How to calculate allowable permitted assimilative capacity of river under influence of hydropower development

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Abstract: Calculating the allowable permitted assimilative capacity under influence of hydropower development is meaningful for water pollution prevention. This paper takes Nan River as the research object, and uses river one-dimensional model, lake uniform mixing model and Dillon model to calculate the allowable permitted assimilative capacity of chemical oxygen demand and total phosphorus and ammonia nitrogen in Nan River. The results show that allowable permitted assimilative capacity of chemical oxygen demand and total phosphorus and ammonia nitrogen are 6901.93, 511.78 and 150.31 t/a, respectively in Nan River. This paper can provide guidance for the determination of APAC of river under the influence of hydropower development.

1. Introduction

For a long time, the emission control standard is the main basis for the implementation of pollutant concentration control for river water environment management. Affected by the high-intensity human activities and domestic sewage discharge, the amount of sewage that can be collected in the river is decreasing day by day, and even if the pollutant source of which pollution concentration is fully up to standard, it is difficult to meet the water environment functional target. It is necessary to accelerate the prevention and control of water pollution, implement comprehensive management of river water environment. In this context, calculating the allowable permitted assimilative capacity (APAC) of rivers and lakes is the basic work for making treatment measures and formulating reduction plans of watershed pollutant emission.

Based on the water quality model under one-dimensional steady-state conditions, Zhang Haiou et al. used the head control model, the standard model and the EU model to calculate the maximum and minimum values of the APAC of the Wei River in Shanxi Province, and used this interval as the final result [1]. Based on the water quality model under one-dimensional steady-state conditions, Zhang Xiao et al. established a segmented summation model with considering the water intake and tributary to calculate the river's APAC. The research results avoided the situation that the result was too strict or too loose [2]. Jin Guohua et al. analyzed the annual average capacity, the self-cleaning time and water exchange coefficient of Poyang Lake, and used the principle of conservation of mass to calculate the APAC of Poyang Lake in different months. The results show that there was no large-scale eutrophication in Poyang Lake [3]. Luo Huiping et al. used the one-dimensional and two-dimensional steady-state models to calculate the APAC of the river network area and reservoirs in the Taihu Basin. The results show that the relationship between APAC and total amount of pollutant from land into
water is reasonable [4]. Liang Xiu et al. calculated the APAC of Chang Lake by using the lake uniform model, Dillon model and Hetianjian model. The results showed that aquaculture contributed a lot to the pollution of chemical oxygen demand (COD) and total phosphorus (TP) [5]. Although there are many studies on the APAC in natural rivers and lakes, there are few studies on the APAC of river under the influence of hydropower development.

This paper takes Nan River as the research object, and uses River one-dimensional model, Lake uniform mixing model and Dillon model to calculate the APAC of COD, TP and ammonia nitrogen (NH$_3$-N) in Nan River. This paper can provide guidance for the determination of APAC of river under the influence of hydropower development.

2. Study area

The Nan River is a mountainous river. It is a tributary of the right bank of the middle reaches of the Han River. It originates from the scorpion in the southeast of Shennongjia, and flows through the Shennongjia forest area, Fangxian County, Baokang County and Gucheng County, China, and then is merged into the Han River in 5 km downstream of Chengguan Town in Gucheng County, with a length of 267.5 km and a catchment area of 6497 km$^2$. The Nan River contains two first-level functional zones: one protected area with a river length of 20 km, one reserved area with a river length of 243 km.

| No. | Water function zoning | Starting section | Termination section | Length (km) | Water quality monitoring section | Water quality target [6] |
|-----|------------------------|------------------|--------------------|------------|---------------------------------|--------------------------|
| 1   | Shennongjia Nature Reserve | River-head       | Gaojiawuchang, Hongping Town, Shennongjia | 20         | Songluo Town                    | II                       |
| 2   | Gucheng Reserve         | Gaojiawuchang, Hongping Town, Shennongjia | Gaojiawuchang, Hongping Town, Shennongjia, Wangjiazui, Chengguan Town, Gucheng | 243        | Maqiao reservoir                | III                      |

