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Evaluating Urban Land Carrying Capacity Based on the Ecological Sensitivity Analysis: A Case Study in Hangzhou, China

Jin Yeu Tsou ¹, Yanfei Gao ¹, Yuanzhi Zhang ^{2,3,*}, Genyun Sun ⁴, Jinchang Ren ⁵ and Yu Li ^{6,*}

¹ Center for Housing Innovations, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China; jinyeutsou@cuhk.edu.hk (J.Y.T.); gaoyanfei2016@163.com (Y.G.)

² National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

³ Key Lab of Lunar Science and Deep-Space Exploration, Chinese Academy of Sciences, Beijing 100012, China

⁴ School of Geosciences, China University of Petroleum (East China), Qingdao 266580, China; genyunsun@163.com

⁵ Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G1 1XQ, UK; jinchang.ren@strath.ac.uk

⁶ Faculty of Information Technology, Beijing University of Technology, Beijing 100124, China

* Correspondence: yuanzhizhang@cuhk.edu.hk (Y.Z.); yuli@bjut.edu.cn (Y.L.); Tel.: +86-10-6480-7833 (Y.Z.)

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Abstract: In this study, we present the evaluation of urban land carrying capacity (ULCC) based on an ecological sensitivity analysis. Remote sensing data and geographic information system (GIS) technology are employed to analyze topographic conditions, land-use types, the intensity of urban development, and ecological environmental sensitivity to create reasonable evaluation indicators to analyze urban land carrying capacity based on ecological sensitivity in the rapidly developing megacity of Hangzhou, China. In the study, ecological sensitivity is grouped into four levels: non-sensitive, lightly sensitive, moderately sensitive, and highly sensitive. The results show that the ecological sensitivity increases progressively from the center to the periphery. The results also show that ULCC is determined by ecologically sensitive levels and that the ULCC is categorized into four levels. Even though it is limited by the four levels, the ULCC still has a large margin if compared with the current population numbers. The study suggests that the urban ecological environment will continue to sustain the current population size in the short-term future. However, it is necessary to focus on the protection of distinctive natural landscapes so that decision makers can adjust measures for ecological conditions to carry out the sustainable development of populations, natural resources, and the environment in megacities like Hangzhou, China.

Keywords: urban areas; ecological sensitivity; urban land carrying capacity (ULCC); remote sensing data; geographic information system (GIS)

1. Introduction

Urban land resources are the basis of human survival and social development, wherein reasonable use of land refers to the requirement to achieve cities' sustainable development goals [1]. However, with the fast growth of the urban population, the continuous expansion of the urban scale, rapid social-economic development, and increasing pressure on land resources, people and urban land become monumental contradictions. In the combined system of Population-Resources-Environment-Development (PRED), land resources are immovable and non-renewable, placing these characteristics in an immovable central position [2]. Meanwhile, estimating the size of the population that land resources can carry is an essential issue in the ecosystem [2], where urban land carrying capacity (ULCC) becomes the crux of

carrying capacity studies [2]. Due to the uneven distribution of urban populations, a shortage of land resources restricts the development of megacities in China; thus ULCC has become an increasingly important constraint in the process of urban development [3].

Ecological sensitivity refers to the ability of an ecosystem to adapt to external disturbances, including the resilience of the ecosystem after destruction [4]. Urban carrying capacity defines the number of people that a country or region could continue to support with its own land resources, which is based on the expected levels of economic, technological, and social development and the corresponding material standard of living in different time scales [5,6]. In short, this term describes the number of people in the area that the land can sustain in the long-term [5,6]. Therefore, urban land carrying capacity can be defined as the level of human activities, population growth, patterns and extent of land use, and physical development that can be sustained by the urban environment without causing serious degradation and irreversible damage [7].

The topic of land resources as it relates to the carrying capacity of the population has been attracting the attention of governments, scientists, and even ordinary citizens since the 1970s. Before 1970, the concept of land population carrying capacity was basically limited to the field of ecology or perhaps slightly extended beyond that sphere [8–10].

Starting in the 1970s, most scholars gradually diversified this field of study and no longer rigidly stuck to a single aspect of the carrying capacity. Consideration was extended from the land carrying capacity to the comprehensive carrying capacity [11–13]. In addition, the approach has been further extended by diversifying. For example, the agricultural ecological zone method (AEZ) was used by the Food and Agriculture Organization (FAO) [13], while the ecological footprint method was initially reported [14] to measure the degree of sustainable development.

The development of current research on ULCC has moved from the traditional, isolated, and one-sided productive forces and from emphasizing individual productive forces of land evolution to the integrated ecological security of land evolution [15]. Among these, ecological sensitivity analysis is popularly applied to evaluate ULCC. Rapid population growth ties to the high-speed development of society and economy in megacities such as Hangzhou, China raise the problem of a shortage of land resources. Consequently, it is urgent to investigate the carrying capacity of land population in the city in order to guide future planning and sustainable development.

Although there are several ways to calculate ULCC that have been developed in recent decades, two widely used approaches that have been developed are ecological footprint analysis (EFA) and the index system method (ISM) [16]. EFA is an approach determined by calculating the biologically productive land and water area. In contrast, ISM, including various elements of environment, economy, society, and resources, is applied to evaluate ULCC comprehensively. ISM has been chosen to assess ecological sensitivity in this article, and the result of ULCC was calculated based on an ecological sensitivity evaluation [16]. In this study, therefore, we focus on the evaluation of urban land carrying capacity based on the ecological sensitivity analysis using remote sensing data and geographic information system (GIS) technology in the selected study area.

2. Study Area and Data

2.1. Study Area

Hangzhou, which is located in the north of Zhejiang Province (Figure 1), with the geographical coordinates of 29°11'N–30°33'N and 118°21'E–120°30'E, and the area of 3068 km², was selected as the study area and includes eight districts: Shangcheng, Xiacheng, Jianggan, Gongshu, Xihu, Binjiang, Xiaoshan, and Yuhang [17]. The landform is diverse with mountainous terrain and water, and the characteristics of the terrain are high in the west and low in the east, since the west is a hilly area and the east is a plain [17].

