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Water quality changing trends of the Miyun Reservoir

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Abstract: In order to simulate changes in the water quality of the Miyun Reservoir due to continuous descent of surface water level, a 3-D ecological hydrodynamic model was developed through coupling the water quality analysis simulation program (WASP) with the environmental fluid dynamics code (EFDC). The model was then calibrated and verified. Four scenarios (S1, S21, S22 and S23) were simulated using the model. Results show that the water quality of the Miyun Reservoir under conditions of low surface water level is apparently affected by different amounts of inflow and different total phosphorus (TP) loadings. The chlorophyll-*a* concentration might exceed 10 μg/L in many areas of the Miyun Reservoir (This limitative value is seen as a critical value of eutrophication) when large loadings of TP enter due to the amount of inflow increasing. Results of scenario S23 indicate that control of TP loadings can decrease chlorophyll-*a* concentration effectively, and the water quality of the Miyun Reservoir will improve or retain its *status quo*.

Key words: water quality model; hydrodynamic model; scenario analysis; changing trends

The natural process of eutrophication in many aquatic systems has been greatly accelerated through the addition of nutrients from various waste discharges, and physical changes to the system itself. The Miyun Reservoir is one such system. The Miyun Reservoir, situated in Miyun County, is the biggest reservoir in the north of China. It has a capacity of 4.375 km^3 and a corresponding water surface area of 188 km^2 (see Fig. 1). Now, the Miyun Reservoir is the most important drinking water resource of Beijing, providing 1.5×10^6 m^3/d, about 1/2 of the city's water supply.

Chao River

Bai River

Bai River dam

Chao River dam

Fig. 1 The Miyun Reservoir

As the most important drinking water resource, water quality of the Miyun Reservoir has been paid more and more concern by the public. Water quality monitoring data indicates that the main problem of the Miyun Reservoir is eutrophication[1] and in recent years surface water level has been continuously descending, so many researchers and governors are concerned about the water quality when a large inflow occurs. In order to solve this problem, a 3-D ecological hydrodynamic model was developed using the water quality analysis simulation program (WASP)[2] and the environmental fluid dynamics code (EFDC)[3].

1 Model Description and Development

Water quality modeling is generally implemented with the box or finite-segment approach. The box model approach is based on the principle of mass balance and has been widely used in water quality modeling in the past two decades. The box model is so named because it calls for dividing the study area into a series of segments or boxes, and writing the mass balance equation for each segment by assuming complete mixing with each box. Aided by the rapid development of computer technology, dynamic models are applied to substitute the steady-state models as decision support tools. In a dynamic model, the time dependent mass transport calculation is driven by the flow information provided by a hydrodynamic model through a model coupling process. The 3-D ecological hydrodynamic model of this study was one such model, which linked WASP (water quality model) and EFDC (hydrodynamic model) using the indirect coupling approach.

The WASP was first developed in 1981 as a tool for interpreting and predicting water quality responses to natural phenomena and man-made pollution for various pollution management decisions. Although it has

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undergone several revisions, its fundamental relationships have remained relatively unchanged. With respect to eutrophication, these relationships stemmed largely from the works by Thomann et al[4,5]. WASP is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. The time-varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the basic program.

While the fundamental relationships can be found in detail in Ref. [2], Fig. 2 provides an overview of relationships between the eutrophication state variables simulated by WASP. The WASP has been used on many different water bodies over the years and simulated a variety of conditions effectively, such as the Potomac Estuary[4] and Green Bay, Lake Michigan[6], where eutrophication and PCB contamination were examined. In China, the WASP has also been used in the Three Gorges Reservoir[7] and the Miyun Reservoir[8].

