Analysis of Factors Affecting Water Environment Quality Based on Flow Analysis

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Abstract. Taking Tianjin as an example, based on the existing research results, this author improves the framework of urban water flow map and draws a urban water flow map, by using the idea of process, and approaching from the reverse thinking of water environment → discharge (sewage) outlet→sewage treatment→ sewage collection→ water consumption→water supply →water resources. On this basis, the principal component regression method is used to find key factors affecting water environment quality in Tianjin, and provide a decision support for the overall optimization and integrated control of the urban water system.

Keywords: water flow analysis, water flow map, principal component regression, water environmental quality.

1. Introduction
As an important material carrier, water connects social economy with natural environment through the development, use, discharge, treatment and reuse, etc. of water resources, forming an interactive whole, which runs through the whole complex natural-social-economic system. With the development of social economy, the urban water system is more and more complicated. The structure of the system has gradually evolved from the original water source- supply- consumption- drainage to water source-treatment- supply- consumption- drainage-treatment-reuse. Every link is constantly enriched, and the relationship between each subsystem is also getting closer and closer. Their mutual constraint or support is increasingly evident. The complexity of urban water system leads to the increasing complexity and systematisms of water problems inside the city. To understand and solve the problems with the urban water system, we must use systematic thinking and scientific methods to carry out systematic deployment and planning.

2. Analysis of Urban Water Flow and Drawing of Water Flow Map
Similar to the energy flow map, water flow map is a graphic display of the flow and activity of water inside the urban water environment system, and the most intuitive and visual representation technique in urban water flow analysis. By drawing a water flow map, we can clearly see the motion process of water between subsystems and links of the urban water system, understand the correlation between each subsystem and Link of water flow, so as to understand the factors affecting water environment
quality in the city, set up a simulation model for the operation of urban water system, identify key
decision factors in the optimization of urban water system, as well as implementation paths and
control priorities in water quality improvement.

As early as the 1990s, Prof. Bao Jingling and others began to focus their attention on the
application of water flow map in the planning and management of urban environment. Based on an
analysis of regional water flow analysis, scholars including Yang Baochen established a generalized
objective programming method for regional water environment planning. In this work, for the first
time, we have drawn an urban water system network diagram, i.e., water flow map, and visualized the
composition of regional water environment systems in the links of the development of water resource,
water supply, water consumption, drainage, treatment, reuse and exterior drainage, etc. By taking
water as a kind of material flow, Ouyang Zhiyun and other scholars set up a urban water system
sensitivity model based on system dynamics, by analyzing the characteristics and behaviors of water
flow in complex urban ecosystems, made a simulation analysis on urban water system in Tianjin and
came up with policy suggestions on the optimization of water system.

Based on the existing research results, aimed at improving the water environment quality, in line
with the requirements of fine management over the existing urban water environment, through the
reverse thinking of water environment→discharge (sewage) outlet→sewage treatment→sewage
collection→ water consumption→water supply→water resources, we analyzed the operational links
and system activities of the urban water system one by one, and drew an urban water flow map. Details are shown in Figure 1.

![Urban Water Flow Map](image)

**Figure 1. Urban Water Flow Map**

3. **Building an Analysis Model for Factors Affecting the Surface Water Environmental Quality**
The discussion on influence factors of environmental can be traced back to Malthus’s stress on the
relationship between population growth and scarcity of natural resources, which emphasized that
overpopulation was the key factor leading to the dilemma of environmental resources, and believing
that the most urgent and important thing in mitigating the environmental impact was to reduce
population. At present, domestic and foreign scholars have carried out research on factors affecting
water environment quality, mainly from single factor and multiple factors. Single factor research is concentrated on urbanization, industrialization, economic development, urban sprawl, etc., while multi-factor research focuses on analyzing and discussing the mechanism of how the above-mentioned factors influence water environment quality using data models empirically.

