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Land-use suitability analysis for urban development in Beijing

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ABSTRACT

Land-use suitability analyses are of considerable use in the planning of mega-cities. An Urban Development Land-use Suitability Mapping (UDLSM) approach has been constructed, based on opportunity and constraint criteria. Two Multi-criteria Evaluation (MCE) methods, the Ideal Point Method (IPM) and Ordered Weighted Averaging (OWA), were used to generate the opportunity map. The protection map was obtained by means of constraint criteria, utilizing the Boolean union operator. A suitability map was then generated by overlaying the opportunity and protection maps. By applying the UDLSM approach to Beijing, its urban development land-use suitability was mapped, and a sensitivity analysis undertaken to examine the robustness of the proposed approach. Indirect validation was achieved by mutual comparisons of suitability maps resulting from the two MCE methods, where the overall agreement of 91% and kappa coefficient of 0.78 indicated that both methods provide very similar spatial land-use suitability distributions. The suitability level decreases from central Beijing to its periphery, and the area classed as suitable amounts to 28% of the total area. Leading attributes of each opportunity factor for suitability were revealed, with 2256 km^2, i.e. 70%, of existing development land being overlaid by suitable areas in Beijing. Conflicting parcels of land were identified by overlaying the resultant map with two previous development blueprints for Beijing. The paper includes several recommendations aimed at improving the long-term urban development plans for 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, land-use suitability analysis has been applied to the assessment of agricultural land (Feizizadeh and Blaschke, 2013), determination of land habitats for animal and plant species (Store and 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). Land-use suitability analysis methods may be categorized as overlay mapping methods, Multi-criteria Evaluation (MCE) methods, and Artificial Intelligence (AI) methods (see Collins et al., 2001; Malczewski, 2004). Overlay mapping is easy to undertake and is routinely applied in land-use suitability analysis for urban development (see McHarg, 1969; Lyle and Stutz, 1983; Miller et al., 1998), but has shortcomings such as inappropriate standardization of suitability maps, and untested or unverified assumptions of independence among suitability criteria (Hopkins, 1977; Pereira and Duckstein, 1993). To overcome these drawbacks, overlay mapping is often implemented alongside other land-use suitability analysis methods for urban development (McCloskey et al., 2011; Park et al., 2011). Many case studies use MCE methods, including Weighted Linear Combination (WLC) (Dai et al., 2001), the Weighted Potential-Constraint Method (Zong et al., 2007), the Ideal Point Method (IPM) (Ekmekçioğlu et al., 2010), Analytic Hierarchy Process (AHP) (Javadian et al., 2011; Park et al., 2011), Ordered Weighted Averaging (OWA) (Jiang and Eastman, 2000; Malczewski, 2006), the Land Suitability Index (LSI) Model (Marull et al., 2007), and the Ecological Niche Suitability Model (Ouyang and Wang, 1995). Although independence and uncertainty are considered, MCE methods depend heavily on the input data which are assumed precise and accurate. Moreover, the resulting land-use suitability patterns can depend on the choice of standardization method or multi-criteria method. With this in mind, it has been suggested that two or more multi-criteria methods should be applied to dilute the

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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). Artificial intelligence has also been applied to aid the description of complex systems for inference and decision making using modern computational techniques, such as Matter-Element Model (Gong et al., 2012), Artificial Neural Networks (Park et al., 2011), and Cellular Automata (Ligtenberg et al., 2001). The black box nature of AI methods makes them tolerant of imprecision, ambiguity, uncertainty, and partial truth (Porta et al., 2013), but can often be unconvincing (O'Sullivan and Unwin, 2003).

Taking stock of the foregoing brief review, an Urban Development Land-use Suitability Mapping (UDLSM) approach is proposed 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 and Eastman, 2000; Malczewski, 2004). Beijing is taken as the study area because it is suffering adverse ecological damage resulting from rapid, relatively uncontrolled urban expansion. In 2010, the urban population of Beijing reached 86% of its 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 covering the whole of Beijing is generated, 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 behind land-use suitability analysis