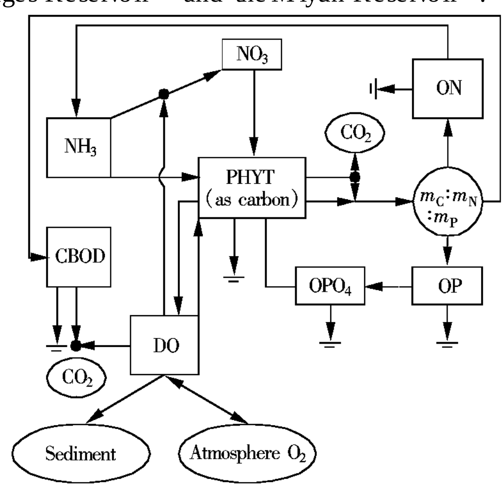

Fig. 2 Relationships between WASP eutrophication state variables

The EFDC model was developed at the Virginia Institute of Marine Science[9]. The physics of the EFDC model and many aspects of the computational scheme are equivalent to the widely used Blumberg-Mellor model[10] and Chesapeake Bay model[11]. The EFDC model solves the three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motions for a variable density fluid. The model uses a stretched or sigma vertical coordinate and Cartesian or curvilinear, orthogonal horizontal coordinates. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. The model has been applied to Virginia's James and York River estuaries[12], the entire Chesapeake Bay estuarine system and Lake Okeechobee[13].

Partly due to this proven track record, the WASP and EFDC were used to simulate hydrodynamic and eutrophic conditions in the Miyun Reservoir.

The ecological hydrodynamic model could be used to do scenario analysis while three steps of works were being completed.

The first step in the modeling was that a series of segments were created to define the shape and size of the Miyun Reservoir. A simulation time step corresponding to the segmentation scheme was chosen. This segmentation scheme was determined upon consideration of data resolution, temporal resolution, and spatial limitations. Ultimately, the cell size was segmented as 1 km ×1 km except for some parts of Bai River entrance, which was accomplished using GIS tools (see Fig. 3). Simulation time steps were defined as 60 s (hydrodynamic simulation) and 0.05 d (water quality simulation). More detailed descriptions of segmentation and time step determination can be found in Refs. [2, 14].

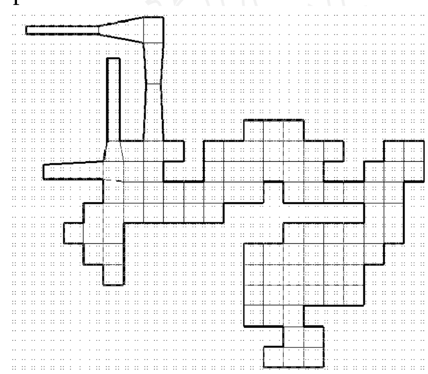

Fig. 3 Segmentation of the Miyun Reservoir

The second step was the calibration and verification of the hydrodynamic model (EFDC) using inflow data of Bai River and Chao River, surface water elevation of the Miyun Reservoir, outflow data, precipitation, evaporation, leakage and other usage data. Fig. 4 shows a high level of correlation between simulated values and observed values in both the calibration and verification stages.

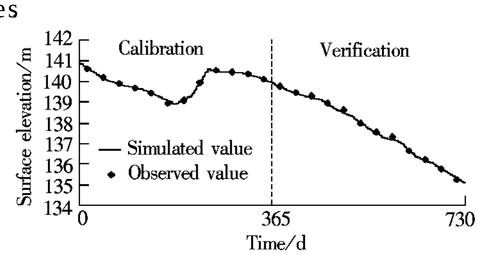

Fig. 4 Surface water elevation of the Miyun Reservoir

The third step was the calibration and verification of the water quality model (WASP). Initial concentrations, flows (from EFDC), and loadings were entered as inputs into the model. Limited to the length of this paper, figures of comparison between simulated and observed values are not listed here because Jia and Cheng[8] have given detailed results of calibration and verification of the WASP in their Miyun research. The calibration and verification results were found to meet the needs of the application.

