A Novel Water Quality Assessment Method Based on Combination BP Neural Network Model and Fuzzy System

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***Abstract*—As the forefront of complex nonlinear science and artificial intelligence science, artificial neural network has began to be applied in the field of water quality control and planning step by step. According to the fuzzy feature of water quality information, this paper proposes a membership degree Back-Propagation network (MDBP) for water quality assessment with combining fuzzy mathematics and artificial neural network. The proposed MDBP model combines the merits of artificial neural network method and fuzzy evaluation method, which overcomes effectively the shortcoming of other assessment methods. With improving the accuracy and reliability of the assessment method, the method has a higher flexibility than other conventional approach and its programs have a better adaptability and more convenient application. The assessment method is closer to the reality with considering the continuity of the changes of water quality environment.**

***Index Terms*—Water Quality, Fuzzy Mathematics, Back-Propagation Neural Network, Assessment Method**

I. Introduction

The water quality assessment is basic program to plan and manage water quality and important base of computing water environment capacity and controlling water pollutant, which shows the total information of water environment quality. In practice, there are many assessment methods used to water quality assessment. For example, the integrated index approach shows the uncertain characters of water quality changes, which holds the needs of water quality function classification. The practice shows that all of these used methods need to suppose subjective parameters and concrete assessment mode, so the assessment results always have obviously subjectivity and restrained applicability. In theory, the artificial neural network method with potentiality can solve the problem. As for the artificial neural theory, the function of learning and memorizing can provide the basic theory and methods for water quality assessment mode and classification problem. In the reference [1] the un-point pollutant sources drainage area is assessed by using the method of Bayesian concepts and combining artificial neutral network. In reference [2-4], the Back-Propagation network model with multi-input, multi-output and multi-layer is adopt to assess integrated water quality, and the qualitative description is used in water quality classification. But the shortcoming of this method is that the output mode must be obtained not by learning but artificially loading. Thus the assessment results can not be objective, direct and compact enough.

In this paper, a new water quality assessment method is studied, which can be so much more effective and objective to overcome the shortcoming of the present artificial neural network method. A membership degree Back-Propagation network for water quality assessment with combining fuzzy mathematics and artificial neural network is proposed, which combines the merits of artificial neural network method and fuzzy evaluation method, and then the model overcomes effectively the shortcoming of other assessment methods. So the assessment method is closer to the reality with considering the continuity of the changes of water quality environment. The experiment and analysis show that the new water quality assessment method which combines BP neural network model and fuzzy system is effective.

II. The Principle of Back Propagation Neural Network Model

A. The Basic Structure of Back Propagation Network Model

In 1985, Rumelhart and Meclelland proposed Back Propagation neural network model. Error Back Propagation usually called BP network in short, which is one of the most widely applied neural network model. [5]From the structure, BP network is typical multi-layer network which has not only input layer nodes and output layer nodes, but also one layer or multi-layer recessive nodes. In BP network, the consecutive layers are complete connected, but no connections in different nodes of same layer. [6]

The structure of the BP neural network model with three layers is shown as fig.1. In the BP neural network model, the weigh coefficients between different layers can be adjusted automatically. Except for the input layer, the process units in other layers have nonlinear input/output connection. That is to say, the characteristic

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functions of the process units are differentiable, which are usually S type function (Sigmoid function) $f(x)$, that is

$$f(x) = \frac{1}{1+e^{-x}} \tag{1}$$

The study process of BP neural network includes forward propagation and error back-propagation. If given some input mode, the BP network will study for every input mode in accordance with the followed methods. The input mode are transferred from input layers to the hidden layer units, by which the input mode can be processed, the new output mode will be transferred to output layer, that is called forward propagation. If the output mode is not expected, the error signals will return along the origin route, connection weights of neurons in every layer should be corrected to make the error signals least, that is error back-propagation. Forward propagation and back propagation repeatedly, until the expected output mode can be obtained

The learning process of BP network begin from a set of random weights and thresholds, any selected samples can be input. The output can be computed by forward-back method. Usually this error is big, the new weights and thresholds of the mode must be computed over again by the back propagation. For all of the samples, the process should be done repeatedly again and again, to get the appointed accuracy. In the process of network operation, the system error and single mode error can be followed. If the network learning successfully, the system errors will decrease with increasing of iterative time, at last converge at a set of steady weights and thresholds.

