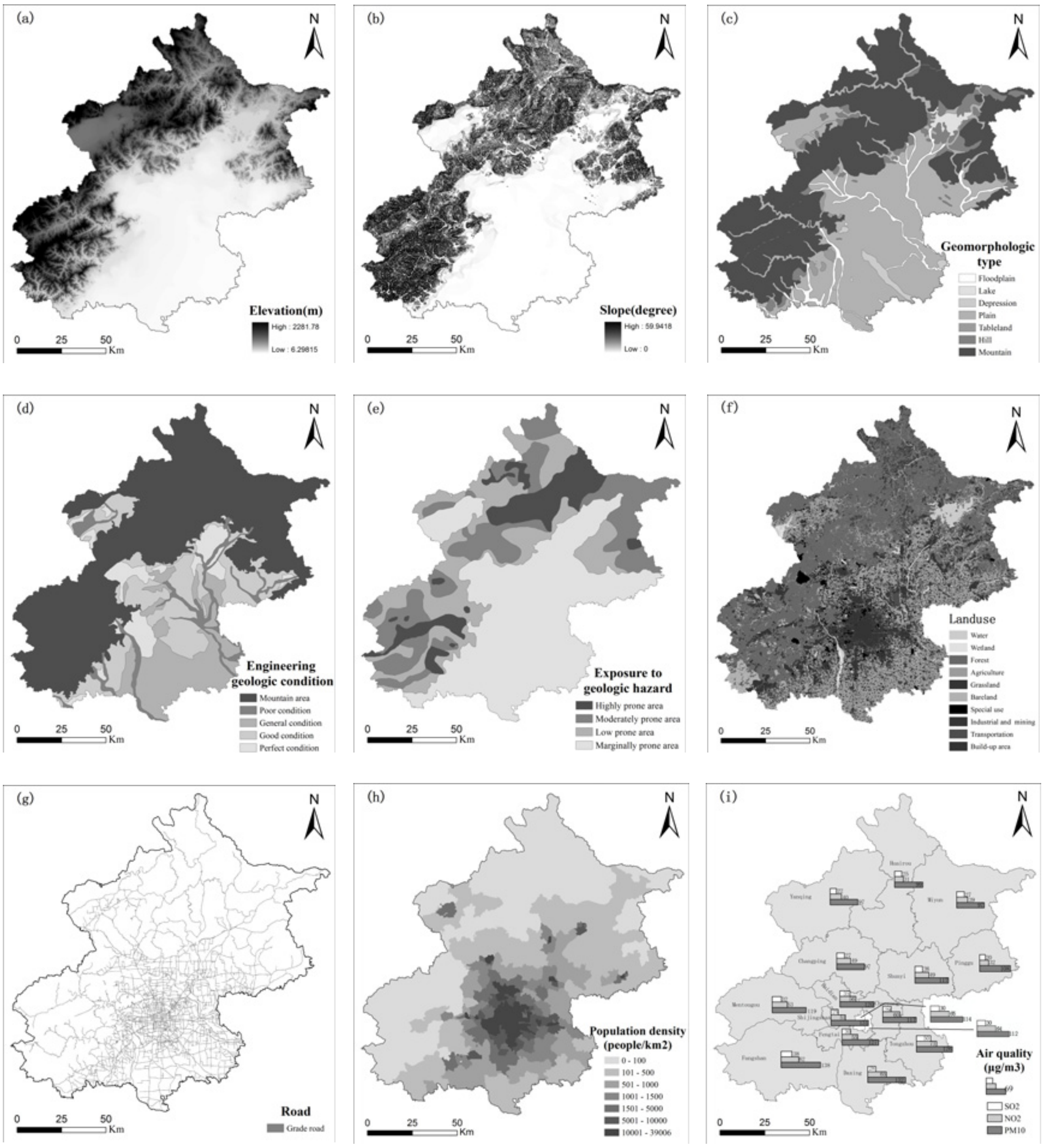

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Figure 3

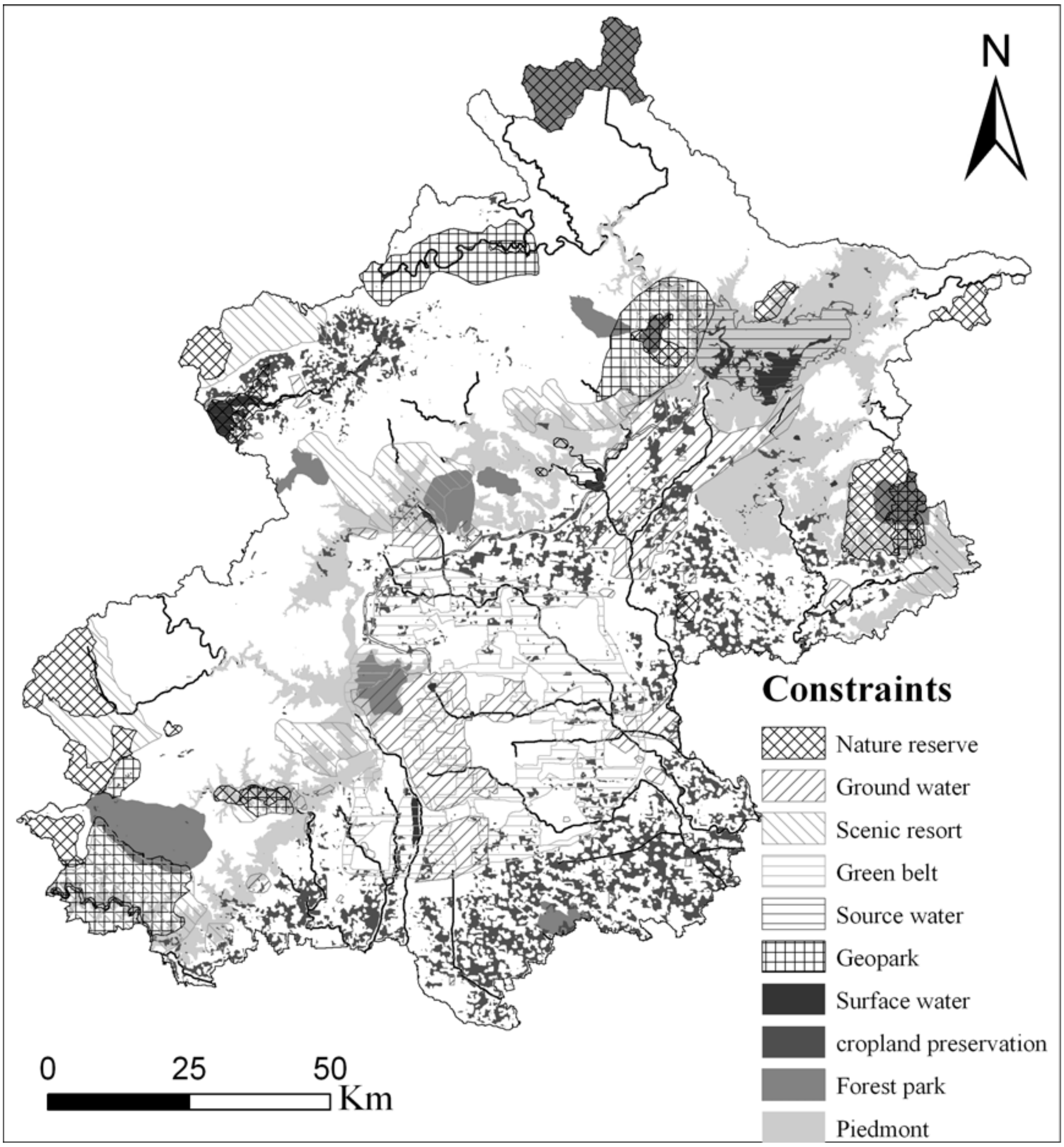

Fig.3 Composite map of constraint factors

Figure 4

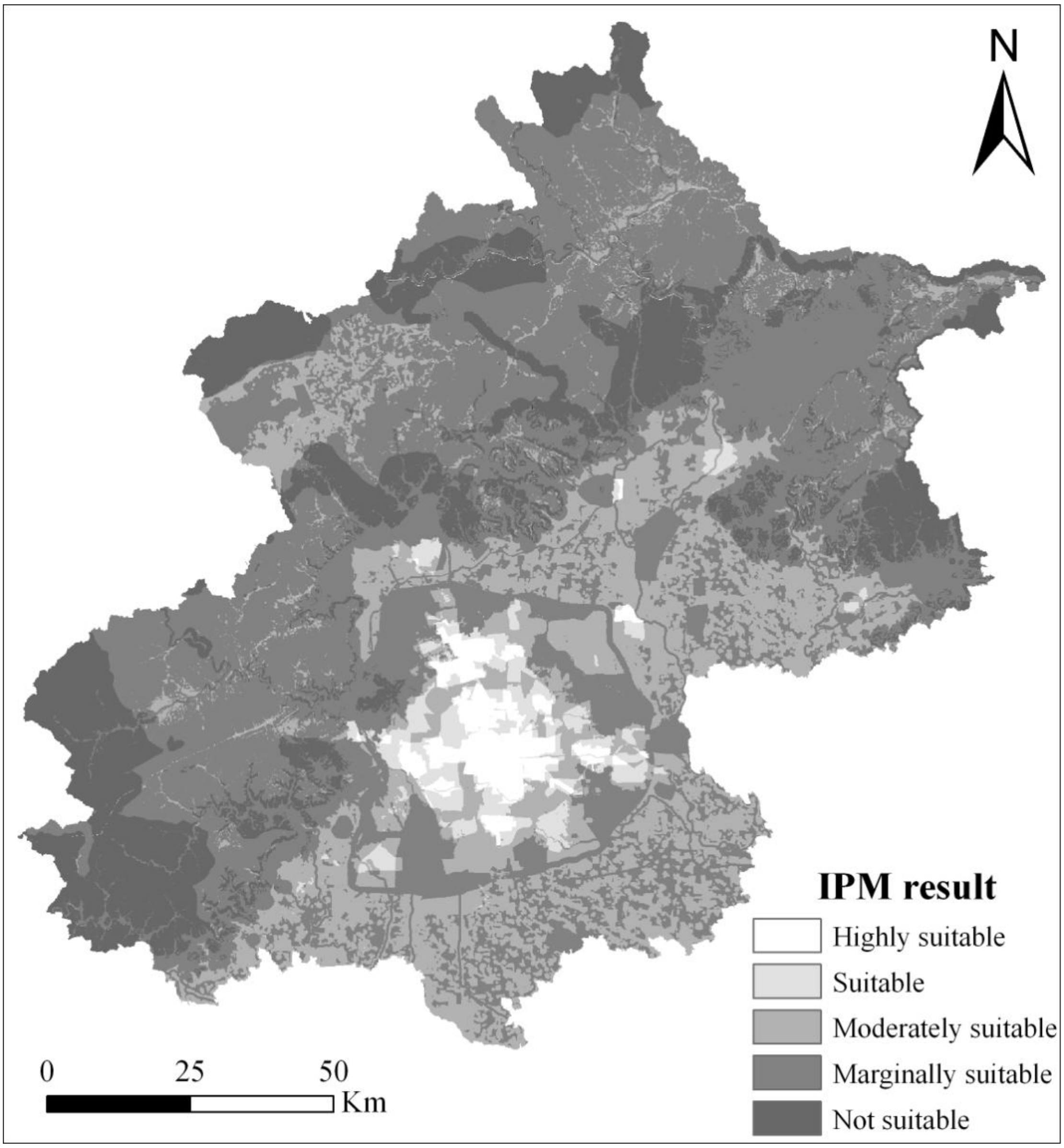

Fig. 4 Land-use suitability generated by the ideal point method

Figure 5

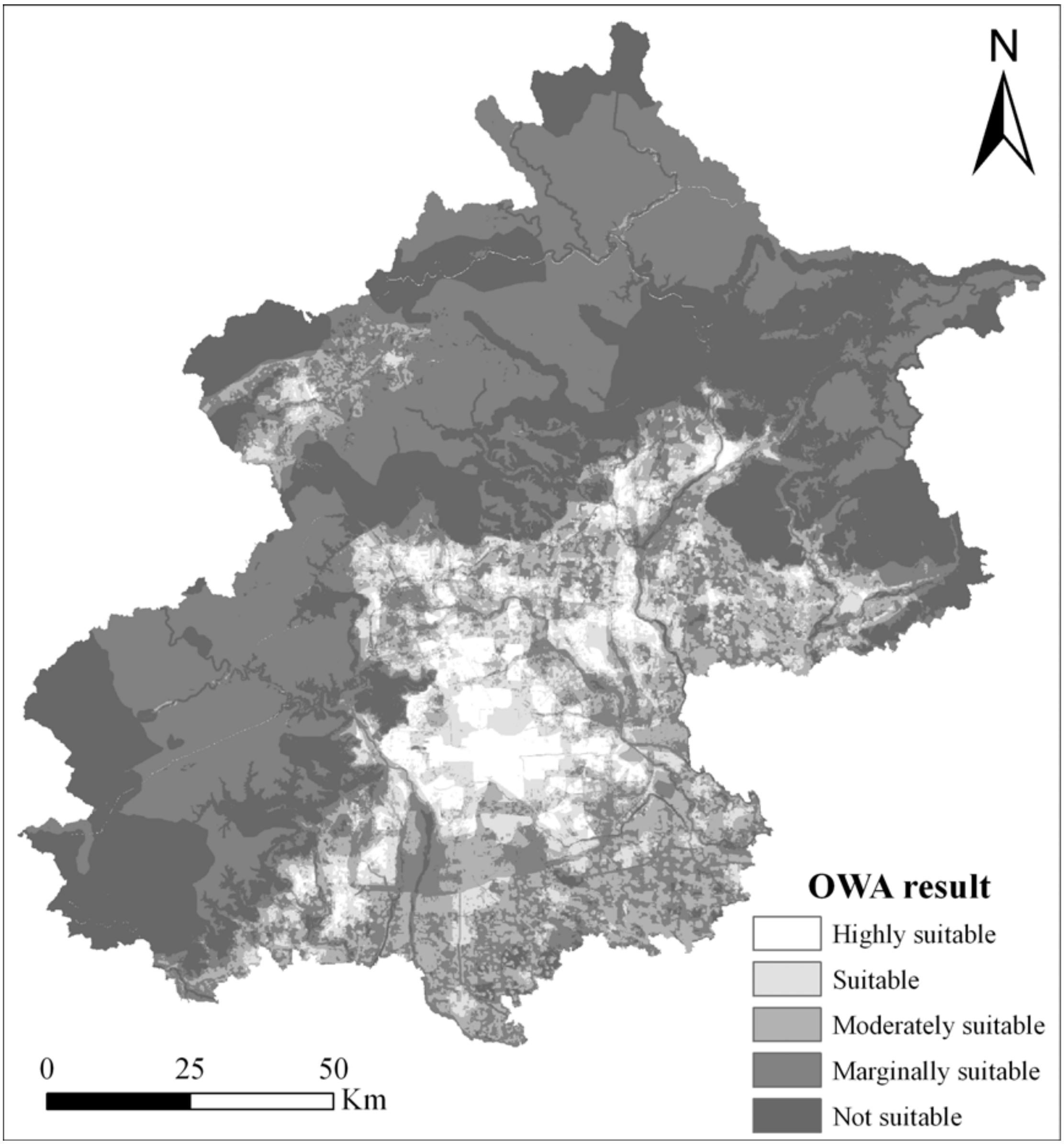

Fig. 5 Land-use suitability map generated by OWA approach

Figure 6

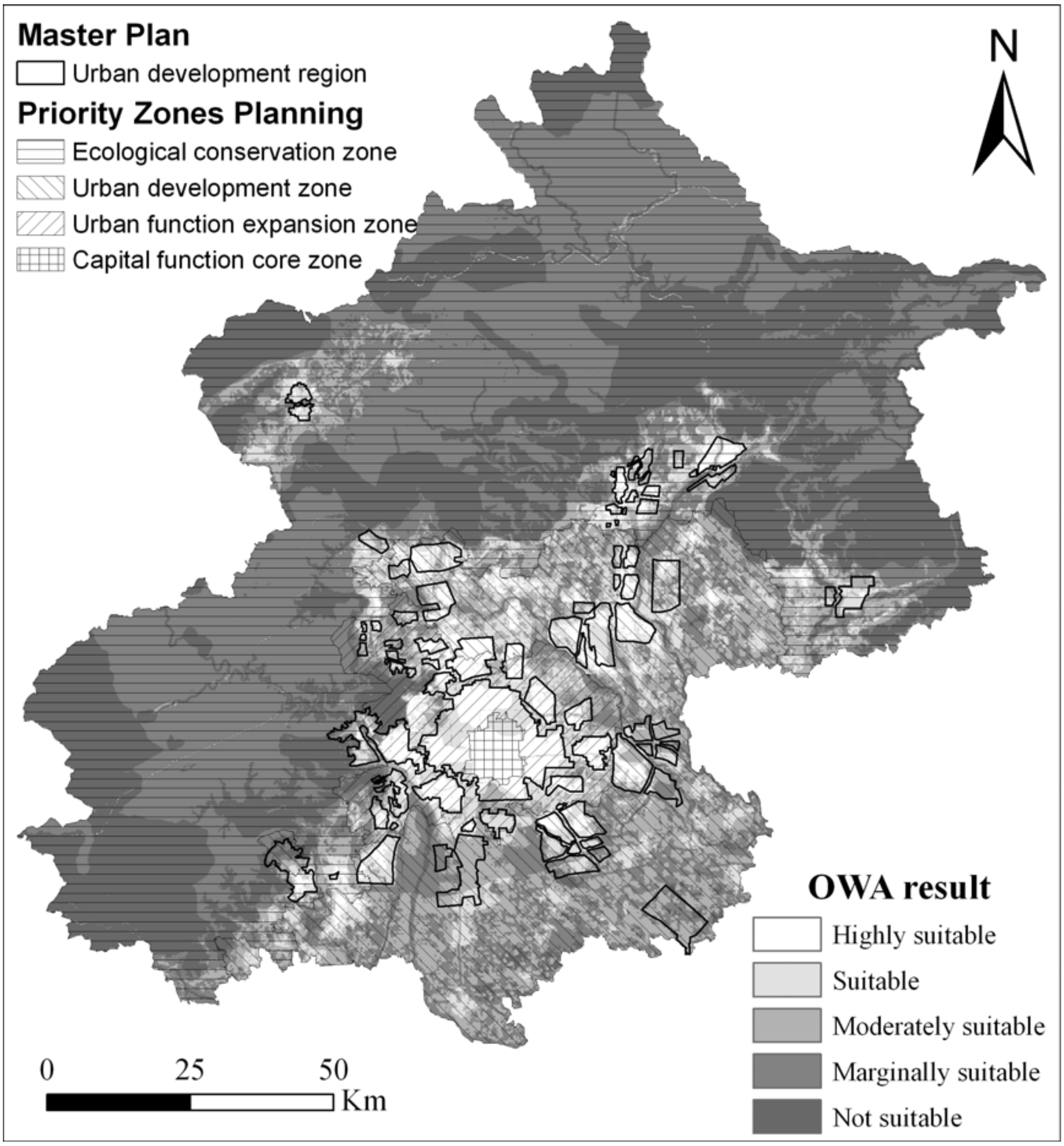

Fig.6 Suitability map of OWA overlaid with spatial patterns from the Beijing *Master Plan* and *Priority Zones Planning*

