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Resources and Environmental Pressure, Carrying Capacity, And Governance: A Case Study of Yangtze River Economic Belt

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Abstract: The analysis of the relationship between regional resources and environment and human activities plays an important role in sustainable regional development. This study proposes the pressure–capacity–governance (PCG) model, an analytic framework for the assessment of the resources and environmental pressure (REP), carrying capacity (RECC) and governance (REG) levels over a large watershed scale, with the Yangtze River Economic Belt (YREB) as the study area. A limiting factor analysis is used to recognize the limiting factors of the regional RECC. The coupling analysis of resources and environmental pressure–capacity–governance identifies the regional potential and utilization direction. The research results are as follows. (1) The REP, RECC and REG levels of the YREB exhibit spatial differences. The REPs of the upper reaches are lower than those of the lower reaches, which does not match the RECC but matches the REG levels. (2) The proportions of unused land, water resources, and atmospheric environmental quality are the main limiting factors of the regional RECC. (3) The PCG analysis framework is used as the basis to divide the YREB into several subareas to analyse the resources and environmental potential carrying capacity and utilization direction of different types of region. This research may provide decision-making references for regional sustainable development at the large watershed scale.

Keywords: resources and environmental pressure (REP); resources and environmental carrying capacity (RECC); resources and environmental governance (REG); limiting factors; mechanism

1. Introduction

With the rapid development of urbanization and industrialization in China, the contradiction between socioeconomic development and the population, resources and environment has become increasingly prominent, becoming a major bottleneck for regional sustainable development [1]. The concept of carrying capacity describes the relationship between resources, environment and human activities to ensure sustainability [2–4]. However, the relationships among these elements continue to need profound interpretation. In recent years, studies have proposed the concept of planetary boundaries for estimating a safe operating space for humanity with respect to the functioning of the earth system [5,6]. However, this method is considerably large-scale and is unsuitable for regional-scale studies. Therefore, choosing an effective method has become an important issue in analysing the relationships between regional resources, environment and human activities, and providing operable and effective regulation countermeasures to realise a sustainable regional strategy.

Carrying capacity originated in the fields of demographics [7], ecology [8] and was discussed in the looming limits of the resource consumption and environment degradation resulting from excessive human activities [9–11]. During the 200 years since its conception, the research on carrying capacity has changed from researches of biotic population growth law to the comprehensive carrying capacity covering natural resource endowments and human development demands [12]. The scopes of carrying capacity applications have been expanded, such as land resource carrying capacity [13,14], water resource carrying capacity [15–17], environmental carrying capacity [18–20], ecological carrying capacity [21–23], cultural carrying capacity [24,25], social carrying capacity [26,27] and comprehensive resources and environmental carrying capacity [28–31]. The progression of carrying capacity has gradually attached importance to the influence of human activity factors on the carrying capacity [12]. The evaluation object has gradually shifted from a single resource and environmental element to the carrying capacity for multiple or comprehensive elements [32]. Nowadays, carrying capacity is widely employed in urban planning, resource and environmental management and becomes the key indicator to measure the sustainable development.

The evaluation methods of resources and environmental carrying capacity (RECC) mainly include the ecological footprint method [33,34], energy analysis [35], system dynamics [36] and the comprehensive evaluation method [37,38]. Ecological footprint is a resource supply–demand balance method, which is more applicable at the global level [39]. The energy analysis method takes energy as the dimension and transforms different kinds of energy and substance in the system into the same standard energy. However, high parameter demands limit the application of this analysis method [40]. The system dynamics model can quantitatively analyse the intrinsic relationship between the structure and function of various complex systems; however, it is difficult to select the parameter indicator, and the large quantity of data limits the application of the model and the similitude to reality [41]. By building a multilevel indicator system, a comprehensive evaluation method can be used to evaluate the regional carrying capacity [42]. Two common indicator systems are as follows: one assumes that the standards of resources, environment, economy, society and other criteria are additive [43,44]; the other aims to build a "pressure-state-response"(PSR) [45] or "driving force-pressure-state-impact-response" (DPSIR) [46] model as a system layer or distinguish between pressure indicators and support indicators [42,47].

Although the existing literature has studied various focuses and models on RECC [48], some limitations exist: (1) The current research area on RECC mainly aims at a single city [30,31], which lacks an analytical framework for the RECC at the large watershed scale. Therefore, it lacks the comparison among regions based on more detailed indicators. It is not conducive to the establishment of a unified early warning mechanism of RECC [47]. (2) Most studies divide the RECC system into resources criterion, environment criterion, human society criterion and calculate the comprehensive indicators [43,44]. These indicators cannot distinguish the regional resource and environmental status and the effects of human activities on the systems (e.g., the economic pressure and the governance measures). Moreover, few studies analyse the limiting factors of the regional RECC. (3) Some studies mainly discuss special evaluations of a single element of the carrying capacity [13–20], which can only provide partial understandings of sustainability. Some comprehensive RECC studies focus on simple superposition of many statistical indicators without considering the relationship among various elements. It is not conducive to provide decision-making references for regional sustainable development.

As a watershed economic belt with international impact, the Yangtze River Economic Belt (YREB) has immense ecological status, comprehensive power and development potential. Taking YREB as the example, this study builds an evaluation model to analyse the resources and environmental pressure (REP), carrying capacity (RECC) and governance (REG) levels of each city in the zone, as well as proposes the potential carrying capacity and utilization direction. The detailed objectives are as follows: (1) build a conceptual pressure–capacity–governance (PCG) model at the large watershed scale; (2) assess the regional REP, RECC and REG levels, as well as analyse the differences among regions; identify the limiting factors of the RECC of the YREB; and (3) analyse the regional potential carrying capacity and utilization direction based on the coupling types of the REP, RECC and REG.

2. Materials and Methods

2.1. Study Area

The YREB refers to the nearby economic circle along the Yangtze River, covering two municipalities, which are directly under the central government of Shanghai and Chongqing, and nine provinces (i.e., Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Sichuan, Yunnan and Guizhou). The YREB's land resources account for 21.4% of China's land area, with a population accounting for 42.9% of the total population in China, supporting 44.1% of China's GDP in 2018 (China Statistical Yearbook 2019). The YREB is the most important economic zone in China with substantial development potential. The internal development of this region is significantly different from that in other regions. Moreover, this region is divided into upper, middle and lower reaches (Figure 1). The upper reaches include Chongqing, Sichuan, Guizhou and Yunnan, with an area accounting for 55.1% of the zone, with a population accounting for 33.2% of that of the zone and supporting 23.3% of the zone's GDP. The middle reaches include Jiangxi, Hubei and Hunan, with an area accounting for 27.4% of the zone and a population of 29.2% of that of the zone, supporting 24.3% of the zone's GDP. The lower reach area includes Shanghai, Jiangsu, Zhejiang and Anhui, with an area accounting for 17.4% of the zone and a population accounting for 37.6% of that of the zone, supporting 52.5% of the zone's GDP.

