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Dynamic evaluation of regional water resources carrying capacity based on set pair analysis and partial connection number

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ABSTRACT

In order to quantitatively evaluate and analyze regional water resources carrying capacity (WRCC) and to describe the micro motion between connection number components, a more applicable evaluation model was sought. Firstly, an evaluation index system and grade standards for a regional WRCC were constructed. Then, a method for determining the connection number was proposed, which considered the micro motion between the connection number components in the system structure. Finally, an evaluation model based on set pair analysis (SPA) and partial connection number (PCN) that used subtraction set pair potential (SPP) to identify vulnerability factors was built, and identification results were compared with the total partial connection number (TPCN). The model was applied to Huaibei City, Anhui Province, China. The results showed that: the WRCC grade value was between 2 and 3 which was poor; the support and regulation subsystem grade value was between 2 and 3, and the pressure subsystem grade value was between 1 and 2. SPP identified that the support force and regulation force subsystem were the vulnerable subsystems. Eight indexes, including water resources per capita, rate of ecological water consumption and density of population, were the main indicators causing the poor WRCC, which were in good agreement with the local measured data. In addition, the SPP and TPCN were compared to further verify rationality of the connection number determination method and reliability of the identification results. The model established in this paper has strong applicability and can also be used for the dynamic evaluation of other resources, including the environment and ecological carrying capacity. The results in this study provide a scientific basis for water resources management and decision-making.

Key words: Connection number, Huaibei City, PCN, SPA, SPP, WRCC evaluation

HIGHLIGHTS

- Based on partial connection number, a method for calculating the connection number of a regional water resources carrying capacity (WRCC) evaluation sample was proposed.
- A dynamic evaluation model of a regional WRCC was constructed based on set pair analysis and partial connection number.
- Reasons for poor WRCC in Huaibei City, China are identified and results compared with local measured data.

1. INTRODUCTION

Water resources are indispensable basic natural resources to support economic development and ecological environment construction (Peng *et al.* 2021). For decades, water resources have become a strategic resource restricting the development of today's world, and gradually become a public social resource with an economic nature (Dai *et al.* 2019; Chi *et al.* 2021). Corresponding to the important position of water resources is the unfavorable position of water security, as a result of human misuse, water environmental pollution, unreasonable development and utilization of water resources, which will bring about problems such as intensified conflict between supply and demand of water resources, unbalanced space of water resources, etc., which seriously restrict regional sustainable development (Gao *et al.* 2021; Liu 2021). In view of the complexity and severity of water security, scholars all over the world have put forward solutions (Wu *et al.* 2020; Zhao *et al.* 2021). Of these, water resources carrying capacity (WRCC) can quantitatively measure and analyze water resources security from

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the characteristics and interactions between water resources and the socio-economic and ecological environment, which has become an important research field (Cui *et al.* 2018).

The original concept of 'carrying capacity' comes from mechanics in physics, which refers to the resistance of an object to external objects (Kessler 1994). With the development of human society, the concept of carrying capacity has been cited in other research fields, such as ecological carrying capacity (Abia *et al.* 2017). Robert E. Park and Ernest W. Burgess first put forward the concept of ecological carrying capacity in 1921 (Aboulfotoh 2018). Since the 1960s, carrying capacity has been applied to the research of social, economic and natural systems. In the early 1980s, UNESCO and FAO put forward the concept of resource carrying capacity (Ahmed *et al.* 2019). The concept of WRCC began in the late 1980s and originated from the research on sustainable utilization of natural resources. WRCC can be regarded as the maximum supporting capacity of water resources to population, ecological environment, economy and society with water resources as limiting factor, which is a comprehensive key index to measure water security (Zhang *et al.* 2010). When WRCC exceeds a certain threshold, it will seriously limit sustainable development of economy and society. Therefore, research on the evaluation and diagnosis of regional WRCC has attracted more and more scholars' attention, and has always been a key and challenging issue in the field of water resources security (Wu *et al.* 2020; Zhou *et al.* 2021). Taking the view that elements of a WRCC system form the carrying state, the evaluation and diagnosis of water resources carrying capacity is undertaken by constructing evaluation index systems, evaluation grade standards and an evaluation model, then judging whether water resources can support the maximum economic and social development scale of the region without damaging the ecological environment. Finally, the main reasons for the poor WRCC are identified and diagnosed. WRCC prediction is not only about early warning and regulation, but also an important basis for scientific decision-making of water resources management and the formulation of disaster prevention and reduction measures (Cui *et al.* 2018). It can help to implement a strict water resources management system and realize both sustainable utilization of regional water resources and water security.

At present, the evaluation methods of regional WRCC mainly include: the fuzzy comprehensive evaluation method (Liu *et al.* 2019; Xu 2020), principal component analysis method (Li & Meng 2017), system dynamics method (Wang *et al.* 2021), grey correlation method (Wang *et al.* 2020) and the set pair analysis (SPA) connection number method (Wang *et al.* 2009; Kang *et al.* 2019; Deng *et al.* 2021). The SPA connection number method is widely used because it can deeply analyze and quantitatively express the rich information involving evaluation sample data and evaluation grades (Men & Liu 2018), which provides an effective way for evaluation of WRCC and identification of vulnerability factors. However, for the application of the SPA connection number method in the evaluation and diagnosis of WRCC, there are also the following problems:

(1) The process of determining the connection number only considers the uncertainty between the evaluation index value and the evaluation grades in the macro state, and does not consider the micro movement between connection number components in system structure, that is, the dynamic evolution characteristics (Meng & Zhang 2021; Giao *et al.* 2021);
(2) Due to the interaction between water resources, socio-economic and ecological environment systems, there is a high degree of complexity and uncertainty. Currently, there is a lack of quantitative evaluation model with strong applicability (Ren *et al.* 2021);
(3) It is challenging to accurately identify and diagnose the vulnerability subsystem(s) and index(es) of WRCC. Whether the recognition results are consistent with the local measured data is an important way to judge and measure the effectiveness of the recognition method. At present, there are few studies in this field (Cui *et al.* 2018).

Currently, China is one of the countries lacking water resources in the world. Per capita water resources are less than one quarter of the world's (Borgomeo *et al.* 2015). With the continuous development of China's national economy and society, regional water resources security (Yang *et al.* 2019; Drangert 2021) and water resources vulnerability (Chhetri *et al.* 2020; Xiang & Li 2020) have become an important bottleneck factor seriously restricting sustainable development. Huaibei City is a prefecture city in Anhui Province in East China. It is not only an important resource-based city in China, but also one of the 114 cities with serious water shortage in China. The total amount of regional water resources is small, and the per capita water resource is less than 400 m^3, indicating that the water shortage situation is severe. Therefore, accurately evaluating the grade of WRCC in Huaibei City, and identification of vulnerability subsystem(s) and index(es) of the WRCC system is very vital for scientific decision-making and water resources management. Based on the theory of SPA and partial connection number (PCN), this study intends to introduce a mobility matrix that can reflect and characterize the micro motion between components in the structural system, so as to explore the dynamic balance mechanism between the different connection number components. Then, a method to determine the connection number is proposed. A dynamic quantitative evaluation model of regional WRCC based on SPA and PCN is constructed and applied to Huaibei City, Anhui Province, and the vulnerability subsystem(s) and index(es) of the WRCC system are diagnosed and identified. This study will provide technical support for regional water resources management in order to realize the sustainable utilization of water resources.

2. CONSTRUCTION OF REGIONAL WATER RESOURCES CARRYING CAPACITY EVALUATION MODEL BASED ON SET PAIR ANALYSIS AND PARTIAL CONNECTION NUMBER

A dynamic evaluation model of regional WRCC based on SPA and PCN was constructed by comprehensively adopting SPA, PCN and set pair potential (SPP) methods. The establishment process of this model generally included the following 6 steps, shown in Figure 1.

