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Original Research Paper

A Model for Assessing Water Purification Capacity of Algae to Eutrophication at Large-Scale

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ABSTRACT

It has been observed that water in the reservoirs has a trend towards eutrophication even under natural environment, while human activity makes the situation worse. Studies on eutrophication are mainly focused on nutritive salt control. It is an effective method to remove the nutrient substance by using attached algae; however, due to experimental limitations, the theoretical results from the lab study are commonly inapplicable to the natural environment. In this paper, based on a case study on the Hada reservoir, we have built a hydrodynamic-quality model that represents the current state of the reservoir. With the help of the model, we can verify the development of eutrophication of the reservoir and simulate the spatial-temporal evolvement, using *Cladophora*, to deal with eutrophication within a shallow water reservoir.

INTRODUCTION

It has been noticed that eutrophication is one of the most important factors for water pollution in natural lakes and reservoirs, which is also the inducement of many secondary environmental crisis (Shouliang Huo et al. 2013). Major source of eutrophication is the industrial and domestic wastewater with high-level of nitrogen and phosphorus, which could lead to the rapid accumulation of algae and in turn bereave the natural function of water body (Allison et al. 2014). Nitrogen and phosphorus are the reactants and products in many industries, and they are drawn into and pollute the water body, mainly by using the abluent and farm chemicals and fertilizers (Huo et al. 2013). As the pollution is inevitable and severe with a long period, the eutrophication caused by nitrogen and phosphorus has become a major environmental problem demanding prompt solution and received tremendous attention from both government and the academia (Aguiar et al. 2011).

Under lightening condition, the growth of algae consumes nitrogen and phosphorus in the water and makes use of CO2 as carbon source rather than organic carbon (Lee et al. 2009). Because applying suspended algae is not considered as a research hotspot of sewage treatment due to its great response to environmental factors and lack of effective control, current studies on eutrophication control are mainly focused on immobilized well-grown algae within the shallow water area (Liu et al. 2011). It is commonly pointed out in the literature that, immobilized algae is effective in removing nitrogen and phosphorus with a rate of 90% and above, only in proper conditions concerning temperature, pH and luminous range (Gibson et al. 2000). Immobilized algae becomes a popular method for pollution treatment due to its efficiency in removing eutrophication and feasibility of gathering (Michael et al. 2009). However, so far, related studies only stay on lab-scale research and lack of practical investigation (Badgley et al. 2011). Such situation severely hampers the development and application of this new technique.

Current studies on the eutrophication control give more attention on the mechanism of producing and removal of nitrogen and phosphorus, and therefore, the methods which obtain encouraging data results are hardly applicable in real practical projects (Scott et al. 2006). As the natural ecosystem cannot be regarded as a precisely determinate process, the experiments with fixed conditions are unable to give an adequate assessment of the removing of nutrient substance under natural conditions (Xiankui Zeng et al. 2013). There has been progress in the mathematical modelling of eutrophication with stochastic differential equations, and it can be expected that more methods and techniques of mathematical modelling will be applied to the study of water body eutrophication (Kazuo Nadaoka & Hiroshi Yagi 1998), to make the simulation more trustful, and to ensure the reaction parameters obtained from experiments applicable to the scale of natural situations so as to predict the extensibility of newly developed methods for eutrophication control.

MATERIALS AND METHODS

Immobilized Algae Restoration for Eutrophication Control in Shallow Lakes

Using inserted immobilized algae for sewage disposal is a very efficient method for ecosystem sewage purification with a low cost. When the algae is more than adequate, it only needs to move out the stroma and brush off the inserted algae. *Cladophora* algae has a strong ability for depollution in lucent water body, and thus it is suitable for the biological restoration of shallow water body with eutrophication (Sonja & Erik 2004).

The effectiveness of *Cladophora* algae of removing nitrogen: *Cladophora* algae is efficient for removing nitrogen in lakes with eutrophication. We controlled the temperature of the experiment system with fluctuations within 15-20°C, and pH 8, dissolved oxygen between 7 to 10 mg/L, and used the fluorescent lamp (3000lx, 10 hours a day) as natural light. Table 1 shows the daily change in nitrogen by using *Cladophora* algae, in such situation, from which one can see that the best removal rate for NH_3-N occurs on the 8th day.