The main objective of this paper is to simulate changing trends in water quality when a large inflow occurrs during a state of low water level. As mentioned above, eutrophication is the main water quality threat of the Miyun Reservoir, and the limiting nutritious factor is phosphorus. Fig 5, which is drawn from simulating results of the ecological hydrodynamic model, also supports this conclusion that ortho-phosphate concentration limits the growth of algae. The following scenario design will consider especially these effects which resulted from TP concentration changes.

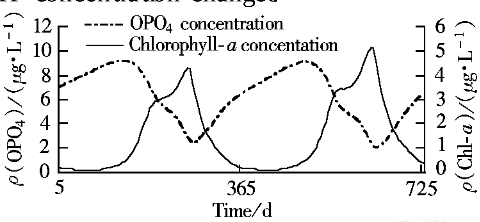

Fig. 5 Correlation of chlorophyll-*a* and OPO_4 concentration

2 Design of Scenarios

The scenarios were designed by considering changes of hydrologic conditions and water quality conditions of inflow. S1 was the basic scenario which adopted actual data for the Miyun Reservoir in 2002. S2 increased the amount of flow between June and September. Tab. 1 shows the data of inflow changes of the Chao River and Bai River. Tab. 2 shows water quality changes of the Chao River and Bai River. S21 kept the same water quality data as that of S1 in the hydrologic condition for S2. S22 increased TP concentration compared to S1 in the hydrologic condition for S2. S23 decreased TP concentration compared to S1 in the hydrologic condition for S2.

Tab. 1 Flow data of S1 and S2 $10^6 m^3$/month

Month	Basic scenario S1		Scenario S2	
	Bai River	Chao River	Bai River	Chao River
1	7.427	10.737	7.427	10.737
2	11.634	9.652	11.634	9.652
3	11.454	12.116	11.454	12.116
4	7.934	8.749	7.934	8.749
5	9.462	8.653	9.462	8.653
6	9.813	2.670	25.920	25.920
7	9.332	6.008	53.568	53.568
8	30.126	8.608	53.568	53.568
9	6.334	3.753	25.920	25.920
10	6.343	6.791	6.343	6.791
11	6.116	6.653	6.116	6.653
12	5.804	4.322	5.804	4.322

Tab. 2 TP concentrations of S1, S21, S22, S23 mg/L

Month	Basic scenario S1		Scenario S21		Scenario S22		Scenario S23	
	Bai River	Chao River	Bai River	Chao River	Bai River	Chao River	Bai River	Chao River
1	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01
2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
3	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.02
4	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.02
5	0.03	0.04	0.03	0.04	0.03	0.04	0.03	0.04
6	0.03	0.04	0.03	0.04	0.04	0.04	0.01	0.01
7	0.04	0.02	0.04	0.02	0.06	0.06	0.01	0.01
8	0.04	0.03	0.04	0.03	0.06	0.06	0.01	0.01
9	0.01	0.01	0.01	0.01	0.04	0.04	0.01	0.01
10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
11	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
12	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

3 Results and Discussion

The results of the analysis of the four scenarios (S1, S21, S22 and S23) are shown in Fig 6 to Fig 8. Fig 6 gives the spatial distribution of average chlorophyll-*a* concentration for each scenario in August. Chlorophyll-*a* concentration in August often reaches the largest amount because climate conditions at this time are the most suitable. Fig 7 and Fig 8 show time varying chlorophyll-*a* concentrations at two points in the reservoir. The location of the two points is shown in Fig 6 (a).

Fig 6 indicates that water quality of scenarios S21 and S22 are apparently worse when large loadings of TP enter the water body, due to the amount of inflow increasing, and chlorophyll-*a* concentration might exceed 10 μg/L in many areas of the Miyun Reservoir (this limitative value is seen as a critical value of eutrophication)[1]. However, when TP loadings decrease as in scenario S23, the water quality of the Miyun Reservoir would be better or retain its *status quo*. The result has an important implication for simu-

(a) (b)

(c) (d)

Fig. 6 Spatial distribution of average chlorophyll-*a* concentration in August (a) Scenario S1; (b) Scenario S21; (c) Scenario S22; (d) Scenario S23

lating low water level conditions because the water bodies with higher water levels have a larger capacity and stronger ability to dilute toward existing loadings.