Step 1: determine the evaluation index system and evaluation grade standards of the regional WRCC. According to the principle that regional water resources support, pressure and regulation interact to form the regional WRCC, system structure analysis was carried out (Cui *et al.* 2018; Wang 2021). Combined with the characteristics of the study area, expert consultation, literature research and other methods, the evaluation index system $\{x_{jk}|\ j=1,\ 2,\ \ldots,\ n_k;\ k=1,\ 2,\ 3\}$ and grade standards $\{s_{gj}|\ g=1,\ 2,\ldots,\ n_g;\ j=1,\ 2,\ \ldots,\ n_j\}$ of the regional WRCC were established. The corresponding evaluation sample data set was recorded as $\{x_{ijk}|\ i=1,\ 2,\ \ldots,\ n_i;\ j=1,\ 2,\ \ldots,\ n_k;\ k=1,\ 2,\ 3\}$, where x_{ijk} was the index j value in the k-th subsystem of the i-th sample; n_i was the number of evaluation samples; n_k was the number of evaluation indexes in the k-th subsystem, and obviously $n_1+n_2+n_3=n_j$; n_g was the number of evaluation grades. Without losing generality, three evaluation grades (i.e., $g=3$) for each evaluation index and $g=1,\ 2,\ 3$ representing three different states for the WRCC were taken: $g=1$ stood for 'loadable' water resources, which meant a strong WRCC. Regional water resources still had large carrying capacity, and the water supply was relatively good; $g=2$ stood for 'critical overloaded' water resources, which meant average WRCC. The development and utilization of regional water resources was of a considerable scale, but there was still a certain potential for development and utilization. The supply and demand of water resources can meet the social and economic development of the region to a certain extent; $g=3$ stood for 'overloaded' water resources, which meant weak WRCC. The regional WRCC was close to the saturation value, and the potential for further development and utilization was small. In the long run, there

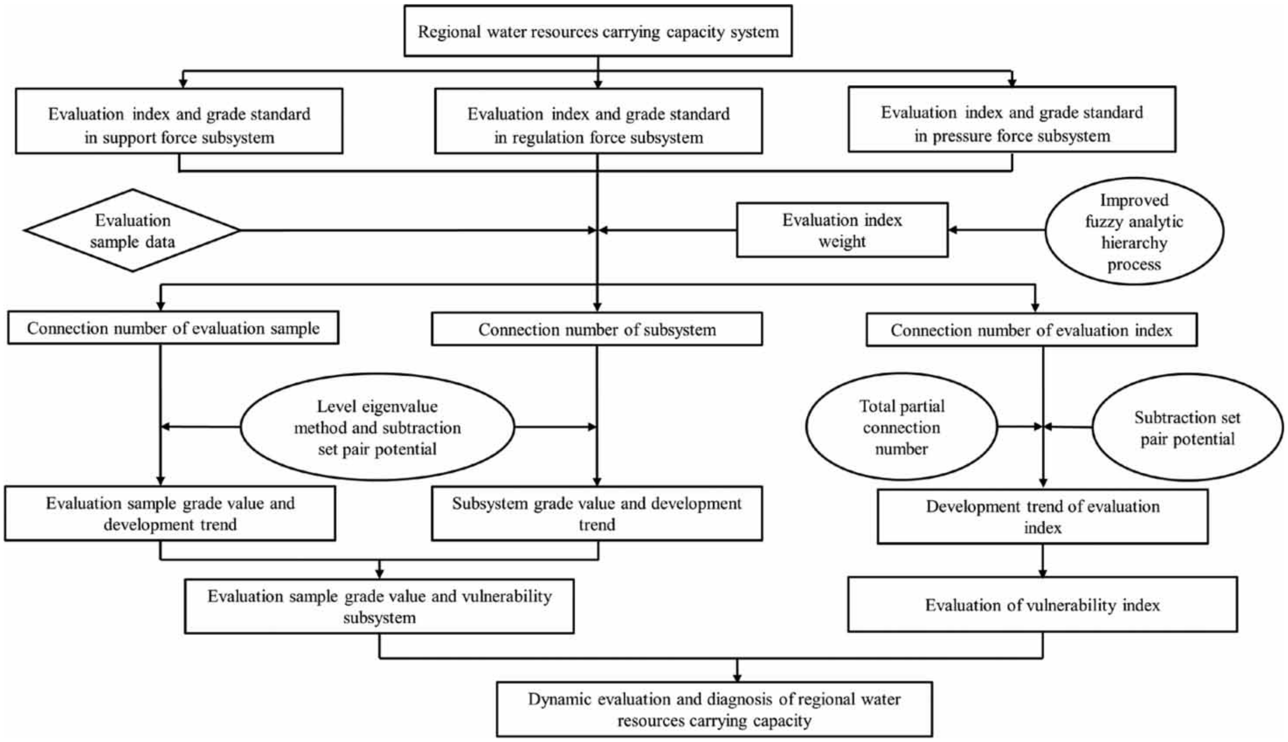

Figure 1 | Construction of the dynamic evaluation model of regional water resources carrying capacity based on set pair analysis and partial connection number.

will be a shortage of water resources, which restricts the coordinated development of regional social economy. Therefore, corresponding control measures should be taken in time.

Step 2: the single index connection number of WRCC evaluation sample was calculated. SPA is a connecting mathematical method proposed by Chinese scholar Zhao Keqin in 1989 (Zhao & Xuan 1996). It can integrate the certainty and uncertainty of a problem into a unified conclusion and study the internal relationship between each element of the system and the whole system. The basic idea of SPA is to quantitatively compare and analyze the close attributes of two sets $\{x_{ijk}\}$ and $\{s_{gj}\}$ in similarity, difference and opposition under a given problem background. Here, certainty includes similarity and opposition, and uncertainty is expressed as difference. Obviously, if the attributes of two sets are closer, the similarity is greater. By analyzing the characteristics of the two sets, SPA establishes a mathematical model of the relationship between certainty and uncertainty. Arithmetic expression of the ternary connection number is as follows (Xie & Guo 2018):

$$u = a + bI + cJ \tag{1}$$

where a, b, and c are the degree to which the evaluation index belongs to grades 1, 2, and 3, respectively. I is the difference coefficient, and J is the opposition coefficient, $J = -1$. Formula (1) establishes the basic model of SPA. For the given value x_{ijk} of the regional WRCC evaluation index, the connection number u_{ijkg} was calculated through SPA between x_{ijk} (index j value of the k-th subsystem of the i-th sample) and the evaluation grade standard s_{gj}.

For the index (positive index) whose evaluation grade g increases with the increase of the index value x_{ijk} (i.e., the larger the index value, the better the carrying status was), the calculation formula of ternary connection number is as follows (Wang *et al.* 2009):

$$\begin{cases} u_{ijk1} = 1 \\ u_{ijk2} = 1 - 2(s_{1j} - x_{ijk})/(s_{1j} - s_{0j}), \; s_{0j} < x_{ijk} \leq s_{1j} \\ u_{ijk3} = -1 \end{cases} \tag{2}$$

$$\begin{cases} u_{ijk1} = 1 - 2(x_{ijk} - s_{1j})/(s_{2j} - s_{1j}) \\ u_{ijk2} = 1 \quad , s_{1j} < x_{ijk} \leq s_{2j} \\ u_{ijk3} = 1 - 2(s_{2j} - x_{ijk})/(s_{2j} - s_{1j}) \end{cases} \tag{3}$$

$$\begin{cases} u_{ijk1} = -1 \\ u_{ijk2} = 1 - 2(x_{ijk} - s_{2j})/(s_{3j} - s_{2j}) \, , s_{2j} < x_{ijk} \leq s_{3j} \\ u_{ijk3} = 1 \end{cases} \tag{4}$$

