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Estimation of Water Environmental Capacity Considering Hydraulic Project Operation in the Xiangyang Reach of the Han River, Central China

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ABSTRACT

Using the Xiangyang Reach of the Han River as an example, this paper evaluates the changes of water environmental capacity after the implementation of Cuijiaying Hydro-junction project. The allowable pollutant loads entering the Xiangyang Reach were estimated using two-dimensional steady state water quality model with different data sets. The water environmental capacity has declined in the reservoir area of the Cuijiaying Hydro-junction project during the low-flow period; it is appearing to increase slightly in the upper and lower stream of this reservoir. However, the state of flow may turn into the state of reservoirs flow in the reservoir area, and the changes of hydrological regime may cause the water flow and the nutrient contents suitable for the occurrence of ecological environment problems.

Keywords: Han River; Water Environmental Capacity; Cascade Development; Pollutant Loading

1. Introduction

The Han River is the longest tributary of the Yangtze River, with a watercourse length of 1577 km and a total drainage area of 159,000 km^2. The Han River Basin is one of the major agricultural production bases in China, and plays a significant role in regional economic development. Due to its plentiful water resources [1], the Basin cascade development is being implemented [2]. Meanwhile, changes of hydrological regime may inevitably impact the aquatic environment of the Han River, especially to the water environmental capacity. Moreover, the rapid urbanization and industrialization are beginning to affect water quality in this area. From 1992 to 2005, large-scale algal blooms had taken place five times in the middle and lower reaches of the Han River because of the ecological environment degradation [3].

Total amount control for water pollutants is one of the main methods to resolve water environmental problems in China [4,5]. Comprehensively understanding the water environmental capacity, namely the maximum allowable pollutant loads discharging into the water body, is a prerequisite to effective pollution control. With the aim of providing a valuable aid to the strategies of water pollution control, the influence of water conservancy projects on water environmental capacity is increasingly draw more attention in China [6-8].

The current study aims to estimate the water environmental capacity through a case study of the Xiangyang Reach of the Han River in Central China. Using two-dimensional steady state water quality model, we evaluated the variation of water environmental capacity considering the dam operation in this area.

2. Study Area

Xiangyang city is located in the middle reach of the Han River (**Figure 1**). With a total area of 19,727.68 km^2, it has a population of around 5,888,786 in 2009. The Han River runs through the city from north to south with a length of 195,000 m. There are five tributaries in the Xiangyang Reach: South River, North River, Xiaoqing River, Tangbai River, and Man River. The Cuijiaying Hydro-junction project, located in downstream of the Xiangyang urban area, is the third step of cascade development in the middle and lower reaches of the Han River [9]. Normal storage level of the project is 62.73 m. The project, which is mainly used for shipping and electricity generation, has been completed in July, 2010.

3. Methods

According to the actuality of total amount control for water pollutants in China [10], chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) were selected as the calculation factors in this study. We divided the Xiangyang Reach of the Han River into six computa-

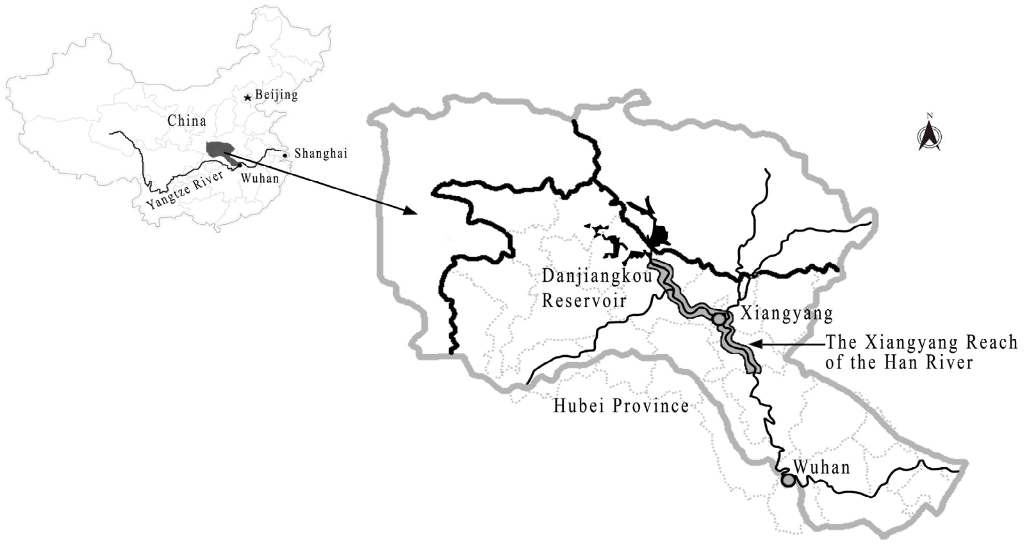

Figure 1. Study area.

tional units based on the water environmental function zone of Hubei Province [11], as shown in **Table 1**. The point source pollution data in 2007 for this study was obtained from the Xiangyang Environmental Monitoring Station.