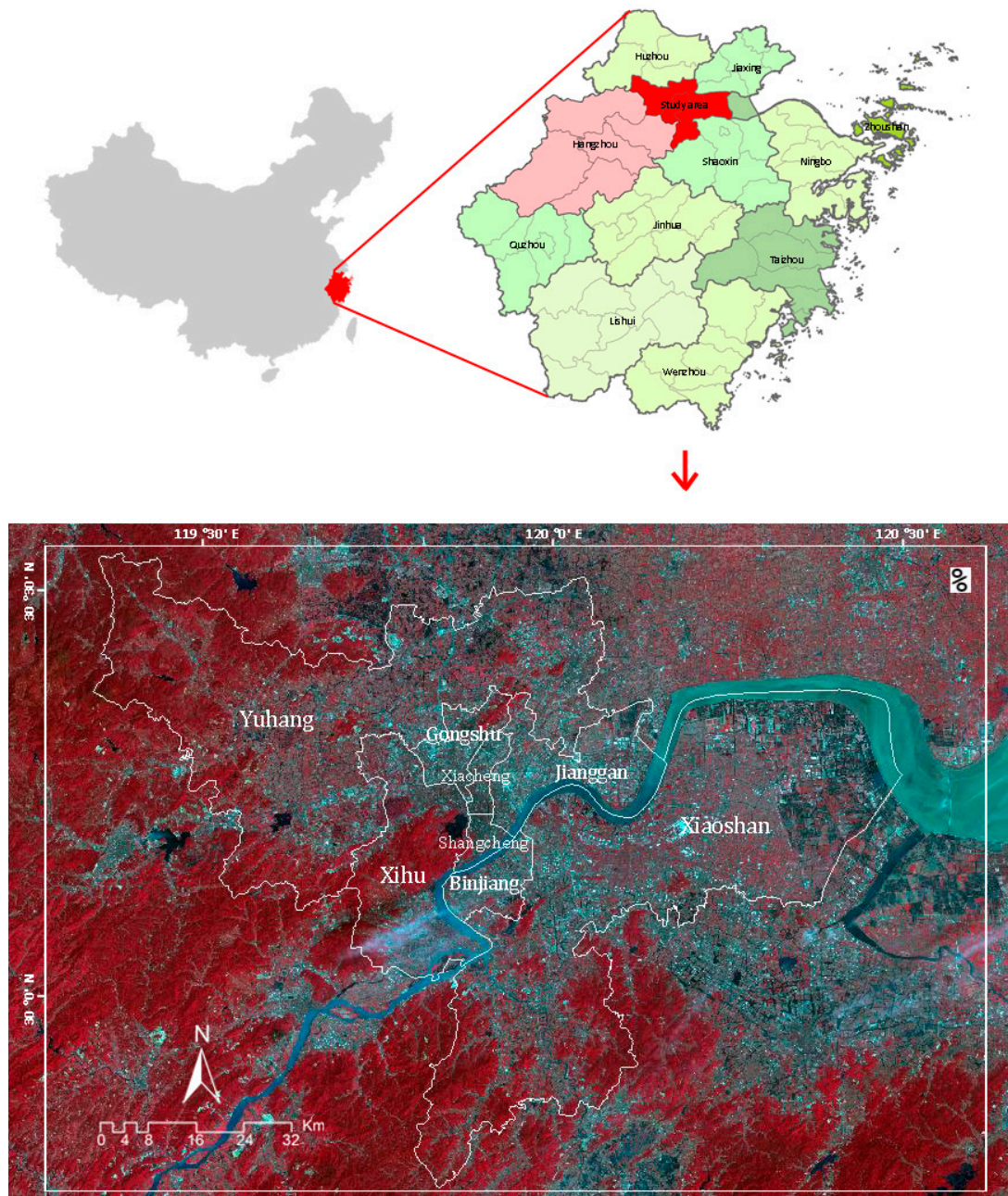


Figure 1. The location of the study area.

It has a sub-tropical monsoon climate with four distinct seasons, adequate light, and abundant rainfall, while the features of the climate are mild and humid, as shown in Table 1. The annual average temperature is 16.95 °C, annual precipitation is 1438.0 mm, relative humidity is 75.8%, and sunshine time is 1709.4 h (China Meteorological Administration).

Table 1. Climate data for Hangzhou.

Climate Data for Hangzhou (1981–2010 Normals, Extremes 1951–Present)				
Category	Daily Mean (°C)	Average Precipitation (mm)	Average Relative Humidity (%)	Mean Monthly Sunshine (h)
Data	16.95	1438.0	75.8	1709.4

2.2. Data Collection

- (1) Map Data: A Hangzhou administrative boundary map (1:25,000) of the eight districts (see Figure 1) collected from the Hangzhou planning bureau website (<http://www.hzplanning.gov.cn/>) has been used for image geometric correction and other map layers of vectorization and digitization.
- (2) Digital Elevation Model (DEM) and Slope (°) Data: The Digital Elevation Model (DEM) image and slope image (with the resolution of 30 m) of the study area were collected from the geospatial data cloud (<http://www.gscloud.cn/>). The DEM data is used to analyze the topographic conditions in the study [18].
- (3) Remote Sensing Data: A cloud free Landsat ETM+ image data acquired on 14 April 2013 was obtained from United States Geological Survey (<http://glovis.usgs.gov/>) with path number 119 and row number 039.
- (4) Statistical Data: the social and economic data, such as the population and the area of the eight districts, were collected from the 2014 statistical yearbook via the web portal of the bureau of statistics (<http://www.hangzhou.gov.cn/col/col805741/index.html>).

3. Methodology

3.1. Evaluation Index

The key purpose of an ecological sensitivity evaluation is to clarify the possibility of ecological environmental problems occurring in a region, along with its hazard rating. It is formulated to the corresponding protection and improvement measures for sensitive areas with different grades [4]. The ultimate objective of the evaluation is the sustainable development of the economy, society, and environment so that the ecosystem can meet the needs of human production and life while minimizing the damage to the ecological environment.

Constructing a reasonable evaluation index system is the focus of a comprehensive evaluation of ecological sensitivity. It needs to combine the actual situation of the study area with the evaluation content to construct an appropriate index [14]. The calculation of ISM also involves three steps: selecting indexes, identifying the criterion of the system, and assigning weights to the coefficients [16]. The selection principles of the first step are as follows [19]: (1) averting inclusion relation, intersectionality, and repeatability; i.e., similar indexes are avoided in the process of choosing; (2) taking representative indexes into account foremost, which means the indexes could highlight the relationship between land resource development and sustainable urbanization; and (3) adjusting indexes by local conditions such as location, environment, and resources. For the second stage, a standard grading is used to classify the scale interval into four value groups between 0 and 1 with corresponding scores (1, 2, 3, 4) [20,21]. A higher value corresponds to higher ecological sensitivity.

In the ISM, the weights greatly contribute to the evaluation index. Thus the third step is to determine the weights by mean squared error (MSE), which reflects the discrete degree of random variables and can be calculated by Equations (1)–(3) [16]. Then the integrated ULCC is expressed by Equation (4).

$$\bar{E}_j = \frac{n}{1} \sum_{i=1}^n Y_{ij} \quad (1)$$

$$\sigma(E_j) = \sqrt{\sum_{i=1}^n (Y_{ij} - \bar{E}_j)^2} \quad (2)$$

$$W_j = \frac{\sigma(E_j)}{\sum_{i=1}^n \sigma(E_j)} \quad (3)$$

$$F_i = \sum_{j=1}^n Y_{ij} \times W_j \quad (4)$$

where E_j is the average value of the random variables, $\sigma(E_j)$ is the MSE, W_j is the weight coefficient, and F_i is the ULCC value.

