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Evaluation of the Sustainable Use of Land Resources in the Cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal

Fei Shi [1,2], Yuanyuan Lu [2], Longgao Chen [1,*] and Wei-Ling Hsu [3]

[1] School of Public Policy and Management, China University of Mining and Technology, Xuzhou 221116, China; 20201@squ.edu.cn
[2] School of Civil Engineering and Architecture, Suqian University, Suqian 223800, China; luyeewan@outlook.com
[3] School of Civil Engineering, Jiaying University, Meizhou 514015, China; 202107013@jyu.edu.cn
* Correspondence: chenlonggao@cumt.edu.cn; Tel.: +86-13615113851

Abstract: Sustainable development is an important topic of urban research. The rational use of land resources is of great significance for urban development and is conducive to promoting regional governance and coordinated development. The purpose of this study was to construct an effective evaluation framework for urban land resources to maintain sustainable urban development. Taking the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal as the research object, this study constructed an evaluation system for the sustainable use of land resources including the dimensions of economic level, social development, and environmental resources. The statistical data for 2010, 2015, and 2020 were selected to comprehensively calculate and evaluate the level of sustainable use of land resources in the study area via the analytic hierarchy process (AHP)-entropy combined weight method, which combines the analytic hierarchy process and the entropy weight method. According to the research results, the sustainable use of land resources in the study area presented an overall upward trend from 2010 to 2015, and an overall downward trend from 2015 to 2020. Overall, the study area was in a critically sustainable stage, although the annual change rate of the level of sustainable use of land resources showed significant fluctuations and exhibited a spatial pattern of progressive increase from north to south. The cities in southern Jiangsu were in the initially sustainable and basically sustainable stages; those in central Jiangsu were in the critically sustainable and initially sustainable stages; and those in northern Jiangsu were in the unsustainable and critically sustainable stages. This study proposed a scientific and effective evaluation method for cities along the Grand Canal to explore the efficient, sustainable use of land resources in the future. The evaluation framework constructed on this basis can serve as an important reference for urban governance and is expected to guide the sustainable use and development of land resources for other cities of the same type.

Keywords: analytic hierarchy process; entropy weight method; decision-making analysis

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1. Introduction

The concept of sustainable development, first proposed in the *Report of the World Commission on Environment and Development (1987): Our Common Future*, advocates meeting the needs of the present generations without compromising the ability of future generations to meet their own needs [1]. Nowadays, sustainable development is an important topic of urban research. As a natural–economic complex system formed by the interaction between humans and nature, land resources are means of production that can be utilized by humans within a certain time and scope to provide welfare. On account of their limited quantity, irreplaceability, uneven quality, and fixed locations, land resources have become

a foundation of human survival, production, and life. In this sense, the sustainability of urban development is closely related to the rational use of land resources.

Unreasonable land use, blind urban expansion and illegal land use behavior have brought about a great change in land use patterns, the urban ecological landscape and the climate, and even affected ecological diversity and ecosystem balance, increasing ecological pressure, which has seriously interfered with the sustainable development of land resources [2,3]. Faced with a serious land use situation, the sustainability of land resource use has become a cornerstone of sustainable development in China, as it can coordinate the relationship between the security of land supply and demand and the conservation of land resources, as well as promote crop security and the healthy, sustainable social and economic development. In other words, the sustainable use of land resources is of great significance for urban development.

The evaluation of the sustainable use of land resources focuses on the status of the sustainable use of land within a certain spatial scope. As an extension of land use suitability in temporal and spatial dimensions, it comprehensively evaluates the ability of land resources to meet human needs in a certain time and space, both qualitatively and quantitatively. At present, researchers in this field mainly concentrate on specific research topics, such as agricultural land and urban land analysis, and rarely attempt to comprehensively evaluate land use in the cities located along China's river basins. The purpose of this study is to construct an effective evaluation framework for urban land resources to maintain sustainable urban development. In view of the unique geographical features and land use characteristics of the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal, this study selected several evaluation indicators reflecting the characteristics of the study area, and developed an evaluation system suitable to measure the sustainable use of land resources in the study area. This system is highly representative in terms of evaluating sustainable land use in the study area specifically and in the cities along the Grand Canal in general, and offers a valuable reference for other cities of the same type.

As pointed out by the World Commission on Environment and Development (WCED) of the United Nations in the *Report of the World Commission on Environment and Development: Our Common Future*, sustainable development assessment should comprehensively consider economic, environmental, and social issues. Accordingly, the purpose of land use should be to pursue the coordination of land functions and achieve sustainable land use. To this end, this study proposed an evaluation index system for sustainable land use including the three aspects of economy, society, and environmental resources. Then, the level of sustainable use of land resources in eight cities was comprehensively calculated and evaluated using the analytic hierarchy process (AHP)-entropy combined weight method, which combines the AHP and the entropy weight method. This paper focuses on the balanced growth of land use. Only the comprehensive and coordinated development of land use is sustainable land use, which can further promote the improvement in climate, landscape construction and the balance of ecological system with land as the carrier. The results of this study confirmed that, in relation to sustainable land use, a series of measures should be taken to achieve a scientific development characterized by multidimensional coordination and overall promotion.

1.1. Research Status of Sustainable Use of Land Resources

After 1950, European and American countries experienced increasingly intense conflicts between rapid economic development and limited environmental resources, which triggered reflections from scholars. In 1990, the concept of sustainable land use was innovatively introduced at the first International Workshop on Sustainable Land Use Systems. In 1976, to support international research, the Food and Agriculture Organization (FAO) of the United Nations developed an International Framework for the Evaluation of Sustainable Land Management (FESLM), a document that evaluates the land use status of different countries around the world. However, due to the continuous emergence of social issues, FESLM [4] proved to be unable to meet the needs of modern land use planning,

as it only focuses on the current characteristics of land use and fails to either perform a spatiotemporal dynamic analysis on land use or provide sustainable economic, ecological, and social improvement measures.

Several scholars conducted relevant studies based on FESLM [4]. John studied the change trend of sustainable land use in Mokakos from 1930 to 1990 [5]. Bouman proposed a framework for regional land use analysis, which measures the relationship between biophysics and economic sustainability, offering a comprehensive assessment of sustainable land use [6]. In China, research on sustainable land use began in 1995 with a study on the sustainable development of cultivated land. Since the formulation of China's Agenda 21: White Paper on China's Population, Environment, and Development in the 21st Century [7], scholars have proposed a series of evaluation systems and methods of sustainable land use from different academic perspectives. Lu, Ke et al. measured the sustainability of urbanization and the degree of urban sustainable land use using necessary control variables and instrumental variables [8].

By relying on dynamic change models and standard deviation ellipse analysis, Xiao et al. assessed the dynamics of cultivated land patterns during three periods in the Shanghai and Hangzhou Bay (SHB) area [9]. Zhang et al. presented a conceptual classification framework, and adopted a set of spatialization models to assess, identify, quantify, and visualize land use functions in the spatial grid context [10]. Deng et al. analyzed the land use transformation and land ecological efficiency in Hebei Province, China using stochastic frontier analysis (SFA) and other statistical analyses [11]. Taking Hangzhou, China as a case study, Zhu et al. determined the trade-off and synergetic effect between land use functions and their influencing factors from a geographical spatial perspective [12]. Notably, specific evaluation indicators and methods are still in an early stage of research and vary across countries and regions.

