A model for the effects of water hyacinths on water quality in an experiment of physico-biological engineering in Lake Taihu, China

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Abstract

A model for an experiment of physico-biological engineering purifying lake water in Lake Taihu by using water hyacinths (Eichhornia crassipes (Mart.) Solms) was constructed. The model included 14 state variables. They are NH₄⁺-N, NO₃⁻-N, PO₄³⁻-P, nitrogen and phosphorus in detritus, phosphorus in the pore water, exchangeable phosphorus and nitrogen in the sediment layer, density, nitrogen and phosphorus in phytoplankton, and nitrogen and phosphorus in water hyacinths. The external forcing functions were solar radiation, water temperature, concentrations of nutrients, phytoplankton and detritus in inflow water and the retention time of the water in physico-biological engineering. The results of the model simulating the growth of phytoplankton and water hyacinths, and the cycling of nitrogen and phosphorus inside physico-biological engineering were coincident with the results observed. In order to decide which process would affect the water quality in the experiment, to which parameter the water quality indexes such as phytoplankton, NH₄⁺-N, NO₃⁻-N, PO₄³⁻-P are sensitive has been analyzed by the use of the model. It has been discussed how to culture and harvest the water hyacinths. The filtering effect has also been estimated. The model could be used as a tool to guide physico-biological engineering design and its management. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Model; Physico-biological engineering; Water quality; Water hyacinths; Lake Taihu
1. Introduction

Drinking water has to be provided from surface water in the south eastern part of China due to the high population density and overuse of ground water. This water is often highly eutrophicated and there is therefore a need for cheap and ecologically neutral methods for purifying the surface water. In this paper a model of the use of water hyacinths in an experimental ecosystem for improving the water quality of drinking water was presented in the small Wulihu Bay in Lake Taihu.

Lake Taihu is located in the east part of China among 30°5′–32°8′N and 119°8′–121°55′E. It is one of the five largest freshwater lakes in China, with a catchment area of 36,500 km², a surface area of 2,338.1 km², and an average water depth of 1.9 m. The annual average air temperature is 14.9–16.2°C. The climate is an SE–NW monsoon climate. The mean annual precipitation is 1000–1400 mm, the mean annual evaporation 941 mm, the mean annual runoff into the lake 4100 million m³ (Sun et al., 1993). There are six large cities and about 34,182 million people around the lake. The economic development of this part of China has been fast in recent years, and the population increases quickly. Therefore, more and more waste water was discharged into the lake which has become highly eutrophicated. In the summer of 1990, there were big problems with phytoplankton bloom taking place in the lake. About 119 factories had to cease production and the people living in Wuxi City could not have sufficient drinkable water during the period. This caused a loss of 112 million Chinese Yuan, i.e. approx. US$ 13330000 in Wuxi.

A new method for purifying the lake water was urgently needed at that time. So a series of experiments on how to improve the water quality have been carried out in Lake Taihu (Pu et al., 1993; Dou et al., 1995; Hu and Pu, 1995, Pu et al., 1995; Pu and Hu, 1996). Some experiments focused on the possibility of using aquatic plants to remove the nutrients. *Eichhornia crassipes* (Mart.) Solms has been selected as one important kind of water plant cultured in the experimental area for improving water quality, since it can grow quickly and take up a lot of nutrients from water, such as phosphorus, nitrogen (Yan, 1986; Wu et al., 1987a,b; Zhang, 1989; Dou et al., 1995). It is a kind of free-floating water plant whose leaves are above the water surface. It reproduces rapidly by budding. Water hyacinths in the water surface can minimize the light penetration to the water column below and therefore phytoplankton is outcompeted. This is a favorable situation from the point of ecological management as the nutrients are concentrated in water hyacinths instead of in phytoplankton, because water hyacinths can be more easily harvested with nets or forks and used as feed for pigs and fish. Besides taking up nutrients, water hyacinths have also been reported to take up heavy metal ions (Dai et al., 1991) from the water and to metabolize organic substances such as phenol (Wu et al., 1987a,b). Culturing of water hyacinths can improve water transparency. At the beginning of our experiment the water transparency was 40 cm, after 4 days culturing it changed to 2.0 m. If this water flows to another place without too many water hyacinths covering the water surface, submerged plants can increase growth. Because the water hyacinths can shade the light on the water surface, a lower water temperature below water hyacinths can be observed. In summer, with some water hyacinths covering the water surface (not too many), some submerged plants can survive.

2. Background of the experiment

2.1. Physical and chemical characteristics of the experimental site

The experimental area, 2000 m² and a mean depth of 2.0 m in summer, is situated in the north-east part of the small Wulihu bay in Lake Taihu (see Fig. 1a). It is in the intake area of Wuxi Zhongqiao Drinking Water Plant near Wuxi city. It is divided into 10 channels, each 40 m long and 5 m wide, enclosed by nontoxic chemical fiber cloth. Water from the outside can only enter the southern side of the channel (see
Fig. 1. (a) The topographical map of the Lake Taihu. (b) The schematic diagram of the engineering experiment for improving water quality.
Fig. 1b). The water quality in the experimental area was worse than that in the other parts, with a high average density of chlorophyll a and concentrations of nutrients, which are shown in Table 1. The water quality parameter COD in this area was even worse in 1994 (see Table 1) (Li, 1996a). TP (in P₂O₅) and TN concentrations in the sediments were high, up to 0.20 and 0.21% of the dry weight. Exchangeable phosphorus in sediment is up to 2.64% of total phosphorus in the bottom sediment. Its concentration in pore water was high, up to 52.7 mg/l (in P₂O₅). The pH of bottom water varied between 6.8 and 7.2. The sediment surface was anaerobic during the sampling period with Eₕ values from −120 to −356 mV.

