Spatio-temporal variability in the thermal regimes of the Danjiangkou reservoir and its downstream river due to the large water diversion project system in central China
Pan Chen, Lan Li and Hongbin Zhang

ABSTRACT
Understanding water temperature variation in regulated rivers and reservoirs becomes increasingly important as the environment and ecosystem are approaching their thermal limits. In this paper, a multi-model approach is used to quantitatively access the spatio-temporal change in thermal structures of the Danjiangkou reservoir and its downstream river. The area is subject to thermal and hydrological alterations due to three large water diversion projects and related auxiliary projects, including a project to heighten the Danjiangkou dam and two small downstream reservoirs. It is found that the Danjiangkou dam heightening project alters water temperature seasonally, increasing it in winter and decreasing it in summer; while the three large water diversion projects and the two small downstream reservoirs mitigate the effect. Water temperature change in the downstream river is also studied from the aspects of release temperature and release discharge of the Danjiangkou reservoir. The former mainly changes the water temperature near the dam, while the latter affects the recovery rate and the recuperation distance. Ecological impact of the water temperature change is discussed based on the spawning of fish, indicating that the spawning periods may lag behind and the optimal spawning locations may move downstream.

Key words | Danjiangkou reservoir, ecological impact, large water diversion project system, spatio-temporal variability, thermal regimes, water temperature

INTRODUCTION
Water temperature is one of the most significant physical variables of water bodies affecting most water quality characteristics (Cluis 1972; Albek & Albek 2009; Hadzima-Nyarko et al. 2014). In addition, it plays an important role in the biological cycles of many aquatic organisms and changes in species composition (Watanabe 1998; Politano et al. 2008; Rayne et al. 2008; Hilderbrand et al. 2014). Generally, humans have changed the thermal structures in reservoirs and rivers by undertaking water conservancy projects, which may have an adverse influence on the environment and ecosystem (Smith 1975; Preece & Jones 2002). Hence, much attention has been paid to the influence of these projects on the water temperature distribution in reservoirs and the thermal regime in rivers (Webb & Walling 1993; Preece & Jones 2002). Previous studies have mainly focused on the effect of a single project such as a reservoir or a water diversion project (Meier et al. 2005; Khangaonkar & Yang 2008; Wang 2013). In fact, many reservoirs and river reaches are subject to multi-source thermal disturbances caused by several projects (Prats et al. 2010), but the effects of different sources of thermal disturbances have rarely been reported in the literature (Prats et al. 2012). Therefore, it is necessary to analyze the water temperature change caused by a series of projects in order to better understand their effects on the environment and guide project operation and water resources management in the future.

The causes of water temperature change due to water conservancy projects need to be researched in order to accurately...
evaluate and predict their effects on thermal regimes of water bodies. Many studies have discussed the water temperature variation of the downstream river caused by relevant projects with a reservoir from the aspects of either the release temperature or the release discharge. If thermal stratification occurs, water from deep-release reservoirs cools the river in summer and warms it in winter (Null et al. 2013). In addition, different operations of reservoirs can alter water temperature regimes because they change the release discharge and then affect thermal inertia in the river (Carron & Rajaram 2001; Meier et al. 2005; Khangaonkar & Yang 2008). However, these studies focused only on the direct effect due to these projects and ignored the indirect effect due to the thermal structure variation of the reservoirs. For example, when the influence on downstream river temperature by water diversion projects from the reservoirs is analyzed, it is often the effect of reduction in discharge (direct effect) that is considered. In fact, reducing discharge may change the thermal structure in the reservoir, affecting the release temperature and impacting the thermal regimes of the receiving rivers and streams (indirect effect). Therefore, both the water temperature structure in the reservoir and its downstream rivers should be studied to obtain a comprehensive and reasonable evaluation of the water temperature change in the river.

To quantify water temperature alterations caused by water conservancy projects, previous studies often used the concept of recuperation distance, which represents the distance needed to recover to natural state (Herb & Stefan 2011; Prats et al. 2012). In fact, recuperation distance is usually obtained based on some assumptions and simplifications, and cannot represent the real situation. In the study, recuperation distance is calculated based on the assumption that when the influence of release temperature from a reservoir on the stream temperature downstream is less than or equal to 5%, the river reaches its natural state. The advantage of the approach is that the calculation is simple as the stream temperature does not need to be obtained first.

Simulation and forecasting water temperature would substantially enhance analyzing the ecological impact of water conservancy projects. Previous studies have suggested that water temperature change will influence fish habitats in the river (Preece & Jones 2002; Bartholow et al. 2004) and agricultural activities in surrounding regions due to cool water release from deep reservoirs (Yang et al. 2012). Some indexes are used in these studies to assess whether the change is biologically critical. For example, Bartholow et al. (2004) used indexes including temperature degree-days, annual exposure, and macro-habitat suitability as relative guidelines to reveal biologically relevant differences between scenarios. As well, spawning opportunities index, which is the ratio of the time of water temperature above the minimum water temperature requirement for spawning against the whole spawning period, was applied to qualitatively evaluate Keepit Dam’s ecological influence (Preece & Jones 2002). In this study, two indexes, including spawning opportunities index and the time to reach the minimum threshold for spawning are used to assess the possible ecological impact as they can judge spatial and temporal effects of the water temperature variation, respectively.

Danjiangkou reservoir and its downstream river is a typical system subject to multi-source thermal disturbances, including three large water diversion projects and related auxiliary projects. In this study, a series of scenario simulations involving different project operations are carried out based on a multi-model approach. The Environmental Fluid Dynamics Code (EFDC) model, which includes three-dimensional (3-D) hydrodynamic and water quality modules (Hamrick et al. 1999; Jeong et al. 2010), is used to simulate reservoir temperatures. In addition, an analytical solution model based on the equilibrium temperature concept (ETM) model is used to estimate stream temperatures. ETM is a simple approach to estimate monthly average water temperature downstream of the dam based on monthly average release temperature, air temperature, and flow volume. More details about the ETM model are given in the section ‘Modeling approach’. The main objectives of this study are: (1) to quantitatively evaluate the thermal temporal-spatial change of the Danjiangkou dam and its downstream river; (2) to analyze the causes of the thermal regime change in the downstream river; and (3) to predict the ecological impact based on fish spawning due to these projects.