1.2. Research Status of Evaluation Indicators for the Sustainable Use of Land Resources

In 1993, the FAO released for the first time the FESLM [4], which outlines the basic principles, procedures, and five evaluation criteria (i.e., productivity, security, protection, acceptability, and viability) of sustainable land use. Based on the FESLM, scholars from different countries and regions have conducted research on the sustainable use status of land resources. In 1997, the ISSS Sub-Commission F Land Evaluation Congress: Geo-Information for Sustainable Land Management [13] (SLUMIS) advocated the selection of indicators based on the availability, sensitivity, and quantifiability of data, and divided them into three categories, namely, environmental technology, economy, and society. At present, more than 300 evaluation indicators have been constructed in the world, and some evaluation systems have been applied in research.

On the basis of the five evaluation principles of FESLM, Cornworth proposed a series of indicators selection criteria for the evaluation of land use sustainability [14]. In investigating the change in the sustainability status of land use, Preris, Dumanski et al. constructed an evaluation system using the pressure–state–response (PSR) model, and used it to evaluate land quality, summarizing the influencing factors of land degradation [15,16]. Schuler, Suarma et al. developed an indicator system including social, economic, and environmental aspects, and used it to assess the sustainability of land use change in Yogyakarta, Indonesia [17]. Mumtas explored the sustainability of intensive land use based on an indicator system covering productivity, security, protection, acceptability, and viability [18]. Chinese scholars have also conducted research on relevant indicator systems from related perspectives. Zou and Liu constructed a model based on the widely recognized "ecological-production-living" perspective of global sustainable development, and selected Nan'an, a typical coastal city, to conduct empirical analysis [19]. He et al. assessed the sustainability status of land use based on an indicator system including economic progress, social stability, urban improvement, and ecological balance [20].

Later, researchers and experts conducted empirical studies on different regions based on this indicator system. Chao et al. constructed an indicator system from the dimensions of

production, life, and ecology, and used it to assess sustainable land use in Hubei Province, China [21]. Xuan constructed an indicator system composed of a social economy and ecological environment, and performed a coupling analysis of urban land use benefits in Xiamen [22]. He introduced the concept of PSR into land use research, and constructed a regional evaluation system based on human–environment interaction [23]. As can be seen from these studies, the selection of indicators basically focused on economy, society, and environmental resources [24,25], which can provide an important reference to construct graded evaluation indicators.

This study focuses on the balanced growth of land use, as only comprehensive and coordinated land use can be regarded as sustainable. Compared to existing studies, this study contributes to a detailed understanding of sustainable land use in China, offering experience and suggestions for other developing countries around the world.

2. Overview of the Study Area and Evaluation Methods

2.1. Overview of the Study Area

The Beijing–Hangzhou Grand Canal is the longest artificial canal in the world, and a vast waterway system stretching on the eastern plain of China for 1794 km, starting from Beijing in the north and ending in Hangzhou in the south. It is one of the largest water conservancy projects in human history, linking up five major rivers in China [26,27]. Dating back to the 5th century BCE, it was added to the World Cultural Heritage List of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) on 22 June 2014 [28].

The Jiangsu Section of the Beijing–Hangzhou Grand Canal has a total length of 628 km and runs through Jiangsu Province from north to south. Its natural environmental characteristics are similar to those of Jiangsu Province as a whole. Jiangsu Province accounts for approximately 1% of China's total territory, and is characterized by flat terrain, numerous lakes, dense water networks, and land–sea interdependence. Due to differences in climate, topography, biodiversity, parent materials, and land formation time, the study area has a wide range of soil types, including zonal soil and nonzonal soil. The land resources in the study area have very high production potential. The scope of this study covered eight cities in Jiangsu Province, namely Xuzhou, Suqian, Huai'an, Yangzhou, Zhenjiang, Changzhou, Wuxi, and Suzhou, as shown in Figure 1.

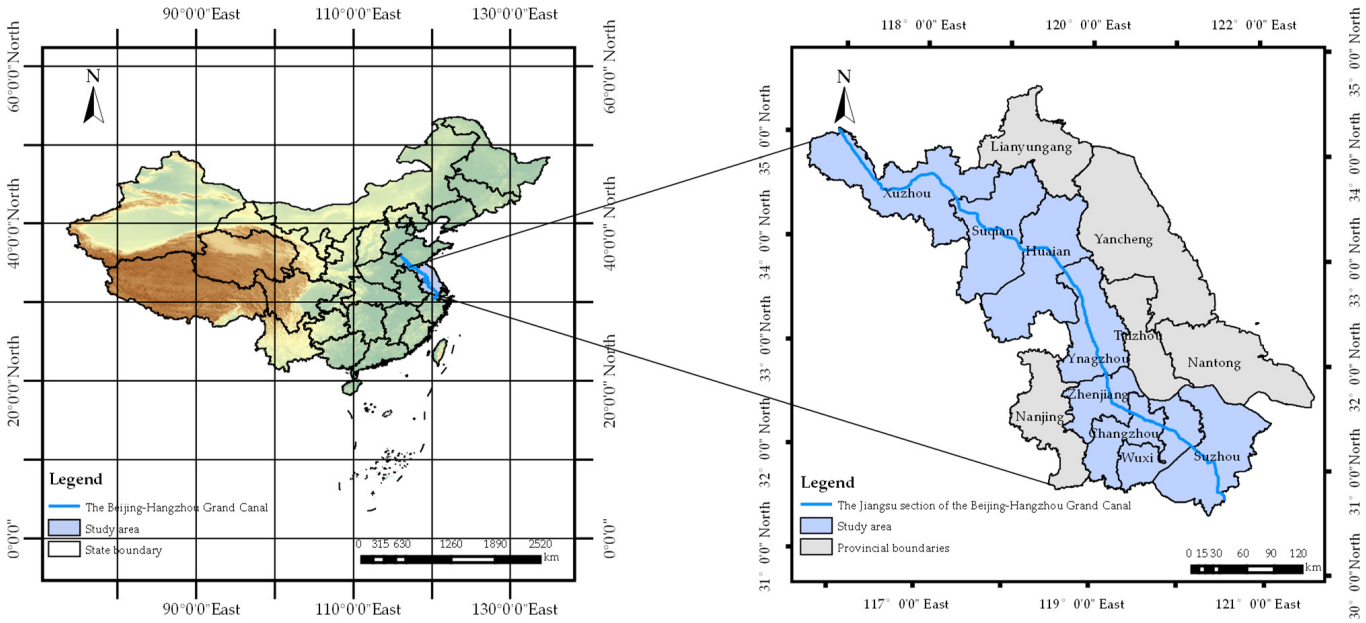


Figure 1. Drainage map of the Jiangsu Section of the Beijing–Hangzhou Grand Canal.

