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Regionalization of water environmental carrying capacity for supporting the sustainable water resources management and development in China

Zimu Jia[a], Yanpeng Cai[a], Yan Chen[b], Weihua Zeng[a,*]

[a] State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China
[b] Chinese Academy for Environmental Planning, Ministry of Environmental Protection, Beijing 100012, China

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ABSTRACT

With the rapid economic growth and social development in China, conflicts over water resources between human and nature are continuously increasing which is attracting the attention of researchers. At the same time, discharge of water pollutants and exploitation of water resources pose a daunting challenge to the sustainable development of economy and society. China consists of 34 provincial administrative regions having similar or different characteristics in the levels of economic development, water resource endowment, water environmental capacity and water environmental pressure. Among these, it is meaningful to analyze spatial similarities and variations in water environmental carrying capacity (WECC), which contributes to carrying out different and scientific strategies for the management of water environment and for sustainable economic and social development in China. An index system is established to quantify WECC from the perspectives of carrying capacity, environmental pressure, vulnerability of water environment and exploitation and utilization potential. The k-means clustering method is applied to conduct the similarity combination based on the quantification of 4 integrated indicators using catastrophe progression method. The silhouette coefficient is introduced to measure the quality of clustering and to determine the optimal clustering number. The obtained results indicate that carrying condition of water environment becomes more and more better and exploitation and utilization potential of WECC is decreasing gradually from the east to the west in China, and there are more overload in the north provinces and less in the south. In addition, water environmental vulnerability in the west is higher than that of central and eastern provinces in China. The optimal clustering number is 4 obtained by calculating the silhouette coefficient. Also, 31 provinces are categorized into 4 sub-areas i.e. key protected area, controlled development area, optimized development area and prioritized development area. The suggestions on the corresponding bidirectional regulation to different sub-areas are also put forward to provide a scientific reference to rational distribution of economic development, elaborate management of water environment as well as regional sustainable development in the future.

1. Introduction

Water environmental carrying capacity (WECC) refers to the primary ability of water bodies to supply resources to the socio-economic development and to remove the pollutants discharged by rural and urban areas and factories. It is an important indicator that reflects the regional sustainability and is closely related to the economy, population, technology and natural environment (Graymore et al., 2010; Liu and Borthwick, 2011). With a rapid economic growth and social development in China, the associated problems of water contamination and shortage of water resources have become serious bottlenecks which challenge and limit the sustainable development at the regional as well as at national levels (Chen et al., 2016a; Liu et al., 2017). The disordered spatial development and irrational processes in the urbanization and industrialization destroy the essential water environment thereby affecting the local people at this stage and potentially might affect their next generation, which further brings a huge threat to the sustainable development of these regions (Fan and Li, 2009). At present, an increasing number of researchers have realized that the scale and intensity of economic and social development cannot exceed certain carrying capacities of the water system in a specific region. At the same time, the potential damages to water system cannot threaten the survival and development of future generations (Gunderson, 2014; Hák et al., 2016; Tran, 2016). Thus, it is of great significance for local decision makers to be well aware of information related to carrying capacity of water environment within a specific region.

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* Corresponding author.
E-mail addresses: jiazimu1988@163.com (Z. Jia), zengwh@bnu.edu.cn (W. Zeng).

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China's climate is mainly dominated by dry seasons and wet monsoons, which leads to prominent precipitation differences between the south and north provinces. Also, the eastern and coastal provinces are much more densely populated than the western and interior regions. The vast majority of population lives in major cities that are mainly located in the Yangtze River Delta, Pearl River Delta and North China Plain. The gap in GDP per capita between coastal and inland areas had increased from 200 Yuan in 1978 to 19,630 Yuan in 2008 (Fan et al., 2010). In addition, the eastern developed regions are affected with severe environmental problems of water due to overexploitation, for instance, the degradation of water quality in the regional environment. The western underdeveloped regions usually have vulnerable environment for water. Especially, the upstream areas of western rivers are the key conservation areas of water source and are the ecologically fragile districts in China (Fan and Li, 2009). Since the functions in regional economy and society and basic conditions for water environment are varied, and thus the corresponding strategies and development policies should be approached in a different way. The reasonable spatial arrangement targeting the development and conservation requires an urgent attention for the rapidly changing society in China (Liu et al., 2015). Zoning is an effective measure to divide an area into sub-areas based on similar characteristics in order to identify the differences between sub-areas and to implement the appropriate environmental management policies (Fadlelmawla et al., 2011; Oliveira et al., 2011; Shi and Zeng, 2014).

Researchers pay more attention to the environmental carrying capacity of water bodies and combine rational utilization with preservation in promoting the sustainable development (Lane et al., 2014; Liu et al., 2015; Wang and Xu, 2015; Wang et al., 2014). Previous studies on WECC and sustainable development were mainly focused on a single component, namely available water resource or water assimilative capacity, such as evaluation of water resources carrying capacity (WRCC) through the water shortage risk simulation obtained by following a mathematical method derived from system dynamics (Feng et al., 2008), analysis of the supported population in areas which considers various parameters related to water demand and supply (Ait-Aoudia and Berezowska-Azzag, 2016; Li et al., 2010; Ming, 2011; Song et al., 2011), and calculation of water environmental capacity (WEC) using an innovative holistic method (Chen et al., 2014). Zhou et al. (2015) proposed a comprehensive index to assess the water environmental supporting capacity from the perspectives of carrying capacity, pressure and pollution prevention capacity, and categorized the Huaihe River Basin into eight classes and provided guidance for coordinating the sustainable development of water environment and economy. Liu (2012) calculated the water carrying capacity index in terms of water resource and consumption and considered it as a basic factor to reveal the spatial differences in the sustainable urban capacities. Most of the abovementioned studies only consider the pressure dimension into the final value, which is used to describe and assess WECC. In reality, WECC is a complex system possessing the attributes relevant to both nature and human society. Numerous factors involving population, economy, resource availability and technology, act as positive or negative feedback to the carrying capacity (Gilmour et al., 2005; Giupponi et al., 2004). The contribution of other factors to WECC cannot be substituted and compensated by a single pressure-dimension. It is to be noted that by simply relying on one component to assess and zone the water environment is insufficient. The obtained results tend to hide a number of inherent characteristics of WECC in spatial distributions.

The rest of the paper is organized as follows. Section 2 describes the methodology in detail, which mainly consists of the catastrophe models and the k-means clustering method. In addition, the data sources are represented in this section. Section 3 presents a range of results and discussions for the evaluation and zoning of the water environmental carrying capacity in 31 provinces. Finally, Section 4 summarizes the main findings of the paper and gives the conclusions.

2. Methodology

The clarity of concept plays a key role in evaluating the water environmental carrying capacity, which is the foundation to establish an evaluation index system. Due to the complexity of its internal mechanisms and diversity of regional environmental systems (including natural, social and economic environments), it seems to be impossible to analyze and assess all the activities that determine the WECC. Therefore, it is necessary to select several typical and quantifiable indicators to represent the inherent characteristics of WECC. Also, the changes in the WECC can be regarded as a catastrophic process. In the stable equilibrium of a subsystem, a small but a gradual change might rapidly lead to the collapse of the whole system. Catastrophe theory can deal directly with catastrophic changes, which is applied to assess the WECC. The assessment results based on catastrophe models provide the assessment values of 4 top-level indicators for each province. The k-means clustering is a popular and a widely applied clustering method employed for the classification of multi-variable data sets. Therefore, 31 provinces are classified into proper groups using k-means clustering method to maximize the variations in different categories.