After applying immobilized algae (*Cladophora* algae), the removal rate of NH_3-N in water is jointly controlled by the algae growth and has a clear relationship with the experimental time length. To obtain the real-time NH_3-N degradation rates of each moment, we have to determine the NH_3-N concentration in the series, which is a difficult task even in labour condition. Interpolation by certain regression equation needs a high relation. For processing the data (as given in Table 1), nonparametric statistical analysis was used to predict the NH_3-N concentration and removal rate (by eq.1, eq. 2 and eq. 3).

$$C_{in}(t) = \frac{1}{\sum_{i=2}^{14} \exp\left[-(t-t_i)^2\right]} \sum \left\{ \exp\left[-(t-t_i)^2\right] \bullet C_{in_i} \right\} \quad ..(1)$$

$$C_{out}(t) = \frac{1}{\sum_{i=2}^{14} \exp\left[-(t-t_i)^2\right]} \sum \left\{ \exp\left[-(t-t_i)^2\right] \bullet C_{out} \right\} \quad ...(2)$$

$$\text{Removal rate} = \frac{C_{in} - C_{out}}{C_{in}} \quad ...(3)$$

Where, *C(t)* is the NH_3-N concentration of t moment, mg/L; *t* is the test time, day; t_i is the i[th] day; C_{out} is the NH_3-N concentration out of treatment system; C_{in} = the initial concentration of each time step, as given in Table 1.

We use the calculated value as the removal rate of NH_3-N of each moment, the *Cladophora* algae growth cycle in the experiment (14 days) as put-gain period, each final concentration of each simulation as the initial concentration of the next step simulation.

Table 1: Variations of nitrogen in the inflow and outflow of *Cladophora* algae treatment system.

Time (d)	NH_3-N mg/L		
	In flow	Outflow	In-Out
2[th]	0.89	0.69	0.2
4[th]	0.94	0.69	0.25
6[th]	0.84	0.61	0.23
8[th]	1.03	0.59	0.44
10[th]	0.86	0.54	0.32
12[th]	0.95	0.64	0.31
14[th]	0.88	0.61	0.27

The influence of *Cladophora* algae to COD: The main factors for the accumulation of COD in water, include the solubility diffusion of organic substances in the mud, and the metabolin from algae reproduction or death. The changing of COD along time, in the experiment shows that the performance of COD removal is only remarkable under low water-depth and good light transmission conditions. Since natural lakes are much deeper than the water in experimental settings, and the period of putting in *Cladophora* algae for restoration is preferred to be short because of the series of problems caused by the excessive growth, when the algae grows in specific conditions, we can approximately neglect the influence of *Cladophora* algae to the concentration of COD.

Numerical Simulation on Hada Reservoir

Model: Hada reservoir is located in the second Songhua River in Jilin Province, China. It can be regarded as a shallow lake, with the horizontal scale much larger than the vertical scale, and thus we can neglect the changing of flow along the vertical direction. By using the Navier-Stocks equation and combining with the Boussinesq and the hydrostatic pressure assumptions, we built a 2-dimensional equation for the reservoir's hydraulic description. Finally, we obtain the convection-diffusion equation with specified definite conditions, as shown in eq.4.

$$\frac{\partial(d+\zeta)c}{\partial t} + \frac{1}{\sqrt{G_{\zeta\zeta}}\sqrt{G_{\eta\eta}}}\left\{\frac{\partial\left[\sqrt{G_{\eta\eta}}(d+\zeta)uc\right]}{\partial\xi} + \frac{\partial\left[\sqrt{G_{\xi\xi}}(d+\zeta)vc\right]}{\partial\eta}\right\} = \frac{d+\zeta}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\left\{\frac{\partial}{\partial\xi}\left[D_H\frac{\sqrt{G_{\eta\eta}}}{\sqrt{G_{\xi\xi}}}\frac{\partial C}{\partial\xi}\right] + \frac{\partial}{\partial\eta}\left[D_H\frac{\sqrt{G_{\xi\xi}}}{\sqrt{G_{\eta\eta}}}\frac{\partial C}{\partial\eta}\right]\right\} - \lambda_d(d+\zeta)c + S \quad ...(4)$$