The rapid development of urbanization has promoted an irreversible change in land use. The Chinese government has adopted the National New Urbanization Plan focusing on

the rational use of resources, which is of great significance for the sustainable, rational and intensive use of land [29]. The empirical cities selected in this study were all ancient cities with a history of more than one thousand years. Due to the rapid development of China's urbanization in the past two decades, most cities have serious problems such as insufficient land use efficiency and are far from the level of new urbanization. This indicates that the quality of current urbanization is low, urban expansion is frequent, and the coordinated development of urbanization and sustainable land use has not been realized. Therefore, for the sustainable development of cities, the empirical scope selected is of great significance.

The cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal present a promising prospect of rapid socioeconomic development, showing a significant improvement in their comprehensive strength in regional development. Since 2000, the regional GDP has maintained a high growth rate, and the industry focus has gradually shifted to tertiary industries, giving rise to a further optimization of the industrial structure. In 2020, the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal had a total population of 45.5201 million and a regional GDP of CNY 6522.218 billion, accounting for 62.342% of the GDP of Jiangsu Province. The eight prefecture-level cities in the study area ranked among the top 100 in terms of GDP in China.

2.2. Evaluation Methods

2.2.1. Research Methods for the Evaluation of the Sustainable Use of Land Resources

Effective evaluation methods provide a scientific guarantee to assess the sustainable use of land resources. The depth of research advances with the diversification of evaluation methods. Stefanović, Milutinović et al. performed a comparison between the analysis and synthesis under the AHP and the information deficiency method, and assessed the sustainability of waste management scenarios on this basis [30]. Sarkar et al. conducted a comprehensive study on sustainable land use in Prussia based on the AHP and the Geographic Information System (GIS) technology [31]. Cristian et al. evaluated spatial land use in the Bucharest Metropolitan Area using the AHP and expert opinion systems [32]. Sherwin, Abbas et al. assessed land suitability and agricultural production sustainability in Mazandaran Province, Iran using a combined approach (Fuzzy-AHP-GIS) [33].

Mohamed, Saleh et al. studied the sustainable development level of agricultural land use in the north of Sinai, Egypt using an indicator system based on GIS spatial modeling [34]. To evaluate the sustainable use of land resources, Chinese experts tend to use econometrics models, such as the AHP, the entropy weight method, the linear proportional transformation method, principal component analysis (PCA), the comprehensive index model, the grey correlation model, and GIS calculation. Qian et al. evaluated the sustainable use of land resources using the AHP [35]. Zhang et al. identified the main factors in the evaluation of the sustainability of urban land use through PCA [36]. Ruan and Liu proposed a GIS-based soft computing (GSC) method and used it to assess and map land use suitability for urban development in Ili Valley, China [37].

Jin evaluated the sustainable use of land resources using the technique for order of preference by similarity to ideal solution (TOPSIS) method and the objective degree model [20,38]. Li and Fan analyzed sustainable land use with the aid of the grey correlation model [39]. Yuan et al. conducted research on the sustainable status of land resource use based on an improved entropy weight method [40], on which basis later scholars have conducted empirical studies on different regions [22,41]. Zhao et al. combined the entropy weight method with the grey correlation model to evaluate land use sustainability in Henan Province, China; as shown by this literature review, PSR, AHP, and the entropy weight method are relatively mature methods for applied analysis.

In synthesis, a preliminary consensus has been reached on the concept of sustainable land use and on the framework to establish an appropriate evaluation indicator system. In this research field, several methods, technologies, and case studies have been proposed. While the selection of evaluation indicators for sustainable land use varies from place to place, the majority of countries focus on three aspects (i.e., economy, society, and environ-

mental resources) in the construction of evaluation systems. On this basis, the sustainable status of land use is evaluated and analyzed, and improvement measures are put forward. However, further improvements are still needed in the selection of evaluation indicators and methods. The breadth and depth of research on the construction of evaluation systems and the evaluation of sustainable land use are insufficient. Further efforts are still needed to create a sound evaluation system, select appropriate evaluation indicators and methods, and apply them to the entire evaluation process. In addition, the countermeasures and suggestions regarding the dynamic changes in each region also need to be closely linked with the latest evaluation.

Land use/cover change (LUCC) research is closely related to the launches of international scientific programs since the 1990s, which has led to several key research directions. While the effectiveness of each program varies, we divide the history of LUCC research into three phases, namely, the process phase (1990–2004), the impact phase (2005–2013) and the sustainability phase (2014–present), depending on the major concerns of each program [42]. Jin used the computable general equilibrium of land use change and dynamics of land system models; under the green development scenario, indexes such as grassland, cultivated land, unused land, forest coverage, water body and construction land were selected to determine the sustainable mode of land development [43]. Liang et.al applied a patch-generating land use simulation model that integrates a land expansion analysis strategy and a CA model based on multitype random patch seeds [44]. LUCC is the most important factor in the sustainable development of the city. The indicators selected for evaluation refer to the important discussion of previous studies. This study discusses the time dimension and analyzes until 2020.

Data including government bulletins, statistical yearbooks, etc., that could be collected for this study and measurable indicators were gathered. These quantifiable indicators of land-scape fragmentation can help urban decision makers make systematic judgments. However, the Chinese government needs a reference basis for landscape fragmentation. The spatial standards of landscape ecological structure fragmentation still need city decision makers further efforts.

Based on the relevant research results at home and abroad and the urban characteristics of this study area, the core index structure evaluation system is selected. The constructed index is the main method of information measurement to measure and evaluate the state of and change in the city in this study. At the level of evaluation index, this study comprehensively combs the characteristics of the systematization level. As the index system is composed of independent indicators, the selection of evaluation indicators follows the principles of scientific objectivity, operability, comprehensive and systematic, regional and so on. The indicators selected in this study are the key to determine the system architecture. On the basis of the results of the literature analysis, this study aimed to evaluate the sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal. For this purpose, we adopted economic feasibility, social acceptability, and environmental resource sustainability as reference layers, and selected 18 indicators according to the availability and quantifiability of data to construct an evaluation system (Table 1).

The indicator weights were determined using the AHP-entropy combined weight method. A comprehensive index model was used to calculate the evaluation results of the sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal in 2010, 2015, and 2020. The changes in the level of sustainable use of land resources in the study area were analyzed from the perspective of both a temporal and a spatial dimension.

Table 1. Evaluation system of the sustainable use of land resources.

