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Characteristics of reservoir water temperatures in high and cold areas of the Upper Yellow River

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Abstract

Several reservoirs have been built in the high and cold areas of the Yellow River. This study analyzed the annual and seasonal distributions and variation characteristics of the water temperatures of reservoirs in different reaches based on water temperature observations. The results show that (1) the temperature of the water released from the reservoirs is less than 2 °C and is 2–4 °C lower than the natural temperature in the research area in the spring. Reservoirs in this area freeze in the winter, the water temperature structures of the reservoirs exhibit thermal stratification with inversion profiles, and the inversion profiles are greater than 50 m thick. The reservoir water is mixed to 4 °C and then becomes stratified in mid-April. Similarly, the stratified conditions turn to mixed conditions in November. (2) The operating conditions of the reservoirs influence the water temperature distributions in the reservoirs and the water temperatures of the downstream river channels. (3) The temperature of the water released from the reservoirs is significantly lower than the natural water temperature in the spring, which affects the spawning of downstream fish. (4) A three-dimensional water temperature simulation model was created, and the simulation results show that stratified intake can reduce the impacts of low water temperatures.

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Keywords

Upper Yellow River
High and cold areas
Water temperature
Stratified intake

Introduction

After a reservoir is impounded, the water form will change from a river to a lake. Additionally, there will be a different water temperature structure (Wang et al. 2012) in the reservoir due to changes in the reservoir capacity, operation mode, climate and other factors. Consequently, such changes can lead to variations in sluicing and influence the temperature of the downstream river (Webb et al. 2008; Ormerod 2009). The water temperature affects the biological habitats in a river ecosystem and is a key quality factor (Elliott et al. 1995). Cyclical changes in temperature can considerably affect an aquatic environment (Sinokrat and Stefan 1993), such as impacting the water quality of a river, the growth and breeding of aquatic organisms and crop irrigation (Hellawell 1986; Ward 1985; Webb and Walling 1993). Water temperature has a significant influence on the water quality and biological distribution in a reservoir, and the formation of thermal stratification can lead to a vertical density gradient that will prevent the mixing of water, which affects the vertical distribution of particles and dissolved substances (Moreno-Ostos et al. 2008; Yu et al. 2010).

For deep-water stratified reservoirs, especially power generation reservoirs (water inlets are located at the bottom of reservoirs), sluicing occurs from the cold water layer at the bottom in the summer and the warmer water layer at the bottom in the winter. This phenomenon causes the temperature of the river water downstream of the dam to show a “warm in winter and cool in summer” pattern (Gore 1977; Webb and Walling 1988; Saltveit et al. 1994), which differs from the pattern before a reservoir is built. That is, the water temperatures below the dam in the spring and summer are significantly lower than the natural temperatures, which is commonly referred to as cold water pollution (CWP) or the low water temperature effect. In addition, dams will increase the water temperature of a river in the fall and affect the feeding and metabolism of aquatic organisms, especially fish that prefer cold water. The populations of most aquatic organisms, especially fish that have specific temperature preferences, are expected to decline or become extinct because biological processes such as growth, reproduction and survival are affected when the water temperature exceeds the required thresholds (Taniguchi et al. 1998; Caissie 2006). Therefore, the impacts of the water temperature of a reservoir on aquatic organisms and ecological processes have become an important focus of river health assessments.

Previous studies of the water temperatures of reservoirs or rivers have focused on water bodies in temperate plains, and few studies have investigated reservoirs and rivers in high and cold areas (Guobin 2011; Youcai et al. 2014; Xuejun et al. 2014). Our study investigates the alpine region of the upper reaches of the Yellow River in China, with a focus on Eling Lake to the Liujiaxia section of the Yellow River. Specifically, the Longyangxia, Lijiaxia and Liujiaxia Reservoirs are selected as typical reservoirs in this study. Through analyzing and evaluating multiple decades of water temperature data from the reservoirs and basin hydrological stations, the characteristics of the water temperature distribution and the factors that are influenced by the large reservoirs in the high and cold area are discussed. Moreover, the influences of reservoir discharge on the river water temperature and fish species are analyzed. Finally, a model is created to simulate how stratified intake methods could reduce the effects of low water temperatures. The result is of great significance for research on the effects of reservoir water temperatures in high and cold areas and can provide guidance for planning future hydropower stations in cold areas.