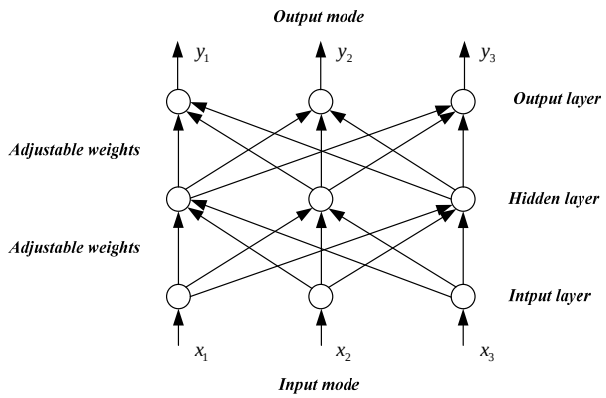

Figure 1. the BP network model structure with three layers

B. The Mathematical Principle of Back Propagation Network Model

The propagation formulas for BP network study are used to adjust the weights and thresholds. In fact, the network study process is a process in which weights and thresholds of network connection are revised repeatedly according to the propagation formula in the direction of least error. There are some symbol conventions:

O_i : output of node i ;

net_j : input of node j ;

w_{ij} : connected weight from node i to node j ;

θ_j : threshold of node j ;

y_k : actual output of node k in output layer;

t_k : expected output of node k in output layer. Obviously, for hidden node j :

$$\left.\begin{aligned} net_j &= \sum w_{ij} O_i \\ O_j &= f(net_j - \theta_j) \end{aligned}\right\} \tag{2}$$

In study process of BP algorithm, the errors of every output node can be computed according to the following formula:

$$e = \frac{1}{2}\sum_k (t_k - y_k)^2 \tag{3}$$

The connection weights can be corrected according to the following formula:

$$w_{ij}(t+1) = w_{ij}(t) + \Delta w_{ij} \tag{4}$$

In the formula, $w_{ij}(t)$ and $w_{ij}(t+1)$ are separately connection weights from node j to node k at time t and $t+1$; Δw_{ij} is variation of connection weights.

In order to improve the connection weights in the gradient change direction of error E, Δw_{ij} can be computed:

$$\Delta w_{ij} = -\eta \frac{\partial e}{\partial w_{jk}} \tag{5}$$

In the formula, η is gain factor, $\frac{\partial e}{\partial w_{jk}}$ can be computed:

$$\frac{\partial e}{\partial w_{jk}} = \frac{\partial e}{\partial net_k}\frac{\partial net_k}{\partial w_{jk}}$$

Thus

$$\frac{\partial net_k}{\partial w_{jk}} = \frac{\partial}{\partial w_{jk}}\sum_j w_{jk} O_j = O_j \tag{6}$$

$$\delta_k = \frac{\partial}{\partial net_k}$$

Thus

$$\Delta w_{ij} = -\eta \frac{\partial e}{\partial w_{jk}} = -\eta \delta_k O_j \tag{7}$$

When computing δ_k , it is essential to distinguish the output layer nodes and hidden layer nodes. If node k lies in output layer, thus:

$$\delta_k = \frac{\partial e}{\partial net_k} = \frac{\partial e}{\partial y_k}\frac{\partial y_k}{\partial net_k}$$

Because of

$$\frac{\partial e}{\partial y_k} = -(t_k - y_k) \qquad \frac{\partial y_k}{\partial net_k} = f'(net_k)$$

Thus

$$\left.\begin{aligned} \delta_k &= -(t_k - y_k) f'(net_k) \\ \Delta w_{jk} &= \eta (t_k - y_k) f'(net_k) O_j \end{aligned}\right\} \tag{8}$$

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If node k is not the node in output layer, connection weights effect on hidden node, then δ_k can be computed by the following formula:

$$\delta_k = \frac{\partial e}{\partial net_k} = \frac{\partial e}{\partial O_k}\frac{\partial O_k}{\partial net_k} = \frac{\partial e}{\partial O_k} f'(net_k) \tag{9}$$

That is

$$\frac{\partial e}{\partial O_k} = \sum \delta_m w_{km} \tag{10}$$

Thus

$$\delta_k = f'(net_k)\sum_m \delta_m w_{km} \tag{11}$$

The formula shows that δ in low layer can be computed by δ in the upper layer.

