Evaluation of water resources system vulnerability based on co-operative co-evolutionary genetic algorithm and projection pursuit model under the DPSIR framework

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Abstract. Water resources vulnerability control management is essential because it is related to the benign evolution of socio-economic, environmental and water resources system. Research on water resources system vulnerability is helpful to realization of water resources sustainable utilization. In this study, the DPSIR framework of driving forces-pressure–state–impact–response was adopted to construct the evaluation index system of water resources system vulnerability. Then the co-evolutionary genetic algorithm and projection pursuit were used to establish evaluation model of water resources system vulnerability. Tengzhou City in Shandong Province was selected as a study area. The system vulnerability was analyzed in terms of driving forces, pressure, state, impact and response on the basis of the projection value calculated by the model. The results show that the five components all belong to vulnerability Grade II, the vulnerability degree of impact and state were higher than other components due to the fierce imbalance in supply-demand and the unsatisfied condition of water resources utilization. It is indicated that the influence of high speed socio-economic development and the overuse of the pesticides have already disturbed the benign development of water environment to some extents. While the indexes in response represented lower vulnerability degree than the other components. The results of the evaluation model are coincident with the status of water resources system in the study area, which indicates that the model is feasible and effective.

1. Introduction

As the combined influence of climate change and human activities, the shortage of local water resources is becoming an increasingly serious problem. In order to realize the water resources system sustainable utilization, it is necessary to make a reasonable evaluation of the water resources system vulnerability. At present, the research on water resources system vulnerability is mainly carried out from qualitative to quantitative gradually. In general the water resources system is always regarded as a whole to conduct the research, while it is seldom to analyse the influence of the different components to the whole system.

The purpose of this study is to evaluate the vulnerability of regional water resource system. An index system based on the DPSIR framework and the Projection Pursuit model are applied to synthesizing the socio-economic and environmental factors which may impact the vulnerability of water resources and understanding the distinct cause-and-effect relationships in regional water resources system.
2. Construction of the evaluation index system of water resources system vulnerability

2.1. Connotations of water resources system vulnerability
In the process of water resources utilization in domestic living, production and environment, water resources system vulnerability, which is derived from the temporal-spatial distribution characteristic of water quality and quantity in particular area, has easily damaged property showed up when system is threatened by climate change, natural disaster, human activity and so on. If the damage is allowed to continue, the forces will be accumulated to a certain extent which causes severely damage to water resources system [1-3].

Combined with the characteristics of water resources system, the connotations of water resources system vulnerability in this study are as follows: (1) Water resources system vulnerability is a state which reflects the vulnerability degree acted by the external forces. (2) Water resources system vulnerability has the temporal-spatial properties. (3) Natural condition is the determinant of the intrinsic vulnerability of the water resources system, while the human activity plays a determined role in the extrinsic influences and it is the driving factor. (4) Time delay characteristics: When acted by the external forces, water resources system will try to keep the original state, thereby the system will show up time delay features from being acted by the external forces to showing up the vulnerability. (5) Recessive characteristics: when the system hasn’t show up the vulnerability clearly, it cannot be accounted for the inexistence. Only by being forced to withstand enough external threatens, the system vulnerability characteristics could be shown up clearly. (6) Reversibility: System vulnerability can be reduced by effective measures implementation.

2.2. Construction of the evaluation index system of water resources system vulnerability based on DPSIR framework
A number of studies in water resources system problems analyzing were used the DPSIR framework model [4, 5]. Bowen and Riley used the framework for analyzing the interrelationships of socio-economic and coastal environmental dynamics. The crucial driving forces which impacted on the changes in groundwater ecosystems status due to human activities were analyzed [6, 7]. Combined with other methodologies, DPSIR framework was applied to research the correlative pressures and influences of changes in coastal area water quality for evaluating the feasibility of the European Water Framework Directive [8]. Considered with environmental and socio-economic sciences, the original DPSIR framework was used for addressing the primary issue of eutrophication [9]. Bianet Jago-on et al. integrated the existing data of subsurface environment to understand the interrelationships among subsurface environmental issues with DPSIR framework [10]. River environmental conditions in Balkans were analyzed with DPSIR framework [11]. Correlation studies have demonstrated that the DPSIR framework is an effective method to assess the sustainability in agriculture and water management with the core of “cause-effect relationship” [12, 13]. The DPSIR framework was utilized widely in water resources system sustainability and vulnerability evaluation through combining with data mining and intelligent algorithm technology [14, 15]. Thus, the DPSIR framework is a helpful approach in analyzing the relationships between water resources and socio-economic systems because of its effect on addressing the causes, impacts and responses to changes in water resources system [16, 17].