2.2. Purpose of the experiment

Water hyacinths were cultured in the experiment to minimize the density of phytoplankton, improve water quality and increase the water transparency. The water quality parameters inside and outside the channel were measured every day or every second day. The water in the channel was pumped out to simulate the water pumping of Zhongqiao Water Plants from Wulihu Bay.

3. Ecological model construction of the experiment

3.1. Conceptual diagram of model

The main physical, chemical and biological processes are: (1) nutrients (phosphorus, ammonium nitrogen, nitrate nitrogen uptake by phytoplankton and water hyacinths); (2) growth of phytoplankton and water hyacinth; (3) mortality of phytoplankton and water hyacinths; (4) settling of detritus; (5) mineralization of detritus; (6) nutrient release from sediment; (7) oxidation of ammonium nitrogen. The external control functions are: water temperature, solar radiation, water flow into and out of the experimental ecosystem, and nutrient concentrations of water flowing in and out of the experimental ecosystem. Therefore, the ecological model should include: phytoplankton, water hyacinths, NH₄-N, NO₃-N, PO₄³-P, nitrogen and phosphorus in sediment and detritus. Its conceptual diagram is shown in Fig. 2.
Table 1
Annual mean water quality of Wulihu Bay from 1991 to 1994

<table>
<thead>
<tr>
<th>Year</th>
<th>Chl.a (mg/l)</th>
<th>COD (mg/l)</th>
<th>BOD (mg/l)</th>
<th>TN (mg/l)</th>
<th>NO$_3^-$ (mg/l)</th>
<th>NO$_2^-$ (mg/l)</th>
<th>NH$_4^+$ (mg/l)</th>
<th>TP (mg/m$^3$)</th>
<th>PO$_4^{3-}$ (mg/m$^3$)</th>
<th>DO (mg/l)</th>
<th>SD (m)</th>
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</thead>
<tbody>
<tr>
<td>1991</td>
<td>34.5</td>
<td>14.9</td>
<td>2.21</td>
<td>2.1</td>
<td>0.37</td>
<td>0.03</td>
<td>0.53</td>
<td>74.1</td>
<td>13.9</td>
<td>9.1</td>
<td>0.47</td>
</tr>
<tr>
<td>1992</td>
<td>30.1</td>
<td>18.2</td>
<td>46.9</td>
<td>0.46</td>
<td>0.19</td>
<td>2.75</td>
<td>397</td>
<td>31.8</td>
<td>5.1</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>23.3</td>
<td>9.2</td>
<td>6.64</td>
<td>0.53</td>
<td>0.13</td>
<td>1.99</td>
<td>186</td>
<td>16.7</td>
<td>0.56</td>
<td></td>
<td>0.41</td>
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<tr>
<td>1994</td>
<td>38.2</td>
<td>57</td>
<td>10.9</td>
<td>0.56</td>
<td>0.25</td>
<td>4.12</td>
<td>150</td>
<td>91.7</td>
<td>0.56</td>
<td></td>
<td>0.48</td>
</tr>
</tbody>
</table>
3.2. The mathematical equations in model

3.2.1. Equations for growth of phytoplankton and water hyacinths

The mass conservation law can be used to establish the equations of the model. For phytoplankton the following equations are used.

\[
\frac{dB_{ph}}{dt} = GAB - MA + INA - OUTA
\]

(1)

\[
\frac{dN_{ph}}{dt} = NH_{uph} + NO_{uph} + N_{phi} - N_{pho} - N_{phm}
\]

(2)

\[
\frac{dP_{ph}}{dt} = P_{uph} + P_{phi} - P_{pho} - P_{phm}
\]

(3)

where \(B_{ph}, N_{ph}, P_{ph}, GAB, MA, INA, OUTA\) are phytoplankton density in mg/l, nitrogen and phosphorus in phytoplankton in mg/l, phytoplankton growth, phytoplankton mortality, input of phytoplankton due to water inflow, loss of phytoplankton due to water outflow respectively. \(N_{pho}\) and \(P_{pho}\) are the loss of nitrogen and phosphorus in phytoplankton due to the outflow of water; \(N_{phi}\) and \(P_{phi}\) the input of nitrogen and phosphorus in phytoplankton due to the water inflow; \(N_{phm}\) and \(P_{phm}\) the loss of nitrogen and phosphorus in phytoplankton due to mortality of phytoplankton. Mortality is a source of nitrogen and phosphorus in detritus which will be described later; \(NH_{uph}, NO_{uph}\) and \(P_{uph}\) are the uptakes of phytoplankton for \(NH_4^+\)-N, \(NO_3^-\)-N and \(PO_4^{3-}\)-P, respectively.

