



# Prediction of water temperature in stratified reservoir and effects on downstream irrigation area: A case study of Xiaohushan reservoir

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## ABSTRACT

With increasing concern in environmental and ecological protection, more studies have focused on solving the problems caused by dam. Large reservoirs often release low-temperature water in spring and summer, which have adverse effects on downstream ecosystem. The 3-D Environmental Fluid Dynamics Code (EFDC) and 1-D longitudinal stream temperature model were used in this paper, to predict the water temperature in reservoir and canal and analyze the effects on irrigation area. The results indicate that the affected area is within a 55 km distance mainly in the period between April and June. Some management and engineering measures should be adopted to reduce the impact.

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## 1. Introduction

Water temperature plays a critical role in aquatic environment. The deep water of a stratified reservoir is usually low-temperature and anoxic, it will cause the sediments decomposing to release heavy metals, phosphate and toxic substance, etc. The aquatic ecosystem, water quality and crops will be influenced by the cool water releasing from the reservoir.

Given the importance of water temperature's role in ecosystem, there has been growing interest in simulating water temperature and analyzing the impact. [Yearsley \(2009\)](#) developed a one-dimensional stream temperature model and analyzed the impact of climate changes on stream temperature in the Columbia River system. Improvements to existing forecast models and semi-weekly 10-day water temperature forecasts have been made during the salmon migration season ([Morrison and Foreman, 2005](#)). [Bonnet et al. \(2000\)](#) designed a numerical model of the hydrodynamic and thermal structure of an artificial lake, which was developed as a basis for an ecological water-quality model and it is applied to discuss the impact of withdraw level of a reservoir. [Gu et al. \(1999\)](#) studied the weather-dependent flow requirements for summer river temperature control by quantitative temperature–flow relationships. The study result of [Gu et al. \(1993\)](#) showed that the cold water from reservoir affect the early rice most, late rice followed.

We usually use one-dimensional water temperature model to calculate river temperature, two or three-dimensional model to simulate lake and reservoir temperature. However, for large water, three-dimensional model is time consuming and uneconomic. So

in general case, two-dimensional water temperature model can well simulate the flow field and temperature field of a reservoir.

This study simulates the vertical distribution of water temperature in Xiaohushan reservoir which is planning to be built, and predicts the re-warming process along the downstream river and irrigation canal. And then analysis of the effects on downstream irrigation areas has been made.

## 2. Model description

The water temperature simulating calculation has two steps: reservoir simulation and channel simulation. Environmental Fluid Dynamic Code (EFDC) is adopted to calculate the water temperature in reservoir, and then 1-D longitudinal stream temperature model is used for calculating water temperature in channel.

### 2.1. EFDC model

The EFDC model was initially developed by Virginia Institute of Marine Science, and subsequently sponsored by US EPA. It is a general purpose modeling package for simulating one, two, three-dimensional flow, transport, and biogeochemical processes in surface water systems including lakes, reservoirs, rivers, estuaries, wetlands, and coastal region ([Sangman et al., 2010](#)).

Compared with other simulation systems, advantages of EFDC model is obvious. For example, the coordinate transformation of EFDC can well fit the actual terrain and free water surface, users can select 1D, 2DV, 2DH or 3D function by modify parameters, the output data of EFDC has a wide range of application. Especially, the simulation precision of hydrodynamics components has reached a very high level.