For evaluating the water resources system vulnerability, socio-economic factors, ecological environment factors and intrinsic factors of water resources system should be synthesized. At present, the widely used DPSIR framework can reflect the system’s integrity, causal association and co-evolution characteristics. Also it can represent the continuous feedback mechanism of the different kinds of factors in water resources system, which provides a good research approach to analysis the water resources system vulnerability. By consulting the existing framework of the index system of water resources system and the correlational researches of the water resources system vulnerability, 31 indexes were chosen in this study to construct the evaluation index system of water resources system vulnerability based on the DPSIR framework (table 1). In the progress of choosing the indexes, one
important consideration was the overlap of the indexes. If some indexes had similar meaning, the more commonly used index would be chosen.

In this study, the DPSIR framework was applied to understanding the linkages and interdependencies of socio-economic, eco-environment and water resources system. Causal relationships of water resources system issues are analyzed using information from water resources bulletins, statistical communiques on national economic and social development, and results from previous studies in order to create links and indicators of the components of DPSIR.

Based on the review of different studies, researches in vulnerability evaluation field (Kyung, et al. 2011), the cause and effect relationship between socio-economic system and water resources system in the DPSIR framework are shown in figure 1.

![Figure 1. The cause and effect relationships of DPSIR Framework in this study.](image)

2.3. Standard of the evaluation index

For evaluating the vulnerability scientifically and reasonably, the grade standard is essential to measure the degree of vulnerability. Based on the review of related researches (Wang and Zhang, 2010), the hierarchical evaluation grades dividing is a critical and difficult step. If the number of grades is too few, the accuracy of the evaluation results would be affected; otherwise it is too cumbersome with too many grades. In this study, the evaluation criterion of water resources system vulnerability was divided into 4 grades: grade I - weak vulnerability, grade II - medium vulnerability, grade III - strong vulnerability, grade IV - very strong vulnerability (table 1).

| Indicators    | Units            | Description                        | Grade I | Grade II | Grade III | Grade IV |
|---------------|------------------|------------------------------------|---------|----------|-----------|----------|
| Driving forces| Drought index $D_1$ | annual evaporative power           | <1      | 1~2      | 2~4       | >4       |

