Study on effect of different reservoir water diversion modes on river water quality improvement

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Abstract. Urban river water pollution is a serious environmental issue and tends to become worse. One of the key measures to improve urban river water quality is to divert water from upstream reservoir to downstream river course to flush pollutants. In this paper, a one-dimensional hydrodynamic and water quality model of Hun River network was developed based on HEC-RAS model. Different reservoir water diversion modes for sewage discharge were simulated and their effect on the water quality improvement of downstream river course was analysed. The results show that under different diversion flow rates, the larger the diversion flow rate, the better the effect on water quality improvement, and that when total water diversion volume is fixed, the effect of long-term diversion with a low flow rate is better than that of short-term diversion with a high flow rate on downstream water quality improvement. The research results can provide scientific support for optimization of the operation of water diversion from reservoir for sewage discharge.

1. Introduction

The rapid urbanization accompanied by over-exploitation of water resources and excessive discharge of sewage has led to the deterioration of river water quality and damage to the ecological environment. One of the effective means to improve river eco-environment is to improve the water quality through reasonable water regulation while managing water pollution [1-2], i.e., diverting large quantities of water that is relatively low in pollutant concentration into polluted water. This can quickly achieve improved water quality by reducing the concentration of pollutant and by increasing the water exchange rate. The reservoir ecological regulation is to protect or improve the ecological environment of the reservoir area and downstream river course for realization of harmonious development of human and nature, which can be used to alleviate the deterioration of river eco-environment [3].

In general, there are numerous case studies on the application of traditional water regulation in China, but reservoir ecological regulation is still in the stage of theoretical research and exploration, and most research on reservoir ecological regulation is about emergency eco-environmental water diversion, while research on river ecological restoration in the developed regions like Europe and the United States mainly focuses on protection of species diversity [4-6]. In recent years, more and more attention has been paid to the effect of water diversion on improving water quality in China. Xia Kun et al [7] simulated and calculated the effect of current water diversion on the inner Qinhuai River based on MIKE11 model. Yin Hong et al [8] set the scenarios of water quality exceeding standard caused by pollutant accumulation in dry season plus non-point source release due to rainfall or sudden water pollution accident, simulated the effect of water diversion, water pumping and other control measures based on WASP model, and analyzed the response relationship between different control schemes and
the effect on improving water quality. Pang Cuichao et al [9] analyzed the effect of water diversion for sewage discharge on improving the water environment of all rivers of Hexi river system of Nanjing City based on WASP model. Li Zijia et al [10] simulated and analyzed the influence of various regulation measures of water diversion for sewage discharge on the water quantity and quality of urban water system in Shihong County based on MIKE11 model. Tong Chaofeng et al [11] developed a one-dimensional hydrodynamic and water quality model of river network to simulate the changes of water quality of the external Qinhuai River corresponding to different water supply in different periods and under different operation and control modes of gate control system. Lu Wei et al [11] comprehensively considered the effect of different quantity and duration of water diversion as well as the water diversion mode on improving water quality of Shangtang River based on MIKE11 model, and proposed that the water diversion efficiency should be taken as the basis to determine the best water diversion scheme. All the above studies focused on the analysis of water diversion flow rates required for achieving the corresponding water quality objectives, but few on the water diversion duration.

In this paper, aiming at the shortcomings in current research on reservoir water diversion for sewage discharge and taking Hun River as the research case, a one-dimensional hydrodynamic and water quality model for Hun River is established based on HEC-RAS model. The effect of the water diversion modes, such as water diversion volume and duration, on water quality of downstream river course is studied, which provides scientific support for optimization of reservoir water diversion mode for sewage discharge.

2. General situation of the research region

Hun River originates from the west side of Gunma Ridge, a branch of Changbai Mountain in Wandianzhi Town, Qingyuan County, Fushun City. The schematic diagram of Hun River is shown in Figure 1. Hun River flows through the cities and counties of Qingyuan, Xinbin, Fushun, Shenyang, Liaozhong, Liaooyang, Haicheng and Tai'an and discharges into Daliao River after confluence with Taizi River at Sanchahe. Hun River has a total length of 415 kilometers with watershed area of 11,500 square kilometers. The average gradient of the river is 0.420%. The average annual precipitation for many years is 742.3 mm. The average annual runoff depth for many years is 220.9 mm. The average width of the watershed is 46.9 km. The bend coefficient of the river course is 1.7 and the shape coefficient is 0.09. The hilly area accounts for 65% of the total watershed area and the plain area accounts for 35%. The main tributaries on the right bank include Ying'e River, Zhangdang River, Wanquan River, Xihe River and Puhe River; on the left bank are Suzi River, Sa'erhu River, She River, Dongzhou River, Guchengzi River, Lagu River, Baitabao River, etc. Most of the tributaries are concentrated in the middle and upper reaches above Shenyang, of which 31 tributaries have a watershed area of more than 100 square kilometers each, and tributaries of Dongzhou River, Guchengzi River, Zhangdang River and Puhe River have a larger watershed area.