After the processes of the ISM calculation, the four levels of evaluation index were selected (Table 2), the weights were determined (Table 3). The weights are used to analyze the ecological sensitivity in the study.

Table 2. The ecological sensitivity evaluation factors rating table.

Primary Evaluation Factors	The Secondary Evaluation Factors	Ecological Sensitivity Level	Attribute Hierarchical	Scale Interval	Score
Topographic condition	Elevation (m)	Highly sensitive	≥ 200	0.75–1	4
		Moderately sensitive	100–200	0.5–0.75	3
		Lightly sensitive	50–100	0.25–0.5	2
		Non-sensitive	< 50	0–0.25	1
	Slope ($^{\circ}$)	Highly sensitive	≥ 25	0.75–1	4
		Moderately sensitive	15–25	0.5–0.75	3
		Lightly sensitive	5–15	0.25–0.5	2
		Non-sensitive	< 5	0–0.25	1
Land use type	Land use type	Highly sensitive	Forest land, water area, bare land	0.67–1	3
		Moderately sensitive	Cultivated land	0.33–0.67	2
		Non-sensitive	Build-up land	0–0.33	1
Regional development intensity	The distance from residential area (km)	Highly sensitive	≥ 1.5	0.75–1	4
		Moderately sensitive	1–1.5	0.5–0.75	3
		Lightly sensitive	0.5–1	0.25–0.5	2
		Non-sensitive	< 0.5	0–0.25	1
	The distance from primary traffic road (km)	Highly sensitive	≥ 3	0.75–1	4
		Moderately sensitive	2–3	0.5–0.75	3
		Lightly sensitive	1–2	0.25–0.5	2
		Non-sensitive	< 1	0–0.25	1
	Population density (person/km ²)	Highly sensitive	< 2000	0.75–1	4
		Moderately sensitive	2000–4000	0.5–0.75	3
		Lightly sensitive	4000–6000	0.25–0.5	2
		Non-sensitive	≥ 6000	0–0.25	1
Eco-environmental sensitivity	The distance from eco-environmental sensitive area (km)	Highly sensitive	< 0.2	0.75–1	4
		Moderately sensitive	0.2–0.5	0.5–0.75	3
		Lightly sensitive	0.5–1	0.25–0.5	2
		Non-sensitive	≥ 1	0–0.25	1

Table 3. The weights of factors.

	Weight
Elevation	0.09
Slope	0.09
Land use type	0.14
Residential area	0.24
Main roads	0.10
Population density	0.23
Eco-environment	0.11

3.2. Evaluation Methods

3.2.1. Topographic Condition

Topographic condition is an important factor affecting ecological sensitivity, which not only affects the scope of human activities but also characterizes the possibility of the occurrence of natural disasters [1]. This indicator usually includes elevation, slope, and slope direction, but, combined with

the actual situation of the study area, the aspect of slope direction has little effect on the regional ecological sensitivity [1]. Higher and steeper terrain will result in a higher possibility of natural disasters occurring with higher ecological sensitivity. Therefore, in this study, elevation and slope were selected as topographic condition factors for the ecological sensitivity evaluation.

Using the spatial analysis functions of ArcMap, a single factor evaluation was carried out. The elevation and slope were divided into four grades and classified according to Table 2. Since the original data of elevation and slope are divided into three pieces, it was necessary to combine them into a whole map to classify the ecological sensitive levels and obtain the elevation sensitivity map and slope sensitivity map.

3.2.2. Land Use Types

Different land use types reflect different ecological sensitivity. Based on the landscape ecology, human activities tend to make the outline of a landscape patch regular, which artificially increases the stability of patches, reducing the ecological sensitivity [1]. As a result, the ecological sensitivity of natural forest and grass is higher than that of built up areas after artificial transformation [1].

Classification has been conducted with the support of ENVI and ArcMap. Prior to the image classification, we first performed preprocessing such as registration, calibration, and geometric correction. The blue, green, red, near infrared, and mid-infrared bands (i.e., bands 1–5 and 7) of the Landsat TM/ETM + images were stacked together as a multi-spectral image for the classification. The map vectorization of eight districts of Hangzhou was accomplished in ArcMap, which was imported into ENVI as the mask for image cropping (Figure 2).

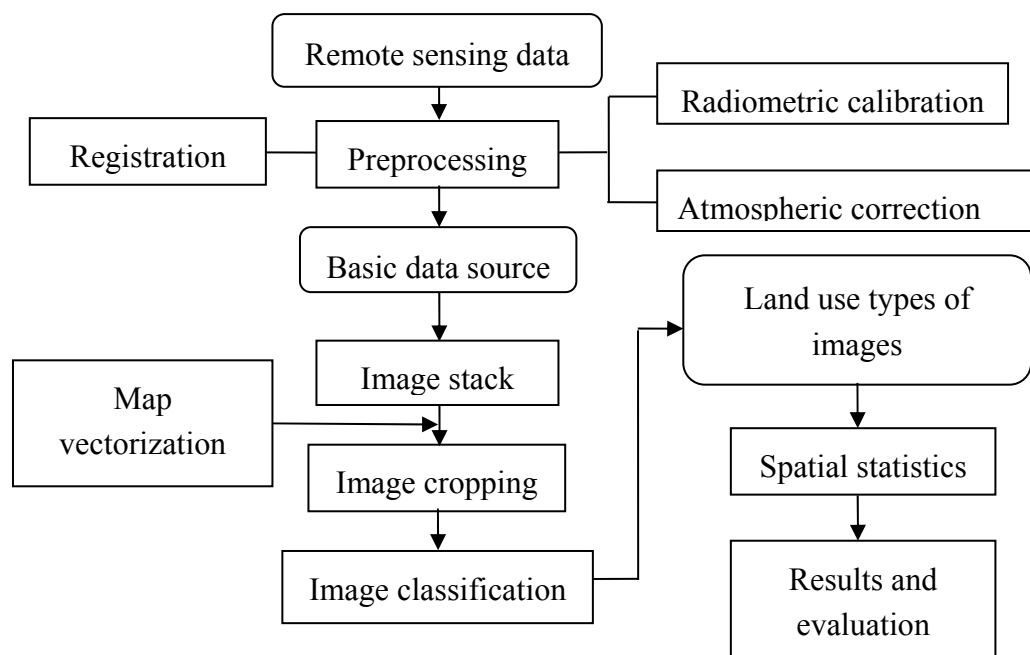


Figure 2. The flowchart of the data processing of land use classification.

In the image classification of land use types, we adopted the land use status classification standards 21010-2007 [22]. The image was classified into four types: water, forest area, built-up area, and bare land (see Figure 3). The maximum likelihood method [23] has been applied in the study, in which the training data sets have been selected using Google Earth and field survey data. Visual interpretation was used to refine the post-classification results, which were transformed into spatial analysis and statistics for the five types of land use [24].