By referring to existing research results, combined with the drawing and analysis of urban water flow map, through a bond of theoretical analysis and expert consultation, taking the availability and continuity of data into overall account, we selected 16 indicators to build an evaluation indicator system for key factors affecting surface water quality in the city (see Tab. 1 for details). The selected evaluation indicators of influence factors of water quality included socioeconomic development and resource utilization, but also natural climate conditions. Theoretically, these indicators had both positive and negative influence on water environment quality. Through a theoretical analysis, the 16 indicators selected were classified into 5 categories: economic development, social development, resource utilization, pollution control and environmental capacity. The author further established an analysis indicator system regarding the influence factors, in order to analyze the influence factors. Given the strong correlation among socioeconomic indicators, through a comparative analysis of analysis methods of influencing factors, we decided to analyze the key influence factors by principal component analysis.

### Table 1. Analysis Indicator System for Influence Factors of Water Environmental Quality

| Indicator Category          | No. | Name of Indicator                              | Results of Regression Analysis |
|-----------------------------|-----|------------------------------------------------|-------------------------------|
| Environmental capacity      | C1  | Inbound water                                  | -0.0012                       |
|                             | C2  | Rainfall                                       | -0.1467                       |
|                             | C3  | Per capita GDP                                  | 0.1477                        |
| Economic development        | C4  | The proportion of industry in GDP              | -0.2119                       |
|                             | C5  | The proportion of tertiary industry in GDP     | 0.2476                        |
|                             | C6  | Irrigation area                                | 0.1421                        |
|                             | C7  | The population of permanent residents          | 0.1519                        |
|                             | C8  | Urbanization rate                              | -0.1014                       |
| Social development          | C9  | The average consumption level of residents in  |                               |
|                             |     | the whole city                                 | 0.1580                        |
|                             | C10 | Per capita daily water consumption             | 0.1487                        |
| Resource utilization        | C11 | Fresh water consumption per unit of industrial |                               |
|                             |     | added value                                    | -0.2231                       |
|                             | C12 | Reuse rate of industrial water                 | 0.0015                        |
|                             | C13 | Utilization coefficient of irrigation water    | 0.2648                        |
|                             | C14 | Target emission rate of industrial wastewater  | 0.2815                        |
|                             | C15 | Centralized treatment rate of urban sewage      | 0.2208                        |
|                             | C16 | Ecological water consumption                   | 0.0963                        |

In this model, one of the difficulties was to identify characterization indicators for surface water environmental quality. On the one hand, the monitoring data of long time series didn’t match. On the other hand, the spatial uniformity of surface water environmental quality was poor, and the setting of monitoring points had a great effect on the monitoring results of water environmental quality. In the actual course, the facilities at monitoring sites of the surface water environment changed dramatically, which affected the continuity and comparability of surface water environmental quality. To tackle this problem, by browsing and collecting the water environment quality monitoring reports and original monitoring results in Tianjin, the case city, from 1986 to 2015, based on the experts’ opinions, the author established an indicator, “the proportion of serious pollution in major rivers (%) = number of
seriously polluted rivers/number of rivers with monitoring data × 100%” to characterize the surface water quality of major rivers. For those based on the new standard after 2002, rivers whose evaluation results were poor Class V were regarded as seriously polluted. For those based on the old standard before 2002, the results P obtained by dividing the comprehensive evaluation indicator by the number of monitoring items included in the statistics were categorized into 4 classes, that is, p≤0.5 for mildly polluted, 0.5<P≤2 for moderately polluted, 2<P≤4 for heavily polluted, and P>4 for seriously polluted.

4. Analyzing Factors Affecting Water Environment Quality in Tianjin

The main sources of each influence factor included: Environmental Quality Report in Tianjin, Tianjin Statistical Yearbook, China Statistical Yearbook, China Statistical Yearbook on Environment, Tianjin Water Resources Bulletin, Statistical Bulletin on National Economic and Social Development, etc. Through SPSS 2.0, a principal component regression analysis was performed on the 16 variables and dependent variables selected (the proportion of serious pollution in major rivers).

4.1. Collinearity Analysis among Influence factors
Since there may be correlation between the variables selected, we first needed to make a collinearity diagnosis on the independent variables. The results were shown in Table 1. As manifested by the results, many indicators had a large VIF value of above 10, which indicated that there was a serious multicollinearity problem, so we needed to do a principal component analysis first.