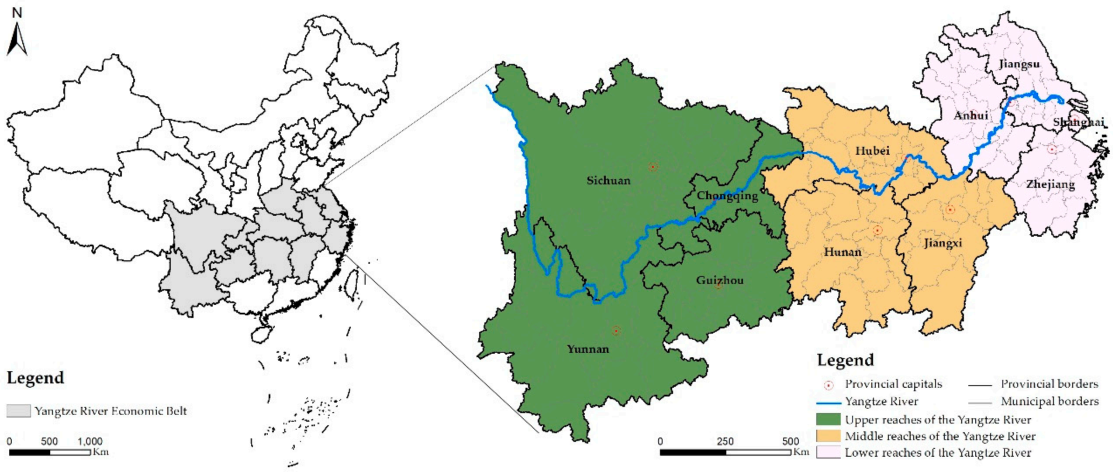


Figure 1. Location of the Yangtze River Economic Belt (YREB).

2.2. Data Source

The data used in this research are from the land use/land cover data interpreted from Landsat TM images in 2015. The water resource, atmospheric environment and water environment data are from the water resources bulletins and the environmental status bulletins of the provinces and cities in 2015. The data on resources and environmental pressure, resource utilization and governance are from the China Regional Statistical Yearbook, China City Statistical Yearbook and the yearbooks of the provinces and cities in 2016.

2.3. Methods

2.3.1. Conceptual Framework

This study builds a PCG conceptual model to explore a clear evaluation indicator system (Figure 2). With the development of urbanization and industrialization, during the process of human resource use, when people's irrational activities exceed the regional resources and environmental carrying capacity, such problems related to food security and destruction of the ecological environment may exert 'pressure' on the regional resources and the environment. With pressure, the original system is bound to take governance measures according to various carrying capacity characteristics. Accordingly, through formulating plans and technological innovation to release the resources and environmental potential carrying capacity, the systematic pressure can be relieved. Thereafter, governance measures will lead to new pressure, thereby introducing changes to the status of resources and environmental systems. Therefore, governance measures should be updated. Such a circulation of 'action-feedback-action' constitutes a PCG model for regional resources and the environment.

REP reflects the pressure on resources and the environment caused by socioeconomic activities, such as population growth, resource consumption, and environmental pollution [30]. The status of RECC reflects the support of the resources for regional socioeconomic development, ecological environment basis and environmental protective capability of the region. REG reflects the positive activities of human beings in improving the regional carrying capacity, such as improvements in science and technology and the establishment of reasonable policies [42]. This study uses a coupling analysis of REP, RECC and REG to evaluate the resources and environmental potential carrying capacity and future utilization direction of the cities in the YREB.

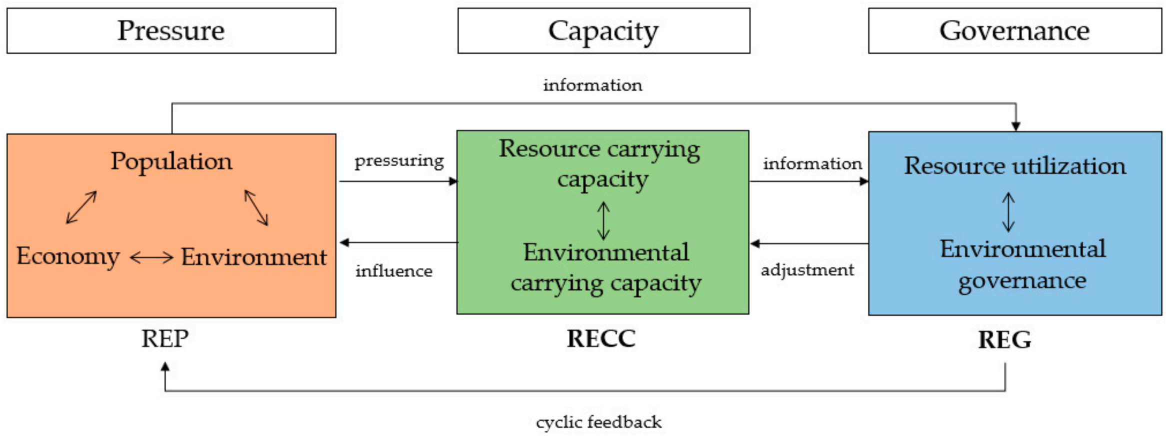


Figure 2. Pressure-capacity-governance (PCG) conceptual model.

Figure 3 describes the procedures for determining REP, RECC and REG. This framework establishment process generally consists of three steps and is conceptually straightforward. On the basis of the PCG conceptual model, the first step is the construction of an indicator system, assessment of the REP, RECC and REG levels and analysis of the differences amongst regions. The second step is the analysis of the limiting factors of RECC. The last step is the identification of the regional potential and utilization direction based on the coupling types of the REP, RECC and REG.