**DATA AND METHODS**

**Study area**

The study area includes Danjiangkou reservoir and its downstream river (Figure 1). The Danjiangkou reservoir...
(32°36′–33°48′N; 110°59′–111°49′E) is located on the borders of the Hubei province and Henan province, China. Its drainage area of approximately 95,000 km² includes the upper Han River and the Dan River with backwater lengths of 177 km and 80 km, respectively (Zhang et al. 2013). During flooding periods (May to September), its outflow includes two parts, i.e., the water used for hydropower and surplus water from the overflow weir. Hence, the release temperature is affected by the temperature of both parts from May to September. The bottom elevation and the height of hydropower intake are 115.0 m and 7.5 m, respectively. The bottom elevation of the overflow weir is 138 m. The study stream reach downstream from Danjiangkou reservoir involves the middle and lower reaches of Han
River, totaling 650 km. The study area has a north sub-tropical monsoon climate with rapid and severe climate transitions. Annual mean temperature is 15–16°C. Precipitation is subject to large inter-annual variability, with 800–1,000 mm yr⁻¹, of which 80% is concentrated between May and September (Li et al. 2008).

The Danjiangkou dam was heightened in 2010, from 157.0 to 170.0 m, as a precursor to the large water transfer projects that followed. Currently, there are three long-distance water transfer projects being developed in the study area. The first is the South-to-North Water Transfer Project, which was completed at the end of 2014. 9.5 × 10⁹ m³ of water are extracted every year from the Danjiangkou reservoir and delivered to Beijing, Tianjing, and other cities along the water transfer route. The second is the Ebei Water Transfer Project, with construction about to start in 2015. This will transfer 1.398 × 10⁹ m³ of water per year from the reservoir to the Ebei area. The third is Han River-to-Wei River Water Transfer Project, which is scheduled for completion in 2015. It will deliver 1 × 10⁹ m³ of water yearly from the Han River upstream of the Danjiangkou reservoir to the Wei River. To control the effect of these water diversion projects on the hydrological regime variability downstream of the Danjiangkou reservoir, there are two small reservoirs, finished in 2000 and 2010, respectively, known as Wangfuzhou and Cuijiaying. The two reservoirs are located 30 km and 134 km downstream from the Danjiangkou reservoir, respectively. Table 1 shows the physical characteristics of the two small reservoirs, alongside those of the Danjiangkou reservoir before and after heightening.

Four species of Chinese carp, including Mylopharyngodon piceus, Clenopharyngodon idellus, Hypophthalmichthys molitrix, and Aristichthys nobilis, are widely distributed in the middle reaches of the Han River (Danjiangkou reservoir to Zhongxiang City). There are five spawning sites accounting for 36.22% of the length of this reach (Li et al. 2006). The minimum temperature threshold for spawning in these species is 18°C and the breeding period runs from late May to early August (Shi & Huang 2009). As water temperature variation due to these conservancy projects has affected fish habitats in the study reach, these fish can be used as a marker of ecological impact in the study.

Data source

For the study, topographical, reservoir operation, hydrological and meteorological data have been collected. The first three kinds of data were directly provided by the Yangtze River Water Resources Commission, and the last by the National Climate Centre (NCC) of China Meteorological Administration (CMA) and downloaded from the website: http://cdc.nmic.cn/.

Water temperature was monitored in the Danjiangkou reservoir during the period from 1969 to 1980. A monitoring section was set 200 m upstream from the dam, which consisted of six or seven vertical profiles, each containing nine to 16 measuring points. The distance between adjacent profiles was 110 m. Vertical profiles consisted of observation at several fixed water depths, including surface, 0.1, 0.5, 1.0, 2.0, 3.0, 5.0, 10.0, 15.0, 20.0, 25.0, 30.0, 35.0, 40.0, 50.0, 60.0 m, and bottom. The monitoring section recorded the water temperature variation of the whole cross section from the surface to the bottom and from the left bank to the right bank. Figure 2(a) shows the spatial distribution of the water temperature at the cross section on 15 August 1970. The section was observed once monthly at 8:00 a.m. on the 15th of the month. Another vertical profile, 50.0 m upstream from the dam, was also arranged for supplemental measurements and observed three to six times a month. This profile was close to the hydropower intake and hence could record its temperature variations. Figure 2(b) showed the water temperature variation at the hydropower intake during the period from 04/1973 to 05/1974. Therefore, these measurements recorded spatial and temporal variations of water temperature upstream of the dam. Water temperature was collected using a 95A semiconductor thermometer within ±0.1°C of the true water temperature. The probe was cleaned and calibrated against a reference thermometer three or four times a year.

Table 1 | Physical characteristics of the three reservoirs in the study area

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Normal water level, m</th>
<th>Utilizable capacity, 10⁹ m³</th>
<th>Hydropower capacity, MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Danjiangkou (heightened)</td>
<td>157 (170)</td>
<td>17,450 (29,050)</td>
<td>900</td>
</tr>
<tr>
<td>Wangfuzhou</td>
<td>86.23</td>
<td>150</td>
<td>109</td>
</tr>
<tr>
<td>Cuijiaying</td>
<td>62.73</td>
<td>245</td>
<td>96</td>
</tr>
</tbody>
</table>
There were two hydrological stations in the upstream of Danjiangkou reservoir, i.e., Baihe and Zijingguan, and four hydrological stations in the study reach, i.e., Huangjiagang, Xiangyang, Zhuandouwan, and Nianpanshan, that recorded water temperature, water level, and flow at 8:00 a.m. each day during the period from 1969 to 1980 (Figure 3). Water temperature measurements were collected at the depth of 0.5 m near the base water gauge using a 591 frame type thermometer within ±0.2°C of the true values. Water level was measured utilizing water gauge near the river bank and flow was measured utilizing current meter method. The reported monthly averages were calculated based on these records.

