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Effects of Flood on Thermal Structure of a Stratified Reservoir

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Abstract

An important factor in aquatic environment is water temperature, which influence many important processes in an aquatic ecosystem. In this paper, a 3-D model of thermal-hydrodynamic was developed to simulate the thermal structure in stratified reservoir, taking YE reservoir, a typical canyon reservoir in south-west China as an example. The simulated results showed that YE reservoir is a stratified reservoir, and water column in reservoir have two overturning periods per year separated by periods of stratification. In this case, 7-days flood process (from Jul.17th to Jul.23th) during the normal flow year was taken as a inflow charge, the results showed if the temperature of flood is the same as that of the outflow from the reservoir, the thermal structure will maintain the former status, and if the temperature of flood is lower than that of the outflow, the flood will cause thermocline erosion to some extent. And in this case, the effect time can last two months. By changing the outlet location, simulations demonstrate that the outlet elevation is the main factor controlling the thermal structure in YE reservoir.

Keywords: water temperature; thermal structure; stratified reservoir; flood; numerical simulation.

1. Introduction

Reservoirs, man-made lakes, usually are built to store water for later use, such as water supply, agricultural irrigation, flood control and power generation etc. Inflow and withdrawal lead to decrease in water retention time of reservoir comparing with the lake of the same morphometry[1]. For this reason, reservoir are usually considered as water column intermediate between rivers and lakes, sharing some characteristics with both. The thermal behavior and hydrodynamics in a reservoir is essential which affect the vertical exchanges of dissolved and particulate matter[2-4]. This becomes important if the reservoir is stratified. For example, during the summer, the water column is highly stratified, with a shallow mixed layer. Although the light is high, due to the weaken of water exchange in the vertical direction, and hence the concentration of nutrients in the mixed layer is quite low, and photosynthetic rates are also low[5, 6]. Therefore, the thermal structure is important in aquatic environment.

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The thermal structure is mainly affected by two aspect. One is the internal variables such as reservoir morphometry and light extinction coefficient of water. The other is external factors[7-10], such as inflow, outflow, wind, air temperature, outlet location, dam operation. Xavier Casamitjana[7] study effects of the water withdrawal in Boadella reservoir. Brett M. Johnson[9] analyze the effects of climate and dam operations on blue mesa reservoir by a one-dimensional thermal model, found that climate and hydrology appear to exert stronger control over reservoir thermal structure than reservoir operations. Dale M. Robertson[11] study the response relationship between the change of the thermal structure and changes in air temperature. The results show that inflow is one of the main influence factors of thermal structure, and the degree of stratification varies with inflow temperature. During the prediction of thermal structure, an average inflow value was adopt, do not consider the effect of the flash flood. And hence in this paper, take the typical canyon reservoir, YE reservoir in South-West China as an example; analyze the characteristic of thermal structure, and consider two different temperature of 7-days flood process influence on the thermal structure. At the same time, due to the outlet location can exert an obvious effect on hydrodynamics of reservoirs. So, in this paper, study the influences degree on the thermal structure by changing the outlet location.

Materials and Methods

Study Area: The YE reservoir is the first one among a cascade of reservoirs situated in upstream of the ER river in south-east China and now which is in planning and design stage. The YE reservoir is about 10 km long and 500 m wide. The maximum depth is 105 m at the dam site. The normal water level is EL.3516m, and the intake of its power station is located at 45 m below the normal water level.

Governing Equation: Based on the assumption that river flow is incompressible, the hydrodynamic equations are given by:

The depth-averaged continuity equation is given by:

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

Where is the free surface elevation above reference datum [m], G and G are the coefficients used to transform curvilinear to rectangular co-ordinates. d is the depth below the reference datum [m]; H=(d+ is the total water depth [m], U and V are the depth-average velocity in and directions, respectively [m/s]. u, v and are the flow velocity in the , and directions, respectively [m/s], of which, is the vertical velocity relative to the moving plane, and can be computed from the continuity equation.

The momentum equations in and directions

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

and

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

Q is the contributions per unit area due to the discharge or withdrawal of water, etc. *f* is the Coriolis parameter (or inertial frequency) [1/s]. *P* and *P* are gradient hydrostatic pressure in and directions separately [kg/m^{2}s^2]. *F* and *F* are turbulent momentum flux in and directions separately [m/s^2]. *M* and *M* are source or sink of momentum in and directions separately [m/s^2]; $_V$ is vertical eddy viscosity [m^2/s].