Table 1. Evaluation index system and evaluation criterion of water resources system vulnerability based on DPSIR.
|                     |                     |                     |     |          |          |     |
|---------------------|---------------------|---------------------|-----|----------|----------|-----|
| Precipitation $D_2$ | mm                  | water depth that    | >800| 500–800  | 200–500  | <200|
|                     |                     | was converted       |     |          |          |     |
|                     |                     | from liquid and     |     |          |          |     |
|                     |                     | solid water falling |     |          |          |     |
|                     |                     | down to the earth   |     |          |          |     |
|                     |                     | from the atmosphere |     |          |          |     |
| Natural population growth rate $D_3$ | % | trend of natural growth of population | <2 | 2~15 | 15~20 | >20 |
| Primary industry proportion $D_4$ | % | Ratios of primary industry to GDP | <3 | 3~15 | 15~30 | >30 |
| Tertiary industry proportion $D_5$ | % | Ratios of tertiary industry to GDP | >60 | 45~60 | 30~45 | <30 |
| Urbanization rate $D_6$ | % | Ratios of urban population to total population | >80 | 50~80 | 20~50 | <20 |
| Pressure Average per capita water resources $P_1$ | m³ | multi-year average per capita water resources | >1700 | 1000~1700 | 500~1000 | <500 |
| Average per mu water resources $P_2$ | (m³, hm²) | multi-year average per mu water resources | >1500 | 700~1500 | 400~700 | <400 |
| Cropland acreage per capita $P_3$ | hm² | Cropland acreage per capita in Tengzhou | >1 | 0.6~1 | 0.1~0.6 | <0.1 |
| Industrial COD emission concentration $P_4$ | (mg.L⁻¹) | COD emission concentration in industrial sewage in the region | <60 | 60~100 | 100~150 | >150 |
| Urban per capita green area $P_5$ | m² | urban public green area per capita in the region | >10 | 8~10 | 7~8 | <7 |
| Per capita water consumption $P_6$ | (m³,a⁻¹) | annual per capita water consumption in the region | <500 | 500~800 | 800~1000 | >1000 |
| Urban per capita domestic water consumption $P_7$ | (L.d⁻¹) | domestic water consumption in the urban area | <75 | 75~150 | 150~200 | >200 |
| State Water consumption for industrial added value of ten thousand yuan $S_1$ | (m³, ten thousand yuan⁻¹) | Ratios of industrial water supply to gross industrial production in the region | <30 | 30~90 | 90~200 | >200 |
| Exploitation and utilization | % | Ratios of exploited | <30 | 30~60 | 60~100 | >100 |
| Efficiency of Underground Water $S_2$ | Groundwater to exploitable groundwater |
|--------------------------------------|--------------------------------------|
| Agricultural Water Proportion $S_3$ | Ratios of agricultural water to total water consumption in the region |
| Leakage Rate of Pipe Network $S_4$ | Ratios of water leakage to water consumption leaving the factory in the region |
| Unit Area Irrigation Water Consumption $S_5$ | (m$^3$. hm$^{-2}$) Average irrigation water consumption in per mu of farmland |
| Water Consumption per Unit of GDP $S_6$ | (m$^3$. ten thousand yuan $^{-1}$) Ratios of water supply in the region to Gross Domestic Product |

| Impacts | Forest Coverage Rate $I_1$ | Percentage of forestry area in the region to area of land |
|---------|---------------------------|--------------------------------------------------------|
|         | Ratio Up to the Standard of Water Quality $I_2$ | Ratios of amounts that is up to the standard of water quality to total amounts of water sources in the city |
|         | Green Coverage Rate $I_3$ | Percentage of green coverage area to total area of the land in the city |
|         | Proportion of Eco-Environmental Water Consumption $I_4$ | Ratios of off-stream eco-environmental water consumption to total water consumption |
|         | Grain Yield per Cubic Meters of Water $I_5$ | Ratios of agricultural production water consumption to grain yield |

| Responses | Utilization Rate of the Recycled Water $R_7$ | Ratios of utilized recycled water |
|-----------|---------------------------------------------|----------------------------------|

| $\%$ | $<40$ | $40-55$ | $55-75$ | $>75$ |
|------|-------|-------|-------|-------|
| $\%$ | $<5$  | $5-15$ | $15-30$ | $>30$  |
| (m$^3$. hm$^{-2}$) | $<3000$ | $3000-5200$ | $5200-7200$ | $>7200$ |
| (m$^3$. ten thousand yuan $^{-1}$) | $<100$ | $100-200$ | $200-400$ | $>400$ |
| $>60$ | $40-60$ | $10-40$ | $<10$ |
| $100$ | $98-100$ | $90-98$ | $<90$ |
| $>60$ | $30-60$ | $10-30$ | $<10$ |
| $>5$  | $3-5$  | $2-3$  | $<2$  |
| $>3$  | $1.5-3$ | $0.6-1.5$ | $<0.6$ |
| $>20$ | $10-20$ | $5-10$ | $<5$  |
3. Establishment of evaluation model of water resources system vulnerability based on co-operative co-evolutionary genetic algorithm (CCGA) and projection pursuit

3.1. Co-operative co-evolutionary genetic algorithm
CCGA is a kind of GA based on multi-population’s concurrent evolution, which is more suitable for solving the complex optimization problems because multi-population can better correspond to objects of different nature.