Early approaches for land-use suitability analysis evolved from the sun-print overlay of Charles Elliot and Warren Manning (Miller, 1993; Mcharg, 1996), transparent overlay of Jacqueline Tyrwhitt (Steinitz et al., 1976), and ecological inventory process of McHarg (1969). McHarg's approach (Malczewski, 2004) maximizes economic benefits while minimizing environmental damage (Collins et al., 2001), and is regarded as the precursor of ecological suitability analysis in China (see e.g. Ouyang and Wang, 1995; Yang et al., 2009). With advances in land evaluation methodologies, the ecological inventory process gradually extended from physical factors to include ecological and economic-cultural factors (see Boyden, 1981; McHarg, 1981). Examples include urban land-use suitability analyses for Staten Island, U.S.A. (McHarg, 1969), Nakuru, Kenya (Jiang and Eastman, 2000), and South Korea (Park et al., 2011).

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), and involves collective physical, socio-economic, environmental, and ecological perspectives which are quantified through set criteria (see McHarg, 1981; Collins et al., 2001). Land suitability analysis is therefore multi-disciplinary, involving physical science, biophysical science, social science, land science, ecology, and landscaping. The defined land uses can be divided into developmental (Marull et al., 2007) and non-developmental (Malczewski, 2004) categories. 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

Criteria of land-use suitability for urban development are derived from multi-disciplinary scientific theories related to 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). Suitability analysis 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 are determined by spatial location (e.g. the factor slope, with a high gradient location restrictive and a low gradient location permissive for urbanization). The resulting factor maps are used to reflect the degree of opportunity (or suitability) with ranked values allocated to all mapping units. An ecological factor (e.g. forest value or historic value) is usually taken to represent the development constraint (or unsuitability) by means of ranked values for a subset of mapping units in a specific area. The composite map of ecological factors is variously called the suitability map for conservation (McHarg, 1969) or the protection map (McHarg, 1981).

Herein, opportunity criteria and constraint criteria were utilized for urban development land-use suitability analysis. The set of opportunity criteria was 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 comprised terrain elevation (S_1), slope (S_2), and geomorphological type (S_3), and the geology indicators were the engineering geological condition (S_4) and exposure to geological hazard (S_5). Socio-economic suitability was assessed as 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 played a different role in determining the degree of opportunity for urban development and so was assigned a different weight. Ranked values of all opportunity factors were combined with weights for each mapping unit. The set of constraint criteria was primarily

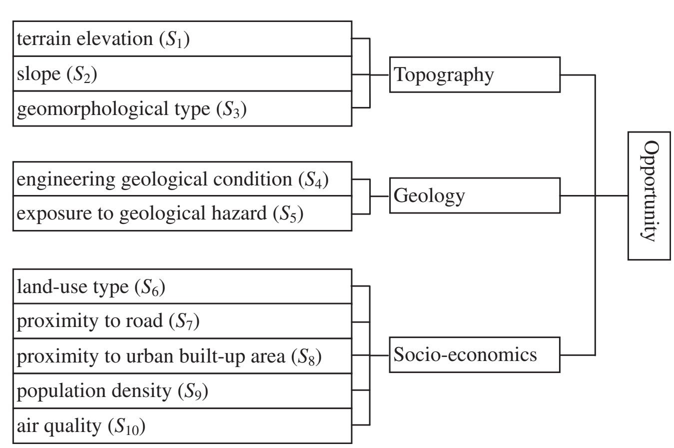

Fig. 1. Physical and socio-economic factors in terms of opportunity for urban development.

concerned with conservation, for which restrictive and prohibitive levels of constraint were identified 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) were taken to be the restrictive factors for urban development. The prohibitive factors were selected to strictly protect against development and consisted 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}). Ecological constraint factors with negative ranked values jointly represented protected or conservation areas by a subset of the mapping unit (each constraint factor covers certain specific units rather than all units).

2.3. *Urban development land suitability mapping*

Using the opportunity and constraint criteria, the capacity of land suitable for urban development was mapped by an overlay of the opportunity map and the protection map. The former was generated using the preselected IPM or OWA approach. And a Boolean union operator was used to combine all the constraint factors into a protection map. All mappings were 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 best alternative is closest to the ideal point. Herein, we used a method based on the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to identify the best alternative, aided by GIS tools (Hwang et al., 1993). TOPSIS is widely used in land sitting and land-use analysis (Ekmekçioğlu et al., 2010; Soltanmohammadi et al., 2010).