Dahuofang Reservoir is located in the middle and upper reaches of the mainstream of Hun River. The dam of the reservoir is located on Xintai River, Dongzhou District, Fushun City. The catchment area above the dam site is 5437 km², the water surface area is 91.2 km², and the maximum discharge capacity is 13400 m³/s. The reservoir is a large-scale water control project mainly for flood control and water regulation, taking into account the comprehensive utilization including breeding, power generation and tourism. The flood protection involves a population of more than 7 million and more than 3 million Chinese mu of cultivated land in 10 counties (or cities, districts), 60 townships (or towns) under the jurisdiction of Shenyang, Fushun, Liaoyang, Anshan and Panjin Cities.
3. Establishment of hydrodynamic and water quality model

In this paper, a one-dimensional hydrodynamic and water quality model for Hun River was developed based on HEC-RAS model. HEC-RAS is a hydrodynamic and water quality simulation software mainly used for calculation of the one-dimensional steady and unsteady flow of river courses and river networks, which was developed by the Hydrologic Engineering Center of the U. S. Army Corps of Engineers. In the hydrodynamic part, HEC-RAS model can simulate not only natural rivers, but also the rivers significantly disturbed by human activities (for example, the rivers built with water conservancy projects that change the hydrodynamic characteristics of the river course, such as reservoirs, sluice gates, pump stations, dikes, bridges). It can simulate not only single river course, but also complex river networks and systems. In the water quality part, HEC-RAS model can be used to carry out temperature simulation (heat source/sink, water temperature), nutrients simulation (dissolved nitrogen --NO$_3$-N, NO$_2$-N, Org-N), dissolved phosphorus simulation (PO$_4$-P, Org-P), algae simulation, CBOD and DO simulation as well as the user-defined simulation of various water quality parameters such as arbitrary conservative and non-conservative substances. HEC-RAS model has been widely applied in hydrodynamic and water quality simulation at home and abroad [13-14].

3.1. Hydrodynamic model

3.1.1. Governing equations and numerical schemes. The governing equations describing the law of one-dimensional unsteady water discharge in the hydrodynamic model are Saint-Venant Equations, which are composed of a continuity equation of mass conservation and a momentum equation of energy conservation. These equations are detailed as below:

(1) Continuity equations

For main channel section:

$$\frac{\partial A_c}{\partial t} + \frac{\partial Q_c}{\partial x_c} = q_t$$

(1)

For floodplain section:

$$\frac{\partial A_f}{\partial t} + \frac{\partial S}{\partial t} + \frac{\partial Q_f}{\partial x_f} = q_t + q_c$$

(2)

(2) Momentum equations
For main channel section:

\[
\frac{\partial Q}{\partial t} + \frac{\partial (Q_V S_c)}{\partial x_c} + g A_c \left( \frac{\partial z}{\partial x_c} + S_c \right) = M_f \tag{3}
\]

For floodplain section:

\[
\frac{\partial Q_f}{\partial t} + \frac{\partial (Q_f V_f)}{\partial x_f} + g A_f \left( \frac{\partial z}{\partial x_f} + S_f \right) = M_c \tag{4}
\]

Where \(q_c, q_f\) are the water exchanged between the main channel and the floodplain, and \(M_c, M_f\) are the momentum flow exchanged between the main channel and the floodplain in unit length.

The finite difference method and Preissmann Implicit Scheme were used in calculation of the flow rate and water level at each node.