As the river width of the Han River is usually in excess of 200 meters, it is necessary to consider the variation of pollutants in longitudinal dispersion and horizontal diffusion [10]. Two-dimensional water quality model, therefore, is suitable for calculation of water environmental capacity under given the unique hydrological conditions within the Xiangyang Reach.

Under steady flow conditions, fundamental equation of two-dimensional water quality model is written as:

$$E_x \frac{\partial^2 C}{\partial x} + E_y \frac{\partial^2 C}{\partial y} - u_x \frac{\partial C}{\partial x} - u_y \frac{\partial C}{\partial y} - kC = 0 \quad (1)$$

where u_x is the longitudinal velocity (m/s); u_y is the horizontal velocity (m/s); E_x is the longitudinal dispersion coefficient (m^2/s); E_y is the horizontal diffusion coefficient (m^2/s); C is the contaminant concentration (mg/L); K is the decay coefficient (1/d); x is the longitudinal coordinates (m); y is the horizontal coordinates (m).

Supposing u_y and E_x are approximate to zero under conditions of little changes in water depth, Equation (1) is converted to the following expression:

$$C(x,y) = \frac{M}{h\sqrt{4u\pi E_y}} \exp\left(-\frac{uy^2}{4E_y x}\right) \exp\left(-k\frac{x}{u}\right) + C_0 \exp\left(-k\frac{x}{u}\right) \quad (2)$$

where M is the pollutant emission rate (g/s); C_0 is the background pollutant concentration of the river (mg/L); C is the pollutant concentration (mg/L); K is the decay coefficient (1/d); x is the longitudinal coordinates (m); y is the horizontal coordinates (m); h is the average water depth (m); u is the average longitudinal velocity (m/s).

Assuming the degradation of background pollutant concentration is negligible, the model which can be applied to estimate water environmental capacity in the Xiangyang Reach gives the following formula:

$$W = \left(C(x,y) - C_0\right) H \sqrt{u\pi x E_y} \exp\left(\frac{y^2 u}{4E_y x} + k\frac{x}{u}\right) \quad (3)$$

where W is the water environmental capacity (t/a).

30Q10 is selected as the design flow (314 m^3/s) in the light of data from the Xiangyang hydrometric station, and the designed flow velocity is 0.31 m/s. The river depth and width are derived from our investigation (**Table 2**).

The horizontal diffusion coefficient (E_y) is usually determined by the empirical correlation or field survey method. In this study, we adopted the following empirical correlations [12]:

Table 1. Computational units in the Xiangyang Reach of the Han River.

Computational unit	Environmental functional category	Length (m)
Shenwan-Xianrendu	II	38.5
Xianrendu-Baijiawan	II	47.2
Baijiawan-Zhakou	III	14
Zhakou-Qianying	III	12
Qianying-Yujiahu	III	7.6
Yujiahu-Guo’an	II	53.2

Table 2. Average river width and depth of each computational unit in the Xiangyang Reach.

Computational unit	Sewage outlet and tributary	Width (m)	Depth (m)
Shenwan-Xianrendu	Jiangshan	180	2.8
	Damingqu	180	2.8
Xianrendu-Baijiawan	Jinhuan	235	2.7
Zhakou-Qianying	Xiaoqing River	323	2.42
	Tianjiu	160	3.3
	Nanqu	323	4.52
	Yuliangzhou	160	3.3
	Xiangyang power plant	390	3.35
Yujiahu-Guoan	Yakou	390	3.35

$$E_y = a_y \cdot H \cdot U^* \quad (4)$$

$$U^* = \sqrt{gHI} \quad (5)$$

where a_y is non-dimensional coefficient; H is average river depth (m); U^* is frictional velocity (m/s); g is gravity acceleration (m/s^2); I is gradient of the river (‰).

According to the Surface water environmental capacity of Hubei Province Technical Report, decay coefficient (K) is assigned values as follows: K_{COD} = 0.18d – 1， $K_{NH_3\text{-}N}$ = 0.08d – 1. The upper limit value of water quality standard is selected as the background pollutant concentration of the Xiangyang Reach.