CCGA provides a feasible approach in which it is relatively convenient to integrate a variety of evolutionary methods, while still containing the fundamental evolutionary behaviors of iterative
Figure 2. The Calculation procedures of CCGA according to DPSIR framework [22].
procedures in the algorithm [18-20]. Considering the five components of DPSIR framework, CCGA was applied by dividing five sub-populations as a suitable approach to calculate the optimal projection value of Projection Pursuit Model for evaluating the vulnerability of water resources system. The CCGA computing process is shown in figure 2 and the main procedures are as follows [21]:

**Main procedures:**

```
for each sub-population s do begin
    Pop_s(gen) = randomly initialized population (0-1)
    evaluate fitness of each individual in Pop_s(gen)
end for
while termination condition = false do begin
    gen = gen + 1
    for each sub-population s do begin
        select Pop_s(gen) from Pop_s (gen -1) based on fitness evaluation
        apply genetic operators to Pop_s(gen)
        evaluate fitness of each individual in Pop_s(gen)
    end for
end while
```

First, based on the research contents and the review of related researches, the evaluation model of water resources system vulnerability was established. And the initial population was divided into five sub-populations according to the structure of DPSIR framework. In this way the complex multivariable problem could be converted into five simple problems by sub-population genetic algorithm operating. Each sub-population evolved independently and only exchanged information when it was time to evaluate the individuals with other sub-populations. Secondly, an optimal individual and a representative individual in each other sub-population were selected to form be-evaluated combinations with the individuals in the be-evaluated sub-population, each be-evaluated individual was participated in two combinations forming, one combination was formed with the optimal individual in each other sub-population, and the other combination was with the representative individual in each other sub-population. Thirdly, every individual in be-evaluated sub-population was evaluated by comparing the fitnesses of two combinations in which the be-evaluated individual had been participated the forming. And the combination with the better fitness was preserved (figure 3). The fitness of each individual in each sub-population was calculated and the optimal combination of each generation was preserved after comparing procedure. Then all the optimal combinations of each generation were compared for finding the global optimal combination as the optimal projection direction to calculate the projection values.

### 3.2. Projection pursuit

In this study, projection pursuit was selected due to its fundamental which high dimensional data can be projected to low dimensional space. By optimizing projection index function, projected vector, which can reflect the characteristics of high dimensional data can be found. Without giving the weight of the evaluation index in advance, the artificial disturbance can be avoided by analyzing data in the low-dimensional space. \( p \) was defined as the amount of indexes in water resources system vulnerability evaluation. \( n \) was defined as the amount of samples. \( \{ x_i^* | i = 1, 2, ..., n \} \) was defined as sample value of the evaluation index system of water resources system vulnerability. \( \{ x_i | i = 1, 2, ..., n \} \) was defined as standardized index value. \( z_i \) was defined as projection eigenvalue of sample \( i \) in one-dimensional linear space [23, 24].
Figure 3. Fitness calculation and evaluation in CCGA [22].

3.3. Evaluation model of water resources system vulnerability based on co-operative co-evolutionary genetic algorithm and projection pursuit

The steps of the establishment of evaluation model of water resources system vulnerability based on co-evolutionary genetic algorithm and projection pursuit are as follows.

Step 1: standardization of indexes. Since different units of basic indexes were utilized in socio-economic, water resources and environmental system of DPSIR framework, a trade-off operate was required to normalize the actual values of the indexes. The following equation was used on the indexes which had the opposite change tendency compared with the water resources system vulnerability.

\[
x_{ij} = \frac{x_{i}^{*} - x_{\text{min},j}}{x_{\text{max},j} - x_{\text{min},j}}
\]

In a similar way the following equation was used on the indexes which had the same change tendency compared with the water resources system vulnerability.

\[
x_{ij} = \frac{x_{\text{max},j} - x_{i}^{*}}{x_{\text{max},j} - x_{\text{min},j}}
\]

In equation (2), \( x_{\text{max},j} \) and \( x_{\text{min},j} \) were defined as the maximum and minimum of the index \( j \) of the index system respectively. The values of \( x_{i,j} \) which were calculated by equations (1) and (2) were evaluation indexes in the region of \([0, 1]\).