(1) A relatively comprehensive definition of WECC is formed which emphasizes water resources, assimilative capacity of environment, vulnerability of water environment and utilization potential of water resources and water environment.
(2) A comprehensive assessment index system of WECC is established according to the framework of the concept, which comprises 4 indices in the target layer, 7 indices in the criterion layer and 26 indices in the indicator layer. These indices cover the major factors and thus reflect the basic characteristics of WECC.
(3) The catastrophe models are applied to assess the 4 indices in the target layer. First, the standardization equation is adopted to make the raw data in the indicator layer dimensionless. Then, the entropy method is used to quantify the relative importance of each of the control variables in the catastrophe model. Following this, the comprehensive quantitative recursion calculation is performed using normalization formula to obtain the respective total catastrophic values of the 4 indices. Finally, the assessment results of 4 indices in each of the provinces are determined and are mapped based on the natural breakpoint classification method.
(4) The silhouette coefficient is introduced to evaluate the quality of clustering and to determine the optimal clustering number. 31 provinces are divided into their corresponding categories using k-means clustering method to identify the similarities and differences amongst different groups.

2.1. Concept and implications of water environmental carrying capacity

Water environmental carrying capacity (WECC) is the limit at which human activity has an influence on the water environment and results in undesirable changes to the environment (Liu and Borthwick, 2011). As an integral part of ecological environment, the water has environmental properties. In addition, the water body belongs to the category of water resources, and has resource properties. Water environmental capacity and water resources constitute the foundation of the WECC. The WECC represents the self-sustaining, self-regulating and self-purification ability of water environment system. The water self-purification capacity refers to the ability of water environment to reduce the concentration of pollutants through physical, chemical and biological effects and thereby improving the water quality and restoring the ecobalance. The water self-purification capacity is quantified in the form of water environmental capacity, which is the basis of the carrying capacity of water environment. As the core element of water environment, water body has the basic supply capacity which could satisfy the needs of production and household. Water resources quantitatively represent the capacity of supply of water resources, which constitutes the support base of water environmental carrying capacity. The limitation of water environmental capacity and water resources is the root cause of the limitation of water environmental carrying capacity.

Water environmental carrying capacity is emphasized as the maximum of human activities which are sustained by multiple hierarchical levels such as resource consumption and environmental deterioration, accompanied by the development with finite water environment and resources (Kessler, 1994; Monte-Luna et al., 2004). WECC refers to a dynamic multifaceted relationship affected collectively by water resources carrying capacity, water environmental capacity, pressure caused by human activities and exploitation, vulnerability of water environment and utilization potential of water resources and water environment. Water environmental carrying capacity is the objective and concrete reflection of functional structure of the water body. The understanding and utilization of environmental characteristics and resource characteristics of water bodies directly affect their carrying conditions, and humans can adjust the size and direction of the water environmental carrying capacity through their own behavior. Therefore, the water environmental carrying capacity combines natural and social attributes, which are mainly affected by environmental conditions, resource endowment, technological level and institutional arrangement. Water environmental carrying capacity is not only concerned with water resources and environmental assimilative capacity. Instead, the concept of WECC should emphasize the aspects of environmental carrying capacity (including water resources, environmental assimilative capacity, vulnerability of water environment and utilization potential of water resources and water environment), which are addressed in the majority of Strategic Environmental Assessments (SEAs) and environmental planning decisions in China (Liu and Borthwick, 2011).

The carrying status of water resources or water environment is taken to the degree transgressed by environmental stress due to human disruption, which relates to the threshold of available water resources for human demand or carrying capacity of the aquatic environment for the discharged waste. The carrying status is the original and primary implication of water environmental carrying capacity. It can provide the necessary scientific information to the decision-makers. The social and economic systems are the main supporting bodies of water environment, and the composition, structure and state of the system affect the carrying capacity and carrying status. Therefore, the carrying capacity of water environment cannot be separated from specific technology and management. The limitation of water environmental carrying capacity is related to the level of technology and management, which are mainly embodied in the level of economic and technological development and utilization of water resources, water consumption and the level of pollutant discharge and structure in all the industries and the phases of social life, as well as in the optimal allocation of water resources. The exploitation and utilization potential generated by the economic development, technological progress and improvement of population quality can strengthen the assimilative capacity of water bodies and water resources supporting capacity. Therefore, it is possible to enhance the carrying capacity and its exploitation and utilization potential of water environment by improving the level of economy and technology and readjusting the industrial structure. Vulnerability conveys the extent to which the water environment is susceptible to sustaining the damage or harm owing to human activities. It is a function of the sensitivity of water environment to damages, and the adaptive capacity to offset the potential harms{Liverman, 1990 #33}. WECC is put forward based on an understanding of the mutual relationships between water environment and sustainable economic and social developments. Moreover, WECC is considered as a criterion to judge whether the economic and social developments coordinate with the water environmental system and plays an important role in the sustainable development of a region or a country.

2.2. Construction of a comprehensive evaluation index system

At present, most of the studies dealing with WECC can be integrated into sustainable development, which are dominant in China (Dang and Liu, 2012; Dou et al., 2015; Li et al., 2016; Ren et al., 2016; Zhang et al., 2015). However, a unified research method has not been established and the comprehensive index system is used as a primary evaluation method on WECC (Wang et al., 2017). Due to the complexity of water environmental system and the diversity of economically, socially and environmentally influencing factors, it is seemingly impossible to assess and analyze all the activities that determine WECC. Therefore, it is necessary to establish an index system and to select the typical and quantifiable indicators to represent the practical status of WECC (Berck et al., 2012). The United Nations Statistics Division (UNSD) sets several selection criteria for the indicators, which should be relevant and measurable, methodologically sound, easy communication and access, limited in number and outcome focused (Hák et al., 2016). In the paper, the proposed indicators were based on the above selection criteria and during the consultation at which several organizations and experts (National Bureau of Statistics, Ministry of Environmental Protection and experts from academia and civil society) submitted detailed comments on the those indicators. Besides the conceptual aspect, the data availability and overall feasibility were assessed. It also ensured the completeness of indicators and emphasized the linkages among the indicators thereby avoiding the uncertainties in the process of selection. The appropriate indicators were selected to represent the basic characteristics of WECC from the perspectives of water environmental carrying status, water resources carrying status, vulnerability of water environment and exploitation and utilization potential, as shown in Table 1.

2.3. Evaluation of the four integrated indices

In this paper, water environmental carrying capacity is the evaluation target, which is divided into water environment carrying status, water resources carrying status, vulnerability of water environment and exploitation and utilization potential. Due to the different natural environments, social and economic development levels and water environment management levels existing in China's provinces, there are obvious differences in the carrying capacity of water environment among different provinces. The catastrophe progression method is a simple and effective way to reflect the spatial differences through the comprehensive evaluation of research objectives. Catastrophe progression method derived from catastrophe theory is widely applied in the multi-criteria evaluation to solve the problems of multi-criteria assessment (Chen et al., 2016b). The 4 types of models are used commonly, including folded catastrophe, cusp catastrophe, swallowtail catastrophe and butterfly catastrophe. In these models, f refers to the potential function of state variables x, whereas a, b, c, and d represent the control variables of the state variable. Any state of the system is a function of state and control variables. According to catastrophe theory, the set of all critical points of the potential function forms an equilibrium surface. Its equation is developed from the first derivative $f'(x) = 0$, and the associated singularity set is derived from the second derivative $f''(x) = 0$. The bifurcation points in the set equation of the catastrophe system is obtained by eliminating "x" through $f'(x) = 0$ and $f''(x) = 0$. When the control variables in the bifurcation points of the set equation meet the requirements, a catastrophe will occur in the system. The normalized formula is derived from the decomposed form of the bifurcation points in the set equation, which is used to transform different states of control variables into the same state. The values of state and control variables in the normalization formula range from 0 to 1. The catastrophe progression of each control variable can be computed from the initial fuzzy subordinate function, using recursive algorithms subjected to the normalization formula. During the process of computation, the complementary and non-complementary principles must be

Table 1
Comprehensive evaluation index system of water environmental carrying capacity.

