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A Spatio-Temporal Dynamics Analysis of Water Resouces Carrying Capacity Based on Panel Data: Evidence from Qinghai Province, China

Qianwen Yu*(**)†, Fengping Wu* and Yuting Chen***
*School of Business, Hohai University, Nanjing 211100, China
**Department of System Designing Engineering, University of Waterloo, Waterloo, ON, N2L 3G1, Canada
***International Business School of Suzhou, Xi’an Jiaotong-Liverpool University, Suzhou, 215123, China
†Corresponding author: Qianwen Yu

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ABSTRACT

Water resources carrying capacity (WRCC), an important component of natural resources carrying capacity, has a crucial influence on the social and economic development of a country or a region. This paper use panel data to evaluate regional WRCC based on the new requirements of the Most Stringent Water Resources Management System (MSWRMS) in China. Firstly, under the “Three Red Lines” constraints from the MSWRMS, we propose a new concept, the Strictest Water Resources Carrying Capacity (SWRCC), and build an evaluation index system for SWRCC. Secondly, in the field of panel data analysis, a grey time clustering evaluation model of SWRCC is proposed based on Compact-Center-point Triangular Whitenization Weight Function (CCTWF). By using the grey time clustering coefficient to characterize the temporal dimension of panel data, the temporal characteristics of SWRCC assessment and the importance degree of the evaluation index are reflected. Finally, we take Qinghai Province as an example to carry out empirical research. The empirical results show that the SWRCC presents obvious regional differences in the eight administrative districts of Qinghai Province. Regions subjected to lower levels of SWRCC will be restricted by problems of water use efficiency. By contrast, due to rapid socio-economic development, regions with higher SWRCC will face significant water resource problems of high total water consumption and poor water quality.

INTRODUCTION

Water is an irreplaceable fundamental resource that human beings rely on for survival. It also is a basic condition for the sustainable development of social economy (Huang et al. 2001). Since the end of the 20th century, as the global climate and environment have changed, the world is increasingly experiencing water security problems, such as shortages, water environment deterioration and soil erosion (Koch et al. 2016). Although China, as the largest developing country, is rich in water resources, the country’s available water is less than one quarter of the world average. So water security problems also seriously hamper the sustainable development of China’s social economy (Ge et al. 2016).

In the research on sustainable development, the idea of carrying capacity was first applied to biology and ecology. In 1921, Park & Burgess (1920) put forward the concept of carrying capacity for the first time in a human ecology journal. Subsequently, various concepts and theories of carrying capacity have been introduced to different fields, such as urban areas (Irankhahi et al. 2017), land (Jaimes et al. 2012), carbon (Diego et al. 2017), sediment (Zheng et al. 2014), and water (Yue et al. 2015). Specifically, water is increasingly important in current socio-economic development; thus, Water Resources Carrying Capacity (WRCC) has attracted considerable attention. So far, there is no uniform definition of WRCC, either in China or internationally, leading to confusion in its characterization. Based on a review of the literature, the views on how to characterize WRCC can be broadly divided into three categories: The first category considers water supply capacity and the water resources exploitation scale as the characterization index (Xu 1993, Liu et al. 2017). The second category focuses on the largest population that can be supported by water resources (Ait-Aoudia et al. 2014, Ait-Aoudia et al. 2016 and Qin et al. 2016). The third category considers the development scale of a social economic system as the main characterization (Song et al. 2011, Wang et al. 2017). As shown by the above literature, more and more factors have been considered in the definition of WRCC, thus providing a theoretical basis for future research. However, in the existing literature, most studies evaluate regional WRCC under a certain condition that is designed randomly by researchers. In fact, the impact of external environment conditions in different countries, especially the policy environment, are always ignored. At present, in response to the rapid changes in population, economic structure and ecological environment, China has formulated a series of laws, regulations, and rules for water resource management. In 2009, China's Ministry of Water Resources held the Chinese conference on water conservancy and first proposed the Most Stringent Water Resources Management System (MSWRMS) (Li et al. 2016, Desheng 2015). In addition, it proposed the "Three Red Lines" to limit the total water resources consumption, to support efficient water resources utilization efficiency, and to restrict pollutants entering water function zones. From then on, in accordance with the No. 1 Document of the Central Government and the 18th CPC National Congress, all provinces and subdivisions of China were required to implement the MSWRMS and "Three Red Lines" (Zang et al. 2016). Therefore, studying the regional WRCC based on MSWRMS and "Three Red Lines" framework is of great practical significance.

In terms of calculation methods, a variety of methods have emerged to quantify water resources carrying capacity. The most widely used model for WRCC, the fuzzy comprehensive evaluation method, has been widely applied to assess the water resource environments (Meng et al. 2009, Dong et al. 2010). On this basis, the evaluation index system of WRCC was analysed to evaluate the water resources in the study area (Cui et al. 2012). Wang Ran et al. (2016) proposed the index system of mineral resources carrying capacity to evaluate the diversity of Chinese mineral resources in the national sustainable development plan. Furthermore, system dynamics was applied in a study by Yu Luo et al. (2015) for assessing ecological carrying capacity. Xie et al. (2014) established a system dynamics model to simulate the trends for a basin between 2011 and 2030. Additional methods have also been used. For example, Ren Chongfeng et al. (2016) presented a metabolic theory and applied it to the evaluation of WRCC.

