A novel system of indicators for evaluating system resilience of regional agricultural water resources

Dong Liu, Yang Ding, Qiang Fu, Dan Zhao, Muhammad Imran Khan, Tianxiao Li and Muhammad Abrar Faiz

ABSTRACT
Constructing a reasonable evaluation index system is important for characterizing water and land resources and for ecological restoration. To solve random and incomplete problems using a traditional evaluation index system, a novel model for evaluating regional agricultural water resources using a resilience index system was proposed. In addition, a new method for an evaluation index system and the filtering of key indicators were investigated. Based on the structural characteristics of a regional agricultural water resource system (AWRS), the model for an evaluation index system was built by constructing a hierarchical indicator architecture using a hierarchical framework model. The index weight was calculated using criteria importance through intercriteria correlation (CRITIC). Then, index completeness was ensured using principal component analysis, and the reliability of the results was tested using the analytic hierarchy process. The model was applied to the Jiansanjiang Administration of Agricultural Reclamation in Heilongjiang, China. The main results included the following: (1) the index was optimized from 46 to 32, which identified the key indicators that affect the resilience of the Jiansanjiang Administration AWRS, and (2) an evaluation index system was constructed with a completeness of 85.6%. The results of this study provide an important and practical model for studying the resilience of related resources and environmental fields.

Key words | agricultural water resource system, index system, resilience

INTRODUCTION

Water resources have become an increasingly important determinant of agricultural sustainability, especially in arid and semi-arid regions (Forouzani & Karami 2011). Supporting regional social economic sustainable development, agricultural water resources are the foundation of strategic resources and are becoming important limiting factors in grain production areas. Due to climate change and population increases, strong anthropogenic disturbances of agricultural water resource systems (AWRSs) have occurred. Therefore, increasing water scarcity and water pollution, decreasing water levels, land desertification, grassland degradation and other ecological and environmental problems have led to growing interest in resilience as an important dimension of socio-ecological sustainability (Maleksaeidi et al. 2015). The gradual degeneration of AWRSs has impacted and impaired agricultural sustainability. Moreover, fewer opportunities and the decline of regional societies have been identified. Thus, many researchers and policy-makers have considered improving the resilience of natural and social systems (SSs) to enhance the resilience of regional AWRSs (Mnisi & Dlamini 2012).
Resilience is defined as the capacity of a system to absorb disturbance and reorganize while changing to retain essentially the same function, structure, identity, and feedback mechanisms (Adger et al. 2011). Management is important because it can damage or increase resilience, depending on how the system re organizes in response to management activities (Folke et al. 2002). Although theoretical advancements have been made regarding resilience as a framework for sustaining the relationships between humans and the environment (Gunderson & Holling 2003), resilience is a concept that has not yet been operationalized (Cumming et al. 2005), and the utility of resilience for practical management remains underdeveloped (Olsson et al. 2004; Walker & Meyers 2004). Even in theory, as some authors (Berkes & Jolly 2000; Cumming et al. 2005) have stated, the thresholds between desirable and undesirable states and resilience are difficult to measure due to the complex and dynamic behaviours of systems over time and the multidimensional, abstract and complex nature of resilience, which make it difficult to operationalize. In fact, without a developing standard, it is often difficult to validate the calculations resulting from non-standard variables (Allen & Davis 2010).

Water resources affect diverse social-ecological systems; however, farm households, for which agricultural production is the primary source of direct and indirect employment and income, are the most affected by this critical natural resource (Ringler et al. 2010). An AWRS includes a large complex system and a semi-artificial ecosystem that encompasses society, economics, the environment, ecology and resources. In this large system, resilience is affected by natural, social, economic, and cultural factors, as shown in Figure 1. Therefore, an attempt to select indicators for each system and to develop a scale for assessing resilience in response to various disasters is an essential step in sustainability planning.