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

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

where x_{ij} was the criteria value, i represented the grid cell of each criterion raster layer in ArcGIS, j represented criteria, and w_j represented each criterion's weight. There were a total of m grid cells and n criteria. Weights were determined by the AHP method. Criterion values were aggregated via

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

where $\bar{x}_j$ was the mean value of column vector j, where $j = 1, 2 \ldots, n$. Hence, $\bar{x}_j$ was 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} were 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 an arbitrary criterion value and M_{1j}/M_{2j} was calculated from,

$$S_{1i} = \sqrt{\sum_{j=1}^{n} \left(p_{ij} - M_{1j}\right)^2}, \; S_{2i} = \sqrt{\sum_{j=1}^{n} \left(p_{ij} - M_{2j}\right)^2} (i = 1, 2 \ldots m) \tag{3}$$

Then the similarity was given by,

$$T_i = \frac{S_{2i}}{S_{1i} + S_{2i}} \; (i = 1, 2\ldots, m) \tag{4}$$

where $T_i \in [0,1]$. All calculations were undertaken using ArcGIS. After transforming all criteria data into raster format with level values ranging from 1 to 5, the raster layers were further standardized and overlaid with each other using raster calculator tools. The opportunity degree was 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 was used herein, and involves two sets of weights: criterion weights and order weights. The OWA formula is:

$$\text{Opportunity degree} = \sum_{j=1}^{n} \left(\frac{u_j v_j}{\sum_{j=1}^{n} u_j v_j} \right) Z_{ij} \tag{5}$$

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 incorporating a trade-off measure indicating the degree of compensation between criteria (Jiang and 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).

A min–max disparity approach was used to assign order weights (Wang and Parkan, 2005) as follows:

$$\text{Minimize}\left\{ \underset{j \in \{1,\ldots,n-1\}}{\text{Max}} \left| v_j - v_{j+1} \right| \right\} \tag{6}$$

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

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

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

$$\text{Trade off} = 1 - \sqrt{\frac{n \sum (w_j - 1/n)^2}{n-1}} \tag{7}$$

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

2.3.2. Protection mapping

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

2.3.3. Suitability mapping

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

2.4. Study area and materials

2.4.1. Study area

Beijing is situated at the northern extremity of the North China Plain and has an area of about 16,411 km^2. Its geography 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 occupied approximately 21% of the total area of Beijing, and development land taken from farmland from 2000 to 2010 occupied an area greater than 200 km^2. 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

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

2.4.3. Data standardization

All factor maps were normalized onto 100 m $\times$ 100 m grid layers. From the above multi-criteria database for all mapping units (grid), values were 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 was used to quantify the opportunity and constraint levels which are from 1 to 5 (see Table 1a) and -1 and -0.6 (see Table 1b) respectively. The scoring system was built according to relevant regulations and standards of Beijing (See Table 1) with a proper understanding of each factor's intrinsic properties and its impact on land suitability for urban development. Here, a higher score indicated 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.

2.4.4. Weights

Table 2 lists the opportunity factors obtained by the Analytic Hierarchy Process (AHP) method (Saaty and Vargas, 2001). AHP involved construction of a pair-wise comparison matrix, each factor rated against every other factor by assigning values in the range 1–9 (Saaty, 1980). The components of the eigenvector summed to unity, and so the resulting vector of weights reflected the relative importance of the various factors (Dai et al., 2001). The matrix data were derived from a survey 9 experts in urban ecology and environmental assessment. Table 2 also lists the final criterion weights for the OWA approach. Table 3 presents the order weights calculated from the criterion weights and the degree of ANDness and ORness (value of α, see above OWA approach). Here, the choice of $\alpha = 0.8$ reflects a relatively strict standpoint that Beijing is only included provided most factors meet their thresholds.

3. Results

3.1. The map resulting from IPM

Fig. 2 shows the urban development land-use suitability distribution for Beijing. It can be seen that the land-use suitability level decreases from central Beijing to its outskirts and from the central, eastern and southern plains to the 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 coincides with 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 900 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.

