Effect of river damming on phosphorus retention in China

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Abstract. The construction of hydropower stations not only improves water conservancy and hydropower generation, but also seriously hinders the natural biogeochemical circulation of rivers, resulting in phosphorus retention in reservoirs, eutrophication of water bodies, and finally phosphorus pollution. Therefore, it is of great significance to study the effect of phosphorus retention in the closure of dams of hydropower stations. In order to solve this problem, this paper, based on the global news model, simulated the retention of phosphorus in eight dams and reservoirs in China. The results showed that: (1) phosphorus production was higher in the densely populated and economically developed basins along the southeast coast of China, among which the phosphorus production was highest in the Yangtze river basin and the pearl river basin, reaching 139 kg/(km$^2$· yr) and 161 kg/(km$^2$· yr), respectively. (2) China's dams are mainly built in the middle and lower reaches of the Yangtze river, which is closely related to the rich water resources and the developed regional economy. It is worth mentioning that the dams with the highest phosphorus retention are also located on the major rivers of the Yangtze, Yellow and Huai rivers. In general, the areas with high phosphorus retention are mainly concentrated in central and southern China. Population, economy, latitude, area, runoff and other factors will be the key factors to determine phosphorus retention.

1. Introduction
The damming of hydropower stations not only develops water conservancy and produces electric energy, but also seriously interferes with the natural biogeochemical circulation of rivers and produces many negative ecological and environmental effects [1]. Damming will also lead to a large number of nutrients trapped in the reservoir, resulting in eutrophication and deterioration of water quality [2], and finally phosphorus pollution [3]. Water pollution not only affects the aquatic environment and People's Daily life, but also causes considerable economic losses in serious cases [4]. Therefore, the effect of dam closure on phosphorus retention in reservoirs is worth further study.

Basin of phosphorus pollution source analysis and control is more and more attention and research, however, in recent years, the domestic research mainly small watershed non-point source pollution, and no considering the influence of hydropower station dam [5, 6, 7], while foreign research using the global data [8], dam and reservoir caused by damming the river closure for the global basin reservoir phosphorus retention summarize quantitative analysis [9]. The Global NEWS model can simulate and calculate the phosphorus element output of the Global basin [10]. However, in the corresponding
program developed by the model, the phosphorus element retention of the river by the dam is only roughly replaced by a coefficient multiplication [11].

However, no one has simulated the phosphorus retention caused by the damming of specific hydropower stations, and the comparative analysis of the total phosphorus retention in the basin has not been studied. We in the Global system after the study and research of NEWS model, closed model of dam retention coefficient of options, and then the calculation of specific calculation phosphorus retention capacity, specific to each reservoir in river basin as the unit classification summary, comparative analysis and get the key factor of the phosphorus retention amount.

2. Study area and data
We study the eight major rivers flowing into the east coast of China, as shown in figure 1. They are respectively the Heilongjiang River, the Liao River, the Luan River, the Hai River and the Yellow River basins flowing into the Bohai Gulf in the north of China, the Yangtze River and the Huai River, which flow into the yellow sea, are located in central China. Located in the south of China, the Pearl River basin empties into the South China Sea [12]. The eight rivers cover a total area of 5.66 million square kilometers, about 60 percent of China's land area, and span the entire latitude of China from south to north. Among them, the Yangtze River, the Yellow River and the Pearl River are the three major hydroelectric rivers in China, with their basins covering 1.79 million, 890,000 and 410,000 square kilometers respectively.

![Figure 1. Eight major river basins in China](image)

The grid polygon data of the eight drainage basins used in this study comes from stn-30p river system developed by Vorosmarty et al in 2000 [13], which is a 0.5°×0.5° grid data set, and also includes the drainage area and other important data used to calculate the phosphorus element output of the drainage basin.

As for the data in the NWES model, it comes from the data provided by Mayorga et al., which is based on the data in a single basin in 2000, including more than 10 input data used to calculate the yield of phosphorus elements (DIP, DOP and PP) in the basin, including artificial fertilizers, animal fertilizers and artificial removal [14].

