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Modelling the influence of thermal discharge under wind on algae

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ABSTRACT

Wind-driven processes exert an important impact on aquatic ecosystems, especially on shallow reservoirs. Flow and heat transport under wind in the Douhe reservoir in China were simulated by a two-dimensional mathematical model. Areas corresponding to different temperature rises were calculated for different wind speed conditions with high frequency. It is shown that high temperature rise areas increase for maximum wind speed conditions while low temperature rise areas keep constant for various wind speed conditions. The concentration of Chl.a decreases with the increase of wind speed, indicating that low wind speed is suitable for algae blooming in the Douhe reservoir. The effects of wind on *Bacillariophyta* biomass growth become more obvious with the increase of temperature rise areas. The influenced areas of lower temperature rise (0.2–1.49 °C) and higher temperature rise (1.5–2 °C) zone are 8.57×10^6 m^2 and 5.18×10^6 m^2, respectively, and corresponding total variation amounts of *Bacillariophyta* biomass are 2.24×10^5/m^2 and 0.42×10^5/m^2, respectively. Results show that wind has a significant impact on ecological effects due to thermal discharge from thermal power plant into shallow reservoirs.

1. Introduction

Various ecological responses caused by thermal discharge from power plants into water bodies change the abundance and structure of aquatic species (Kinne, 1970; Strauss and Puckorius, 1984; Mallin et al., 1994; Bamber and Seaby, 2004). The temperature of hot water discharged from power plants is typically 7–10 °C higher than that of the receiving water (Langford, 1990), which results in a temperature rise envelope, i.e., the so-called temperature rise area (Takemura et al., 1985; Casamitjana et al., 2003). The increase of water temperature leads to the enhancement of metabolism of organics and the decrease of dissolved oxygen concentration (Encina et al., 2008; Chen et al., 2011). Corresponding temperature rises may affect the reproduction, growth and survival of aquatic species, for example the biomass of algae. Moreover, wind is the main driving force of water moving in the shallow reservoir; the variation of wind speed changes the process of thermal transport and subsequently alters the distribution of algae species (Mirbagheri et al., 2012; Wu and Chen, 2014a). Algae are a biological indicator of water quality in an aquatic environment; the variation in algae biomass can provide ecological information on the degree of eutrophication of the water area. Therefore, analysis of the temperature rise of the receiving water environment under wind conditions has significant implications on the assessment of environmental status of reservoirs or lakes.

Regarding the effects of thermal discharge on the receiving water area, there have been various studies that focus on the changing biomass of aquatic species in specific areas of lakes and estuaries. The results given by Takemura et al. (1985) show that photosynthesis is inhibited for temperature below 4 °C, and partly inhibited for temperature between 4 and 11 °C in Lake Kasumigaura. Melton and Serviss (2000) presented the relationship of temperature rises at different stations in the Anclote River and the mortality of aquatic species. Based on field samplings and the plankton population model, Holland et al. (2003) compared the plankton distribution under different temperature areas in Lake Baikal. By sampling data on the maximum photosynthetic rate of algae, numerical researches are focused on the effects caused by elevated temperature on the decreasing of biomass of algae (Casamitjana et al., 2003; Han et al., 2005; Kazuhisa and Chikita, 2007; Kentzer et al., 2010; Choi et al., 2012). These researchers are almost focused on the changing of algae biomass in a certain temperature rise area, but that in the whole study area cannot be elaborated accurately. The distribution of aquatic species due to changes of hydrodynamic conditions (such as wind speed conditions) cannot be illustrated distinctly.

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Moreover, some efforts have also been made to simulate the variation of the temperature diffusion area under different temperature gradients (Poornima et al., 2006; Jiang et al., 2008; Wu et al., 2011, 2012; Wu and Chen, 2014b; Chen et al., 2012; Helfer et al., 2012). Riou (1989) presented a two-dimensional model by taking the interaction of air and sea into account to forecast the temperature rise due to thermal pollution. Han et al. (2004) used a depth-averaged convection–diffusion model to predict the side discharge into open-channel flow under steady wind conditions. Chen et al. (2011) analysed influenced region due to various outlet position in the estuary near the power plant, based on a three-dimensional numerical model. Nitin and Lee (2005) investigated the distribution of algae in the coastal area with genetic arithmetic, indicating that tidal force plays a dominant role for the thermal transport in tidal estuaries, and wind effects can be neglected. However, for the shallow reservoir, wind is the main force to drive flow. The variation of flow pattern due to the wind speed cannot be neglected for the mixing process of hot water in the shallow reservoir. The effects of wind on ecological effects of thermal mixing in the reservoir have not been well understood.

Several researches have been conducted on eutrophication of the Douhe reservoir, with focus on water quality assessment of the reservoir (Lu et al., 2001; Zheng and Xu, 2011; Xu et al., 2012). However, the hydrodynamic condition variation due to the change of wind speed condition was neglected. Presented in this paper is a numerical analysis on the effects of wind speed on temperature diffusion and the variation of biomass of the dominant algae.