The learning process of BP network begin from a set of random weights and thresholds, any selected samples can be input. The output can be computed by forward-back method. Usually this error is big, the new weights and thresholds of the mode must be computed over again by the back propagation. For all of the samples, the process should be done repeatedly again and again, to get the appointed accuracy. In the process of network operation, the system error and single mode error can be followed. If the network learning successfully, the system errors will decrease with increasing of iterative time, at last converge at a set of steady weights and thresholds. [7]

C. The Study Algorithm of Back Propagation Network

In BP network model, the study algorithm of BP network can be described as the following rules.

Step 1 Initializing study parameters and BP network parameters. That is to set random numbers in $[-1,1]$ for Neuron threshold and connection weights in hidden layers and output layers.

Step 2 Proposing the training mode of BP network. That is to select a training mode from the training mode set, and put the input mode and expected output mode to the BP network.

Step 3 Forward propagation process. That is to compute the output mode of the network from the No.1 hidden layer for the given input layer. If error energizing, executing the step 4, else returning to step 2, and providing next training mode for the algorithm.

Step 4 Back propagation process. That is to correct the connection weight of every unit in different layer from output layer to the first hidden layer, and following the rules:

1) Computing the error δ_k of different units in the same layer.

2) Correcting the connection weights and threshold.

For connection weights, the correcting formula is:

$$w_{jk}(t+1) = w_{jk}(t) + \eta\delta_k O_j \tag{12}$$

For threshold, the correction method is same as the study method of connection weights.

3) Repeating the Above-mentioned correcting process to get expected output mode.

Step 5 Turn back to step 2, and doing step 2 to step 3 for the every training mode of training mode set, until every training mode meet the expected output.

III. The Principle of Back Propagation Neural Network Model

A. The Basic Principle of Fuzzy Mathematics

Assumed that X represents a set of some objects, which is called co domain. For a subset A in X, it can be expressed by its characteristic function, that is

$$\mu_A(x) = \begin{cases} 1 & x \in A \\ 0 & x \in \bar{A} \end{cases} \tag{13}$$

In this, μ_A is a function defined in X, its values belong to $\{0,1\}$,which is called characteristic function of A. For $x \in X$, if $\mu_A(x) = 1$, thus, x is element of A. But if $\mu_A(x) = 0$, thus, x isn't the element of A. So we can define fuzzy sets:

In co domain X, for any element $x \in X$, if there is a formula corresponding real function $\mu_A(x)$:

$$\begin{aligned} \mu_A(x):\ X &\to [0,1] \\ X &\to \mu_A(x) \end{aligned} \tag{14}$$

Then all elements x meeting the formula assemble a set which is a fuzzy set A in set X. For $x \in X$, μ_A is membership function of A. $\mu_A(x)$ is called membership degree from x to A.[6]

The Relationship that expresses uncertain relationship using fuzzy Sets is defined fuzzy relation. [8] Fuzzy relation R between set X and Y is fuzzy subset defined in $X \times Y$, its membership function is shown as:

$$\mu_R:\quad X \times Y \to [0,1] \tag{15}$$

If X is same as Y, so R is called the fuzzy relation in X. If the co domain is product of n sets $X_i (i = 1, 2, \cdots, n)$ $X_1 \times X_2 \times \cdots \times X_n$, its corresponding fuzzy relationship R is called n dimensions fuzzy relation.

If X and Y are both limited subsets, then $X = \{x_1, x_2, \cdots, x_m\}$, $Y = \{y_1, y_2, \cdots, y_n\}$, thus the fuzzy relation in $X \times Y$ can be expressed by :

$$R = \begin{bmatrix} \mu_R(x_1, y_1) & \mu_R(x_1, y_2) & \cdots & \mu_R(x_1, y_n) \\ \mu_R(x_2, y_1) & \mu_R(x_2, y_2) & \cdots & \mu_R(x_2, y_n) \\ \cdots & & & \cdots \\ \mu_R(x_m, y_1) & \mu_R(x_m, y_2) & \cdots & \mu_R(x_m, y_n) \end{bmatrix} \tag{16}$$

The above matrix is called fuzzy matrix, its element $\mu_R(x_i, y_i)$ in the scope of 0 between 1.