Target layer	Criterion layer	Indicator layer	Units
Water environment carrying status (A_1)	Water environmental capacity (B_1)	Surface water resources (C_1)	100 million m^3
		Influx water resources (C_2)	100 million m^3
		Monitoring section proportion ofI-III class water (C_3)	%
		Monitoring section proportion of worse thanVclass water (C_4)	%
	Water pollution load (B_2)	COD discharged by point source (C_5)	ton
		Nitrogen discharged by point source (C_6)	ton
		COD discharged by non-point source (C_7)	ton
		Nitrogen discharged by non-point source (C_8)	ton
Water resources carrying status (A_2)	Water resources carrying capacity (B_3)	Total amount of water resources (C_9)	100 million m^3
		Water use per capita (C_{10})	m^3
	Water resources demand (B_4)	Total amount of agricultural water use (C_{11})	100 million m^3
		Total amount of industrial water use (C_{12})	100 million m^3
		Total amount of household water use (C_{13})	100 million m^3
		Total amount of ecological water use (C_{14})	100 million m^3
Exploitation and utilization potential of WECC (A_3)	Water resources utilization (B_5)	Water resources used per unit of industrial added-value (C_{15})	m^3/ten thousand Yuan
		Reuse rate for industrial purpose (C_{16})	%
		Saving water rate for industrial purpose (C_{17})	%
	Wastewater treatment (B_6)	COD emission quantity per unit of industrial added-value (C_{18})	ton/ten thousand Yuan
		Nitrogen emission quantity per unit of industrial added-value (C_{19})	ton/ten thousand Yuan
		Wastewater treatment concentration rate (C_{20})	%
	Investment and personnel (B_7)	GDP (C_{21})	100 million Yuan
		Total investment in the treatment of environmental pollution (C_{22})	100 million Yuan
		Investment completed in wastewater treatment (C_{23})	10 thousand Yuan
		Personnel of environmental protection system (C_{24})	person
Water environmental vulnerability (A_4)	Proportion of national nature reserves in the total area of territory (C_{25})		%
	Proportion of protected source rivers in the total length of rivers (C_{26})		%

Table 2
Summary of the common catastrophe models.

Category	Dimension of control variables	Potential function	Bifurcation set	Normalization formula
Folded model	1	$f(x) = x^3+ax$	$a = -3x^2$	$x_a = \sqrt{a}$
Cusp model	2	$f(x) = x^4+ax^2+bx$	$a = -6x^2$ $b = 8x^3$	$x_a = \sqrt{a}$ $x_b = \sqrt[3]{b}$
Swallowtail model	3	$f(x) = x^5+ax^3+bx^2+cx$	$a = -6x^2$ $b = 8x^3$ $c = -3x^4$	$x_a = \sqrt{a}$ $x_b = \sqrt[3]{b}$ $x_c = \sqrt[4]{c}$
Butterflymodel	4	$f(x) = x^6+ax^4+bx^3+cx^2+dx$	$a = -10x^2$ $b = 20x^3$ $c = -15x^4$ $d = 4x^5$	$x_a = \sqrt{a}$ $x_b = \sqrt[3]{b}$ $x_c = \sqrt[4]{c}$ $x_d = \sqrt[5]{d}$

followed. The former means control variables complement each other and each of them tends to reach the average value, for example, in case of butterfly model, $x=(x_a + x_b + x_c + x_d)/4$. The latter implies that the control variables cannot offset each other and thus expressing the state variable "x" with the smallest catastrophic membership value of control variables (Zhang et al., 2009). In this paper, the calculation of B-level membership values uses "B" as state variable and "C" as control variable. The calculation of membership values of A_1 to A_3 uses A as state variable and B as control variable. However, the membership value of A_4 uses A_4 as the state variable and "C" as control variable. The details of the catastrophe models have been shown in Table 2.

To eliminate the discrepancy among the raw data in the unit of each indicator and the order of magnitude, it is necessary to perform the standardization. The indicators related to different properties can generally be divided into positive and negative ones and thus all the indices are standardized using the following Eqs. (1) and (2):

$$f_{ij} = (X_{ij} - X_{min})/(X_{max} - X_{min}) \tag{1}$$

$$f_{ij} = (X_{max} - X_{ij})/(X_{max} - X_{min}) \tag{2}$$

where, f_{ij} is the standardized value of the jth indicator in the ith region; X_{ij} is the original value of the jth indicator in the ith region; *Xmax* and *Xmin* are the maximum and the minimum value of the indicators respectively. Eq. (1) is for positive indices, whereas Eq. (2) is for negative indices.

Each control variable has a different influence on the state variable and thus it is important to quantify their relative importance, i.e. the weight of every control variable. To avoid errors and shortcomings of subjective judgments, the entropy weight method was selected to determine the weights of control variables, which was mainly applied to assess and analyze the utilized values of indicators based on their own information (Kang and Xu, 2012; Wellmann and Regenauer-Lieb, 2012). The Eqs. (3)–(6) are expressed as follows:

$$f'_{ij} = X_{ij}/\overline{X_j} \tag{3}$$

$$p_{ij} = f'_{ij}/\sum_{i=1}^{n} f'_{ij} \tag{4}$$

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij}\ln p_{ij} \tag{5}$$

$$w_j = \frac{1 - e_j}{m - \sum_{j=1}^{m} e_j} \tag{6}$$

where, f'_{ij} is the standardized value; X_{ij} is the original value of the jth indicator in the ith region; X_j is the average value of the jth indicator; p_{ij} is the proportion of the jth control variable in all the control variables; e_j is the entropy value of the jth control variable; n is the number of regions; m is the number of control variables; w_j is the weight of each control variable, i.e. the relative importance of each control variable.

2.4. Zoning of water environmental carrying capacity via k-means clustering

The k-means clustering is an unsupervised recognizable pattern in which the objects prepared to be classified in a data set are efficiently computed and categorized into proper groups (Malinen et al., 2014). There exists several types of indicators that are appropriate for describing the characteristics of objects and are being regarded as the basis of classification. In this study, water environmental carrying capacity is assessed in terms of water environment carrying status, water resources carrying status, vulnerability of water environment and exploitation and utilization potential. The evaluation results based on the catastrophe progression method provide each region with the assessment values of 4 integrated top-level indicators. These 4 types of indicators are the classification criterion of k-means clustering method. Regions are classified into corresponding categories using k-means clustering method to identify the similarities and differences present in different groups. The non-hierarchical classification method consists of the following 5 steps (Pandit et al., 2011):

Step 1: Specify the number of clusters (classes) k;

Step 2: Randomly choose the initial centers of k clusters among the input data set being clustered, i.e. Z_k;

Step 3: Calculate the distance of the certain province, A_i (i = 1, …, n) to the kth cluster center. A_i refers to the evaluation results of 4 integrated top-level indicators in each of the provinces, if:

$$||Ai - Zp|| \leq ||Ai - Zk|| \tag{7}$$

then A_i is assigned to the closest cluster, C_p (p = 1, …, k);

Step 4: If Eq. (7) is not valid, the average of A-level indicators of provinces in each cluster is calculated and designated as the new center. Then the provinces are reassign to the new closest cluster, C_j (j = 1, …, k);

Step 5: Repeat the steps 3–5 until the objective function converges to a minimum. The objective function is defined as shown in the following Eq. (8):

$$J = \sum_{k=1}^{k}\sum_{x\in C_j} |x - Z_j| \tag{8}$$

where, x is the province belonging to the cluster, C_j; Z_j is the jth cluster center.