For the index (negative index) whose evaluation grade g decreases with the increase of the index value x_{ijk} (i.e., the smaller the index value, the better the carrying status was), the calculation formula of ternary connection number is as follows (Wang *et al.* 2009):

$$\begin{cases} u_{ijk1} = 1 \\ u_{ijk2} = 1 - 2(s_{1j} - x_{ijk})/(s_{1j} - s_{0j}), \; s_{0j} > x_{ijk} \geq s_{1j} \\ u_{ijk3} = -1 \end{cases} \tag{5}$$

$$\begin{cases} u_{ijk1} = 1 - 2(x_{ijk} - s_{1j})/(s_{2j} - s_{1j}) \\ u_{ijk2} = 1 \quad , s_{1j} > x_{ijk} \geq s_{2j} \\ u_{ijk3} = 1 - 2(s_{2j} - x_{ijk})/(s_{2j} - s_{1j}) \end{cases} \tag{6}$$

$$\begin{cases} u_{ijk1} = -1 \\ u_{ijk2} = 1 - 2(x_{ijk} - s_{2j})/(s_{3j} - s_{2j}) \, , s_{2j} > x_{ijk} \geq s_{3j} \\ u_{ijk3} = 1 \end{cases} \tag{7}$$

where $\{s_{0j}, s_{1j}\}$, $\{s_{1j}, s_{2j}\}$ and $\{s_{2j}, s_{3j}\}$ are the interval endpoint values of grade 1, grade 2 and grade 3, respectively; x_{ijk} is the sample value and u_{ijkg} the connection number. For a positive index, $s_{0j} < s_{1j} < s_{2j} < s_{3j}$, and for a negative index, $s_{0j} > s_{1j} > s_{2j} > s_{3j}$. Obviously, the connection number u_{ijkg} ($u_{ijkg} \in [-1, 1]$) can be used as a measure of the closeness between x_{ijk} and s_{gj}; u_{ijkg} is transformed into the relative membership degree v^*_{ijkg} ($v^*_{ijkg} \in [0, 1]$), and the calculation formula is as follows

(Zhao & Xuan 1996; Jin *et al.* 2015):

$$v^*_{ijkg} = 0.5 + 0.5u_{ijkg} \tag{8}$$

where v^*_{ijkg} is the relative membership degree, and represents the relative membership degree of the WRCC evaluation sample value x_{ijk} belonging to grade 1, 2 and 3. $i = 1, 2, \ldots, n_i$; $j = 1, 2, \ldots, n_k$; $k = 1, 2, 3$; $g = 1, 2, 3$. In order to make the sum of the relative membership degree v^*_{ijk1}, v^*_{ijk2} and v^*_{ijk3} equal to 1, the connection number components can be processed by the following formulas (Jin *et al.* 2015):

$$v_{ijkg} = \frac{v^*_{ijkg}}{v^*_{ijk1} + v^*_{ijk2} + v^*_{ijk3}} \tag{9}$$

$$u_{ijk} = v_{ijk1} + v_{ijk2}I + v_{ijk3}J \tag{10}$$

where v^*_{ijkg} is the relative membership degree; u_{ijk} is the single index connection number of the WRCC evaluation sample and v_{ijk1}, $v_{ijk2,}$ v_{ijk3} are the single index connection number components; and $v_{ijk1} + v_{ijk2} + v_{ijk3} = 1$. I and J have the same meaning as in formula (1).

Step 3: construct the migration matrix based on PCN and calculate the index value connection number of evaluation sample *i* and subsystem *k*. On the surface, the single index value connection number components v_{ijk1}, v_{ijk2} and v_{ijk3} of the evaluation sample reflect the similarity, difference and opposition value. Meanwhile, from the background of the WRCC evaluation, v_{ijk1}, v_{ijk2} and v_{ijk3} quantitatively describe the degree of a single index value belonging to grade 1, 2 and 3, respectively, and the coincidence degree expression between sample values and evaluation grades in the complex system of the WRCC are realized, which is a very important part in the comprehensive evaluation. It can be seen that the connection number method is a powerful tool which can deeply analyze and quantitatively express specific uncertainty problems, and it is unique in its interpretation of physical connotation. However, it should be noted that there is mutual transformation and migration among the similarity, difference and opposition components of the connection number. According to the philosophical principles of the universality of connection, the absoluteness of movement and the universality of contradiction, the components of the connection number always have similarity, difference and opposition levels and their mutual transformation and migration, thus forming the system structure. Obviously, in this system structure, the components of the connection number are no longer independent, but influence each other through contradictory movement at the micro level. Most existing studies do not consider the relationship structure characteristics of mutual migration and transformation (dynamic evolution) between connection number components after calculating them. Instead, the connection number components (such as maximum membership degree method, attribute recognition method and level eigenvalue method) are directly used for the comprehensive evaluation of practical problems. It is then possible to see how to quantitatively describe and express the influence on the dynamic evolution of the connection number components in the connection number system structure at the micro level, and to intuitively see the micro movement and migration of the system under the macro static state, so as to grasp the migration law more objectively and accurately, and deeply reveal the essential characteristics of the system. The PCN focuses on the quantitative description of the set pair system relationship structure at the micro level, which can be derived from the system level relationship of connection number components (Xie *et al.* 2014; Xie & Guo 2018). Taking the ternary connection number $u = a + bI + cJ$ as an example, the partial positive connection number is as follows (Dingtian & Xiaoxi 2011):

$$\partial^+\mu = \partial^+a + \partial^+bi^+ = \frac{a}{a+b} + \frac{b}{b+c}i^+ \tag{11}$$

where $\partial^+a = a/a + b$ and $\partial^+b = b/b + c$ are the partial positive connection number of connection number components a and b, respectively; i^+ is the difference coefficient. For ∂^+a it can be considered that the current a was originally at the level b, which was a positive migration from level b to a. For ∂^+b it can be considered that the current b was originally at level c, which was a positive migration from level c to b. The partial positive connection number indicates that the set pair event has a positive development trend. The larger the value, the greater the positive development trend of the event.

Similarly, a partial negative connection number is as follows (Dingtian & Xiaoxi 2011):

$$\partial^- \mu = \partial^- b i^- + \partial^- c j = \frac{b}{a+b} i^- + \frac{c}{b+c} j \tag{12}$$

where $\partial^- b = b/a + b$ and $\partial^- c = c/b + c$ are the partial negative connection number of connection number components b and c, respectively; i^- is the difference coefficient and j the opposition coefficient. For $\partial^- b$ it can be considered that the current b was originally at the level a, which was a negative migration from the level a to b. For $\partial^- c$ it can be considered that the current c was originally at the level b, which was a negative migration from level b to c. The partial negative connection number indicates that the set pair event has a negative development trend. The smaller the value, the greater the negative development trend of the events. The PCN reveals the contradictory movement of the connection number components at the micro level, and can quantitatively express the mutual migration and transformation of the connection number components in the set system structure. To sum up, the PCN, as an adjoint function of the connection number, can be expressed as the function f (a, b, c) of the connection number components, realizing qualitative and quantitative characterization of the movement direction and increment size of the connection number components at macro static and micro level. Taking the structural system's connection number components as the driving object and the 'information energy' stored in the connection number components as the driving force, and the migration to different opposition levels as the driving direction, the updating and iteration of the connection number components can be realized, which make the determined connection number components more reasonable and following the micro motion law.

