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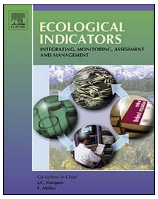

Original articles

Effect of inter-basin water transfer on water quality in an urban lake: A combined water quality index algorithm and biophysical modelling approach

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ABSTRACT

To improve water quality and alleviate eutrophication in a polluted urban lake, water diversion, a common method of basin management, is planned. In this study, we used the physiology-based water quality model, the General Ecosystem Module (GEM) in FVCOM, to investigate the potential influence of transferred water on the water quality index (WQI) and comprehensive eutrophication state index (TLI) of the lake. A fuzzy synthetic evaluation algorithm was applied to quantify the value of the WQI objectively. Our results indicate that total nitrogen and total phosphorus (TN and TP) are the most dominant pollutants influencing water quality, accounting for 63.6% of the weighting. In addition, overflow of municipal sewage after rainfall contributed to the decrease of the WQI (class IV in spring and class V in summer). This slow-flow shallow water body was categorised as a light eutrophic lake according to the TLI calculation. As an important factor that influences pollutant retention and water exchange, residence time (τ_e) was also considered. A multi-objective optimisation method was used as an effective method to guide practical management, considering the hydrodynamic conditions (τ_e), water quality (WQI) and economic cost (M). First, the WQI, τ_e and economic cost of different parts of the lake were investigated under different inflow discharge scenarios using our combined approach. Then, the Wolves Colony Search Algorithm was used to minimise the dimensionless objective function, which is comprised of the three factors above. The calculated environmental water demand of Lake Gantang (GTL) and Lake Nanmen (NML) was 0.0456 and 0.0417 million $m^3\ d^{-1}$, respectively. Under optimal water diversion conditions, this lake changes to a mesotrophic lake of class III with good water body exchange capacity. Overall, our combined model can be a guide for the local government and decision-makers and used to evaluate the optimal amount of transferred water at a minimum cost for inter-basin management.

1. Introduction

Urban lakes, characterised as small water bodies located in cities, act as important recreation and flood regulation sites. They are usually slow-flow, shallow water bodies with municipal pipe networks around them, leading to low self-cleaning capacity. Therefore, urban lakes are likely to be particularly susceptible to the effects of water management and human activities (Wu et al., 2014). Owing to the lack of municipal sewage pipeline construction in China, the overflow of sewage pipes around lakes can cause contamination with pollutants and lead to water quality degradation (Chen et al., 2009). With intensive economic development, the consequences of this kind of pollution are increasingly serious. External pollution sources, internal sources (nutrient release from sediment) and hydrodynamic conditions (local circulation) are all critical factors resulting in water quality degradation (Wang, 2014). Therefore, the implementation of water quality improvement projects in heavily polluted urban lakes is imperative for water management. Inter-basin water transfer from other clean water bodies is an effective and widely used method to relieve water quality deterioration (Jin et al., 2015; Mao et al., 2012; Wang, 2014; Xiao et al., 2004). The theory is that transferring large amounts of low-nutrient water can reduce net nutrient loading and increase the flushing rate in a lake (Hu et al., 2010). Importantly, an appropriate water quality evaluation indicator should be chosen to assess the degree of improvement in lake pollution as a result of such water transfer projects.

The Water Quality Index (WQI), which summarises different quality

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parameters, and transforms large quantities of water quality data into a single number, has been widely used to evaluate water quality (Simões et al., 2008; Wu and Chen, 2013). The object of the WQI is to classify water quality as excellent, good, regular, bad and poor. However, the selection of the weighting factors for each quality parameter during the formulation of the index was largely based on subjective measures or related research (Wu and Chen, 2013). At the same time, "eclipsing" occurs, which can lead to mistakes in the evaluation when extremely poor environmental quality exists, but the overall index does not reflect this fact (Pesce and Wunderlin, 2000). The fuzzy synthetic evaluation method is often used to solve this problem (Chang et al., 2001; Zhi-hong 2006; Jing-nan, 2006), by introducing the objective weight of entropy and the membership function. In addition, the water residence time is an easily overlooked indicator in lakes which reflects the spatio-temporal scale of pollutant retention and quantifies the possible effects of changes in nutrient loads on nutrient concentration levels (Ajibode et al., 2013; Dettmann, 2001; Sweeney et al., 2003). In lakes, the spatial and temporal status of water quality change. Hence, it is necessary to obtain enough water quality data to calculate the varying WQI. The use of monitoring data is considerably challenging and problematic, especially in predicting the resulting values after water transfer scenarios. At the same time, estimating pollutant transport and transformation is challenging due to complex hydrodynamic and bio-chemical processes. Practically, a reasonable numerical technique that takes into account the complicated physical-ecological processes would be a useful tool to present both a spatially and temporally explicit evaluation of water quality status in the whole lake. However, the method of linking water quality index algorithms with ecological modelling has been scarcely reported (Wu and Chen, 2013).

Therefore in the present study, we employed the Finite Volume Community Ocean Model (FVCOM), which is an unstructured grid, finite-volume, three-dimensional primitive equation model. We chose an urban lake in Jiujiang City in China as a case study to: (1) calculate the spatial-temporal water quality indicators using fuzzy synthetic evaluation algorithms; (2) develop a numerical biophysics model in which the interactions between physical and physiological processes can be incorporated. The purpose of this study is to: 1) explore the effect of water transfer on water quality status and water renewal timescales in an urban lake by combining the evaluation algorithms and numerical approach; and 2) identify the optimum level of inter-basin discharge for solving the pollutant problem.