Selecting indicators for evaluating and constructing an indicator system is the most important and complex part of resilience evaluations of regional AWRSs. Attempts to select indicators and build an evaluation index system for assessing the resilience of water resource and related systems have been made in response to various disasters. Zhang et al. (2010) established the primary framework for an indicator evaluation system to study the basic meaning of the term Green Mine. Alessa et al. (2008) established an Arctic Water Resource Vulnerability Index to assess the relative vulnerability of communities or resilience to factors that affect freshwater resources at the watershed scale. De Carvalho et al. (2012) presented an information system for evaluating the indicators of an organization by people to develop a resilience monitoring system of organizations by using a computerized support system. Kotzee & Reyers (2016) used the principles of resilience outlined by Biggs et al. (2012) to guide the selection of variables for measuring flood resilience. Khalili et al. (2015) used the formative qualitative method referred to as the ‘Yin’ case study approach (Yin 1989) to identify social resilience indicators of communities to flooding. Speranza et al. (2014) proposed a framework for communicating with practitioners regarding the identification and improvement of the factors that build resilience and for monitoring the effectiveness of policies and practices aimed at building livelihood resilience. These studies focused on the evaluation method itself and paid very little attention to the construction of an evaluation index system, which is the foundation of any evaluation. Our study fills this gap by emphasizing the process of establishing and optimizing an evaluation index system for a regional AWRS.

The lack of an organized and standard metric for measuring the resilience of a regional AWRS and the fact of the capacity of the system to adapt to the adverse effects of decreasing natural resources determine the severity of the impacts and the adaptation costs. Studying a regional AWRS and using a standard scale to measure resilience is necessary.
to (1) identify indicators that affect the resilience of the system and (2) construct an evaluation index system.

**METHODOLOGY**

**Constructing the initial evaluation index system**

**Principles of constructing an indicator system**

A complete indicator system should be (1) systematic, (2) simple, (3) scientific, (4) generally comparable, and (5) operable (Lin et al. 2009).

**Determining the hierarchical indicator architecture**

The hierarchical framework (HF) model is used to determine the hierarchical indicator architecture that shows the hierarchy and relevance of the entire system. The highest level GI is also called the goal level, representing the resilience of the evaluation system. The middle layer AI is composed of several indicators that are necessary for realizing this goal, and each indicator is composed of different factors or links that form the next layer of the middle layer. The bottom layer RI is the specific index layer, which is composed of the specific indicators that are directly or indirectly related to the target, as shown in Figure 2 (Tu et al. 2012).

In Figure 2, the solid lines with arrows connect the total target and the middle level indicators of the next level, and the broken lines with arrows, which represent connections that may or may not exist between subsystems in different levels, connect the levels within the middle layer or connect the middle layer and a specific index layer.

**Principles of specific indicator selection**

The principles of a specific indicator selection are characterized by the following eight standards: measurability (M), vulnerability (V), predictability (P), typicality (T), controllability (C), integrity (I), responsibility (R), and stability (S) (Dale & Beyeler 2001). Integrity applies to the construction of the entire indicator system, and the remaining seven standards are requirements for selecting specific indicators (Lin et al. 2009).

**Optimizing the evaluation index system**

In this paper, a combination of CRITIC and principal component analysis (PCA) was applied to optimizing the evaluation index system to simplify the complex indicator system and improve the accuracy of the evaluation results.

**Constructing the relational matrix \( P_{jg} \)**

The relational matrix \( P_{jg} \) is constructed according to the hierarchical indicator architecture, where \( P \) represents an indicator’s relationship to the \( n \) layer and the \( n-1 \) layer, \( j \) is the \( j \)th indicator of the \( n-1 \) layer, and \( g \) is the \( g \)th indicator of the \( n \) layer. If \( j \) and \( g \) are associated, \( p_{jg} = 1 \); otherwise, \( p_{jg} = 0 \).

\[
P = \begin{bmatrix}
p_{11} & \cdots & p_{1g} \\
\vdots & \ddots & \vdots \\
p_{j1} & \cdots & p_{jg}
\end{bmatrix}
\] (1)

