Study of a diagnosis method of watershed water problems based on control units-- Taking Ashihe river basin as an example

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Abstract. The water quality often showed obvious spatial and temporal changes characteristics of a river system in the basin. However, the conventional water quality diagnosis method which based on the standard of cross-section, easily overlook the spatial-temporal characteristics of pollution load in the basin. Under the concept of ecological environment spatial management and control, the method for diagnosing water environmental problems which had been named the Equivalent pollution Load Duration Curve method was proposed. Combining the hydrological process of the main stream with the water quality concentration of the section, it could been used to effectively identify the main over standard pollutants and their sources in different control units of the river basin. From the results of the application evaluation of a certain basin, it showed that the excessive period was concentrated in the flood season. The main excessive factor was total phosphorus (TP) in the upstream area of the basin, which indicates that for the upstream control unit of the Basin, agricultural and other non-point sources were the main pollution sources. Meanwhile the main over standard pollutant was NH\textsubscript{3}-N, which was over standard in the whole period in the river estuary area. The pollution reduction control scheme of this control unit should focus on the industrial and living sources.

Keywords: control unit; diagnosis of water problems; improved Nemerow comprehensive pollution index method; Equivalent Load Duration Curve Method.

1. Introduction
In current basin management, the scholars generally believed that the key technologies of river basin management include not only water quality automatic monitoring system, water environment real-time control and demonstration system, but also accurate diagnosis of water problems, integrated basin environment simulation technology, water environment decision support system, and so on. As the first part of basic analysis, diagnosis of water problems method was based on water ecological function zoning, water quality requirements of water function areas. It had been used to analysis and evaluate physical, chemical and biological characteristics of the control unit. In order to determine the damage type and degree of the water body of the control unit, identify the main over-standard factors or factors that have large risk of exceeding the standard, and clarify the key points of water management.
As the most important primary tributary of the Songhua River Basin flowing through the urban area of Harbin, a large quantity of urban sewage, industrial wastewater and rural non-point source pollution flow into Ashihe river due to extensive development of social economy and destruction of ecological environment in recent years. The water quality in some parts of Ashihe river was defined as inferior grade V. These polluted parts have been listed in Water Pollution Control Planning in Songhua River Basin as tributaries with poor water quality. The pollution directly affects the quality of water environment in Harbin. The inner section of Ashihe river estuary was the only state-controlled inferior V-section stipulated in Objective Responsibility Letter for Water Pollution Prevention and Control of Heilongjiang Province. The task of water quality improvement in Ashihe River was grim and urgent. Therefore, Ashihe River Basin has also become the priority control unit of pollution control in Songhua River Basin.

In recent decades, due to the extensive economic growth structure, the low sewage treatment rate of industrial waste water and the high pollution intensity of agricultural non-point source, the superposition of point source and non-point source pollution in the Ashihe River Basin was serious and the water quality was seriously polluted. The water quality monitoring section of the river basin was mainly grade V or even inferior grade V. The main pollution characteristics were organic pollution, nitrogen and phosphorus pollution. The serious water pollution areas were concentrated in urban river sections. The main pollution indicators were COD, NH3-N, TP and BOD which have been listed in Water Pollution Control Planning in Songhua River Basin as tributaries with poor water quality. Under the background of the serious reality of the superposition of point source and non-point source pollution in the Ashihe River Basin, there were few studies on the pollution situation and non-point source pollution sources in different periods of time in the basin. Wang [1] had used water quality monitoring technology and nitrogen stable isotope tracing technique to sample water in Ashihe river and analysis it. In order to study the nitrogen pollution characteristics and NO3-N sources of the Ashihe River during the farmland water withdrawal period. And the status monitoring and pollution characteristics analysis of pollution status in different periods of the Basin had been carried out. The study was about three stages which were snow melting period, clear water period and icing period. The results showed that during the snow melting period, the snow-melting runoff was mainly polluted by the non-point source pollutants of planting and livestock breeding. Non-point source pollutants were mainly produced in the early stage of snow melting, and the TP, TN (total nitrogen) and NH3-N concentrations were high, and non-point source pollution contributed also significantly.