2.1 Reservoir

In Nan River, there are 8 large and medium-sized reservoirs, including 3 large reservoirs with a total storage capacity of 916 million cubic meter and a utilizable capacity of 417 million cubic meter, 5 medium-sized reservoirs with a total storage capacity of 175 million cubic meter and a utilizable capacity of 52 million cubic meter.

| Type           | Name       | Total storage capacity (100 million m$^3$) | Utilizable capacity (100 million m$^3$) | Normal water level (m) | Mean annual runoff (100 million m$^3$) |
|----------------|------------|------------------------------------------|----------------------------------------|-------------------------|----------------------------------------|
| Large reservoir| Sanliping  | 4.99                                     | 2.11                                   | 416                     | 8.77                                   |
|                | Siping     | 2.69                                     | 1.45                                   | 315                     | 9.94                                   |
|                | Baishuiyu  | 1.48                                     | 0.61                                   | 198                     | 23.4                                   |
| Medium-sized   | Longtanzui | 0.064                                    | 0.0576                                 | 530                     | 3.7528                                 |
| reservoir      | Maqiao     | 0.26                                     | 0.04                                   | 483.7                   | 7.6700                                 |
|                | Guoduwan   | 0.27                                     | 0.08                                   | 218                     | 20.53                                  |
|                | Nanhe      | 0.83                                     | 0.24                                   | 151.5                   | 25.00                                  |
|                | Miaozitou  | 0.12                                     | 0.06                                   | 119.5                   | 23.70                                  |

2.2 Runoff

The runoff of the Yangriwan, Kaifengyu hydrological station and Miaozitou hydropower station are selected to describe the runoff processes of the upper, middle and lower reaches of the Nan River. According to the daily flow monitoring data from 2006 to 2016, the annual average flow in the upper reaches of the Nan River is between 14 – 24 m$^3$/s, and the average annual flow is 18.71 m$^3$/s; the annual average flow in the middle reaches of the Nan River is between 20 – 64 m$^3$/s, and the average
annual flow is 45.88 m³/s; the annual average flow in the lower reaches of the Nan River is between 33 – 95 m³/s, and the average annual flow is 59.93 m³/s. Nan River is a medium river [7].

2.3 Water quality

There are two water quality monitoring sections, which are Songluo Town and Maqiao reservoir in the water functional zones mentioned above. The monitoring indicators are 24 items, including Permanganate index, COD, TP and NH₃-N in environmental quality standards for surface water [6]. The monitoring frequency is once a month. In 2016, the yearly control rates of water quality in water functional zones in Nan River were greater than 80%, only the water quality of Gucheng Reserve was substandard in March, and the exceeding standard factor was TP.

3. Methods and data

3.1 Method of APAC of Nan River

Influenced by the reservoirs, the Nan River is characteristic of segmented lakes. This paper uses the reservoirs as the boundary, divide the river into many reaches, and calculates APAC in river between two adjacent reservoirs and nature river in which there is not hydraulic engineering, and then the APAC of whole river is determined.

3.1.1 River between two adjacent reservoirs. River one-dimensional model, lake uniform mixing model, lake non-uniform mixing model, lake eutrophication model and lake stratification model can be used to calculate the APAC of Nan River, which is a medium river.

When the average water depth is less than 10 m and the water exchange coefficient [7] is less than 10, lake stratification model should be used to calculate the APAC. However, the opposite is true in river between any two adjacent reservoirs. Therefore, the lake stratification model should not be adopted. The water quality in Nan River show overall reaching the standard. However, in some months, the eutrophication key indicator, TP exceeded the standard. Compared with the tributary and bay of large and medium-sized lakes, the pollutants of the rivers and their tributaries above the dam site can be transferred into the reservoir at a faster rate (relative to the lake), this characteristic cannot be described by the non-uniform mixing model. Based on the above-mentioned points, this paper mainly uses the river one-dimensional model and the lake uniform mixing model to calculate the APAC of COD and NH₃-N, respectively, then selects the minimum, and uses the Dillon model to calculate the TP of APAC.