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B. The Design of Membership Degree BP Neural Network

The paper adopted a three layers BP network to build the membership degree BP network for water quality assessment. In the structure, the network has one input layer one output layer and one hidden layer. The output layer can expressed water quality classification by one neuron, actual testing parameters are six, so input layer has six neurons, hidden layer has three neurons [9].

In order to make the assessment more objective and certain, this paper puts the membership degree of fuzzy mathematics into BP network. The membership degree BP network model is built on combining the fuzzy system and neural network in series. In the series connection, output of neural network is input of the fuzzy system. Membership degree can be computed, then the exact and concrete water quality classification can be put out. The membership degree BP network for water quality assessment is shown as fig. 2.

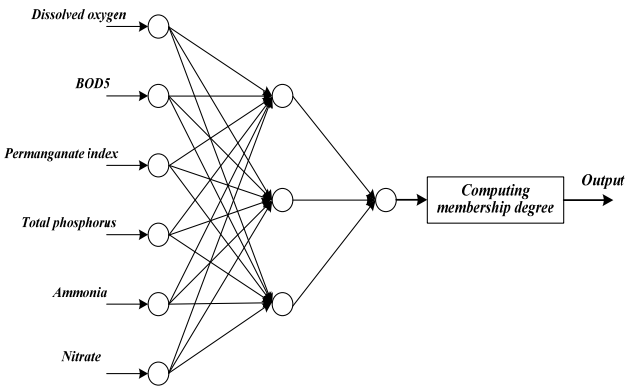

Figure 2. The framework of BP neural network combining membership degree

According to fuzzy mathematics theory, the standard water quality classification 1-5 as co domain can be defined. For n assessment parameters of some standard water quality classification, we suppose that the membership degree to itself is zero, so a fuzzy subset $\overline{E}$ can be gotten. We suppose that the membership degree to other is zero, subset $\overline{F}$ can also be gotten. In here, the membership degree to standard water quality classification for n assessment parameters of other water quality samples must belong to $[0,1]$, and building fuzzy subset $\overline{A}$. Therefore, the problem of assessing water quality sample transforms into computing the membership degree to two neighboring standard water quality classification. In this paper, the membership function is built as following formula.

$$u(x)=\begin{cases}1 & x=a\\ 1-f(x) & a<x<b\\ 0 & x=b\end{cases} \tag{17}$$

In the formula, a,b stand for the classification of neighboring two water quality samples, the membership degree to every standard water quality classification of test sample can be computed by the formula (17).

IV. THE PRINCIPLE OF BACK PROPAGATION NEURAL NETWORK MODEL

A.. The Model of BP Neural Network Algorithm

According to the point of mathematics, BP algorithm is a generalized function convergence numeric method, and it has training and testing processes. The whole training process includes forward and back propagation. After being built, the BP network model is tested by other samples to testify the effectiveness and validity of the model. The results show that the BP network model and its algorithm are effective. The algorithm of BP neural network is shown as in fig.3.