As k-means clustering method requires the user to prespecify the number of clusters, it is indispensable in measuring the clustering quality. The silhouette coefficient combines both cohesion and separation, which is rather independent from the number of clusters (Aranganayagi and Thangavel, 2007). For the province i, the silhouette coefficient is expressed as:

$$s_i = \frac{b_i - a_i}{max\,(a_i,\, b_i)} \tag{9}$$

where, a_i is the average distance of the ith province to all other provinces in the same cluster; b_i is the average distance of the ith province to all other provinces in different clusters.

The optimal clustering number can be obtained by calculating the average silhouette coefficient of all the provinces. For one clustering with k categories, the average silhouette coefficient refers to the average of silhouette coefficients of provinces belonging to the cluster. The equation representing this is given as follow:

$$\bar{s}_k = \frac{1}{n}\sum_{i=1}^{n} s_i \tag{10}$$

where, n is the total number of provinces in the data set. The value of silhouette coefficient ranges from −1 to1. Besides, a higher value represents better clustering quality.

2.5. Data sources

This study assessed the WECC of 31 provinces in the mainland China (except Hong Kong, Macau and Taiwan of China, due to the unavailability of relevant data) in 2014. C_1, C_2, C_3, and C_4 are collected from the Environmental Status Bulletins of 31 provinces in 2014, published by environmental departments of governments at the provincial levels. C_1 to C_4 are used for the construction of a butterfly catastrophe model and for the estimation of B_1. C_5, C_6, C_7, and C_8 are collected from the China Statistical Yearbook on Environment (2015), published by the National Bureau of Statistics of China and Ministry of Environmental Protection of China. C_5 to C_8 are used for the construction of a butterfly catastrophe model and for the estimation of B_2. C_9 to C_{14} are collected from the China Statistical Yearbook (2015), published by the National Bureau of Statistics of China. C_9 and C_{10} are used for the construction of a cusp catastrophe model and for the estimation of B_3. C_{11} to C_{14} are used for the construction of a butterfly catastrophe model and for the estimation of B_4. C_{15}, C_{18}, C_{19} and C_{21} are collected from the China Statistical Yearbook (2015). C_{16}, C_{17}, C_{20}, C_{22}, C_{23}, and C_{24} are collected from the China Statistical Yearbook on Environment (2015). C_{15} to C_{17} are used for the construction of a swallowtail catastrophe model and for the estimation of B_5. C_{18} to C_{20} are used for the construction of a swallowtail catastrophe model and for the estimation of B_6. C_{21} to C_{24} are used for the construction of a butterfly catastrophe model and for the estimation of B_7. C_{25} and C_{26} are collected from the book “Water Function Zoning of National Key Rivers and Lakes”, published by the Ministry of Water Resources of China. C_{25} and C_{26} are used for the construction of a cusp catastrophe model and for the estimation of water environmental vulnerability. Due to the absence of official data of influx water resources in some of the provinces, such as Heilongjiang, Hainan, Chongqing, Tibet and Xinjiang, the values are assumed to be zero in this study.

3. Results and discussion

3.1. Evaluation results of water environmental carrying capacity

This study describes the basic characteristics of WECC based on the established index system from the aspects of carrying capacity, environmental pressure, vulnerability of water environment and exploitation and utilization potential, and also the 4 integrated indicators of WECC have been quantified using catastrophe progression method in 31 provincial administrative regions in China. The results obtained through the studies are shown in Table 3.

3.2. Spatial distribution of the evaluation results of integrated indicators

3.2.1. Spatial distribution of the water environment carrying status

The spatial distribution of water environment carrying status of 31 provinces is shown in Fig. 1. Eastern and central provinces in China could be considered relatively as economically developed and population concentrated areas. These provinces mainly represent the worst carrying status of the water environment. Whereas, most of the western

Table 3
Evaluation results of water environmental carrying capacity in 31 provinces of China.

Region	Assessed value of water environment carrying status	Assessed value of water resources carrying status	Assessed value of exploitation and utilization potential of WECC	Assessed value of water environmental vulnerability
Beijing	0.8609	0.6255	0.8966	0.9932
Tianjin	0.6712	0.5889	0.8876	0.9800
Hebei	0.7711	0.6815	0.9375	0.9722
Shanxi	0.8838	0.6956	0.9207	0.9562
Inner Mongolia	0.8585	0.7239	0.9143	0.8050
Liaoning	0.7748	0.7003	0.8994	0.8676
Jilin	0.8662	0.7395	0.9033	0.8757
Heilongjiang	0.7547	0.7858	0.8867	0.8595
Shanghai	0.8877	0.6611	0.9105	0.9107
Jiangsu	0.8652	0.6821	0.9440	0.9815
Zhejiang	0.9000	0.7898	0.9526	0.9334
Anhui	0.9215	0.7647	0.9218	0.9611
Fujian	0.8961	0.8006	0.9373	0.9450
Jiangxi	0.9044	0.8159	0.9130	0.9668
Shandong	0.4163	0.6906	0.9564	0.9857
Henan	0.7802	0.7168	0.9386	0.9585
Hubei	0.9007	0.7761	0.9144	0.9289
Hunan	0.8170	0.8096	0.9161	0.9107
Guangdong	0.4647	0.7478	0.9456	0.9556
Guangxi	0.9189	0.8247	0.8909	0.9778
Hainan	0.9185	0.7751	0.8610	0.4675
Chongqing	0.9163	0.7780	0.9111	0.9347
Sichuan	0.8476	0.8339	0.9362	0.9012
Guizhou	0.9260	0.8116	0.8842	0.9220
Yunnan	0.9283	0.8256	0.8866	0.7882
Tibet	0.9543	0.9992	0.3779	0.3714
Shaanxi	0.8974	0.7454	0.9152	0.9235
Gansu	0.9172	0.7236	0.7911	0.7857
Qinghai	0.9367	0.8297	0.8449	0.3651
Ningxia	0.9003	0.5488	0.5220	0.8958
Xinjiang	0.8931	0.7409	0.8738	0.8634

provinces exhibit better water environment carrying status. The most severely overloaded areas are mainly distributed in Circum-Bohai-Sea region, Heilongjiang and Guangdong. Intensive human activities have caused enormous water environmental pressures in these areas. Table 3 demonstrates that Shandong is the most serious one with the lowest quantified value of 0.4163, followed by Guangdong province with the value of 0.4647. Shandong is a large agricultural province where most of the pollutants are discharged by agricultural non-point sources. Whereas, Guangdong confronts with the problem of overloaded water environment contributed by the most serious point source of pollution. The utilized water environmental capacity in Bohai Rim region is relatively scarce but the pollution load is relatively large. Such a combination makes the assessed value of water environment carrying status at lower level. In contrast, Tibet, Qinghai, Yunnan and Guizhou have better performance on the carrying status of the water environment because of the characteristics of relatively abundant water resources and low pollutant emissions.