Supplementary Table 2 indicates the relationships between the suitability for urban development and each opportunity factor. Most of the suitable area (i.e. *highly suitable*, *suitable*, and *moderate suitable*) has elevation less than 100 m (85%) and slope less than 2°(91%). 79% of the suitable area is located on plains, 82% has good engineering geological condition, and 89% is hardly prone to geological hazards. Suitability for urban development is higher in the built-up and unused areas, and lower in others. Areas closer to

Table 1a
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[d]		Hardly prone area	Slightly prone area	–	Moderately prone area	Highly prone area
S_6[e]		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)[f]	City-level	<500	500–1000	1000–1500	1500–2000	>2000
	County-level	<250	250–500	500–750	750–1000	>1000
S_8 (m)[g]		<500	500–1000	1000–1500	1500–2000	>2000
S_9 (people/km^2)[h]		>1000	700–1000	400–700	200–400	0–200
S_{10}[i]	SO_2 (μg/m^3)	<30	<30	<40	<60	–
	NO_2 (μg/m^3)	<50	<50	<70	<80	–
	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] Score assignment refers to the Beijing *Master Plan* and *Priority Zones Planning*.
[e] Score assignment is based on the current layout of Beijing and the ecosystem services value of land cover according to Costanza (1997).
[f] Score assignment is based on the spatial agglomeration effects of roads and the basic buffer value is 250 m.
[g] 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.
[h] Score assignment refers to the agglomeration effect of population density using empirical classification.
[i] Score assignment is based on *Ambient Air Quality Standard* (SEPA, 1996).

roads are more suitable for development, and 83% of the land is closer than 1000 m to country-level roads. Suitability decreases far away from the built-up areas. 74% of suitable areas in the region have a population density of more than 400 persons per km^2. But, only 27% of suitable areas meet China's Class II Standard for ambient air quality.

An overlay analysis between the present land-use map (see Supplementary Fig. 1(f)) and the IPM map provided information on the ratio of the existing development/non-development areas to the *suitable/not suitable* areas. Here, the development areas included special use, industrial and mining, transportation, and built-up areas, the others were classed as non-development), 2256 km^2, i.e. 70%, was overlaid by *suitable* areas (grouping *highly suitable*, *suitable*, and *moderately suitable* as *suitable*, the others as *not suitable*). 2485 km^2 (52%) of suitable area (mostly being *moderately suitable*) remained non-development.

3.2. The map resulting from OWA

Fig. 3 shows the final urban development land-use suitability map. Figs. 2 and 3 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 4567 km^2 is suitable for urban development. Similar relationships can be observed between the suitability for urban development and each opportunity factor in the resultant OWA map.

3.3. Sensitivity analysis

A sensitivity analysis was undertaken by altering the weights of the ten opportunity factors which directly affect suitability. However, altering the weights did not necessarily change the resultant suitability map. Table 4 indicates the OWA suitability map's

Table 1b
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 2
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 3
The OWA order weights generated by the min–max disparity approach with $\alpha = 0.8$.

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.

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 were equally decreased by (20/9)% to keep the sum of weights equal to 1). The high consistency (see Table 4, generated by a kappa analysis) indicates that the suitability map remains almost unchanged even though the absolute values of the degree of suitability altered with the increased weight. Similar findings were 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 was stable despite small changes in the weights utilized by both methods.

3.4. Comparison of IPM and OWA resultant maps

Table 5 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 was indicated by the area that