According to the above, referring to the basic concept and connotation of PCN, this paper applied PCN to depict the mutual migration of connection number components of the WRCC evaluation sample, and then put forward a method to determine the connection number, hoping to realize the rationality and accuracy of WRCC evaluation; meanwhile, the vulnerability subsystem(s) and index(es) were identified. Migration matrix $X = \begin{bmatrix} 1 & \partial^- b & \partial^- b \partial^- c \\ \partial^+ a & 1 & \partial^- c \\ \partial^+ b \partial^+ a & \partial^+ b & 1 \end{bmatrix} = \begin{bmatrix} 1 & \dfrac{b}{a+b} & \dfrac{b}{a+b}\dfrac{c}{b+c} \\ \dfrac{a}{a+b} & 1 & \dfrac{c}{b+c} \\ \dfrac{b}{b+c}\dfrac{a}{a+b} & \dfrac{b}{b+c} & 1 \end{bmatrix}$ can be defined based on PCN. The representation of matrix X in a, b and c, for component a of the connection number, there was a micro dynamic movement from a, b and c to a, and it was obvious that the possibility of component a transferring to itself was 1. Both components b and c had migration to component a, so the migration of components b and c to component a needed to be considered. $\partial^+ a$ reflected the migration rate of component b to a, and $b\partial^+ a$ is the migration value of component b to a. $\partial^+ b \partial^+ a$ reflected the migration rate of component c to a, that is, component c first transformed to component b and then to component a. Component b was the bridge between components a and c, and $c\partial^+ b \partial^+ a$ was the migration value of component c to a. According to the above, the new similarity component transformed by the PCN is $a + b\frac{a}{a+b} + c\frac{b}{b+c}\frac{a}{a+b}$. Similarly, for the connection number component b, there was a micro dynamic movement from components a, b and c to b, and the new difference component transformed by the PCN was $b + a\frac{b}{a+b} + c\frac{b}{b+c}$. For the connection number component c, there was also a micro dynamic movement from components a, b, and c to c, and the new opposition component transformed by the PCN was $c + b\frac{c}{b+c} + a\frac{b}{a+b}\frac{c}{b+c}$. The above process can be described by formula (13):

$$\begin{aligned} R = UX = [a, b, c] & \begin{bmatrix} 1 & \dfrac{b}{a+b} & \dfrac{b}{a+b}\dfrac{c}{b+c} \\ \dfrac{a}{a+b} & 1 & \dfrac{c}{b+c} \\ \dfrac{b}{b+c}\dfrac{a}{a+b} & \dfrac{b}{b+c} & 1 \end{bmatrix} \\ = & \left[a + b\frac{a}{a+b} + c\frac{b}{b+c}\frac{a}{a+b},\ b + a\frac{b}{a+b} + c\frac{b}{b+c},\ c + b\frac{c}{b+c} + a\frac{b}{a+b}\frac{c}{b+c} \right] \end{aligned} \tag{13}$$

where $U = [a, b, c]$ is the original connection number matrix and R is the evaluation sample connection number matrix transformed by the migration matrix X. Substituting the single index connection number components v_{ijk1}, v_{ijk2} and v_{ijk3} in formula (10) into formula (13) gives:

$$[v_{ijk1}, v_{ijk2}, v_{ijk3}]\begin{bmatrix} 1 & \dfrac{v_{ijk2}}{v_{ijk1}+v_{ijk2}} & \dfrac{v_{ijk2}}{v_{ijk1}+v_{ijk2}}\dfrac{v_{ijk3}}{v_{ijk2}+v_{ijk3}} \\ \dfrac{v_{ijk1}}{v_{ijk1}+v_{ijk2}} & 1 & \dfrac{v_{ijk3}}{v_{ijk2}+v_{ijk3}} \\ \dfrac{v_{ijk2}}{v_{ijk2}+v_{ijk3}}\dfrac{v_{ijk1}}{v_{ijk1}+v_{ijk2}} & \dfrac{v_{ijk2}}{v_{ijk2}+v_{ijk3}} & 1 \end{bmatrix}$$

$$= \left[v_{ijk1} + v_{ijk2}\frac{v_{ijk1}}{v_{ijk1}+v_{ijk2}} + v_{ijk3}\frac{v_{ijk2}}{v_{ijk2}+v_{ijk3}}\frac{v_{ijk1}}{v_{ijk1}+v_{ijk2}}, v_{ijk2} + v_{ijk1}\frac{v_{ijk2}}{v_{ijk1}+v_{ijk2}} + v_{ijk3}\frac{v_{ijk2}}{v_{ijk2}+v_{ijk3}}, v_{ijk3} + v_{ijk2}\frac{v_{ijk3}}{v_{ijk2}+v_{ijk3}} + v_{ijk1}\frac{v_{ijk2}}{v_{ijk1}+v_{ijk2}}\frac{v_{ijk3}}{v_{ijk2}+v_{ijk3}}\right] \tag{14}$$

Referring to formula (9), we get the single index connection number u'_{ijk} of the WRCC evaluation sample determined by the method in this paper:

$$u'_{ijk} = v'_{ijk1} + v'_{ijk2}I + v'_{ijk3}J \tag{15}$$

where v'_{ijk1}, v'_{ijk2} and v'_{ijk3} are the single index connection number components of the WRCC evaluation sample obtained by the migration matrix transformation, and $v'_{ijk1} + v'_{ijk2} + v'_{ijk3} = 1$. Obviously, these components are obtained by the superposition of the macro static state and the micro motion state. According to formula (15), the index value connection number u'_i of the i-th evaluation sample can be calculated by formula (16) and the index value connection number u'_{ik} of the k-th subsystem of the i-th evaluation sample can be calculated by formula (17). Formulas are as follows (Xie *et al.* 2014):

$$u'_{ik} = v'_{ik1} + v'_{ik2}I + v'_{ik3}\,J = \sum_{j=1}^{n_k} w_j\, v'_{ijk1} + \sum_{j=1}^{n_k} w_j\, v'_{ijk2}I + \sum_{j=1}^{n_k} w_j\, v'_{ijk3}\,J(i = 1, 2, \cdots n_i; k = 1, 2, 3) \tag{16}$$

$$u'_i = v'_{i1} + v'_{i2}I + v'_{i3}\,J = \sum_{j=1}^{n_k}\sum_{k=1}^{3} w_j\, v'_{ijk1} + \sum_{j=1}^{n_k}\sum_{k=1}^{3} w_j\, v'_{ijk2} + \sum_{j=1}^{n_k}\sum_{k=1}^{3} w_j\, v'_{ijk3}\,J(i = 1, 2, \cdots n_i) \tag{17}$$

where w_j is the weight of evaluation index j, which is determined by the fuzzy analytic hierarchy process based on the accelerated genetic algorithm (AGA-FAHP) (Jin *et al.* 2015).

Step 4: calculate the WRCC grade of the *i*-th evaluation sample and each subsystem by using the level eigenvalue method. According to i-th evaluation sample and each subsystem index value connection number obtained in step 3, the grade value is calculated by using the level eigenvalue method (Zhang & Zhang 2011):

$$h_{ik} = \sum_{g=1}^{3} v'_{ikg} * g \tag{18}$$

$$h_i = \sum_{g=1}^{3} v'_{ig} * g \tag{19}$$

where h_{ik} and v'_{ikg} are the WRCC grade value and connection number of the k-th subsystem of the i-th evaluation sample; h_i and v'_{ig} are the WRCC grade value and connection number of the i-th evaluation sample.

Step 5: calculate the SPP based on index value connection number of the *i*-th evaluation sample and each subsystems of the regional WRCC; distinguish the state development trend of each subsystem, and then identify the vulnerability subsystem(s) of the WRCC system. Set pair potential (SPP) is also an adjoint function of connection number. The basic idea is how to transform the connection number which contains the information of uncertainty trend into the overall development trend of certainty, that is, to realize the transformation from uncertainty to certainty, so as to distinguish the development trend of the system. Common SPPs are: division SPP and generalized SPP. The SPP for the ternary connection number $u = a + bI + cJ$ has a wide application range and profound physical meaning, focusing on how to reasonably allocate the difference degree component b to the similarity degree component a and the opposition degree component c. The SPP of ternary connection number is (Cui *et al.* 2018):

$$s'_1(u) = [a + ba] - [c + bc] = (a - c)(1 + b) \tag{20}$$

where, $s'_1(u)$ is the SPP; $a = v'_{i1}$, $b = v'_{i2}$, $c = v'_{i3}$, when calculating $s'_1(u)$ of i-th evaluation sample; $a = v'_{ik1}$, $b = v'_{ik2}$, $c = v'_{ik3}$, when calculating $s'_1(u)$ of each subsystem.