3.2.2. Spatial distribution of the water resources carrying status

The spatial distribution of the water resources carrying status of 31 provinces is illustrated in Fig. 2. Most of the northern provinces of China are more serious than the southern ones in terms of water resources carrying status. In reality, there is more rain in the south and less in the north. Therefore, the southern regions are relatively rich in water resources. The most severe overloaded areas are mainly located in Beijing-Tianjin-Hebei region, Yangtze River Delta region, Shandong and Ningxia. The low assessed values of water resources carrying status in these regions are primarily contributed by the imbalance between demand and supply of water resources. The available water resources are relatively scarce, which result in smaller carrying capacity of water resources, for example in Ningxia and Tianjin. In addition, an excessive demand for water resources has resulted in a huge increase in pressure for the water environment. The agricultural demand for water resources in Hebei and Shandong is relatively large and the industrial water demand of Jiangsu is the largest. In contrast, the southwestern provinces exhibit better carrying status of the water environment, which are directly benefitting from the relatively abundant water resources and lower demands.

3.2.3. Spatial distribution of exploitation and utilization potential of water environmental carrying capacity

The spatial distribution of exploitation and utilization potential of water environmental carrying capacity in the 31 provinces is shown in Fig. 3. It is found that the exploitation and utilization potential of water environmental carrying capacity is decreasing gradually from the east, then to the middle and to the west part of China, where Jiangsu, Zhejiang and Guangdong showing the highest and Tibet indicating the lowest. The trends basically correlate with the differences in spatial distribution of the level of economic development in China. Thus, the observed result indicates that the level of economic development is the dominant factor that affects the exploitation and utilization potential of water environmental carrying capacity. The investments in wastewater treatment, the level of utilization of water resources and the capacity of wastewater treatment are closely associated with the economic development. With a massive economy larger than those of other provinces, eastern provinces such as Jiangsu, Zhejiang and Guangdong are the areas with the highest exploitation and utilization potential of China. In contrast, a relatively lower GDP and investment in wastewater treatment lead to lower exploitation and utilization potential of WECC in most of the western provinces. Table 3 shows that Tibet is the lowest area with the value of 0.3779, followed by Ningxia with the value of 0.5220 owing to its relatively weaker economy.

3.2.4. Spatial distribution of water environmental vulnerability

The spatial distribution of water environmental vulnerability of 31 provinces is shown in Fig. 4. Provinces with higher vulnerability of water environment are mainly distributed in the western part of China, such as Tibet, Qinghai, Hainan and Inner Mongolia. These regions are located in the upstream areas of main rivers which are the key nourishing and cherish areas of water sources. Table 3 shows that Qinghai is the most fragile region with the lowest assessed value of 0.3651, followed by Tibet with the value of 0.3714. These observed results could be attributed to higher proportions of national nature reserves as well as due to the longest protected source rivers. Larger areas of national nature reserves and more than 2000 km length of protected source rivers lead to low adaptive and resuming capacity which in turn results in high sensitivity and vulnerability. In contrast, the central and eastern provinces in China demonstrate lower water environmental vulnerability as a whole due to the location of downstream areas of main rivers and a lower proportion of national nature reserves based on relatively smaller areas.

3.3. The clustering zoning of water environmental carrying capacity

The *k*-means clustering analysis was performed after quantifying the 4 integrated indicators from 31 provinces in China. Given the total numbers of provinces, the zoning number should be less than 10. The clustering analysis was carried out on 2 to 10 clusters and the average silhouette coefficient versus the clustering number was plotted as shown in Fig. 5. A higher value represents better clustering quality, From Fig. 5, it could be observed that the average silhouette coefficient is the largest i.e. 0.578, when $k = 4$. Therefore, the optimal clustering observed at $k = 4$ is used for the zoning of WECC i.e. categorizing 31 provinces into 4 sub-areas. The result of clustering zoning is mapped by

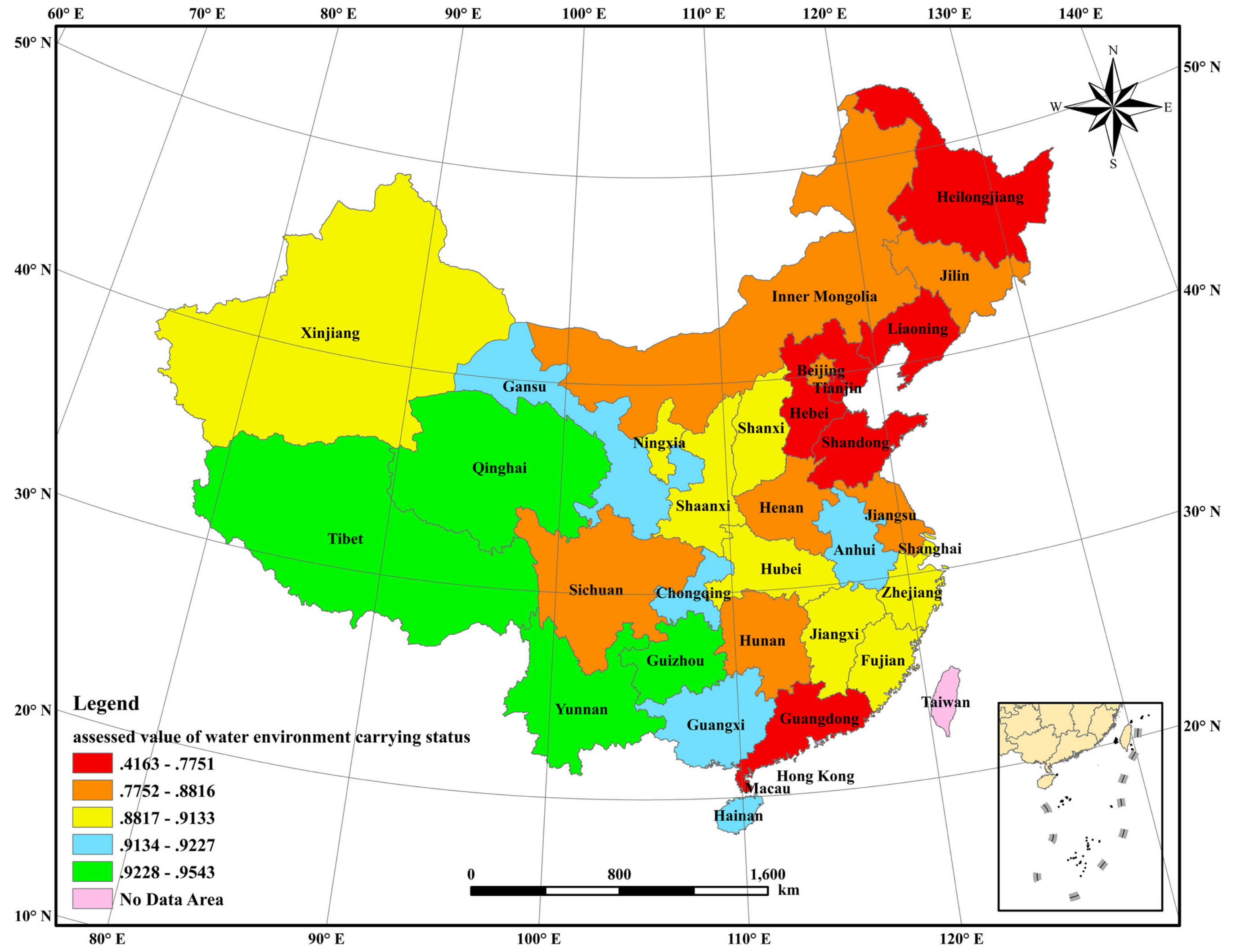

Fig. 1. Zoning map of water environment carrying status.

reference to relevant national planning as shown in Fig. 6.