**Constructing the inclusion criteria matrix \( R_{g \times 7} \)**

According to the eight index inclusion standards, a linear \( g \times 7 \) inclusion criteria matrix is constructed to select and...
optimize the individual indicators as follows:

\[ R = \begin{bmatrix} r_{11} & \cdots & r_{17} \\ \vdots & \ddots & \vdots \\ r_{61} & \cdots & r_{67} \end{bmatrix} = [R_1, R_2, \cdots R_m, \cdots R_g]^T \]  

(2)

where \( g \) is the index of the \( n \)th layer, and 7 represents the seven index inclusion standards. When the index satisfies condition \( I \), \( r_g = 1 \); otherwise, \( r_g = 0 \).

To achieve balance between science and integrity (Lin et al. 2009), indicators that cannot meet the conditions are removed first. Next, indicators that meet five inclusion standards (MVTCS) are directly selected. The indicators falling between these two conditions are retained to improve resolution. A vector \( L \), which is based on the five inclusion standards, is constructed according to the above principles, where the items that meet the MVTCS are designated by 1 and the remaining items are designated by 0:

\[ L = [1, 1, 0, 1, 0, 1, 1] \]  

(3)

**Optimizing the index system**

To achieve completeness and simplicity requirements, the objective function can be set to

\[ \text{Min} Z = \sum_{m=1}^{g} r_m \]  

(4)

Additionally, the following constraints must be satisfied when the five index inclusion standards listed above are met. The evaluation index is selected as follows:

\[ r_m = 1 \text{ if } L \times R_m ^T \geq 5. \]  

(5)

If the \( m \)th value of the specific index layer is selected, \( r_m = 1 \); otherwise, \( r_m = 0 \).

To construct the vector \( R = [r_1, r_2, \cdots r_g] \) and ensure a link between the indicators, Equation (6), which indicates that the lower-level indicator and the upper-indicator are linked, must be satisfied.

\[ R \times P ^T > 0 \]  

(6)

To ensure the completeness of the index system, the weight of the index system must reach a certain accuracy, which is defined by Equation (7). This paper uses PCA, with 0.85 as a criterion for determining the completeness of the index:

\[ R \times W_{Ri} \geq 0.85 \]  

(7)

where \( W_{Ri} = [w_{R1}, w_{R2}, \cdots w_{Rg}] \) and the matrix \( W_{Ri} \) is composed of the weights of the specific indicators.

**STUDY REGION**

Heilongjiang Province is a major agricultural province, which is the important commodity grain base of China, and has made great contributions to the protection of national food security and modernization since the founding of new China. Great achievements have been made in the development of agriculture, while Heilongjiang Province has paid a heavy price in the aspects of ecology, resources and environment. In the process of developing agriculture, the excessive exploitation and utilization of agricultural resources leads to the degradation of agricultural elements, especially agricultural water resources. Predatory behaviours relying on agricultural resources and expanding extension to achieve the development and utilization of agricultural resources have led to a complete degradation of the factors that sustain the sustainable development of agriculture, especially in agricultural water resources. These problems are reflected in the Jiansanjiang Administration, so the paper chooses Jiansanjiang Administration as the study region. The Jiansanjiang Administration of Agricultural Reclamation in Heilongjiang, China, is located in the hinterland of the Sanjiang Plain between 46°49′47″–48°12′58″ (north latitude) and 132°31′38″–134°32′19″ (east longitude) and covers a total area of 12,300 km² (Liu et al. 2014). Fifteen medium- and large-sized state-owned farms (see Figure 3) and abundant water resources are under the jurisdiction of the Jiansanjiang Administration, which focuses on land use. The region has a mild and humid climate, flat terrain, and fertile soil, making it suitable for rice cultivation. Furthermore, the region is a base for green rice production in China and enjoys the title ‘China’s Green Rice City’. Due to the recent impacts of national food policy and the
econonomic benefits resulting from a stimulus, the cultivated
area devoted to rice production has increased, and rapid
increases in rice cultivation have increased the amount of
water required for farmland irrigation. Consequently, several
problems have occurred, including the over-exploitation of
groundwater, illogical land and water resource allocation,
and changes in land-use structure. Recognizing the resilience
of AWRSs, elucidating the ecosystem recovery mechanism
to realize the sustainability of a water resource system, and
correctly and scientifically allocating and utilizing limited
water resources have become topics of research in this
region to achieve sustainable water resource utilization and
development. Therefore, the exploration and analysis of
the factors that impact the resilience of a regional AWRS
and the construction of a complete resilience evaluation
index system for the regional AWRS that provides a scienti-
cfic basis for further exploration of the regional AWRS are
necessary.