\(GAB\) can be written in following form:

\[
GAB = gr_{ph} \cdot B_{ph}
\]

where \(gr_{ph}\) is the growth rate of phytoplankton.

The limitation of the growth rate of phytoplankton is described in the classical two steps. The first step is uptake of nutrients in accordance with the Michaelis–Menten kinetics, and the second step is determined by the internal nutrient concentration. The uptakes of nitrate nitrogen, ammonium nitrogen and phosphorus are (Bendoricchio et al., 1993, 1994; Cai, 1995):

\[
NH_{uph} = VmNH_{ph} \cdot NH_{pre} \cdot N_{pro-ph} \cdot NH \cdot B_{ph}/(NH + Km_{NH-ph})
\]

\[
NO_{uph} = VmNO_{ph} \cdot (1 - NH_{pre}) \cdot N_{pro-ph} \cdot NO \cdot B_{ph}/(NO + Km_{NO-ph})
\]

\[
P_{uph} = VmP_{ph} \cdot P_{pro-ph} \cdot P \cdot B_{ph}/(P + Km_{P-ph})
\]

where \(VmNH_{ph}, VmNO_{ph}\) and \(VmP_{ph}\) are the nutrient maximum uptake rates of phytoplankton for ammonium nitrogen, nitrate nitrogen and phosphorus, respectively; \(N_{pro-ph}\) and \(P_{pro-ph}\) the normalized saturation values for the intracellular nutrient; \(Km_{NH-ph}, Km_{NO-ph}\) and \(Km_{P-ph}\), the half-saturation constants for each of these three nutrients; \(NH, NO, P\) concentrations of \(NH_4^+\)-N, \(NO_3^-\)-N and \(PO_4^{3-}\)-P in water. \(NH_{pre}\) ratio of \(NH_4^+\)-N of the soluble nitrogen in the water, it is:

\[
NH_{pre} = NH/(NH + NO)
\]

The normalized saturation constants for nutrients are expressed as:

\[
N_{pro-ph} = (N_{max-ph} - N_{ph}/B_{ph})/(N_{max-ph} - N_{min-ph})
\]

\[
P_{pro-ph} = (P_{max-ph} - P_{ph}/B_{ph})/(P_{max-ph} - P_{min-ph})
\]

where \(N_{max-ph}\) and \(P_{max-ph}\) are the maximum quotas of phytoplankton for nitrogen and phosphorus, respectively, \(N_{min-ph}\) and \(P_{min-ph}\) the minimum quotas of phytoplankton for nitrogen and phosphorus, respectively.
The growth rate of phytoplankton can now be written as follows:

\[ gr_{ph} = G_{max\_ph} \cdot F(N_{ph}, P_{ph}) \cdot F(T) \cdot F(I), \]

\( G_{max\_ph} \) is the intrinsic value for growth rate of phytoplankton; \( F(N_{ph}, P_{ph}), F(T), F(I) \) are the functions of \( N_{ph} \) and \( P_{ph} \), water temperature \((T)\) and light \((I)\) affecting the phytoplankton growth, which are formulated as:

\[ F(N_{ph}, P_{ph}) = \text{min}(1 - N_{min\_ph} \cdot B_{ph}/N_{ph}, 1 - P_{min\_ph} \cdot B_{ph}/P_{ph}), \]
\[ F(T) = e^{-0.007(T - 25)}, \]
\[ F(I) = I_0 \cdot \left\{ I/1 - \exp\left[-2(1.7/TSP + 0.014B_{ph})]\right\} \cdot \max(1 - B_{wh}/320.0, 0.0) \]

where \( T \) is water temperature \((^\circ C)\); \( TSP \) is Secchi Disc depth \((m)\); \( I_0 \) is daily average of incident light strength \((\text{uE/m}^2/\text{s})\); \( B_{wh} \) is the biomass density of water hyacinths; \( IK \) is the saturation constant of phytoplankton for light. The term \( \max(1 - B_{wh}/320.0, 0.0) \) reflects the influence of water hyacinths on light in water.

The mortality of phytoplankton is composed of two parts. One is the general mortality of phytoplankton without the influence of water hyacinths, while the other part is influenced by water hyacinths because of the shading effect. From this the following equation can be obtained:

\[ MA = R_{m\_ph} \cdot B_{ph} + (1 - R_{m\_ph}) \cdot B_{ph} \cdot (1 - F(I)) \]

where \( R_{m-ph} \) is the normal death rate of phytoplankton. The losses of nitrogen and phosphorus in phytoplankton due to its death can be written as:

\[ N_{phm} = MA \cdot N_{ph}/B_{ph} \]
\[ P_{phm} = MA \cdot P_{ph}/B_{ph} \]