From Fig 7 and Fig 8, it appears that effects of different scenarios appeared after June since all the changes began in June. At P1, peak values changed from 4.5 μg/L to 6.7 μg/L on about the 260th day.

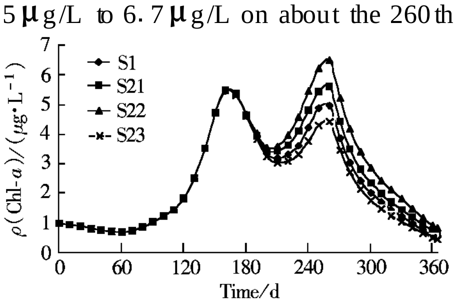

Fig. 7 Chlorophyll-*a* concentration curve varying with time at P1 (shown in Fig 6 (a))

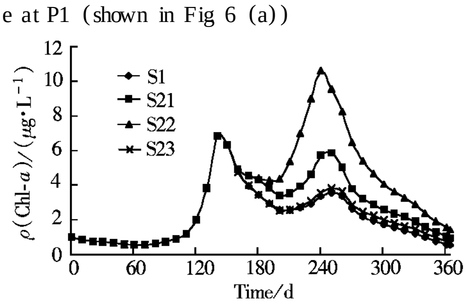

Fig. 8 Chlorophyll-*a* concentration curve varying with time at P2 (shown in Fig 6 (a))

At P2, peak values changed from 3.5 μg/L to 10.6 μg/L on about the 240th day. Since P1 was further from the entrance point than P2, the influence of inflow on P1 was then less than that on P2 (The same result could also be gotten from Fig 6 (c)).

According to possible changing trends in water quality in the future, the following several recommendations are made:

1) Strengthen water quality monitoring during flood season. This measure can help in the understanding of changing trends in water quality over time.

2) Phosphorus is the main limiting factor of eutrophication in the Miyun Reservoir. So adopting effective steps of phosphorus reduction is an important action in the water quality management of the Miyun Reservoir.

3) Research on non-point source (NPS) pollution should deepen. Where water quality of inflow is dominantly affected by non-point source pollution in flood season, deep consideration of NPS is necessary.

4 Conclusion

A 3-D ecological hydrodynamic model was developed using WASP and EFDC. Four scenarios (S1, S21, S22 and S23) were simulated using the model. It indicated that water quality (such as chlorophyll-*a*) of the Miyun Reservoir under the condition of low surface water level was appearently affected by different amounts of inflow and different TP loadings. Chlorophyll-*a* concentration might exceed 10 μg/L in many areas of the Miyun Reservoir (This limiting value is seen as a critical value of eutrophication) when large loadings of TP enter the water body due to the amount of inflow increasing (At high surface water level it may not appear because of large ability to dilute). However, when TP loadings decrease as in scenario S23, the water quality of the Miyun Reservoir would change for the better or retain its *status quo*.

In order to prevent deterioration of water quality, measures should be adopted in time, such as strengthening water quality monitoring during flood season, controlling phosphorus emissions, and researching NPS pollution more deeply.

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密云水库水质变化趋势研究

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摘要:为模拟近年来密云水库水位不断下降引起的水质变化的问题,开发了三维生态-动力学模型来进行密云水库水质模拟,该模型耦合了水质模型WASP和水动力学模型EFDC.首先进行了模型参数率定和验证.在此基础上,研究模拟了4个情景方案(S1, S21, S22和S23).结果表明,密云水库处于低水位时,水质受来水水量和营养物负荷的影响显著.当出现一次大来水量,入库负荷增大,叶绿素*a*的质量浓度可能在很大区域内都超过10 μg/L的富营养化警戒线.同时,情景S23表明,控制TP负荷可有效降低叶绿素的质量浓度,水库水质能得到有效改善或保持现状.

关键词:水质模型;水动力学模型;情景分析;变化趋势

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