2. Materials and methods

2.1. Description of study area

Lake Gantang (GTL) and Lake Nanmen (NML) (29°44′17″–29°49′23″ N; 116°58′36″–116°59′51″ E), located near the middle part of the Yangtze River Delta, are well-known shallow lakes around Jiujiang City (Fig. 1a). The water in these two lakes is linked with each other via the Sixian Bridge (SXB). The whole urban lake covers an area of about 1.33 km^2 with an average depth of 2.5 m. The wet season occurs from April to September with frequent heavy rain. The average annual total precipitation of the basin is 1600 $\mathrm{mm\ yr}^{-1}$. As a recreational lake, the water level is controlled at 15.62 m. The Zhakou pump station (seen in Fig. 1) in GTL pumps lake water into the Yangtze River when the water level is above maintenance level. Owing to the backward construction of municipal pipes, after rainfall, six overflow sites can become point sources of pollutants, as seen in Fig. 1. In order to improve water quality, the local government has planned to transfer water from the Yangtze River yearly into this lake to dilute and divert pollutants out of the lake. Nine inlets have been set up for this water transfer project. Five and four sites are located at NML and GTL, respectively. The maximum designed flow discharge from the Yangtze River is 0.12 million $\mathrm{m}^3\ \mathrm{d}^{-1}$.

2.2. Model overview

The method used in this study combines water quality index algorithms with Eulerian biophysical modelling. The latter module provides the values of the state variables used for the calculation of the water quality index in the former module. If the WQI cannot meet the water quality target, the water transfer discharge will be adjusted to re-calculate the water quality parameters. A flowchart of this method is presented in Fig. 2. A detailed description of this coupled approach is presented in the following section.

2.2.1. The biophysical model based on FVCOM

The Finite Volume Community Ocean Model (FVCOM), which is an unstructured grid, finite-volume, three-dimensional primitive equation ocean model, was applied to supply hydrodynamic information, such as temperature, current velocity and vertical turbulence (Chen et al., 2006). The calculated results from the hydrodynamic model are used as external forcing for biochemical processes. The output interval in the generated hydrodynamic file was set as one hour, which guaranteed the capture of external hydrodynamic variation. The General Ecosystem Module (GEM) in FVCOM, in off-line mode, utilizes the hydrodynamic file for pollutant transport and reflects local biochemical processes. The advection and diffusion equations of variables are described in Chen et al. (2006). The original variables and equations in GEM were modified in this study. The variables of GEM comprise of: 1) Chlorophyll a concentration (Chla); 2) dissolved inorganic nitrogen (DIN), which includes ammonium (NH_4^+) and nitrate (NO_3^- and NO_2^-); 3) dissolved inorganic phosphorus (DIP); 4) biological oxygen demand (BOD_5); and 5) dissolved oxygen (DO). The calibrated parameters in GEM are shown in Table 1. The details of the biological processes are as follows:

1) Chlorophyll a concentration (Chla)

$$\frac{\mathrm{dChla}}{\mathrm{dt}} = (\mu_\mathrm{p} - \mu_\mathrm{D} - \mathrm{k_{sed}}/\mathrm{dz})\mathrm{Chla}. \tag{1}$$

where μ_p (d^{-1}) is the specific proliferation rate, μ_D (d^{-1}) is the mortality rate, dz is the water layer depth and $\mathrm{k_{sed}}$ ($\mathrm{m\ d}^{-1}$) is the settling rate of phytoplankton. The proliferation rate is described using a maximum rate, which is limited by temperature, light, and nutrient concentration:

$$\mu_\mathrm{p} = \mu_\mathrm{max}\mathrm{L_T L_I}\min(\mathrm{L_N},\ \mathrm{L_P}) \tag{2}$$

where μ_max (d^{-1}) is the maximum growth rate; $\mathrm{L_T}$ is the temperature limitation term, $\mathrm{L_I}$ the light limitation term and $\min(\mathrm{L_N},\mathrm{L_P})$ is the nutrient limitation term. The limitation terms are as follows (JÖHNK et al., 2008; Robson and Hamilton, 2004):

$$\mathrm{L_T} = 1 + 5.77\left(1.3^{\mathrm{T}-\mathrm{T_{opt}}} - 1 - \frac{\mathrm{LN}(1.3)}{\mathrm{LN}(1.37)}\left(1.3^{\mathrm{T}-\mathrm{T_{opt}}} - 1\right)\right). \tag{3}$$

$$\mathrm{L_I} = \frac{\mathrm{I(z)}}{\mathrm{I_k}}\exp\left(1 - \frac{\mathrm{I(z)}}{\mathrm{I_k}}\right). \tag{4}$$

$$\min(\mathrm{L_N},\ \mathrm{L_P}) = \min\left(\frac{\mathrm{DIN}}{\mathrm{DIN+K_{DIN}}},\ \frac{\mathrm{DIP}}{\mathrm{DIP+K_{DIP}}}\right). \tag{5}$$

where T (°C) is the water temperature, $\mathrm{T_{opt}}$ is the optimum growth temperature; I ($\mathrm{W\ m}^{-2}$) is the irradiance of the position where agents are located, $\mathrm{I_k}$ ($\mathrm{W\ m}^{-2}$) is the saturation light intensity, and $\mathrm{K_{DIN}}$ ($\mathrm{mg\ L}^{-1}$) and $\mathrm{K_{DIP}}$ ($\mathrm{mg\ L}^{-1}$) are the half-saturation constants of nitrogen and phosphorus, respectively. For simplicity, the mortality rate includes respiration, excretion and mortality loss. The death rate is adjusted for temperature based on the common Arrhenius formulation:

$$\mu_\mathrm{D} = \mu_\mathrm{D}(20)\vartheta^{\mathrm{T}-20}. \tag{6}$$

where $\mu_\mathrm{D}(20)$ is the specific loss rate at 20 °C, and ϑ is the temperature multiplier for death (dimensionless).

2) Dissolved inorganic nitrogen (DIN)