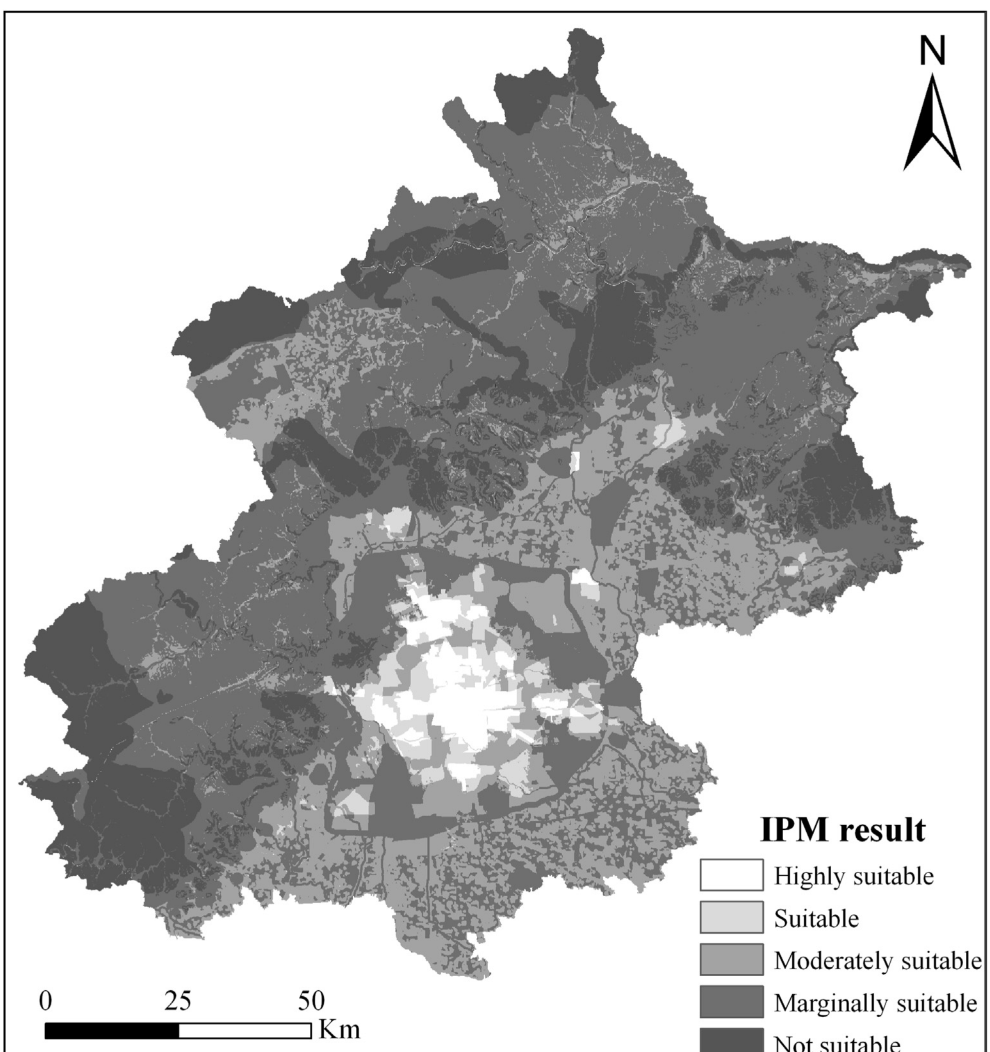

Fig. 2. Land-use suitability generated by the ideal point method.