DATA SOURCES

Thirty-seven indicators of the resilience of the water
resource system of the Jiansanjiang Administration were
evaluated using a CRITIC–PCA model. Evaluation indicator
monitoring data from 2005 to 2014 were obtained from the
Statistical Yearbook of the Jiansanjiang Administration of
Agricultural Reclamation in Heilongjiang.

RESULTS AND ANALYSIS

Original selection of evaluation index

Figure 2 shows that the construction of the evaluation
index system for the regional AWRS should begin with
the following four subsystems of interdependence and
interaction: the AWRS, the SS, the economic system
(ES), and the ecological environment system (EES).
Combined with a literature analysis (Yang & Yang
2008) and considering the practical conditions of the
Jiansanjiang Administration, a preliminary resilience
evaluation index system was constructed for a regional
AWRS that contained four levels and 46 indicators.
The actual significance of all the indicators was defined
according to eight standards for evaluating the standard
conformity accuracies of each indicator. The direction of
the data was also defined, which was ‘positive’ (P) or
'negative' (N) for each index relative to the target of the evaluation system (Zhang & Zheng 2015), as shown in Table 1.

All of the included indicators must meet the inclusion criteria. However, some problems can exist, e.g., the indicator system can be too large, the linear correlation between the indicators can be too large, etc. Therefore, to optimize the indicators, the indexes that do not meet the most important criteria, cannot be quantified, or are not sensitive or stable should be deleted. According to the results of a standard compliance assessment, nine indexes, including the Geology and Geomorphology, Infiltration Capacity, Amount of Surface Water Resource, Amount of Ground Water Resource, Water Conservancy Information, Engineering Renewal Rate, and Legal System Perfect Rate indexes, can be eliminated.

Construction of an evaluation index tree

The remaining 39 indicators were divided into the following four categories based on the guidelines provided in Figure 2 and the specific requirements of the Jiansanjiang Administration for the construction of a regional AWRS (Figure 4). The total target AWRS is the resilience of the AWRS of the Jiansanjiang Administration. The middle layer of the index includes two layers: the second layer consists of the AWRS, EES, SS and ES, and the third layer consists of the Agricultural Water Resource Condition System (AWRS$_1$), Utilization System (AWRS$_2$), Management System (AWRS$_3$), Water Pollution (EES$_4$), Environmental Treatment (EES$_5$), Population Resources (SS$_6$), Social Resources (SS$_7$), Water Economy (ES$_8$), and Social Economy (ES$_9$). The index layer includes Temperature ($R_1$), Evaporation($R_2$), the Recharge Modulus ($R_3$), Water Producing Coefficient ($R_4$), Amount of Water Resources Per Capita ($R_5$), Quantity of Water Resources Per Unit of Cultivated Land Area ($R_6$), Annual Precipitation ($R_7$), Total Amount of Water Resources ($R_8$), Water Resource Utilization Rate ($R_9$), Exploitable Modulus ($R_{10}$), Reservoir Occupancy ($R_{11}$), Water Facility Perfect Rate ($R_{12}$), Water Consumption Per Unit Area of Farmland ($R_{13}$), Domestic Water Quota ($R_{14}$), Million GDP Water Consumption ($R_{15}$), Unilateral Water Grain Output ($R_{16}$), Million People Having Water Conservancy Science and Technology Personnel ($R_{17}$), Annual Investment Growth Rate of Water Conservation Scientific Research Funds ($R_{18}$), Irrigation Rate ($R_{19}$), Water Resource Rate ($R_{20}$), Amount of Agro-Contaminant ($R_{21}$), Chemical Fertilizer Utilization Ratio ($R_{22}$), Amount of Industrial Waste Water Discharge ($R_{23}$), Urban Life Waste Water Emissions ($R_{24}$), Ratio of Sewage to Runoff ($R_{25}$), Vegetation Coverage ($R_{26}$), Environment Water Use Rate ($R_{27}$), Quota of Urban Green Land ($R_{28}$), Population Density ($R_{29}$), Out-migration Rate ($R_{30}$), Natural Growth Rate of the Population ($R_{31}$), Infield Rate ($R_{32}$), Public Satisfaction ($R_{33}$), Primary School Enrolment Rate ($R_{34}$), Doctors Per Million People ($R_{35}$), Unilateral Water GDP ($R_{36}$), Unilateral Output Value of Agricultural Water Supply ($R_{37}$), Per Capita GDP ($R_{38}$), and Farm Family Per Capita Net Income ($R_{39}$).