Step 6: calculate the SPP based on single index value connection number of the regional WRCC, distinguish the state development trend of each index, and then identify the vulnerability index(es) of the WRCC system. To illustrate the reliability of this method, total partial connection number (TPCN) was calculated and compared with the SPP. Meanwhile, the identification results are compared with the local measured data to investigate whether they are consistent, and there are few quantitative studies in this field. The TPCN is as follows (Xie & Guo 2018):

$$p_1(u) = a/(a + b) + b/(b + c)I_1 + b/(a + b)I_2 + c/(b + c)J \tag{21}$$

where, $p_1(u)$ is the TPCN; $a = v'_{ijk1}$, $b = v'_{ijk2}$, $c = v'_{ijk3}$, $I_1 = [a/(a + b)]/[a/(a + b) + b/(b + c)]$, $I_2 = -[c/(b + c)]/[b/(a + b) + c/(b + c)]$ and $J = -1$.

According to the theory of SPA (Zhao & Xuan 1996), the set pair potential of connection number reflects the development trend of water resources carrying state on the macro certainty level. Obviously, given that $s'_1(u) \in [-1, 1]$, the SPP can be divided into five equal parts, and the corresponding interval and status are shown in Table 1.

Among them, the index with SPP at $(-1, -0.2)$ (i.e., counter potential status or partial counter potential status) can be considered as the vulnerability index(es) of the regional WRCC, which needs to be regulated.

3. EVALUATING AND DIAGNOSING WATER RESOURCES CARRYING CAPACITY IN HUAIBEI, CHINA

Huaibei City is a prefecture-level city in Anhui Province. It is an important resource-based city in East China, and a new modern industrial city. It was built in 1960, built due to coal and developed with coal. By the end of 2019, it had jurisdiction over Xiangshan District, Duji District, Lieshan District and Suixi County, and five provincial development zones, covering an area of 2,741 km^2, and a permanent population of about 2,187,000. The industrialization rate is 39%, and the urbanization rate of permanent residents is 65.9%. Huaibei City is located in a semi humid monsoon climate zone of a warm temperate zone, with distinct seasons, mild climate and moderate rain. The annual average precipitation is about 832 mm, but the annual variation is large and the distribution is uneven in the year. The maximum annual precipitation is 3.0 times the minimum annual precipitation; precipitation in June to September accounts for 65%–70% of the year. Huaibei City is one of the 114 cities facing serious water shortage in China. The total water resources in the region are less than 400 m^3 per capita, and the water shortage situation is more severe. Therefore, it is very important to evaluate the WRCC level and identify the vulnerability subsystem(s) and index(es) of the WRCC system accurately.

The dynamic evaluation model of regional WRCC based on SPA and PCN was applied to Huaibei City, Anhui Province. According to the physical formation mechanism of WRCC and referring to the existing research results, an evaluation index system and evaluation grade standards were constructed (Cui *et al.* 2018), and the weight was determined by AGA-FAHP (Jin *et al.* 2015), shown in Table 2.

The evaluation sample data of WRCC in Huaibei City came from the Anhui statistical yearbook. Combined with Table 2, data for each index were brought into formulas (2)–(10) to obtain the single index connection number of the evaluation sample. It should be pointed out that there was micro motion in the connection number components under the macro

Table 1 | SPP status level

$s'_1(u)$	(−1.0, −0.6)	(−0.6, −0.2)	(−0.2, 0.2)	(0.2, 0.6)	(0.6, 1.0)
Status	Counter potential	Partial counter potential	Equilibrium potential	Partial identical potential	Identical potential

Table 2 | Evaluation index system, evaluation grade standards, evaluation index weight and subsystems of regional WRCC (1 mu = c.666.7 m^2)

Water Resources Carrying Capacity System	Evaluation Index	Weight	Grade 1 (Loadable status)	Grade 2 (Critical status)	Grade 3 (Overloaded status)
Water resources carrying support force subsystem (B_1)	C_1 water resources per capita (m^3/person)	0.1332	≥ 1670	1670–1000	< 1000
	C_2 production modulus of water resources (10^4 m^3/km^2)	0.1332	≥ 80	80–50	< 50
	C_3 water supply per capita (m^3/(person·year))	0.1056	≥ 450	450–350	< 350
	C_4 rate of vegetation coverage (%)	0.028	≥ 40	40–25	< 25
Water resources carrying regulation force subsystem (B_2)	C_5 rate of water resources utilization (%)	0.0396	≤ 40	40–70	> 70
	C_6 gross domestic product per capita (10^4 yuan/person)	0.0792	≥ 24840	24840–6624	< 6624
	C_7 standard rate of sewage discharge (%)	0.0596	≥ 90	90–70	< 70
	C_8 standard rate of water function area (%)	0.0792	≥ 95	95–70	< 70
	C_9 rate of ecological water consumption (%)	0.0632	≥ 5	5% – 1%	< 1
Water resources carrying pressure force subsystem (B_3)	C_{10} daily domestic water consumption per capita (L/(person·day))	0.0792	≤ 70	70–180	> 180
	C_{11} water consumption per 10^4 yuan ($m^3/10^4$ yuan)	0.0582	≤ 100	100–400	> 400
	C_{12} water consumption per 10^4 yuan of value-added by industry ($m^3/10^4$ yuan)	0.0484	≤ 50	50–200	> 200
	C_{13} density of population (person/km^2)	0.0288	≤ 200	200–500	> 500
	C_{14} rate of urbanization (%)	0.0454	≤ 50	50–80	> 80
	C_{15} water consumption per mu for agricultural irrigation (m^3/mu)	0.0192	≤ 250	250–400	> 400

state, and the components can migrate and transform with each other. Therefore, to achieve the certainty and accuracy of the evaluation results, it was necessary to consider the micro motion. The single index new connection number of the evaluation sample can be obtained by bringing each component of formula (10) into formula (14). In order to have a more comprehensive and profound understanding of WRCC in Huaibei City, Anhui Province, first the support force subsystem, regulation force subsystem and pressure force subsystem of the WRCC were evaluated and analyzed. The single index connection number components of formula (15) were weighted by formula (16) to get the connection number v'_{ikg} of each subsystem, shown in Tables 3–5; then the WRCC system was evaluated and analyzed, meanwhile the single index connection number components of formula (15) were weighted by formula (17) to obtain the connection number v'_{ig} of evaluation samples. The changes of WRCC evaluation grade value and connection number components from 2010 to 2015 are shown in Table 6 and Figures 2 and 3.