The zoning result of water environmental carrying capacity in the 31 provinces is illustrated in Fig. 6. Sub-area one is the key protected area and mainly located on the upper and middle parts of important rivers in China, including Tibet, Qinghai, Yunnan, Guangxi, Guizhou and Hainan. Despite the fact that the water resources in the sub-area are relatively rich and carrying status of water environment is better, the aquatic ecological environment is actually very fragile. These types of areas consist of crucial source of rivers and nature reserves with special values, belonging to key nourishing and cherish areas of source of water and fragile districts of water environment in China, which are significant for preserving the rich bio-diversity and water environment security. In addition, this sub-area is attributed to the relatively lower GDP and lower investment in wastewater treatment, leading to low exploitation and utilization potential of WECC. Therefore, large-scale urbanization and industrialization developments in this region should be highly and seriously restricted due to the high vulnerability of water environment and the most fundamental and important ecological spaces such as water areas, forests and grasses must be effectively protected and a positive restoration should be carried out.

Sub-area two is the controlled development area which primarily consists of northwestern provinces, where water resources are comparatively deficient due to the arid climate conditions and reduced rainfall. Despite the carrying capacities of water environment and water resources both overloaded seriously, the issue of overloaded water resources has become more prominent as compared to the overloaded water environment. In additon, the vulnerability of water environment is relatively high and the exploitation and utilization potential of WECC is at a medium level as a whole. Therefore, economic and social development should be suitable for local water conditions and within the carrying capacity of water resources. The areas characterized by water-deficient regions should be given priority to support and to develop a water-saving agriculture, such as actively popularizing the techniques and equipments of sprinkler and drip irrigations. In addition, promoting the recycled water through the price adjustment of industrial and residential water is the key to improving the conservation of water.

Sub-area three is the optimized development area and mainly distributed in China's economically developed eastern coastal areas that have a large and concentrated population, in particular the Bohai Rim, Yangtze River Delta and Pearl River Delta. In these areas, the modernization levels of urbanization and industrialization are higher than those of other regions. The enormous amount of industrial and domestic pollutants discharged frequently by the intensive human activities exert huge pressures on the water environment and water resources than they are designed to deal with. Despite the fact that the water environment and resources have most severely exceed their capacities, this sub-area has a great potential for pollution prevention as well as resource utilization which could be benefitted through advanced economy. In addtion, vulnerability of water environment is the lowest because of a very small number of national nature reserves and due to the poor protection

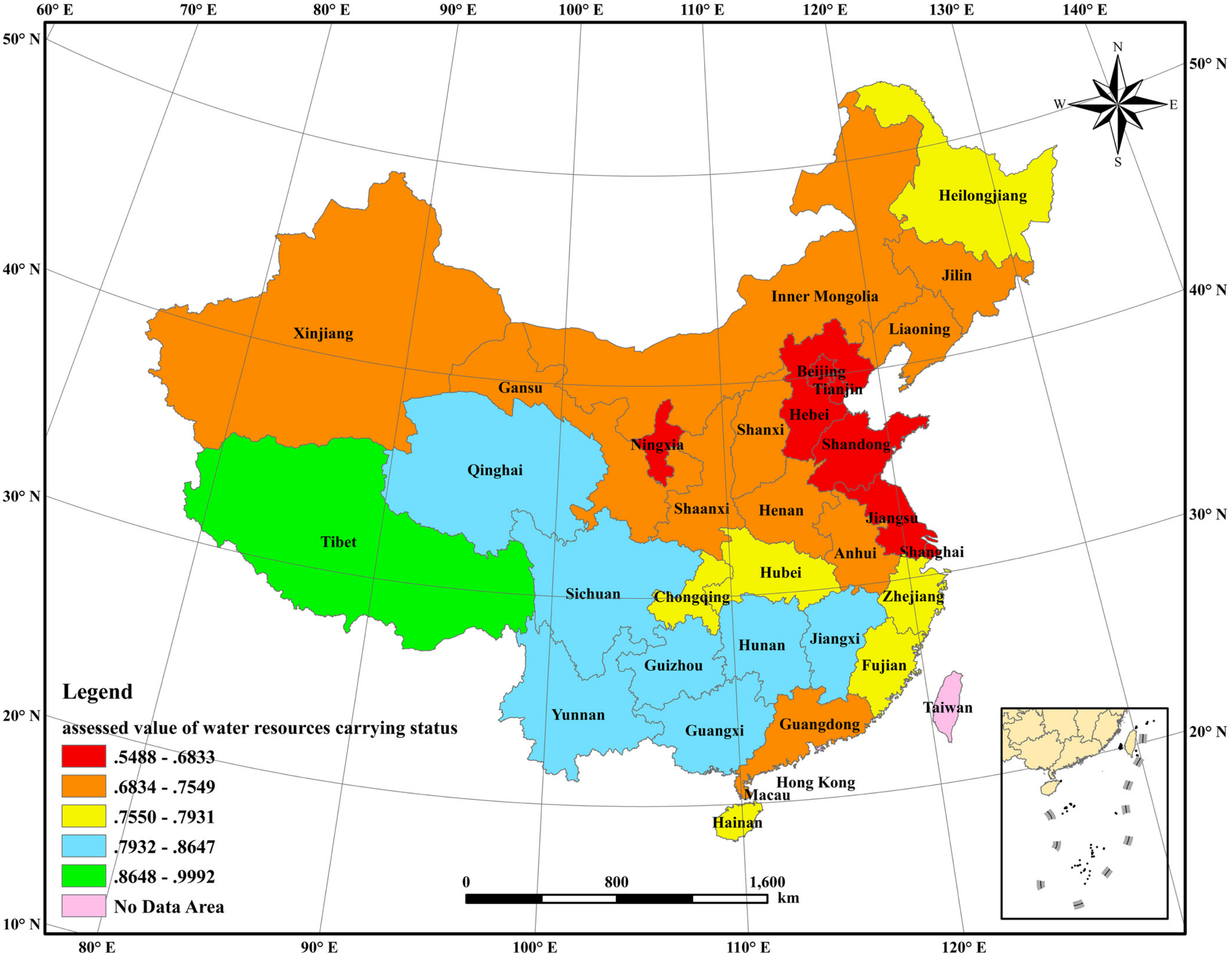

Fig. 2. Zoning map of water resources carrying status.

of source rivers. The fundamental measures for reducing the pollutants produced by the industrial, agricultural and urban domestic sources include optimizing the industrial structure, strengthening the centralized treatment of wastewater in the industrial parks, upgrading and reconstruction of the sewage treatment plants and promoting the formula of fertilization by soil testing. Moreover, water diversion and water reclamation and reuse are effective ways to be considered in increasing the available water resources.

Sub-area four is the prioritized development area which geographically belongs to the middle and lower regions of Yangtze River. This area has a lower assessed value of water environmental vulnerability obtained through lower proportions of protected source rivers in the total length of rivers and national nature reserves based on the relatively small areas. The water environment and resources carrying conditions are mildly beyond the carrying capacities, and the exploitation and utilization potential of WECC is much higher. Consequently, this region is regarded as an important area focusing on the industrialization and urbanization. In the future, the major orientation of development could be in enlarging the urban scale through scientifically promoting the aggregation of population in an orderly way, and constructing a green industrial system with high technology and with an added value. In addition, this sub-area should consider taking the construction of sponge city that provides an opportunity in improving the ability of comprehensive utilization of urban rainwater which in turn will reduce the urban non-point pollution caused by the runoff of storm water.