However, the evaluation of WRCC needs to consider the comprehensive development of a whole water resources system in a given period based on panel data analysis. Most studies have been limited to the analysis of static cross-sectional data, ignoring both the developing situation of water resource systems and any dynamic evolving trends. Furthermore, due to the influence of natural factors such as elevation, topography, latitude, and atmospheric circulation, Qinghai Province has the unique continental climate of the plateau. It is seriously deficient in freshwater resources, both in sources and quality, but studies relevant to Qinghai's WRCC are absent. It is vital to fill the gap in Qinghai's water resources management and effective implementation of the MSWRMS.

Under such circumstances, this study firstly defines the Strictest Water Resources Carrying Capacity (SWRCC) and gives the construction details of the indicator system. Then, the grey time clustering model based on panel data is introduced to evaluate SWRCC under the new scenarios of the most stringent water resources management in China. To verify the practicality of the method, Qinghai Province in China, was chosen as an empirical study.

INDEX SYSTEM OF SWRCC

As the key method to help China solve its water security problems, MSWRMS is also a summary of contemporary water management ideas (Ge et al. 2017). Combined with an analysis of MSWRMS and under the restraint of the "Three Red Lines" (Kluger et al. 2016, Ma 2016), this current paper puts forward a new concept based on previous studies: the Strictest Water Resources Carrying Capacity (SWRCC). In contrast to macro WRCC, SWRCC takes China's condition into consideration, and is therefore, more specific.

In the selection of SWRCC indicators, priority must be given to the principles and indexes that meet the require-

Table 1: "Three Red Lines" quantitative index system.

Object Layer	Principle Layer	Index Layer	No	Attribute
Spatiotemporal dynamics analysis of SWRCC	Total water consumption	Surface water utilization degree (%)	h_1	Profit type
		Groundwater utilization level (%)	h_2	Profit type
		Per capita water resources(m^3/capita)	h_3	Profit type
		The red line of total water utilization (10^8m^3)	h_4	Profit type
	Water use efficiency	Industrial water consumption per unit GDP ($m^3/10^4$Yuan).	h_5	Cost type
		Repeated use rate of industrial water (%)	h_6	Profit type
		Irrigation water consumption per unit area (m^3/hm^2)	h_7	Cost type
		Irrigation water effective-utilization coefficient (%)	h_8	Profit type
		Per capita water utilization (m^3)	h_9	Cost type
	Water quality	Comprehensive water pollution index (%)	h_{10}	Cost type
		Industrial waste water discharge standard-meeting rate (%)	h_{11}	Profit type
		Urban sewage treatment rate (%)	h_{12}	Profit type

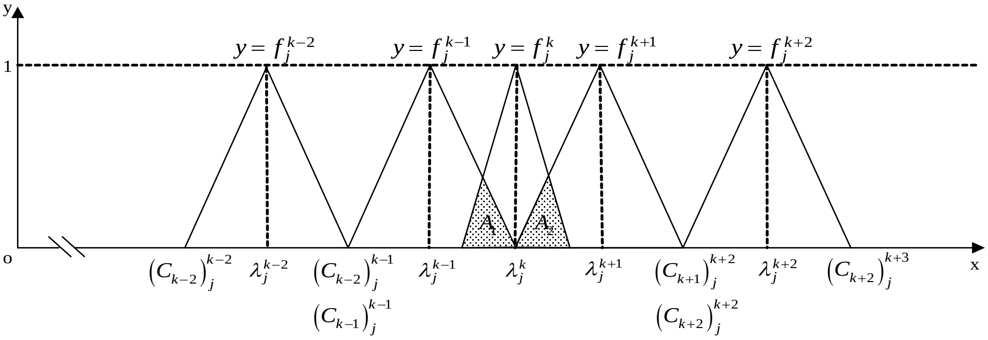


Fig. 1: A sketch of constructing the CCTWF.

ments of MSWRMS: total water consumption, water use efficiency, water quality. The index system must promote the stability of the water resources system, the effective use of water resources, and the effective prevention and control of water pollution. In addition, these indexes must refer to the relevant ones used in national and regional planning. Furthermore, the selection of indicators should be scientific and practical, to guide and monitor the level of SWRCC in different regions. According to these principles, this study presents a “Three Red Lines” quantitative index system that includes three subsystems and 12 indicators. The index system is shown in Table 1.

The meaning of these indexes can be illustrated as follows: (1) Surface water utilization degree (h_1) reflects the development and utilization extension of surface water resources in different areas; (2) Groundwater utilization level (h_2) shows the development and utilization extension of water resources in Qinghai Province; (3) Per capita water resources (h_3) refers to the number of water resources used by an individual in a region during a certain period; (4) The red line of total water utilization (h_4) represents the nation’s control of the regional water distribution quota; (5) Industrial water consumption per unit GDP (h_5) reflects the economic benefits obtained by industrial water utilization per unit. A smaller indicator value means higher industrial water-resource-use efficiency; (6) Repeated use rate of industrial water (h_6) is the ratio between the volume of industrial reused water and the total water used; (7) Irrigation water consumption per unit area (h_7) is the ratio between regional current water use and its irrigation area; (8) Irrigation water effective-utilization coefficient (h_8) reflects agricultural-irrigation water-use efficiency. The higher the coefficient, the higher the agricultural-irrigation water-use efficiency; (9) Per capita water utilization (h_9) shows the regional residents’ daily water-use level; (10) Comprehensive pollution index of water quality (h_{10}) shows the state of water pollution. The higher the value in the index, the greater the amount of regional sewage; (11) Industrial wastewater discharge standard-meeting rate (h_{11}) refers to the ratio between the discharge quantity of standard-meeting industrial sewage and the total sewage discharge quantity. (12) Urban sewage treatment rate (h_{12}) reflects the coordination between people’s life and water environment, and 100% means a green life.