For water hyacinths analogous equations are formulated:

\[ \frac{dB_{wh}}{dt} = GWH - MWH - OUTWH - BHAR \quad (4) \]
\[ GWH = gr_{wh} \cdot B_{wh} \]
\[ \frac{dN_{wh}}{dt} = NH_{uwh} + NO_{uwh} - N_{whm} - N_{whh} \quad (5) \]
\[ \frac{dP_{wh}}{dt} = P_{uwh} - P_{whh} - P_{whm} \quad (6) \]

\[ NH_{uwh} = VmN_{wh} \cdot NH_{pre\_wh} \cdot N_{pro\_wh} \cdot NH \cdot B_{wh}/(NH + Km_{nh\_wh}) \]
\[ NO_{uwh} = VmNO_{wh} \cdot (1 - NH_{pre\_wh}) \cdot N_{pro\_wh} \cdot NO \cdot B_{wh}/(NO + Km_{no\_wh}) \]
\[ P_{uwh} = VmP_{wh} \cdot P_{pro\_wh} \cdot P \cdot B_{wh}/(P + Km_{p\_wh}) \]
\[ N_{pro\_wh} = (N_{max\_wh} - N_{wh}/B_{wh})/(N_{max\_wh} - N_{min\_wh}) \]
\[ P_{pro\_wh} = (P_{max\_wh} - P_{wh}/B_{wh})/(P_{max\_wh} - P_{min\_wh}) \]
\[ gr_{wh} = G_{max\_wh} \cdot F(N_{wh}, P_{wh}) \cdot F_{wh}(T) \cdot F_{wh}(I_0) \]
\[ F(N_{wh}, P_{wh}) = \text{min}(1 - N_{min\_wh} \cdot B_{wh}/N_{wh}, 1 - P_{min\_wh} \cdot B_{wh}/P_{wh}) \]
The symbols for water hyacinths above have analogous meanings, as in the equations for phytoplankton. The formulations of dynamics of water hyacinths differ from the phytoplankton dynamics at one point. There is neither input nor output of water hyacinths with water flow. However, there is loss of biomass, nitrogen and phosphorus of water hyacinths due to the harvesting of water hyacinths. The terms related to this are expressed as:

\[ BHAR = \max(B_{wh} - K_{bwh}, 0.0)/DT \]

\[ N_{whh} = BHAR \cdot N_{wh}/B_{wh} \]

\[ P_{whh} = BHAR \cdot P_{wh}/B_{wh} \]

where \( K_{bwh}, N_{whh}, P_{whh} \) are the density of water hyacinths for beginning harvest, the outputs of nitrogen and phosphorus due to the harvesting; \( DT \) is the time interval for calculation.

### 3.2.2. Equations for phosphorus cycling

The nutrient cycle includes chemical, physical and biological processes which are shown in Fig. 2. Mathematical equations for phosphorus and nitrogen can be achieved by using the mass conservation law. The equations for phosphorus cycling are:

\[
\frac{dP}{dt} = P_i + P_{d,m} + P_{s,r} - P_o - P_{wh} - P_{uph} \tag{7}
\]

\[
\frac{dP_d}{dt} = P_{di} - P_{d,m} + P_{wh} - P_{do} - P_{ds} + P_{phm} \tag{8}
\]

\[
\frac{dP_{pw}}{dt} = P_{ber} - P_{s,r} \tag{9}
\]

\[
\frac{dP_{be}}{dt} = P_{ds} - P_{ber} \tag{10}
\]

where \( P_d \) is the phosphorus concentration in water in the form of detritus; \( P_{pw} \) the phosphorus concentration in pore water in the upper layer of bottom that is 20 cm thick. It is converted to the amount in the whole water column for calculation convenience. \( P_{be} \) is the exchangeable phosphorus in the upper layer of bottom divided by water volume; \( P_i \) and \( P_o \) are the inorganic phosphorus input and output due to the water inflow and output, respectively; \( P_{d,m} \) is the phosphorus release from detritus mineralization; \( P_{s,r} \) is the phosphorus exchange between the inorganic phosphorus in the water column and in the pore water; \( P_{ds} \) is the loss of phosphorus in the form of detritus due to the sink of detritus; \( P_{ber} \) is the release of the exchangeable phosphorus of the upper layer of the bottom sediment to the pore water; \( P_{di}, P_{do} \) are the phosphorus input and output in form of detritus, respectively.

\( P_{d,m} \) can be written as (Jørgensen, 1988):

\[
P_{d,m} = P_d \cdot V_{md} \cdot K_{mdt}^{T-20}
\]

According to Nielsen’s mud–water exchange experiment (1974), \( P_{s,r} \) can be written in the following form:
\[ P_{s-r} = \begin{cases} V_{mpp} \cdot \left(10.0 P_{pw} - P\right) \cdot \frac{T + 273}{280 \cdot 0.7} \cdot \left(1.0 - \left(\frac{P_{h} - 7}{P_{h_{\text{max}}} - P_{h_{\text{min}}}}\right)^2\right) & \text{when } DO = 0.0 \\ 0.0 & \text{when } DO > 0.0 \end{cases} \]

where \( P_{h} \) is the value of the pore water and \( P_{h_{\text{max}}}, P_{h_{\text{min}}} \) are its maximum and minimum values. Because the sediment of the experimental site is anaerobic, \( P_{s-r} \) can be simplified as:

\[ P_{s-r} = V_{mpp} \cdot \left(10P_{pw} - P\right) \cdot \left(T + 273\right)/280/0.7 \]

\( P_{\text{ber}} \) is expressed by using a first-order kinetic equation and can be written as:

\[ P_{\text{ber}} = V_{\text{rex}} \cdot K_{\text{ext}}^{-20} \cdot P_{\text{be}} \]