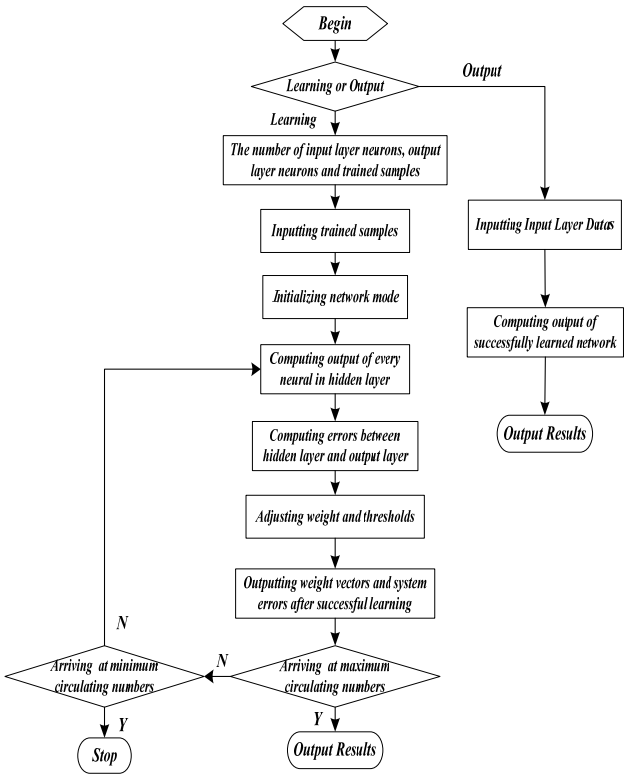

Figure 3. The algorithm process of BP neural network

B. The Training of BP Neural Network

The whole network training process includes forward propagation and error back-propagation, the training process are shown as followed.

1) Assignment the weighs w_xh, w_hy between nodes and need threshold u_h, u_y, the assigned values are Nonzero Random initial valuebetween (-1,1).

2) Inputting input vector X of one training sample and target output vector T.

3) Computing output vector Y.

Computing output vector H of hidden layers:

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$$\left.\begin{aligned} net_h &= \sum_i w_xh_{ih} \cdot X_i - u_h_h \\ H_h &= (net_h) = 1/1+\exp(-net_h) \end{aligned}\right\} \quad (18)$$

Computing output vector Y of output layers:

$$\left.\begin{aligned} net_j &= \sum_h w_hy_{hj} \cdot H_h - u_y_j \\ Y_j &= (net_j) = 1/(1+\exp(-net_j)) \end{aligned}\right\} \quad (19)$$

4) Computing the difference mount δ

Computing difference mount of output layers δ_j

$$\delta_j = Y_j(1-Y_j)(T_j - Y_j) \quad (20)$$

Computing difference mount of hidden layers δ_h:

$$\delta_h = H_h(1-H_h)\sum_j w_hy_{hj}\delta_j \quad (21)$$

5) Computing correction mount of weigh dw, and correction mount of threshold du.

Computing weigh correction mount of output layers dw_hy, correction mount of threshold du_y:

$$\left.\begin{aligned} dw_hy_{hj} &= \delta_j H_h \\ du_y_j &= -\eta\delta_j \end{aligned}\right\} \quad (22)$$

Computing weigh correction mount of hidden layers dw, correction mount of threshold du:

$$\left.\begin{aligned} dw_xh_{ih} &= \eta\delta_h X_i \\ du_H_h &= -\eta\delta_h \end{aligned}\right\} \quad (23)$$

6) Updating weigh mount w_hy, and threshold u_y.

Updating weigh mount of output layer w_hy and threshold u_y:

$$\left.\begin{aligned} w_hy_{hj} &= w_hy_{hj} + dw_hy_{hj} \\ u_y_j &= u_y_j + du_y_j \end{aligned}\right\} \quad (24)$$

Updating weigh mount of hidden layer w_hy and threshold u_y:

$$\left.\begin{aligned} w_xh_{ih} &= w_xh_{ih} + dw_xh_{ih} \\ u_h_h &= u_h_h + du_h_h \end{aligned}\right\} \quad (25)$$

(c) The testing of BP neural network

After being building, the character of model must be tested by using the samples which are not used in building the model, so that the Correctness and Practicality of the model can be verified.

The computing format of the testing process is showed as followed.

1) Adopted the stable Weight matrices after trained w_xh, w_hy and Threshold vector u_h, u_y.

2）Input vector X of testing samples.

3）Computing output vector Y.