In order to clarify the impact of point source and non-point source pollution loads about the water environment quality in the Ashihe River Basin, scholars calculated the water pollution load situation of Acheng District and Harbin City in Ashihe River Basin based on a large number of investigations and monitoring of basin pollution sources. Chen [2] had evaluated and estimated the pollution status and load of the non-point source pollution in the villages along the river in the Harbin urban area of the Ashihe River. Zhou [3] had used the equivalent pollution load ratio method to estimate the total pollution load of agricultural non-point source pollutants in the Ashihe River Basin. Wang [4] had proposed a method to estimate non-point source pollution during spring snow melting period based on online monitoring runoff concentration method aiming at the formation characteristics of non-point source pollution in Northeast China. He took the Ashihe River Basin as an example using this method. Wang [1] had also discussed the spatial characteristics of point source and non-point source pollution loads in the Ashihe River Basin. It was believed that the source of the upper reaches of the Ashihe River was less polluted, which were mainly the pollution of natural causes (soil organic nitrogen and atmospheric subsidence nitrogen). In the upstream source area, it was contaminated by farmland water withdrawal, domestic sewage and livestock and poultry farming sewage. The middle reaches were mainly affected by farmland dewatering pollution and livestock and poultry farming. The downstream was mainly affected by urban industrial waste water.
2. Division of control units in the Ashihe River basin

The Ashihe River belonged to the primary tributary of the right bank of the main stream of Harbin River section of the Songhua River. It located in the southern part of Heilongjiang Province, between 126°40’~127°42’ east longitude and 45°05’~45°49’ north latitude. It was the longest river flowing through Harbin city, as shown in Figure 1.

A complex basin could be divided into several independent and interconnected units by dividing control units[5], which would be easy to carry out water management. By solving the water environment problem in the control unit, the water quality target of each control unit and the purpose of protecting the water ecological function of the basin could be achieved. Thereby facilitating the system management of the basin and implementing target management plan of basin water quality.

Based on the information of DEM and land use type distribution in the Ashihe River Basin, the ARCGIS hydrological analysis method was used to divide the basin into 30 relatively independent catchment areas. Combining with the administrative divisions of villages and towns, the spatial distribution characteristics of pollution sources in the basin, considered of environmental management enforceability, four control units of the Ashihe River Basin had been identified. They were Xiquanyan Reservoir Control Unit, Ashihe River Upstream Control Unit, Ashihe River Midstream Control Unit and Ashihe River Downstream Control Unit.

![Figure 1. Control Units of the Ashihe River basin](image)

| Control unit           | Function                          | Population Within River 1km /Person | Length of river segment /Km | Area /Km² |
|-----------------------|-----------------------------------|-------------------------------------|----------------------------|-----------|
| Xiquanyan Reservoir   | Water conservation; Agriculture and Forestry | 20,000                             | 211.5                      | 1146      |
| Ashihe River Upstream | Agriculture                        | 16,600                             | 132.6                      | 568       |
| Ashihe River Midstream| Agriculture and Habitancy          | 107,500                            | 376.26                     | 1178      |
| Ashihe River Downstream| Industry and Habitancy            | 52,800                             | 188.14                     | 532       |
3. Water quality assessment of the Ashihe River Basin based on control unit

3.1. Water quality status of the Ashihe River basin

As an important tributary of the Songhua River, the Ashihe River played an important role in the normal industrial and agricultural production and social life of Harbin City. The Ashihe River was divided into two water environment functional zones. Part one was 81.25km from the river source to Acheng District and the water quality target was grade II. The another one was 61.25km from Acheng District to the river estuary and the water quality target was grade IV.

The water quality of the Ashihe River estuary station continued to be inferior grade V from 2011 to 2015. The main pollutant indicator was NH$_3$-N and the average concentration was 5.85 mg/L. According to the relevant requirements of the state and province, the annual average concentration of NH$_3$-N in this section should be controlled below 3.5 mg/L. The grade V water body should be reached before the end of 2018.

The water quality of the Volga Bridge station was between grade III and IV which was the outlet of Ashihe River Midstream. The NH$_3$-N content and the permanganate index fluctuated. Compared with 2013, the permanganate index increased by 14.3% and the NH$_3$-N content decreased by 42.8% in 2016.