Table 2. Results of Collinearity Diagnosis

| Model                                           | Unstandardized Coefficient | Standardized Coefficient | T    | Significance | Collinearity Statistics |
|-------------------------------------------------|---------------------------|--------------------------|------|--------------|-------------------------|
| (Constant)                                      | -588.971                  | 749.826                  | - .785 | .446         |                         |
| Inbound water                                   | .036                      | .317                     | .014 | .113         | .912                    | 494          | 2.024                     |
| Rainfall                                        | .019                      | .018                     | - .121 | -1.046       | .314                    | .578          | 1.731                     |
| Per capita GDP                                  | -.002                     | .001                     | -4.043 | 1.657        | 1.121                   | .001          | 768.057                   |
| The proportion of industry in GDP               | 4.358                     | 6.286                    | .767 | .693         | .500                    | .006          | 158.167                   |
| The proportion of tertiary industry in GDP      | 4.162                     | 5.186                    | 1.280 | .803         | .437                    | .003          | 328.506                   |
| Irrigation area                                 | 2.767                     | .971                     | 2.575 | .284         | .014                    | .009          | 105.399                   |
| The population of permanent residents           | .314                      | .193                     | 3.090 | 1.624        | .128                    | .002          | 467.095                   |
| Urbanization rate                               | .156                      | .159                     | 1.45  | .986         | .342                    | .356          | 2.807                     |
| The average consumption level of residents in the whole city | .006                      | .003                     | 2.541 | 1.766        | .101                    | .004          | 267.293                   |
| Per capita daily water consumption              | .291                      | .566                     | .097 | .514         | .616                    | .219          | 4.565                     |
| Fresh water consumption per unit of industrial added value | -.556                     | -.309                    | -.820 | -1.801       | -.095                   | .037          | 26.743                    |
| Reuse rate of industrial water                  | -342.298                  | 487.623                  | -.188 | -.702        | .495                    | .108          | 9.221                     |
| Utilization coefficient of irrigation water     | 1412.762                  | 623.001                  | -.2507 | 2.268        | -.041                   | .006          | 157.709                   |
| Target emission rat of industrial wastewater    | .345                      | .770                     | .352  | .448         | .661                    | .013          | 79.630                    |
| Centralized treatment rate of urban sewage      | -.766                     | .400                     | -1.086 | 1.916        | .078                    | .024          | 41.456                    |
| Ecological water consumption                    | 7.362                     | 14.605                   | .240  | .504         | .623                    | .034          | 29.378                    |
4.2. Principal Component Analysis of Influence Factors

The variance extraction analysis (Table 3) and principal component load matrix (Table 4) of the 16 statistical variables were obtained through calculation. The eigenvalues of the first four principal components were all greater than 1 and the cumulative contribution rate was up to 86.391%, greater than the required 85%, so these four principal components were extracted.

Table 3. Variance Extraction Analysis

| Component | Initial Eigenvalue | Extraction Sums of Squared loadings |
|-----------|--------------------|-------------------------------------|
|           | Total% of Variance | Cumulative %                        |
| 1         | 8.407              | 52.547                              |
| 2         | 2.963              | 18.520                              |
| 3         | 1.395              | 8.718                               |
| 4         | 1.057              | 6.607                               |
| 5         | .712               | 4.452                               |
| 6         | .572               | 3.577                               |
| 7         | .476               | 2.973                               |
| 8         | .193               | 1.207                               |
| 9         | .106               | .662                                |
| 10        | .054               | .339                                |
| 11        | .032               | .202                                |
| 12        | .019               | .120                                |
| 13        | .005               | .032                                |
| 14        | .005               | .029                                |
| 15        | .002               | .011                                |
| 16        | .001               | .005                                |