METHODOLOGY

Characterization of Multi-index Panel Data

Panel data has a complex data structure, which contains both cross-sectional data and a time series, and has spatial and temporal dimensions. It includes single-index panel data and multi-index panel data. Compared with single-index panel data, the structure of multi-index panel data is more complicated, not only reflecting the spatial characteristics of SWRCC at a certain point, but also reflecting the dynamic evolution of SWRCC at a certain time. In this study, the multi-index panel data is calculated for evaluating SWRCC.

Assume that there is a set of n objects, and that the value of indicator j ($j=1,2...,m$) for sample i($i=1,2,...,n$) at time t ($t=1,2...,T$) is x_{ij}^{T} . Then, the matrices of the original data structure under multi-index panel data can be expressed as follows:

(1) There are T two-dimensional matrices at time points. At one point in time, the original data values of multi-objects and multi-indices can be described as a two-dimensional matrix:

$$X^{(0)}(t)=\begin{bmatrix} x_{11}^{t} & x_{12}^{t} & \cdots & x_{1m}^{t} \\ x_{21}^{t} & x_{22}^{t} & \cdots & x_{2m}^{T} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1}^{t} & x_{n2}^{t} & \cdots & x_{nm}^{t} \end{bmatrix},\ t=1,2,...,T \qquad ...(1)$$

(2) There are two-dimensional matrices under indexes.

Under one index, the original data values of multi-object and multi-time can be described as a two-dimensional matrix:

$$X^{(1)}(j)=\begin{bmatrix} x_{1j}^{1} & x_{1j}^{2} & \cdots & x_{1j}^{T} \\ x_{2j}^{2} & x_{2j}^{2} & \cdots & x_{2j}^{T} \\ \cdots & \cdots & \cdots & \cdots \\ x_{nj}^{1} & x_{nj}^{2} & \cdots & x_{nj}^{T} \end{bmatrix},\ j=1,2,...,m \qquad ...(2)$$

(3) There are two-dimensional matrices under indexes. Under an object, the original data values of multi-index and multi-time can be described as a two-dimensional matrix:

$$X^{(2)}(i)=\begin{bmatrix} x_{i1}^{1} & x_{i2}^{1} & \cdots & x_{im}^{1} \\ x_{i1}^{2} & x_{i2}^{2} & \cdots & x_{im}^{2} \\ \cdots & \cdots & \cdots & \cdots \\ x_{i1}^{T} & x_{i2}^{T} & \cdots & x_{im}^{T} \end{bmatrix},\ i=1,2,...,n \qquad ...(3)$$

Dimensionless Treatment of Panel Data

Before calculating the SWRCC, indicators with different units must be rendered dimensionless in the evaluation index system. According to the different effects of indicators on SWRCC, the initial multi-index panel data matrices are normalized with (4), used for positive indexes (profit type), and (5), used for negative indexes (cost type):

(1) The dimensionless formula for positive indicators (profit type) is

$$x_{ij}^{t}=\frac{y_{ij}^{t}-b_{j}}{a_{j}-b_{j}} \qquad ...(4)$$

(2) The dimensionless formula for negative indicators (cost type) is

$$x_{ij}^{t}=\frac{a_{j}-y_{ij}^{t}}{a_{j}-b_{j}} \qquad ...(5)$$

Where, $i=1,2,...,n$, $j=1,2...,m$ and $t=1,2...,T$; n is the total number of regions, j means the number of indexes, T denotes the number of time points; a_j and b_j respectively represent the minimum and maximum values of indicator j among different regions; x_{ij}^{t} refers to indicator values after normalizing; and y_{ij}^{t} represents the indicator values before normalizing.

Spatio-temporal Dynamics Analysis Model

After the dimensionless treatment of multi-index panel data, we propose using a spatio-temporal dynamics analysis model to evaluate the SWRCC, i.e., the grey time clustering model based on compact-center-point triangular whitenization weight function (CCTWF). This model can be summarized as follows: firstly, defining the triangular whitenization weight function based on panel data by CCTWF; secondly, counting the clustering weight of each index by improving the method based on maximizing the weighted sum of squares; thirdly, determining the grey time clustering weight in different time points; finally, we get the grey synthetical clustering coefficient matrix, and we obtain the grey clustering results of each criterion according to the principle of selecting the maximum value of synthetical clustering coefficients.

Compact-center-point triangular whitenization weight function: The conventional triangular whitenization weight function has some defects in practical application, such as the confused crossing properties of a grey cluster and non-standard rules for choosing end-points. In order to solve these uncertainty and random problems, according to Wang et al. (2015), the compact-center-point triangular whitenization weight function method is used to evaluate the SWRCC of each region. This CCTWF method, based on the panel data, involves two basic steps.

We assume that $X^{(1)}(j)$ represents the values of object i for clustering index j under time points t, and that $n\times T$ is the number of values.

Step 1: By clustering the object i into different grey clusters of S, and classifying all observation values for clustering index j according to the definition of quantiles, we can get the grey center points $\lambda_j^1,\lambda_j^2,\cdots,\lambda_j^s$ of the index. Then we extend the grey cluster in left-right directions, and add center points λ_j^0, λ_j^{s+1} to form a new center of sequence $\lambda_j^0,\lambda_j^1,\cdots,\lambda_j^{s+1}$.