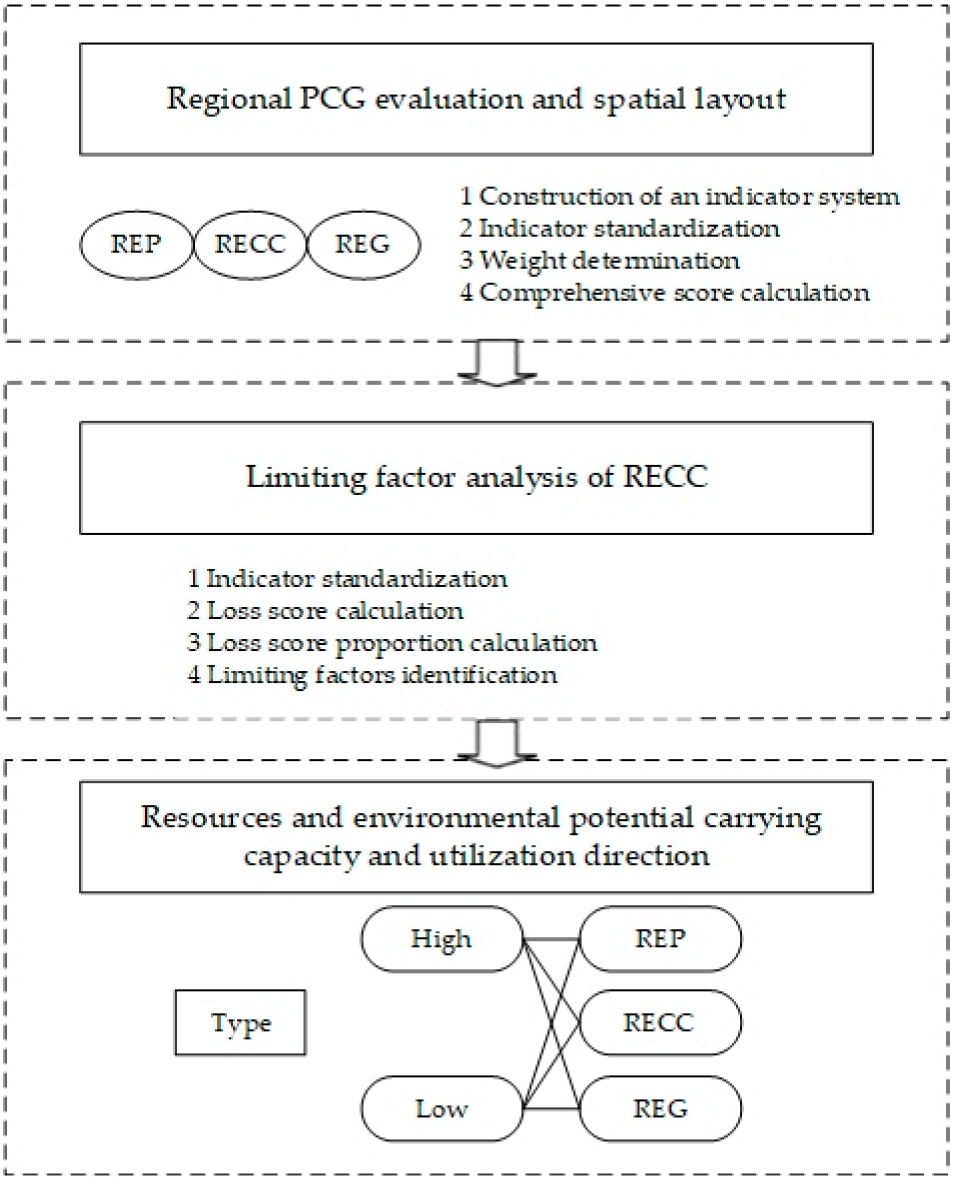


Figure 3. The flowchart of the current study.

2.3.2. PCG evaluation

Construction of an Indicator System

According to the PCG evaluation model, this paper follows the basic principles of scientificity, systematization, regionality, hierarchy, openness and dynamism based on references to the existing literature research indicator system, and combined with data quantification and availability, attempts to build a resources and environmental pressure-carrying capacity-governance evaluation indicator system for the YREB (Tables 1–3). Resources and environmental pressure are mainly considered from the three aspects of population, economy and environment. Resources and environmental carrying capacity include resource carrying capacity and environmental carrying capacity. The resources and environmental governance include the resource utilization and environmental governance levels.

Indicator Standardization

The min-max normalization method is used to standardize the data and ensure that the data standardized are between 0 and 1. The specific methods are as follows:

$$F_{ij} = (f_{ij} - f_{min})/(f_{max} - f_{min}) \text{ (positive indicator)} \tag{1}$$

$$F_{ij} = (f_{max} - f_{ij})/(f_{max} - f_{min}) \text{ (negative indicator)} \tag{2}$$

where f_{ij} and F_{ij} are the original and standardized values of the indicator, respectively, and f_{max} and f_{min} are the maximum and minimum values of the indicator, respectively.

Weight Determination

The analytical hierarchy process (AHP)–entropy weight method (EWM) is used for weight determination to overcome the shortcomings of the strong subjectivity of the AHP and the overdependence of the EWM on the indicator value. Accordingly, the indicator weight determination becomes substantially reasonable. The AHP method is used to determine the subjective weight of indicators, including the establishment of a comparison matrix, the calculation of a weight vector, verification of the consistency of the judgement matrix, and determination of the weight of indicators. The EWM method is used to determine the objective weight of indicators. The specific calculations are as follows:

$$P_{ij} = F_{ij}/\sum_{i=1}^{m} F_{ij} \tag{3}$$

$$k = 1/lnm \tag{4}$$

$$e_j = -k\sum_{i=1}^{m} P_{ij} \times lnP_{ij} \tag{5}$$

$$w_j = \left(1 - e_j\right)/\sum_{j=1}^{n}\left(1 - e_j\right) \tag{6}$$

where P_{ij} represents the indicator proportion of indicator j for city i; m is the total number of cities; e_j illustrates the entropy of indicator j; and w_j is the weight value of indicator j.

The AHP-EWM method is used to determine the comprehensive weight of the evaluation indicators.

$$W_j = \beta w'_j + (1 - \beta)w''_j \tag{7}$$

where β is the preference coefficient, and 0 ≤ β ≤ 1. After consultation with relevant experts, the coefficient β was set to 0.6. w'_j is the weight value of indicator j calculated by AHP and w''_j is the weight value of indicator j calculated by EWM.

