Evaluation of Carrying Capacity on Water Resources Based on Improved Water Footprint Method

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Abstract. A water footprint based principal component analysis method (WFPCA) has been proposed for evaluation of carrying capacity on water resources. The evaluation indexes can be defined based on the water footprint theory. Then the comprehensive evaluation value of water resources carrying capacity can be generated by the method of principal component analysis. The developed WFPCA method has been applied in the case study in Tongliao City, China. The results show that the indexes defined based on the water footprint theory can reflect the interactions between human being activities and water resources systems. The readjustment of water utilization structure affects the practical water use and the virtual water footprint in Tongliao City. The comparison of comprehensive evaluation values from 2010 to 2019 indicates that the water resources carrying capacity in Tongliao City continues to increase, which is benefited from the reasonable planning of water resources systems and the effective management of environment systems.

1. Introduction
The carrying capacity on water resources is an important index for measuring the match level between economic development and water management[1]. Many methods have been developed for the evaluation of water resources carrying capacity, such as the methods of fuzzy comprehensive evaluation, multi-objective analysis, artificial neural network and principal component analysis, et al[2]. Among them, the principal component analysis method (PCA) has been widely used. There is a relatively objective criterion to determine the weight of indexes, and the dimension of high variant space for data sample can be lower by using the PCA method[3]. However, the real water resources demands, which correspond to the consumptions of residents, could not be properly reflected.

The water footprint theory was proposed based on the theories of water resources and ecological footprint[4]. The advantage of water footprint theory is that it can reflect the demands and occupations of water resources for social, economic and environmental systems. Therefore, this paper would combine the water footprint theory and the PCA method into a general framework for evaluating water resources carrying capacity in Tongliao City, China.

2. Methodology

2.1. Water Footprint Theory
The bottom-up method is used for calculation of water footprint (WFP, m³), which can be regarded as directly and indirectly water used for goods production and inhabitants consumption [4]. The components of WFP are practical water use (WU, m³) and virtual water footprint (VWF, m³):

\[
WFP = WU + VWF
\]
\[ WFP = WU + VWF. \]  
(1)

\[ WU = IWU + DWU + EWU \]
(2)

\[ VWF = \sum_{i} C_i \times VWF_i \]
(3)

where \( IWU \), \( DWU \) and \( EWU \) are industrial, domestic and environmental water use, respectively (m\(^3\)). \( C_i \) is the consumption for agricultural product \( i \) (kg). \( VWF_i \) is the unit virtual water footprint for agricultural product \( i \) (m\(^3\)/kg).

### 2.2. Water footprint based principal component analysis method

In this study, a water footprint based principal component analysis method (WFPCA) would be proposed combining the water footprint theory and the PCA method into a general framework to evaluate the carrying capacity on water resources. Based on the water footprint theory, the evaluation indexes can be defined.

(a) Average water footprint per capita (\( WFP_{pc} \), m\(^3\)/cap):

\[ WFP_{pc} = \frac{WFP}{TP} \]
(4)

where \( TP \) is the total population. The index shows the capacity on water resources for supporting population.

(b) Average water footprint per area (\( WFP_{pa} \), m\(^3\)/km\(^2\)):

\[ WFP_{pa} = \frac{WFP}{TA} \]
(5)

where \( TA \) is the total area (km\(^2\)). The index shows the water resources carrying capacity per area.

(c) Rate of water footprint variation (\( WFPR \), \%):

\[ WFPR = \frac{WFP_2 - WFP_1}{WFP_1} \times 100\% \]
(6)

where \( WFP_2 \) and \( WFP_1 \) are the current and the previous values of water footprint, respectively (m\(^3\)). The index shows the variations in water resources.

(d) Water footprint efficiency (\( WFPE \), $/m^3$):

\[ WFPE = \frac{GDP}{WF} \]
(7)

where \( GDP \) is the gross domestic product ($).

(e) Rate of environmental water use (\( EWUR \), \%):

\[ EWUR = \frac{EWU}{WFP} \times 100\% . \]
(8)

The index shows the emphasis given to environment.

(f) Rate of water waste (\( WWR \), \%):

\[ WWR = \frac{WW}{WFP} \times 100\% . \]
(9)

where \( WW \) is the water waste (m\(^3\)). The index shows the degree of effective utilization for water resources.

(g) The water resources pressure (\( WP \), \%):

\[ WP = \frac{WFP}{AW} \times 100\% , \]
(10)

where \( AW \) is the available water resources. These indexes can reflect the impact of water resources carrying capacity on social, economic and environmental systems. \( WFP_{pc} \), \( WFP_{pa} \) and \( WFPR \) are
indexes related to social system. \(WFPE\) is an index related to economic system. \(EWUR\), \(WWR\) and \(WP\) are indexes related to social systems.