Computing the output vector of hidden layer H:

$$\left.\begin{aligned} net_h &= \sum_i w_xh_{ih} \cdot X_i - u_h_h \\ H_h &= f(net_h) = \frac{1}{1+\exp^{-net_h}} \end{aligned}\right\} \quad (27)$$

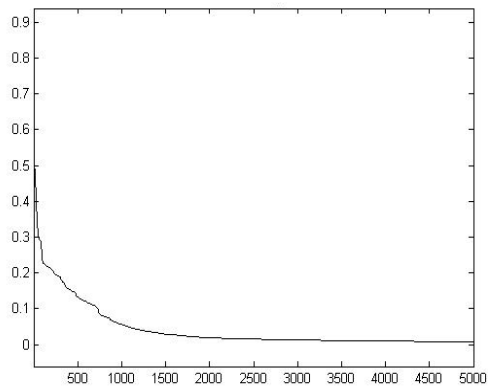
Computing the output vector of hidden layer Y:

$$\left.\begin{aligned} net_j &= \sum_h w_hy_{hj} \cdot H_h - u_y_j \\ Y_j &= f(net_j) = \frac{1}{1+\exp^{-net_j}} \end{aligned}\right\} \quad (28)$$

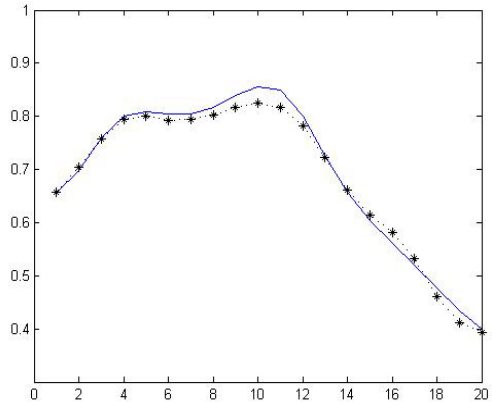
V. THE EXPERIMENT AND ANALYSIS OF BP NEURAL NETWORK FOR WATER QUALITY ASSESSMENT

In the learning process of network, some standard water quality classification is adopted in learning samples. With considering that the range of activation function is $[0,1]$, and water quality classification is from the first class to the fifth class, so the five water quality classifications are only part of the whole range, and no attaching the limited values 0 and 1.

In this paper, target outputs are $0.1, 0.3, 0.5, 0.7, 0.9$, and the output represents No.1-5 water quality classifications. As the most important parameters in debugging the BP network, learning rate $\eta = 0.68$, Impulse coefficient $\alpha = 0.5$, then the network can be trained after 1600 iterations.



(a) Errors curve of learning process



(b) Testing result curve of network for some samples

Fig. 4 The learning process curve of the network

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Then the accuracy of the trained network can be accepted. The accuracy of the trained network is accepted, and the learning process curves are shown in fig 4.

After being trained, the BP network has held the characters of water quality classification, which can recognize the samples effectively. In experiment, the testing results of membership degree BP network are shown as table1 & table 2.

TABLE I.

THE INTERMEDIATE RESULTS OF MEMBERSHIP DEGREE BP NETWORK

Index / Sample	Dissolved oxygen (mg/l)	BOD5	COD Mn	Total phosphorus	Ammonia	Nitrate	Output of network	Water quality classification
1	5.02	2.86	4.61	0.81	0.023	4.39	0.41	Ⅱ～Ⅲ, near Ⅲ
2	8.91	0.77	1.17	0.18	0.015	0.13	0.093	Ⅰ
3	6.78	3.42	3.32	0.23	0.07	0.93	0.17	Ⅰ～Ⅱ, near Ⅰ
4	7.56	0.71	0.71	0.19	0	0.1	0.096	Ⅰ
5	3.54	6.15	8.05	1.36	0.05	1.00	0.62	Ⅲ～Ⅳ, near Ⅳ
6	4.13	1.33	1.24	0.46	0.02	1.1	0.22	Ⅰ～Ⅱ, near Ⅱ
7	10.22	1.33	1.26	0.17	0	0.06	0.092	Ⅰ
8	6.32	4.57	5.56	0.78	0.19	0.97	0.42	Ⅱ～Ⅲ, near Ⅲ
9	9.67	1.57	3.16	0.21	0	0.31	0.1	Ⅰ～Ⅱ, near Ⅰ
10	4.96	6.58	6.55	1.1	0	0.23	0.56	Ⅲ～Ⅳ, near Ⅲ

TABLE II.