Modeling approach

Thermal structure in the Danjiangkou reservoir is modeled with a 3-D EFDC model, and stream temperatures in the downstream river are calculated using ETM model. Results (the release temperatures) from the EFDC model are used as the input of ETM model to estimate stream temperatures.

Reservoir water temperature model

The model is a general purpose modeling package for simulating 1-D, 2-D, and 3-D flow, transport, and biogeochemical processes, initially developed by Virginia Institute of Marine Science, and subsequently developed by the US Army Corps of Engineers sponsored by the US EPA (Jeong et al. 2010). It has been used extensively to simulate hydrodynamic and water quality variations in rivers, lakes, reservoirs, wetlands, estuaries, and coastal regions integrated with a water-column eutrophication model (Park et al. 2005; Luo & Li 2009). The EFDC model is selected in this study because it can well simulate thermal structure in deep reservoirs.
Water temperature is modeled using the 3-D form of the advection–dispersion equation:

\[
\frac{\partial}{\partial t} \left( m_x m_y H T \right) + \frac{\partial}{\partial x} \left( m_x H u T \right) + \frac{\partial}{\partial y} \left( m_x H v T \right) + \frac{\partial}{\partial z} \left( m_x m_y \omega T \right) \\
= \frac{\partial}{\partial x} \left( \frac{m_x A_x}{m_x} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{m_x A_y}{m_y} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( m_x m_y \frac{A_z}{H} \frac{\partial T}{\partial z} \right) + m_x m_y H S_T
\]

where \( T \) is water temperature (°C); \( u, v, \) and \( \omega \) are velocity components (m s\(^{-1}\)) in the curvilinear, orthogonal coordinates, \( x, y, \) and \( z \)-directions, respectively; \( A_x, A_y, \) and \( A_z \) are turbulent diffusivities (m\(^2\) s\(^{-1}\)) in the \( x, y, \) and \( z \)-directions, respectively; \( S_T \) is source and sink terms per unit volume (°C s\(^{-1}\)); \( H \) is water column depth (m); and \( m_x, m_y \) are horizontal curvilinear coordinate scale factors.

In Equation (1), on the left-hand side, the first term is local acceleration term and the last three terms are the advective transport terms; on the right-hand side, the first three terms account for the diffusive transport and the last term represents the kinetic processes and external loads for each of the state variables. The kinetic equation is

Figure 3 | Monthly water temperature (a), flow (b), and water level (c) during the period from 1969 to 1980.
solved using a second-order accurate trapezoidal Crank-Nicholson scheme (Park et al. 2005). The calculation of the heat fluxes (source terms) is based on the NOAA Geophysical Fluid Dynamic Laboratory’s atmospheric heat exchange formulation (Rosati & Miyakoda 1988; Yang et al. 2012):

\[ \Phi = \Phi_I - (\Phi_B + \Phi_C + L \Phi_e) \]  

(2)

\[ \Phi_I = I \times [(F \times e^{-B_c H_f(x-1)} + (1 - F) \times e^{-C_c H_f(x-1)})] \]  

(3)

\[ \Phi_B = \varepsilon \sigma T_a^4 (0.39 - 0.05 e^{0.5}) (1 - B_c C_c) \]  

\[ + 4 \varepsilon \sigma T_e^4 (T_e - T_a) \]  

(4)

\[ \Phi_C = \rho_a c_a \sqrt{U_w^2 + V_w^2} (e_{sa} - R_h e_{sa})(0.622 p_a^{-1}) \]  

(5)

\[ \Phi_e = \rho_a c_p c_h \sqrt{U_w^2 + V_w^2} (T_e - T_a) \]  

(6)

where \( \Phi \) is the net surface heat flux; \( \Phi_I \) is the solar shortwave radiation; \( \Phi_B \) is the net longwave radiation; \( \Phi_C \) is the convective heat flux; \( L \) is the latent heat of evaporation; \( \Phi_e \) is the evaporation heat flux; \( I \) is the downward flux of solar radiation at the water surface \( (W \text{ m}^{-2}) \); \( F \) is a distribution fraction between 0 and 1, for thermal processes, which is determined by model calibration in the EFDC model; SF and SS are fast and slow scale attenuation coefficients \( (\text{m}^{-1}) \), respectively; at the bottom, \( z = 0 \), and free surface, \( z = 1 \); \( \varepsilon \) is the emissivity \((0.97)\); \( \sigma \) is Stefan–Boltzmann constant \((5.67 \times 10^{-8} \text{ J} \text{ m}^{-2} \text{ s}^{-1} \text{ K}^{-4})\); \( T_e \) and \( T_a \) are the water surface and air temperatures \( (\text{C}) \), respectively; \( e_{sa} \) is the vapor pressure \( (\text{mb}) \); \( B_c \) is an empirical constant equal to 0.8; \( C_c \) is the fractional cloud cover; \( \rho_a \) is the air density \((1.2 \times 10^{-3} \text{ g} \text{ cm}^{-3})\); \( c_a \) and \( c_h \) are dimensionless evaporation and convective transfer coefficient on the order of \( 10^{-3} \) in magnitude, respectively; \( U_w \) and \( V_w \) are the components of the wind velocity at 10.0 m above the water surface; \( e_{sa} \) and \( e_{sa} \) are the saturation vapor pressures \( (\text{mb}) \) corresponding to the water surface and air temperatures, respectively; \( R_h \) is the fractional relative humidity; \( p_a \) is the surface air pressure \( (\text{mb}) \); and \( c_p \) is the specific heat capacity \((1.005 \times 10^3 \text{ J} \text{ kg}^{-1} \text{ K}^{-1})\).