| Reservoir   | Depth (m) | water exchange coefficient (-) | Model for calculating APAC | COD/NH₃-N | TP     |
|-------------|-----------|---------------------------------|---------------------------|-----------|--------|
| Longtanzui  | 7.40      | 59                              | River one-dimensional model, lake uniform mixing model | Dillon model |
| Maqiao      | 8.34      | 30                              |                           |           |        |
| Sanliping   | 25.60     | 2                               |                           |           |        |
| Siping      | 17.40     | 4                               |                           |           |        |
| Guoduwan    | 6.70      | 76                              |                           |           |        |
| Baishuiyu   | 11.40     | 16                              |                           |           |        |
| Nanhe       | 9.50      | 30                              |                           |           |        |
| Miaozitou   | 3.00      | 198                             |                           |           |        |

(1) Lake uniform mixing model. The equation for the lake uniform mixing model is:

\[
V(t) \frac{dC}{dt} = C_{in}(t)Q_{in}(t) - C_{out}(t)Q_{out}(t) + S(t) + rV(t)
\] (1)

A steady state form is introduced into the model, then \( V(t) \frac{dC}{dt} = 0 \), and the attenuation of pollutants in the reaction term is considered, then \( r = -KC \). When the pollutant concentration in the outflow
reach the water quality target of the reservoir, the amount of external source and sink pollutant entering the reservoir is the reservoir’s APAC, which can be expressed as:

\[ W = 31.536(C_{\text{out}} - C_0 + \frac{KC_V}{86400}) \]  

(2)

where \( W \) is the APAC, t/a; \( C_s \) is the water quality target of the reservoir, mg/L; \( C_0 \) is the pollutant concentration of inflow, mg/L; \( V \) is the reservoir volume under designed hydrological conditions, m\(^3\); \( C_{\text{out}} \) and \( C_{\text{in}} \) are pollutant concentration of outflow and inflow, respectively, mg/L; \( K \) is pollutant attenuation coefficient, 1/s.

(2) Dillon model. The calculation equation for the Dillon model is:

\[ M_N = \frac{C_s - hQ}{V}A \]  

(3)

\[ R_p = 0.426e^{-0.271/Q} + 0.547e^{-0.00949/Q} \]  

(4)

where \( M_N \) is the APAC, t/a; \( A \) is the water area under designed hydrological conditions, m\(^2\); \( Q \) is the outflow from the lake or reservoir, m\(^3\)/a; \( R_p \) is the retention coefficient of phosphorus in lake or reservoir, dimensionless; \( h \) is average depth under designed hydrological conditions, m; others have the same meaning as before.

(3) River one-dimensional model. River one-dimensional model can be expressed as:

\[ C_x = C_0 \exp(-\frac{Kx}{u}) \]  

(5)

Where \( C_0 \) is pollutant concentration of initial section, mg/L; \( x \) is the distance from initial section, m; \( u \) is the flow velocity under designed hydrological conditions, m/s; \( C_x \) is the pollutant concentration of which is \( x \) far from initial section, mg/L; \( K \) is pollutant attenuation coefficient, 1/s.

When the sewage outlet is located in the middle of the river, the pollutant concentration in the lower section of the water functional zone and its corresponding APAC are calculated as follow:

\[ C_{x+k} = C_x \exp\left(-\frac{KL}{u}\right) + \frac{mQ}{2u} \exp\left(-\frac{KL}{u}\right) \]  

(6)

\[ M = \frac{[C_x - C_0 \exp\left(-\frac{KL}{u}\right)]Q}{2u} \]  

(7)

where \( L \) is the length of river, m; \( Q \) is flow under designed hydrological conditions, m\(^3\)/s; others have the same meaning as before.

3.1.2 Nature river. The Nan River is a medium river. The river one-dimensional as mentioned before is used to calculate the APAC of COD, NH\(_3\)-N and TP from the last reservoir, namely Miaozitou Hydropower Station to the estuary of Nan River.

3.2 Parameters of method for calculating APAC

3.2.1 Parameter for river between two adjacent reservoirs. The parameters include designed hydrological conditions, \( C_i \), \( C_o \) and pollutant attenuation coefficient.