2. Study site

The Douhe reservoir, as a terminal regulating reservoir since 1986, is located in Tangshan city, Hebei Province, as shown in Fig. 1. The catchment's area and normal water level are 530 km^2 and 34 m, respectively. The reservoir is serving as an industrial and domestic water source. The major inflows are from the northern Guan River and the Quanshui River. The discharges of the four tributaries are relatively low compared with the two major inflows.

3. Model description

The mean water level of the Douhe reservoir is 3.4 m, and thermal stratification was not apparent. A two-dimensional hydrodynamic and thermal transport model is used to simulate the variation of flow and temperature distribution in the reservoir. The momentum transport equation in orthogonal coordinates (ξ, η) in Delft3D-FLOW model are written as follows (WL|Delft Hydraulics, 2006):

$$\frac{\partial\zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)U\sqrt{G_{\eta\eta}}\right]}{\partial\xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)V\sqrt{G_{\xi\xi}}\right]}{\partial\eta}=Q \tag{1}$$

$$\begin{aligned}&\frac{\partial u}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial\xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial\eta}+\frac{\omega}{d+\zeta}\frac{\partial u}{\partial\sigma}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial\eta}\\&-\frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial\xi}-fv=-\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi+F_\xi\\&+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}\left(\nu_v\frac{\partial u}{\partial\sigma}\right)+M_\xi\end{aligned} \tag{2}$$

$$\begin{aligned}&\frac{\partial v}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial\xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial\eta}+\frac{\omega}{d+\zeta}\frac{\partial v}{\partial\sigma}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial\xi}\\&-\frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial\eta}+fu=-\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta+F_\eta\\&+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}\left(\nu_v\frac{\partial v}{\partial\sigma}\right)+M_\eta\end{aligned} \tag{3}$$

$$Q=H\int_{-1}^{0}(q_{in}-q_{out})d\sigma+P-E \tag{4}$$

where ζ is the water level above the reference plane, t is the time axis (coordinate), $G_{\xi\xi}$ and $G_{\eta\eta}$ are coefficients used to transform curvilinear coordinates to rectangular coordinates, Q is the source (or sink) term, the quantity per unit area to the discharge or

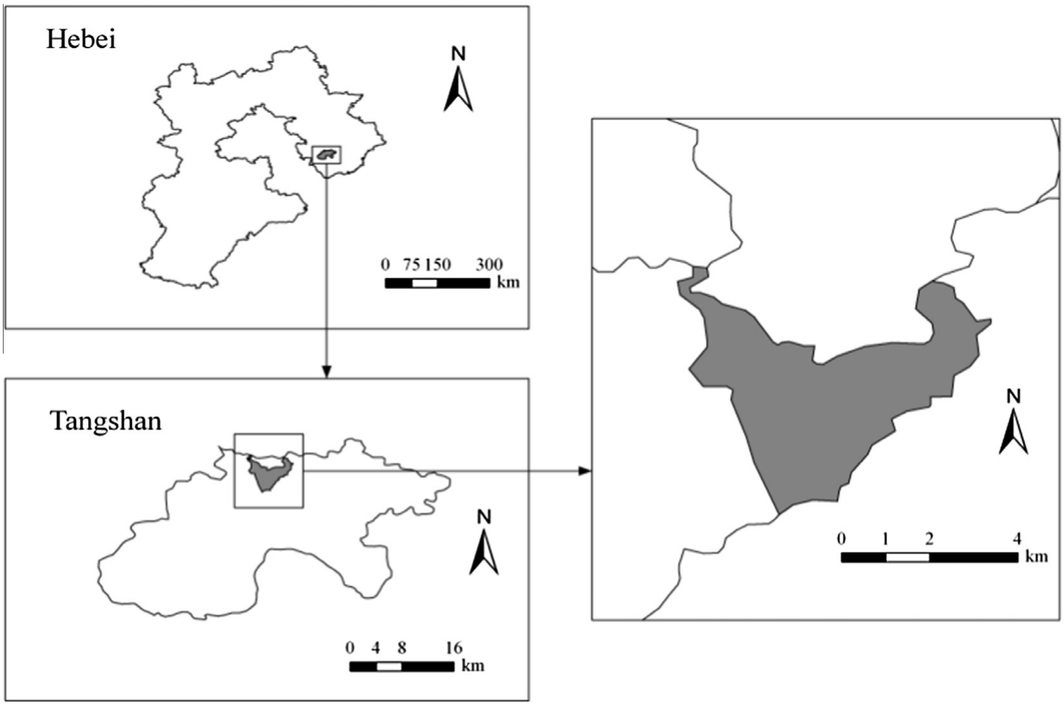

Fig. 1. Geographical location of Douhe reservoir.

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