The water quality of the Shuanghe station was between grade II and III which was Xiquanyan Reservoir Control Unit. The NH$_3$-N content showed a slow downward trend, and the permanganate index showed a fluctuating downward trend. Compared with 2013, the permanganate index decreased by 26.2% and the NH$_3$-N content decreased by 46.6% respectively in 2016.

Overall of the basin, water quality status of the Ashihe River was mildly polluted in 2015. According to the annual average value, the water quality in the Shuanghe station, Xiquanyan Reservoir and Ma'anshan station met the standard of grade III. The water quality of the Volga Bridge's upper section met the standard of grade IV. The water quality of the Xinyigou met the standard of grade V. The water quality of the Ashihe River was inferior grade V. The proportions of grade III sections, grade IV sections, grade V sections, and inferior V sections were 37.5%, 25%, 25% and 12.5% respectively. The upper section of the Volga Bridge and the Xinyigou reached the water body functional zone planning target, the other sections not reached the target. The main pollution indicators were NH$_3$-N and COD of the Ashihe River. The overall water quality was mildly polluted in 2016. According to the annual average value, Shuanghe station met grade II water quality, Ma'anshan station met grade III water quality. The water quality in the lower section of Acheng Town, Volga Bridge, Xinyigou were met grade IV water quality. While the water quality in the section of the Ashihe River was inferior grade V. Among the seven monitoring sections, the proportion of grade II sections was 14.3%, the proportion of grade III sections was 14.3%, the proportion of grade IV was 57.1% and the proportion of inferior grade V was 14.3%.

![Figure 2. Concentration of COD changed in the Ashihe River from 2011 to 2015](image-url)
3.2. Water quality assessment based on improved Nemerow comprehensive pollution index method

In order to scientifically evaluate the problems of water environment in the basin\cite{6,7} and avoid the evaluation distortion caused by the commonly used single factor index or comprehensive grade evaluation method\cite{8,9}, many scholars have proposed to use the Nemerow comprehensive pollution index method to evaluate the current status of water quality in the basin\cite{10,11}. The Nemerow index method was a weighted multi-factor environmental quality assessment method that highlights the maximum value, emphasized the influence and effect of pollutants with the largest pollution index on environmental quality, thus reflecting the degree of pollution of water bodies. This application was widely used in the evaluation of water environment quality. However, in the actual application process, the traditional Nemerow index method had a risk that reduce the sensitivity of environmental quality assessment.

In order to better evaluate the overall situation of water environment quality, the traditional Nemerow index method was corrected based on the original method, avoiding the disadvantages of neglecting important pollution factors. At the same time, considering that the impact of Constrained and Unconstrained Optimization on the accuracy of water quality assessment, the maximum factor term was simultaneously weighted. The improved Nemerow index method was as follows:

\[
F_i = \frac{c_i}{s_{ij}} \quad (i = 1, 2, ..., n; j = 1, 2, ..., m) \quad (1)
\]

\[
F_{DO_i} = \begin{cases} 
\frac{468}{31.6+t} - \frac{DO_i}{\left(\frac{468}{31.6+t} - DO_s\right)}, & DO_i > DO_s \\
10 - 9 \frac{DO_i}{DO_s}, & DO_i < DO_s 
\end{cases} \quad (2)
\]

\[
\omega_{ij} = \frac{R_{ij}}{\sum_{i=1}^{n} R_{ij}} = \frac{s_{max}/s_{ij}}{\sum_{i=1}^{n} (s_{max}/s_{ij})} \quad (3)
\]

\[
\bar{F}_i = \frac{1}{n} \sum_{i=1}^{n} F_i \quad \Rightarrow \quad \bar{F}'_i = \sum_{i=1}^{n} \omega_i F_i \quad (4)
\]
\[ F_{imax} = \frac{F_{imax} + F_w}{2} = \frac{\text{max}(F_i) + F_w}{2} \]  

\[ P'_j = \sqrt{\frac{F_{imax}^2 + F_i^2}{2}} \]  