Step 2: Let $b_j^k=\frac{\lambda_j^{k-1}+\lambda_j^k}{2}$, $k=1,2,\cdots,s$, and assuming that $\alpha_k=\min\left\{b_j^{k+1}-\lambda_j^k,\lambda_j^{k+1}-\lambda_j^k\right\}$, $\beta_k=\min\left\{\lambda_j^k-b_j^k,\lambda_j^k-\lambda_j^{k-1}\right\}$, then the grey interval of the grey cluster k is given by $\left[(c_k)_j^k,(c_k)_j^{k+1}\right]=\left[\lambda_j^k-\beta_k,\lambda_j^k+\alpha_k\right]$. Specifically, if $\lambda_j^k=\frac{b_j^k+b_j^{k+1}}{2}$, we can get $(c_k)_j^k=b_j^k$, $(c_k)_j^{k+1}=b_j^{k+1}$. When $k=1$, $f_j^1\left[-,-,\lambda_j^1,(c_1)_j^2\right]$ is the whitening weight function of the lower limit measure; when $k=s$, $f_j^s\left[(c_s)_j^s,\lambda_j^s,-,-\right]$ is the whitening weight function of the upper limit measure; and when $k=2,3,\cdots,s-1$, let $\left[(c_k)_j^k,(c_k)_j^{k+1}\right]$ be the grey interval of the grey cluster k, connecting points $\left((c_k)_j^k, 0\right)$, $\left(\lambda_j^k, 1\right)$ and $\left((c_k)_j^{k+1}, 0\right)$, we can define the triangular whitenization weight function of the clustering index *j* under the time point *t* belonging to the grey cluster *k* as $f_{ij}^k\left(x_{ij}^t\right)$, $k = 1, 2, ..., s$, $i = 1, 2, ..., n$, $j = 1, 2..., m$ and $t = 1, 2..., T$. Fig. 1 shows a sketch of the construction of the CCTWF.

For the observation value x_{ij}^t of the index *j* under the time point *t*, we can calculate $f_{ij}^k\left(x_{ij}^t\right)$, $k = 1, 2, ..., s$, $i = 1, 2, ..., n$, $j = 1, 2..., m$ and $t = 1, 2..., T$. This equation is expressed as:

$$f_{ij}^k\left(x_{ij}^t\right) = \begin{cases} 0, & x_{ij} \notin \left[(c_k)_j^k, (c_k)_j^{k+1}\right] \\ \dfrac{x_{ij}^t - (c_k)_j^k}{\lambda_j^k - (c_k)_j^k}, & x_{ij} \in \left[(c_k)_j^k, \lambda_j^k\right) \\ \dfrac{(c_k)_j^{k+1} - x_{ij}^t}{(c_k)_j^{k+1} - \lambda_j^k}, & x_{ij} \in \left[\lambda_j^k, (c_k)_j^{k+1}\right] \end{cases} \quad ...(6)$$

Grey indicator clustering weight: The grey indicators' clustering weights reflect the importance of an indicator, and have a great impact on the clustering results. If $V_j(W_i)^2$ is the weighted sum of squares of the whitening weight function value, it can be described as follows:

$$V_j(W_i)^2 = \sum_{k=1}^{s} V_j^k(W_i)^2 = \sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)w_{ij} \quad ...(7)$$

Where, $W_i = (w_{i1}, w_{i2} \cdots, w_{ij})$ is the non-normalization clustering weights vector of research region *i* and meets $\sum_{j=1}^{m} w_{ij}^2 = 1$. Here, V_i^k represents the sum of squares between the compact-center-point triangular whitenization weight function f_{ij}^k and f_{ij}^l , $l, k = 1, 2, \cdots, s$.

Let V_i^2 be the weighted sum of squares of the whitening weight function values for *m* indicators; it's formula is $V_i^2 = \sum_{j=1}^{m} V_j(W_i)^2 = \sum_{j=1}^{m}\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)^2 w_{ij}$. Assuming that D_i^2 denotes the *m* dimensional vector, the vector can be defined as

$$D_i^2 = \left[\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{i1}^k - f_{i1}^l)^2, \ \sum_{k=1}^{s}\sum_{l=1}^{s}(f_{i2}^k - f_{i2}^l)^2, ..., \ \sum_{k=1}^{s}\sum_{l=1}^{s}(f_{im}^k - f_{im}^l)^2\right].$$

Therefore, V_i^2 can be further expressed as $V_i^2 = D_i^2 W_i$. According to the requirements of maximizing deviations, we propose the optimal model in Equation (8):

$$\max F(W_i) = \max V_i^2 = D_i^2 W_i \quad ...(8)$$

$$s.t. \begin{cases} W_i^T W_i = 1 \\ W_i \geq 0 \end{cases}$$

Then, we construct the Lagrange function in Equation (9):

$$L(W_i) = D_i^2 W_i + \lambda(W_i^T W_i - 1) = \sum_{j=1}^{m}\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)^2 w_{ij} + \lambda(\sum_{j=1}^{m} w_{ij}^2 - 1) \quad ...(9)$$

Where λ is a random coefficient and $i = 1, 2, ..., n$, $j = 1, 2..., m$, $l, k = 1, 2, \cdots, s$.