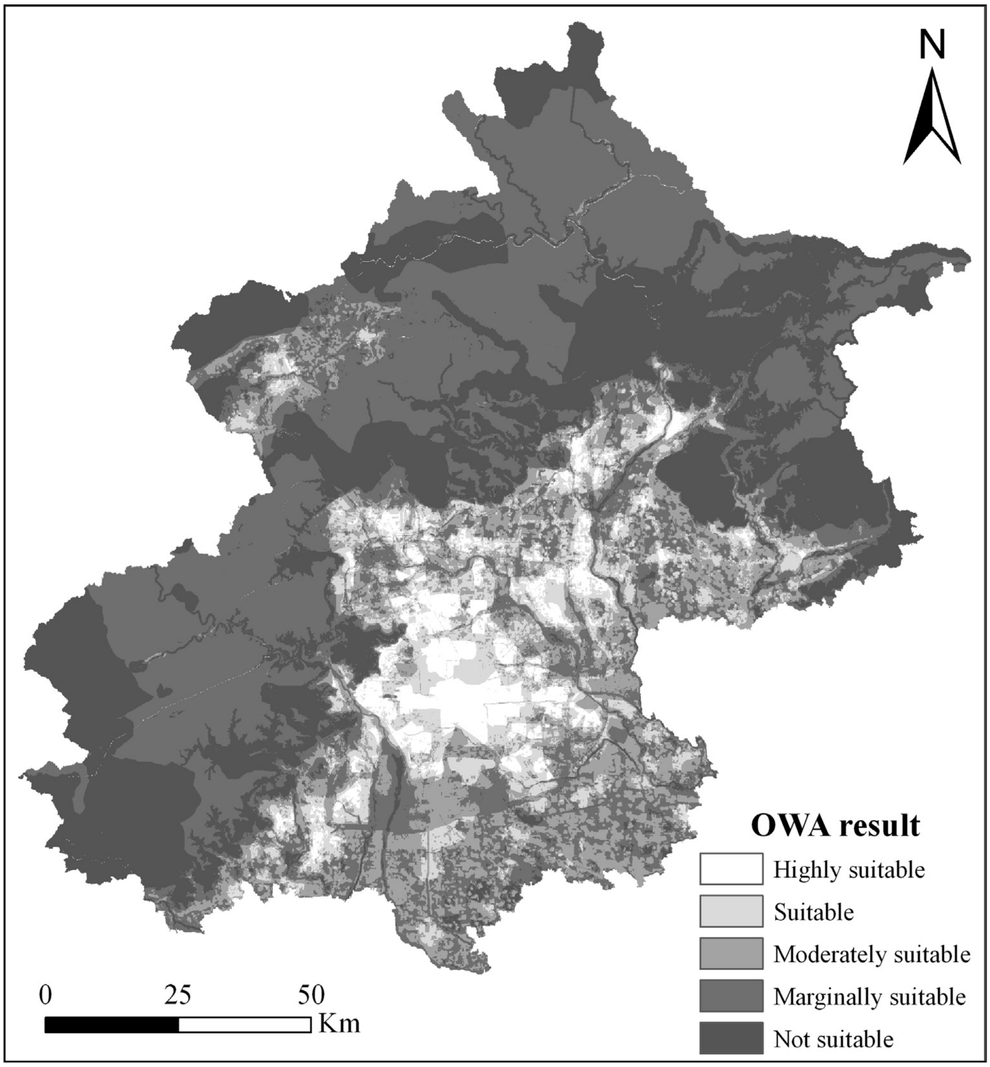

Fig. 3. Land-use suitability map generated by OWA approach.

had the same degree of suitability as that of the total sum. The values of overall agreement and kappa are 70% and 0.57 respectively, under a strict comparison of two maps involving five suitability levels, and indicate high agreement and moderate contingency (Landis and 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 provided very similar spatial distributions of land-use suitability.

Table 4
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

4. Discussion

A criteria system has been established to enable analysis of land-use suitability for urban development. Opportunity and constraint factors were derived scientifically from relevant disciplines (including geology, geomorphology, hydrology, ecology, sociology, and economics). Moreover, the database for mapping criteria utilized information from trusted primary sources, and the process by which criteria values are ranked adhered strictly to existing local regulations and standards (Table 1).

Table 5
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		

The MCE methods used to generate the opportunity map are particularly well suited to ensuring independence and combination of multi-criteria. The core of IPM involved 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 generated 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 were combined using calculations of their Euclidean distances from an ideal point. Hence, there was 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 meant 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 provided control of the degree of compensation among criteria. The choice of $\alpha = 0.8$ corresponded to strict decision making, and its 0.68 trade-off indicated moderate compensation among the factors, which maintained the independence of each criterion. Hence we conclude that the OWA approach provided more accurate results given its rational basis, and so is useful for providing practical decisions.

Using the suitability map, the *Master Plan* and *Priority Zones Planning* were evaluated in terms of the ecological fit between their spatial patterns. Fig. 4 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 were in accordance with areas classified as *moderately suitable*, *suitable*, and *highly suitable*, which confirmed the *Master Plan* has a good ecological fit to the suitability map. There were 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. 4). The first three zones were primarily related to development and roughly corresponded to areas in the suitability map classified as *moderately suitable*, *suitable*, and *highly suitable*. The ecological conservation zone was consistent with areas that are *marginally suitable* and *not suitable*, and most of the 63 protected areas named in *Priority Zones Planning* were 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 indicated a satisfactory ecological fit between the sustainability map and *Priority Zones Planning*.