According to Tables 3–6 and Figures 2 and 3:

(1) The values of the similarity component, difference component and opposition component changed after transformation by the mobility matrix. Taking the connection number of the evaluation sample in 2015 as an example, the original

Table 3 | Evaluation grade value and SPP of the support force subsystem of the WRCC in Huaibei City from 2010 to 2015

	Connection number components			Connection number components					
Years	v_{ik1}	v_{ik2}	v_{ik3}	v'_{ik1}	v'_{ik2}	v'_{ik3}	Level eigenvalue method	SPP s'_1	Status
2010	0	0.277	0.723	0	0.335	0.665	2.665	−0.888	Counter potential
2011	0	0.264	0.736	0	0.321	0.679	2.679	−0.897	Counter potential
2012	0	0.289	0.711	0	0.346	0.654	2.654	−0.880	Counter potential
2013	0	0.287	0.713	0	0.343	0.657	2.657	−0.883	Counter potential
2014	0	0.301	0.699	0	0.355	0.645	2.645	−0.874	Counter potential
2015	0	0.279	0.721	0	0.336	0.664	2.664	−0.887	Counter potential

Table 4 | Evaluation grade value and SPP of the regulation force subsystem of the WRCC in Huaibei City from 2010 to 2015

	Connection number components			Connection number components					
Years	v_{ik1}	v_{ik2}	v_{ik3}	v'_{ik1}	v'_{ik2}	v'_{ik3}	**Level eigenvalue method**	**SPP** s'_1	**Status**
2010	0.092	0.478	0.430	0.097	0.475	0.428	2.331	−0.488	Partial counter potential
2011	0.129	0.469	0.402	0.133	0.468	0.399	2.266	−0.390	Partial counter potential
2012	0.142	0.478	0.380	0.148	0.478	0.374	2.226	−0.334	Partial counter potential
2013	0.145	0.485	0.370	0.149	0.486	0.365	2.215	−0.320	Partial counter potential
2014	0.156	0.491	0.353	0.161	0.488	0.351	2.190	−0.283	Partial counter potential
2015	0.162	0.490	0.348	0.168	0.487	0.345	2.177	−0.263	Partial counter potential

Table 5 | Evaluation grade value and SPP of the pressure force subsystem of the WRCC in Huaibei City from 2010 to 2015

	Connection number components			Connection number components					
Years	v_{ik1}	v_{ik2}	v_{ik3}	v'_{ik1}	v'_{ik2}	v'_{ik3}	**Level eigenvalue method**	**SPP** s'_1	**Status**
2010	0.432	0.404	0.164	0.413	0.421	0.166	1.753	0.351	Partial identical potential
2011	0.444	0.408	0.148	0.424	0.426	0.150	1.726	0.391	Partial identical potential
2012	0.464	0.386	0.150	0.439	0.409	0.152	1.713	0.404	Partial identical potential
2013	0.460	0.388	0.152	0.434	0.411	0.155	1.721	0.394	Partial identical potential
2014	0.465	0.380	0.155	0.439	0.404	0.157	1.719	0.395	Partial identical potential
2015	0.465	0.377	0.158	0.438	0.402	0.160	1.722	0.390	Partial identical potential

connection numbers are 0.219, 0.360 and 0.421, which were transformed into 0.209, 0.393 and 0.398. The similarity component and opposition component decreased, while the difference component increased. If the value of a component decreased in a connection number structure system in which they are not independent of each other, there must be an increasing component. PCN can excavate the micro motion between components and quantify it. It makes people realize the result of microscopic movement in a macroscopic state.

(2) The grade value of the WRCC in Huaibei City was between 2 and 3, that is, between critical overloaded and overloaded status, and indicating that the WRCC was poor, which was consistent with SPP and its reflected status (both in partial counter potential). Cui *et al.* 2018 reported the construction of an SPA evaluation model and its application to WRCC evaluation in Anhui Province. The results showed that the WRCC in Northern Anhui Province was relatively severe. By calculating the index number connection number, index value connection number and their geometric average

Table 6 | Sample evaluation grade value and SPP of WRCC in Huaibei City from 2010 to 2015

	Connection number components			Connection number components					
Years	v_{i1}	v_{i2}	v_{i3}	v'_{i1}	v'_{i2}	v'_{i3}	**Level eigenvalue method**	**SPP** s'_1	**Status**
2010	0.191	0.368	0.441	0.185	0.397	0.418	2.233	−0.326	Partial counter potential
2011	0.204	0.362	0.434	0.196	0.393	0.411	2.215	−0.299	Partial counter potential
2012	0.214	0.366	0.420	0.205	0.398	0.397	2.192	−0.269	Partial counter potential
2013	0.213	0.367	0.420	0.203	0.399	0.398	2.195	−0.272	Partial counter potential
2014	0.218	0.370	0.412	0.208	0.401	0.391	2.183	−0.257	Partial counter potential
2015	0.219	0.360	0.421	0.209	0.393	0.398	2.190	−0.264	Partial counter potential

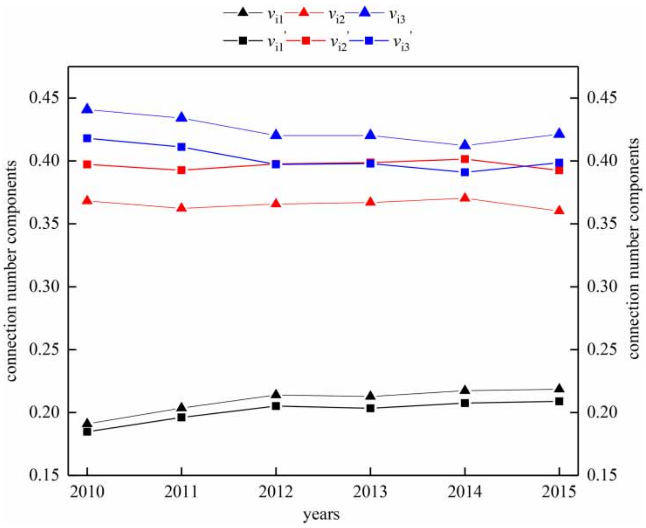

Figure 2 | Comparison of connection number components.

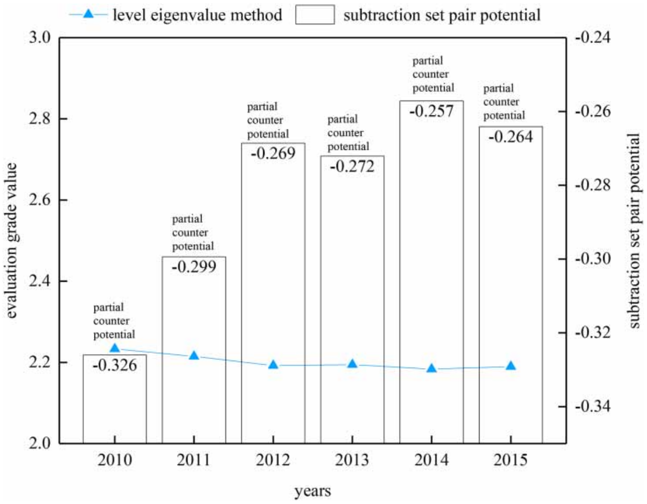

Figure 3 | Evaluation grade value and SPP of the WRCC in Huaibei City from 2010 to 2015.

connection number, then using the level eigenvalue method, the grade values of the WRCC in Huaibei City were 2.33, 2.30 and 2.32, respectively. This was in good agreement with the results of this paper, and the relative error was less than 5%. In addition, the reduction of water resources in Northern Anhui was the reason for its long-term overload. Gao *et al.* 2013 reported that the evaluation model of comprehensive development and utilization of water resources was constructed by matter–element analysis method and applied to Xiangshan District, Duji District, Lieshan district and Suixi County of Huaibei City. The results showed that the evaluation grade value of Xiangshan district was 3; the WRCC was saturated (i. e., overloaded status); the potential for further development and utilization was small, and the contradiction between supply and demand of water resources was prominent. The evaluation grade value of Duji district and Lieshan district was 2, which indicated that the scale of water resources development and utilization was large, and the potential of water resources utilization was small (i.e., the critical overloaded status). The evaluation grade value of Suixi County was 1, which indicated that the potential and trend of further development and utilization of water resources were optimistic (i. e., the loadable status). The largest area of Huaibei City in Suixi County has few industrial enterprises and a small population concentration, so the demand for water resources is small. It can be seen that the overall WRCC of Huaibei City was between grade 2 and 3, that is, between the critical overloaded and overloaded status, which was basically consistent with the research results of this paper.