Let $\dfrac{\partial L}{\partial w_{ij}} = \sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)^2 + 2w_{ij}\lambda = 0$. By solving the optimal model, we can get the non-normalization clustering weight w_{ij} , which is presented in Equation (10):

$$W_i = (w_{i1}, w_{i2} \cdots, w_{ij}) =$$

$$\left[\frac{\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{i1}^k - f_{i1}^l)^2}{\sqrt{\sum_{j=1}^{m}\left[\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)^2\right]^2}}, \frac{\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{i2}^k - f_{i2}^l)^2}{\sqrt{\sum_{j=1}^{m}\left[\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)^2\right]^2}}, ..., \frac{\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{im}^k - f_{im}^l)^2}{\sqrt{\sum_{j=1}^{m}\left[\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)^2\right]^2}}\right] \quad ...(10)$$

After the normalization of w_i , η_i is expressed in Equation (11):

$$\eta_i = (\eta_{i1}, \eta_{i2}, \eta_{i3}, ..., \eta_{ij}) =$$

$$\left[\frac{\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{i1}^k - f_{i1}^l)^2}{\sum_{j=1}^{m}\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)^2}, \frac{\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{i2}^k - f_{i2}^l)^2}{\sum_{j=1}^{m}\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)^2}, ..., \frac{\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{im}^k - f_{im}^l)^2}{\sum_{j=1}^{m}\sum_{k=1}^{s}\sum_{l=1}^{s}(f_{ij}^k - f_{ij}^l)^2}\right] \quad ...(11)$$

Where η_{ij} denotes the grey clustering weights vector of indicator *j* for the research region *i*, and f_{ij}^k represents the CCTWF of indicator *j* belonging to the grey cluster *k* at the time point *t* , $i = 1, 2, ..., n$, $j = 1, 2..., m$, $l, k = 1, 2, \cdots, s$.

Grey Time Clustering Weight: The grey time clustering weight illustrates the time dimension of the panel data. In this study, we propose an objective method for determining the clustering time coefficient. The smaller the distance between the cross-sectional data matrix and the ideal point matrix at a certain point in time, the greater the weight. For the two-dimensional matrix $X^{(0)}(t)$, the ideal point for each subject can be defined as $x_{ij}^0 = \max\limits_{1\le t\le T} x_{ij}^t$. We can calculate the distance d_t between the normalized value and the ideal point at each time point by using Equation (12):

$$d_t = \sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}(x_{ij}^t - x_{ij}^0)^2},\ t = 1,2,...,T \qquad ...(12)$$

Then, according to the distance d_t, w_t can be measured by Equation (13):

$$w_t = \frac{\frac{1}{1+d_t}}{\sum_{t=1}^{T}\frac{1}{1+d_t}},\ t = 1,2,...,T \qquad ...(13)$$

Where w_t is the clustering time coefficients at each time point. Obviously, the higher value of d_t shows the greater grey time clustering weight. The grey time clustering weight of different time points can be presented as $W = [w_1, w_2, ..., w_T]$. Clearly, each w_t satisfies the relationship that $\sum_{t=1}^{T} w_t = 1$.

Calculation of integrated clustering coefficients: According to the grey indicator clustering weight and grey time clustering weight obtained from the above equations, the clustering coefficients matrix $\sum_i$ of the object *i* belonging to the grey cluster *k* in *T* time points can be presented as in Equation (14):

$$\left[\sum\nolimits_i\right]_{T\times s} = \begin{bmatrix} \sigma^{(1)} \\ \sigma^{(2)} \\ \vdots \\ \sigma^{(T)} \end{bmatrix} = \begin{bmatrix} \sigma_i^{1(1)} & \sigma_i^{2(1)} & \cdots & \sigma_i^{s(1)} \\ \sigma_i^{1(2)} & \sigma_i^{2(2)} & \cdots & \sigma_i^{s(2)} \\ \cdots & \cdots & \cdots & \cdots \\ \sigma_i^{1(T)} & \sigma_i^{2(T)} & \cdots & \sigma_i^{s(T)} \end{bmatrix} \qquad ...(14)$$

Where, $\sigma_i^{s(T)} = f_{ij}^k \cdot \eta_i$, f_{ij}^k is the CCTWF of the clustering indicator *j* belonging to the grey cluster *k* at the time point *t*, and η_i is the weight vector of the object *i*. $\sigma^{(T)}$ denotes the clustering coefficients vector of the object *i* belonging to the grey cluster *k* in *T* time points, and $k = 1,2,...,s$, $i = 1,2,...,n$, $j = 1,2...,m$ and $t = 1,2...,T$. Then, we can determine the integrated clustering coefficients of object *i* belonging to the grey cluster *k* by using Equation (15):

$$\sigma_i^{\sum i} = W \bullet \sum\nolimits_i = \left[\sigma_i^1 \quad \sigma_i^2, ..., \quad \sigma_i^k\right],$$
$$i = 1,2,...,n, k = 1,2,...,s \qquad ...(15)$$

When $\max\limits_{1\le k\le s}\{\sigma_i^k\} = \sigma_i^k$, it can be judged that the object *i* belongs to the grey cluster *k*, which means we can determine the grey clustering result of object *i* by choosing the maximal element of its integrated clustering coefficients. If two or more objects belong to the grey cluster *k*, we can sort these objects and judge the priority of each by analysing the size of its integrated clustering coefficients.

EMPIRICAL STUDY

Data Source

The study area is Qinghai Province (89°35'-103°04'E, 31°9'-39°19'N), China. Qinghai is one of the important provinces in western China, with a land area of 721,000 km². It is composed of eight administrative districts: Xining City (XN), Haidong City (HD), Yushu Tibetan Autonomous Prefecture (YS), Haixi Prefecture (HX), Haibei Prefecture (HB), Hainan Prefecture (HN), Huangnan Prefecture (HGN), Golog Prefecture (GL), as shown in Fig. 2. According to the corresponding indexes, we select eight of the province's administrative districts as gray time clustering objects, and the clustering time is from year 2011 to 2015. The relevant data of water resources are derived from the Qinghai Water Resources Bulletin. The relevant socio-economic data come from the Qinghai Statistical Yearbook (2011-2015), as well as the Qinghai Statistical Subdivisions of the National Economic and Social Development (2011-2015).