### 3.2.3. Equations for nitrogen cycling

Three forms of nitrogen compounds are very important water quality parameters for drinking water, as well as for general water quality. Because the conversion from \( \text{NH}_4^+ - \text{N} \), to \( \text{NO}_2^- - \text{N} \) and then to \( \text{NO}_3^- - \text{N} \) is the rate-limiting process in nitrification, and \( \text{NO}_3^- - \text{N} \) is unstable, this model does not include \( \text{NO}_3^- - \text{N} \). It is assumed that ammonium nitrogen is oxidized to nitrate nitrogen in one step. By using this simplification, the first kinetic equation for ammonium nitrogen and nitrate nitrogen can be derived:

\[
\begin{align*}
\frac{d\text{NO}}{dt} &= \text{NO} + \text{NO}_{d-m} + \text{NHO} - \text{NO}_o - \text{NO}_{uwh} - \text{NO}_{uph} \\
\frac{d\text{NH}}{dt} &= \text{NH}_i + \text{NH}_{d-m} - \text{NHO} - \text{NH}_o - \text{NH}_{uwh} - \text{NH}_{uph} + N_{s-r}
\end{align*}
\]  

(11)  

(12)

where \( \text{NO}_{d-m}, \text{NH}_{d-m} \) are the releases of nitrate and ammonium nitrogen, respectively, due to the mineralization of detritus, which are formulated as:

\[
\begin{align*}
\text{NO}_{d-m} &= 0.45 V_{dm} \cdot K_{\text{mtd}}^{-20} \cdot N_d \\
\text{NH}_{d-m} &= 0.55 V_{dm} \cdot K_{\text{mtd}}^{-20} \cdot N_d
\end{align*}
\]

where \( N_d \) is the nitrogen concentration in detritus and \( N_{s-r} \) is the release of ammonium nitrogen from the sediments. It is related to pH, in this paper it is given the value of \( e^{0.151(T - 20) \cdot (0.00004N_s + 0.00008)} \). The oxidization of ammonium nitrogen is

\[ \text{NHO} = V_{\text{no}} \cdot \text{NH} \]

The equations for nitrogen in detritus and in the upper layer of bottom are:

\[
\begin{align*}
\frac{dN_d}{dt} &= N_{di} + N_{whm} + N_{phm} - N_{ds} - NH_{d-m} - NO_{d-m} - N_{do} \\
\frac{dN_s}{dt} &= N_{ds} - N_{s-r} - N_{sl}
\end{align*}
\]  

(13)  

(14)

where \( N_{sl} \) is the denitrification in bottom sediments. The other terms not described in Eq. (11), Eq. (12), Eq. (13) and Eq. (14) have analogous meaning as in equation Eq. (7), Eq. (8), Eq. (9) and Eq. (10).