Wherein, \(c_i\) was the measured concentration of the i-th pollution factor (mg/L, i=1, 2,...,n). \(DO_i\) was the measured dissolved oxygen concentration (mg/L). \(DO_s\) was the standard concentration of DO (mg/L). \(T\) was the water temperature (°C). \(s_{ij}\) was the standard value of the j-th standard of the i-th pollution factor (mg/L). \(s_{max}\) was the maximum value of j-th standard pollution factor standard value. \(\omega_{ij}\) was the weight value of the i-th pollution factor of j-th standard value. \(F_i\) was the single relative pollution index of the i-th pollution factor (standard index). \(F_{DO,i}\) was the standard index of DO. \(\bar{F}_i\) was the average of the individual pollution index \(F_i\). \(F_{imax}\) was the corrected maximum pollution index considering the maximum pollution concentration and maximum weight. \(F_w\) was the single pollution index of the pollution factor with the highest weight. \(P'_j\) was the j-th standard improved Nemerow Comprehensive Pollution Index.

Based on the monthly monitoring data of the water quality indicators of four monitoring sections from the upstream to the estuary in the Ashihe River Basin from 2012 to 2014, the improved Nemerow comprehensive pollution index method was used to evaluate the water quality grades of conventional monitoring sections in Ashihe River Basin under different water targets, different water periods. The results were as shown in following table 2. The evaluation results showed that the water quality of the Ashihe River estuary was in a very poor grade for a long time. The overall evaluation grade of the middle reaches of the Ashihe River was between reaching standard and excellence; the period with poor rating was in the dry season. The overall assessment of the water in the upper reaches of the Ash River met the standard. The evaluation of water quality about the upper reaches of Xiquanyan Reservoir had been poor in some periods. The water quality target of the Xiquanyan Reservoir was grade II (GB3838-2002).

**Table 2. Nemerow Comprehensive Pollution Index and Grade Evaluation in Ashihe River Basin**

| Year | Period | Shuanghe | Maanshan station | Volga Bridge | Ashihe River Estuary |
|------|--------|----------|------------------|--------------|---------------------|
|      |        | Pj'      | Grade            | Pj'          | Grade              |
| 2012 | Dry    | Fine     | 0.47             | Fine         | 0.68               | Good               | 2.52               | Bad                |
|      | Nomal  | 0.59     | Good             | 0.45         | Fine               | 0.51               | Fine               | 1.72               | Bad                |
|      | Wet    | 0.56     | Good             | 0.47         | Fine               | 0.38               | Fine               | 1.50               | Bad                |
|      | Dry    | Fine     | 0.60             | Good         | 1.26               | Poor               | 1.77               | Bad                |
| 2013 | Nomal  | 1.50     | Poor             | 0.82         | Good               | 0.73               | Good               | 1.64               | Bad                |
|      | Wet    | 1.24     | Poor             | 0.74         | Good               | 0.60               | Fine               | 1.16               | Bad                |
|      | Dry    | Fine     | 0.79             | Good         | 0.54               | Fine               | 1.63               | Bad                |
| 2014 | Nomal  | 0.84     | Good             | 0.52         | Fine               | 0.47               | Fine               | 1.61               | Bad                |
|      | Wet    | 0.99     | Good             | 0.56         | Fine               | 0.51               | Fine               | 1.43               | Bad                |

4. Water quality diagnosis of the Ashihe River Basin based on Equivalent Load Duration Curve Method

4.1. Hydrological process simulation of Ashihe River basin under diachronic meteorological conditions

In the process of basin water management, the analysis of the overall load situation of the river basin was one of the basic works. Combining water quality monitoring data with the same period flow data, the pollutant flux of each section can be determined. And then the point source and non-point source pollution load of the each section could be further analyze. However, due to limited monitoring capabilities, there were fewer hydrological monitoring points in the basin, and it was difficult to achieve water quality monitoring once a day. It was difficult to carry out detailed analysis of the water quality process in the basin by online monitoring.
Considered the problems in the river basin management, the verification hydrological model of the Ashihe River Basin based on the HSPF model [12,13] had been used to simulate inversion on flow process of mainly stream in the Basin. It was constructed using long-term sequence meteorological data on the basis of analysis of DEM, land use and soil types in the Basin. The daily flow process of the Acheng hydrological station on the Ashihe River in the basin was used to verify. The Pearson correlation coefficient between the simulated and measured values of the monthly average flow rate change process was 0.941. It suggested that the hydrological model of the Ashihe River Basin could basically reflect the process of runoff production and convergence under the changes of meteorological conditions in the basin. The results were shown in Figure 5. Based on the daily variation process of the meteorological conditions in the Ashihe River Basin, the daily flow variation process of the main stream and tributaries was stimulated refined. The monthly average flow statistics of the Ashihe River Basin were shown in the Figure 6.