According to "Three Red Lines" quantitative indicator system, this study selects 12 indicators, including controls over total water consumption, water use efficiency and water quality. According to the corresponding data, we select eight of the province's administrative districts as gray time clustering objects, and the clustering time is from year 2011 to 2015. The relevant data of water resources are derived from the Qinghai Water Resources Bulletin. The relevant socio-economic data comes from the Qinghai Statistical Yearbook, as well as the Qinghai Statistical Subdivisions of the National Economic and Social Development. The observed values for the 12 indicators between 2011 and 2015 are shown in Table 2.

Calculation of SWRCC

To facilitate the evaluation of water resources for Qinghai Province, the SWRCC is divided into three grades. I represents that regional SWRCC is weak, and the development potential is so small that continuing to develop water resources will threaten the environment. III represents that regional SWRCC is strong, and the potential for further development is great. II is between I and III, and indicates that, although the development and utilization of water

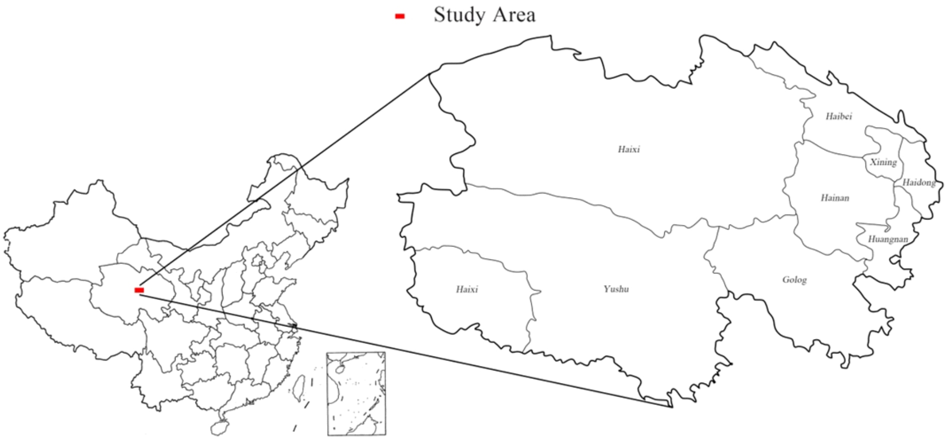


Fig. 2. Location of the study area.

resources have reached a certain scale, there is a certain potential for development and utilization.

Based on the initial data of indexes in Table 2, the initial multi-index panel data matrices are normalized first. After the normalization, we can calculate $f_{ij}^{k}\left(x_{ij}^{t}\right)$ of 12 indexes for the eight administrative districts from 2011 to 2015. For example, the CCTWF of Xining City (XN) and Haidong City (HD) can be expressed as follows:

$$f_1^1=\begin{cases}0 & ,x\notin[0.135,0.675]\\ \dfrac{x-0.135}{0.47-0.135},x\in[0.135,0.47] \\ \dfrac{0.675-x}{0.675-0.47},x\in[0.47,0.675]\end{cases};\ f_1^2=\begin{cases}0 & ,x\notin[0.675,0.94]\\ \dfrac{x-0.675}{0.88-0.675},x\in[0.675,0.88] \\ \dfrac{0.94-x}{0.94-0.88},x\in[0.88,0.94]\end{cases};\ f_1^3=\begin{cases}0 & ,x\notin[0.94,1.1]\\ \dfrac{x-0.94}{1-0.94},x\in[0.94,1] \\ \dfrac{1.1-x}{1.1-1},x\in[1,1.1]\end{cases}$$

$$f_2^1=\begin{cases}0 & ,x\notin[0.35,0.945]\\ \dfrac{x-0.35}{0.9-0.35},x\in[0.35,0.9] \\ \dfrac{0.945-x}{0.945-0.9},x\in[0.9,0.945]\end{cases};\ f_2^2=\begin{cases}0 & ,x\notin[0.945,0.995]\\ \dfrac{x-0.945}{0.99-0.945},x\in[0.945,0.99] \\ \dfrac{0.995-x}{0.995-0.99},x\in[0.99,0.995]\end{cases};\ f_2^3=\begin{cases}0 & ,x\notin[0.995,1.1]\\ \dfrac{x-0.995}{1-0.995},x\in[0.995,1] \\ \dfrac{1.1-x}{1.1-1},x\in[1,1.1]\end{cases}$$

According to the values of CCTWF, using Equation (11), we can acquire the 12 grey indicators clustering weights for the 8 administrative districts between 2011 and 2015. Table 3 shows the grey indicators' clustering weights in the year 2015.

Then, according to Equation (12), the grey time clustering weight $W=\left[0.212,0.205,0.197,0.211,0.175\right]$ can be obtained by calculating the distance between the normalized value and the ideal point at each time point. Finally, calculating the integrated clustering coefficients between 2011 and 2015, using Equations (14) - (15), we can acquire the results of SWRCC (Table 4). The results of each principle are shown in Table 5.

Then, according to Tables 4 and 5, the spatial distribution of SWRCC under the "Three Red Lines" and each principle in the 8 districts are shown in Fig. 3.