### 3.1.2. River system generalization and boundary conditions

The source and sink terms considered in the model mainly include 9 main tributaries, 40 main water intakes and 10 main sewage outfalls on the mainstream of Hun River. The downstream topographic section of the river course is located at Yingkou Hydrological Station and the upstream topographic section is located at the downstream of Dahuofang Reservoir of Hun River. There are 88 large topographic sections measured at field in the river course in total. The daily discharge of Dahuofang Reservoir in 2014 was taken as the upper boundary condition, and the water level of Yingkou in 2014 was used as the lower boundary. The initial conditions were set by hot start mode. The period of simulation is from January to December 2014.

### 3.1.3. Parameter calibration and model validation

Considering the stability and time requirement of calculation of the model, the time step was set to 3-5min. and the space step was set to 500-800m. The empirical value was set first and then the model was calibrated. The roughness of the river course is the main parameter to be calibrated. The roughness values were preliminarily set based on the roughness values of natural river courses taken from the existing literature and data, and then calibrated according to the simulation results. The final calibrated results of roughness are: 0.022-0.031 for main channel, 0.035-0.12 for floodplain. The specific values of each reach are given in Table 1. Huanglatuo Hydrological Station was chosen for validation of flow rate and water level, and the measured data of Huanglatuo Station from April to November 2014 was used for validation (the data of the station from January to March and December 2014 are missing). The validation results are given in Table 2. The results in Figure 2 show that the simulation values of the model are in good coincidence with the measured values, which indicates that the established hydrodynamic and water quality model of Hun River can accurately reflect the hydrodynamic process of Hun River.

| Table 1. Calibrated results of roughness in the main stream of Hun River |
|----------------------------|-----------------|-----------------|
| River                      | Stream segment  | Roughness       |
|                            |                 | Main channel    | Floodplain |
| Hun River                  | Fushun-Shenyang | 0.032           | 0.120      |
|                            | Shenyang-Huanglatuo | 0.028         | 0.080      |
|                            | Huanglatuo-Xingjiawopeng | 0.030         | 0.120      |
|                            | Xingjiawopeng-Sanchahe | 0.030         | 0.120      |
3.2. Water quality model

3.2.1. Governing equation and longitudinal dispersion coefficient. The governing equation of water quality model is a one-dimensional convection diffusion equation, i.e.,

$$\frac{\partial (CA)}{\partial t} + \frac{\partial (CQ)}{\partial x} = \frac{\partial}{\partial x} \left[ (E_s + E_i + E_e) \frac{2C}{\partial x} A \right] + \sum S A$$

(5)

The finite volume method is used as the numerical method, and the Quickest-Ultimate explicit scheme is used as the numerical scheme.

The longitudinal dispersion coefficient $D$ is determined by Fischer Empirical Formula, and the parameter value setting is based on the hydrodynamic simulation results. The calculation method is as follows:

$$D = m \cdot 0.011 \frac{u^2 W^2}{h u}$$

(6)

Where $m$ is the customized factor; $u$ is the surface current velocity, in m/s; $W$ is the average width of the section, in m; $h$ is the average depth of the section, in m; $u^*$ is the shear velocity.

The shear velocity $u^*$ can be calculated by the following formula:

$$u^* = \sqrt{g Ri}$$

(7)

Where $g$ is the gravitational acceleration; $R$ is the hydraulic radius, in m, which is equal to the average depth $h$ of the section; and $i$ is the friction gradient.

3.2.2. Boundary Conditions. The COD data and ammonium nitrogen measured monthly in Fushun City in 2014 were used as the upper boundary conditions. The source and sink terms are consistent with the hydrodynamic model, including tributaries, sewage outfalls and water intakes. The monthly measured data of 2014 was adopted for tributaries and sewage outfalls. When measured data is missing in a month, linear interpolation is used to make up the missing part. The initial conditions are set in the same way as in the hydrodynamic simulation and the hot start mode is adopted. The time period of simulation is from January to December 2014.

Table 2. Calibrated results of integrated degradation coefficient of pollutants in main stream of Hun River