(1) Designed hydrological conditions. The designed hydrological conditions of each partition need to be determined separately in different reaches. The calculation of APAC between two adjacent reservoirs should take the lowest monthly average water level in the past 10 years or the water volume corresponding to the average monthly water level with the guaranteed rate of 90% as designed hydrological conditions. River runoff is the main inflow of each reservoir. According to Code of practice for computation on allowable permitted assimilative capacity of water bodies, the average monthly discharge with the guaranteed rate of 90% or the lowest average monthly discharge during the past 10 years is regarded as the designed flow. If hydraulic engineering exists in river, the minimum discharge flow of hydraulic engineering or minimal ecology base runoff in the river can be used as the
designed flow.

In this paper, the water area, average water depth and volume corresponding to the utilizable capacity of each reservoir are selected as the designed water quantity conditions. The daily flow of each reservoir during 2006 – 2016 were selected, and the average monthly average flow was calculated, which was used as the inflow and outflow of flow of two adjacent reservoirs. Take 10% of the average annual discharge of each reservoir as the minimal ecology base runoff of the downstream rivers. By comparing the lowest average monthly discharge and the ecological base flow of the river, the maximum value is taken as the designed flow. According to the field measurement, the maximum flow velocity during the study period is 0.22 m/s, the minimum value is 0.01 m/s, and the average flow velocity is 0.11 m/s. Combined with the topography and dam blocking effect, considering the most unfavorable situation, in P0 – P7 designed flow velocities are set to be between 0.15 – 0.30 m/s.

Table 4. Designed hydrological conditions for different districts

| Reservoir name | Partition | Water area(km²) | Water depth(m) | Volume (100 million m³) | Outflow (m³/s) | Inflow (m³/s) |
|----------------|-----------|-----------------|----------------|-------------------------|----------------|---------------|
| Longtanzui     | P0        | 0.90            | 7.40           | 0.0576                  | 1.19           | 1.19          |
| Maqiao         | P1        | 1.37            | 8.34           | 0.14                    | 3.45           | 2.45          |
| Sanliping      | P2        | 10.74           | 25.60          | 2.11                    | 4.67           | 3.45          |
| Siping         | P3        | 8.25            | 17.40          | 1.45                    | 4.56           | 4.67          |
| Guoduwan       | P4        | 1.35            | 6.70           | 0.08                    | 6.51           | 4.56          |
| Baishuiyu      | P5        | 5.51            | 11.40          | 0.61                    | 7.42           | 6.51          |
| Nanhe          | P6        | 4.33            | 9.50           | 0.24                    | 7.93           | 7.42          |
| Miaozitou      | P7        | 0.88            | 3.00           | 0.06                    | 7.52           | 7.93          |

(2) $C_s$ and $C_o$. The Nan River has the Shennongjia Nature Reserve and the Gucheng Reserve. The water quality targets are II and III, respectively. The P0 is located in Shennongjia Nature Reserve. The target concentration of water quality, $Cs$, should meet following requirements: COD $\leq$ 15 mg/L, NH$_3$-N $\leq$ 0.5 mg/L; TP $\leq$ 0.025 mg/L; P1 – P8 are located in the Gucheng Reserve, $Cs$ should meet following requirements: COD $\leq$ 20 mg/L, NH$_3$-N $\leq$ 1 mg/L, TP $\leq$ 0.05 mg/L. P0 mainly accepts incoming water from Shennongjia Nature Reserve, concentration of COD, NH$_3$-N and TP in incoming water, $C_o$, should meet following requirements: COD $\leq$ 15 mg/L, NH$_3$-N $\leq$ 0.15 mg/L, TP $\leq$ 0.01 mg/L. For other reaches, $C_o$ should meet following requirements: COD $\leq$ 20 mg/L, NH$_3$-N $\leq$ 1 mg/L, TP $\leq$ 0.05 mg/L.