Step 2: index function construction of projection pursuit. The essence of projection pursuit was to find the optimal projection direction which could reflect the data characteristics to maximum extent and contain the data information fully. And \( z_{i} \) was the one-dimensional projection value by multiplying \( x_{ij} \) by \( a = (a_{1}, a_{2}, ..., a_{p}) \).

\[
z_{i} = \sum_{j=1}^{p} a_{j} \cdot x_{ij}
\]

In equation (3), \( a_{j} \) was defined as vector of unit length, and \( \sum_{j=1}^{p} a_{j}^{2} = 1 \).
If \( a = (a_1, a_2, \ldots, a_p) \) was the optimal projection direction, put it into the equation (3) and the projection values of water resources system vulnerability could be calculated, and then water resources system vulnerability could be analyzed quantitatively. When projection values were synthesized, more information of \( z_i \) was expected to extract. So projection indicator function \( Q(a) \) was constructed as the basis to choose the optimal projection direction. \( Q(a) \) could be calculated by the following equation:

\[
Q(a) = S_z D_z
\]  
(4)

\[
S_z = \sqrt{\frac{1}{n-1} \sum_{i=1}^{a} (z_i - \bar{z})^2}
\]  
(5)

\[
D_z = \sum_{i=1}^{n} \sum_{k=1}^{n} (R - r_{ik}) \cdot f(R - r_{ik})
\]  
(6)

In equations (4) and (5), \( S_z \) was defined as standard deviation of projection value \( z_i \). \( D_z \) was defined as local density of projection value \( z_i \). \( \bar{z} \) was defined as average value of projection value \( z_1, z_2, \ldots, z_m \). \( R \) was defined as window radius of local density, which could be got by experiment and the value was 0.1 times of \( S_z \) in general. \( f(R - r_{ik}) \) was defined as unit step function. When \( R > r_{ik} \), \( f(R - r_{ik}) = 1 \); otherwise \( f(R - r_{ik}) = 0 \). The bigger \( D_z \) was, the more obvious the classification was.

When projection indicator function \( Q(a) \) reached the maximum, the optimal projection direction could be found.

Step 3: projection indicators function optimization using CCGA model. As the scheme set of samples was confirmed, the change of projection indicator function \( Q(a) \) was only concerned with the projection direction \( a \). When \( Q(a) \) reached the maximum, \( a \) was the optimal projection direction. The maximum objective function and constraint condition were as follows:

\[
\begin{cases}
\text{max } Q(a) \\
\|a\| = 1
\end{cases}
\]  
(7)

The maximum objective function was a complex non-linear optimization problem, in which \( \{a_j|j = 1, 2, \ldots, p\} \) was optimization variable. Then CCGA was chosen to optimal the results, there were five sub-populations, and the variables amount in Driving forces sub-population was 6, in Pressure sub-population was 7, in State sub-population was 6, in Impact sub-population was 5, in Response sub-population was 7.

Step 4: classification of evaluation standards and the evaluation model application in study area. First, according to the index value corresponded with the vulnerability evaluation grade, put the optimal projection direction \( a^* \) calculated by standardization into equation (3) to get the range of the projection value corresponded with each grades, so that the grade division standard of the system vulnerability could be determined. Secondly, put \( \{x_{ij}|i = 1, 2, \ldots, n; j = 1, 2, \ldots, p\} \) into equation (3) to calculate the projection value \( y \) of water resources system vulnerability in the study area. The vulnerability range could be confirmed and the evaluation of water resources system vulnerability in study area could be measured comparably with the projection values of evaluation standard grades.

### 4. Application example

#### 4.1 General situation in study area

The data used in this study mainly includes meteorological, socio-economic, and water utilization data. The socio-economic data were taken from the “Tengzhou Statistical Yearbook”. The hydrologic data
were provided by the water authority in Tengzhou (Water Authority in Tengzhou, 2009) and obtained from Tengzhou City Water Resources Sustainable Utilization Planning Report.