The environmental water management of foreign countries has experienced the stage of “pollution - prevention and control - protection - ecological management”, which has been transferred from pollution prevention and control to the restoration and protection of the ecosystem. For example, the United States takes water ecological zoning as the basis of management, comprehensively considers water ecological resources and human disturbance, and realizes the integrated management of water resources and water environmental quality. In contrast, China will continue to take pollution prevention and control as its main task for a relatively long period of time. The demand on water resources and pollution of water environment have obvious regional characteristics. As a unified management system in China, the research and the results of water environment carrying capacity based on administrative division will be beneficial to more effective prevention and control of environmental pollution. The population size and economic scale in a certain space unit can be controlled within the allowable limits of water environment carrying capacity, and the pattern of governance after pollution can be reversed. With a gradual implementation of the positioning of each zoning, the developmental activities which do not meet the function of orientation of water environment carrying capacity will be significantly reduced, and the industrial and living pollution emissions will be effectively controlled. Compared with the small-scale and decentralized layout, the concentration of economy and population will greatly improve the level of

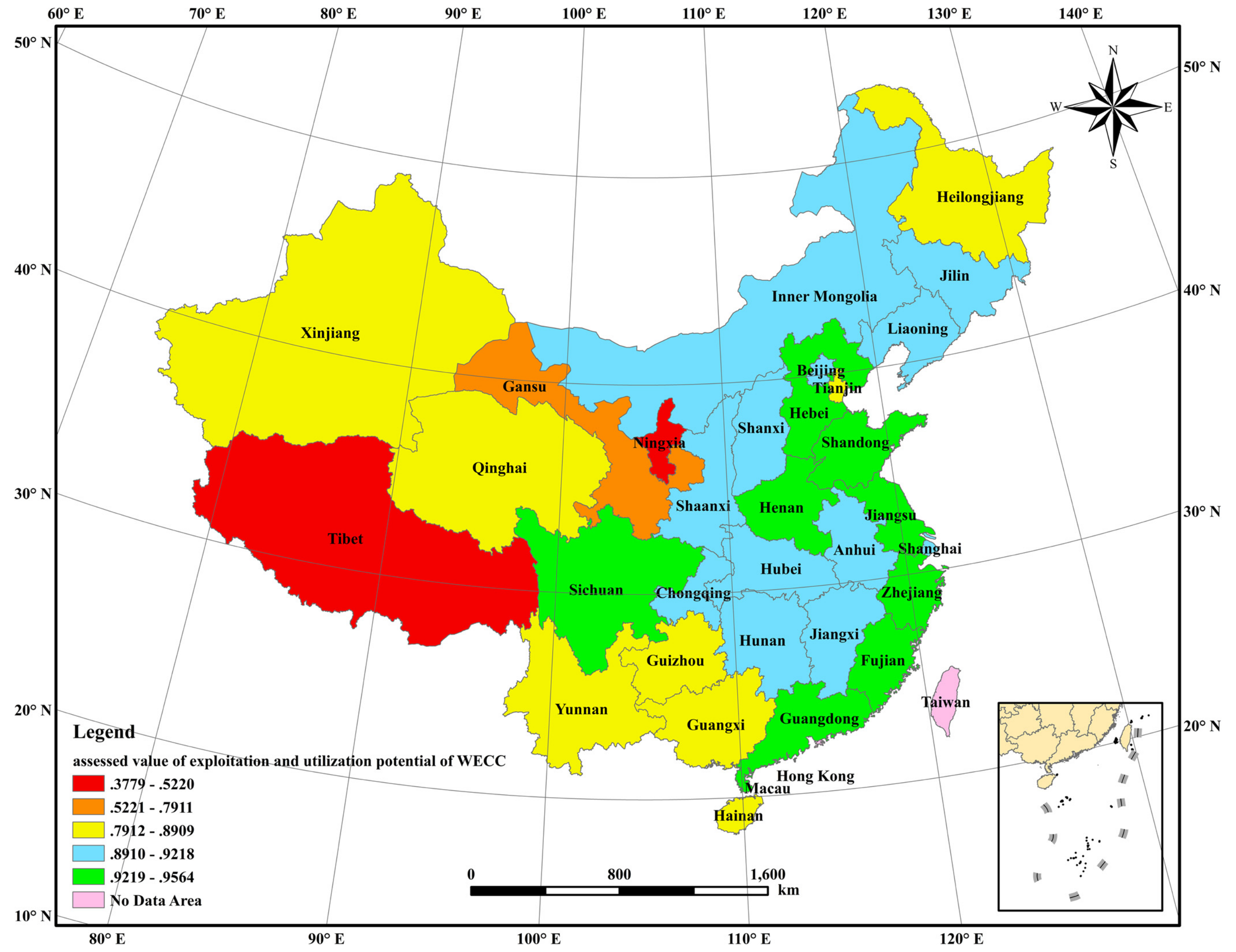

Fig. 3. Zoning map representing the exploitation and utilization potential of WECC.

pollution control.

The Chinese government has clearly put forward the strict management of water resources as an important strategic measure to speed up the transformation of the pattern of economic development. Therefore, it is required to establish the control system on the water amount and control system on the efficient water-use, and to delimit a red line of water resources control and utilization. The zoning result of water environment carrying capacity could be an important basis for the establishment of above systems and the red line. In particular, the control zone of water resource overloaded seriously based on the zoning result might clarify the responsibilities and tasks of water resources management and protection in the corresponding provinces. Based on the outcome obtained through the zoning, an allocation plan for the main river water should be formulated in the future, and the control index system of total water consumption should be established. The planning on national economic and social development and planning on urban master and the layout of major construction projects should be adapted to the resource conditions of local water. For the regions where the total amount of water reached or exceeded the control target, the approval of new water intake for the construction projects could be suspended. Whereas, for areas where the total amount of water used is close to the control index, the new water intake should be restricted. The government will have to strictly limit the construction of water-intensive industrial projects in areas with insufficient water resources, and setting standards for the conservation of water is mandatory. Water technology, equipment and products that do not meet the water-saving standards should be banned or phased out rapidly.

At present, the implementation of national plan for major function oriented zoning has been elevated to national strategy. The plan for major function oriented zoning requires comprehensive consideration of resource and environment carrying capacity, existing developmental intensity and development potential in different regions, and overall plans for the population distribution, economic layout, land use and urbanization pattern. The plan for major function oriented zoning is the action plan of scientific territorial development, which is the strategic, fundamental and restrictive planning of the development of land and space. The zoning result of water environment carrying capacity could provide strong support for the better implementation of plan for major function oriented zoning and the deepening of the detailed regional policies. According to the zoning result, Circum-Bohai-Sea region, Yangtze River Delta region and Pearl River Delta region have been identified as the optimized developmental areas. It is to promote such regions characterized by population concentration, high intensity of development and water resources and environmental overload to take the lead in transforming the economic development pattern and readjusting the economic structure. In the middle and lower reaches of the Yangtze River, some provinces with higher potential of water environmental carrying capacity and better demographic and economic conditions have been determined as prioritized development areas,