**Stream temperature model**

ETM is a physically based model, which estimates stream temperatures using equilibrium temperature theory on the basis of air temperature, flow volume, water temperature, and stream morphology information. The model derives from the advection–dispersion-heat balance equations after assuming steady state condition, complete vertical and lateral mixing in river cross sections, advection dominating over dispersion (longitudinal) (Walters et al. 2000; Wright et al. 2009) as follows:

\[ \frac{Q}{A} \frac{dT}{dx} = \frac{H_f}{\rho C_p D} \]  

(7)

where \( T \) is water temperature \( (\text{C}) \); \( Q \) is river discharge \( (\text{m}^3 \text{ s}^{-1}) \); \( A \) is cross-sectional area \( (\text{m}^2) \); \( D \) is mean flow depth \( (\text{m}) \); \( \rho \) is water density \((1,000 \text{ kg} \text{ m}^{-3})\); \( C_p \) is heat capacity of water \((4,185 \text{ J} \text{ kg}^{-1} \text{ C}^{-1})\); and \( H_f \) is the net rate of heat exchange across the water surface \( (W \text{ m}^{-2}) \). This net heat flux can be linearized as a function of equilibrium temperature by assuming that the net rate of heat exchange is proportional to the departure from the temperature equilibrium (Bustillo et al. 2014):

\[ H_f = K_e (T_e - T) \]  

(8)

where \( T_e \) is equilibrium temperature \( (\text{C}) \), defined as the water temperature at which the net rate of heat exchange at the water body interface is 0. \( K_e \) is an overall heat exchange coefficient \( (W \text{ m}^{-2} \text{ C}^{-1}) \) related to air temperature, wind speed, and relative humidity. Substituting \( H_f \) from Equation (8) into Equation (7) and solving the differential equation gives an equation for stream temperature:

\[ T = T_e + (T_0 - T_e) \exp \left( -\frac{K_e A x}{\rho C_p D Q} \right) \]  

(9)

where \( T_0 \) is the temperature at the upstream boundary \( (\text{C}) \).

Many previous studies to model river water temperature using the equilibrium temperature concept have considered \( K_e \) as a constant, yielding satisfactory model performance (Maré & Armengol 2008; Bustillo et al. 2014). Therefore, we also considered \( K_e \) as a single-valued adjustable
parameter in this study. By contrast, $T_e$ cannot be considered as a constant, so we calculated $T_e$ based on the linear relationship between equilibrium and air temperature ($T_a$) (Caissie et al. 2003):

$$T_e = a_e T_a + b_e$$  (10)

where $a_e$ and $b_e$ are regression coefficient parameters between $T_e$ and $T_a$. Figure 4 shows a comparison between monthly water temperature and monthly air temperature at Huangjiagang and Nianphanshan stations. The correlation is stronger at the Nianphanshan station, which indicates that monthly water temperature is quite close to monthly equilibrium temperature at the monitoring position far away from the dam. Therefore, we can determine the initial values of $a_e$ and $b_e$ through the linear relationship between downstream water temperatures, which are not affected by the dam, with air temperature. The final parameters can be determined from the observed data.

**Numerical grid**

In the study, the EFDC model uses the horizontally curvi-linear orthogonal grid. Grid sensitivity analysis indicates that model performance is better with finer grid. However, this would inevitably result in more computational cost. As a trade-off between the accuracy and efficiency, the grid map in Figure 5 is selected. It consists of 1,500 cells horizontally, with the cell size ranging from 0.2 to 1.7 km. Furthermore, 40 layers are considered vertically.

**Model initialization**

The EFDC model operates on a 4-minute time step, although daily input and output data are used. Initial conditions of the model include surface water level at the reservoir, and boundary conditions include reservoir inflow and water temperature at inlet, and outflow at outlet. The position of inlet boundary is determined by reservoir flood analysis. A uniform velocity distribution is assumed at the inlet. Dirichlet boundary condition is used for flow field calculation at the inlet and outlet boundary, and water temperature calculation at the inlet boundary. In detail, the discharge and water temperature at Baihe and Zijingguan hydrological stations are used as the inlet boundary condition of the upper Han River and Dan River, respectively. As well, the release discharge of Danjiangkou reservoir is used as the outlet boundary condition to provide the information of different outflow positions in the vertical direction, including hydropower intake and overflow weir. The calculated output temperatures include the temperature of hydropower intake and overflow weir. These temperatures are obtained through taking an average of corresponding vertical layer at two locations.

The ETM model is implemented on a monthly time scale along the river which is discretized by 1 km cells in this study. Boundary conditions of the ETM model include stream inflow and water temperature at inlet. In detail, the calculated release temperature and observed release discharge are used as the inlet boundary condition. The release temperature of the Danjiangkou reservoir is on a
daily time scale and hence its average monthly values are finally used as input of the ETM model.

**Simulation scenarios and input data**

To quantitatively analyze the influence of the large water diversion projects, the Danjiangkou dam heightening project, and the two small reservoirs downstream, on the thermal structures in the Danjiangkou reservoir and its downstream river, four scenario simulations are carried out using a multi-model approach, including EFDC and ETM models. The first scenario (S1) is the reference situation, which does not consider the effect of any of the projects. The second scenario (S2) just considers the effect of heightening the Danjiangkou dam. Both dam heightening project and large water diversion projects are taken into account in the third scenario (S3). The fourth scenario (S4) is comprehensive, considering the influence of all the above projects, including the project to heighten the Danjiangkou dam, large water diversion projects, and two small reservoirs downstream.