Comprehensive Score Calculation

According to the determined evaluation factors and their corresponding weights, the comprehensive score is calculated through a quantitative model.

$$Z = \sum_{j=1}^{n} F_{ij} \times W_j \tag{8}$$

where Z is the comprehensive score, F_{ij} is the standardized value of indicator j for city i and W_j is the weight of the evaluation factor.

Table 1. Evaluation indicator system for the resources and environmental pressure (REP).

Target Layer	Standard Layer	Indicator Layer	Calculation Method	Units	AHP	EWM	Weight
REP	Population	Population Density	Total population/ land area	Person/km^2	0.1667	0.1810	0.1724
		Population urbanization rate	Urban population/ total population	%	0.1667	0.0848	0.1339
	Economy	Per capita GDP	GDP/total population	Yuan	0.1111	0.1622	0.1315
		Proportion of secondary and tertiary industries	Output value of the second and third industries/GDP	%	0.1111	0.0552	0.0887
		GDP growth rate	Annual growth rate of GDP	%	0.1111	0.0317	0.0793
	Environment	Industrial Sulphur Dioxide emission intensity	Volume of industrial Sulphur Dioxide emission/industrial added value	Ton/yuan	0.1111	0.2190	0.1543
		Industrial waste water discharged intensity	Volume of Industrial waste water discharged/ industrial added value	Ton/ 10,000 yuan	0.1111	0.2190	0.1543
		Application intensity of chemical fertilizer	Consumption of chemical fertilizers/total sown areas of farm crops	Ton/ 1000 hm^2	0.1111	0.0471	0.0855

Table 2. Evaluation indicator system for the resources and environmental carrying capacity (RECC).

Target Layer	Standard Layer	Indicator Layer	Calculation Method	Units	AHP	EWM	Weight
RECC	Land resource carrying capacity	Per capita cultivated land area	Cultivated land area/total population	hm^2/person	0.1000	0.0319	0.0728
		Ratio of forest land	Forest land area/ land area	%	0.1000	0.0644	0.0858
		Ratio of unused land	Unused land area/ land area	%	0.0500	0.4317	0.2027
	Water resource Carrying capacity	Water resources per capita	Total water resources/total population	m^3/person	0.0625	0.1852	0.1116
		Ratio of water area	Water area/land area	%	0.0625	0.1500	0.0975
		Matching index of agricultural water and cultivated land	(agricultural water consumption of evaluation unit/agricultural water consumption of research area)/(cultivated land area of evaluation unit/cultivated land area of research area)	- -	0.0625	0.0513	0.0580
		Matching index of domestic and industrial water and urban industrial and mining land	(domestic and industrial water consumption of assessment unit/domestic and industrial water consumption of study area)/(industrial and mining land area of assessment unit/industrial and mining land area of study area)	- -	0.0625	0.0515	0.0581
	Atmospheric environment	Atmospheric environmental quality index	Proportion of days above grade II air quality	%	0.2500	0.0280	0.1612
	Water environment	Water environment quality index	Proportion of inferior V water body	%	0.2500	0.0060	0.1524

Table 3. Evaluation indicator system for the resources and environmental governance (REG).

Target Layer	Standard Layer	Indicator Layer	Calculation Method	Units	AHP	EWM	Weight
REG	Resource utilization level	Irrigation rate of cultivated land	Effective irrigation area/cultivated land area	%	0.1250	0.1285	0.1264
		Grain yield per unit area	Grain yield/ grain sown area	Ton/hm^2	0.1250	0.0978	0.1141
		Utilization rate of water resources	Annual water consumption/ annual average total water resources	%	0.2500	0.5985	0.3894
	Environmental governance level	Ratio of common industrial solid wastes comprehensively utilized	Common industrial solid wastes comprehensively utilized/Common industrial solid wastes produced	%	0.1667	0.0853	0.1341
		Ratio of Consumption Wastes treated	Harmless treatment capacity/production capacity of domestic waste	%	0.1667	0.0527	0.1211
		Ratio of waste water Centralized treated of sewage work	Sewage treatment capacity/total sewage discharge capacity	%	0.1667	0.0372	0.1149

2.3.3. Spatial Analysis Method

Local Moran's I is used to measure the local spatial autocorrelation of the resources and the environmental pressure-capacity-governance level indicators. Its formula is expressed as follows:

$$I_i = \frac{(x_i - \bar{x})}{\frac{\sum_{j=1,j\neq i}^{n}(x_j - \bar{x})^2}{n-1}} \sum\nolimits_{j=1,j\neq i}^{n} w_{ij}(x_j - \bar{x}) \quad (9)$$

where x_i is an attribute for feature i, $\bar{x}$ is the mean of the corresponding attribute, n is the total number of features and w_{ij} is the spatial weight between features i and j.

The z_{I_i}-score for the statistics is computed as:

$$z_{I_i} = (I_i - E[I_i]) / \sqrt{V[I_i]} \quad (10)$$

where:

$$E[I_i] = -\sum\nolimits_{j=1,j\neq i}^{n} w_{ij} / (n-1) \quad (11)$$

$$V[I_i] = E\left[I_i^2\right] - E[I_i]^2 \quad (12)$$

2.3.4. Limiting Factor Analysis Method

Limiting factor identification is used to analyze which factors limit the regional development. The limiting factors are identified by measuring the loss score proportion [49]. By using this method, this study analyses the limiting factors of the regional RECC. The calculation process is expressed as follows.

Indicator Standardization

The evaluation indicators are selected for standardization and weight determination. This research uses the results of indicator standardization and weight determination in Section 2.3.2.

Loss Score Calculation

$$L_{ij} = \left(1 - F_{ij}\right) W_j \quad (13)$$

where L_{ij} is the loss score value of indicator j for city i.

Loss Score Proportion Calculation

$$P_{ij} = L_{ij} / \sum_{j=1}^{n} L_{ij} \quad (14)$$

where P_{ij} is the loss score proportion of indicator j for city i.

Limiting Factors Identification

According to the loss score proportion, an appropriate threshold is chosen to identify the limiting factors. The threshold of the loss score proportion is determined to be 8% in this study through a series of experiments and analyses.