Determining the index weight through CRITIC

Weight determination is an area of focus and is a difficult part of any multi-target evaluation and decision-making method because different target weight distributions can cause large differences in evaluation results and no generally accepted method exists for determining the weights. The weighting methods that are commonly used for the evaluation index (i.e., the expert evaluation method and analytic hierarchy process (AHP)) are very subjective and easily lead to deviations in the evaluation results. The CRITIC method is used for determining the objective weights based on the quantification of two fundamental notions of MCDM: the contrast intensity and the conflicting characteristics of the evaluation criteria (Diakoulaki et al. 1995). The CRITIC method is used to determine the index weight when determining the objective attributes of the index weight, which are shown in Table 2.

Optimization and selection of the evaluation index system

Combined with Equation (2) and the evaluation index tree of the agricultural water resources of the Jiansanjiang
### Table 1 | The standard conformity accuracy and direction of the indicators

<table>
<thead>
<tr>
<th>System</th>
<th>Subsystem</th>
<th>Index</th>
<th>Meaning and calculation formula</th>
<th>Standard conformity accuracy</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWRS</td>
<td>Agricultural Water Resource Condition System</td>
<td>Temperature</td>
<td>Characterizes the evaporation of water (°C).</td>
<td>MVPTS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geology and Geomorphology</td>
<td>Regional topographic features.</td>
<td>MTS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaporation</td>
<td>Characterizes the amount of water entering the air by evaporation (10^5 m³).</td>
<td>MVPTS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Infiltration Capacity</td>
<td>Characterizes the amount of water that infiltrates into the soil (10^5 m³).</td>
<td>MPR</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Recharge Modulus</td>
<td>Total amount of recharging water per unit area (10^4 m³/km²). Area of water resources per unit area.</td>
<td>MPTCS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water Producing Coefficient</td>
<td>(Annual precipitation × Area)/Total amount of water resources (%). Precipitation conversion rate.</td>
<td>MPTCRS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amount of Water Resources Per Capita</td>
<td>Total amount of water resources/Population quantity (10^4 m³/person). Per capita water resources in the region.</td>
<td>MPTCS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quantity of Water Resources Per Unit of Cultivated Land Area</td>
<td>Total amount of water resources/Cultivated land area (10^4 m³/km²). Unit cultivated land area water resources.</td>
<td>MPTCS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Annual Precipitation</td>
<td>Characterizes the source of water resources and aridity (mm).</td>
<td>MVPTR</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amount of Surface Water Resources</td>
<td>Dynamic replenishment of surface water by atmospheric precipitation (10^5 m³).</td>
<td>MTS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amount of Ground Water Resources</td>
<td>Shallow underground water that is directly related to surface water (10^8 m³).</td>
<td>MTS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Amount of Water Resources</td>
<td>The sum of the surface water and underground water quantities (10^8 m³).</td>
<td>MPTS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Utilization System</td>
<td>Water Resource Utilization Rate</td>
<td>Total water supply/Total amount of water resources (%). Exploitation degree of the water resource.</td>
<td>MVPTCS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exploitable Modulus</td>
<td>Total amount of exploiting water per unit area (10^4 m³/km²). Reflects the water supply situation per unit area.</td>
<td>MVPTCS</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reservoir Occupancy</td>
<td>Reservoir area per unit area (%). Development degree of water conservancy projects.</td>
<td>MVTCS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water Facility Perfect Rate</td>
<td>Undamaged water supply facilities/Total area of all water conservancy facilities (%).</td>
<td>MVPTCS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water Consumption Per Unit Area of Farmland</td>
<td>Farmland irrigation water quantity/Farmland irrigation area (10^4 m³/km²). Agricultural irrigation efficiency.</td>
<td>MVPTCS</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Domestic Water Quota</td>
<td>Total domestic water consumption/Resident population (m³/person). Residential water use efficiency.</td>
<td>MVPTCS</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Million GDP Water Consumption</td>
<td>Total water consumption/GDP (m³/10^4 RMB). Water economic relations.</td>
<td>MVPTCS</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unilateral Water Grain Output</td>
<td>Average grain yield per hectare relative to the irrigation quota (kg/m³).</td>
<td>MPTCS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>Management System</td>
<td>Million People Having Water Conservancy Science and Technology Personnel</td>
