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Investigation on and analysis of pollution sources of Haojia village reservoir in Yibin, Sichuan Province, China

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ABSTRACT

Given the situation of pollution in Haojia Village Reservoir, the chemical oxygen demand (COD), total nitrogen and total phosphorus were analyzed, which showed that the reservoir water quality belonged to Grade IV surface water. According to the analysis on reservoir water pollution, the main exogenous input was excessive agricultural application of nitrogen and phosphorus fertilizers, and the major endogenous sources of water pollution were sediments of COD, total nitrogen and total phosphorus. Moreover, fencing, fish farming, and sewage runoff were also important causes of water quality variation in the reservoir. It shows that the environmental capacity of Haojia Village Reservoir is lower than that of the stored pollutants. The reservoir is under a stable stratified water temperature structure, which is less conducive to water self-purification. The water quality of the reservoir might continue to deteriorate.

Keywords: Reservoir; Pollution sources; Environmental capacity; Water temperature structure

1. Introduction

The southern part of Sichuan Province, China, is characterized by medium to low mountains and hills, among which, 70% are mountains, 10% is water, and 20% are fields. Reservoirs were built between the 1950s and the 1970s. At the beginning, most reservoirs were small and medium. Along with the economic development, the functions of reservoirs gradually changed from irrigation and flood control to farming, offering drinking water and tourism. As the economic function of the reservoirs was gradually intensified, the water quality decreased increasingly, which significantly affected their functions. In this study, taking Haojia Village Reservoir in Yibin as the research object, the main pollution sources were analyzed based on the water quality investigation in 2016.

2. Overview

With the capacity of 18.3 million m^3, normal capacity of 13.4 million m^3 and water surface of 175.5 hectares, Haojia Village Reservoir was completed in 1967. It is a tributary of Jiangjia River in the South Guanghe River basin of the Yangtze River, and has a catchment area of 2411 hectares. This reservoir was included in a regional scenic spot in 1988 and was approved by the People's Government of Sichuan Province as the first provincial Wetland Park in 2008. Crops account for 65% of the park and 35% is vegetation, especially the bamboo forest. Haojia Village Reservoir is over 70 km long, which is mainly distributed in the surrounding. The main crops are rice, corn and sweet potatoes, which are mainly distributed in its south bank.

3. Materials and methods

The agricultural surface sources were analyzed and calculated on Google Earth Pro 7.1.7. The concentration

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of NH_3-N in wastewater was detected via an HJ-535-2009 Nessler's reagent spectrometer; total nitrogen was measured by an HJ-636-2012 ultraviolet spectrophotometer using potassium persulfate, while COD (GB11914-89) was determined with a potassium dichromate method.

4. Results and analysis

4.1. Water quality test

4.1.1. COD change

Reservoir water temperature in 2016 and chemical oxygen demand (COD_{Cr}) are shown in Fig. 1. According to the Surface Water Environment Quality Standard (GB3838-2002), the functions of surface water can be divided into Grade I to Grade V, in which Grade I to Grade III are with the COD_{Cr} limit of 15 and 20 mg/L respectively. These three grades of water can be used as drinking water sources, while Grade IV to Grade V with the COD_{Cr} limit of 30 and 40 mg/L cannot be used as drinking water.

Comparison between water temperature and COD indicated that COD increased along with the rise of water temperature, which is closely related to temperature, rainfall and water purification. The change of reservoir water COD_{Cr} from April to November was more than 20 mg/L, which did not meet the standard of Grade III, and the change of COD_{Cr} of the remaining months was less than 20 mg/L, indicating that the water could be used as drinking water.

4.1.2 Changes in ammonia nitrogen (AN) and total nitrogen (TN)

With the development of industry, agriculture and tourism around the reservoir, the AN and TN contents in the reservoir gradually increased and became the limiting factors of the drinking water function of the reservoir. The data of AN and TN in the reservoir in 2016 are mapped in Fig. 2.

Fig. 2 shows the seasonal changes of AN and TN. AN was gradually intensified with time. The AN content in May was above 0.5 mg/L, which exceeded the limiting value of Grade III surface water and reached its peak in July and August, and then gradually declined. According to regulations, 1.0 mg/L of TN content suggests that the surface water quality changed between Grade IV and V.