Where, *c* is the concentration of pollutant (kg/m^3): *u, v* are the velocity in the ε, η directions (m/s); D_H is the horizontal diffusion coefficient (m^2/s); λ_d is the attenuation coefficient

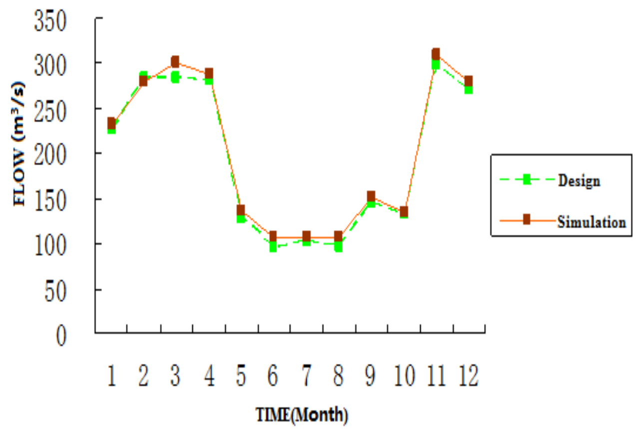


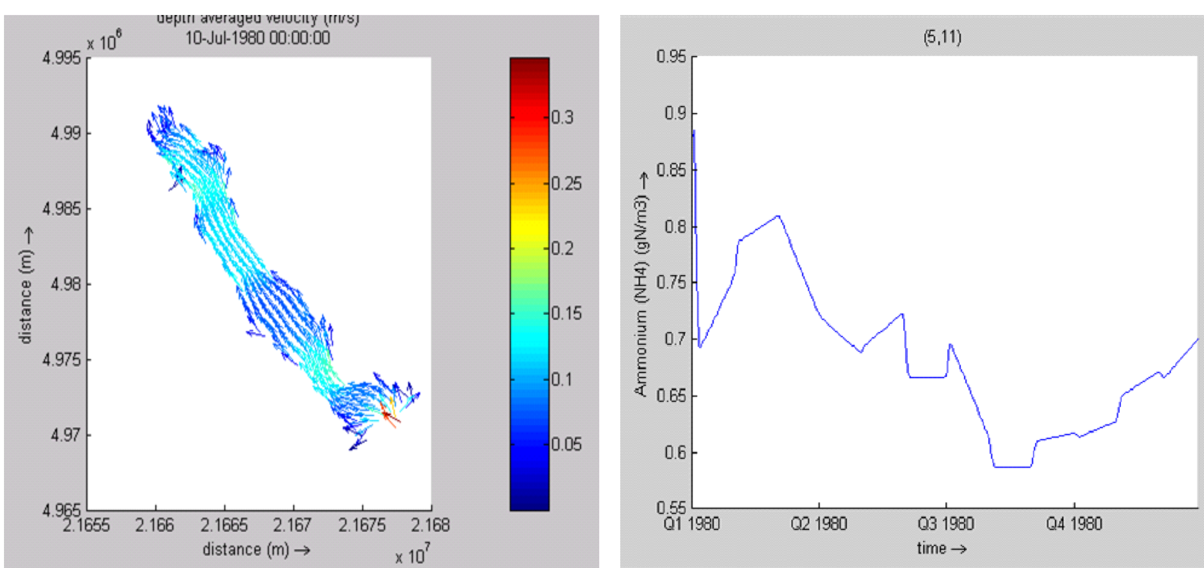
Fig. 1: Flow verification (comparison of design outflow and simulation outflow).

of pollutant (calculated in eq. 3 as removal rate, s^{-1}); S is the adsorption, degradation or precipitation of pollutant.

The initial condition of the model is specified by the momentum equation with time t = 0, while the boundary conditions include the motion boundary, the bottom boundary, the surface boundary, the open boundary and the close boundary. We got the terrain by trigonometric interpolation method with the existing terrain data.