The indexes are defined based on the water footprint theory. Then the comprehensive evaluation value can be generated by the PCA method, whose principle is to lower the dimension of high variant space for data sample. The procedure of PCA can be shown in Figure 1.

\[
\text{Standardization for sample data } X = [X_1, X_2, \ldots, X_p]^T.
\]

\[
\text{Calculation for correlative coefficient matrix } R,
\]

\[
\text{Calculation and sort for eigenvalue } \lambda \text{ and eigenvector } \mu,
\]

\[
\text{Calculation for contribution rate and accumulative contribution rate } e_i,
\]

Select \(z_1, z_2, \ldots, z_p(z_j) = \mu_1 x_1 + \mu_2 x_2 + \ldots + \mu_p x_p\) as principal component,

\[
\text{Calculation for weight of principal component } \omega_i = \lambda_i / \sum_{j=1}^{p} \lambda_j (j = 1, 2, \ldots, k),
\]

\[
\text{Calculation for comprehensive evaluation value } Z_i = \sum_{j=1}^{k} \omega_i z_i.
\]

**Figure 1.** The procedure of PCA

### 3. Application

#### 3.1. Case study

Tongliao City located at the east of Inner Mongolia. It plays an important role in promoting the joint-construction of the "Belt and Road" initiative[5]. The city belongs to semi-arid climate. The wettability ranges from 0.3 to 0.7. The annual precipitation ranges from 305mm to 485mm. There are 612 lakes in the city, with a total catchment area of 292.9 square kilometres and total water storage of 3.53 million cubic meters. In this study, the proposed WFPCA method would be applied to evaluate water resources carrying capacity in Tongliao City. The related data records from 2010 to 2019 are provided, reference to Statistical Yearbook of Tongliao City and Inner Mongolia Water Resources Bulletin.

#### 3.2. Results analysis

The change processes of total water resources, total water footprint and water resources pressure are shown in Figure 2. The total water footprint was pushed steadily higher from 2010 to 2019. The value of water resources pressure significant changes following the fluctuation of total water resources. For example, the total water resources reached highest in 2012 and lowest in 2011. The water resources pressure reached lowest in 2012, corresponding to relative abundant water resources. The water resources pressure reached highest in 2011, corresponding to relative insufficient water resources.
Moreover, the persistent high pressures of water resources from 2013 to 2015 and from 2017 to 2019 represent the high demand on water resources in Tongliao City.

![Figure 2](image.png)

**Figure 2.** The changes processes of water resources

The comparison between virtual practical water footprints is shown in Figure 3. The value of practical water use is decreasing on the whole, indicating a decreasing use of industrial, domestic and environmental water. The increasing value of virtual water footprint indicates an increasing value of agricultural products, which is particularly obvious in the case of total water footprint growth.

![Figure 3](image.png)

**Figure 3.** Comparison between the virtual water footprint and the practical water use

There are 7 indexes, shown from Equations (4) to (10) are selected for representing water resources carrying capacity in Tongliao City. Two principal components are defined. The corresponding load matrix of principal component is shown in Table 1. The principal component $z_1$ has significant positive correlations with indexes $WFP_{pc}$, $WFP_{pw}$, and $WFPE$, which can reflect the affection of social and economic factors for water resources. The principal component $z_2$ has significant positive
correlations with indexes $WFP_{pc}$, $WFP_{pa}$, $WFPE$, $EWUR$ and $WP$, which can reflect the affection of social, economic and environmental factors for water resources.

| Indexes | $z_1$ | $z_2$ |
|---------|-------|-------|
| $WFP_{pc}$ | 0.961 | 0.078 |
| $WFP_{pa}$ | 0.965 | 0.080 |
| $WFPR$ | -0.591 | -0.049 |
| $WFPE$ | 0.983 | 0.112 |
| $EWUR$ | -0.431 | 0.715 |
| $WWR$ | -0.957 | -0.186 |
| $WP$ | -0.192 | 0.844 |

The results of comprehensive evaluation are shown in Figure 4. The value of comprehensive evaluation continues to increase from 2010 to 2018. The fastest-growing segment is from 2017 to 2018, with the value of evaluation from 0.59 to 0.82. The value falls back after the significant rise. For its part, the water resources carrying capacity in Tongliao City is getting stronger in recent years. It profit from the reasonable planning of water resources and the effective management of environment. However, Tongliao City is still arid, required more attention than other regions with plenty of water supply.

![Figure 4. The comprehensive evaluation values](image)

4. Concluding Remarks
In this study, a WFPCA method has been proposed for evaluation of carrying capacity on water resources in Tongliao City, China. The following conclusions are drawn: (1) the indexes defined based on the water footprint theory can reflect the affection of social, economic and environmental factors
for water resources; (2) the persistent high pressures of water resources from 2013 to 2015 and from 2017 to 2019 represent the high demand on water resources in Tongliao City; (3) the agricultural products are increasing with the decreasing use of industrial, domestic and environmental water; (4) the carrying capacity on water resources in Tongliao City is getting stronger in recent years.

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