Effects of sediment content changes on the growth of phytoplankton in Dongting Lake

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Abstract. After the construction of the Three Gorges Dam (TGD) on the Yangtze River, the reservoir’s regulation and storage for upstream flow and downstream river channel erosion (caused by the discharge of clear water) led to a significant reduction in the amount of sediment entering Dongting Lake from the Yangtze River. The decrease in sediment entering the lake led to a decrease in sediment content and an increase in lake transparency. These factors caused the growth of algae in Dongting Lake, and the level of lake eutrophication increased. Based on the AQUATOX aquatic ecology model, this study analyses the responses of phytoplankton and chlorophyll $a$ in each area of Dongting Lake and the changes in the nutritional status of the water body under the scenario of the continuing decline in sediment content while other factors remain unchanged. The results show that as the sediment content decreases, the biomass of phytoplankton and the content of chlorophyll $a$ will show increasing trends in each area of Dongting Lake. In this case, eutrophication will continue to develop in Dongting Lake.

1. Introduction
Dongting Lake is an important freshwater lake in the middle and lower reaches of the Yangtze River. In recent decades, many water conservancy projects have been built upstream of rivers entering Dongting Lake. Among these projects, the Three Gorges Project has had the greatest impact on Dongting Lake in the recent period and has led to significant changes in its water and sediment conditions. Many scholars have conducted research on the ecological impact caused by dam constructions. Fang et al. analysed the effects of hydrodynamic conditions on the microbial community[1] and sediment effects on the mobility of heavy metals[2]. Huang et al. explored surface charge distribution of fine sediment[3] and how sediment resuspension exerts significant effects on P behaviour in shallow lake ecosystems[4]. Xie et al. discussed the impact of the Three Gorges Project on vegetation succession of the Dongting Lake wetland[5].

The current research on the ecological changes of Dongting Lake mostly focus on analysing monitoring data and discussing the reasons for the changes. These studies lack the capability for assessment of future ecological changes of Dongting Lake under predetermined conditions and cannot provide decision-makers with a basis for formulating water management policies. In this study, we take Dongting Lake as the target area and use AUATOX to model the ecosystem of Dongting Lake to simulate the decline in sediment content in the lake. This study primarily aims to 1) discuss the change in phytoplankton biomass in Dongting Lake under the condition of decreasing sediment concentration and 2) evaluate the impact of this change on the ecological status of the lake.
2. Materials and methods

2.1. Study area
Dongting Lake is located on the south side of the Yangtze River between 28°30' N~30°20' N and 110°40' E~113°10' E. Dongting Lake is composed of three lake areas, namely, East Dongting Lake, South Dongting Lake and West Dongting Lake. Dongting Lake receives inflows from the Yangtze River through three channels (the Songzi, Hudu, and Ouchi Rivers) and from the Four Rivers (Xiangjiang, Zishui, Yuanshui, and Lishui Rivers). The water from the Yangtze River flows from west to east, passes through West Dongting Lake, South Dongting Lake, and East Dongting Lake, and finally flows back into the Yangtze River at Chenglingji. The river network is shown in Figure 1.

![Figure 1. The map of Dongting Lake and the rivers entering the lake. ① West Dongting Lake, ② South Dongting Lake, ③ East Dongting Lake, TGD - Three Gorges Dam.](image)

2.2. Main models
In this simulation, we mainly used the following two models.

2.2.1. Water and sediment model. Most hydrological stations are built on major rivers rather than on tributaries. To obtain the discharge into each lake area of Dongting Lake, we can use mathematical models. For aquatic areas with simple structures, such as the neighbourhood of the dam for the Three Gorges Project reservoir, a three-dimensional model can accurately simulate the water and sediment [6]. It uses the finite analytic method to solve the equations of mass and momentum conservation and also the transport equation for suspended sediment[7]. For complex river networks, such as Dongting Lake, one-dimensional numerical models are more popularly used because they can be easily programmed and take less time than do two- and three-dimensional numerical models[8]. Therefore, we relied on the research of Fang Hongwei and others calculations to apply the one-dimensional river network unsteady flow mathematical model to calculate the discharge of each node of the Dongting Lake river network[9]. The network contained 52 nodes, 72 river reaches, and 116 sections.

By using this model, when the inflow discharge of the Yangtze River and the Four Rivers is known, the inflow discharge of West Dongting Lake, South Dongting Lake, and East Dongting Lake and values of exchange discharge between lake areas can be calculated.

2.2.2. AQUATOX aquatic ecological model. AQUATOX is an ecological model developed by the U.S. Environmental Protection Agency. It combines aquatic ecosystem, chemical fate, and ecotoxicological constructs to obtain a truly integrative fate and effects model. It is a general, mechanistic ecological risk assessment model intended to be used to evaluate past, present, and future direct and indirect
effects from various stressors, including nutrients, organic wastes, sediments, toxic organic chemicals, flow, and temperature, in aquatic ecosystems. Taking phytoplankton as an example, the main calculation equation of its biomass is (each item on the right side of the equation has corresponding calculation equations) [10]:

\[
d\text{Biomass} = \text{Loading} + \text{Photosynthesis} - \text{Respiration} - \text{Excretion} - \text{Mortality} - \text{Predation} - \text{Breakage} + \text{Washout} - \text{Washin}
\]

Compared with other models, the advantage of AQUATOX is that we can use it to build an aquatic food web, including multiple genera and guilds of periphyton and phytoplankton, and simulate material, energy flow and chemical changes. The scope of its application includes streams, rivers, ponds, lakes, reservoirs and estuaries. Many cases have achieved favourable simulation results.