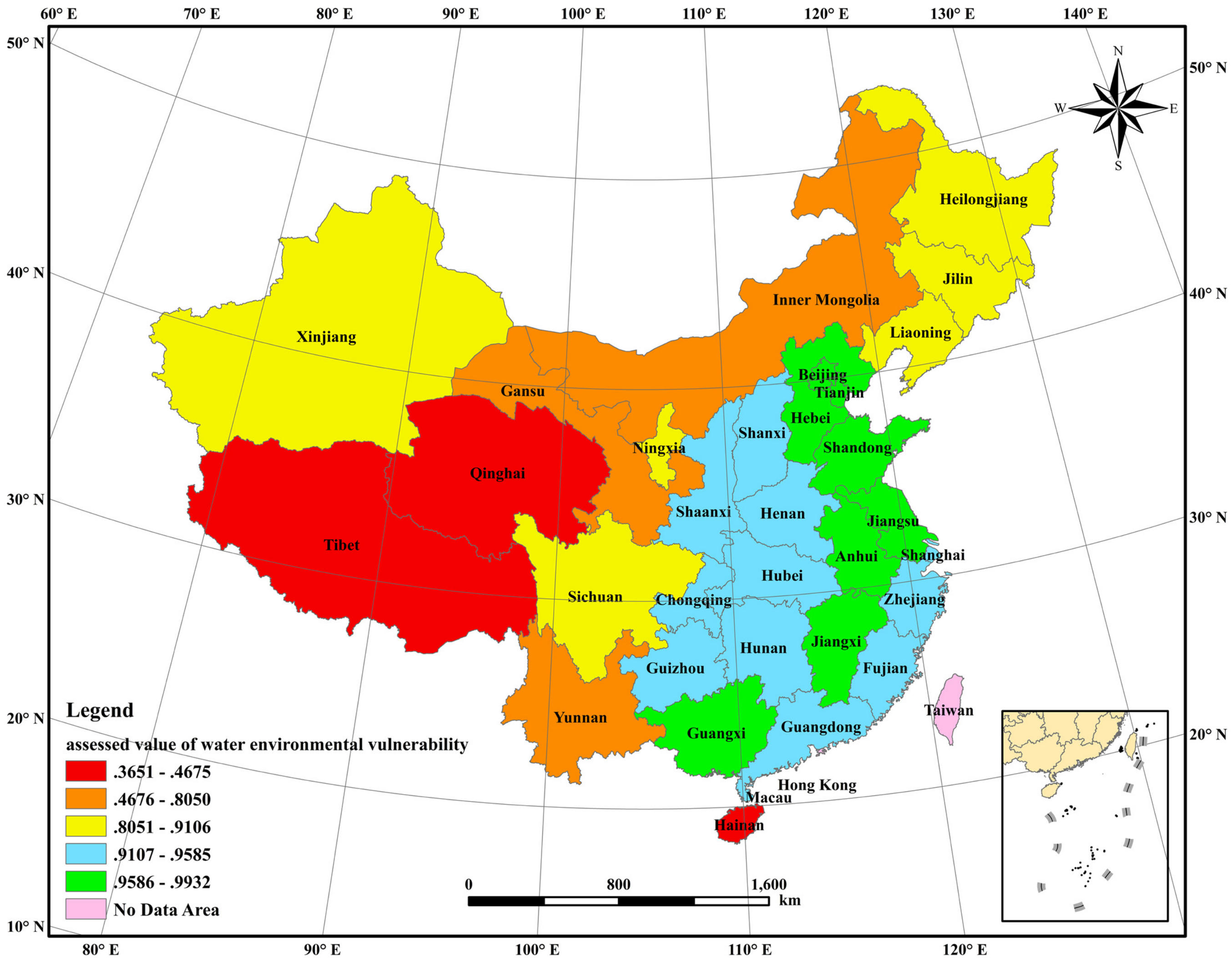

Fig. 4. Zoning map of vulnerability of water environment.

which is in order to guide the production factors to concentrate in these areas, to promote the industrialization and urbanization, and to speed up the economic development. In addition, the western parts that do not have conditions for large-scale industrialization and urbanization development have been designated as key protected area. The policies of the state to support ecological environment protection and improve people's livelihood will be more concentrated in such areas, which can develop the services and living conditions of local public as soon as possible.

4. Conclusions

An index system of water environmental carrying capacity is established by carefully considering the perspectives of water

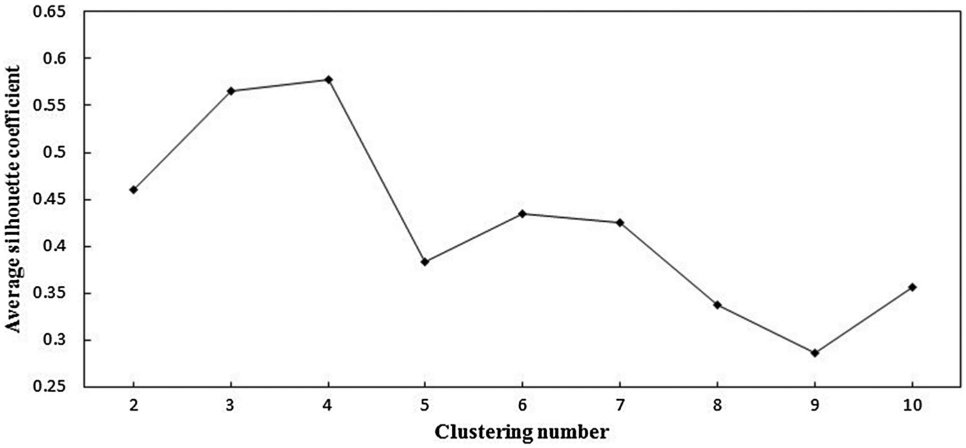

Fig. 5. Average silhouette coefficient versus clustering number.

Fig. 6. Zoning map of WECC.

environment carrying status, water resources carrying status, water environmental vulnerability and exploitation and utilization potential. Besides, quantification is carried out on the integrated indicators based on the catastrophe progression method. Then, the spatial distribution of 4 comprehensive factors representing WECC is analyzed. The obtained results through this investigation reveal that the carrying condition of water environment becomes increasingly better and the exploitation and utilization potential of WECC is decreasing gradually from the east to the west in China, which corresponds to the differences existing in the spatial distribution of the level of economic development. As far as the water resources carrying status is concerned, there are more overloading provinces in the north and less in the south, which is roughly the same as with the distribution of precipitation. In addition, water environmental vulnerability in the west is higher than that of central and eastern provinces due to different locations along the main rivers and also due to the spatial distribution of national nature reserves.

The *k*-means clustering method is applied to identify the similarities as well as different characteristics of WECC in the 31 provinces. The silhouette coefficient is introduced to measure the clustering quality and to determine the optimal zoning number. The observed results show that the average silhouette coefficient is the largest when $k = 4$, which represents the best clustering quality, i.e. the optimal clustering number is 4. Therefore, 31 provincial administrative regions are categorized into 4 areas, including key protected area, controlled development area, optimized development area and prioritized development area. Following this, suggestions on the corresponding bidirectional regulation to different sub-areas have been put forward to provide a scientific reference to the rational distribution of economic development and in assisting the management of water environment and regional sustainable development.

However, several points should be noted carefully. At first, due to the absence of official data of influx water resources especially in some of the provinces, the values are assumed to be zero. Therefore, the data may cause biased estimation and hence on the obtained results, which is a common weakness of the empirical studies. Furthermore, in the western regions such as Tibet, despite the water resources are relatively rich and carrying status of water environment is better, the aquatic ecological environment is actually fragile as such regions are located in the upstream areas of main rivers. The water environmental vulnerability has an effect on the assessment results of WECC. However, the measurable indicators are currently difficult to obtain from the relevant yearbook, and thus it will be an important work to explore WECC with quantified indicators of water environmental vulnerability to be considered for the future studies. This may provide useful insights about the spatial differences of WECC and the choice of right ways to promote the sustainable development of water system in China.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.03.030.

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