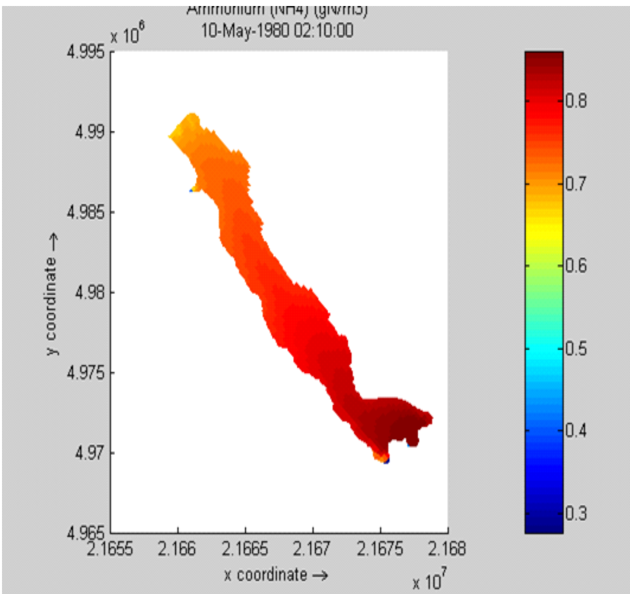
Conditions: We used the normal reserve-water-level of the reservoir on 10 January 1980 as the initial condition, the measured NH_3-N concentration as bottom value, and set time interval as 10 min. The close boundary of the reservoir is movable but inaccessible condition, i.e., the flow velocity at the bank of the reservoir is 0. The influence of wind to the flow velocity is considered as the surface boundary, and the average wind speed over the years is adopted. There are six open boundaries in the reservoir (inflow, outflow, municipal water for Qianguo city and Songyuan city, general main water diversion channel and irrigation water).

In the experiment with the *Cladophora* algae, the NH_3-N degrading coefficient is obtained as removal rate calculated from eq. 1, eq. 2 and eq. 3, the daily degrading rate is