Target Layer	Criterion Layer	Indicator Layer	Unit	Nature of Indicator
A. Sustainable use of land resources	B_1. Economic feasibility	X_1: GDP growth rate	%	+
		X_2: per-capita GDP	CNY/person	+
		X_3: proportion of the tertiary industry in GDP	%	+
		X_4: agricultural output value per unit area of cultivated land	CNY/hm^2	+
		X_5: agricultural output value per unit area of forest land	CNY/hm^2	+
		X_6: proportion of industrial output value in GDP	%	+
	B_2. Social acceptability	X_7: urban/rural income ratio		-
		X_8: Engel coefficient of urban households	%	-
		X_9: Engel coefficient of rural households	%	-
		X_{10}: urbanization rate	%	+
		X_{11}: natural population growth rate	‰	-
		X_{12}: per-capita cultivated land area	hm^2/person	+
	B_3. Environmental resource sustainability	X_{13}: ratio of cultivated land area	%	+
		X_{14}: ratio of forest land area	%	+
		X_{15}: ratio of grassland area	%	+
		X_{16}: green coverage rate of built-up area	%	+
		X_{17}: water resources per unit area of land	m^3/km^2	+
		X_{18}: per-capita land area	hm^2/person	+

Note: "+" represents a positive indicator, and "-" a negative indicator.

2.2.2. Determination of Indicator Weights

1. Nondimensionalization of indicators

The data in this study mainly included land use data and statistical data on economy, population, environment, and social development. Land use data were retrieved from the official website of the Resource and Environment Science and Data Center (http://www.resdc.cn/). Specific statistical data were mainly taken from the *Jiangsu Statistical Yearbook*, the *Jiangsu Rural Statistical Yearbook*, the *China Urban Statistical Yearbook*, and the *China Urban Construction Statistical Yearbook*. The urban statistical yearbooks of the eight cities investigated were used as supplements. At the same time, the work reports and the statistical bulletins of Jiangsu Provincial People's Government and of the municipal people's governments of the cities concerned, as well as the statistical reports of relevant departments, such as the Department of Natural Resources and the Department of Ecology and Environment, were used to make up for the missing data in the yearbooks.

The evaluation indicators for the sustainable use of land resources include various factors. Considering the large number of indicators and the great differences between them, all indicator data were nondimensionalized using a mathematical method to make them comparable. To accurately reflect the actual characteristics during original data processing, the extreme value method (1–2) was ultimately chosen to process positive and negative indicators, as follows:

$$\text{Positive indicators}: \ r_{ij} = \frac{x_{ij} - min(x_i)}{max(x_i) - min(x_i)} \quad (1)$$

$$\text{Negative indicators}: \ r_{ij} = \frac{max(x_i) - x_{ij}}{max(x_i) - min(x_i)} \tag{2}$$

where r_{ij} denotes the nondimensionalized value of x_{ij}; x_{ij} denotes the value of the jth object of the ith indicator; $min(x_i)$ denotes the minimum of the ith indicator; and $max(x_i)$ denotes the maximum of the ith indicator.

2. The AHP

Proposed by T. L. Saaty in 1973, the AHP is a hierarchical weight decision analysis method [45] that has been widely used for evaluation. It incorporates subjective judgments into evaluation and categorizes systematic problems into hierarchical relationships with rigorous logical structures between different layers [46,47]. Decision-related factors are divided into different layers, and on this basis, they are compared in a pairwise fashion to obtain their weights, providing references for decision makers. The specific steps are as follows:

(1) Construction of the hierarchical structure

The first step was to construct an indicator system by dividing evaluation indicators according to their relationships. The sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal was taken as the target layer. The criterion layer was constituted by economy, society, and environmental resources. A total of 18 indicators were selected as the indicator layer (Table 1).

(2) Creation of the pairwise comparison matrix

In addition to the target layer, other layers of factors should also be established for comparison, based on the estimates of top-layer factors. Therefore, in each pair of comparative design-related questionnaires, experts should be invited to check the scale of each pair of item comparisons using a scale from 1 to 9. Regarding the content and description of the scale, for a group of n factors in the matrix, it was necessary to perform $n\ (n-1)/2$ pairs of comparison. Then, the comparison results of these n factors were placed at the top of pairwise comparison matrix A. Since on the diagonal there are n ratios used to compare these factors with each other, they were all assigned a constant value of 1. The value at the bottom of the matrix was the reciprocal of the value at the corresponding position at the top. The resulting matrix was expressed as follows:

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{3}$$

If the weight of a factor was given, it could be expressed as follows:

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} W_1/W_1 & W_1/W_2 & \cdots & W_1/W_n \\ W_2/W_1 & W_2/W_2 & \cdots & W_2/W_n \\ \cdots & \cdots & \cdots & \cdots \\ W_n/W_1 & W_n/W_2 & \cdots & W_n/W_n \end{bmatrix}, \tag{4}$$

$$a_{ij} = w_i/w_j, \ a_{ij} = 1/a_{ji}, \ W = [W_1, W_2, \ldots, W_n]^T = \begin{bmatrix} W_1 \\ W_2 \\ \cdots \\ W_n \end{bmatrix} \tag{5}$$

where

W_{ij} denotes the weight of factor i; a_{ij} denotes the ratio of relative importance between two factors ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, n$).

(3) Calculation of eigenvalues and eigenvectors

The next step was to calculate the eigenvalues of the matrix and obtain the weights of the factors at each layer. Each eigenvector was calculated by multiplying the factors in each column, taking the geometric mean of their products, and then performing normalization, as follows:

$$W_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}},\ i,\ j = 1,\ 2,\ \ldots,\ n \tag{6}$$

The pairwise comparison matrix A was multiplied by the solved eigenvector W_i to obtain a new eigenvector W_i'. Each vector value of W_i' was divided by the corresponding vector value of the original vector W_i, thereby obtaining the arithmetic mean of various values and calculating λ_{max}, as follows:

$$A \cdot W = \lambda_{max} \cdot W, \tag{7}$$

$$\mathrm{A} = \begin{bmatrix} W_1/W_1 & W_1/W_2 & \ldots & w_1/w_n \\ W_2/W_1 & W_2/W_2 & \ldots & w_2/w_n \\ \ldots & \ldots & & \ldots \\ W_n/W_1 & W_n/W_2 & \ldots & w_n/w_n \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ \ldots \\ W_\mathrm{n} \end{bmatrix} = \begin{bmatrix} W_1' \\ W_2' \\ \ldots \\ W_\mathrm{n}' \end{bmatrix}, \tag{8}$$

where

$$\lambda_{max} = \frac{1}{n}\left(\frac{W_1'}{W_1} + \frac{W_2'}{W_2} + \ldots + \frac{W_\mathrm{n}'}{W_\mathrm{n}}\right), \tag{9}$$

(4) Consistency check

For the purpose of avoiding logical errors in the values of the pairwise comparison matrix, the consistency index (*C.I.*) was first calculated to check the consistency of the matrix, as follows:

$$C.I. = \frac{\lambda_{max} - n}{n - 1}, \tag{10}$$

where λ_{max} denotes the maximum eigenvalue of matrix A; n denotes the number of evaluation factors.

A value of $C.I.$ equal to 0 means that these n factors have equal importance under a certain criterion. A value of $C.I.$ greater than 0 means that there are disagreements in the judgments between experts. That is, the smaller the value of $C.I.$, the higher the consistency in the answers given by experts. Saaty's suggestion is that the value of $C.I.$ be lower than 0.1, and that the maximum allowable deviation be 0.2. Satty proposed a random index (*RI*), the values of which are provided in Table 2.