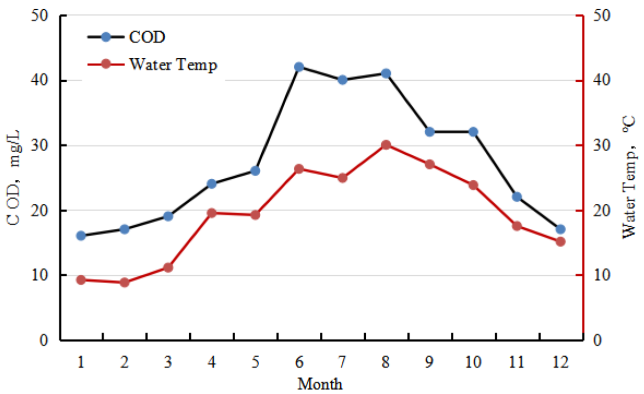

Fig. 1. Changes of CODCr in reservoir water in 2016.

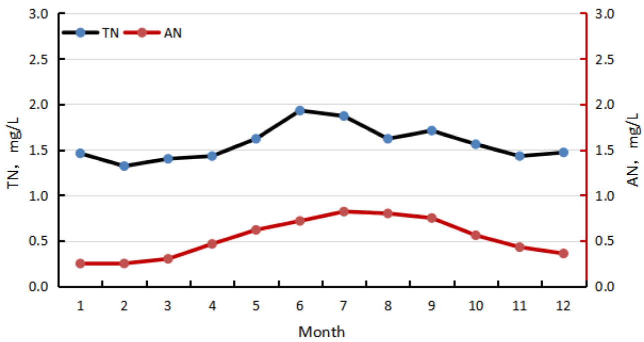

Fig. 2. TN and AN Changes of the reservoir in 2016.

4.1.3. Organic sediments in the collection area

Because of those long-term external inputs, aquaculture, fish bait waste, residues of sediments and aquatic organisms, the sediments of organic and inorganic pollutants have become severe secondary pollution of the reservoir, forming a serious threat to the aquatic environment.

The silting condition of the reservoir was investigated during the consolidation and renovation project in 2002. The thickness of silt was 2 and 5 m; the thickness of its upper layer was 30–50 cm and the color of sediments was dark black. The analysis of total nitrogen and total phosphorus in black mud is illustrated in Table 1. If the reservoir sediment thickness was 40 cm and the black water area in the reservoir was 175.5 ha (1,754,491 m^2), the reservoir sediment amount would be about 701,796 m^3, accounting for 3.82% of total capacity; the proportion would be 1.4 m and the weight would be 982,515 tons.

As shown in Table 1, the organic matter (OM) content of organic sludge in the reservoir was 15.98 g/kg, with the total volume of 15,700 tons. TP was 0.682 g/kg with 670 tons. The total nitrogen content was 1.356 g/kg with 1,332 tons. As the seasonal temperature changed, rain and summer fish activities were intensified, which produced water exchanges and lowered the level of the bottom of the pollutant library (including TN) into the water, causing water indicators such as TN to exceed limits and to induce eutrophication. The increase of temperature and anaerobic conditions accelerates the release of TN and TP in the reservoir sediment, and the good oxygen conditions inhibit the isolation of TN and TP. Enhanced illumination can accelerate the discharge of TP in the sediment, but rarely affects the release of TN [1].

4.2. Analysis of the causes of water pollution

4.2.1. Agricultural surface pollution

China Three Major Food Crops Fertilizer Utilization Research Report, issued by the Ministry of Agriculture in 2013, indicates that the three major grain crops in China (rice, maize, wheat) utilize 33%, 24% and 42% of nitrogen, phosphate and potash fertilizers on average respectively. The three major crops in China do not highly depend on fertilizers and there is still much room for improvement.

Farming is an important part of the income for farmers who live near the reservoir. Through visiting, surveying and mapping, for locating the Google Earth Pro reservoir catchment area for rice, wheat and maize and quar-

Table 1
Organic sediment composition of Haojia Village reservoir

Test items	Number of samples					Average	Weight (tons)
	1	2	3	4	5		
Thickness (cm)	10	40	35	50	40	40	982,515
OM, g/kg	8.2	15.8	16.3	22.4	17.2	15.98	15,700
TN, g/kg	0.37	1.06	1.47	2.56	1.32	1.356	1,332
TP, g/kg	0.16	0.45	0.85	0.74	1.21	0.682	670

terly using rice planting, and the planting mode of winter wheat and summer maize rotation, the total planting area was about 1160 hectares, accounting for 48.1% of the total catchment area. Wheat and maize are mainly planted on the slopes, which suffered from serious soil erosion in 15º–25º. Water and soil erosion caused serious sedimentation of reservoirs, which accounted for about 30% of the reservoir capacity.

Based on the 2008 survey of three major grain crops in China [2] and fertilizer utilization ratios as well as planting areas of the three major crops in China, the N, P and K fertilizer use rates were estimated in the reservoir (Table 2).

The nitrogen fertilizer induces the loss of ammonia volatilization (about 40–50% of the applied amount) during the application, and the volatile ammonia will re-enter the surface through rainfall [3].