3. Results

3.1. Regional PCG evaluation and Spatial Layout

According to the PCG evaluation model, the PCG indicators of the YREB at various levels can be obtained by calculation, thereby showing significant spatial differences (Figure 4). Figure 4a–c shows that the REP indicator indicates a trend of being 'high in the east and low in the west' with comparatively high indicator values in the lower reaches of the Yangtze River and the provincial capitals. The RECC indicator shows a trend of being 'high in the west and low in the east' and 'high in the south and low in the north'. The REG indicator shows a trend of being 'high in the east and low in the west'.

Local indicators of spatial association (LISA) is used to further analyse the spatial distribution rules of the PCG indicators for the YREB (Figure 4d–f). The LISA value is an indicator to measure the degrees of similarity (positive correlation) and difference (negative correlation) between spatial unit attributes and surrounding units. Four categories, namely, High-High, High-Low, Low-High and Low-Low, were clustered based on the LISA statistics. The local spatial autocorrelation shows that the hotspot clusters (High-High areas) of REP indicator are mainly distributed in southern Jiangsu, northern Zhejiang and Shanghai in the lower reaches of the Yangtze River. In contrast, the cold spot clusters (Low-Low areas) are mainly distributed in Sichuan in the upper reaches. The hotspot clusters (High-High areas) of the RECC indicator are mainly distributed in western Sichuan, northwest Yunnan and northern Jiangxi, while the cold spot clusters (Low-Low areas) are mainly distributed in Jiangsu, Shanghai, northern Anhui, and eastern Hubei in the lower reaches. The hotspot clusters (High-High areas) of the REG indicator are mainly distributed in Jiangsu, Shanghai and eastern Anhui in the lower reaches area, while the cold spot clusters (Low-Low areas) are mainly distributed in the upper reaches, such as Sichuan, Yunnan and Guizhou. Generally, the REP indicator is larger in the lower reaches than in the upper reaches. The RECC indicator is larger in the upper reaches than in the lower reaches. The REG indicator is larger in the lower reaches than in the upper reaches. The resources and environmental pressure levels of the YREB do not match the carrying capacity but do match the governance level.

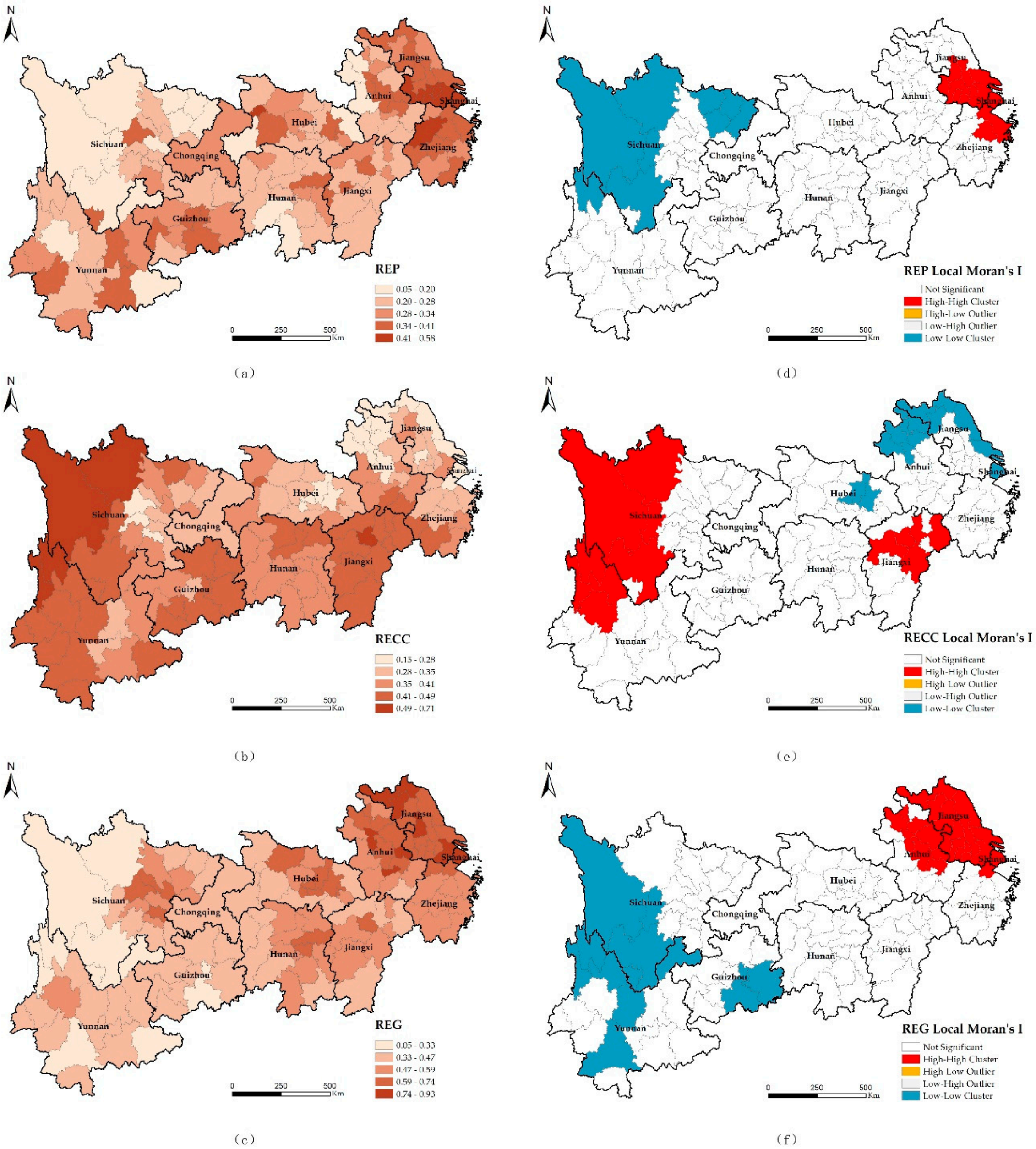


Figure 4. Spatial distribution and local indicators of spatial association (LISA) mapping of the PCG indicators of YREB in 2015.

3.2. Limiting Factor Analysis of RECC

Figure 5 shows the spatial distribution of the limiting factors for each city unit in the YREB. Generally, more than 60% of the cities in the YREB are limited by the ratio of unused land, per capita water resources, ratio of water area, and atmospheric environmental quality, which have a great influence on the regional RECC.