Table 2. *RI* values at each layer of the AHP.

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54

For matrices with the same order, the ratio of $C.I.$ to $R.I.$ is called the consistency ratio (*C.R.*); it was expressed as follows:

$$C.R. = \frac{C.I.}{R.I.} \tag{11}$$

A value of $C.R. < 0.1$ indicates a high consistency between matrices.

(5) Calculation of indicator weights

The weights of the evaluation indicators used to assess the sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal

were calculated according to the weight calculation steps of the AHP. Firstly, the weight of the criterion layer (B) was calculated, and then the weights of the 3 indicator layers were determined separately, thereby obtaining the weights of 18 specific indicators (Table 3).

Table 3. Weight statistics of the analytic hierarchy process.

Indicator	Weight	Indicator	Weight	Indicator	Weight
X_1	0.019	X_7	0.034	X_{13}	0.028
X_2	0.034	X_8	0.065	X_{14}	0.137
X_3	0.065	X_9	0.065	X_{15}	0.137
X_4	0.034	X_{10}	0.034	X_{16}	0.045
X_5	0.039	X_{11}	0.034	X_{17}	0.077
X_6	0.059	X_{12}	0.019	X_{18}	0.077

3. The entropy weight method

The concept of entropy was first introduced into scientific theories by Shannon in 1948 to reflect the uncertainty of information [48]. The entropy weight method measures comprehensive indicators using mathematical methods. Compared with the subjective weighting method, the entropy weight method [49] relies on the amount of data provided by each indicator to determine the weight, thereby effectively avoiding subjective participation and significantly improving the objectivity of decision making, compared to the subjective weighting method. By increasing the differences between parameters, the entropy weight method makes it possible for weights to more objectively reflect the differences between indicator data.

The entropy weight method combines mathematics and computer technology, and utilizes the information provided by various data to determine indicator weights from the perspective of objective weighting. In this way, it eliminates human interferences, and to some extent compensates for the shortcomings of subjective weighting. By virtue of its scientificity and authenticity, it has been widely applied in the evaluation field.

r_{ij} is the standardized value after nondimensionalization (m evaluation indicators and n evaluation objects). The calculation method is as follows:

(1) Quantification of each indicator and calculation of the proportion f_{ij} of the jth indicator in the ith line:

$$f_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}} (i = 1,\ 2,\ 3,\ \cdots,\ m;\ j = 1,\ 2,\ 3, \cdots,\ n) \tag{12}$$

(2) Calculation of the entropy value H_i of the ith indicator:

$$H_i = -k \sum_{j=1}^{n} f_{ij} ln f_{ij} \tag{13}$$

where $k = \frac{1}{lnn}$; when $f_{ij} = 0$, it was assumed that $f_{ij} ln f_{ij} = 0$.

(3) Calculation of the diversity coefficient h of the i-th indicator:

$$h = 1 - H_i \tag{14}$$

For a given indicator i, the smaller the difference in the indicator value of x_{ij}, the greater the value of H_i. When all the values of x_{ij} were equal, $H_i = 1$, in which case indicator i had little effect. On the contrary, the greater the difference in the indicator value of x_{ij}, the smaller the value of H_i, and the greater the value of h_i. This means that that indicator had a greater importance and a more significant effect on the evaluation object.

(4) Calculation of the weight of the i-th indicator:

$$w_i = \frac{h_i}{\sum_{i=1}^{m} h_i} \tag{15}$$

where w_i denotes the final indicator weight value, $0 \leq w_i \leq 1$, $\sum_{i=1}^{m} w_i = 1$.

(5) Calculation of indicator weights

The weights of the various evaluation indicators of the sustainable use of land resources in the study area were calculated according to the specified steps based on the dimensionless data of the indicators (Table 4).

Table 4. Weights of the indicators assigned through the entropy weight method.

Indicator	2010	2015	2020
X_1	0.060	0.046	0.076
X_2	0.061	0.045	0.050
X_3	0.057	0.037	0.046
X_4	0.121	0.074	0.047
X_5	0.083	0.082	0.078
X_6	0.043	0.033	0.066
X_7	0.047	0.041	0.039
X_8	0.009	0.034	0.037
X_9	0.035	0.040	0.039
X_{10}	0.056	0.059	0.055
X_{11}	0.038	0.042	0.033
X_{12}	0.047	0.071	0.060
X_{13}	0.056	0.045	0.040
X_{14}	0.081	0.094	0.086
X_{15}	0.056	0.076	0.083
X_{16}	0.050	0.037	0.040
X_{17}	0.054	0.060	0.080
X_{18}	0.046	0.083	0.046

4. The AHP-entropy combined weight method

The weights calculated using the AHP were combined with those obtained using the entropy weight method to obtain the comprehensive weight $\overline{w}_i$ of the indicator. The formula for the comprehensive weight of the i-th indicator was as follows:

$$\overline{w}_i = \alpha w_i + \beta \omega_i \tag{16}$$

where w_i is the i-th weight value of the AHP; ω_i is the i-th weight value of the entropy method. It was assumed that the weights determined using the two methods had the same importance, that is, $\alpha = \beta = 0.5$, and $\alpha + \beta = 1$. The weight values obtained using the AHP-entropy combined weight method are presented in Table 5.

Table 5. Combined weight values of the evaluation system of the sustainable use of land resources in the study area.

Indicator	2010	2015	2020
X_1	0.040	0.033	0.047
X_2	0.048	0.040	0.042
X_3	0.061	0.051	0.056
X_4	0.078	0.054	0.041
X_5	0.061	0.060	0.059
X_6	0.051	0.046	0.062

Table 5. *Cont.*

Indicator	2010	2015	2020
X_7	0.040	0.037	0.037
X_8	0.037	0.049	0.051
X_9	0.050	0.052	0.052
X_{10}	0.045	0.047	0.044
X_{11}	0.036	0.038	0.033
X_{12}	0.033	0.045	0.039
X_{13}	0.042	0.036	0.034
X_{14}	0.109	0.116	0.111
X_{15}	0.096	0.106	0.110
X_{16}	0.047	0.041	0.042
X_{17}	0.066	0.069	0.079
X_{18}	0.061	0.080	0.061

2.2.3. Comprehensive Evaluation Method

The comprehensive value of the sustainable use of land resources was calculated based on a comprehensive index model. In this model, a comprehensive operation was performed in the form of summation. In this way, the obtained weights of each indicator were added to calculate the comprehensive value of the evaluation results, followed by an intuitive comparative analysis. The formula employed for the model is as follows:

$$PI_i = \sum_{j=1}^{n} w_j \times r_{ij} \quad (17)$$

where PI_i denotes the comprehensive index; w_j denotes the combined weight of the i-th indicator; and r_{ij} denotes the nondimensionalized value of the i-th object of the i-th indicator.

For the sake of a comprehensive and intuitive analysis on the sustainable use of land resources, it was necessary to establish definition criteria. Following expert opinions and the classification criteria proposed by different researchers, this study divided the sustainable use of land resources into five levels, as shown in Table 6.