The inputs of the two models include meteorological data, hydrological data, and water temperature. For different scenarios, the meteorological data are the same, while the other two are different. The meteorological input and the simulated output of the two models are shown in Table 2, while the hydrological and water temperature inputs at the four scenarios are shown in Table 3. For the EFDC model, all these data are measured and needed as inputs. As well, these hydrological and water temperature data are regarded as the initial and boundary conditions of the EFDC model. The values of the boundary conditions used at four simulation scenarios are shown in Figure 6. For the ETM model, the inflow water temperature is the reservoir release temperature calculated by EFDC model, and stream inflow discharge and the normal water levels at two small reservoirs are measured. Table 3 and Figure 6 show that the main differences are the surface water elevation in the Danjiangkou reservoir between S1 and S2, the inflow and outflow of the reservoir between S2 and S3, and the normal water level of Wangfuzhou and Cuijiaying reservoirs between S3 and S4. Noticeably, the outflow of EFDC model at S3 and S4 includes the release water from the Danjiangkou reservoir and diversion water from the South-to-North Water Transfer Project and Ebei Water Transfer Project. For S4, as the two small reservoirs have typical river-type, low-head stream-flow hydroelectric plants, it is assumed that the area is vertically mixing and thus simulated by a 1-D analytical solution.

**Model calibration and validation**

The EFDC model parameters, mainly for thermal processes were calibrated by field data of water temperature collected from the Danjiangkou reservoir during three hydrological years, a wet year (04/1974–03/1975), a normal year (04/1970–03/1971), and a dry year (04/1977–03/1978). Water temperature measurements were compared with the simulated values at the corresponding vertical layer. Hydrological guarantee rate of the flow for the three hydrological years were $P = 25\%$, $P = 50\%$, and $P = 75\%$, respectively. A comparison of the meteorological conditions

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**Table 2 | Model meteorological input and simulated output**

<table>
<thead>
<tr>
<th>Model</th>
<th>Meteorological input</th>
<th>Simulated output</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFDC</td>
<td>Daily air pressure, air temperature, percent relative humidity, precipitation, wind speed, wind direction, evaporation, total incident solar radiation, cloud cover</td>
<td>Reservoir water temperature</td>
</tr>
<tr>
<td>ETM</td>
<td>Monthly air temperature</td>
<td>Stream water temperature</td>
</tr>
</tbody>
</table>

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*Figure 5 | Grid map for Danjiangkou reservoir.*
is shown in Figure 7. The intra-annual variation patterns of the precipitation and air temperature were similar, with heavier rain and higher temperature in summer than in winter. The mean annual temperature was 15.0 °C, 15.1 °C, and 15.5 °C for wet, normal, and dry year, respectively, indicating small temperature differences among the three hydrological years. However, annual precipitation showed very significant differences, and the values were 1,014, 764, and 526 mm in the 3 years. This suggested that the selected hydrological years could represent both average and extreme weather situations. The model was validated with the measured temperature data for another three hydrological years, a wet year (04/1975–03/1976), normal year (04/1973–03/1974), and dry year (04/1978–03/1979).

Equation (9) used river morphology information to calculate the downstream water depth (D) and water temperature (T). Cross sections at Huangjiagang and Nianpanshan hydrological stations and river bed elevation of 1 km resolution along the study reach were available regarding river morphology. This led to the empirical relationships used thereafter that relate the mean river depth (D) with the river discharge (Q): 

\[ D = 3.03 \times Q^{0.11} \quad (R^2 = 0.95) \]

and mean flow velocity (v) with the river discharge (Q): 

\[ v = 0.0013 \times Q^{0.81} \quad (R^2 = 0.98) \]

These relationships could then be used to calculate river water temperature. The ETM model used the same calibration and validation periods as the EFDC model. During the periods, hydrological data were used as inputs for the stream temperature model. Monthly water temperatures at four hydrological stations (Huangjiagang, Xiangyang, Zhuandouwan, and Nianpanshan) were used to calibrate the model parameters, regression coefficient parameters \(a_v\) and \(b_v\), and heat exchange coefficient \(K_v\), and validate the modeling results.

Model performance was assessed with mean signed error (MSE), mean absolute error (MAE), and root mean square error (RMSE):

\[
	ext{MSE} = \frac{\sum (P_i - Q_i)}{n} \quad (11)
\]

\[
	ext{MAE} = \frac{\sum |P_i - Q_i|}{n} \quad (12)
\]

\[
\text{RMSE} = \sqrt{\frac{\sum (P_i - Q_i)^2}{n}} \quad (13)
\]
where $P_i$ and $Q_i$ are predicted and observed values of water temperature at the Danjiangkou reservoir and its downstream river, and $n$ is the number of observations.

**Scale factor and recuperation distance**

Equation (9) can be expressed as:

$$T = C_x T_0 + (1 - C_x) T_e$$

(14)

with

$$C_x = \exp \left( -\frac{K_x A x}{\rho C_p D Q} \right)$$

(15)

where $C_x$ is the scale factor which reflects the influence of $T_0$ and $T_e$ on stream water temperature.

Equation (14) can quantitatively distinguish the impact of the release temperature of the dam ($C_x T_0$) and the equilibrium temperature $(1 - C_x) T_e$. The former part reflects the effect of human disturbance from the dam, while the latter represents the influence of meteorological conditions, as equilibrium temperature is a function of air temperature. This study mainly focuses on the effect of human disturbance ($C_x T_0$), and therefore the meteorological conditions remain constant for different scenarios.

For a smaller $C_x$, the influence of $T_e$ is much larger according to Equation (14), which indicates that it is much easier to reach natural state at a given position ($x$). Therefore, $C_x$ can be regarded as an indicator of recovery rate at this position, and for a given river reach, $\sum C_x / x$ can be regarded as an indicator of its recovery rate. From Equation (15), it is seen that $C_x$ is related to distance ($x$), depth ($D$), area ($A$), and discharge ($Q$). For a

![Figure 6](https://iwaponline.com/hr/article-pdf/47/1/104/368986/nh0470104.pdf)
given river morphology, $D$, $A$, and $Q$ are related and can be converted to each other. Therefore, $A/Q$ can be assumed as $1/Dv$, where $v$ is velocity. This indicates that a change of river discharge will affect $C_x$ at a given position and then influence the recovery rate of the stream temperature.