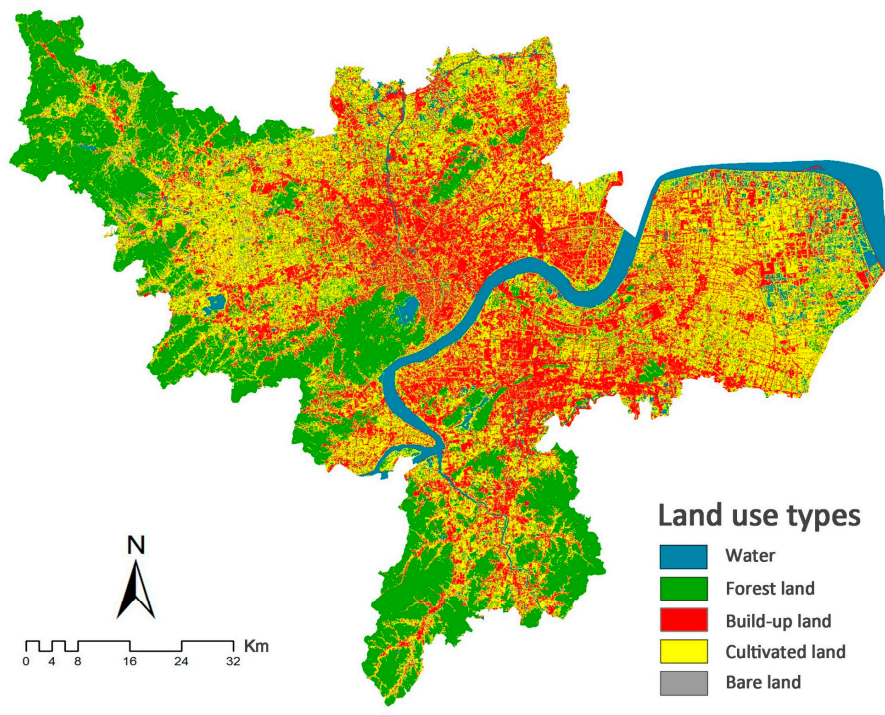


Figure 3. Image classification of land use types in the study area.

The classified land use data were divided into three grades (Table 2) in ArcMap10.2 to obtain the sensitivity map of land use types.

3.2.3. Regional Development Intensity

Due to long-term human activities, regional development intensity influences the ecological sensitivity. In the rapid urbanization, the resident distribution, traffic accessibility, and population density are considered the three main factors of regional development intensity [1]. Closer to residential areas and main traffic roads, the higher population density means that a higher degree of urban development and the transformation of the original ecological environment are more obvious. The levels of ecological sensitivity depend on whether it is conducive to develop built-up areas with ecological environments, as well as whether it is favorable to carry a larger population [1]. This means that with a higher degree of urban developing and a higher level of urbanization, the ecological environment of the areas is more suitable for urban built-up areas with the lower ecological sensitivity.

(1) Residential Area

In the study, 75 sub-districts and 20 towns in the eight districts of Hangzhou were used as 95 residential areas. We used the polygons to express the 95 residential areas and the points to indicate their central locations. Since the sub-districts and towns are not exactly residential areas, we used Google Earth to identify and vectorize the center location of these selected 95 residential areas in ArcMap, as shown in Figure 4. The distance sensitivity of residential areas was buffered by the Euclidean distance [25].

(2) Primary Traffic Roads

According to the present situation, the 42 main roads in the eight districts of Hangzhou have been vectorized, while the method of Euclidean distance is used for buffering [25]. Table 2 shows the criteria by which the road distance sensitivity grades are created (Figure 5).

(3) Population Density

To obtain the population density map, we first made a geography registration of the administrative borders of the eight districts in ArcMap. The population density fields were then added. According to the statistical yearbook, the data are inputted and transferred to the grid, finally producing the population density sensitivity map.

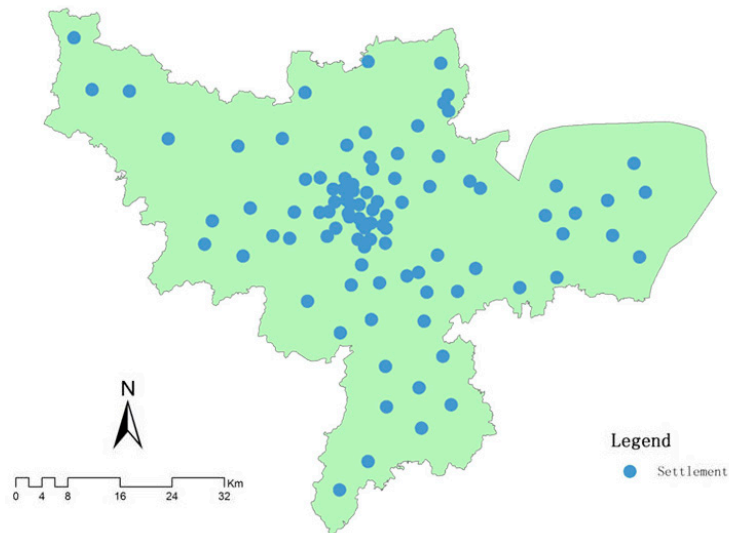


Figure 4. The vector results of 95 settlements.

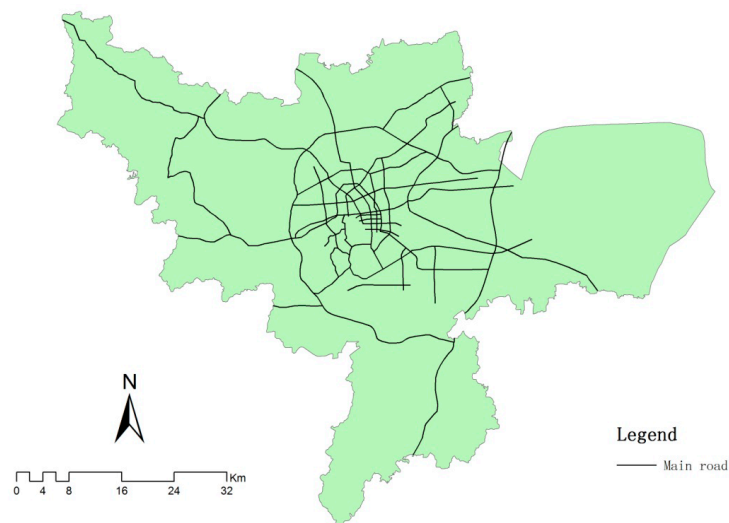


Figure 5. The vector results of 42 main roads.

3.2.4. Eco-Environmental Sensitivity

Based on the actual situation of Hangzhou, ecological regions (patches), canals (corridors), and 48 ecological points, which are important for the protection of ecological environments, have been selected for vectorization (Figure 6). These ecological regions were expressed as polygons, including the Qiantang River, lakes, the Grand Canal, the West Lake Scenic Area, Xixi Wetland, and Ban Shan National Forest Park, while 48 ecological points were identified and digitized using Google Earth. Using maximum sensitivity as the principle, we obtained the final sensitivity map of the ecological environment.