Table 6. Criteria to assess the level of sustainable use of land resources.

Comprehensive Value	<0.35	0.35–0.45	0.45–0.55	0.55–0.7	>0.7
Criteria	Unsustainable	Critically sustainable	Initially sustainable	Basically sustainable	Comprehensively sustainable

The comprehensive values of the sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal in 2010, 2015, and 2020 could be calculated using Formula (17) for the comprehensive evaluation method, as shown in Table 7.

Table 7. Comprehensive values of the sustainable use of land resources in the study area in 2010, 2015, and 2020.

City	2010	2015	2020
Wuxi	0.684	0.639	0.620
Xuzhou	0.403	0.460	0.401
Changzhou	0.566	0.590	0.571
Suzhou	0.490	0.528	0.517
Huai'an	0.427	0.588	0.420
Yangzhou	0.424	0.494	0.442
Zhenjiang	0.507	0.594	0.532
Suqian	0.320	0.314	0.333

3. Analysis of the Sustainable Use of Land Resources in the Cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal and Countermeasures

3.1. Analysis of the Sustainable Use of Land Resources in the Cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal

3.1.1. Analysis of Temporal Characteristics

A total of 18 evaluation indicators were selected from three dimensions based on the data collected from statistical yearbooks, and were used to reflect the current situation of land use, the quality and quantity of natural resources, the level of socioeconomic development, the level of people's living standards, and the status of environmental resources in the study area. With the support of the abovementioned indicator system and analysis methods, a comprehensive analysis was performed of the sustainable use of land resources in the study area and its three subsystems (i.e., economy, society, and environmental resources) in 2010, 2015, and 2020. Then, the change characteristics of the temporal patterns of the level of sustainable use of land resources in the study area in these 3 years were comparatively analyzed.

1. Comprehensive evaluation results

A comprehensive index model (Formula (17)) was used to calculate the comprehensive scores for the sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal and the three subsystems (i.e., economy, society, and environmental resources). The evaluation results are shown in Figure 2 and Table 8.

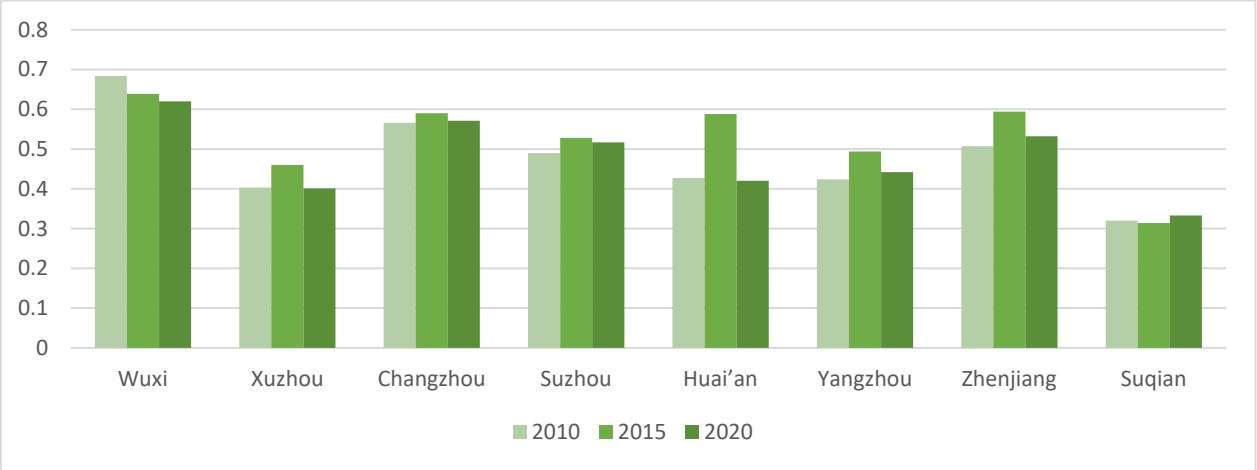


Figure 2. Histogram of the comprehensive evaluation results of the sustainable use of land resources in the study area in 2010, 2015, and 2020.

2. Change trend analysis

Looking at the comprehensive evaluation results and their histogram, it can be seen that, from 2010 to 2015, the level of sustainable use of land resources improved continuously in the study area as a whole, but not at the level of individual cities. From 2015 to 2020, an overall downward trend was observed, except in Suqian. More specifically, the comprehensive score for the level of sustainable use of land resources in Huai'an increased from 0.427 in 2010 to 0.588 in 2020, with an increase of 0.161 (37.705%). Clearly, from 2010 to 2015, Huai'an achieved great success in terms of sustainable land use. In the case of Suqian, although the level of sustainable use of land resources improved continuously, the city remained in an unsustainable state. The highest and lowest values of the comprehensive score were 0.333 in 2020 and 0.320 in 2010, respectively. The lowest value is attributable to the low score of the economy subsystem (only 0.048), while the highest value occurred because of the rapid socioeconomic development in recent years, which entailed a rapid growth of the score of the economy subsystem. Since 2010, the cities along the

Jiangsu Section of the Beijing–Hangzhou Grand Canal have basically been going through an alternation between the critically sustainable stage and the initially sustainable stage.

Table 8. Comprehensive evaluation results of the sustainable use of land resources in the study area in 2010, 2015, and 2020.

City	Year	Criterion Layer Indicator *B*			Comprehensive Score	Sustainability Grade
		B_1	B_2	B_3		
Wuxi	2010	0.249	0.166	0.269	0.684	BS
	2015	0.192	0.173	0.274	0.639	BS
	2020	0.207	0.160	0.253	0.620	BS
Xuzhou	2010	0.132	0.097	0.174	0.403	CS
	2015	0.127	0.127	0.206	0.460	IS
	2020	0.099	0.126	0.176	0.401	CS
Changzhou	2010	0.174	0.170	0.222	0.566	BS
	2015	0.167	0.161	0.261	0.590	BS
	2020	0.204	0.142	0.226	0.571	BS
Suzhou	2010	0.223	0.168	0.099	0.490	IS
	2015	0.193	0.196	0.139	0.528	IS
	2020	0.249	0.170	0.097	0.517	IS
Huai'an	2010	0.076	0.092	0.259	0.427	CS
	2015	0.164	0.111	0.313	0.588	BS
	2020	0.053	0.092	0.275	0.420	CS
Yangzhou	2010	0.129	0.136	0.159	0.424	CS
	2015	0.164	0.144	0.187	0.494	IS
	2020	0.150	0.155	0.137	0.442	CS
Zhenjiang	2010	0.113	0.114	0.280	0.507	IS
	2015	0.158	0.177	0.260	0.594	BS
	2020	0.142	0.163	0.226	0.532	IS
Suqian	2010	0.048	0.100	0.172	0.320	Unsustainable
	2015	0.080	0.075	0.160	0.314	Unsustainable
	2020	0.083	0.069	0.182	0.333	Unsustainable

Note: basically sustainable: BS; critically sustainable: CS; initially sustainable: IS.