Under the shallow water assumption, the vertical momentum equation reduces to the hydrostatic pressure equation. Vertical acceleration due to buoyancy effects or sudden variations in the bottom topography is not taken into account. The resulting equation is:

$$\frac{\partial P}{\partial\sigma}=-g\rho H=-g\rho(d+\zeta) \quad (4)$$

Considering the temperature effect on hydrodynamic field, the thermal transport equation and the state equation of water are needed. The thermal transport equation can be expressed by:

$$\frac{\partial(d+\zeta)T}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\left(\frac{\partial\left[\sqrt{G_{\eta\eta}}(d+\zeta)uT\right]}{\partial\xi}+\frac{\partial\left[\sqrt{G_{\xi\xi}}(d+\zeta)vT\right]}{\partial\eta}\right)+(d+\zeta)\frac{\partial\omega T}{\partial\sigma}$$
$$=\frac{d+\zeta}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\left(\frac{\partial}{\partial\xi}\left[\frac{D_H}{\sigma_{c0}}\frac{\sqrt{G_{\eta\eta}}}{\sqrt{G_{\xi\xi}}}\frac{\partial T}{\partial\xi}\right]+\frac{\partial}{\partial\eta}\left[\frac{D_H}{\sigma_{c0}}\frac{\sqrt{G_{\xi\xi}}}{\sqrt{G_{\eta\eta}}}\frac{\partial T}{\partial\eta}\right]\right)+\frac{1}{d+\zeta}\frac{\partial}{\partial\sigma}\left[\frac{\upsilon_{\mathrm{mol}}}{\sigma_{\mathrm{mol}}}+\max\left(\frac{\upsilon_{3\mathrm{D}}}{\sigma_c},D_V^{\mathrm{back}}\right)\frac{\partial T}{\partial\sigma}\right]+S \quad (5)$$

where D_H and D_V are horizontal and vertical diffusion coefficient separately [m^2/s]. $_{\mathrm{mol}}$ is the kinematic viscosity coefficient [m^2/s]. $_{\mathrm{3D}}$ is the part of eddy viscosity due to 3D turbulence [m^2/s]. $_{\mathrm{c0}}$ is the constant Prandtl-Schmidt number assigned the value 0.7. *S* is the source/sink term per unit area due to the discharge.

The density of water is a function of temperature *T*, given as follows:

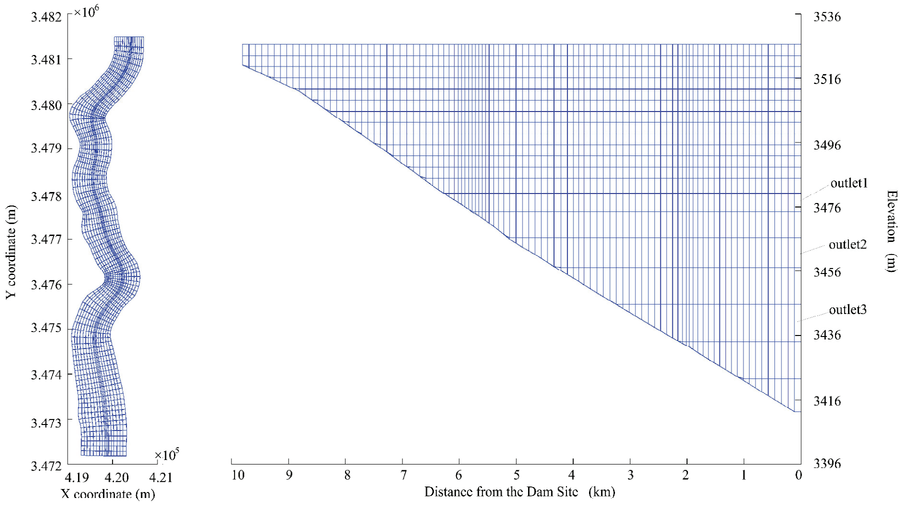
$$\rho=\begin{pmatrix}1.02027692\times10^{-3}+6.77737262\times10^{-8}\times T-9.05345843\times10^{-9}\times T^2+8.64372185\times10^{-11}\times T^3\\ -6.42266188\times10^{-13}\times T^4+1.05164434\times10^{-18}\times T^7-1.04868827\times10^{-20}\times T^8\end{pmatrix}\times9.8\times10^5 \quad (6)$$

In this paper, *k*- turbulence closure model is adopted, see reference [12].

Numerical schemes for governing equations: In this paper, a finite difference scheme is adopted to discrete the governing equations. For horizontal plane, the orthogonal curvilinear grids are applied to discrete the computational domain. The ADI (Alternating Direction Implicit) method is used to solve the discrete governing equations based on the staggered grid method. However, not all variables are defined at the same location in the grid. The process and detailed technology of its numerical simulation can be found in relevant literatures[13, 14].

Grid Generation and Boundary Conditions

Grid Generation: Considering the geographical features, the computational domain is approximately 10 km long. Based on the measured terrain, the computational domain has a grid system of 100 (along flow direction)× 19 (in cross-section direction) in simulation area. The grid size along the flow direction is about 100m, and the grid size in the cross-section direction range from 20m to 100m. While in the vertical direction, 20 layers of grids have been fixed (see Fig. 1).