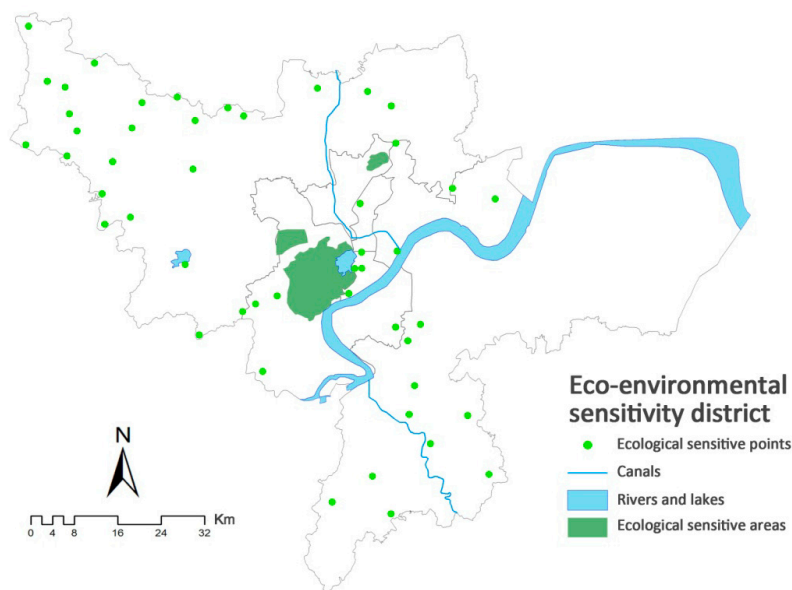


Figure 6. The vector results of eco-environmental sensitivity district.

3.2.5. Comprehensive Evaluation Using Ecological Sensitivity Analysis

In the comprehensive evaluation, the weights for each factor have been determined using mean squared error (MSE) (Table 3). According to the single factor of sensitive area scale table (Table 2), the weighted results have been obtained using the raster calculator function. Then the whole sensitive area has been divided into four levels: highly sensitive, moderately sensitive, lightly sensitive, and non-sensitive areas.

3.3. ULCC Calculation

The ULCC is calculated based on the levels of ecological sensitivity. On the basis of the comprehensive evaluation using ecological sensitivity analysis, the area of the ecological environment that is fully protected as the prerequisite and the maximum environmental capacity that the urban land resources can support can be calculated according to the ecological sensitivity levels [26]. By combining this with the land construction standard, it is possible to evaluate whether the regional land resources can meet the demand of the scale of land planning and support the actual population [19].

In the study, we applied the method of ecological land from comprehensive evaluation using ecological sensitivity analysis in the same way as previous studies [19] to calculate the ULCC.

4. Results and Discussion

4.1. Evaluation Using Single Factors

4.1.1. Topographic Analysis

Hangzhou is located in the middle and low reaches of hilly areas in the Yangtze River and in the Qiantang River estuary, and the plain dominates the study area. From the analysis of elevation sensitivity and slope sensitivity levels (see Figure 7a,b), the majority of the city lies in non-sensitive areas, while the three other types of sensitive areas are mainly concentrated in the mountainous area of the western part of the West Lake Scenic Area, the National Forest Park in the northern part of Hangzhou, the northwestern part of Hangzhou, and the south mountain foothills.

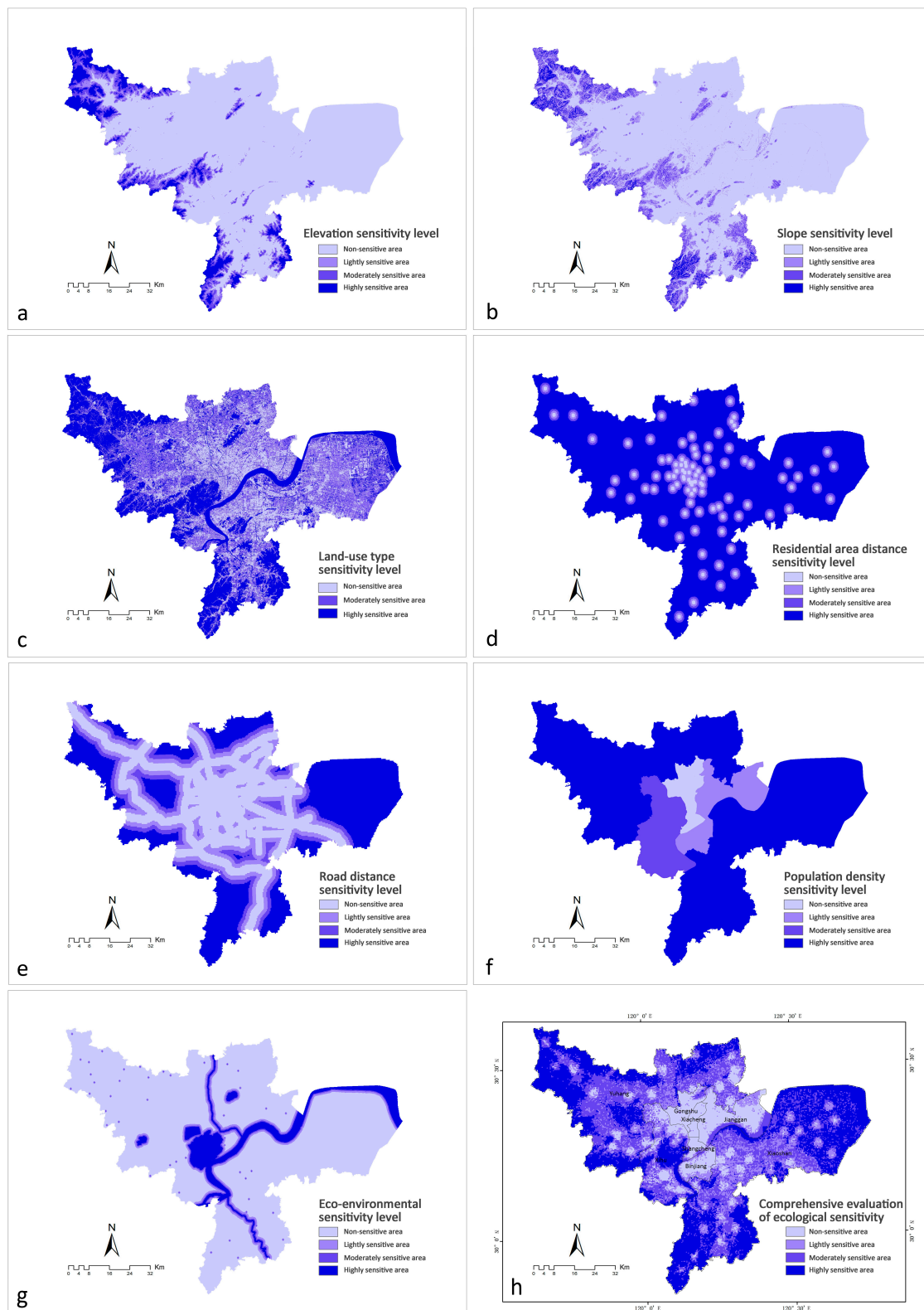


Figure 7. (a) Elevation sensitivity level; (b) slope sensitivity level; (c) land-use type sensitivity level; (d) residential area distance sensitivity level; (e) road distance sensitivity level; (f) population density sensitivity level; (g) eco-environmental sensitivity level; (h) comprehensive results.