Figure 5a–c shows that, in terms of the three single factors of land resource carrying capacity, the cities limited by the indicator of per capita cultivated land area are distributed in Zhejiang, Jiangxi and Hunan in the lower reaches of the Yangtze River. Meanwhile, the cities limited by the forestland area ratio indicator are mainly distributed in Sichuan in the upper reaches and Jiangsu and Anhui in the lower reaches. Except for some cities in the upper reaches of the Yangtze River, other cities in the zone are limited by the ratio of unused land. These regions should enhance the protection of cultivated land, forestland and unused land, as well as restrict the unlimited expansion of construction land in the future. Insufficient unused land has become an important limiting factor for the land resource carrying capacity of the YREB. Figure 5d–g shows the four limiting factors of the water resource carrying capacity. The majority of the cities in the zone are unexpectedly limited by the indicators of the per capita water resource and ratio of water area. Moreover, the majority of the cities in the upper reaches have a comparatively low matching degree with their agricultural water. The domestic and industrial water in Sichuan and Yunnan in the upper reaches has a comparatively low matching degree with the land for mining and industry. Therefore, focus should be directed to the reasonable exploitation and protection of the YREB's water resources. The cities limited by the atmospheric environmental quality index, such as Chongqing, Hubei, Anhui, and Jiangsu, are mainly distributed in the middle and lower reaches (Figure 5h). Moreover, attention should be directed to the atmospheric governance and environmental protection of these regions. The few cities limited by the water environment quality index are mainly distributed in Jiangsu, Anhui and Yunnan (Figure 5i). Accordingly, effort should be exerted to protect the water environment quality in these regions.

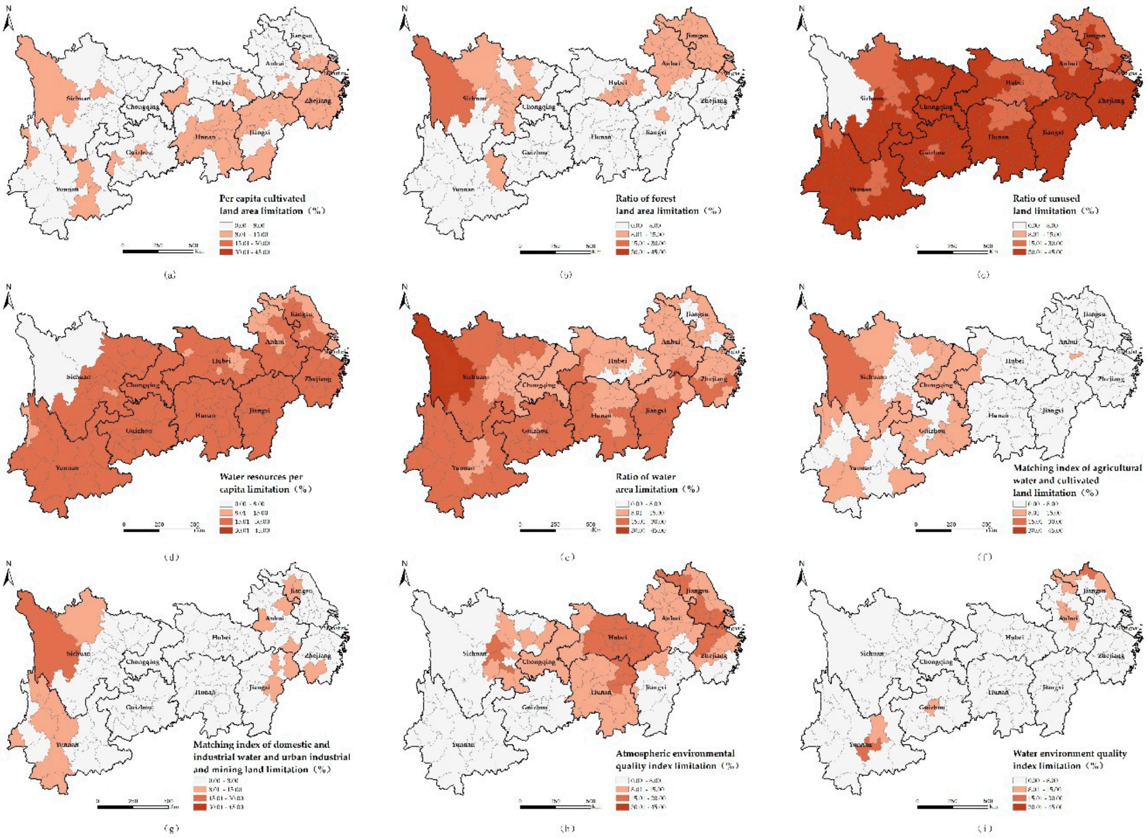


Figure 5. Limiting factor analysis for the resources and environmental carrying capacity (RECC) in the YREB in 2015.