The nitrogen and potash fertilizers are mostly water-soluble and will dissolve in the water body. Phosphorus is mostly water-insoluble, and in summer rainstorm rinse, it will enter the reservoir through soil erosion.

Table 2
Application of chemical fertilizers in the reservoir area

Terms	N	P_2O_5	K_2O
Application rate (kg/hm^2)	230	90	80
Application amount, t	266.8	104.4	92.8
Availability, %	33	24	42
Losses, %	89.38	15.87	26.92

Note: nitrogen, phosphate and potassium fertilizers were calculated at 50%, 20% and 50% without the use of crops respectively.

4.2.2. Pollution of aquaculture

Aquaculture in Haojia Village Reservoir began in 1992, formed a scale production in 1993 and peaked in 2000. Due to the larger density of fish fencing, abundant baits were put into the reservoir. A part of the bait was dissolved in water directly, while the others were absorbed by fishes and left the water body through fishing, and fish waste remained in the reservoir bottom, forming an organic pollution source. For artificial fish feeding, each ton of fishes generated about 0.8 ton of organic matter, including 0.08 ton of N and 0.014 ton of P, leading to eutrophication. With the drainage coefficient in calculation, the pollution results of artificial fish farming are shown in Table 3.

Table 3
Pollution caused by artificial fish farming

Year	Aquaculture area	Fish quantity, ton	OM	TN	TP
2000	1020	204	163.2	14.28	2.856
2011	710	142	113.6	9.94	1.988
2016	375	75	60	5.25	1.05

4.2.3. Household pollution from people living around the reservoir

Household pollution of farmers is sewage from kitchen, bathing, washing, toilet and so on. The sewage in kitchen is full of organic matter, such as cellulose, starch, sugar and fat protein. Direct discharge will lead to an increase volume of organic matter in water. The wastewater produced by bathing, washing and so on contains a great number of inorganic materials such as nitrogen, phosphorus and sulfur which will lead to excessive algae proliferation by direct discharge, thereby further aggravating the eutrophication of the water body.

Preliminary statistics shows that more than 300 farmers who lived in the reservoir area are less than 2 km away from the water body. The pollutant discharge coefficient of rural domestic sewage was determined as reported before [4].

With the rapid economic growth around the reservoir, the living standard of the residents is constantly improved. As a result, the amount of garbage in rural areas is increasing day by day and the garbage composition is increasingly complex, which further makes the garbage management difficult. At present, the garbage in the reservoir area is disposed by stacking simply. In summer, garbage decomposes into nitrogen-containing organic matter and forms landfill leachate. With the erosion of rainwater, the harmful components enter the reservoir with landfill leachate and become a pollution source of the water body.

5. Influences of reservoir characteristics on pollution

5.1. Influence of the water temperature structure on reservoir pollution

The influence of light on the reservoir water is distributed vertically in an uneven way. The water temperature distribution can be divided into stable, transitional and hybrid patterns by adopting the method of α-β and the depth/width ratio, which mainly judges the water temperature structure from the inflow water and the flood:

$$\alpha = \text{average annual runoff} \div \text{total capacity} = 0.79$$

$$\beta = \text{flood total flow} \div \text{total capacity} = 0.11 \tag{1}$$

where $\alpha < 10$, $10 < \alpha < 20$, and $\alpha > 20$ indicate stable, transitional and hybrid stratification, respectively.

In general, α determines the reservoir that belongs to the stratified type or the mixed type, but when the flood conditions are not at the same time, the hierarchical model can also be mixed; therefore β is used as a second discriminant standard. For layered reservoirs, deluge flood with $\beta > 1$ will destroy the original structure of the water temperature and make it a temporary hybrid type, and when $\beta < 0.5$, the flood does not significantly impact the water temperature structure.

The values of α and β define whether the reservoir is in a stable stratified water temperature structure. In this structure, with the increase of water, the pH and dissolved oxygen gradually decrease, which is highly consistent with the water temperature changes, while COD increases gradually, indicating that pollution is intensified with the increase of water. When sufficient sunlight, moderate temperature, and rich nutrients were provided for the surface water of the reservoir, the explosive growth of aquatic plants may happen, leading to eutrophication and even blooming. Instead, when the deep water is under a hypoxia condition, the endogenous phosphorus will increase easily, which accelerates the release of phosphorus from the sediments. When layering is not evident, the phosphorus released from the sediment will infiltrate into the surface water, thereby providing rich nutrients for the eutrophication of surface water and increasing the potential risks of water quality deterioration.

5.2. Reservoir water environment capacity

Water environmental capacity is defined as the amount of pollutants the water body can hold without affecting the common use of water, or the pollutants can be regulated and purified while maintaining ecological balance.