<td>Water conservancy proposed by scientific and technical personnel/Total population (population/10^6 people). Characterization of water conservancy science and technology.</td>
<td>MPTCS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water Conservancy Information</td>
<td>Index composed of computer, telephone penetration rate, disaster forecast monitoring system coverage, and office automation level.</td>
<td>PTS</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Annual Investment Growth Rate of Water Conservation Scientific Research Funds</td>
<td>Characterization of water conservancy (%).</td>
<td>MVPTCS</td>
<td>P</td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>System</th>
<th>Subsystem</th>
<th>Index</th>
<th>Meaning and calculation formula</th>
<th>Standard conformity accuracy</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation Rate</td>
<td>Water saving irrigation area/Effective irrigation area (%)</td>
<td>MVPTCS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engineering Renewal Rate</td>
<td>Characterization of the development of water conservancy projects (%)</td>
<td>PCS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legal System Perfect Rate</td>
<td>Based on a perfect management structure, whether to have application management regulations for comprehensive evaluations (%)</td>
<td>CS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Resource Rate</td>
<td>Characterizes the effective management of water resources (%)</td>
<td>MPCS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EES Water Pollution</td>
<td>Characterization of the pollution status of water resources in agricultural production (10^4 t)</td>
<td>MVPTCRS</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical Fertilizer Utilization Ratio</td>
<td>Fertilizer application rate/Farmland area (kg/hm²). Chemical fertilizer usage.</td>
<td>MPTCRS</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount of Industrial Waste Water Discharge</td>
<td>Characterization of the pollution status of water resources used in industrial production (10^4 t).</td>
<td>MVPTCS</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Life Waste Water Emission</td>
<td>Characterization of the pollution status of water resources used for urban life (10^4 t).</td>
<td>MVPTCS</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio of Sewage to Runoff</td>
<td>Waste water discharge/(Runoff coefficient × runoff area) (%). The degree of river pollution due to surface runoff.</td>
<td>MVPTCRS</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental Treatment Vegetation Coverage</td>
<td>(Woodland + pasture + garden area)/Area (%). Vegetation condition.</td>
<td>MVPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment Water Use Rate</td>
<td>Ecological and environmental water consumption/Total water consumption. (%). Water status of the ecological environment.</td>
<td>MVPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quota of Urban Green Land</td>
<td>Urban irrigation green land water volume/Irrigation area (10^4 m³/km²). Urban greening water situation.</td>
<td>MVPTCS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population Resources Population Density</td>
<td>Resident population/Area (population/km²). Water pressure caused by the number of people.</td>
<td>MPTCRS</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Growth Rate of the Population</td>
<td>Emigration/Total population (%).</td>
<td>MPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS Outmigration Rate</td>
<td>Characterizes the population growth rate (%).</td>
<td>MPTCRS</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Social Resources Infield Rate</td>
<td>Cultivated land area/Area (%). Agricultural land use.</td>
<td>MPTCRS</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public Satisfaction</td>
<td>Characterization of public satisfaction with agricultural water use (%).</td>
<td>MPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary School Enrolment Rate</td>
<td>Characterizes the local education level (%).</td>
<td>MPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doctors Per Million People</td>
<td>Characterizes the local medical level (population/10^4 people).</td>
<td>MPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ES Water Economy Unilateral Water GDP</td>
<td>GDP/Total water consumption (10^4 RMB). Economic benefit of water.</td>
<td>MPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unilateral Output Value of Agricultural Water Supply</td>
<td>Gross agricultural product/Total agricultural water consumption (RMB/m³). Economic benefits of agricultural water use.</td>
<td>MPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Social Economy (SE) Per Capita GDP</td>
<td>Socio-economic conditions.</td>
<td>MPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farm Family Per Capita Net Income</td>
<td>Characterization of the living standards of the residents (10^4 RMB).</td>
<td>MPTCRS</td>
<td>P</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: The letters in the fifth column in the table represent seven of the eight standards mentioned above.
Administration, the inclusion criteria matrix $R_{(39 \times 7)}$ and the relation matrix $P_{(9 \times 39)}$ were constructed:

$$R = [r_1, r_2, r_3, r_4, r_5, r_6, r_7, r_8, r_9, r_{10}, r_{11}, r_{12}, r_{13}, r_{14}, r_{15}, r_{16}, r_{17}, r_{18}, r_{19}, r_{20}, r_{21}, r_{22}, r_{23}, r_{24}, r_{25}, r_{26}, r_{27}, r_{28}, r_{29}, r_{30}, r_{31}, r_{32}, r_{33}, r_{34}, r_{35}, r_{36}, r_{37}, r_{38}, r_{39}]$$

This result indicates that 23 indexes must be determined and selected.

Equation (4) should be used to achieve completeness and simplicity requirements. To ensure that the indicators are linked, Equation (6) must be satisfied. When considering the practical operability and simplicity requirements, Equation (7) was used to delete an index to ensure the completeness of the index system. The calculation process is as follows:

$$\text{Min}Z = \sum_{m=1}^{8} r_m$$

$$R \times P_{(9 \times 39)}^T > 0$$

$$R \times W_{Ri}^T \geq 0.85$$

$$r_m = 0, 1$$

Thus, the optimum solution is $\text{Min}Z = 32$, and $R \times W_{Ri}^T = 0.856$.

Therefore, the following 32 indicators were selected: $R_1, R_2, R_3, R_4, R_5, R_6, R_7, R_8, R_9, R_{10}, R_{11}, R_{12}, R_{13}, R_{14}, R_{15}, R_{16}, R_{17}, R_{18}, R_{19}, R_{20}, R_{21}, R_{22}, R_{23}, R_{24}, R_{25}, R_{26}, R_{27}, R_{28}, R_{29}, R_{30}, R_{31}, R_{32}, R_{33}, R_{34}$ and $R_{37}$. The results fit the actual conditions of the Jiansanjiang Administration very well. The weights and ranking of the selected indicators are shown in Table 3.