(3) The support force subsystem and regulation force subsystem grade value were between 2 and 3 (support force subsystem grade value ranging from 2.645–2.679, regulation force subsystem grade value from 2.177 –2.331), and the pressure subsystem grade value was between 1 and 2 (pressure force subsystem grade value ranging from 1.713–1.753). From the perspective of subsystems, SPP of the support force subsystem was in the interval $[-1, -0.6]$, and its trend was counter potential from 2010 to 2015; SPP of the regulation force subsystem was in the interval $[-0.6, -0.2]$, and its trend was partial counter potential; SPP of the pressure subsystem was in the interval [0.2, 0.6], and its trend was partial identical potential, which showed that the vulnerability subsystems which caused the poor WRCC in Huaibei City were the support force subsystem and regulation force subsystem.

To make the formulation of control measures more targeted and realize the sustainability of water resources, it is important to accurately find the vulnerability index(es) that led to the critical overloaded and overloaded status, then carry out targeted control to alleviate and solve the current problem of poor WRCC. Therefore, it was necessary to further diagnose and identify the vulnerability index(es) of WRCC system for regulation. The transformed components v'_{ijk1}, v'_{ijk2} and v'_{ijk3} were brought into the formulas (20) and (21) to calculate the average value of SPP and TPCN of WRCC evaluation samples for Huaibei City, shown in Table 7. The annual variation of SPP and TPCN of each index are shown in Figures 4–6.

According to Table 7 and Figures 4–6:

(1) In the support force subsystem of the WRCC: the SPP of the four evaluation indexes of water resources per capita, production modulus of water resources, water supply per capita and rate of vegetation coverage changed in the interval $[-1, -0.6]$ in 2010–2015, which were counter potential and consistent with the trend of TPCN. It can be seen that the above four indexes were the vulnerability indexes of the support force subsystem in Huaibei City. Among them, water resources per capita, production modulus of water resources and water supply per capita are significantly correlated with the amount of water coming from the area, while the status of the three indexes was counter potential, indicating that the local water resources are scarce and there was a water shortage phenomenon. According to the water resources bulletin, affected by natural rainfall, topography and other factors, the distribution of water resources in Anhui Province had obvious North-South differences. Taking 2015 as an example, the water resources per capita of Huaibei City (located in the north of Anhui Province in China), Hefei City (located in the middle of Anhui Province) and Huangshan City

Table 7 | SPP average values of ternary connection number and their status for WRCC evaluation samples in Huaibei City from 2010 to 2015 (1 mu = c.666.7 m^2)

Evaluation indexes	SPP average value	Status	TPCN average value
C_1 water resources per capita (m^3/person)	−0.942	Counter potential	−1.191
C_2 production modulus of water resources (10^4 m^3/km^2)	−0.868	Counter potential	−1.025
C_3 water supply per capita (m^3/(person · year))	−0.833	Counter potential	−0.964
C_4 rate of vegetation coverage (%)	−0.808	Counter potential	−0.923
C_5 rate of water resources utilization (%)	−0.758	Counter potential	−0.845
C_6 gross domestic product per capita (10^4 yuan/person)	0.599	Identical potential	0.648
C_7 standard rate of sewage discharge (%)	−0.747	Counter potential	−0.828
C_8 standard rate of water function area (%)	−0.376	Partial counter potential	−0.360
C_9 rate of ecological water consumption (%)	−0.805	Counter potential	−0.923
C_{10} daily domestic water consumption per capita (L/(person · day))	0.356	Identical potential	0.364
C_{11} water consumption per 10^4 yuan (m^3/10^4 yuan)	0.790	Identical potential	0.894
C_{12} water consumption per 10^4 yuan of value-added by industry (m^3/10^4 yuan)	0.674	Partial identical potential	0.770
C_{13} density of population (person/km^2)	−0.804	Counter potential	−0.915
C_{14} rate of urbanization (%)	0.307	Partial identical potential	0.290
C_{15} water consumption per mu for agricultural irrigation (m^3/mu)	0.940	Identical potential	1.186

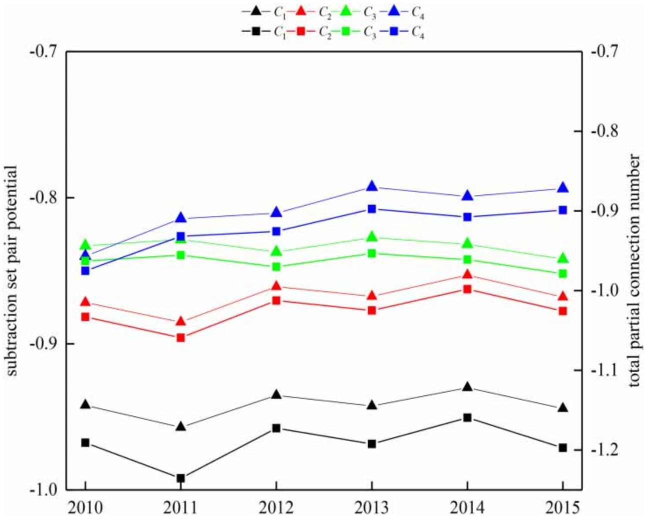

Figure 4 | Subtraction set pair potential and total partial connection number of each index of the support force subsystem in Huaibei City from 2010 to 2015. (C_1 = water resources per capita, C_2 = production modulus of water resources, C_3 = water supply per capita C_4 = rate of vegetation coverage. △ represents SPP, □ represents TPCN).

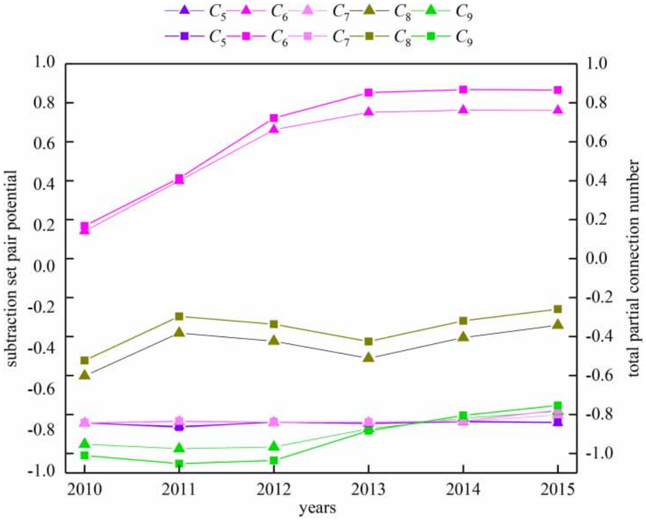

Figure 5 | Subtraction set pair potential and total partial connection number of each index of the regulation force subsystem in Huaibei City from 2010 to 2015. (C_5 = rate of water resources utilization, C_6 = gross domestic product per capita, C_7 = standard rate of sewage discharge, C_8 = standard rate of water function area, C_9 = rate of ecological water consumption. △ represents SPP, □ represents TPCN).