The reservoir and dam data used to calculate the retention of hydropower dams are derived from GRanD database, which is a very comprehensive and verified global database of reservoir DAMS, including key data such as reservoir capacity, annual discharge, and hydraulic residence time used to calculate the retention rate of phosphorus elements for hydropower stations and dams [8].
3. Methods

The calculation of phosphorus retention in hydropower station is divided into two steps: (1) phosphorus (DIP, DIP and PP) production in eight major basins is calculated by using the Global NEWS model; (2) the retention rate of phosphorus elements in the hydropower station was calculated from the dam data in the GRanD data set, so as to further calculate the retention amount of phosphorus elements (RP, TP).

3.1. Global NEWS model

When Global NEWS is a Global, visualized, multi-element and multi-form model of nutrient element output in river basin, which is specifically used to simulate and calculate the yield of N, P, C, Si and other nutrient elements in the basin and the export volume to the ocean [11]. In this study, only P's basin yield calculation is needed. The Global NEWS model will simulate and calculate 6,982 river basins around the world [13]. All Global NEWS models have predicted the average annual yield (kg/km²) and exports (tons) of nutrients in the basin.

The global news model system is unique in that it can be used to predict the size and source of multiple nutrient elements (C, N, P, Si) in form (dissolved/particles, organic/inorganic). Here, nutrient elements have different forms, and we use the first letter of the word instead: D for dissolved form; P said particles (particulate) form; O stands for organic; I said inorganic (inorganic). For example, DOP stands for dissolved organophosphorus, a nutrient form, and so on.

3.2. Calculation of phosphorus retention

The phosphorus retention rate calculation model was applied to the Global Reservoirs and Dams (GRanD) database to estimate the TP and RP retention of dams in major river basins around the world. During the whole process, the retention efficiency of phosphorus in the reservoir is defined as

\[ R_X = \frac{X_{in} - X_{out}}{X_{in}} \]

Where \( R_X \) is the fractional retention of TP or RP, and \( X_{in} \) and \( X_{out} \) are the input and output fluxes of TP or RP in units of mass per unit time.

Therefore, for each reservoir, the annual retention of TP and RP in the reservoir can be calculated by multiplying the \( R_X \) value by the corresponding TP and RP input fluxes in the upstream basin.

\[ X_{ret,i} = X_{in,i} - X_{out,i} = R_X \times X_{in,i} \]

For \( X_{in,i} \), we calculated the discharges of dissolved inorganic phosphorus (DIP), dissolved organic phosphorus (DOP) and particulate phosphorus (PP) by using the global-news model and disusing the built-in damming function. Obviously, TP output should be the sum of DIP, DOP and PP, while the corresponding RP output is calculated as the sum of DOP and DIP, plus 20% of PP.

For \( R_X \), the retention of P in lakes and reservoirs is related to hydraulic retention time \( (\tau_r) \). RTP and RRP values derived from the model follow the original equation of P reserve quantity in natural lakes proposed by Vollenweider [15].

\[ R_X = 1 - \frac{1}{1 + \sigma \times \tau_r} \]

\( \sigma \) is a first-order rate constant describing the loss coefficient of P from the water column (see supporting information, section 4, derivation of the equation). The following statistically significant mean values are obtained by nonlinear least squares regression analysis [9]:

For RTP, \( \sigma = 0.801 \text{ y}^{-1} \) (P < 0.05)
For RTP, \( \sigma = 0.754 \text{ y}^{-1} \) (P < 0.05)
4. Results and analysis

4.1. phosphorus yield in the basin

Through the Global NEWS model, we calculated all forms of phosphorus yield (per unit area) in eight basins, including DIP, DOP and PP. The phosphorus yield diagram is shown in figure 2.

![Phosphorus yield map of eight basins.](image)

**Figure 2.** Phosphorus yield map of eight basins. The unit of calculation is ton/year. Dark red indicates large yield, dark blue indicates small yield, and orange indicates medium yield.

It is not difficult to see from figure 1 that the phosphorus yield in the Yangtze river basin is much higher than that in other basins, and that in the pearl river basin is not far behind. In terms of total phosphorus, the yield of Yangtze river and pearl river reached 139 and 161 kg/(km\(^2\)·yr) respectively, which were both very high in the world.