**DISCUSSION**

To verify the reliability and rationality of the results, the AHP was used to calculate the weights of the 39 indicators in the index layer. The results are shown in Table 4.
By using the AHP, the optimal solution of $MinZ = 29$ was calculated, and $R \times W^*_R = 0.860459$. Therefore, the following 29 indicators were selected: $R_5$, $R_6$, $R_9$, $R_{10}$, $R_{11}$, $R_{12}$, $R_{13}$, $R_{14}$, $R_{15}$, $R_{18}$, $R_{19}$, $R_{21}$, $R_{23}$, $R_{24}$, $R_{25}$, $R_{26}$, $R_{27}$, $R_{28}$, $R_{29}$, $R_{30}$, $R_{31}$, $R_{32}$, $R_{33}$, $R_{34}$, $R_{35}$, $R_{36}$, $R_{37}$, $R_{38}$ and $R_{39}$. Moreover, the influence decreased as follows: $R_{37} > R_{36} > R_{39} > R_{38} >$
The primary goal of this paper was to analyse the criteria for index permission when using a model for constructing an evaluation index system. According to the hierarchical relationships of the index system, a primary selection matrix and an optimization matrix were constructed, which effectively removed several indexes that had poor operability or were insensitive and unstable. In the case study, the number of initially selected indexes was reduced from 46 to 39 based on the index selection criteria, which enhanced the effectiveness of the indexes in the model. Constructing the model to optimize the index system can effectively reduce interference by the noise that results from randomly setting indexes and can ensure that the index system is complete and simple. In the case analysis, the completeness of the final index was 85.6%, and the number of indicators was optimized from 39 to 32.

Predatory behaviours relying on agricultural resources and expanding extension to achieve the development and utilization of agricultural resources have led to a series of ecological and environmental problems such as water shortage, water quality deterioration and wetland shrinkage and so on. These problems are reflected in the Jiansanjiang Administration and Heilongjiang Province. The model for evaluating the system resilience of regional agricultural water resources has made an attempt to select indicators for the study system and to develop a scale for assessing resilience in response to various disasters. By reference to the factors which are optimized and selected using the model, policies can be made to maintain the sustainable agricultural development of Heilongjiang Province, including reforming the agricultural water resources management system, enhancing the efficiency of water usage, increasing water investments, decreasing discharge of sewage, the conversion of cropland to forest and grassland and wetland, promoting agricultural water-saving techniques and so on. Therefore, the model could explore and analyse the factors that impact the resilience of a regional AWRS and the construction of a complete resilience evaluation index system for the regional AWRS and provide a scientific basis for further exploration of the regional AWRS in Heilongjiang, China.

CONCLUSION

(1) The regional AWRS resilience evaluation index proposed in this paper can be used to optimize indexes and reduce interference based on the integrity index, which solves the problems of lack of rigour and incomplete index selection for the resilience of traditional evaluation systems. A HF of a resilience evaluation index system for regional AWRSs was constructed based on the principles of index selection, and a set of primary indexes was established using CRITIC to calculate the index weight and PCA to ensure index completeness. Simultaneously, the AHP was used to determine the reliability of the results. Finally, the key indexes involved in the AWRS, EES, SS and ES indicate that the selected indexes are strongly representative and that the model comprehensively evaluates the resilience of local water resource systems.
(4) The interdependence of various complex factors and how their dynamic influences should be reflected in the derived index were examined in this study. However, the details of each subsystem require further study. For example, the AWRSs should include the amount of transit water and the consumption of river and lake water by the ecological environment. However, quantifying these indicators is always a difficult problem in the field of water resources and is worthy of in-depth study. In addition, the process of selecting indicators remains somewhat subjective; thus, more detailed work is required in the future.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

ACKNOWLEDGEMENTS

The authors are grateful for the basic study data provided by the Jiansanjiang Administration of Heilongjiang Province in China.

FUNDING

This work was supported by the National Natural Science Foundation of China (grant numbers 51579044, 41071053, and 51479032), the Specialized Research Fund for Innovative Talents of Harbin (Excellent Academic Leader) (grant number 2013RFXXJ001), and the Science and Technology Program of the Water Conservancy of Heilongjiang Province (grant numbers 201319, 201501, 201503).

REFERENCES


de Carvalho, P. V., de Souza, A. P. & Gomes, J. O. 2012 A computerized system to monitor resilience indicators in organizations. Work 41 (Suppl. 1(6)), 2803–2809.


First received 13 January 2017; accepted in revised form 2 May 2017. Available online 18 May 2017