(located in the middle of Anhui Province) were 276.2 m^3, 628.08 m^3 and 10914.21 m^3, respectively. The water resources per capita of Huangshan City is about 17 times that of Hefei City and 39 times that of Huaibei City. It is noticed that the water resources per capita of Huaibei City changed from 243.41 m^3 to 313.18 m^3 in 2010–2015, which is about 24.13% (243.41/1008.85 × 100%) and 24.47% (313.18/1279.78 × 100%) of the water resources per capita of Anhui Province in the same period, respectively. In addition, after the last ten days of September 2010, there were 61–73 consecutive days of no effective rainfall, so autumn and winter droughts occurred in some areas of northern Huaibei. In the three years from 2011 to 2013, the average annual rainfall in Huaibei City was 653.6 mm, 773.2 mm and 729.5 mm, respectively, which did not reach the provincial average annual rainfall of 1,064.4 mm, 1,173.8 mm and 1,023.4 mm, accounting for 61.41% (653.6/1064.4 × 100%), 65.87% (773.2/1173.8 × 100%) and 71.28% (729.5/1023.4 × 100%), respectively. In 2014, Huaibei City had the least surface water resources in Anhui Province, and the surface water resources in 2015 continued to decrease compared to 2014. The above analysis indicates that the identification results

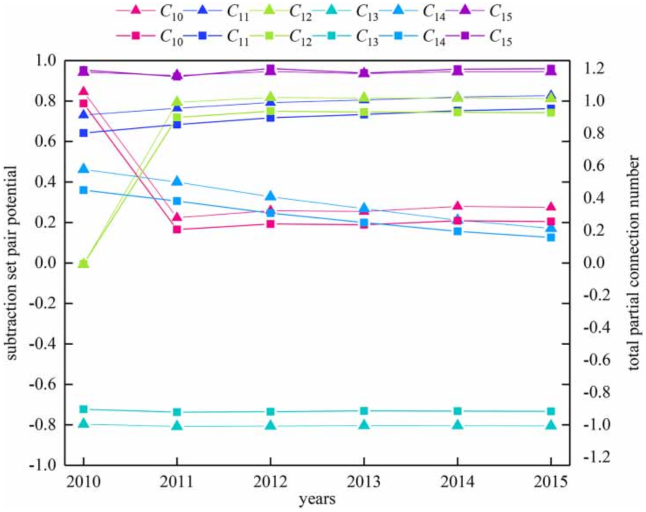

Figure 6 | Subtraction set pair potential and total partial connection number of each index of the pressure force subsystem in Huaibei City from 2010 to 2015. (C_{10} = daily domestic water consumption per capita, C_{11} = water consumption per 10^4 yuan, C_{12} = water consumption per 10^4 yuan of value-added by industry, C_{13} = density of population, C_{14} = rate of urbanization, C_{15} = water consumption per mu for agricultural irrigation. △ represents SPP, □ represents TPCN).

of the evaluation model were consistent with the local measured data, which shows the accuracy of the method to determine the connection number and the reliability of the evaluation model. Rate of vegetation coverage increased gradually from 2010 to 2015, but it was still counter potential in 2015, which was also an important reason for the poor WRCC. The SPP of water supply per capita first increased and then decreased, which shows that the construction capacity of water conservancy facilities, water supply capacity, management capacity of water transmission and distribution process needed to be further improved. It is worth noting that the large-scale water conservancy project under construction diverting water from the Yangtze River to the Huaihe River will provide available water resources for the relatively water deficient Northern Anhui and further solve the problem of water shortage.

(2) In the regulation force subsystem of the WRCC: the SPP of rate of water resources utilization, standard rate of sewage discharge and rate of ecological water consumption changed in the interval $[-1, -0.6]$, and the status was counter potential for a long time for these main indexes causing the poor WRCC in Huaibei City. Among them, the SPP of rate of water resources utilization continued to decline from 2010 to 2013, which may be related to the drought disaster caused by the low annual average rainfall in Huaibei City, resulting in over exploitation of groundwater. Zhu 2013 reported that Huaibei City was a semi-arid area of Anhui Province in eastern China which used to be an area rich in groundwater resources. For many years, the urban human living water and development of industry and agriculture mainly depended on the groundwater resources. After the 1980s, with the growth of population and the development of industry and agriculture, the over exploitation of groundwater had led to the decline of the groundwater level, and to other environmental and social problems (groundwater level from +36 m to −12 m). Although the SPP of rate of ecological water consumption increased slowly, it was counter potential. The SPP of standard rate of water function area showed an upward trend from 2010 to 2015, but it was still partial counter potential in 2015, indicating that standard rate of water function area was an important indicator of poor WRCC in Huaibei City. The SPP of gross domestic product per capita showed an overall upward trend, and the status fluctuated in the identical potential and partial identical potential, which was a factor to improve and enhance the WRCC. The variation trend of TPCN was the same as that of SPP, which showed that SPP was reasonable to diagnose vulnerability factors.

(3) For the pressure force subsystem of WRCC, in 2010–2015, the SPP of density of population changed in interval $[-1, -0.6]$, and the status was counter potential. According to the water resources bulletin, the density of population of Huaibei City changed from 754.99 person/km^2 in 2010 to 777.59 person/km^2 in 2015, indicating that it was the main factor of the poor WRCC. The SPP of rate of urbanization gradually decreased from 0.462 in 2010 to 0.171 in 2015, with the trend of transition from partial potential to equilibrium potential, which was an important factor of the poor WRCC. The trend of daily domestic water consumption per capita, water consumption per 10^4 yuan and water consumption per mu for agricultural irrigation was identical potential, which can not be considered as the cause of the poor WRCC. The SPP of water

consumption per 10^4 yuan of value-added by industry gradually increased from −0.008 in 2010 to 0.812 in 2015, which was an important factor to improve the WRCC of Huaibei City. It was related to the promotion of water saving, the use of water-saving products and the overall improvement of workers' operation technology.

The above analysis results show that the method of determining the connection number proposed in this paper is reasonable. The evaluation model of WRCC based on SPA and PCN can examine the micro motion between connection number components, and quantitatively express the micro motion, so as to make the evaluation results more objective and accurate; the vulnerable subsystems and indexes causing poor WRCC in Huaibei City were accurately identified. This method can describe the microscopic movement of the connection number more deeply, has strong explanatory power, and the recognition result is reliable. It can quantitatively distinguish the relative deterministic carrying status and its development trend under the current macro state.

4. CONCLUSION

In this paper, an evaluation index system and evaluation grade standard of a regional WRCC were constructed by the principle that the regional water resources support, regulate and pressure forces interact to form the regional water resources carrying status. Then, according to the basic principle and connotations of SPA and PCN, a method to determine the connection number was proposed. Finally, a dynamic evaluation model of a regional WRCC based on SPA and PCN was constructed and applied to Huaibei City, Anhui Province. The following conclusions can be drawn:

(1) In 2010–2015, the evaluation grade value of water resources capacity of Huaibei City was between 2 and 3, and it was in the critical overloaded and overloaded status for a long time. The vulnerable subsystems which caused the poor water resources carrying capacity of Huaibei City were the support force subsystem and regulation force subsystem. The vulnerability indexes that caused the poor WRCC were: water resources per capita, production modulus of water resources, water supply per capita and rate of vegetation coverage in the support force subsystem. The water resource shortage was very obvious in Huaibei City. Rate of water resources utilization, standard rate of sewage discharge, rate of ecological water consumption in the regulation subsystem and density of population in the pressure subsystem needed to be artificially regulated to alleviate or solve the existing poor situation. In addition, gross domestic product per capita and water consumption per 10^4 yuan of value-added by industry were two important indicators used to improve the WRCC of Huaibei City. The above evaluation and diagnosis results were in good agreement with the existing research results, indicating that the construction of the evaluation model was reasonable and effective.

(2) The migration matrix constructed based on the PCN principle can quantitatively express the balance mechanism of micro motion between the connection number components, and can clearly see the micro evolution under the macro state, thus the connection number can be determined. Based on the components of the connection number determined by the method in this paper, the vulnerability subsystems and indexes of the Huaibei WRCC system can be accurately identified by SPP; the trend of SPP was consistent with that of the TPCN, and the identification results were in good agreement with the local measured data. It can be seen that the method of determining connection number proposed in this paper was reasonable and effective. The constructed model can accurately identify the vulnerability subsystems and indexes, which is an intelligent method of 'system state trend analysis'.

(3) The evaluation model of regional WRCC based on SPA and PCN has strong adaptability, the status of regional WRCC was evaluated, and the vulnerable subsystems and indexes causing the poor WRCC were diagnosed and identified. This provided a new way for the determination of a connection number, the dynamic analysis of WRCC system, the judgment of its development trend, and had the value of popularity and application in water resources research and decision-making management.

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CONFLICT OF INTEREST

The authors have declared no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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