2.3. Simulation parameters

The water volume of each lake area of Dongting Lake changes significantly with the seasons. The summer when the lake water volume is the greatest was chosen as the initial period of the simulation. The corresponding parameters for each lake area during summer are shown in Table 1.

**Table 1.** Size parameters of each area of Dongting Lake in summer [11].

| Parameter                  | West Dongting Lake | South Dongting Lake | East Dongting Lake |
|----------------------------|--------------------|---------------------|--------------------|
| Water Volume/m³            | \(2.56 \times 10^{10}\) | \(7.54 \times 10^{10}\) | \(1.16 \times 10^{11}\) |
| Site Length/km             | 19                 | 40                  | 55                 |
| Surface Area/m²            | \(3.33 \times 10^8\) | \(9.05 \times 10^8\) | \(1.31 \times 10^9\) |
| Maximum Depth/m            | 12                 | 12                  | 13                 |
| Mean Depth/m               | 3.34               | 2.85                | 5.47               |

The nutritional parameters of the lake areas were measured by the Institute of Hydrobiology, Chinese Academy of Sciences. They are shown in Table 2.

**Table 2.** Nutritional parameters of each lake area of Dongting Lake [12].

| Parameter category | West Dongting Lake | South Dongting Lake | East Dongting Lake |
|--------------------|--------------------|---------------------|--------------------|
| TN (mg/L)          | \(1.78 \pm 0.15\)  | \(1.44 \pm 0.11\)  | \(1.98 \pm 0.14\)  |
| NO3-N (mg/L)       | \(0.74 \pm 0.20\)  | \(0.64 \pm 0.12\)  | \(1.24 \pm 0.15\)  |
| NH4-N (mg/L)       | \(0.36 \pm 0.05\)  | \(0.43 \pm 0.09\)  | \(0.14 \pm 0.02\)  |
| TP (mg/L)          | \(0.07 \pm 0.01\)  | \(0.10 \pm 0.02\)  | \(0.10 \pm 0.01\)  |

The overall area covered by Dongting Lake is between 28°30’ N–30°20’ N. Based on the latitude range, the change in light intensity throughout the year can be calculated. Other parameters, including water temperature, pH, etc, can be obtained through hydrological stations. Some physicochemical parameters are shown in Table 3.

**Table 3.** Changes in physicochemical parameters during the year.

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-------|---|---|---|---|---|---|---|---|---|----|----|----|
| PH    | 7.8 | 7.9 | 8.0 | 7.9 | 7.9 | 8.2 | 7.9 | 8.1 | 8.1 | 8.3 | 8.0 |
| \(\text{T}^a\) | 7.3 | 9.4 | 10.1 | 16.3 | 19.7 | 28.4 | 29.2 | 29.8 | 26.6 | 23.8 | 16.9 | 12.9 |
| \(\text{DO}^b\) | 8.7 | 8.9 | 8.8 | 7.9 | 7.2 | 5.9 | 6.9 | 7.7 | 8.0 | 7.1 | 7.7 | 8.8 |
| \(\text{LI}^c\) | 235 | 268 | 347 | 452 | 550 | 619 | 639 | 605 | 525 | 424 | 325 | 255 |

\(^a\) Temperature: °C \(^b\) Dissolved oxygen: mg/L \(^c\) Light intensity: ly/d
According to some sampling experiments done by researchers[13,14], we can get the wet weight of phytoplankton. We can use the built-in equations and coefficients in AQUATOX to convert wet weight to dry weight required by the model.

2.4. Situation conditions
According to relevant hydrological data, the construction of the Three Gorges Project had little impact on downstream discharge but had a greater impact on the sediment content in the water. Due to the interception effect of the reservoir, the sediment content monitored by Yichang Station showed a significant reduction[15]. Based on this situation, the conditions for this simulation design were as follows:

The simulation duration was 30 years.
During the simulation period, the nutrients and discharge into Dongting Lake did not change significantly compared with previous years.
During the simulation period, the sediment content of Dongting Lake decreased year by year to 30% of the level in the initial simulation period.
Due to the unpredictability of future flow, we used the typical-year method to determine the incoming flow during the simulation period. We took the flow in 1997 as the representative flow in a wet year, the flow in 2001 as the representative flow in a normal year, and the flow in 2006 as the representative flow in a dry year. We combined these typical years in a cycle every ten years and repeated the cycle three times to obtain the incoming flow over thirty years. The combination in the ten-year cycle is shown in Table 4.