| River            | Representative section | Integrated degradation coefficient (d$^{-1}$) |
|------------------|------------------------|---------------------------------------------|
|                  |                        | COD | Ammonium nitrogen |
| Hun River        | Fushun                 | 0.28 | 0.23            |
|                  | Dongling Bridge        | 0.21 | 0.25            |
|                  | Hunhe Sluice           | 0.25 | 0.23            |
|                  | Huanglatuo Bridge      | 0.27 | 0.24            |
3.2.3. Parameter calibration and model validation. The major parameters of water quality model to be calibrated are the integrated degradation coefficient of COD and ammonium nitrogen. The integrated degradation coefficient was calibrated based on the monthly measured data in 2014: The range of COD degradation coefficient is 0.16-0.28/d, and the range of ammonium nitrogen degradation coefficient is 0.11-0.25/d, as shown in Table 2. The validation for water quality simulation was carried out based on the measured data from January to December 2014 at Qijianfang Water Quality Station, as shown in Figure 3. It can be seen from the results in Figure 3 that the COD and ammonium nitrogen simulation values are in good coincidence with the measured values. Therefore, the established hydrodynamic and water quality model of Hun River can accurately reflect the transfer and transformation process of water quality of Hun River, which can be used for studying the effect of different reservoir water diversion modes on improving river water quality.

![Figure 3. Validation of COD and ammonium nitrogen at Qijianfang Water Quality Station in the main stream of Hun River](image)

4. Setting of water diversion scenario and analysis of calculation results

4.1. Effect of different water discharge flow on downstream water quality

In order to investigate the effect of different diversion water flow rate on the downstream water quality, the three scenarios of small, medium and large flow rate were set, respectively. The flow rate of Scenario 1 was set as the outflow rate of Dahuofang Reservoir in May 2014 multiplied by 0.8, the flow rate of Scenario 2 was set as the outflow rate of the reservoir in May 2014, and the flow rate of Scenario 3 was set as the outflow rate of the reservoir in May 2014 multiplied by 1.2. The measured pollutant concentration in the outflow of the reservoir in May 2014 was used as the water quality condition of the diverted water in all scenarios, as shown in Table 3.

| Scenario   | Discharge Flow of Dahuofang Reservoir |
|------------|---------------------------------------|
| Scenario 1 | Water diversion flow rate in May 2014 x 0.8 |
| Scenario 2 | Water diversion flow rate in May 2014 x 1 |
| Scenario 3 | Water diversion flow rate in May 2014 x 1.2 |

The above three different water discharge scenarios were simulated respectively by using the established one-dimensional hydrodynamic and water quality model of Hun River, with May 1 to May 31, 2014 as the simulation period and COD and ammonium nitrogen as the simulation indicators. Two water quality stations in midstream (Qitaizi) and downstream (Yujiafang) of Hun River were chosen as typical stations. The comparison and analysis results of COD and ammonium nitrogen in different scenarios are shown in Figure 4 and Figure 5. The figures indicate that the bigger the water diversion discharge flow, the lower the COD and ammonium nitrogen concentrations and the better the effect on
water quality improvement. Compared with ammonium nitrogen, the response of COD to different
diversion water flow rate is more significant.

![Figure 4. Comparison of COD and ammonium nitrogen of Qitaizi Station in the three diversion flow
rate scenarios](image)

![Figure 5. Comparison of COD and ammonium nitrogen of Yujiafang Station in the three diversion
flow rate scenarios](image)

4.2. Effect of water diversion on downstream water quality with the same water diversion volume but
different water diversion duration

In order to study the effect of different water diversion duration on the downstream water quality of Hun
River under the same water diversion volume, three other scenarios were designed. Under the same total
water volume from Dahuofang Reservoir in May, Scenario 1 was set as water diversion from the
reservoir at a flow rate of 180 m$^3$/s for 5 days, Scenario 2 at a flow rate of 90 m$^3$/s for 10 days, and
Scenario 3 at a flow rate of 60 m$^3$/s for 15 days. The effect of different water diversion modes on the
water quality of Hun River was quantified by analysis and comparison of the water quality results under
different scenarios.

| Scenario | Diverion Flow Rate from Dahuofang Reservoir |
|----------|---------------------------------------------|
| Scenario 1 | 180 m$^3$/s for 5 days, i.e., from May 1 to May 5 |
| Scenario 2 | 90 m$^3$/s for 10 days, i.e., from May 1 to May 10 |
| Scenario 3 | 60 m$^3$/s for 15 days, i.e., from May 1 to May 15 |

The water quality changes in May were simulated respectively for the three scenarios set in Table 4. The
comparison results of COD and ammonium nitrogen concentration are shown in Figure 6 and
Figure 7. Qitaizi and Yujiafang water quality stations on the mainstream of Hun River were chosen as
typical stations. The results show that, from May 1 to May 8, in terms of the concentration of pollutants,
Scenario 3 < Scenario 2 < Scenario 1, i.e., the effect of lower diversion flow rate and longer diversion
duration is better when the total water diversion volume is fixed. The water quality fluctuates slightly in
the period of 10-15 of May and the three scenarios converged after the water diversion ends on May 15.
In general, the effect of Scenario 3, i.e., low diversion flow rate for a long diversion duration, is better than that of high diversion flow rate for a short diversion duration.