4.1.2. Land Use

From Figure 7c, we found that there are three levels, as below:

- (1) The highly sensitive areas are distributed in forest areas, water areas, and their surroundings, which are located at the West Lake Scenic Area, the western part of Tianmu Mountain, the Qiantang River basin, the northern half part of the National Forest Park, and the southern low hills.
- (2) The moderately sensitive areas are mainly concentrated in the parts of mountainous areas that were developed as cultivated land and forest area, small towns in the eastern part of Xiaoshan, and the area of the Yuhang district close to the mountain.
- (3) The non-sensitive areas are located in the old urban center of Hangzhou, the Xiasha center, the Linping center, and the Binjiang district at the south bank of the Qiantang riverside. Due to the impact of human activities in these regions, most native natural landscapes have been replaced by artificial landscapes. An extremely high level of urbanization with a stabilized ecological environment has resulted in a low degree of the ecological sensitivity.

4.1.3. Regional Development Intensity

(1) Residential Area

The impact on the ecological sensitivity is associated with the city's land property. From the residential area distance sensitivity level map (Figure 7d), it can be clearly seen that the settlements in Hangzhou are mainly in the districts of Gongshu, Shangcheng, and Xiacheng. In addition, the area in the west higher education zone of Xihu and the West Lake Scenic Area surroundings (Lingyin, Beishan, West Lake sub-districts), the central part of Jianggan (i.e., Caihe, Zhanongkou, and Sijiqing sub-districts), and the Linping group of Yuhang all show relatively intensive regional distribution. As a result, the regional ecological sensitivity close to sub-districts and towns or more compact distribution residential areas seems low. The distribution of the remaining areas (i.e., Xiaoshan, Binjiang, and Yuhang) is fragmented so the ecological sensitivity of these three areas is highly sensitive.

(2) Primary Traffic Roads

The study considers the influence of the main roads in Hangzhou on ecological sensitivity. The road distance sensitivity level map (Figure 7e) shows the road network concentrated area as being mainly located in the Shangcheng, Xiacheng, Gongshu, and the Xihu; the sensitivity of these areas is low, with a high degree of urbanization. In contrast, the south bank of the Qiantang River (the eastern part of Xiaoshan) and the southern areas of Binjiang offer a sparse road network and less construction land. The northwest part of Yuhang has mountains and forests, reflecting the high sensitivity of ecology in the mountains, where the nature reserve is far away from the main traffic roads.

(3) Population Density

The population density sensitivity level map (Figure 7f) indicates that the population density in the periphery area is obviously different from that in the central area. Highly sensitive areas are situated in those regions that have low development intensity, while low population density is far from the city center such as in the Xiaoshan and Yuhang districts. Moderately sensitive areas are located in areas where development intensity and population density are low such as those areas in the south and west of the West Lake, which is far from urban areas. The lightly sensitive areas are concentrated in the suburban areas with high population density and large populations such as Binjiang and a small portion of Jianggan. Non-sensitive areas are in the regional development areas with high intensity and high population density, holding the largest population of the central city (i.e., Gongshu, Shangcheng, and Xiacheng).

4.1.4. Eco-Environmental Sensitivity

According to eco-environmental characteristics, three types of significant ecological protection areas (ecological points, corridors, and patches) have been selected. The ecologically sensitive areas, predominated by environmental factors, are distributed in forest parks, scenic tourist areas, and water areas. Two major tourist attractions are in the city center, including the Xixi Wetland and the West Lake Scenic Area. From the eco-environmental sensitivity level map (Figure 7g), the highly sensitive areas are mainly concentrated in these two locations. It is also found that this is somewhat predictable as undeveloped areas receive higher ecological sensitivity scores and urbanized areas lower scores. This may suggest that the sensitive index is not intuitive.

In addition, the main sensitive areas around rivers, lakes, and other environmental factors are along the riverbanks and are located on both sides of the Qiantang River and the canal through the city. As Hangzhou downtown is surrounded by mountains in the southwest and northwest, there have been sporadic ecological sensitive points. Tourism activities have been carried out widely, thus it is significant to pay special attention to ecological and environmental protection.

The ecological sensitivity results obtained from the aforementioned four kinds of evaluation factors have been statistically calculated, and the proportion of the sensitive areas at all four levels has been acquired accordingly (Table 4).

Table 4. The sensitivity of each grading proportion data.

	Non-Sensitive Area	Lightly Sensitive Area	Moderately Sensitive Area	Highly Sensitive Area
Each partition proportion	14.23%	17.14%	30.04%	38.59%
Area of each ecological sensitivity (km ²)	436.71	525.86	921.62	1183.82

4.2. Comprehensive Evaluation of Ecological Sensitivity

Figure 7h shows comprehensive results in terms of four levels: non-sensitive, lightly sensitive, moderately ecologically sensitive, and highly ecologically sensitive areas. It is clear that the ecologically sensitive area is increasing progressively from the center to the periphery (Table 5).

Table 5. The proportion of the sensitive areas in the four levels.

	Non-Sensitive Area	Lightly-Sensitive Area	Moderately-Sensitive Area	Highly-Sensitive Area
Elevation	79.46%	6.36%	7.46%	6.71%
Slope	74.95%	12.82%	9.08%	3.15%
Land use type	26.28%	/	38.85%	34.87%
Residential area	2.20%	6.23%	18.49%	73.08%
Main roads	34.30%	17.26%	10.83%	37.60%
Population density	3.88%	8.23%	9.50%	78.38%
Eco-environment	83.04%	5.05%	3.10%	8.81%

(1) Non-Sensitive Area

The non-sensitive area encompasses about 436.71 km², which is mainly concentrated in the central urban area, the Jianggan district, and most areas of the Binjiang district. These areas have already become the built-up area of the city, and the ecological environment has been completely changed by long-term human activities. Therefore, the water, vegetation, and other natural landscapes in this part of the region should be protected to improve the use ratio of the land.

(2) Lightly Sensitive Area

The lightly sensitive ecological area covers 525.86 km², located mainly around edges of the urban center. It also includes the sub-city of Linping in Yuhang and the center of the four major subdistricts of Xiaoshan, i.e., the Chengxiang, Beigan, Xintang, and the Shushan blocks. These areas are the leading edge of urban expansion, or urban fringe, and are the zone of transition from urban ecological to township ecological areas.