Tengzhou City in Shandong Province was selected as the example to conduct the evaluation of water resources system vulnerability in this study. Tengzhou City is located at 116°49'E ~ 117°24'E and 34°50'N ~ 35°17'N in the south of Shandong Province (figure 4), with plenty of sunshine and good rainfall. The multi-year (1956 ~ 2008) mean precipitation is 753.9 mm. The historical maximum precipitation is 1216.8 mm (2003), and the historical minimum precipitation is 433.0 mm (1981). The area belongs to Nansi Lake in Huaihe River Basin. There are hundreds of rivers in the city and five of them are main rivers which had more than 100 km² drainage area. There are 2 large and medium-sized reservoirs, 4 small reservoirs of which the capacity is more than 1 million but less than 10 million cubic meters, 22 small reservoirs of which the capacity is more than 0.1 million but less than 1 million cubic meters, and 227 pond and retaining dams. Tengzhou City has edged itself into the top one hundred countries of the economic competition for years. The industrial structure proportion is 9.6:58.4:32, and per capita GDP has reached 30460 yuan (2008). Called the granary in the south of Shandong Province, it is listed as the commodity grain base and high quality vegetable base in the country. The industry of coal, electricity, chemical industry, construction materials, light industry, cottonocracy and others are all benignly developed in the city. Because of the important occupation in economic and social development, Tengzhou City has a large demand of water. The evaluation of water system vulnerability of Tengzhou City is helpful to make a further understanding about the state of water resources in this region, so that water resources can be taken more advantages and be protected, which will promote the sustainable development of water resources system.

![Figure 4. Location of the study area.](image)

4.2 Water resources vulnerability evaluation

According to the collected data, the data in 2008 were more informative, comprehensive and accurate. In order to ensure the reliability of the research, the data in 2008 was chosen to evaluate water resources system vulnerability in Tengzhou City. Taken collected data, related reports and statistic yearbook into consideration, 31 indicator values of driving forces-pressure-state-impact-response would be achieved. After standardizing the indices by equations (1) and (2) in accordance with each characteristics, and then the standardized indices were optimized by equations (3) to (7). The optimal projection direction of each index was listed in table 2.
According to tables 1 and 2, the degree of system vulnerability could be calculated by equation (3) (table 3). After standardized index value of Tengzhou City was put into equation (5), the projection value of vulnerability was 3.087. The result showed that the water resources system vulnerability in Tengzhou City belonged to grade II in the medium degree.

| Serial number | Index value | Projection direction | Serial number | Index value | Projection direction | Serial number | Index value | Projection direction |
|---------------|-------------|----------------------|---------------|-------------|----------------------|---------------|-------------|----------------------|
| D1            | 1.36        | 0.136                | P6            | 241.4       | 0.146                | I4            | 2.55        | 0.185                |
| D2            | 757.1       | 0.207                | P7            | 61.6        | 0.215                | I5            | 3.8         | 0.167                |
| D3            | 3.75        | 0.153                | S1            | 30.1        | 0.16                  | R1            | 16.7        | 0.162                |
| D4            | 6.63        | 0.132                | S2            | 96.88       | 0.141                | R2            | 46.13       | 0.152                |
| D5            | 32          | 0.187                | S3            | 66.05       | 0.164                | R3            | 75          | 0.195                |
| D6            | 25.08       | 0.181                | S4            | 22          | 0.187                | R4            | 100         | 0.21                 |
| P1            | 407         | 0.21                 | S5            | 249.78      | 0.193                | R5            | 0.59        | 0.171                |
| P2            | 563         | 0.161                | S6            | 83.9        | 0.217                | R6            | 71.1        | 0.181                |
| P3            | 0.7         | 0.186                | I1            | 26.8        | 0.205                | R7            | 56          | 0.185                |
| P4            | 68.78       | 0.171                | I2            | 100         | 0.166                |               |             |                      |
| P5            | 9.03        | 0.196                | I3            | 17.52       | 0.198                |               |             |                      |

According to the collected information of water resources development and utilization in 2008, the agricultural water had occupied a large proportion in Tengzhou City and most was adopted broad irrigation. According to Surface Water Environmental Quality Standard (GB 3838-98), water quality of Cross river in the upper and middle basin was ranked III and water quality of other places was ranked IV or V, so the water environment condition were not going well. There is an increasing trend of regional water resources system vulnerability due to the combined influence of water consumption and pollution. Auxiliary construction of project was on the low levels. Main irrigation canal didn’t match and the water efficiency in canal system of irrigation was very low in our country. Although the study area belongs to the water-affluent area in Shandong Province, water resources development and protection is also of significance. According to the results of evaluation of the model, water resources system vulnerability in Tengzhou City was belonged to the Grade II in the medium degree. It is showed that the result was conformed with the water resources situation to some extent, which indicated that the model was feasible and effective.