3.3. Resources and Environmental Potential Carrying Capacity and Utilization Direction

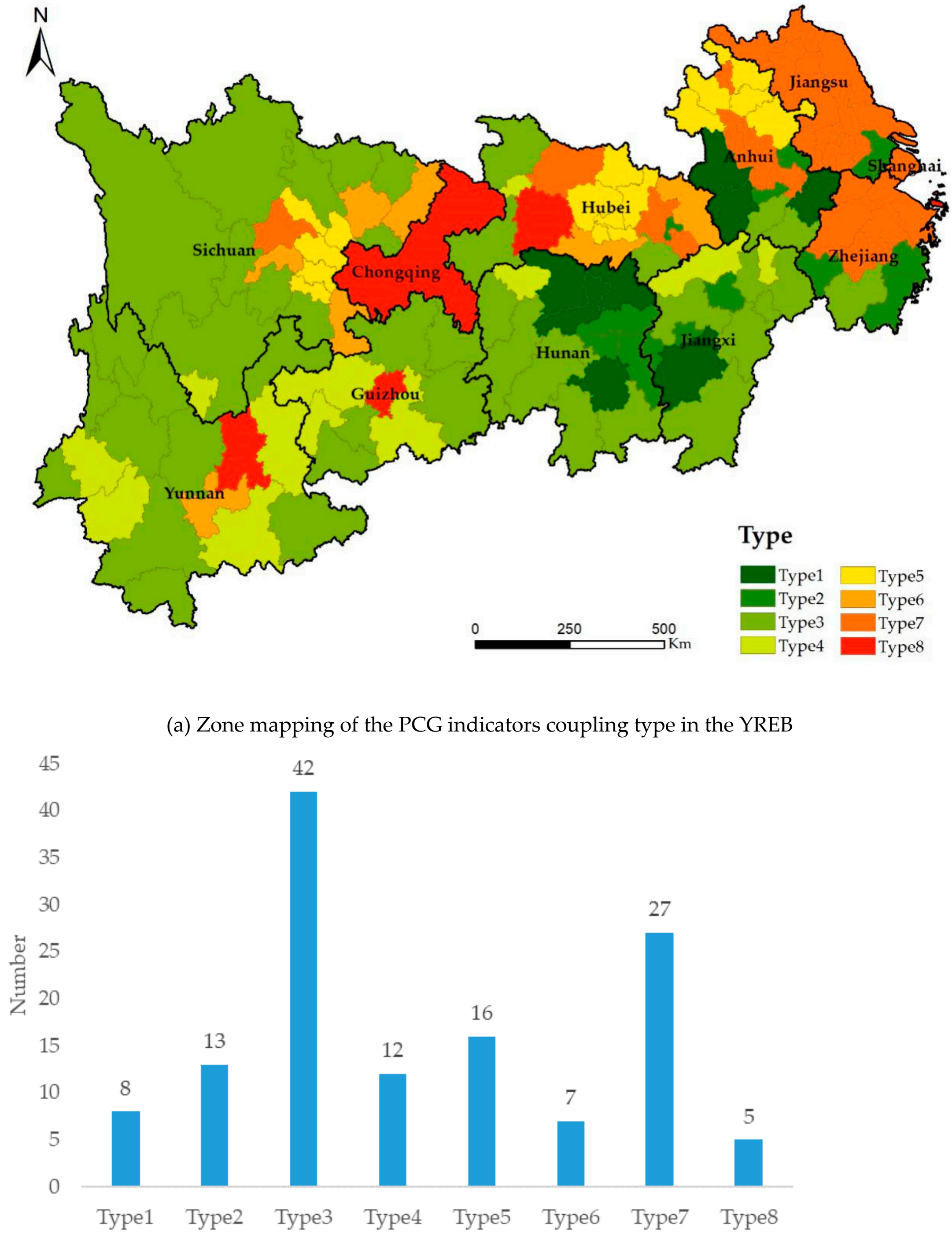
To analyse the regional resources and environmental potential carrying capacity and utilization direction, the relationship among REP, RECC and REG levels should be comprehensively considered. The development of the socioeconomic system depends on various resources. The resource consumption required for socioeconomic development is bound to influence the atmosphere and water environment. When socioeconomic development brings excessive pressure to the environmental carrying capacity, the environment may provide a reactive force, thereby limiting sustainable socioeconomic development. The investment of environmental protection elements (e.g., environmental governance and environmental protection awareness) is added to socioeconomic development, thereby improving the environmental governance level. When the resource system exploits new resources or improves the resource utilization level and the environmental governance level, the RECC will also be improved.

The REP, RECC and REG scores of each city are divided into low or high levels based on the natural breakpoint method. The three layers are overlaid to obtain eight types of spatial combinations (Table 4). Figure 6 shows the classification of the PCG indicators coupling types in the YREB, indicating that the RECC levels of Types 1–4 are higher than Types 5–8. Type 1 has low pressure but high carrying capacity and governance level and belongs to the effective development type with immense potential carrying capacity. A total of 6.15% of the cities in the YREB belong to this type and are mainly distributed in the middle and lower areas of the Yangtze River. The regions in these areas with available conditions should invest resources to develop their economy. Type 2 has high pressure, high carrying capacity and high governance level and belongs to the present-status-maintaining type. A total of 10% of the cities belong to this type and are mainly distributed in the middle and lower areas of the Yangtze River. These areas have good overall carrying capacity situations and need to be maintained. Type 3 has low pressure, high carrying capacity and low governance level and belongs to the utilization-improving type. The majority of the cities are categorized as this type, accounting for 32.31% of the zone. The cities categorized as this type are mainly distributed in the upper and middle areas of the Yangtze River, with high potential carrying capacity. These cities should raise their utilization efficiency, improve their environmental governance level and invest properly to develop their local economy. Type 4 has high pressure, high carrying capacity and low governance level and belongs to the utilization-improving type. A total of 9.23% of the cities are of this type and are mainly distributed in the upper reaches of the Yangtze River. These cities should improve their resource utilization and environmental governance level.

Table 4. Classification of the pressure–capacity–governance (PCG) indicators coupling type.

Type	REP	RECC	REG
1	Low	High	High
2	High	High	High
3	Low	High	Low
4	High	High	Low
5	Low	Low	High
6	Low	Low	Low
7	High	Low	High
8	High	Low	Low

The resources and environmental carrying capacity of Types 5–8 are low. The degree of dependence on resources and the environment by economic development should be reduced during exploitation and utilization. Type 5 has low pressure, low carrying capacity and high governance level and belongs to the resource-limiting type with a general potential carrying capacity. A total of 12.31% of the cities belong to this type and are mainly distributed in the upper, middle and lower areas of the Yangtze River. These regions should change the economic growth mode appropriately and focus on reasonable resource utilization and protection. Type 6 has low pressure, low carrying capacity and governance level and belongs to the inefficient development type with a general potential carrying capacity. A total of 5.38% of the cities are of this type and are mainly distributed in the upper and middle reaches of the Yangtze River. These cities should improve their resource utilization efficiency and environmental governance level to seek new economic growth points. Type 7 has high pressure, low carrying capacity and high governance level and belongs to the endangered development type with low potential carrying capacity. A total of 20.77% of the cities belong to this type and are mainly distributed in the upper, middle and lower areas of the Yangtze River. Most of these cities are in the lower Yangtze River. These cities should change their economic growth mode, reduce their degree of dependence on resources and the environment for economic development and focus on reasonable resource utilization and environmental protection. Type 8 has high pressure, low carrying capacity and low governance level and belongs to the high-risk development type with low potential carrying capacity. A total of 3.85% of the cities are of this type and are mainly distributed in the upper and middle areas of the Yangtze River. These cities should improve the resource utilization efficiency and environmental governance level, and reduce the dependence of economic development on resources.



(b) Number of PCG indicators coupling types in the YREB

Figure 6. Quantity and spatial distribution of the PCG indicators coupling type in the YREB.