(3) Moderately Sensitive Area

The moderately sensitive ecological area comprises 921.62 km², mainly distributed in the area of cultivated land, the tea garden around Xihu District, and most regions of the Yuhang and Xiaoshan district, except for the mountainous areas. Specially, the Banshan National Forest Park in the Gongshu district is a distinctive case as it is in the downtown but also in the ecologically moderately sensitive area.

(4) Highly Sensitive Area

The highly sensitive ecological area is 1183.82 km², mainly located in the northwest Tianmu Mountain area, the woodland in the south part of Xiaoshan, the Qiantang riverside, and the east estuary near the beach; the most special areas are the West Lake Scenic Area and the Tangqi town in the north part of Yuhang. The ecological environment of most of the area is fragile, and the development level is very low; the original ecological environment is retained and reserved.

With the integrated analysis of ecological sensitivity, a comprehensive statistics diagram has been obtained, which vividly reflects the proportion of sensitive areas at all four levels. From Figure 8, it is clear that the proportion of moderately and highly sensitive areas is apparently higher than that of two other types, approximately twice the non-sensitive and lightly sensitive areas. For the moderately sensitive area (30.04%), its natural conditions are decent, yet it is influenced by human activities severely. Therefore, the development and construction activities should be strictly controlled with the principle of building a 'beautiful village' and 'beautiful town'. Moreover, in terms of the highly sensitive areas (38.59%), the protection of mountains and tidal flats will be strengthened and construction land will be forbidden in these areas.

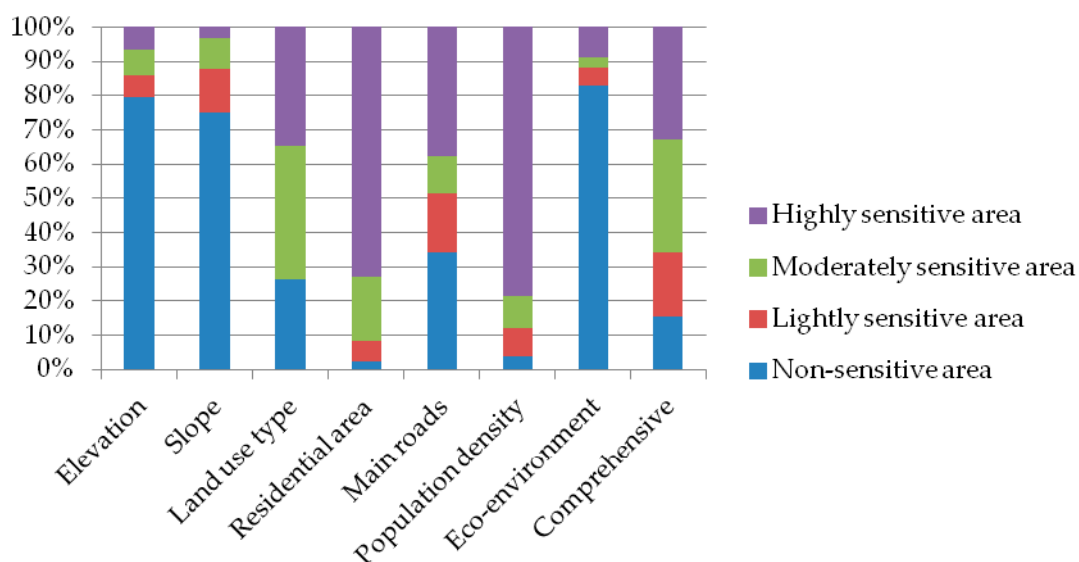


Figure 8. The proportion of the sensitive areas at the four levels.

4.3. Urban Land Carrying Capacity Analysis

From previous studies [19,27], 100% highly sensitive areas, 60% moderately sensitive areas, and 20% lightly sensitive areas have been selected and added up to encompass the ecological land from the comprehensive evaluation of ecological sensitivity in Hangzhou, while the remainder is tagged as construction land.

Based on this ratio, it is deduced that the ULCC area of Hangzhou city is the sum of 40% moderately sensitive, 80% lightly sensitive, and all the non-sensitive areas. From Table 4, the construction land area is determined to be 1332.01 km² after calculation.

The ULCC is related to socio-economic level, policy guidance, and complicated human life style. At present, there is no unified conclusion in this field, and there are different living needs and standards of population carrying capacity objectively [19–21]. Therefore, under the condition that the land area can be calculated, the ULCC of Hangzhou can be calculated by the per capita land demand index. In comparison to the present population of Hangzhou, it can be determined whether the current population exceeds the carrying capacity of the urban land.

The previous studies show that the per capita land demand for human survival and development in the city is 140–200 m² (including residential, traffic, and daily life), compared to a minimum of 140 m² as the international standard [27–29]. Meanwhile, the per capita use of land in different cities is also diverse: for the United States, the figure is 160 m², for Moscow it is 100–105 m², and for China it is 120 m² [30,31]. The figure describing per capita land use announced by the Chinese Ministry of Construction is 105–120 m² [1]. By calculating the area of land available for construction in Hangzhou, the ULCC is calculated according to the per capita land demand index.

According to the calculation in Table 6, no matter which of the above standards is applied, the population of Hangzhou is not over the maximum population carrying capacity. Compared with current population (4.50 million), there is a certain margin in different standards. Under the highest domestic standard, the population will be about 11.10 million, which shows a relatively large margin in the study area.

Table 6. Land population carrying capacity under different standards.

Standard Classification		Population Carrying Capacity	Current Population
International Standard	140 m ² per capita	9.51 million	4.50 million
America Standard	160 m ² per capita	8.32 million	
Muscovitic Standard	100 m ² per capita	13.32 million	
	105 m ² per capita	12.68 million	
Domestic Standard	120 m ² per capita	11.10 million	

4.4. Discussion

Due to the limitations of data collection, the population density of some small towns cannot be accurately estimated. In this study, the data is available only to be expressed by eight districts instead of blocks and towns in detail. For the selection of evaluation index, the factors of some new variables such as water supply, food (agriculture), or energy resources [32,33] are not considered in this study. At present, the study area is a rapid economical developing megacity in China, thus water and food supplies are sufficient and shall not influence the ULCC of Hangzhou in the short term. In addition, energy consumption is hard to express in the data collection of Landsat ETM+ images of 30-m resolution. However, the limitations should be overcome if using high-resolution images of less than 10-m in the near future.

5. Conclusions

In this study, we evaluate the urban land carrying capacity based on the ecological sensitivity using remote sensing data and geographic information system (GIS) technology. It is reasonable to

determine the ecologically sensitive areas in terms of four levels using the evaluation index. The results show that the ULCC has a certain margin if compared to the current population. The ecological environment in the study area can continue to sustain the current size of the population in the short term. However, as it is necessary to address the protection of distinctive natural landscapes, decision makers should adjust measures for ecological conditions to carry out the sustainable development of population, environmental, and land resources in Hangzhou.