### 3.3. Values of the parameters in the model

There are about 30 parameters in this model. Some of them are achieved by measurement, some of them are found from literature studies, and the rest are achieved by calibration which will be described in the next section; they are listed in Table 2.
Table 2
Model parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
<th>Value used</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_m NH_{ph}$</td>
<td>Maximum uptake velocity of phytoplankton for ammonium nitrogen</td>
<td>1/d</td>
<td>0.384</td>
<td>Jørgensen et al., 1991</td>
</tr>
<tr>
<td>$V_m NO_{ph}$</td>
<td>Maximum uptake velocity of phytoplankton for nitrate nitrogen</td>
<td>1/d</td>
<td>0.24</td>
<td>Jørgensen et al., 1991</td>
</tr>
<tr>
<td>$V_m P_{ph}$</td>
<td>Maximum uptake velocity of phytoplankton for phosphorus</td>
<td>1/d</td>
<td>0.01</td>
<td>Jørgensen et al., 1991</td>
</tr>
<tr>
<td>$Km_{nh-ph}$</td>
<td>Half saturation constant of ammonium nitrogen for phytoplankton</td>
<td>mg/l</td>
<td>0.176</td>
<td>Calibration</td>
</tr>
<tr>
<td>$Km_{no-ph}$</td>
<td>Half saturation constant of nitrate nitrogen for phytoplankton</td>
<td>mg/l</td>
<td>0.164</td>
<td>Calibration</td>
</tr>
<tr>
<td>$Km_{p-ph}$</td>
<td>Half saturation constant of phosphorus for phytoplankton</td>
<td>mg/l</td>
<td>0.015</td>
<td>Jørgensen et al., 1991</td>
</tr>
<tr>
<td>$G_{max-ph}$</td>
<td>Maximum growth rate of phytoplankton</td>
<td>1/d</td>
<td>0.11</td>
<td>Jørgensen et al., 1991</td>
</tr>
<tr>
<td>$V_m NH_{wh}$</td>
<td>Maximum uptake velocity of water hyacinths for ammonium nitrogen</td>
<td>1/d</td>
<td>0.002</td>
<td>Calibration</td>
</tr>
<tr>
<td>$V_m NO_{wh}$</td>
<td>Maximum uptake velocity of water hyacinths for nitrate nitrogen</td>
<td>1/d</td>
<td>0.0078</td>
<td>Calibration</td>
</tr>
<tr>
<td>$V_m P_{wh}$</td>
<td>Maximum uptake velocity of water hyacinths for phosphorus</td>
<td>1/d</td>
<td>0.0025</td>
<td>Calibration</td>
</tr>
<tr>
<td>$Km_{no-wh}$</td>
<td>Half saturation constant of nitrate nitrogen for water hyacinths</td>
<td>mg/l</td>
<td>0.3</td>
<td>Jin, 1994</td>
</tr>
<tr>
<td>$Km_{p-wh}$</td>
<td>Half saturation constant of phosphorus for water hyacinths</td>
<td>mg/l</td>
<td>0.15</td>
<td>Calibration</td>
</tr>
<tr>
<td>$G_{max-wh}$</td>
<td>Maximum growth rate of water hyacinths</td>
<td>1/d</td>
<td>0.11815</td>
<td>Measured</td>
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<tr>
<td>$N_{min-ph}$</td>
<td>Minimum quota of phytoplankton for nitrogen</td>
<td>mg N/mg d.w.</td>
<td>0.007</td>
<td>Calibration</td>
</tr>
<tr>
<td>$P_{max-ph}$</td>
<td>Maximum quota of phytoplankton for phosphorus</td>
<td>mg P/mg d.w.</td>
<td>0.015</td>
<td>Cai, 1995</td>
</tr>
<tr>
<td>$N_{max-ph}$</td>
<td>Maximum quota of phytoplankton for nitrogen</td>
<td>mg N/mg d.w.</td>
<td>0.085</td>
<td>Calibration</td>
</tr>
<tr>
<td>$N_{min-wh}$</td>
<td>Minimum quota of water hyacinths for nitrogen</td>
<td>mg N/mg d.w.</td>
<td>0.0158</td>
<td>Dou et al., 1995</td>
</tr>
<tr>
<td>$P_{max-wh}$</td>
<td>Maximum quota of water hyacinths for phosphorus</td>
<td>mg P/mg d.w.</td>
<td>0.016</td>
<td>Dou et al., 1995</td>
</tr>
<tr>
<td>$P_{min-wh}$</td>
<td>Maximum quota of water hyacinths for phosphorus</td>
<td>mg P/mg d.w.</td>
<td>0.001</td>
<td>Jørgensen et al., 1991</td>
</tr>
<tr>
<td>$N_{max-wh}$</td>
<td>Maximum quota of water hyacinths for nitrogen</td>
<td>mg N/mg d.w.</td>
<td>0.096</td>
<td>Jørgensen et al., 1991</td>
</tr>
<tr>
<td>$V_{md}$</td>
<td>Velocity of detritus mineralization at temperature 20°C</td>
<td>1/d</td>
<td>0.022</td>
<td>Cai, 1995</td>
</tr>
<tr>
<td>$K_{md}$</td>
<td>A constant for the influence of temperature</td>
<td>1/d</td>
<td>1.15</td>
<td>Cai, 1995</td>
</tr>
<tr>
<td>$V_{mpp}$</td>
<td>Maximum diffusion coefficient of phosphorus from pore water</td>
<td>1/d</td>
<td>0.005</td>
<td>Calibration</td>
</tr>
<tr>
<td>$V_{cre}$</td>
<td>Release velocity of phosphorus from exchangeable phosphorus to pore water</td>
<td>1/d</td>
<td>0.013</td>
<td>Cai, 1995</td>
</tr>
<tr>
<td>$K_{ext}$</td>
<td>Constant for the influence of temperature</td>
<td>1/d</td>
<td>1.13</td>
<td>Cai, 1995</td>
</tr>
<tr>
<td>$V_{nh}$</td>
<td>Oxidization velocity of ammonium nitrogen</td>
<td>1/d</td>
<td>0.1</td>
<td>Calibration</td>
</tr>
</tbody>
</table>

3.4. Calibration of the model

The result of an experiment of the culturing of water hyacinths in a small square with an area of 25 m² and a depth of 2.1 m, carried out in the summer of 1996, is used to calibrate this model. The experimental time was 7 days. At the beginning of the experiment, the water quality parameters (chl-a, DO, NH₄⁺, NO₃⁻, PO₄³⁻, TP, TN, BOD₅, detritus, primary productivity, water transparency, pH), water temperature inside and outside the square, and solar radiation were measured. After that, these parameters were measured every second day. The model and the parameters were checked by comparing the calculated
results with the experimental values. The parameters achieved by calibration are shown in Table 2. The calculated and the observed results are shown in Table 3. It is shown that the result of the model is consistent with experiment for calibration.

4. Results

4.1. Initial values of the state variables and external function

In the dynamic experiment, the water was pumped out at the north end of the channel and the outside water entered at the southern end to simulate the water pumping of the water plant. In the experiments, the density of phytoplankton and water hyacinth, concentration of chlorophyll-a, NO$_2$ -N, NO$_3$ -N, PO$_4^{3-}$ -P, DO, TP, TN, BOD$_5$, water transparency inside and outside the experimental site, solar radiation in air and in water, pH and temperature were measured. Values for $N_{ph}$, $P_{ph}$, $N_{wh}$, $P_{wh}$, $N_d$, $P_d$ are calculated from these measurements. The initial values for $P_{be}$, $P_{pw}$, $N_i$ are obtained from research reports from Nanjing Institute of Geography and Limnology, Chinese Academy of Science (1990) and Li (1996b). The initial values for state variables are shown in Table 4. The retention time ($Ret$) of water in the experiment is 1.2 days.