Analysis of Results

In Table 4 and Fig. 3a, the eight administrative divisions in Qinghai Province are ranked according to their SWRCC, arranged in the order of smallest to largest, namely Xining, Haidong, Hainan, Huangnan, Haixi, Haibei, Golog and Yushu. The SWRCC, of all other divisions are bigger than those of Xining, Haidong and Hainan, and have certain development potential. The SWRCC values for Xining, Haidong and Hainan are 0.484, 0.490 and 0.823, respectively, and belong to grade I, which means that the SWRCC of the three regions has reached the point of saturation. In other words, further development of Xining, Haidong and Hainan will lead to local water shortage, restricting the local economic growth, so appropriate measures should be taken in the future. The SWRCC of Huangnan, Haixi and Haibei belong to grade II, representing that the development and utilization of water resources in the three regions have reached a certain level, but there is still a certain potential for development and utilization. The SWRCC of Golog and Yushu are 0.799 and 0.834, respectively, showing that their water resource development is still at the initial stage and the water supply situation is more optimistic.

In Table 5 and Fig. 3b, under the principle of total water consumption, we can find that the water withdrawal of Xining, Haidong, Hainan and Haixi has reached or exceeded the control indicators. It is urgent that these regions reduce their groundwater overdrafts and realize the water resources balance. In contrast, the water resource development and utilization levels of Golog and Yushu are not high, so there is still a large potential. In Table 5 and Fig. 3c, the water use efficiency of Xining and Haidong is grade III, while the water use efficiency of Golog and Yushu is in grade I. This contrast reflects that water-use efficiency is related to the

Table 2: The index values of SWCC in Qinghai Province.

Districts	Year	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}	h_{11}	h_{12}
XN	2011	32.00	33.18	0.06	8.47	50.00	58.00	653.00	0.35	332.00	13.32	70.09	74.10
	2012	24.60	16.89	0.06	8.35	28.00	60.00	528.00	0.38	230.00	9.63	70.80	75.00
	2013	37.91	34.48	0.05	8.27	27.00	61.00	523.00	0.41	238.00	17.08	71.00	80.00
	2014	22.72	22.52	0.07	8.18	25.00	63.00	521.00	0.44	245.00	6.67	72.00	81.74
	2015	33.00	20.21	0.06	8.08	28.00	65.00	534.00	0.46	247.00	7.97	75.00	93.47
HD	2011	56.08	13.54	0.07	7.55	71.00	47.00	744.00	0.26	451.00	4.29	54.00	65.00
	2012	30.58	5.05	0.07	7.40	28.00	50.00	651.00	0.27	389.00	1.76	55.70	67.00
	2013	37.21	9.47	0.10	7.30	21.00	50.00	651.00	0.29	382.00	2.75	56.00	69.90
	2014	28.56	8.87	0.11	7.25	28.00	55.00	518.00	0.33	351.00	2.07	56.00	74.00
	2015	35.91	9.09	0.08	7.00	34.00	55.00	482.00	0.35	357.00	2.22	58.00	87.00

Note: Due to the limited space, all panel data in Qinghai Province are not listed.
Data source: Qinghai Water Resources Bulletin (2011-2015), Qinghai Statistical Yearbook (2011-2015) and Qinghai Statistical Subdivisions of the National Economic and Social Development (2011-2015).

Table 3: Grey indicator clustering weight in the year 2015.

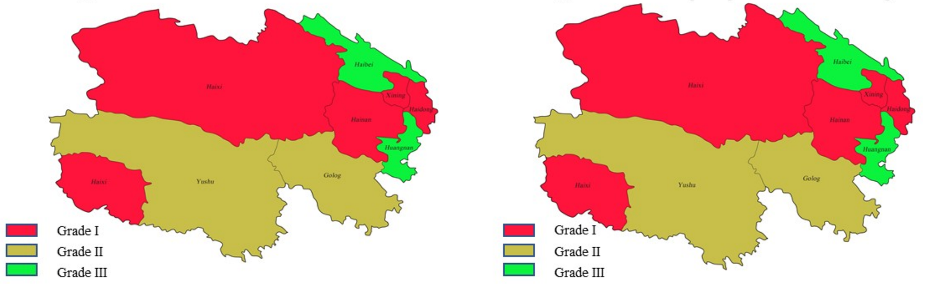
Districts	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}	h_{11}	h_{12}
XN	0.000	0.000	0.335	0.006	0.099	0.001	0.400	0.000	0.159	0.000	0.000	0.000
HD	0.000	0.022	0.121	0.133	0.065	0.163	0.000	0.165	0.044	0.087	0.165	0.033
HB	0.136	0.127	0.038	0.069	0.157	0.148	0.117	0.025	0.098	0.002	0.083	0.000
HN	0.000	0.091	0.000	0.034	0.018	0.031	0.209	0.000	0.214	0.192	0.004	0.206
HGN	0.021	0.003	0.008	0.176	0.284	0.025	0.000	0.096	0.000	0.121	0.035	0.232
GL	0.168	0.170	0.000	0.008	0.000	0.167	0.000	0.045	0.127	0.171	0.017	0.128
YS	0.164	0.132	0.000	0.010	0.000	0.161	0.000	0.003	0.089	0.164	0.121	0.156
HX	0.125	0.225	0.003	0.044	0.023	0.035	0.000	0.296	0.000	0.229	0.020	0.000

Table 4: Evaluation results of SWRCC in Qinghai Province.