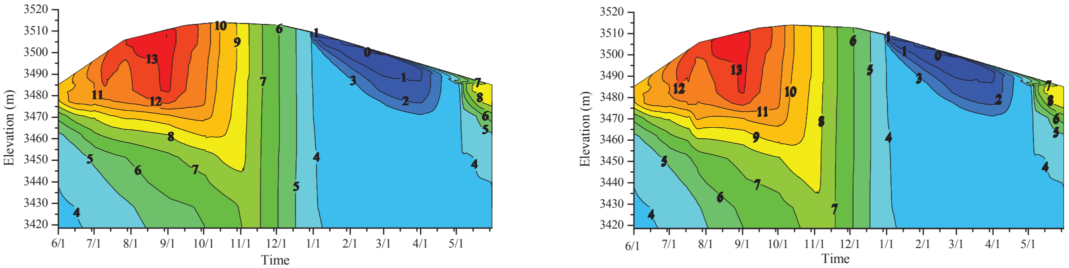
(a) plane grid (b) vertical grid

Fig.1 schematic diagram of grid in YE reservoir (outlet1,outlet2,outlet3 are different locations of outflow in different case)

Initial and Boundary Conditions: In this case, 3-d model of thermal-hydrodynamic is applied to predict the thermal structure in normal flow year (from June 1987 to May 1988). In order to eliminate the error caused by initial condition, the initial conditions are given by "hot start", which means that the initial conditions are established from a restart file. The restart file can be created by repeating hydrological year computation until the difference between the current and former computed temperature and velocity is small enough. As for the upper boundary, the discharge of ER river is adopted, and the lower boundary of the YE dam adopts the total discharge of power station intakes and ecological flow from dam. In this paper, according to once-in-50-years design flood, take 7-days flood (from Jul.17th to Jul.23th) process to consider the effect of flood on thermal structure in YE reservoir.

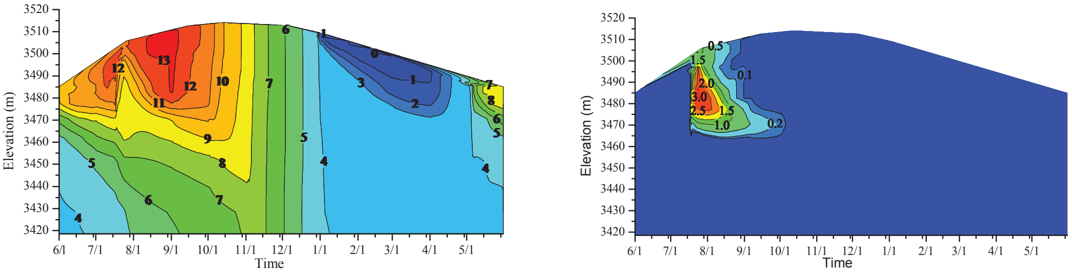
Results and Discussions

Different flood temperatures: Fig.2a, Fig.2b and Fig.2c show the temporal characteristic variation of temperature before dam site along elevation direction in YE reservoir. In Fig.2a, adopt the actual monthly averaged discharge of ER river in normal flow year as the value of inflow, and the inflow temperature was taken the actual monthly averaged. As can be seen from Fig.2a, water column in reservoir have two overturning periods per year separated by periods of stratification. With the atmosphere cools in the fall, heat fluxes from the surface water of warmer reservoir into atmosphere, it becomes denser and sinks. Consequently, the mixed layer becomes deeper and the thermocline begins to break down as shown. This period of downward mixing of surface water caused by surface cooling is called fall overturn. From Fig.2a, we found that between the end of December and early January, the temperature of water reaches 4°C. In early spring, the warming of the surface water causes it to become denser and hence induces downward mixing. And this period is spring overture. Similarly, between the end of April and early May, the temperature of water reaches 4°C.



(a) normal flow with natural temperature

(b) 7-days flood process in normal flow year with natural temperature



(c) 7-days flood with 8℃ process in normal flow year

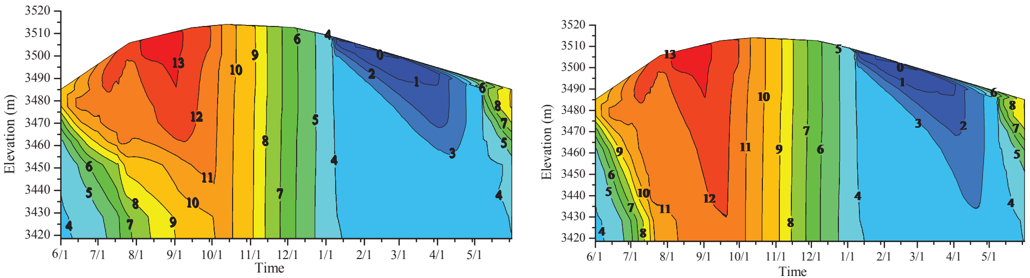
(d) temperature diffence between normal flow and 7-days flood with 8℃ process