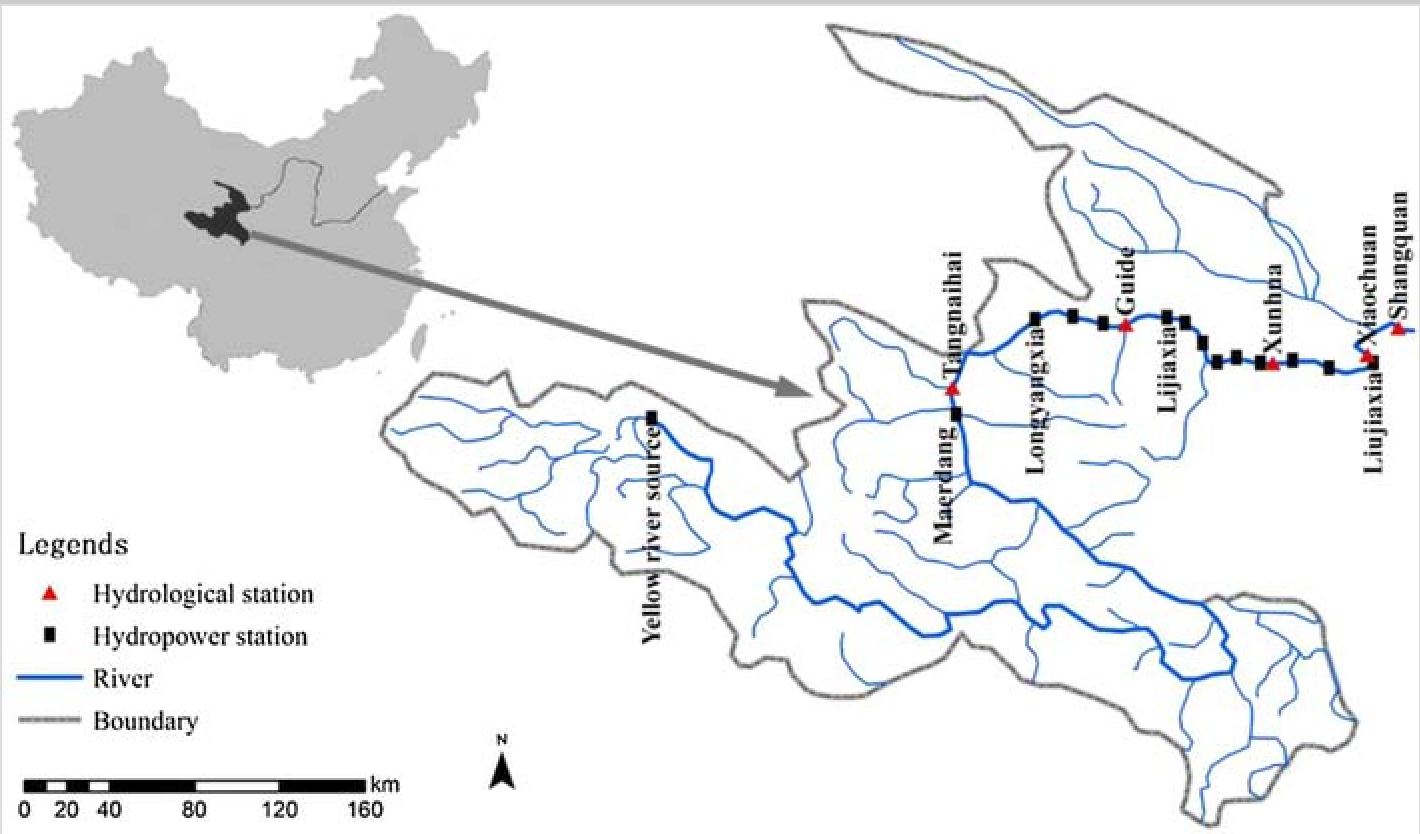
Study area

The upper reaches of the Yellow River are located in central Eurasia; the total length of this section of the Yellow River across Qinghai, Gansu, Ningxia and Inner Mongolia is 3472 km, and the area is 12.2×10^4 m^2. The altitude is higher in the west and lower in the east, with an average altitude of 3800 m (Liqun et al. 2006). The area is surrounded by mountains covered with snow; the climate is cold semi-humid and semi-arid, and the cold periods extend for long durations. The annual average temperature is between − 3.8 and 1.4 °C (YANG Laifei 1997).

The upper reaches of the Yellow River include large geographical gaps and abundant water resources. Notably, rivers mainly flow through canyons. These factors are conducive to hydropower development. A total of 14 large and medium hydropower stations have been built along the 1443-km reach from Eling Lake to the tail of Longyangxia Reservoir, including the Huangheyuan, Banduo, Longyangxia, Laxiwa, Nina, Lijiaxia, Zhiganglaka, Kangyang and Liujiaxia hydropower stations (Fig. 1).