As a result, the economically developed southeast coastal basins, such as the Yangtze river and the pearl river, tend to be areas of high phosphorus production, showing a deep red. By contrast, in the less developed northeast, the heilongjiang, liaohe and luanhe river basins also have small, dark blue phosphorus production due to low population density and GDP. The economic development and population density of the central region are moderate. The phosphorus yield of the Yellow River, huaihe river and haihe river is also in the middle level, showing orange color.

4.2. Phosphorus retention in hydropower stations

According to the dam site information provided by the database, the hydropower stations located in 8 major basins were selected. The phosphorus yield (RP, TP) in 8 basins was calculated and extracted as the phosphorus yield in the upstream catchment area of the dam. Next, we calculated the retention rate of phosphorus element through the data provided by the dam, and finally obtained the retention rate of phosphorus element. Several hydropower stations with significant phosphorus retention were selected for calculation and analysis, as shown in table 1.
Table 1. Calculation table of phosphorus retention in six selected hydropower stations.

| Name     | Three gorges | Danjiangkou | Xiaolangdi | Sanhezha | Sanmenxia | Longyangxia |
|----------|--------------|-------------|------------|-----------|------------|-------------|
| Basin    | Yangtze      | Yangtze     | Yellow River | Huaihe    | Yellow River | Yellow River |
| RRP      | Basin yield kg/(km²·yr) | 65          | 65         | 19        | 43         | 19          |
|          | Retention Mmol·yr⁻¹ | 136         | 59         | 73        | 59         | 58          |
| RTP      | Basin yield kg/(km²·yr) | 139         | 139        | 31        | 74         | 31          |
|          | Retention Mmol·yr⁻¹ | 306         | 131        | 125       | 104        | 100         | 90          |

As can be seen from table 1, the retention of phosphorus in the dam can be observed from the perspectives of RP and TP. The observed results are slightly different, but the overall trend is basically the same. Whether reactive phosphorus or total phosphorus, dams with strong capacity of blocking phosphorus are mainly concentrated in the Yangtze river, Yellow River and Huaihe river basin in China, and most of them are concentrated in the lower reaches of rivers. This is because all three basins have higher phosphorus production, while downstream stations tend to have larger upstream basins, which can accumulate more phosphorus inflow. For RP, dams with retention of more than 10000 mol·yr⁻¹ are not only distributed in the above three river basins, but also in haihe river and pearl river basins. The reason is that these areas have high population density and GDP, leading to a large number of DIP and DOP outputs and RP retention rate, which is mainly composed of population density and GDP. The TP reservoir has a capacity of more than 60,000 mol·yr⁻¹, and the RP reservoir has a capacity of more than 30,000 mol·yr⁻¹, which are concentrated on the main streams of the Yangtze river, the Yellow River and the huaihe river.

According to GRanD database, hydropower stations and dams in China are mainly built in the middle and lower reaches of the Yangtze river, with Dongting lake and Poyang lake being the most concentrated. The two lakes are rich in water, which can be used for irrigation, fishing and hydroelectric power, as well as flood control and damming, which is the main reason why the dams are concentrated in the area. The Heilongjiang basin, by contrast, has few hydroelectric plants, probably because of a lack of water and a low population density. In addition, high latitudes and cold winters make dam construction more difficult, which is an important reason for the sparse distribution of dams. In general, the distribution of hydropower dams in China presents a trend of "more in the south and less in the north", which is closely related to population density, economic development and latitude.

5. Conclusion

In general, this paper takes eight major river basins flowing into the east coast of China and the hydropower dams in the region as the research object, and uses the Global NEWS model and the phosphorus retention rate model to calculate the phosphorus retention of the dams in eight major river basins. Through drawing comparison, tabular calculation and other methods, we made qualitative and quantitative analysis on the factors influencing the retention of phosphorus elements in the dam of the reservoir and drew the following conclusions:

1) The yield of phosphorus is generally in direct proportion to the population density, economic development degree, GDP and other factors in the region. The high yield of phosphorus is often found in the densely populated and economically developed southeast coastal river basin in China, with the Yangtze river and pearl river basin being the most typical.

2) The six dams with the largest phosphorus retention in China are located on the main rivers of the Yangtze, Yellow and Huai rivers.
(3) China's DAMS are mainly built in the middle and lower reaches of the Yangtze river, which is related to its abundant water resources, urgent economic development needs and the middle and low latitudes.

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