Water resources system vulnerability is the comprehensive performance which reflects the effect produced by different kinds of factors to water resources system. The same or similar evaluation results of water resources vulnerability may be caused by various reasons and the reflected problems are multifarious. In order to analyze the impact of various development stage in different components of index framework to the vulnerability, first of all the index system of Driving forces-Pressures-States-Impacts-Responses was put into the model to calculate the optimal projection direction, then the projection values of $z_{cd}^*$ ($c=1,2,...,5$) was defined as the different departments of
DPSIR, \( d = I, II, III, IV \) was defined as the different grades of the standard) corresponded with the grade and the projection values \( y_i \) could be calculated. Secondly the projection values of \( z_{cd}^* \) and \( y_i \) were adjusted to integer between 0 and 4 for comparing and analyzing effectively. For example, the scope of projection values \([1.475, 2.066)\) in grade \( II \) of driving type was adjusted to \([2, 3)\) and the \( y_i = 1.58 \) was adjusted to 2.18. The other projection values were adjusted in the similar way (table 4). Lastly, radar map was drew to show the projection values after the standard transformation (figure 5). From figure 5, results could be concluded as the followings: (1) the five components of the DPSIR framework are all belonged to grade \( II \) in the medium degree and the vulnerability degree of indexes of impacts type and states type was higher than others, which indicated that the influence of high speed economic and social development and the overuse of the pesticide had already destroyed the water environment to some extent. (2) the water resources system vulnerability has been mainly influenced by the fierce imbalance between supply-demand of water resources and the weakness condition of water resources utilization. (3) the indexes of responses type had less impact which indicated that by measures, such as improving the utilization ratio of reuse water and saving more water, adaptive capacity of water resources system towards social-economic development could be improved accordingly relying on scientific and technological progress.

**Table 4.** The contrast of the projection values before and after the standard transformation.

| Index type | Projection values of different grades \( z_{cd}^*(i) \) | Projection values \( y \) | \( y \) projection values after the integer normalization |
|------------|-----------------------------------------------------|--------------------------|-----------------------------------------------------|
| D          | \( \geq 2.066 \) [1.475, 2.066) \( ]0.861, 1.475) \) \(<0.861 \) 1.58 2.18 |
| P          | \( \geq 1.501 \) [1.001, 1.501) \( ]0.667, 1.001) \) \(<0.667 \) 1.24 2.48 |
| S          | \( \geq 2.086 \) [1.635, 2.086) \( ]0.999, 1.635) \) \(<0.999 \) 1.67 2.09 |
| I          | \( \geq 1.208 \) [0.821, 1.208) \( ]0.358, 0.821) \) \(<0.358 \) 0.83 2.02 |
| R          | \( \geq 1.83 \) [1.12, 1.83) \( ]0.547, 1.12) \) \(<0.547 \) 1.62 2.70 |

**Figure 5.** The structure of the water resources system vulnerability in study area.

5. **Conclusions**

The DPSIR framework was adopted to construct the evaluation index system of water resources
system vulnerability. And then the co-evolutionary genetic algorithm and projection pursuit was used to establish evaluation model of water resources system vulnerability. The system vulnerability in Tengzhou City was analyzed in terms of Driving forces, Pressure, State, Impact and Response on the basis of the projection value calculated by the model. The results are coincident with the state of water resources in study area, while indicate that the model is feasible and effective.

Due to the limitations of data, this study only evaluated the vulnerability in 2008. On condition that enough data are available, multi-sample analysis of water resources system vulnerability could provide more bases for the local water resources management. Water resources system vulnerability can be reduced by improving water usage efficiency, capital investment, pollution control, total water consumption control and water quota management.

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