3.1.2. Analysis of the Spatial Differences

A comprehensive evaluation of the sustainable status of land resource use in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal from the temporal dimension can only reflect the dynamic change in time, but not its spatial distribution or spatial change trend. Hence, it was necessary to investigate the spatial differences in the sustainable use of land resources in the study area. To this purpose, the spatial differences in the sustainable use of land resources in the study area and its three subsystems (i.e., economy, society, and environmental resources) were analyzed based on the relevant data of eight prefecture-level cities in the study area in 2010, 2015, and 2020. The spatial distribution of the level of sustainable use of land resources in the study area at a five-year interval was also obtained.

According to the results of the analysis of the spatial distribution status, the level of the sustainable use of land resources in the study area increased continuously from north to south. The overall level in southern Jiangsu was higher than that in northern Jiangsu. Broadly speaking, southern Jiangsu was in the initially sustainable and basically sustainable stages in the study period; central Jiangsu was in the critically sustainable and initially sustainable stages; and northern Jiangsu was in the unsustainable and initially sustainable stages, with a low overall level.

Looking at the dimension of administrative division (Table 9), the cities in the study area could be ranked in descending order in terms of their level of sustainable use of land resources, as follows: Wuxi (0.648) > Changzhou (0.576) > Zhenjiang (0.544) > Suzhou (0.512) > Huai'an (0.478) > Yangzhou (0.453) > Xuzhou (0.421) > Suqian (0.322). On this basis, it can be concluded that the level of sustainable use of land resources in a region is directly related to the local socioeconomic development level.

Table 9. Comprehensive scores for the level of sustainable use of land resources in the study area in 2010, 2015, and 2020.

City	Wuxi	Xuzhou	Changzhou	Suzhou	Huai'an	Yangzhou	Zhenjiang	Suqian
2010	0.684	0.403	0.566	0.490	0.427	0.424	0.507	0.320
2015	0.639	0.460	0.590	0.528	0.588	0.494	0.594	0.314
2020	0.620	0.401	0.571	0.517	0.42	0.442	0.532	0.333
Mean	0.648	0.421	0.576	0.512	0.478	0.453	0.544	0.322
Mean-based ranking	1	7	2	4	5	6	3	8

Looking at the temporal dimension (Figure 3), in 2010, 2015, and 2020, only one city in the study area, i.e., Suqian, remained in an unsustainable stage, accounting for 12.5%. In the 3 years investigated, 25%, 37.5%, and 25% of the cities in the study area, respectively, were in a basically sustainable stage, and were concentrated in southern Jiangsu. In 2020, northern and central Jiangsu (except for Suqian) were in a critically sustainable stage, accounting for more than half of the total number of cities in the study area, while 25% of them were in a basically sustainable stage. In 2010, 2015, and 2020, southern Jiangsu was generally in a basically sustainable stage, while the majority of the cities in northern and central Jiangsu alternated between unsustainable and critically sustainable stages. Although the overall level of sustainable use of land resources in the study area improved to a certain extent, the gap in this regard between the north and the south was widening. Although the figures for 2010 and 2020 are the same, the causes are not the same. In 2010, the cause was the high value of environmental resources, while in 2020, it was due to the increasing social and economic level year by year. On the basis of our research, more qualitative and quantitative analysis of landscape fragmentation can be conducted by future researchers.

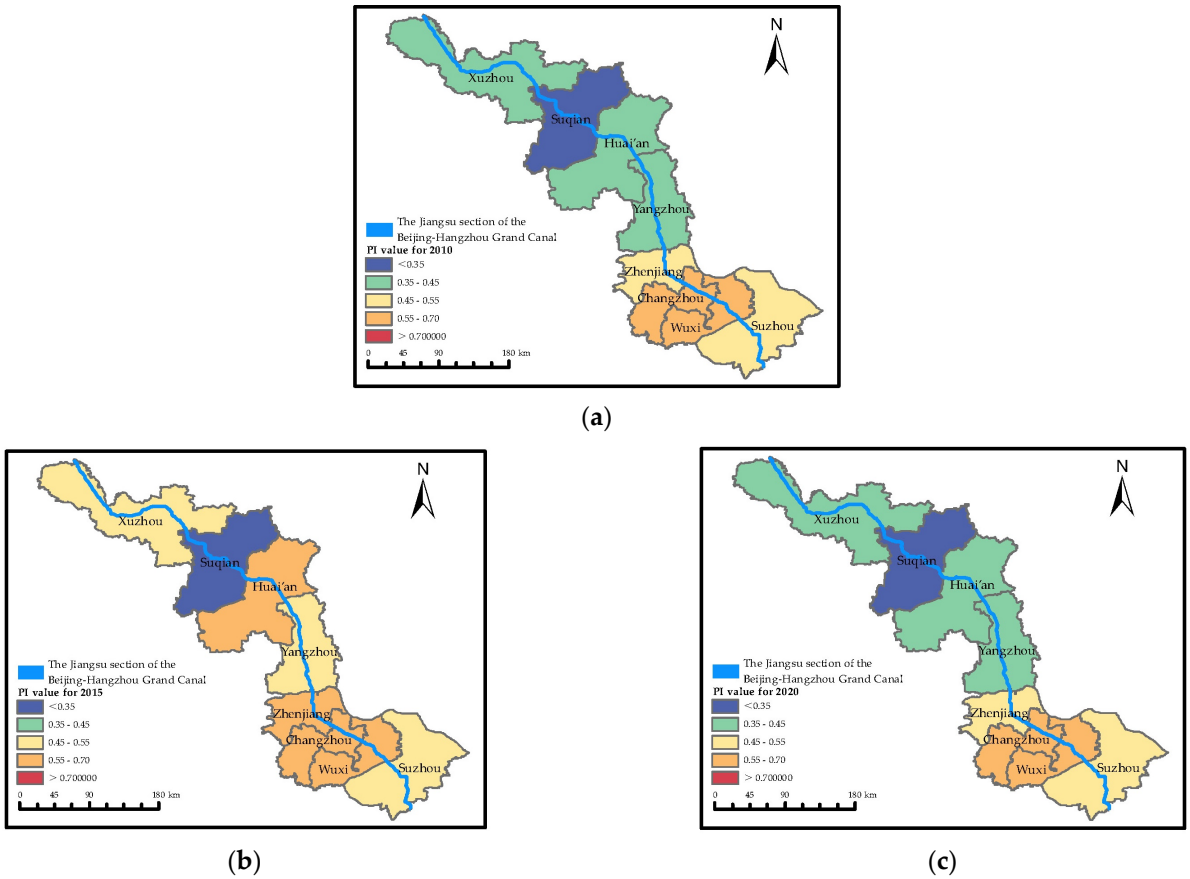


Figure 3. Spatial distribution status of the level of sustainable use of land resources in the study area in 2010, 2015, and 2020. (**a**): 2010; (**b**): 2015; (**c**): 2020.