4. Discussion

This study proposes the PCG model, an analytic framework for assessing the carrying capacity at the large watershed scale, with the YREB as the study area, which makes up for the shortcoming of using a single city or county in previous research. The framework conducts an evaluation framework from three major subsystems (REP, RECC and REG) including 23 basic indicators overall. The study results show that the PCG framework contributes to the study and could also be used in other watersheds throughout the world and provides a reference for policy makers. During current developments, local governments tend to adopt the development policy of setting up trade barriers out of regional protectionism to pursue the growth of the local tax and fiscal revenue, thereby resulting in serious industrial isomorphism and inefficiency of resource utilization [50]. The regions cannot maximize their comparative advantages, thereby substantially wasting regional resource advantages. The PCG framework can facilitate the coordination and planning of the relationship between the central and local governments, the reduction in vicious competitions among local governments and the realization of a joint response according to various development levels and resources and the environmental carrying capacity of regions. The central government should pay more attention to spatial differentiation and create top-level designs for coordinated development. Hence, differentiated resource and environmental management policies should be formulated based on spatial differences. The results show that the resources and environmental pressure of the YREB do not match the carrying capacity but instead match the governance level. For cities with low carrying capacity, the dependence of economic development on resources and the environment should be reduced properly; for cities with high carrying capacity, development should be carried out appropriately on the premise of environmental protection. At the same time, the level of regional resource utilization and environmental governance should be improved, and the resources and environmental potential carrying capacity should be further improved.

By using limiting factor analysis, this study analyses the limiting factors of the regional RECC. The carrying capacity includes the wooden bucket effect theory, which states that the weakest 'limiting factor' determines the overall quality. The results of this study show that the ratio of unused land, per capita water resources, ratio of water area, and atmospheric environmental quality are the main limiting factors of the regional RECC. The unlimited expansion of construction land should be restricted, with the red line limiting the total water resources, while the unified governance and scientific management of watershed water resources should be enhanced. Efforts should be exerted to protect the air quality during future development. This action will be particularly necessary in terms of the water resource carrying capacity. There are considerable water resources in the YREB, with an annual average total of 995.8 billion m^3 of water, which accounts for nearly 35% of the total water resources in the country. The water resource carrying capacity in this region is considered substantial, while the water resource reserve in the YREB is large and its water resource carrying capacity is not high because of the substantial socioeconomic pressures. During future development, all regions should focus on implementing dual control of total water resources and water resource intensity, strictly protecting water resources and promoting water pollution prevention. Meanwhile, urban construction and industrial development must not break through the water resources carrying capacity.

This research analyses the regional resources and environmental potential carrying capacity and utilization direction based on the coupling types of the REP, RECC and REG. The YREB stretches across the three geographic staircases of China, with diverse developing conditions for resources, the environment, transportation and industry. Differentiated governance measures should be adopted according to various types of regional resources and environmental carrying capacity at the micro-level of local practice. The results show that 53.19% of cities in the upper areas of the Yangtze River exhibit low REP, high RECC and low REG. These areas should increase their utilization efficiency, improve their environmental governance level and invest properly to develop their local economy. A total of 56.10% cities in the lower areas of the YREB exhibit high REP, low RECC and high REG. These cities should focus on the transformation and innovation of economic development, reduce the dependence on resources and environment and pay attention to the reasonable utilization of resources and environmental protection. The coupling types of the middle reaches of the Yangtze River are more balanced, with the types including Jiangxi and Hunan being similar to those in the upper reaches, while the types including Hubei are similar to those in the lower reaches.

This study has a few shortcomings. (1) This research takes cities as the research units. Future studies may attempt to use fine-scale grids as the evaluation units for regional carrying capacity research. (2) This paper evaluates only the current existing resources and the environment; it does not take into account interregional exchanges and other liquidity factors. (3) Due to issues related to collecting data for categories such as mineral resources, soil quality and other indicators, those indicators were not included in the indicator system.

5. Conclusions

This study builds a PCG analytical framework to analyse the relationship between regional resources and environment and human activities at the large watershed scale, which is significant for guiding regional development. This framework includes three subsystems: REP, RECC and REG. This clearly distinguishes the regional resource and environmental status and the effect of human activities on the systems, including the economic pressure and the governance measures. Large-scale PCG evaluation and spatial analysis are conducive to the establishment of a unified regional early warning mechanism. Limiting factors analysis of RECC is helpful to identify the shortcomings of regional RECC and put forward suggestions based on local conditions. Analysis of regional potential and utilization direction, comprehensively considering the coupling relationship of REP, RECC and REG, makes the decision-making more targeted and effective.

Taking YREB as the example, the results are as follows. (1) The REP in the upper areas of the Yangtze River is lower than that in the lower areas, which does not match the RECC but matches the REG level. (2) By using limiting factor analysis, we found that the ratio of unused land, water resources, and atmospheric environmental quality are the main limiting factors of the regional RECC. Thus, the government must implement relevant measures to limit the unlimited expansion of construction land, strengthen the unified governance of watershed water resources, and focus on air quality protection. (3) The two main PCG coupling types are as follows: A total of 53.19% cities in the upper areas of the YREB have low REP, high RECC and low REG. These cities should increase their utilization efficiency, improve their environmental governance level and invest properly to develop their local economy. Meanwhile, 56.10% of cities in the lower areas of the YREB exhibit high REP, low RECC and high REG. Accordingly, these cities should reduce their degree of dependence of economic development on resources and the environment, and focus on the reasonable utilization of resources and environmental protection.

According to the analyses, some policy recommendations are suggested as follows. (1) The REP, RECC and REG levels of the YREB exhibit spatial differences. The central government should pay more attention to spatial differentiation and create top-level designs for coordinated development. It is suggested to consider REP, RECC, REG and their spatial differences in regional development planning and dynamically assess them. (2) It is necessary to protect the water resources in the YREB. The structure of water use should be adjusted in terms of systems and policies, and increase technological support to improve the efficiency of water resources utilization. (3) Differentiated governance measures should be adopted according to the various PCG coupling types to ensure sustainable regional development. Moreover, improvements should be made in the control of the total resource management and resource intensity and environmental governance system, and capital investment and technological support should be increased. Meanwhile, effort should be exerted to promote government information publicity, improve the environmental legal system, and strengthen the assessment mechanism. The research is also helpful to provide references for regional sustainable development in other watersheds throughout the world.

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