The results showed that the coefficient of variation of the average flow of the main stream and tributaries of the Ashihe River in different months were large. The variation coefficients of tributaries such as Dashi river, Haigou river, Yuquan river, Liushugou, Dongfenggou, Liangjiagou, Huaijiagou, Miaotaigou and Fanjiagou were above 57%.

4.2. Diagnosis of Basin Water Quality Problems Based on Equivalent Load Duration Curve Method

The application of Load Duration Curve (LDC) could be used to clearly indicate the flow interval when water quality was damaged, and then determine the pollution level of the section by point source and non-point source. The actual monitoring concentration of the water quality indicator on the section could be plotted on the load duration curve after conversion with corresponding flow. In order to count the daily load of pollutants in each Flow Duration Intervals (FDI). If the over-standard point occurred in the
low flow section, it indicated that the main pollution contribution was the point source. If it occurred in the high flow section, it indicated that the main pollution contribution was the non-point source.

In order to visually compare the over standard conditions of different water quality indicators in the same section, the Equivalent Load Duration Curve Method (ELDC) had combined the LDC method with the Equivalent pollution load method. The method had been used to compare the cross-section water quality concentration with the water quality target limit concentration based on the cross-section flow duration curve and plotted an equivalent load duration curve.

\[ L = \frac{C_{is}}{C_{is}} Q_j \]  

Wherein, \( C_{is} \) was the target limit for water quality indicators.

The ELDC method could be conducted a detailed analysis of the pollution situation of each control section in the basin. It could judge the over standard conditions of the pollutants in each section and the main pollution factors under the limitation of the functional targets of different water environments. The method could be used to reasonably analyze various water problems and provided a reliable decision-making basis for basin water management. It was also easy to identify the main over standard factors of the section and determined the hydrological characteristics of the over standard periods.

Based on the results of basin hydrology processes simulations of the main stream and tributaries in the basin, used the water quality monitoring data of different monitoring sections in the basin, the water quality problems of the Ashihe River’s main stream were identified by ELDC method from the view of pollution load flux of river section. It showed that, in the upper reaches of Ashihe River, the main over standard conditions occurred in the large flow interval. The main over standard pollutant in the control unit was TP.

The pollutant fluxes in the upper reaches of the Ashihe River had not exceeded the water quality targets of the respective river segments. The NH3-N pollution was exceeding standard only during some large flow periods. The pollutant flux in the middle and lower reaches, especially in the estuary area of the Ashihe River, was seriously exceeding standard. The main over standard pollutants were NH3-N, COD and TP from large flow to medium-small flow in the periods. The problem of NH3-N pollution was the most serious.

![Figure 7. Equivalent load duration curve of four Control Units of the Ashihe River Basin](image)
5. Conclusion

Only by analysis of water quality index concentration was not enough to evaluate the variation of pollution load and source of water or make scientific and accurate diagnosis of water environmental problems. Combining the hydrological process of section with water quality, the deficiency of environmental diagnosis based on pure water quality change could be avoided.

Based on the hydrological simulations results of the main stream and tributaries in the Ashihe river basin, used the water quality monitoring data of different monitoring sections in the basin, the water quality problems of the Ashihe River’s main stream were identified using ELDC method from the view of pollution load flux of river section.

The results showed that the main over standard conditions occurred during the large flow period in the Xiquanyan Reservoir Control Unit which was the source of the Ashihe River Basin. The main pollutant in the control unit was TP. The pollutant fluxes in the upper reaches of the Ashihe River had not exceeded the water quality targets of the respective river segments. The pollutant flux in the middle and lower reaches, especially in the estuary area of the Ashihe River, were seriously exceeding standard. The main over standard pollutants were NH3-N, COD and TP in the periods from large flow to medium and small flow. The problem of NH3-N pollution was the most serious.

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