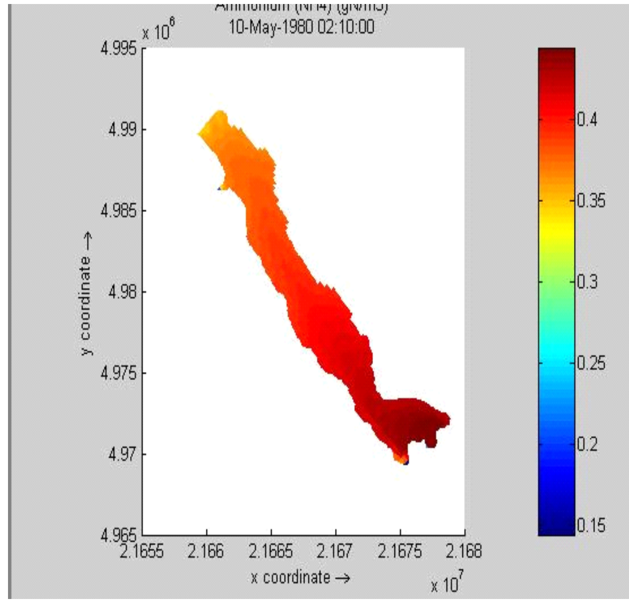


(a) velocity vector diagram (b) NH_3-N-time curve

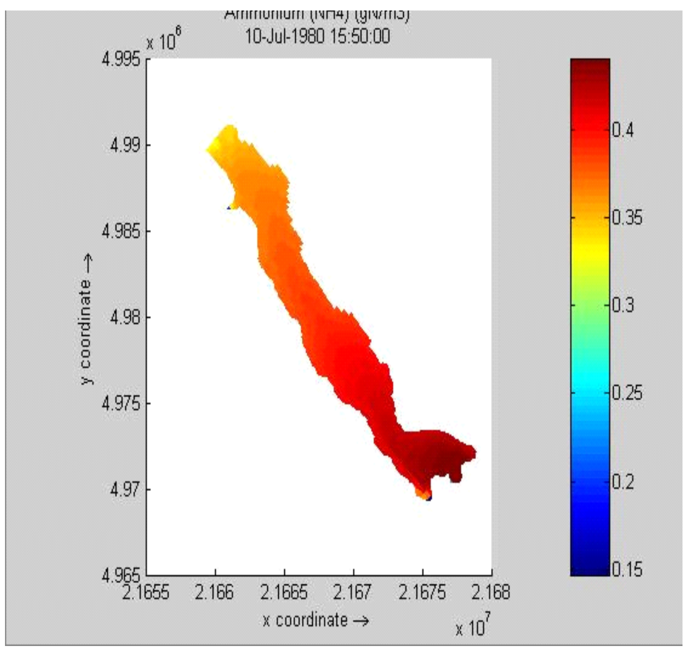
Fig. 2 (a) velocity vector diagram; (b) NH_3-N-time curve under natural conditions at the dam site.



(a) under natural condition (5.10)



(b) after applying immobilized algae (5.10)



(c) after applying immobilized algae (7.10)

Fig. 3: NH_3-N distribution isopleth map (a) under natural conditions (5.10); (b) after applying immobilized algae (5.10); (c) after applying immobilized algae (7.10).

obtained according to the influence of the degrading coefficient and the water quality concentration near the entrance of the reservoir, and the diffusion coefficient is set as $0.022 m^2/s$.

Solution and Verification

With known conditions, we have got the solution of the model and the simulation results for the hydrodynamic-quality of the reservoir with the time step of 10 minutes. And the result of the comparison of design outflow and simulation outflow confirms the validity of the model (Fig. 1).

RESULTS AND DISCUSSION

By the hydrodynamic-quality simulation study on the Hada reservoir, we have verified that hydrodynamic modelling is the precondition for quality modelling, and the distribution changing of concentration field is controlled by flow field. The factors influencing the flow field include the position of entrance and exit, wind, flow rate and the topography of the lake.

By solving the model, we obtain the distribution isopleth map at any time point and the concentration changing plot at any position of the reservoir. The velocity vector diagram (Fig. 2a) shows that the reservoir water moved from upstream to downstream with the velocity around 0.2m/s, and the dead zone and low-velocity area related to terrain. Fig. 2b shows that the NH_3-N concentration changes with seasons significantly, and the highest concentration level appeared in May.

We select the NH_3-N distribution map of May, which has a significant eutrophication, for comparison: on 10th May, the NH_3-N distribution map under natural condition is given by Fig. 3a, while the counterpart after applying immobilized algae is given by Fig. 3b.

The simulation on the water-quality of the reservoir shows that the movement of pollutant in the reservoir fits the hydrodynamic model well, with a high concentration at low-velocity and dead areas, which is consistent with previous studies. And with the immobilized algae technique for eutrophication treatment, the NH_3-N concentration level within the reservoir can be effectively controlled. The changing of concentration within the reservoir is jointly controlled by the flow field, entering concentration, degradation and diffusion. Along the flow direction, the NH_3-N concentration shows a continuous and decreasing process, with a higher level at the end of the reservoir than that at the dam site. Further simulation till 10th July, Fig. 3c shows that the concentration of NH_3-N has no more significant changes. This is mainly due to the mutual equilibrium among the concentration verification caused by the degrading speed, entering velocity and evaporation.

CONCLUSION

1. By simulation study, we have verified the process of eutrophication within a natural reservoir. We have applied the ammonia-nitrogen degrading coefficient, obtained from the experiments with *Cladophora* algae, to the quality model, and assessed its ability for eutrophication treatment, which provided a theoretical support for the use of immobilized algae for eutrophication control of lakes.
2. With numerical models, we can simulate large-scale natural lakes and provide proper predictions to eutrophication treatment by using newly developed methods under natural conditions, which cannot be realized by conventional lab-scale experimental methods. This helps overcome the difficulties which are inevitable with the conventional lab-scale experimental methods. Moreover, this also provides a theoretical foundation for simulation based eutrophication-treatment program.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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