3.2. Countermeasures for the Sustainable Use of Land Resources in the Cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal

Based on the results of the comprehensive analysis of the temporal characteristics of, and spatial differences in, the level of sustainable use of land resources in the study area, the study area should try to achieve the sustainable development of the ecological environment, while at the same time ensuring a healthy socioeconomic development. At present, the cities in the study area, while experiencing a rapid economic development, face problems of environmental pollution and resource waste, which have caused an imbalance between socioeconomic development and environmental resources carrying capacity. Therefore, the study area should strive for a healthy development under the premise of environmental resource conservation. The specific suggestions are as follows:

(1) Adjust the industrial structure and promote economic development

The economy subsystem has made the largest contribution to land use in the Jiangsu Section of the Beijing–Hangzhou Grand Canal, serving as the primary driver for the rapid increase in the *PI* score since 2010. In recent years, the score for the proportion of the tertiary industry in GDP (X_3) has grown continuously, suggesting that the output value of the tertiary industry has improved, playing a vital role in the score for the economy subsystem. Nevertheless, the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal have prioritized environmental protection and resource conservation as important means to reshape economic growth models and optimize economic structures.

(2) Increase fiscal investments and narrow the urban–rural gap

The score for the society subsystem presented an upward trend, which suggests that the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal should increase investment in social construction. The proportion of the score for the per-capita cultivated land area (X_{12}) showed a dramatic decline, while the proportion of the scores for the urban/rural income ratio (X_7), the Engel coefficient of urban households (X_8), and the Engel coefficient of urban households (X_9) gradually increased. The changes in these data can remind urban managers of the unbalanced distribution of wealth between rural and urban areas.

(3) Coordinate human–land contradictions and promote harmonious coexistence

The score for the environmental resource subsystem decreased continuously and was always lower than the comprehensive score during the study period. Currently, the poor performance of the environmental resource subsystem is the main obstacle to the sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal. The weight of the score for the green coverage rate of built-up area (X_{16}) gradually increased, while that of the scores for the per-capita land area (X_{18}) and the ratio of cultivated land area (X_{13}) showed a dramatic decline. Therefore, increasing the per-capita land area, ensuring land use efficiency, promoting intensive land use, and implementing reasonable population and land policies are crucial for the long-term development of the environmental resource subsystem. The cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal were suggested properly delineate basic farmland, strictly implement the system of cultivated land protection, and effectively improve the mechanism of agricultural land use.

4. Discussions

The proportion of initially sustainable and basically sustainable cities increased from 50% in 2010 to 87.5% in 2015 and 50% in 2020. Although the proportion of initially sustainable and basically sustainable cities was the same in 2010 and 2020, the overall score of sustainable use of urban land resources was generally higher in 2020 than in 2010. The level of sustainable use of urban land resources in 2020 was lower than that in 2015, but still improved compared with that in 2010.

From the perspective of the economic subsystem, 62.5% of the cities in 2010 were in the unsustainable and critical sustainable stage. In 2020, the sustainable level of the

economic subsystem is improved to a certain extent, and the economic development gap between the north and the south is more and more obvious. From the perspective of social subsystem, the level of social subsystem of northern and central cities is generally low, and that of southern cities is more developed. The urbanization rate of southern cities is higher than that of central and northern cities on the whole. From the perspective of the environmental resource subsystem, except Suzhou, the level of the environmental resource subsystem of southern cities is generally higher than that of northern cities, mainly because the green coverage rate of built-up areas of southern cities is higher than that of northern cities, the proportion of secondary and tertiary industries is larger, and the average water resource of southern cities is rich. However, the cultivated land resources are very few, especially in Suzhou. While the northern and central cities are relatively rich in cultivated land resources, the built-up areas have less green coverage.

The main limitation of this study is that the measurable indicators of landscape fragmentation are not clearly defined, and only three ratios are considered to analyze the change in land resource utilization including X_{13}: the ratio of cultivated land area, X_{14}: the ratio of forest land area, and X_{15}: the ratio of grassland area. However, these indexes cannot reflect the continuous change in landscape ecological structure. Other quantifiable indicators reflecting landscape fragmentation (such as sustainable landscape pattern [50], landscape fragmentation index [51], etc.) are not included in the scope of this study. As a result, the proposed policy recommendations contain biodiversity and ecological balance incompleteness. In addition, the continuous change in landscape ecological structure should be better utilized to help the sustainable development of cities. In the future, on the basis of this study, we will consider all possibilities such as changes in landscape fragmentation and continuous changes in landscape ecological structure, and come up with recommendations to improve the conservation and large-scale use of land resources, including not only policy measures but also engineering measures such as better use of the region's natural values, biodiversity and ecological balance. It is suggested that future researchers may supplement the deficiencies of quantitative research from the aspect of qualitative research as a comprehensive recommendation for urban decision makers.

5. Conclusions

By referring to relevant studies and following scientific evaluation principles, this study selected 18 evaluation indicators from the dimensions of economic level, social development, and environmental resources based on the actual situation of the study area, and constructed an evaluation system of the sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal. The indicator weights were determined using the AHP-entropy combined weight method. A comprehensive index model was used to calculate the comprehensive scores for the sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal in 2010, 2015, and 2020. The status of the sustainable use of land resources in the study area was analyzed from both a temporal and a spatial dimension.

The findings of this study can be summarized as follows:

1. As shown by the results of the analysis of the temporal characteristics, the comprehensive score for the sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal presented an overall upward trend from 2010 to 2015, and an overall downward trend from 2015 to 2020. Overall, the study area was in a critically sustainable stage, except for Suqian.
2. As shown by the results of the analysis of the spatial differences, the overall level of sustainable use of land resources in the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal exhibited a spatial pattern of progressive increase from north to south. Specifically, southern Jiangsu was in the initially sustainable and basically sustainable stages; central Jiangsu was in the critically sustainable and initially sustainable stages; and northern Jiangsu was in the unsustainable and critically sustainable stages.

3. Depending on the status of the sustainable use of land resources, the cities along the Jiangsu Section of the Beijing–Hangzhou Grand Canal can be divided in three categories. The first category includes cities with a high socioeconomic development level and low environmental resource level, such as Suzhou, Wuxi, and Changzhou. The second category includes cities with lagging socioeconomic development, such as Huai'an, Suqian, and Xuzhou. The third category includes cities falling between the first two categories, such as Yangzhou and Zhenjiang.

Finally, on the basis of the results of this analysis, three countermeasures are proposed: adjust the industrial structure and promote economic development; increase fiscal investments and start to close the urban–rural gap; and coordinate human–land contradictions and promote harmonious coexistence. The evaluation of land use efficiency in developing countries needs further analysis in the future. In addition, models for land use efficiency evaluation should be further improved to achieve more scientific and effective evaluation results. By simulating the spatial layout of land and investigating the spatio-temporal evolution characteristics of land use efficiency, the main factors restricting the improvement in the coordination relationships in different regions were identified. More targeted suggestions are needed in relation to how developing countries can more effectively promote the coordination between efficient land use and land use efficiency.

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