Although the current ecological environment in Hangzhou can continue to support the size of its population, urban planning should not neglect appropriately controlling the land-use types of areas. From ecological protection land to construction land, serious control of space as the basis for regulation should be required. In strengthening the concept of ecological and environmental protection, mountains, water bodies, and scenic spots require the most stringent types of land use management to guide future land use planning and sustainable development.

In addition, water supply and energy consumption will be considered as a new evaluation index in the near future.

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References

1. Yue, W.Z.; Yao, H.N.; Zheng, J.E. Research on land population supporting capacity based on ecological sensitivity—Taking Hangzhou city as an example. *Nat. Res. Econ. China* **2013**, *15*, 52–56.
2. Liu, X.L.; Fang, C.L. Research progress and prospects of urban agglomeration resource environmental bearing capacity. *Prog. Geogr.* **2008**, *27*, 35–42.
3. Mei, W.J.; Zhou, W.L.; Cai, L.T. Regional land population carrying capacity research—Taking Zhoucheng city as an example. *J. Southwest Agric. Univ.* **2010**, *8*, 5–8.
4. Lu, M.; Kong, Y.F. The ecological sensitivity evaluation research progress. *J. Shandong Constr. Univ.* **2014**, *4*, 347–352.
5. Shi, L.Y.; Chen, B.M. *Production Capacity of Land Resources and Population Bearing Capacity Study in China*; China Renmin University Press: Beijing, China, 1991.
6. Feng, Z.M. Land bearing capacity research of past, present and future. *China Land Sci.* **1994**, *8*, 1–9.
7. Sarma, A.K.; Mahanta, C.; Bhattacharya, R.; Dutta, S.; Kartha, S.; Kumar, B.; Sreeja, P. *Urban Carrying Capacity: Concept and Calculation*; Centre of Excellence: Assam, India, 2012.
8. Vogt, W. *Road to Survival*; Sloan, W., Ed.; William Sloane Associates, Inc.: New York, NY, USA, 1984.
9. Alan, W. *The African Husbandman*; Oliver and Boyd: Edinburgh, UK, 1965.
10. Young, C.C. Defining the range: The development of carrying capacity in management practice. *J. Hist. Biol.* **1998**, *31*, 61–83. [[CrossRef](#)]
11. Malthus, T.R. *Essay on the Principle of Population*; Johnson, J., Ed.; St. Paul's Church-Yard Press: London, UK, 1798.
12. Meadows, D.H.; Randers, J.; Meadows, D. *The Limits to Growth*; Universe Books Press: New York, NY, USA, 1972.
13. Slesser, M.; King, J. Resource accounting: An application to development planning. *World Dev.* **1988**, *16*, 293–303. [[CrossRef](#)]
14. Rees, W.E. Ecological footprint. *Concept Encycl. Biodivers.* **2001**, *2*, 229–244. [[CrossRef](#)]
15. Gao, Y.J. Based on urban land bearing capacity of ecological sensitivity evaluation. *Plan. Study* **2013**, *37*, 39–42.

16. Qian, Y.; Tang, L.; Qiu, Q.; Xu, T.; Liao, J. A comparative analysis on assessment of land carrying capacity with ecological footprint analysis and index system method. *PLoS ONE* **2015**, *10*, e0130315. [[CrossRef](#)] [[PubMed](#)]
17. Liu, Y.; Yue, W.; Fan, P. Spatial determinants of urban land conversion in large Chinese cities: A case of Hangzhou. *Environ. Plan. B* **2011**, *38*, 706–725. [[CrossRef](#)]
18. Kim, H.; Willers, J.L.; Kim, S. Digital elevation modeling via curvature interpolation for LiDAR data. *Electron. J. Differ. Equ.* **2016**, *23*, 47–57.
19. Fu, S.F.; Zhang, P.; Jiang, J.L. Based on the development zone planning eia evaluation of bearing capacity of land resources. *Chin. J. Appl. Ecol.* **2012**, *4*, 459–467.
20. Xia, C.Y.; Yan, J.M. Indicator system of implementation evaluation for land use planning. *China Land Sci.* **2006**, *20*, 19–23.
21. Guo, Z.W. Comprehensive Evaluation on Land Resources Carrying Capacity for Beijing City. *Urban Stud.* **2008**, *15*, 24–30.
22. State Administration for Quality Supervision and Inspection and Quarantine Standardization Administration of China. *Land Use Status Classification (GBT 21010-2007)*; China Standards Press: Beijing, China, 2007.
23. Donnay, J.P.; Barnsley, M.J.; Longley, P.A. (Eds.) *Remote Sensing and Urban Analysis*; Taylor & Francis: London, UK, 2001.
24. Li, D.; Xu, S.; Han, D.B. The land use status quo analysis based on GIS and RS. *J. Heilongjiang Inst. Eng.* **2012**, *28*, 23–33.
25. O’Sullivan, D.; Unwin, D.J. *Geographic Information Analysis and Spatial Data*, 2nd ed.; John Wiley: Hoboken, NJ, USA, 2010.
26. Gao, X.Y.; Ge, Y.S. Study on Carrying Capacity of Land Resources Based on Ecological Sensitivity—A Case Study of Quanzhou City, Fujian Province. *Guangdong Agric. Sci.* **2007**, *8*, 123–126.
27. Li, Y.P.; Yang, H. Social dynamic population bearing capacity prediction—Taking Lancangjiang region in Yunnan province as an example. *Chin. J. Popul. Sci.* **2002**, *7*, 43–50.
28. Cai, L.; Mu, G.Z. The index construction research of different population bearing capacity standard. *J. Humanit.* **2008**, *1*, 179–185.
29. Zhang, Y.J.; Zhang, Z.F.; Qi, X.Y. Several problems about population bearing capacity. *Ecol. Econ.* **2008**, *4*, 388–390.
30. Qiang, Z.; Qi, Y.B.; Bai, X.M. Big city cultivated land resources population carrying capacity study—Taking Beijing city as an example. *Res. Dev. Mark.* **2007**, *5*, 147–148.
31. Liu, Q.P.; Lin, Z.S.; Feng, N.H. Population bearing capacity of land resources dynamics simulation and application. *J. Nanjing Norm. Univ.* **2005**, *8*, 114–118.
32. Cottee, J.; Lopez-Aviles, A.; Behzadian, K.; Bradley, D.; Butler, D.; Downing, C.; Farmani, R.; Ingram, J.; Leach, M.; Pike, A.; et al. The local nexus network: Exploring the future of localised food systems and associated energy and water supply. In *Sustainable Design and Manufacturing 2016 (Smart Innovation Systems and Technologies Special Volume)*; Setchi, R., Howlett, R.J., Liu, Y., Theobald, P., Eds.; Springer International Publishing AG: Cham, Switzerland, 2016; pp. 613–624.
33. Le-bail, A.; Dessev, T.; Jury, V.; Zuniga, R.; Park, T.; Pitroff, M. Energy demand for selected bread making processes: conventional versus part baked frozen technologies. *J. Food Eng.* **2010**, *96*, 510–519. [[CrossRef](#)]