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### 2.1.1. Governing equations

The hydrodynamic equations are based on 3-D boundary layer turbulent equations. To accommodate realistic boundaries, the EFDC model uses a stretched or sigma vertical coordinate and Cartesian or curvilinear, orthogonal horizontal coordinates (Craig, 2005). The momentum and transformation equations are:

$$\partial_t(m_x m_y H u) + A(u) - m_x m_y f_e H v = -m_y H \partial_x(p + gH + gz_b^*) + m_y(\partial_x z_b^* + z \partial_x H) \partial_x p + m_x m_y \partial_z(H^{-1} A_v \partial_z u) + Q_u \quad (1)$$

$$\partial_t(m_x m_y H v) + A(v) - m_x m_y f_e H u = -m_x H \partial_y(p + gH + gz_b^*) + m_x(\partial_y z_b^* + z \partial_y H) \partial_y p + m_x m_y \partial_z(H^{-1} K_v \partial_z v) + Q_v \quad (2)$$

$$\partial_z p = -gH_b = -gH(\rho - \rho_0)\rho_0^{-1} \quad (3)$$

$$\partial_t(m_x m_y H) + \partial_x(m_y H u) + \partial_y(m_x H v) + \partial_z(m_x m_y w) = Q_H \quad (4)$$

where

$$A_\psi = (m_y H u \psi) + \partial_y(m_x H v \psi) + \partial_z(m_x m_y w \psi) \quad (5)$$

$$m_x m_y f_e = m_x m_y f - u \partial_y m_x + v \partial_x m_y \quad (6)$$

where  $u$  and  $v$  are the horizontal velocities in the curvilinear-orthogonal horizontal coordinates  $(x, y)$ ,  $w$  is the vertical velocity in the stretched vertical coordinate  $z$ ,  $p$  is the kinematic excess pressure above the reference density,  $\rho_0$ , hydrostatic pressure,  $z_s^*$  is the free surface elevation,  $z_b^*$  is the bottom bed elevation,  $H(= z_s^* - z_b^*)$  is the total water column depth, and  $kV$  is the turbulent viscosity.  $f$  is the actual Coriolis parameter and  $f_e$  is the effective Coriolis parameter.  $Q_u$  and  $Q_v$  represent additional momentum sources and sinks. The source term  $Q_H$  in the continuity Eq. (4) is used to represent direct rainfall, evaporation, groundwater interaction, water withdrawals. Eq. (3) is the vertical hydrostatic pressure balance in terms of the kinematic excess pressure and the buoyancy variable  $b$  (Hamrick and Mills, 2000).

The transport equation in EFDC for temperature is:

$$\partial_t(m_x m_y H T) + A(T) = m_x m_y \partial_z(H^{-1} K_b \partial_z T + \sigma T) + m_x m_y H R_T + S_T \quad (7)$$

where  $K_b$  is the vertical turbulent or eddy diffusivity,  $\sigma$  is a positive settling velocity. Reactive sources and sinks are represented by  $R_T$ . The term  $S_T$  includes the horizontal thermal turbulent diffusion and external sources and sinks, the thermal calculation is listed in Section 2.1.2.

The solution of Eqs. (1)–(4) and (7) requires specification of the vertical turbulent viscosity and diffusivity, horizontal and vertical boundary conditions, and the source and sink terms. To provide the vertical turbulent viscosity and diffusivity, the second moment turbulence closure model (Mellor and Yamada, 1982; Galperin et al., 1988) is used.

**Table 2**

Meteorological data recording near the reservoir (multi-years average).