As $C_x$ can reflect the influence of river discharge on recovery rate, it can also be used to calculate the recuperation distance. We assume that the recuperation distance is the distance that reduces the influence of release temperature to less than or equal to 5% (i.e., $C_x \leq 5\%$). The differences between $T_0$ and $T_e$ are less than 12 °C across the different simulation scenarios, and then the temperature variations outside the recuperation distance are less than 0.6 °C, which reflects a similar effect to Prats et al.’s (2012) definition.

**Ecological impact assessment method**

In this study, fish are used as a marker of the ecological impact due to water temperature variations. Two indexes, the time to reach the minimum threshold for spawning and spawning opportunities index are selected to assess this influence. The former can be obtained through comparing the minimum water temperature requirement for spawning with the water temperature in the river during the spawning period. The latter, which is used to quantify the opportunities of the fish to successfully spawn, can be calculated with the following equation according to Preece & Jones (2002):

$$\text{SPI} = \frac{T_u}{T_p}$$

\( (16) \)
where $T_w$ is the duration of the whole spawning period and $T_a$ is the duration of stream temperature above the minimum water temperature requirement for spawning.

RESULTS

Model performance

Figure 8 compares model results against temperature measurements and Table 4 shows the number of observations ($n$) of the Danjiangkou reservoir and the error statistics during the calibration and validation periods. Figure 8 shows that the model provides very good estimations for different water depth in each period. Overall, the MSEs suggest a good agreement between the model and observations with maximum error in the 0.25°C range. MAEs are less than 0.72°C and RMSEs are within 0.52°C under various hydrological situations. This indicates that the EFDC model can successfully capture the timing and depth of thermal stratification.

Figure 9 shows the comparison between the observed and predicted temperatures, and Table 5 contains the error statistics for the sites in the study reach within the calibration and validation data set. The ETM model provides very good estimations and follows the water temperature variations closely (Figure 9). The MSEs are close to zero (−0.13–0.09°C), indicating no consistent positive or negative bias. For all sites, the MAEs and RMSEs are less than 0.52°C regardless of year. This suggests that the model is capable of simulating water temperature in the study river reaches.

The performance of the EFDC model in validation periods is slightly less satisfactory relative to calibration periods due to the inaccuracy of parameters. For the ETM model, MAEs and RMSEs tend to increase downstream during both calibration and validation periods, because the effect of the tributaries in the model is not considered.

Thermal structure variation in the Danjiangkou reservoir

Elevation–time isotherms (Figure 10) indicate the Danjiangkou reservoir's seasonal thermal cycle. Thermal structures in the reservoir were similar across both hydrological years and simulation scenarios. Thermal structure of the Danjiangkou reservoir at S1 in the normal year is a representative example (Figure 10(b)). The reservoir was approximately isothermal from November to March, before seasonal stratification began in April with heating of the surface layer. A distinct thermocline formed between May and October with a thermal gradient from 0.3 to 0.36°C. The temperature of the surface layer rose from 8.0°C in February to 28°C in August. An increase in temperature was also evident in the hypolimnion, with the average monthly temperature rising from an annual minimum of 8.0°C in February to 16°C in September. The most obvious difference in thermal structures among the three hydrological conditions is that the thermocline minimum (isotherm 18°C) in the dry year was much lower than in the wet year, about 7 m below (Figure 10(a) and 10(c)), which means that surface meteorological conditions can influence the water body close to the bottom of the reservoir when the water surface is low enough in a dry year.

At S2, the thermal gradient of the thermocline decreases to 0.21–0.32°C m⁻¹ and the position of the 18°C isotherm rises by about 2 m relative to S1 in normal year, which may be caused by the increased water depth weakening the heat exchange with the upper water body. In addition, the intra-annual amplitude of bottom temperature decreases by 2°C. This may be also related to the deeper water, which will increase the thermal capacity and decrease the thermal inertia. The thermal structures at S3 and S4 are identical due to the same boundary conditions in Danjiangkou reservoir, shown in Figure 10(e). The positions of the 20, 22, and 24°C isotherms in the thermocline are higher at S3 and S4 than S2, which will affect the release temperature, as the first two isotherms are located within the hydropower intake.

Reservoir release temperature variation

Figure 11(a) shows the release temperature variation, including hydropower intake temperature and surface temperature, at S1 across three hydrological years. Temperature variations at surface layer are similar in the different hydrological years, and all follow the change of air temperature, which rises from April, reaches a maximum in August, and then falls. This indicates that the surface temperature is
mainly affected by the meteorological conditions. Intra-annual temperature variation in hydropower intake lags behind the surface temperature, and the maximum temperature appears in September, except in the dry year. The temperatures in hydropower intake are lower than the surface for thermal stratification between May and

Figure 8 | Comparison of observed and simulated daily water temperature during the calibration period, including a wet year (a), a normal year (b), and a dry year (c); and validation period, including another wet year (d), normal year (e), and dry year (f) at Danjiangkou reservoir.
September. Across the hydrological situations, intra-annual amplitudes are greater in the dry year, about 16.6 °C, than in the wet year, about 15.4 °C.

Figure 11(b) demonstrates the release temperature variation at S2 across the hydrological years. The hydropower intake temperatures are around 1.3–2.4 °C lower in summer and around 0.7–2.8 °C higher in winter, relative to S1. Their intra-annual temperature variation lags behind, for example, the maximum appears in September in the dry year. The difference of hydropower intake temperatures between S2 and S3 is very small in winter, around 0.1–0.2 °C, but becomes obvious in summer, around 0.6–0.8 °C (Figure 11(b) and 11(c)).

Overall, the difference in the release temperature is not significant for different hydrological conditions, which demonstrates that the effect of the hydrological conditions on the release temperature is limited. Therefore, the following analysis is mainly based on the normal year.