Table 1 Information on the data used in the present research

Data name	Data type	Scale	Data source
Terrain elevation Slope	Grid	1:250 000	Beijing DEM (2000)
Geomorphological Type	Shp	1:1 000 000	Beijing geomorphological map(2000)
Engineering geological condition	Image	1:100 000	Beijing engineering geology zonation(2000)
Exposure to geological hazard	Image	1:100 000	Beijing abrupt geological hazard zonation(2000)
Land-use Built-up area	Shp	1:10 000	Beijing land-use digital map (2008)
Road	Shp	1:10 000	Beijing road grade map(2010)
Population density	Table	--	The Sixth National Population Census of Beijing (2010)
Air quality	Table	--	Beijing environmental statement（2011）
Surface water	Shp	1:100 000	Beijing surface water map (2000)
Restrictive factors (except surface water)	Image	1:100 000	Beijing restrictive factor maps(2000)
Prohibitive factors	Image	1:100 000	Beijing prohibitive factor maps (2010)

Table2a

Table 2(a) Ranking and scoring system of opportunity factors for urban development

	Rank	Very high opportunity	High opportunity	Moderate opportunity	Low opportunity	Very low opportunity
	Score	5	4	3	2	1
S_1 (m)[a]		0-100	100-200	200-500	500-1000	> 1000
S_2 (%)[b]		0.3-2	0-0.3, 2-5	5-10	10-25	> 25
S_3[c]		Plain	—	—	Hill and tableland	Mountain, depression, floodplain, lake
S_4[d]		Perfect condition	Good condition	General condition	Poor condition	Mountain area
S_5[e]		Hardly prone area	Slightly prone area	—	Moderately prone area	Highly prone area
S_6[f]		Residential area, industrial and mining land, transportation land, other unused land	Saline-alkali soils, sandy land	Garden plot, dry land, grassland, other agricultural land	Irrigated paddy, vegetable field, weeds, bare exposed gravel	Forest land, land for water facilities, other land
S_7(m)[g]	city-level	< 500	500-1000	1000-1500	1500-2000	> 2000
	county-level	< 250	250-500	500-750	750-1000	> 1000
S_8 (m) [h]		< 500	500-1000	1000-1500	1500-2000	> 2000
S_9 (people/km^2) [i]		> 1000	700-1000	400-700	200-400	0-200
S_{10}[j]	$\mathrm{SO_2}$ (μg/m^3)	< 30	< 30	< 40	< 60	—
	$\mathrm{NO_2}$ (μg/m^3)	< 50	< 50	< 70	< 80	—
	$\mathrm{PM_{10}}$ (μg/m^3)	< 100	100-110	110-120	120-140	—

[a] Score assignment is based on the characteristics of landform and vegetation distribution in China.