|                                | January | February | March  | April  | May   | June   | July   | August | September | October | November | December |
|--------------------------------|---------|----------|--------|--------|-------|--------|--------|--------|-----------|---------|----------|----------|
| Air temperature (°C)           | 3.5     | 5.1      | 9.8    | 16     | 21.2  | 25.2   | 28.8   | 28.6   | 23.7      | 18      | 11.9     | 6        |
| Radiation (MJ/m <sup>2</sup> ) | 204     | 253      | 375    | 392    | 453   | 509    | 545    | 383    | 276       | 314     | 229      | 252      |
| Relative humidity (%)          | 74      | 81       | 77     | 80     | 78    | 82     | 80     | 77     | 78        | 73      | 70       | 67       |
| Wind speed (m/s)               | 3.4     | 3.6      | 3.2    | 3.5    | 2.9   | 2.8    | 2.6    | 3.1    | 2.9       | 2.7     | 3        | 3.1      |
| Air pressure (hpa)             | 1024.6  | 1022.4   | 1018.1 | 1012.8 | 1008  | 1003.7 | 1001.5 | 1003.2 | 1010.5    | 1017.3  | 1022.2   | 1024.6   |
| Precipitation (mm)             | 37.5    | 68.3     | 116.6  | 169.3  | 188.5 | 234    | 184.6  | 120.4  | 94.7      | 74.2    | 60.8     | 36.1     |
| Evaporation (mm)               | 88      | 78       | 98     | 123    | 161   | 161    | 199    | 209    | 148       | 125     | 91       | 98       |
| Wind direction                 | 2       | 2        | 2      | 2      | 2     | 2      | 6      | 7      | 15        | 1       | 2        | 2        |
| Cloudiness (%)                 | 59      | 76       | 75     | 74     | 72    | 77     | 70     | 61     | 63        | 48      | 56       | 55       |

### 2.1.2. The heat fluxes calculation

The heat fluxes calculation in EFDC model are based on the NOAA Geophysical Fluid Dynamic Laboratory's atmospheric heat exchange formulation (Rosati and Miyakoda, 1988).

#### (1) Solar shortwave radiation

$$\Phi_I = 1 * [(F * e^{SF * H * (z-1)}) + (1 - F) * e^{SS * H * (z-1)}] \quad (8)$$

In this equation,  $I$  is the incident shortwave solar radiation at the water surface ( $W/m^2$ ),  $F$  is a distribution fraction between zero and one,  $SF$  and  $SS$  are fast and slow scale attenuation coefficients ( $1/m$ ), at the bottom,  $z = 0$ , and free surface,  $z = 1$ .

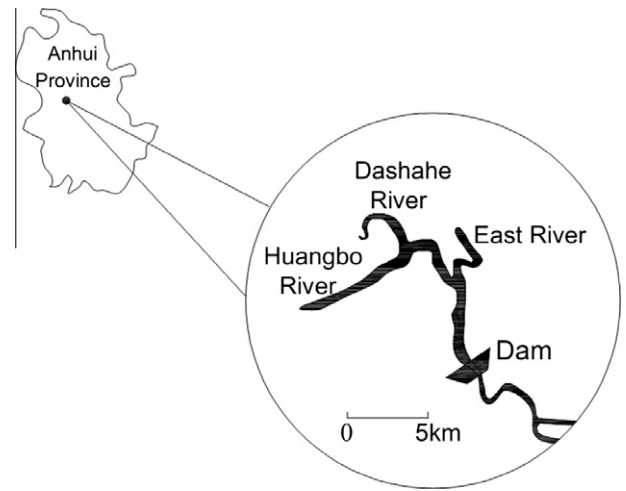
#### (2) Longwave radiation

$$\Phi_G = \varepsilon \sigma T_s^4 (0.39 - 0.05 e_a^{0.5}) (1 - B_c C_c) \quad (9)$$

where  $\sigma$  is Stefan–Boltzman constant,  $\varepsilon$  is the emissivity,  $T_s$  and  $T_a$  are the water surface and atmospheric temperatures,  $e_a$  is the atmospheric vapor pressure in millibars,  $B_c$  is an empirical constant equal to 0.8,  $C_c$  is the fractional cloud cover.

#### (3) Reflected longwave radiation by water surface

$$\Phi_S = 4 \varepsilon \sigma T_s^3 (T_s - T_a) \quad (10)$$



**Fig. 1.** The location of Xiahushan reservoir.

**Table 1**

Morphometric characters of Xiahushan reservoir.

|                         |                                |
|-------------------------|--------------------------------|
| Normal storage level    | 115 m                          |
| Normal storage capacity | $1.72 \times 10^8 \text{ m}^3$ |
| Maximum depth           | 59 m                           |
| Reservoir length        | 21 km                          |
| Tributaries             | 2                              |

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