4. Results and Discussion

4.1. Pollution in the Xiangyang Reach of the Han River

In 2007, the quantity of waste water entering the Xiangyang Reach was 130,414,000 t. The amount of COD was 38,741 t, and NH_3-N was 4418.43 t. **Table 3** shows the amount of pollutants entering the Xiangyang Reach from various pollution sources. Municipal domestic sewage was the primary point source pollution, accounting for nearly 64% of COD and 62% of NH_3-N, respecttively. **Table 4** shows the quantity of pollutants from point source pollution in each computational unit. The pollutant loading mainly originates from Xiangyang urban area with the highest population densities. The chemical fiber industry, textile industry, pharmaceutical industry, and chemical industry are four major industrial pollution sources, whose COD accounted for nearly 76% of industrial pollution.

4.2. Changes of the Hydrological Regime

The Cuijiaying Hydro-junction project has mainly exerted effects on the hydrological regime of the following two areas: the reservoir area and downstream of this project. The flow of reservoir area (backwater area) is mainly influenced by the upstream flow and runoff, and the designed flow of this area is 554 m^3/s. The water level increased from 2.66 m to 62.73 m, and the designed flow velocity is 0.138 m/s. The state of flow may turn into the state of reservoirs flow in the reservoir region, and the hydrological regime changes cause the water flow and the nutrient contents suitable for the occurrence of ecological environment problems.

Meanwhile, the minimum discharging downstream flow (490 m^3/s) is used for designed flow of downstream of the dam. The designed flow velocity is 0.57 m/s, and the water level has increased by 0.15 m.

Table 3. The quantity of pollutants from various pollution sources entering the Xiangyang Reach in 2007.

Pollution source	COD (t)	NH_3-N (t)
Municipal domestic sewage	21905.2	2267.7
Industrial sewage	12388.5	1418.2
Animal breeding	1758.2	353.6
Rural area sewage	1735.2	188.2
Farmland runoff	951.1	190.3
Urban runoff	2.7	0.3

Table 4. The amount of pollutants from point source pollution in each computational uint in 2007.

Computational unit	COD (t)	NH_3-N (t)
Shenwan-Xianrendu	6802.6	553.4
Xianrendu-Baijiawan	11640.6	1256.7
Zhakou-Qianying	10608.1	949
Qianying-Yujiahu	785.4	653.1
Yujiahu-Guo'an	4401	814.4

4.3. Water Environmental Capacity in the Xiangyang Reach of the Han River

Based on the specified water quality and hydrological patterns, the water environmental capacity in the Xiangyang Reach of the Han River was estimated. The results are shown in **Table 5**, which are the maximum allowable pollutants loading entering the river (there is no outfall in the unit of Baijiawan-Zhakou, so this unit does not need to calculate). The water environmental capacity after the implementation of the cascade project is shown in **Table 6**. The water environmental capacity has declined in the reservoir area (Zhakou-Qianying) during the low-flow

Table 5. Water environmental capacity in the Xiangyang Reach of the Han River.

Computational unit	COD (t/a)	NH_3-N (t/a)
Shenwan-Xianrendu	3614.1	576.34
Xianrendu-Baijiawan	1904.4	177.11
Zhakou-Qianying	44986.2	2278.76
Qianying-Yujiahu	3570.1	224.13
Yujiahu-Guo'an	9852.23	197.46

Table 6. Water environmental capacity in the Xiangyang Reach after the implementation of the Cuijiaying project.

Computational unit	COD (t/a)	NH_3-N (t/a)
Shenwan-Xianrendu	3728.3	592.51
Xianrendu-Baijiawan	1905.5	177.6
Zhakou-Qianying	42661.3	2112.2
Qianying-Yujiahu	3612.3	235.1
Yujiahu-Guo'an	10007.6	203.78

period, and it is appearing to increase slightly in the upper and lower stream (Shenwan-Baijiawan, Qianying-Guo'an) of this project.

5. Conclusion

Applying two-dimensional steady state water quality model, we estimated the water environmental capacity of the Xiangyang Reach. Owing to the influence of cascade development, there is a decline of water environmental capacity in the reservoir region, also a growth in the upper and lower stream of the dam. However, the flow rate has declined in the reservoir area, and what should be done is to look for the influence of the cascade development on the aquatic eco-environment. The reservoir area should be a priority region for pollution control. The case study of the Xiangyang Reach shows that municipal domestic sewage was one of the major point source pollution, which contributed the most COD load entering the Han River in 2007. Improvement of sewage treatment facilities should be considered by policy makers in this area.

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