Fig. 1

Study area of the reservoirs in the upper catchment of the Yellow River



This study focuses on the water temperature structure, characteristics and effects of the temperatures of the water discharged from the Longyangxia, Lijiaxia and Liujiaxia Reservoirs that have been built in the region.

The height of the Longyangxia dam is 178 m, the depth corresponding to the normal water level before the dam is 154 m, the total storage capacity is 24.7 billion m^3, the normal water level is 2600 m, and the intake height is 2512 m. The natural annual runoff volume is 20.8 billion m^3 at the dam site, and this total accounts for 35.9% of the total runoff of the Yellow River.

Lijiaxia Reservoir is the third largest reservoir (smaller than the Longyangxia and Liujiaxia Reservoirs) on the river. The dam is 165 m high, and the reservoir capacity is 1.65 billion m^3. Lijiaxia Reservoir began operation at the end of 1996.

Liujiaxia Reservoir is 147 m high, with a total capacity of 5.7 billion m^3. Serious silting has occurred in the reservoir since its impoundment in October 1968. The total amount of sediment was 1.653 billion m^3 at the end of 1986, and the current capacity after repeated flushing is approximately 4.9 billion m^3. The Tao River is a tributary of the Yellow River that is located 1.5 km upstream of Liujiaxia Reservoir. The storage of the Tao River accounts for 2% of the total storage capacity of Liujiaxia Reservoir, and the average annual inflow of sediment is 28.6 million tons.

Materials and methods

Materials

A total of 11 hydrological stations on the main stream in the study area have water temperature and hydrological data. Among them, the Tangnaihai station is the storage control station for Longyangxia Reservoir, which is 135 km from the dam site. In addition, the water temperature at Tangnaihai station represents the natural water temperature condition. The Guide station is located 55 km downstream of Longyangxia Reservoir, and the water temperature changes at this station reflect the influence of the reservoir. The Xunhua station is located between the Lijiaxia and Liujiaxia Reservoirs, and the Xiaochuan station is located 2 km downstream of the Liujiaxia dam site and 33 km downstream of the Shangquang station. Therefore, the water temperature data from the Tangnaihai, Guide, Xunhua, Xiaochuan and Shangquan stations were selected to characterize the water temperatures in the upstream area, downstream area and natural rivers of the Longyangxia, Lijiaxia, and Liujiaxia Reservoirs, respectively. All data were collected from the hydrological yearbooks and local hydrology bureaus. The data from 2006 to 2010 are daily data, and the other data are 10-day or monthly average data. All reservoir temperature data were measured using Mercury thermometers with an accuracy of ± 0.1 °C.

The monthly meteorological data were collected from 14 meteorological stations in the study area from 1959 to 2010, and all data are supported by China's state information center.

Methods

Long-term data sets of river and reservoir water temperatures and air temperatures are used in this study to analyze the characteristics of the reservoirs and the changes before and after the constructions of the reservoirs.

When analyzing the effect of a reservoir on the river water temperature in the study area, the natural water temperature of the site in the same period should be predicted. Predictions of river water temperature are typically based on vertical one-dimensional mathematical models. Model prediction can determine not only the temporal and spatial distributions of the natural water temperature in a river but also the changes in the water temperature downstream of a dam site. The one-dimensional water temperature model based on the heat balance principle and the specific control equation for the vertical one-dimensional water temperature model are as follows:

Water flow continuity equation:

$$W\frac{\partial H}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{3-1}$$

Water flow momentum equation

$$\frac{\partial Q}{\partial t}+\frac{\partial uQ}{\partial x}+gA\frac{\partial z}{\partial x}+\frac{g{n_d}^2Q^2}{AR^{4/3}}=0 \tag{3-2}$$

Water temperature convection-diffusion equation:

$$\frac{\partial (AT)}{\partial t}+\frac{\partial (QT)}{\partial x}-\frac{\partial}{\partial x}\left(AD_{\mathrm{L}}\frac{\partial T}{\partial x}\right)=\frac{W}{\rho C_P}H_{\mathrm{t}}+T_{\mathrm{s}}S \tag{3-3}$$

where W is river width, H is depth, A is the cross-sectional area, Q is flow, q is inflow or outflow, z is the water level, n_d is roughness, R is the hydraulic radius, D_{L} is the longitudinal dispersion coefficient, ρ is the density of water, C_P is the specific heat of water, H_{t} is the daily total heat exchange flux between the water surface and atmosphere, and $T_{\mathrm{s}}S$ is the source and sink term.