Table 4. Principal Component Load Matrix

| Component                                                                 | 1         | 2         | 3         | 4         |
|---------------------------------------------------------------------------|-----------|-----------|-----------|-----------|
| Inbound water                                                             | 364.3     | 320.280   | 656.7     |
| Rainfall                                                                  | -.078     | .559.274  | .535      |
| Per capita GDP                                                            | .957.4    | .197.077  | .055      |
| The proportion of industry in GDP                                         | -.731.2   | .273.415  | .002      |
| The proportion of tertiary industry in GDP                                 | .892.8    | .286.187  | .025      |
| Irrigation area                                                           | -.23.0    | .806.486  | .044      |
| The population of permanent residents                                     | .971.9    | .191.011  | .050      |
| Urbanization rate                                                         | .135.5    | .550.446  | .250      |
| The average consumption level of residents in the whole city              | .970.7    | .164.052  | .062      |
| Per capita daily water consumption                                        | .212.4    | .452.489  | .474      |
| Fresh water consumption per unit of industrial added value                | -.918.1   | .159.169  | .011      |
| Reuse rate of industrial water                                            | -.675.6   | .590.253  | .007      |
| Utilization coefficient of irrigation water                               | .554.6    | .652.496  | .006      |
| Target emission rat of industrial wastewater                              | .857.4    | .461.055  | .049      |
| Centralized treatment rate of urban sewage                                 | .970.7    | .104.062  | .063      |
| Ecological water consumption                                              | .863.8    | .335.076  | .189      |

The first principal component was represented by F1, the second principal component by F2, the third principal component by F3, and the fourth principal component by F4. Through calculation, the expressions of F1, F2, F3 and F4 were derived as follows:
\[ F_1 = 0.13x_1 - 0.03x_2 + 0.33x_3 - 0.25x_4 + 0.31x_5 \\
- 0.08x_6 + 0.33x_7 + 0.05x_8 + 0.33x_9 + 0.07x_{10} \\
- 0.32x_{11} - 0.23x_{12} + 0.19x_{13} + 0.3x_{14} + 0.33x_{15} \\
+ 0.3x_{16} \]

\[ F_2 = -0.19x_1 - 0.32x_2 - 0.11x_3 - 0.16x_4 \\
+ 0.17x_5 + 0.47x_6 - 0.11x_7 - 0.32x_8 - 0.1x_9 \\
+ 0.26x_{10} - 0.09x_{11} + 0.34x_{12} + 0.38x_{13} \\
+ 0.27x_{14} + 0.06x_{15} - 0.19x_{16} \]

\[ F_3 = 0.24x_1 + 0.23x_2 + 0.07x_3 + 0.35x_4 \\
- 0.16x_5 + 0.41x_6 - 0.01x_7 + 0.38x_8 + 0.04x_9 \\
- 0.41x_{10} - 0.14x_{11} + 0.21x_{12} + 0.41x_{13} \\
+ 0.05x_{14} + 0.05x_{15} + 0.06x_{16} \]

\[ F_4 = 0.64x_1 + 0.52x_2 - 0.05x_3 - 0.02x_5 \\
+ 0.04x_6 - 0.05x_7 - 0.24x_8 - 0.06x_9 + 0.46x_{10} \\
+ 0.01x_{11} + 0.01x_{12} + 0.01x_{13} + 0.05x_{14} \\
+ 0.06x_{15} - 0.18x_{16} \]

4.3. **Quantitative Analysis of the Effect of Principal Components on Water Environment Quality**

By taking the standardized variables \( F_1, F_2, F_3 \) and \( F_4 \) as the independent variables, and standardizing data about the proportion of serious pollution in major rivers on behalf of water environment quality as the dependent variables, a regression analysis was carried out, and the results were shown in Table 5. The resulting principal component regression model was as follows:

\[ Y = 0.587F_1 + 0.403F_2 \]

The expressions of \( F_1 \) and \( F_2 \) were brought into the regression equation, to obtained the principal component regression equation represented by standardized variables:

\[ Y = -0.0012x_1 - 0.1467x_2 + 0.1477x_3 \\
- 0.2119x_4 + 0.2476x_5 + 0.1421x_6 + 0.1519x_7 \\
- 0.1014x_8 + 0.158x_9 + 0.1487x_{10} - 0.2231x_{11} \\
+ 0.0015x_{12} + 0.2648x_{13} + 0.2815x_{14} + 0.2208x_{15} \\
+ 0.0963x_{16} \]