THE MEMBERSHIP DEGREE TESTING RESULTS OF SAMPLES TO STANDARD WATER QUALITY

Sample / Classification	1	2	3	4	5	6	7	8	9	10
Ⅰ	0	0.939	0.696	0.971	0	0.393	0.997	0	0.92	0
Ⅱ	0.425	0.061	0.304	0.029	0	0.607	0.003	0.45	0.08	0.729
Ⅲ	0.575	0	0	0	0.403	0	00	0.55	0	0.271
Ⅳ	0	0	0	0	0.597	0	0	0	0	0
Ⅴ	0	0	0	0	0	0	0	0	0	0

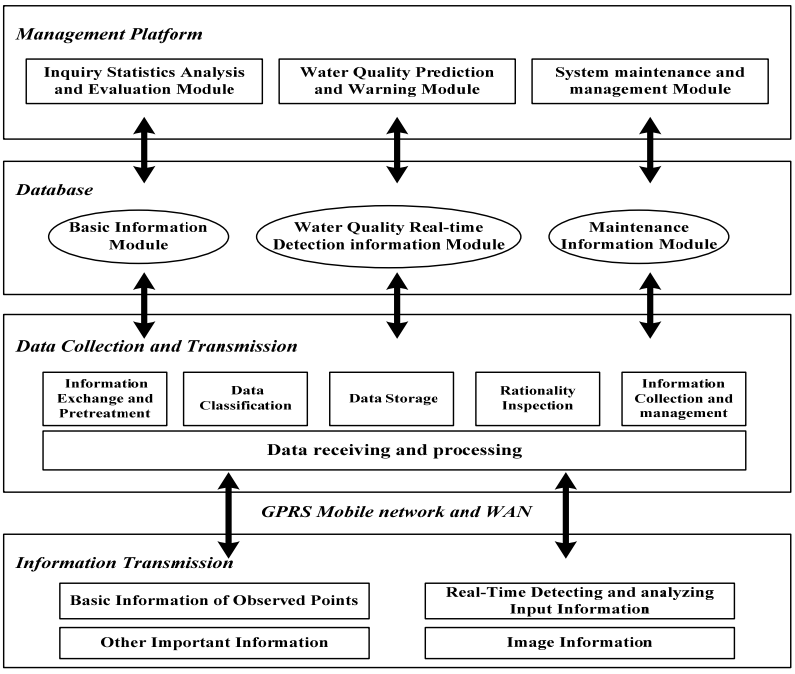

Fig.7 the Software structure of the prediction and warning system

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VI. THE NEW WATER QUALITY ASSESSMENT METHOD APPLIED IN THE PREDICTION AND WARNING SYSTEM

In the paper, the automatic prediction and warning system based on the new water quality assessment methods, which is a whole information system integrating computer hardware technique, communication technique, and software Intelligent analysis technology. The system includes monitoring terminal, user terminal, data transmission channel and data management center. The prediction and warning system can provide some water quality information for the department to making some decision. In the system, the water quality can be predicted based on hydrology and water quality data, natural and geographical environment, by the methods of software technology and theory of mathematical model. The water quality parameters predicted by the system include dissolved oxygen, total phosphorus, ammonia nitrogen, nitrate nitrogen, permanganate index and BOD 5. The software structure of system is shown as fig.7, which can be divided into water quality database module, integrated information analysis module, assessment report generation module, water quality trend analysis module.

The water quality database system includes both water quality database and geography information database. According to the above database, water quality data can be counted and evaluated. The water quality database covers monitoring network information, all kinds of water data and water composition for example total phosphorus, ammonia nitrogen, nitrate nitrogen, permanganate index and BOD_5etc. The geography information database mainly includes all kinds of geographical zoning maps. Based on web, the statistics and evaluation reports can be archived, queried and published automatically. In the system, the water quality trends can be predicted base on the BP model.

VII. CONCLUSIONS

The new water quality assessment method proposed in this paper integrates the fuzzy mathematics theory and artificial neural network. The theoretical analysis shows that the assessment method has theoretical feasibility and great practical utility. The new ideal and method in the paper propose a new way of water quality assessment and develop the application of artificial neural network. The experimental results and research demonstrate that the water quality assessment method has good prospects for further application and development.

VIII. ACKNOWLEDGMENT

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