[b] Score assignment refers to the relationship between slope and urban development according to Liu (1994).

[c] Score assignment is based on the characteristics of different geomorphological type and refers to the Beijing *Master Plan*.

[d,e] Score assignment refers to the Beijing *Master Plan* and *Priority Zones Planning*.

[f] Score assignment is based on the current layout of Beijing and the ecosystem services value of land cover according to Costanza et al. (1997).

[g] Score assignment is based on the spatial agglomeration effects of roads and the basic buffer value is 250 m.

[h] A city center has an exponentially decreasing impact on its hinterland with respect to increasing distance from urban area, and the basic buffer value here is 500 m.

[i] Score assignment refers to the agglomeration effect of population density using empirical classification.

[j] Score assignment is based on *Ambient Air Quality Standard* (SEPA, 1996).

Table2b

Table 2(b) Ranking and scoring system of constraint factors for urban development

	Rank	Restrictive	Prohibitive
	Score	-0.6	-1
C_1[a]	river	—	100 m buffer of city center river / source water river and river body; 210 m buffer of suburb river and river body; 70 m buffer of city drainage river and river body
	lake	500-1500 m buffer	500 m buffer and lake body
	reservoir	100-1000 m buffer	100 m buffer and reservoir body
C_2 (m)[b]		ground source water recharge area	ground source water protection area
C_3 (m)[c]		the area and 30 m buffer	—
C_4[d]	green belt	within restrictive area	—
	the sixth ring road	500 m inward buffer and 1000 m outward buffer	—
C_5[e]		within conservation area	—
C_6 - C_{11}[f]		—	within prohibitive area

[a] Score assignment is based on *Provisions of Beijing Municipality on Demarcating the Protection Scope of Suburban Major Rivers (2010 Amendment))* & *Provisions of Beijing Municipality on Demarcating Isolation Belts Besides both Sides of Urban Rivers (1994 Amendment)* & *Master Plan.*

[b] Score assignment refers to *Administrative Measures of Beijing Municipality for the Protection of Groundwater for Urban Waterworks (1986)* & *Master Plan.*

[c] Score assignment is based on *Regulations on the Protection of Basic Farmland (1998)* & *Land Administration Law of the People's Republic of China (article 31,2004 Amendment).*

[d] Score assignment is based on *The Second Green Belt Planning of Beijing (2003).*

[e] Score assignment refers to *Master Plan*.

[f] Score assignment refers to *Priority Zones Planning.*

Table 3 Opportunity factor weights

Factor	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
Weight	0.1073	0.0891	0.0729	0.0915	0.0583	0.1319	0.1235	0.1367	0.098	0.0908

Table 4 the OWA order weights generated by the min-max disparity approach with α=0.8

Factor[a]	v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}
Order weight	0.2714	0.2286	0.1857	0.1428	0.1000	0.0572	0.0143	0	0	0

[a] v_1 to v_{10} correspond to factors with attribute values ranging from the highest to lowest.

Table5

Table 5 Sensitivity of suitability map to 20% increase in weights

Weights	Areas of each suitability level (km^2)					Contingency coefficient
	1	2	3	4	5	
Initial	5183	6661	2493	1374	699	1.00
$1.2W_{S1}$	5210	6253	2402	1632	915	0.90
$1.2W_{S2}$	5172	6792	2438	1312	697	0.98
$1.2W_{S3}$	5192	6858	2331	1329	700	0.98
$1.2W_{S4}$	5197	6659	2479	1378	697	0.99
$1.2W_{S5}$	5185	6694	2490	1392	649	0.98
$1.2W_{S6}$	5126	6664	2532	1379	709	0.98
$1.2W_{S7}$	5180	6726	2397	1403	704	0.98
$1.2W_{S8}$	5227	6747	2409	1335	692	0.97
$1.2W_{S9}$	5184	6669	2490	1373	694	1.00
$1.2W_{S10}$	5173	6671	2479	1389	698	1.00

Table 6 Comparison of suitability maps between IMP and OWA

OWA map(km^2)	IPM map (km^2)			Overall agreement	Kappa
	suitable	not suitable	total		
suitable	3919	647	4566	91 %	0.78
not suitable	823	11021	11844		
total	4742	11668	16411		