Each coefficient in the principal component regression equation was the influence degree of each influence factor on surface water environment quality.
Table 5. Results of Regression Analysis

| Independent Variable | Coefficient | t    | Sig | R²  | F   |
|----------------------|-------------|------|-----|-----|-----|
| C                    | -2.337E-16  | 0.000| 1.000|     |     |
| F1                   | 0.587       | 4.354| 0.000|     |     |
| F2                   | 0.403       | 2.990| 0.006| 0.546| 7.502|
| F3                   | -0.077      | -0.573| 0.572|     |     |
| F4                   | -0.180      | -1.334| 0.94 |     |     |

5. Discussion

5.1. Socioeconomic Development and Resource Utilization Were Root Causes of Pollutions in Surface Water Environment

Environmental problems, in the final analysis, reflected problems in socioeconomic development and resource utilization in a comprehensive way. From the analysis results, industrial structure had the greatest effect on the water environment quality of major rivers, and the two coefficients of the proportion of industry in GDP and the proportion of tertiary industry in GDP ranked 2nd and 4th respectively. Although the industrial structure in Tianjin experience constant optimization in the last 30 years, as an old industrial base, heavy chemical industries with high water consumption and high emission, such as metallurgy and chemical engineering, with large scales and proportions, still exert a serious impact on the water environment quality of major rivers. From the perspective of resource utilization, the influence of the efficiency of industrial water consumption and agricultural water consumption on the water environment quality of major rivers was significant, the influence degree of utilization coefficient of irrigation water and fresh water consumption per unit of industrial added value ranked 5th and 6th respectively. Agricultural water consumption accounted for the largest proportion in the water consumption throughout the city, especially agricultural irrigation water, which carried plenty of pollutants, such as chemical fertilizers and pesticides, directly flowed into natural water bodies in the form of overland runoff, and formed non-point pollution.

5.2. Pollution Control was a Fundamental Way to Enhance Water Environment Quality

From the analysis results, the target emission rate of industrial wastewater was an indicator with the greatest impact on the water environment quality of major rivers. This was cross-validated with the influence results of industrial structure. Judging from urban domestic pollution control, the impact of urbanization process on water environment was significant. The expansion of city size and population size had led to more sewage output. From the relative variation trends of the proportion of serious pollution in major rivers, urbanization rate and treatment rate of urban sewage, the water environment quality deteriorated with the increase of urbanization rate. However, urbanization would improve the level of sewage treatment and lower the actual discharge of sewage and pollutants. Apart from cutting pollution emissions, artificial ecological water replenishment was also a crucial unconventional measure to improve the water environment quality of rivers and mitigate serious pollution. Since 2013, Tianjin has made every effort to replenish water to the ecological environment in the city center, launched a water system circulation and connection project, and improved the river water quality to a certain extent.

5.3. Serious Shortage of Water Resources, Poor Self-Purification Capacity of Rivers Had Made it Difficult to Improve Water Quality Fundamentally

Under the natural condition of abundant surface water resources, the water environment can purify itself. The quantity of surface water resources depended on the home-grown runoff brought by natural precipitation and inbounds water. From the analysis results, it can be seen that rainfall produced a great impact on the surface water environmental quality of major rivers in Tianjin, ranking 3rd. Subject to the climate, geographical location, terrain and other factors, there was a significant positive correlation between local water resources and rainfall in Beijing-Tianjin-Hebei region, including
Tianjin. In years with large rainfall, the quantity of local water resources was also large. For Tianjin specifically, the rainfall was big, and home-grown runoff and inbound water was large, too, which was beneficial to the improvement of water environment quality of major rivers.

6. Conclusion
Taken together, the impact of water environment quality of major rivers in Tianjin is many-sided and multi-domain. Influences from multiple aspects, such as industry-oriented industrial structure, urbanization process, sewage treatment, and other pollution controls, rainfall, inbound water, ecological water replenishment, etc. have jointly contributed to the surface water environment conditions and variation trend of major rivers in Tianjin. It can also be seen that to enhance the surface water environment quality in Tianjin, we should take the characteristics of the complex social-economic-natural system into overall account, optimize the industrial structure, promote the efficiency of resource utilization, tighten requirements on sewage treatment, increase ecological water consumption through multiple channels, plan as a whole and follow out policies in a comprehensive way.

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