Table 3
The calculated and observated results of the experiment for calibration

<table>
<thead>
<tr>
<th>Day</th>
<th>NH$_4^+$ -N (mg/l) Cal</th>
<th>NH$_4^+$ -N (mg/l) Obs</th>
<th>NO$_2^-$ -N (mg/l) Cal</th>
<th>NO$_2^-$ -N (mg/l) Obs</th>
<th>PO$_4^{3-}$ -P (mg/m$^3$) Cal</th>
<th>PO$_4^{3-}$ -P (mg/m$^3$) Obs</th>
<th>Phytoplankton (mg/l) Cal</th>
<th>Phytoplankton (mg/l) Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.32</td>
<td>0.32</td>
<td>0.23</td>
<td>0.23</td>
<td>3.50</td>
<td>3.50</td>
<td>2.73</td>
<td>2.73</td>
</tr>
<tr>
<td>2</td>
<td>0.29</td>
<td>—</td>
<td>0.25</td>
<td>—</td>
<td>3.25</td>
<td>—</td>
<td>2.14</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>0.28</td>
<td>—</td>
<td>0.25</td>
<td>—</td>
<td>3.40</td>
<td>—</td>
<td>2.00</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>0.31</td>
<td>0.27</td>
<td>0.26</td>
<td>0.24</td>
<td>3.81</td>
<td>3.80</td>
<td>1.98</td>
<td>2.16</td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>—</td>
<td>0.27</td>
<td>—</td>
<td>4.19</td>
<td>—</td>
<td>1.84</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>0.31</td>
<td>0.30</td>
<td>0.30</td>
<td>0.24</td>
<td>4.32</td>
<td>—</td>
<td>1.74</td>
<td>—</td>
</tr>
<tr>
<td>7</td>
<td>0.39</td>
<td>0.44</td>
<td>0.40</td>
<td>0.65</td>
<td>4.50</td>
<td>3.00</td>
<td>1.50</td>
<td>2.20</td>
</tr>
</tbody>
</table>

—, not observated; obs, observated value; cal, calculated value.

Table 4
Initial value of state variables (mg/l)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{ph}$</td>
<td>1.1565</td>
<td>NO</td>
<td>0.163</td>
</tr>
<tr>
<td>$N_{ph}$</td>
<td>0.11565</td>
<td>$N_d$</td>
<td>0.71768</td>
</tr>
<tr>
<td>$P_{ph}$</td>
<td>0.011565</td>
<td>$P_{be}$</td>
<td>3.96</td>
</tr>
<tr>
<td>$R_{wh}$</td>
<td>285.625</td>
<td>$P_{pw}$</td>
<td>2.2704</td>
</tr>
<tr>
<td>$N_{wh}$</td>
<td>9.02575</td>
<td>$N_i$</td>
<td>159.75</td>
</tr>
<tr>
<td>$P_{wh}$</td>
<td>1.473825</td>
<td>$P_d$</td>
<td>0.11505</td>
</tr>
<tr>
<td>$N_{wh}$</td>
<td>0.274</td>
<td>$P$</td>
<td>0.001</td>
</tr>
</tbody>
</table>
4.2. Comparison between calculation and reality

Figs. 3 and 4 are the diagrams of water quality parameters versus time with the outside water entering the channel without filtering. It is shown that the calculated results of water quality parameters NH$_4^+$-N and NO$_3^-$-N are consistent with the observed experimental results. At the beginning of the pumping experiment, the concentrations of NH$_4^+$-N and NO$_3^-$-N in the channel began to increase quickly because of the high concentrations of NH$_4^+$-N and NO$_3^-$-N in the inflow, and as the concentrations of NH$_4^+$-N and NO$_3^-$-N in the inflow decreased the concentration of NH$_4^+$-N and NO$_3^-$-N in the channel increased slowly until maximum values were reached. They then began to decrease, but the calculated results achieved a maximum value earlier than the observed results. The differences were induced by the average of the whole channel. From Fig. 5, we can see that the calculated value of PO$_4^{3-}$-P in the channel varied.
slowly, but there were disturbances of the observed value of $\text{PO}_4^{3-}$-P. The deviation was caused by the difficulty of measuring very low concentrations of $\text{PO}_4^{3-}$-P in the channel. However, the calculated value is consistent with the observed average value $\text{PO}_4^{3-}$-P of the experiment. In Fig. 6 we show curves of phytoplankton concentration. Although the calculated values are not consistent with the observed values, they show the same trend. Therefore, it can be said that the model is consistent with the reality.