Table 4. Combination of years in the ten-year cycle.

| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------|---|---|---|---|---|---|---|---|---|----|
| Type | normal | normal | dry | normal | normal | wet | normal | normal | normal | normal |

3. Results and discussion
Based on the aforementioned design conditions, the calculated results for phytoplankton and chlorophyll $a$ are shown in in Figure 2 (Seasonality in phytoplankton and chlorophyll $a$ data is characterized by abrupt change points in the curve due to the exchange between wet and dry years):

Table 5. The trend analysis of phytoplankton features during the simulation period.

| Species | Lake area | Trend$^a$ | Change ratio$^b$ |
|---------|-----------|-----------|-----------------|
| Diatoms | West Dongting Lake | Increase | 54% |
|         | South Dongting Lake | Increase | 41% |
|         | East Dongting Lake | Increase | 53% |
|         | West Dongting Lake | Increase | 6% |
| Green algae | South Dongting Lake | Increase | 21% |
|         | East Dongting Lake | Increase | 22% |
|         | West Dongting Lake | Decrease | -33% |
| Cyanobacteria | South Dongting Lake | Decrease | -42% |
|         | East Dongting Lake | Decrease | -41% |
|         | West Dongting Lake | Increase | 24% |
| Chlorophyll $a$ | South Dongting Lake | Increase | 24% |
|         | East Dongting Lake | Increase | 32% |

$^a$ The trends are calculated from linear regressions of parameter values on year.

$^b$ The change ratio is calculated from the average values of parameters for the first three normal years and the last three normal years.
Figure 2. Annual average changes in biomass of diatoms, green algae and cyanobacteria and annual average change in chlorophyll $a$ in each lake area during the simulation period.

The results in Figure 2 indicate that for each area of Dongting Lake, diatoms occupied a dominant position among the algae, followed by green algae and cyanobacteria. This is consistent with the survey results of Wang et al. in 2012 [16]. In addition, comparing the results of various years, we can observe that although the sediment content of the lake has changed, the relationships among the dominant and non-dominant components of the phytoplankton community in the entire Dongting Lake area has not changed. Among the lake areas of Dongting Lake, East Dongting Lake exhibited the highest chlorophyll $a$ content, which is related to the higher nitrogen and phosphorus content of East Dongting Lake. This conclusion is consistent with the survey results of Wang et al. in 2016[17]. Through the calculation of biomass, the change trend of phytoplankton during the simulation period is shown in Table 5. We use Spearman's rank correlation coefficient method to analyze the correlation between sediment content and chlorophyll $a$. The results are shown in Table 6.

| Table 6. Correlation analysis between chlorophyll $a$ and sediment content. |
|---|---|---|---|
| | West Dongting Lake | South Dongting Lake | East Dongting Lake |
| $r_s$ | -0.613 | -0.762 | -0.829 |

*a* The simulation duration is 30 years. For $n=30$, $r_{s0.01} = 0.467$
Table 5 and Table 6 show that there is a significant correlation between chlorophyll a and sediment content in the three lake areas. Changes in sediment content had a large impact on the biomass of phytoplankton, and the impact varied among phytoplankton groups. For diatoms and green algae, as the lake's sediment content declined, phytoplankton groups showed an increasing trend, but for cyanobacteria, the biomass showed a decreasing trend. There are many elements affected by sediment content in the lake, such as bed permeability[18], lake transparency, etc. For phytoplankton, changes in transparency may be the main reason for changes in biomass. As the sediment content decreases, the transparency of the lake increases, and the algae are exposed to more light. Therefore, the biomass increases. There is a certain competitive relationship between diatoms and cyanobacteria [19]. Under a situation in which overall nutritional conditions do not change, the increase in the biomass of the dominant diatoms will inevitably plunder a portion of the resources needed for cyanobacteria to live. This led to a decrease in the biomass of cyanobacteria. Chlorophyll a content showed a significant upward trend, with a rise ranging from approximately 20-30%. The reason for the upward trend is similar to that for algae. To a certain extent, the content of chlorophyll a reflects the growth status of phytoplankton and has the ability to characterize the level of lake eutrophication. It plays a key role in the evaluation of lake eutrophication [20]. The initial conditions of this simulation were obtained from the latest measured data[14]. In recent years, the comprehensive nutritional status index of Dongting Lake has approached the standard of mild eutrophication[21]. If the sediment content declines further, as shown by the simulated conditions, it can be inferred from the calculated result for chlorophyll a that the eutrophication level of Dongting Lake will increase.

4. Conclusions
Based on the AQUATOX aquatic ecological model, this study simulated the scenario in which the discharge and nutritional conditions of Dongting Lake remain unchanged, and the sediment content continued to decrease. The simulation results are consistent with some existing survey conclusions and are able to reflect the ecological changes in Dongting Lake to a certain extent. The results show that as the sediment content continues to decrease, the biomass of diatoms and green algae in each area of Dongting Lake will show an increasing trend, and cyanobacteria will show a decreasing trend. The content of chlorophyll a in each lake area will also increase, and the growth range will be approximately 20-30%. Based on the current nutritional status of Dongting Lake and the ecological trend of the simulation, it can be reasonably inferred that eutrophication of Dongting Lake will increase as its sediment content declines in the future.

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