### Stream temperature variation

Figure 12(a) shows the stream temperature change at S1. The warm period (above 28 °C) is mainly in the summer (June to August), and the cold period (below 6 °C) is mainly in the winter (December to February), which is similar to the variation of air temperature. Downstream from the Danjiangkou dam, water temperature tends to gradually recover to its natural state. The temperature changes at S2 are presented in Figure 12(b). The release temperatures of the Danjiangkou dam are lower in summer and higher in winter relative to S1. The high temperature period is confined to between July and August, which is shorter than S1 (June to August). The distance of the reaches with high temperature is approximately 400 km, which is also less than S1 (about 470 km). Figure 12(c) demonstrates temperature variations at S3. The distances of river channel with high and low temperatures are much longer than S2, by 60 km and 80 km, respectively. This is because the release discharge is decreased by the water diversion projects, about 345 m³ s⁻¹, which will reduce thermal inertia and increase the recovery rate of water temperature. As well, the ‘temperature valley’ in July (about 100–350 km) is related to a high volume and slow recovery rate. At S4, the temperature increases about 0.5 °C in summer and decreases about 0.3 °C in winter in Cuijiaying reservoir from 102 to 134 km, compared to S3 (Figure 12(d)). This is because the river has a slower velocity there and longer exposure to atmospheric conditions. The study suggests that these projects will alter the thermal regime of the river in both space and time.

### Table 4

<table>
<thead>
<tr>
<th>Calibration and validation error statistics of daily water temperature by Danjiangkou reservoir at different hydrological years</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wet year</strong></td>
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<tr>
<td><strong>Calibration error statistics</strong></td>
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<tr>
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<td>MSE, °C</td>
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<tr>
<td>MAE, °C</td>
</tr>
<tr>
<td>RMSE, °C</td>
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<tr>
<td><strong>Validation error statistics</strong></td>
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<tr>
<td>n</td>
</tr>
<tr>
<td>MSE, °C</td>
</tr>
<tr>
<td>MAE, °C</td>
</tr>
<tr>
<td>RMSE, °C</td>
</tr>
</tbody>
</table>
Further at S3, the release temperature decreases by 1.4°C compared with S2, and the recovery rate increases to 0.049°C km⁻¹. This increase in the recovery rate results from the reduced flows – 1,240 m³ s⁻¹ at S1, 954 m³ s⁻¹ at S2, and 608 m³ s⁻¹ at S3 – indicating that less water needs to be heated. Finally, considering the
Table 5  Calibration and validation error statistics of monthly water temperatures for each monitoring location in study reach at different hydrological years

<table>
<thead>
<tr>
<th>Site</th>
<th>Distance, km</th>
<th>Wet year</th>
<th>Normal year</th>
<th>Dry year</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>MSE, °C</td>
<td>MAE, °C</td>
<td>RMSE, °C</td>
</tr>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Huangjiagang</td>
<td>6</td>
<td>0.01</td>
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<td>0.23</td>
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<td>Xiangyang</td>
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<td>0.04</td>
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<tr>
<td>Zhuandouwan</td>
<td>209</td>
<td>-0.06</td>
<td>0.43</td>
<td>0.29</td>
</tr>
<tr>
<td>Nianpanshan</td>
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<td>0.06</td>
<td>0.45</td>
<td>0.33</td>
</tr>
<tr>
<td>Validation error statistics</td>
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<td></td>
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</tr>
<tr>
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<td>0.26</td>
<td>0.24</td>
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<tr>
<td>Xiangyang</td>
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</tr>
<tr>
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<td>0.49</td>
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</tr>
<tr>
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<td>-0.09</td>
<td>0.50</td>
<td>0.40</td>
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</table>

Figure 10  Elevation-time isotherm diagrams for Danjiangkou reservoir: (a) wet year, S1; (b) normal year, S1; (c) dry year, S1; (d) normal year, S2; (e) normal year, S3 and S4.
Wangfuzhou and Cuijiaying reservoirs (S4), recovery rates increase in their backwater areas (0–30 km and 102–134 km). For example, recovery rate increases about 0.005 $\text{W}\text{Ck m}^{-1}/\text{C}0$ at the region from 102 to 134 km compared with S3.

**DISCUSSION**

This section first discusses how the release discharge and release temperature in the Danjiangkou reservoir affects the thermal regime in the downstream river. Herein, the effect of the release discharge is analyzed through a scale factor, which can reflect the change of the recovery rate and then can be applied to calculate the recuperation distance for the dam. Thereafter, the impact of the large water diversion projects on the release discharge and release temperature is investigated. Finally, ecological impact of water temperature change is studied based on fish spawning.

![Figure 11](https://iwaponline.com/hr/article-pdf/47/1/104/368986/nh0470104.pdf)

**Scale factor and the release discharge**

Figure 14 compares the longitudinal scale factor ($C_x$) variations for S1, S2, and S3 in August. The scale factors are 0.78, 0.75, and 0.65 for S1, S2 and S3, respectively, for the reach from the Danjiangkou dam to the Cuijiaying dam. This suggests that the effect of human disturbance shown in
Figure 12 | Monthly stream temperatures in the study reach at S1 (a), S2 (b), S3 (c), and S4 (d) during three hydrological years.

Figure 13 | Longitudinal stream temperature profiles at the four simulation scenarios in August.
S2 and S3 is much weaker than that in S1. Previous analysis shows that the corresponding recovery rates are 0.015 °C km⁻¹ for S1, 0.033 °C km⁻¹ for S2, and 0.049 °C km⁻¹ for S3, which can further confirm the analysis. In addition, the recuperation distances of the first three scenarios are 592, 542, and 359 km, respectively. This all results from higher flows – 1,240 in S1, 954 in S2, and 608 m³ s⁻¹ in S3, indicating that a reduction in river discharge will decrease $C_x$ value, weaken the human influence, improve recovery rate, and reduce the recuperation distance. In turn, it also indicates that the recuperation distance in the study can be used to quantitatively compare water temperature variations due to the change of the release discharge. From the aspect of the whole year, the recuperation distances of the three scenarios are 616 km, 758 km, and 578 km, respectively, in summer and 597 km, 500 km, and 314 km, respectively, in winter, showing that the recuperation distance reduces 38 km in summer and 283 km in winter due to the Danjiangkou dam heightening project and large water diversion projects.