4.3. Sensitivity analysis of the model

The results of the model sensitivity analysis are shown in Table 5. It is found that state variable $P$ was most sensitive to the retention time and then to parameter $V_{mNH_{wh}}$; state variable $NO$ was most sensitive to the retention time, then to $V_{mNO_{wh}}$, and then to $V_{mNH_{wh}}$; state variable $P$ was sensitive most to $V_{mp}$.
Table 5  
Results (in %) of the sensitivity analysis of the model by ± 25 change

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NH</th>
<th>NO</th>
<th>P</th>
<th>B\textsubscript{ph}</th>
<th>B\textsubscript{wh}</th>
<th>N\textsubscript{wh}</th>
<th>P\textsubscript{wh}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_m\text{NH}_{wh}$</td>
<td>-3.46</td>
<td>-1.62</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>-1.88</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>+3.58</td>
<td>+1.95</td>
<td></td>
<td></td>
<td></td>
<td>+1.87</td>
<td></td>
</tr>
<tr>
<td>$V_m\text{NO}_{wh}$</td>
<td>&lt;0.1</td>
<td>-11.3</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>+2.10</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>+9.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-2.45</td>
<td></td>
</tr>
<tr>
<td>$V_m\text{P}_{wh}$</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>-97.10</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>+0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+51.16</td>
<td></td>
<td></td>
<td></td>
<td>-0.42</td>
</tr>
<tr>
<td>$V_m\text{NH}_{ph}$</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$V_m\text{NO}_{ph}$</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_m\text{P}_{ph}$</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>-0.64</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+0.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ret</td>
<td>-9.00</td>
<td>-11.12</td>
<td>&lt;0.1</td>
<td>-7.08</td>
<td>&lt;0.1</td>
<td>&lt;0.30</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>10.17</td>
<td>+12.50</td>
<td></td>
<td>10.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{mpp}$</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>+68.06</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>10.95</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-100.0</td>
<td></td>
<td></td>
<td></td>
<td>-9.93</td>
</tr>
<tr>
<td>$V_{rex}$</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>+6.70</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>+0.93</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-6.60</td>
<td></td>
<td></td>
<td></td>
<td>-0.60</td>
</tr>
</tbody>
</table>

i.e. to the diffusion coefficient of phosphorus from pore water, then to $V_m\text{P}_{wh}$, then to $V_m\text{P}_{ph}$, phytoplankton density was only sensitive to retention time; water hyacinth biomass was not sensitive to these parameters, but $P_{wh}$ was sensitive to $V_{mpp}$ and the increment would increase versus time.

5. Discussion

The results show that the model can simulate well the reality of the experiment, so the model can be used as a guide for the design and management of physico-biological engineering for purifying lake water using water hyacinths. For example, the results of the model sensitivity analysis show that retention time has an important influence on the nutrient nitrogen concentration. So, increasing retention time by 25% can improve the purifying capacity of engineering for nitrogen by 10% and can cut down phytoplankton density by 10%. From Table 5, the concentration of phosphorus can be lowered by decrease of the release from sediment. It is found that the nutrient concentrations are sensitive to the nutrient uptake velocities of water hyacinths, but not to that of phytoplankton, which indicates that the growth of water hyacinths determines the water quality. Thus, the big problems which should be solved are how to culture and harvest water hyacinths and how many water hyacinths should be left on the surface of water.

From a long-term point of view, the purifying effect of the ecosystem should be assessed by the net uptake of water hyacinths for nutrients. The net uptake is the nutrient uptaken by water hyacinths minus the nutrient entering water due to mortality. Fig. 7 shows the net uptake curves of water hyacinths for nutrient nitrogen and phosphorus versus the starting density of water hyacinths. The data which were used to draw the figure are from the calculation of the model. It shows the net uptake increase, according to the increase of the starting density, to its maximum and then beginning to decrease as the starting density increases. The optimum starting density of fresh water hyacinths for nitrogen is 9.6 kg/m\textsuperscript{2}, the optimum starting density for phosphorus is 5.12 kg/m\textsuperscript{2}. Because nitrogen pollution is more serious than phosphorus pollution, the optimum beginning density of fresh water hyacinths is 9.6 kg/m\textsuperscript{2}. Fig. 8 shows the net nutrient uptake curves of water hyacinths versus the density at which they are harvested. From the figure, the optimum fresh water hyacinth density for nitrogen is 12.24 kg/m\textsuperscript{2}, and the optimum density for
Fig. 7. Influence of initial density of water hyacinths on net nutrient uptake.

phosphorus is 11.4 kg/m². These two densities are close, so the optimum density for start of harvesting can be considered as the average value of the two: 11.82 kg/m².

Figs. 9–12 are the curves of phytoplankton, ammonium nitrogen, nitrate nitrogen, phosphorus versus time, with the outside water being filtered by a filter cloth as it enters the channel. From these figures, it is found that the filtering action improved the purifying effect greatly, except for phosphorus which is controlled by release from the bottom; the phytoplankton, especially, is cut almost to zero.

Fig. 8. Influence of harvesting density of water hyacinths on net nutrient uptake.
6. Conclusion

An ecological model for experiments proposed for lake water purification using water hyacinths is presented. The calibration and validation show that the results of the model are consistent with the reality. From the model, it is found that $P$ is sensitive to $V_{app}$, $V_{rez}$, $NH$ to $Ret$, $VmNH_{wh}$; $NO$ to $VmNH_{wh}$, $VmNO_{wh}$ and $Ret$; phytoplankton to $Ret$. The optimum initial fresh water hyacinth density is 9.6 kg/m². The optimum fresh water hyacinth density for start of harvesting is 11.82 kg/m². The filtering measures can cut down phytoplankton density greatly and thus improve the water quality in the channel.
Acknowledgements

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