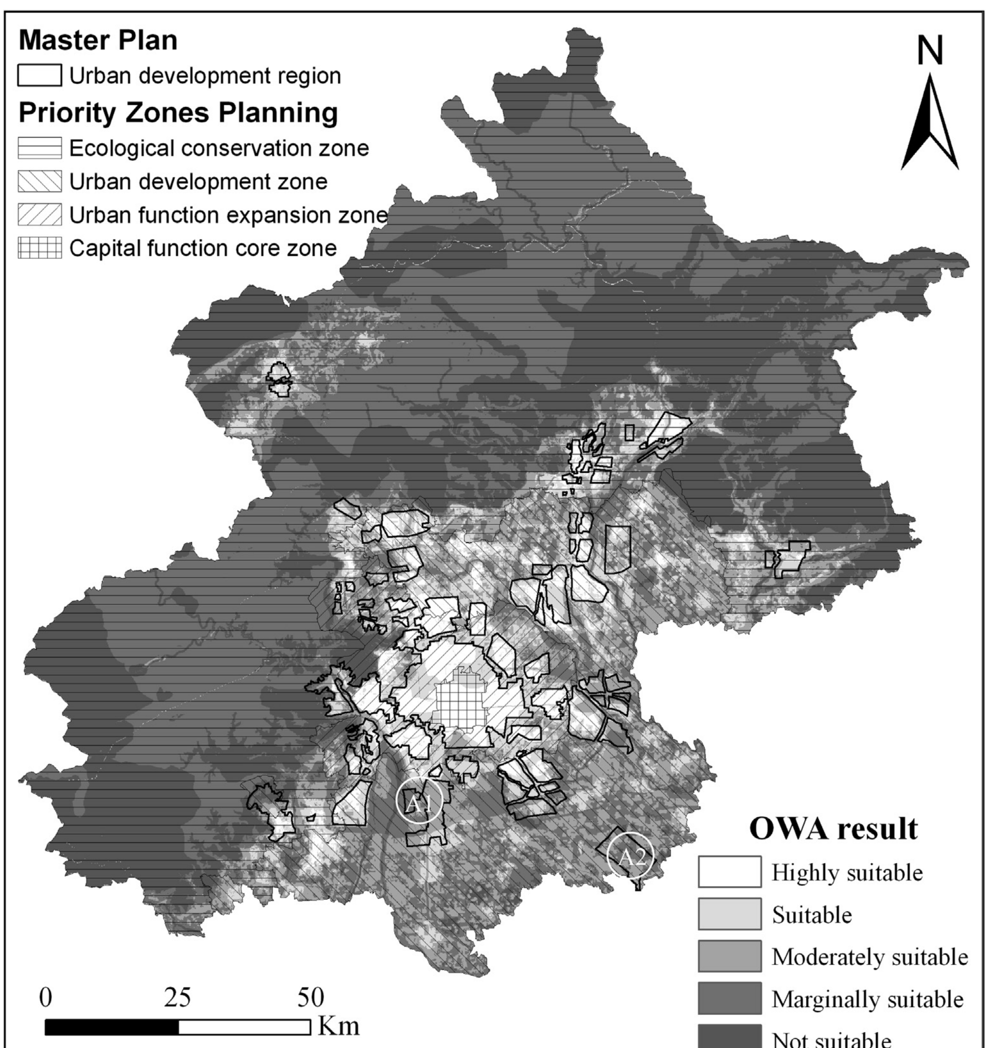

Fig. 4. Suitability map of OWA overlaid with spatial patterns from the *Beijing Master Plan* and *Priority Zones Planning*.

However, there were a few specific land parcels earmarked for urban development that are located in areas classified as *marginally suitable* or *not suitable*, and 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. 4). 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 exceeds the local air quality standard.

The following suggestions are made to address the issues arising from 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, the priority should be to relocate urban development to a more suitable area elsewhere. 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 cropland elsewhere of the same quality and quantity, by paying reclamation fees, and improving the engineering geological conditions.

5. Conclusions

A UDLSM approach was proposed for urban development land-use suitability analysis. The approach presented 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 were generated and converted into a resultant suitability map for Beijing using the UDLSM approach which divided 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 was found to be suitable for urban development and was overlaid by 70% of existing development land, mainly located in the plain, with the remaining land that was unsuitable for further urban development occupying the majority of the 63 protected zones in Beijing. The resultant maps obtained using IPM and OWA methods exhibited very similar patterns of suitability degree; the overall agreement of 91% and kappa coefficient of 0.78 indirectly validated the UDLSM approach. A sensitivity analysis showed that the UDLSM approach gave stable results when subjected to a uniform 20% change in the weighting values. In general, the *Master plan* and *Priority Zones Planning* blueprints for Beijing appeared to have taken ecological fitness properly into consideration, although the analysis indicated that there were a few land parcels whose planned use conflicted with the suitability map and where future countermeasures may be required.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2014.06.020.

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