**The release temperature**

In addition to the release discharge, the water temperature in the downstream river is influenced by the release temperature. The temperature change caused by the release temperature is $C_x \Delta T_0$ (Equation (14)), where $\Delta T_0$ is the variation of the release temperature. Figure 15 shows the longitudinal stream temperature profile pre- and post-dam heightening in August with a constant release discharge and variable release temperature.

![Figure 14](https://iwaponline.com/hr/article-pdf/47/1/104/368986/nh0470104.pdf)

**Figure 14** | Comparison of longitudinal scale factor ($C_x$) profiles at S1, S2, and S3.

![Figure 15](https://iwaponline.com/hr/article-pdf/47/1/104/368986/nh0470104.pdf)

**Figure 15** | Comparison of longitudinal stream temperature profiles in August pre- and post-dam heightening with the same constant release discharge and varying release temperature (solid and dotted lines represent pre- and post-dam heightening conditions, respectively).
Cuijiaying dams, the temperatures decrease by about 3.5 and 2.2 °C with a reduction of the release temperature by 4 °C from the Danjiangkou dam. As $C_x$ reduces longitudinally, the influence of the release temperature also weakens along the river, which indicates that the release temperature mainly affects the area near the dam. As well, the recovery rate of the river reach from Danjiangkou dam to Cuijiaying dam rises from 0.015 to 0.029 °C km$^{-1}$ due to decreasing release temperature.

**The large water diversion projects**

In the study, the impacts of large water diversion projects are considered from two aspects. On the one hand, the projects reduce release discharge, weaken thermal intra, improve recovery rate, and then increase water temperature variability. For example, the intra-annual temperature range of the river reach from 180 to 250 km widens from around 6.3–25.5 to 5.2–26.5 °C. On the other hand, they change thermal structure, reduce release temperature in the reservoir, and decrease water temperature in the downstream river in summer. Longitudinal stream temperature profile at S2’ in Figure 16 is calculated based on the release temperature at S3 and release discharge at S2 in August. The difference between S2 and S2’ can reflect the influence of the release temperature change. At S2’, release temperature decreases by 1.4 °C due to the large water diversion projects, which reduces the temperature at least 0.7 °C near the dam ($C_x \leq 50\%$) relative to S2. However, the maximum difference of temperature between S3 and S2 in this area is about 1.4 °C, which suggests that the effect due to the change of release temperature cannot be ignored when analyzing the influence of water diversion projects.

**Ecological impact**

Herein, the spawning of four major Chinese carp species is used as a marker of ecological impact. A qualitative assessment of spawning opportunities was made by comparison of the water temperature against the minimum threshold during the spawning period (Preece & Jones 2002; Figure 17). The spawning opportunities index and the time to reach the threshold at S1 versus S4 at different locations are shown in Table 6. For all the reaches in the mid-Han River, the time to reach the minimum threshold at S4 shows a lag relative to S1, e.g., about 1.87 months at the Huangjiagang station. Furthermore, the spawning opportunities of fish in S4 are higher when the distance from the Danjiangkou dam is greater. This may result in a reduction of spawning sites, and the optimal spawning locations moving downstream from Huangjiagang (6 km) to Xiangyang (111 km).

**CONCLUSIONS**

Overall, the large water diversion projects and related auxiliary projects, including a project to heighten the Danjiangkou dam and two small reservoirs downstream in central China will change the spatio-temporal distribution of water temperature in the Danjiangkou reservoir and its

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**Figure 16** | Comparison of longitudinal stream temperature profiles at S2, S2’, and S3 in August.
downstream river. The Danjiangkou dam heightening project alters water temperature seasonally, increasing the temperature at hydropower intake around 0.7–2.8 °C in winter and decreasing it around 1.3–2.4 °C in summer. However, the water division projects lead to an improved temperature recovery rate and a reduction in recuperation distance, the former in August rising from 0.015 to 0.049 °C/km (from Danjiangkou dam to Cuijiaying dam), and the latter falling by 38 km in summer and 283 km in winter. Furthermore, two small reservoirs make water temperature recover much faster and further weaken the influence of the Danjiangkou dam heightening project, increasing the temperature about 0.5 °C in summer and decreasing it about 0.3 °C in winter in the backwater region of the Cuijiaying reservoir. Analysis of the respective effects due to each project will guide project operation and water resources management in the near future.

Water temperature alterations in the downstream river due to these projects depend greatly on the release temperature and the release discharge from the Danjiangkou reservoir. Change in the release temperature with the dam heightening project mainly affects the area near the dam. A reduction in river discharge with water diversion projects will decrease $C_x$ value, weaken the effect of the release temperature, improve recovery rate, and reduce the recuperation distance. Based on the traditional studies

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**Figure 17** | Fish spawning period and minimum spawning temperature in relation to water temperature in S1 (a) and S4 (b) for different positions in the mid-Han River.
that focus only on the discharge variation in water diversion, this study also considers the change of the thermal structure and the release temperature in the reservoir. As the influence of the release temperature is very obvious near the dam, it cannot be ignored in analysis of the effect of water diversion projects on the thermal regime of the downstream river.

The projects may have an adverse impact on the ecological environment as they alter the water temperature in the downstream river. The spawning periods for four major Chinese carp species may lag behind as the time to reach the minimum threshold shows a lag relative to the natural condition. Furthermore, the optimal spawning sites may move down along the river as the spawning opportunities of fish are higher when the distance from the Danjiangkou dam is greater. Therefore, some remedial work in the area should be carried out based on the finding of this study in order to weaken the adverse ecological impact.

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REFERENCES


Table 6 | Spawning opportunity index and the time to reach the minimum threshold at S1 and S4 for four major Chinese carp species in the mid-Han River at different positions

<table>
<thead>
<tr>
<th>Distance, km</th>
<th>Site</th>
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