The water environment capacity of the reservoir was determined by adding three parts: dilution capacity, self-purification capacity and migration capacity. At present, the water environment capacity is usually calculated by adopting different water quality models and is deduced on the basis of the water quality models. In most cases, lakes and reservoirs are considered as "mixed reactors". In China, the water quality models of the majority of closed and semi-closed water bodies are established based on the hypothesis of "mixed reactors". The water retention time of a gatehouse reservoir is relatively long, and the water quality is basically stable, which can be regarded as a uniformly mixed water body.

5.2.1. Environmental capacity of organic matter

According to the material balance equation of lakes (reservoirs), the water quality model of organic matter can be written as follows:

$$V\frac{dc}{dt} = Q*Cr - K*C*V - q*C_C \tag{2}$$

where V is the volume of the reservoir (m^3); Q and q are the inflow and outflow of reservoir water (m^3/d); K is the biochemical degradation coefficient of pollutants (d^{-1}); Cr, Cc and C are the average concentrations of pollutants in inflow water, outflow water and the reservoir respectively (mg/L).

When the reservoir is regarded as a steady-state system, $dc/dt = 0$, then:

$$Q*Cr = K*C*V + q*C_C \tag{3}$$

When $C = Cs = Cc$, the pollutant concentration in the reservoir reaches the specified water quality standard.

$$L_C = \frac{Q*Cr}{A} = \frac{K*Cs*V}{A} + \frac{q*C_C}{A} \tag{4}$$

$$L_C = K*Cs*H + \frac{q*C_s}{A} \tag{5}$$

5.2.2. The water environmental capacity model of total nitrogen and total phosphorus

$$L_p = \frac{C_S \times \xi \times H \times A}{1-R}$$

$$\xi = 3153.6\frac{q}{V} \tag{6}$$

$$R = 0.426\exp\left(-0.271\frac{q}{A}\right) + 0.573\exp\left(-0.00949\frac{q}{A}\right) \tag{7}$$

Table 4
Correlation parameters of environmental capacity calculation

Parameter	Value	Remarks
CODcr C_{COD}, mg/L	20	Class III
Total phosphorus C_P, mg/L	0.05	Class III
Total nitrogen C_N, mg/L	1	Class III
Reservoir volume V, m^3	1.34×10^7	Normal water level
Surface area A, m^2	1.75×10^6	Normal water level
Average depth H, m	10	Normal water level
Annual inflow of reservoir water Q_{in}, m^3/a	1.45×10^7	
Annual outflow of reservoir water q, m^3/a	0.958×10^7	
Detention factor R	0.641	
COD degradation coefficient K_{COD}, 1/a	36.5	
Erosion coefficient ξ, 1/a	0.713	
Annual outflow of reservoir water Q_{out}, m^3/s	0.303	
Nitrogen deposition coefficient σ, m/a	13.03	

Table 5
Environmental capacity under different water quality conditions

Water quality standard	COD, t/a	Total nitrogen, t/a	Total phosphorus, t/a
Class I	6446	6.47	0.16
Class II	6446	16.18	0.81
Class III	8595	32.35	1.62
Class IV	12892	48.53	2.43

As shown in Tables 2–5, the environmental capacity of Haojia Village Reservoir is much lower than that of the stored pollutants. If no measures were taken to reduce the amount of pollutants stored, the water quality of the reservoir would continue to decrease.

6. Conclusions

6.1. Current situation of water pollution in the reservoir

The COD and the CODcr from April to November in the reservoir were larger than 20 mg/L, which did not meet the standard of Grade III. The total nitrogen content was more than 1.0 mg/L, which was between Grade IV and Grade V. Organic sediments in the reservoir were serious and rich in organic matter, total nitrogen and total phosphorus.

6.2. Sources of water pollution in reservoirs

The reservoir is dominated by planting and threatened by excessive fertilizer application. The utilization rates of nitrogen (N), phosphate (P_2O_5) and potash (K_2O) are 33%, 24% and 33%, respectively, and the principal source of ammonia nitrogen in the reservoir is the loss of fertilizers. The contaminants of the reservoir sediment are also the main source of organic matter and ammonia nitrogen in the reservoir. In addition, fenced fish farming, domestic sewage and reservoir runoff are also the important causes of the water quality deterioration in the reservoir.

6.3. Tendency for water pollution in the reservoir

It can be seen that the environmental capacity of Haojia Village Reservoir is lower than that of the stored pollutants. The reservoir is under a stable stratified water temperature structure, which is not conducive to water self-purification. The water quality of the reservoir would continue to decrease.

Acknowledgements

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