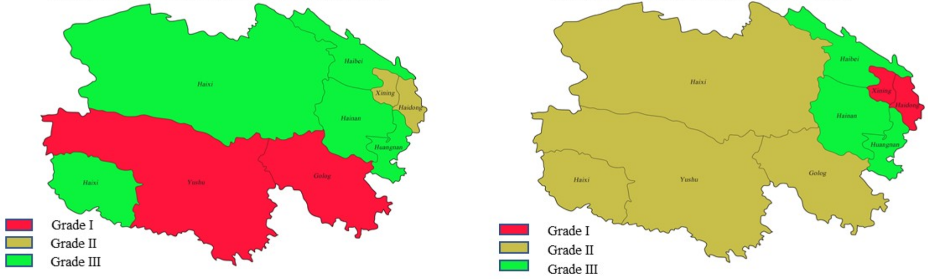
	σ_i^1	σ_i^2	σ_i^3	$\max \sigma_i^s$	grade
XN	0.484	0.361	0.012	σ_1^1	I
HD	0.490	0.129	0.193	σ_2^1	I
HB	0.185	0.574	0.078	σ_3^2	II
HN	0.823	0.344	0.008	σ_4^1	I
HGN	0.233	0.345	0.110	σ_5^2	II
GL	0.023	0.037	0.799	σ_6^3	III
YS	0.030	0.034	0.834	σ_2^3	III
HX	0.253	0.489	0.038	σ_8^2	II

Table 5: Evaluation results of three principles in Qinghai Province.

Districts	Total water consumption			grade	Water use efficiency			grade	Water quality			grade
	σ_i^1	σ_i^2	σ_i^3		σ_i^1	σ_i^2	σ_i^3		σ_i^1	σ_i^2	σ_i^3	
XN	0.294	0.100	0.059	I	0.036	0.011	0.190	III	0.072	0.021	0.016	I
HD	0.514	0.027	0.102	I	0.035	0.129	0.270	III	0.139	0.01	0.080	I
HB	0.002	0.354	0.110	II	0.094	0.194	0.073	II	0.091	0.026	0.005	II
HN	0.092	0.016	0.015	I	0.205	0.304	0.008	II	0.114	0.143	0.072	II
HGN	0.024	0.130	0.028	II	0.179	0.180	0.082	II	0.054	0.065	0.020	II
GL	0.002	0.014	0.322	III	0.429	0.002	0.129	I	0.019	0.021	0.048	III
YS	0.003	0.010	0.368	III	0.416	0.080	0.017	I	0.027	0.034	0.049	III
HX	0.154	0.146	0.032	I	0.100	0.341	0.001	II	0.008	0.141	0.376	III


(a) SWRCC under the "Three Red Lines"

(b) SWRCC under the principle of total water consumption


(c) SWRCC Under the principle of water use efficiency

(d) SWRCC Under the principle of water quality

Fig. 3: Spatial distribution of SWRCC of 8 districts in Qinghai Province.

level of socio-economic development, and the higher the level of socio-economic development, the higher the water-use efficiency. In Table 5 and Fig. 3d, under the principle of water quality, Xining and Haidong have the worst water pollution situation (grade I). In addition, the present condition of water pollution in Huangnan, Hainan and Haibei is far from encouraging. Conversely, the water quality of Haixi, Golog and Yushu is better.

CONCLUSIONS

Building on the Most Stringent Water Resources Management System, this paper has further defined the concept of WRCC to specify the strictest water resources carrying capacity. Based on these concepts, the index system under the restraint of "Three Red Lines" has been proposed. Furthermore, through considering the time influencing factors in SWRCC, this research presents a grey time clustering evaluation model based on panel data. By means of empirical analysis of data for Qinghai Province during the period 2011 to 2015, the following preliminary conclusions are drawn:

Firstly, there is much space to develop the area's water resources. The model evaluating SWRCC for Qinghai Province provides an important reference and a theoretical basis for similar studies in other western regions of China. It also contributes to the implementation of MSWRMS and the "Three Red Lines" in China.

Secondly, the development and utilization of regional water resources in Qinghai are unbalanced, and the distribution of regional SWRCC is irregular. Among the eight administrative districts, the SWRCC of Xining, Haidong and Hainan are weak, and all belong to grade I. If these regions continue to develop their water resources, their environment will be threatened. Although the SWRCC in Yushu and Golog is the highest, the economic development of the two areas is in a backward stage. On the basis of maintaining water security, it is necessary to further accelerate the speed of socio-economic development in Yushu and Golog and make full use of the resource advantages of the two regions to maximize the benefits of the water resources system.

Finally, the total water consumption, water use efficiency and water quality in Qinghai Province still need to be improved. The empirical results show that the areas with large water consumption, such as Xining and Haidong, should strictly implement the MSWRMS and adjust their proportion of industrial water use. In contrast, the areas with little water consumption, such as Haibei, Yushu and Golog, should accelerate their pace of local socio-economic development. Increasing water resources development and utilization in the future will be a key development direction for these regions. Overall, except for Xining and Haidong, the water use efficiency of the districts is still low. Especially in the Qaidam Basin of Haixi Prefecture, as a key development area in the government plan, water consumption is growing quickly. It is essential for Qaidam to rationally plan its industrial and agricultural layout, increase water-saving facilities, and improve water use efficiency. In addition, due to the rapid economic development of Xining and Haidong, their water pollution situation is getting worse and worse, so the waste water discharge should be controlled as soon as possible.

It should be noted that any regional water resources assessments should follow national or regional policies and be combined with the socio-economic development in the region. Therefore long-term research and phased analysis will be required in the future. Constrained as we are by data and model limitations, this study does not display the temporal diversification of regional SWRCC. Further work on these aspects remains to be carried out.

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