Fig.2a-c temperature isoclines before dam site;
Fig.2d temperature difference isoclines between normal flow and 7-days flood with 8°C
(the centerline of the outlet in different cases are all at about EL.3477m)

In Fig.2b, only the discharge from Jul.17th to Jul.23th was changed, and the other parameters were consistent with the former. Fig.2b shows the temperature distribution is quite similar to Fig.2a, only during flood period the temperature distribution has some little differences. This means that in normal flow year, the flood during July exert little influence on the thermal structure when the centerline of the outlet is at about EL.3477m. During the flood period, the flood temperature is about 10.9°C, which is 2°C lower than the surface temperature, thus the inflow will insert in a certain level about 20m below the water surface in which the temperature is similar to flood temperature. In this case, the certain level is exactly same as the outlet location. As a consequence, the flood is directly along the certain level out of the reservoir. In the other word, a shortcut exists between the inflow and the outflow.

In Fig.2c, the flood temperature was taken as 8°C, leaving other inputs intact. As can be seen from Fig.2c, 7-days flood with 8°C cause thermocline erosion from Jul.18th to Aug.1st. Fig.2d shows the temperature differences between normal flow and 7-days flood with 8°C. During flood period, the maximum difference is up to 3.02°C at Jul.24th. And the effect range is above El.3464m, and has no effects on the hypolimnion. At the same time, we found that the effect time can last two months by up to the end of September.

Different Outlet Locations: In a reservoir, the outflow is released from one fixed outlet or several selective outlets at different depth. And that the location of outlet can exert an obvious effect on hydrodynamics of reservoirs has been recognized for a long time. To investigate the effect of outlet location, we simulated temperature distribution of by changing the outlet location. Fig.3a and Fig.3b show the temperature isoclines at the centerline of outlet elevation 3462m and 3440m, respectively. From Fig.2b, Fig.3a and Fig.3b, we can found that the outlet location is closer to bottom, the thermocline is deeper. And this phenomenon is obviously during summer and winter. The reason is that, when the outlet is closer to bottom, in summer, the withdrawal from the outlet is lower, thus the reservoir restores more heat from the radiation, so the temperature of the water column in reservoir will increase. On the contrary, during winter to early spring, because of the inversion structure in reservoir, the temperature of withdrawal from the outlet is higher, and hence, the reservoir release more heat and lead to the temperature of water column is decrease.



(a) the centerline of the outlet is at about EL.3462m

(b) the centerline of the outlet is at about EL.3440m

Fig.3 temperature isoclines before dam site in normal flow year with 7 days flood flow, flood temperature is the same as that of the normal flow year (a. the centerline of the outlet is at about EL.3462m; b. the centerline of the outlet is at about EL.3440m)

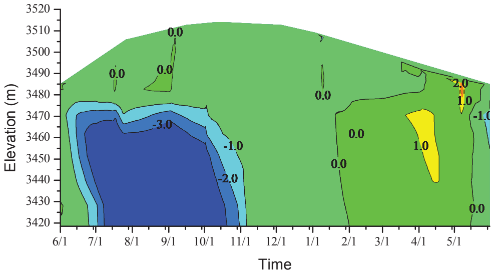


Fig.4 Temperature difference isoclines before dam site between two different outlet locations

Fig.4 shows the temperature difference isoclines between two different outlet locations, one is at EL.3477m, and the other is at EL.3440m. In Fig.4, the positive value notes the temperature of water when outlet location is at EL.3477m is higher than that outlet location is EL.3440m. As can be seen from Fig.4, only when the thermal structure is stratified, the temperature difference exists, and at the other time, the phenomenon does not exist.

Conclusions

The 3-D model of thermal-hydrodynamic described in this paper could provide realistic simulations of development of the thermal structure in the reservoir. Water column in YE reservoir have two overturning periods per year separated by periods of stratification. One occurs in fall, and the other is in spring.

In stratified reservoir, when the inflow temperature is lower than the surface temperature, if the inflow temperature is similar to outflow temperature, then inflow is directly along the certain level out of the reservoir, and inflow has no influence on the thermal structure. And if the temperature of flood is lower than that of the outflow, the flood will cause thermocline erosion to some extent.

In this paper, by changing the outlet location, the simulated results demonstrate that the outlet location is the main factor controlling the thermal structure in YE reservoir. When reservoir is stratified, the outlet location is closer to bottom, the thermocline is deeper.

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