Figure 6. Comparison of COD and ammonium nitrogen contents in Qitaizi Station with the same water diversion volume for different diversion durations

Figure 7. Comparison of COD and ammonium nitrogen in Yujiafang Station with the same water diversion volume for different diversion durations

5. Conclusion
In this paper, a one-dimensional hydrodynamic and water quality model of Hun River was developed based on HEC-RAS model. The effect of different modes of water diversion from Dahuofang Reservoir on improving the river water quality of the mainstream of Hun River was analyzed. The higher the water diversion flow rate, the better the effect on improving downstream water quality. When the total discharge volume is fixed, the effect of lower diversion flow rate for longer diversion duration is better than that of higher diversion flow rate for shorter diversion duration. The research results can provide references for optimization of joint regulating of water quality and water quantity on reservoir water diversion for sewage discharge.

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References
[1] Qian, L., Liu, Y., Chao, J. (2013) The Current Situation and Development Trend of China Joint Regulating of Water Quality and Water Quantity. Environmental Science & Technology, 36: 484-487.
[2] Gu, C., and Huang, X. (2012) The Progress Study on Joint Regulating of Water Quality and Water Quantity. Water Conservancy Science and Technology and Economy, 18: 26-28.
[3] Lu, X., Li, Y., Huang, D., Zhou, D., He, M., and Jiang, W. (2015) Study on Water Diversion Schemes for Improvement of Hydrodynamics in Plain River Network. Water Resources and Power, 33: 93-95+138.

[4] Smith, J A, Dietl, G P. (2019) Molluscan metacommunity dynamics in the Colorado River estuary, Mexico before upstream water diversion. Anthropocene, 25: 100194.

[5] Yan, Z., Yang, H., Dong, H., Ma, B., Sun, H., Pan, T., Jiang, R., Zhou, R., Shen, J., and Liu, J. (2018) Occurrence and ecological risk assessment of organic micropollutants in the lower reaches of the Yangtze River, China: A case study of water diversion. Environmental Pollution, 239: 223-232.

[6] Tang, W., Shan, B., Zhang, H., Zhang, W., Zhao, Y., Ding, Y., Rong, N., and Zhu, X. (2014) Heavy Metal Contamination in the Surface Sediments of Representative Limnetic Ecosystems in Eastern China. Scientific Reports, 4:7152.

[7] Xia, K., Wang, H., Qin, W., and Qian, J. (2015) Evaluation of Effect of Water Quantity Regulation on Improving Water Quality of Inner Qinhuai River. Water Resources Protection, 31: 74-78.

[8] Yin, H., Qian, X., Yao, H., Xia, B., and Gao, H. (2015) Evaluation of Effect of Water Environment Regulation Scheme of River Based on Water Quality Model - Taking Taipu River as an Example. Environmental Protection Science, 41:48-52.

[9] Pang, C., Xu, J., Wang, D. (2012) Research on water environmental scheme of water system in western area of Nanjing City through water diversion from Yangtze River. Yangtze River, 43:76-79.

[10] Li, Z., Dong, Z., Fan, K., Zhang, K., Hu, H., and Wang, Y. (2012) Application of MIKE11 Model in Water Diversion and Flushing Pollutants of Urban River Network in Sihong City. Water Resources and Power, 30:100-103.

[11] Tong, C., Yue, L., Hao, J., Shao, Y., Yan, Y., and Liu, F. (2012) Water Quality Simulation and Water Diversion Effect Analysis of External Qinhuai River in Nanjing. Water Resources Protection, 28:49-54.

[12] Lu, W., and Ying, C. (2014) Effects analysis of river water quality improvement by water diversion. Yangtze River, 45:37-39.

[13] Brunner, G W. (2010) HEC-RAS, River Analysis System Hydraulic Reference Manual. U.S. Army Corps of Engineers Institute For Water Resources Hydrologic Engineering Center.

[14] Ahmed, F. (2010) A hydrodynamic model for the Lower Rideau River. Natural Hazards, 55: 85-94.