(3) Pollutant attenuation coefficient. According to relevant research, the attenuation coefficient of COD in China’s rivers is 0.009 – 0.470 d$^{-1}$, and the attenuation coefficient of NH$_3$-N is 0.105 – 0.350 d$^{-1}$. The attenuation coefficient of COD and NH$_3$-N in the lake is lower than that in the river. Referring to the related research, the attenuation coefficients of COD and NH$_3$-N are taken as 0.04/d and 0.06/d, respectively [8].

3.2.2 Parameter for nature river. The parameters include designed hydrological conditions, $C_s$, $C_o$, and pollutant attenuation coefficient.

(1) Designed hydrological conditions. The daily discharge of Miaozitou Reservoir during 2007 – 2016 are selected to calculate the lowest average monthly average flow, which is 6.5 m$^3$/s. At the same time, 10% of average annual discharge represents the minimal ecology base runoff. Both are compared, then the maximum value is the designed flow, which is 7.52 m$^3$/s. According to the field measurement, the maximum flow velocity during the study period is 0.22 m/s, the minimum value is 0.01 m/s, and the average flow velocity is 0.11 m/s. Combined with the topography and dam blocking effect, considering the most unfavorable situation, the P0 – P7 designed flow velocities are set to be between 0.15 – 0.30 m/s.

(2) $C_s$ and $C_o$. The initial section of the river is the Miaozitou Hydropower Station, which is in the Gucheng Reserve. $C_o$ should meet following requirements: COD $\leq$ 20 mg/L, NH$_3$-N $\leq$ 1 mg/L, TP $\leq$ 0.05 mg/L. The calculation section is in Gucheng reserve, $Cs$ should meet following requirements: COD $\leq$ 20 mg/L, NH$_3$-N $\leq$ 1 mg/L, TP $\leq$ 0.2 mg/L.
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(3) Pollutant attenuation coefficient. The attenuation coefficient of COD in China's rivers is between 0.009 – 0.470 d\(^{-1}\), and the attenuation coefficient of NH\(_3\)-N is between 0.105 – 0.350 d\(^{-1}\). In this paper, the attenuation coefficients of COD, TP and NH\(_3\)-N in the nature river are set to be 0.187/d, 0.08/d and 0.30/d, respectively \(^{[1]}\).

4. Results and discussion

According to the calculating model and parameters, the results of APAC of different pollutant of different reaches in Nan River are shown in Table 5. The APAC of COD, NH\(_3\)-N and TP are 6901.93, 511.78 and 150.31 t/a, respectively.

Table 5. Combining river one-dimensional model and Dillon model to calculate APAC

| Partition | COD (t/a) | NH\(_3\)-N (t/a) | TP (t/a) |
|-----------|-----------|-----------------|----------|
| P0        | 290.47    | 17.59           | 1.72     |
| P1        | 896.84    | 75.31           | 5.98     |
| P2        | 598.10    | 48.21           | 18.84    |
| P3        | 810.25    | 65.31           | 13.36    |
| P4        | 669.74    | 53.91           | 13.33    |
| P5        | 767.75    | 61.72           | 18.99    |
| P6        | 666.72    | 53.55           | 31.34    |
| P7        | 411.48    | 33.02           | 5.45     |
| P8        | 1790.59   | 103.15          | 41.30    |
| Total     | 6901.93   | 511.78          | 150.31   |

Similarly, when the lake uniform mixing model and the Dillon model combination are obtained, the APAC of COD, NH\(_3\)-N and TP are 134788.12, 10648.98 and 150.30 t/a, respectively in Nan River. By comparison, the calculation results of the schemes with less pollution capacity in the two combinations are better, as shown in Table 5. The results are useful river water environment management.

The rationality of the results of the APAC of Nan River is tested, including the rationality analysis of basic data, the simplification of calculation conditions and the rationality analysis of the assumptions, the rationality analysis and test of model selection and parameter determination. The rationality analysis show that the results are reasonable.

5. Conclusion

Considering the influence of the reservoir, this paper generalizes the Nan into a combination between lake/reservoirs and river, and then uses the mathematical model to calculate the APAC of COD, NH\(_3\)-N and TP, which are 6901.93, 511.78 and 150.31 t/a, respectively. The methods provided in this paper can be used to calculated APAC of river under the effect of cascade hydropower development in medium river.

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