Model

To simulate the water temperature of the reservoir, the hydrodynamic model software MIKE 3 (Danish Hydraulic Institute 2005) from the Danish Hydraulics Institute was used. MIKE 3 is a universal three-dimensional mathematical model system that is mathematically based on the Renault averaging Navier–Stokes (NS) equation. MIKE 3 can be applied to simulate unsteady three-dimensional flow for different types of water bodies, and at the same time, changes in the density, topography and meteorological conditions can be fully considered. During the simulation process, the reservoir inflows are set as open boundaries. The inflows of tributaries are set as sources, the dam is a solid boundary, and the reservoir discharge and power generation water inlets are set as sinks. The hydrological station data collected at the tail of the reservoir are used as in-stream hydrologic and water temperature data, and the outflow of the reservoir is used as the discharge data for the reservoir. Both the hydrologic and water temperature data are daily time series. The meteorological data were obtained from the most recent daily time series from weather stations. In this study, data have been collected from all three reservoirs, and long-term water temperature data are available. Therefore, the data from the three reservoirs can be used to validate the reservoir water temperature model and calibrate the parameters.

Results

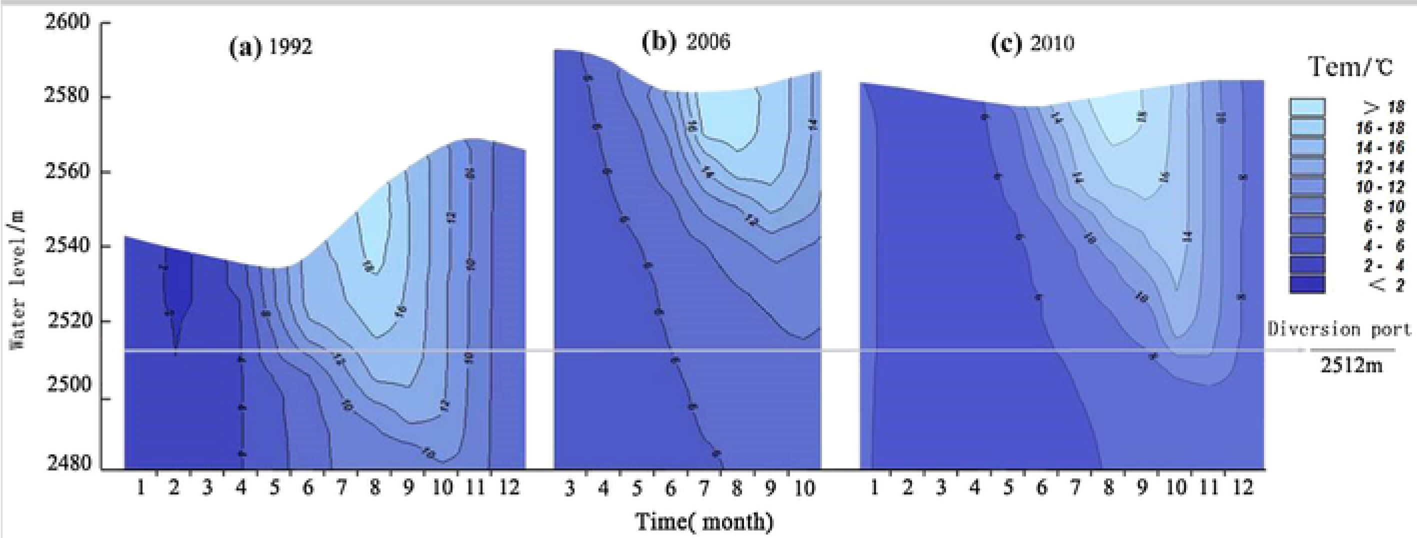
Vertical water temperature structures of the reservoirs

Longyangxia reservoir

Longyangxia reservoir is a typical multiyear regulating storage reservoir. The water temperature data sets from 1992, 2006 and 2010 were complete and used to analyze the vertical structure of the water temperature in front of the dam (Fig. 2). The reservoir was operated at a low water level in 1992, and the annual change in water level was 35.8 m. The impoundment process occurred during the flood season. The water temperature distribution during the non-flood season exhibited mixed and two-tiered distributions from May to October. The reservoir operated at high water levels in 2006 and 2010, with small annual changes in water level. The vertical temperature distribution in the reservoir was mixed from December to April of the following year, and there was a typical three-tiered distribution from June to October, with warm delays in the bottom layer and few annual changes in the temperature of released water, which was approximately 3.6 °C in 2006.

Fig. 2

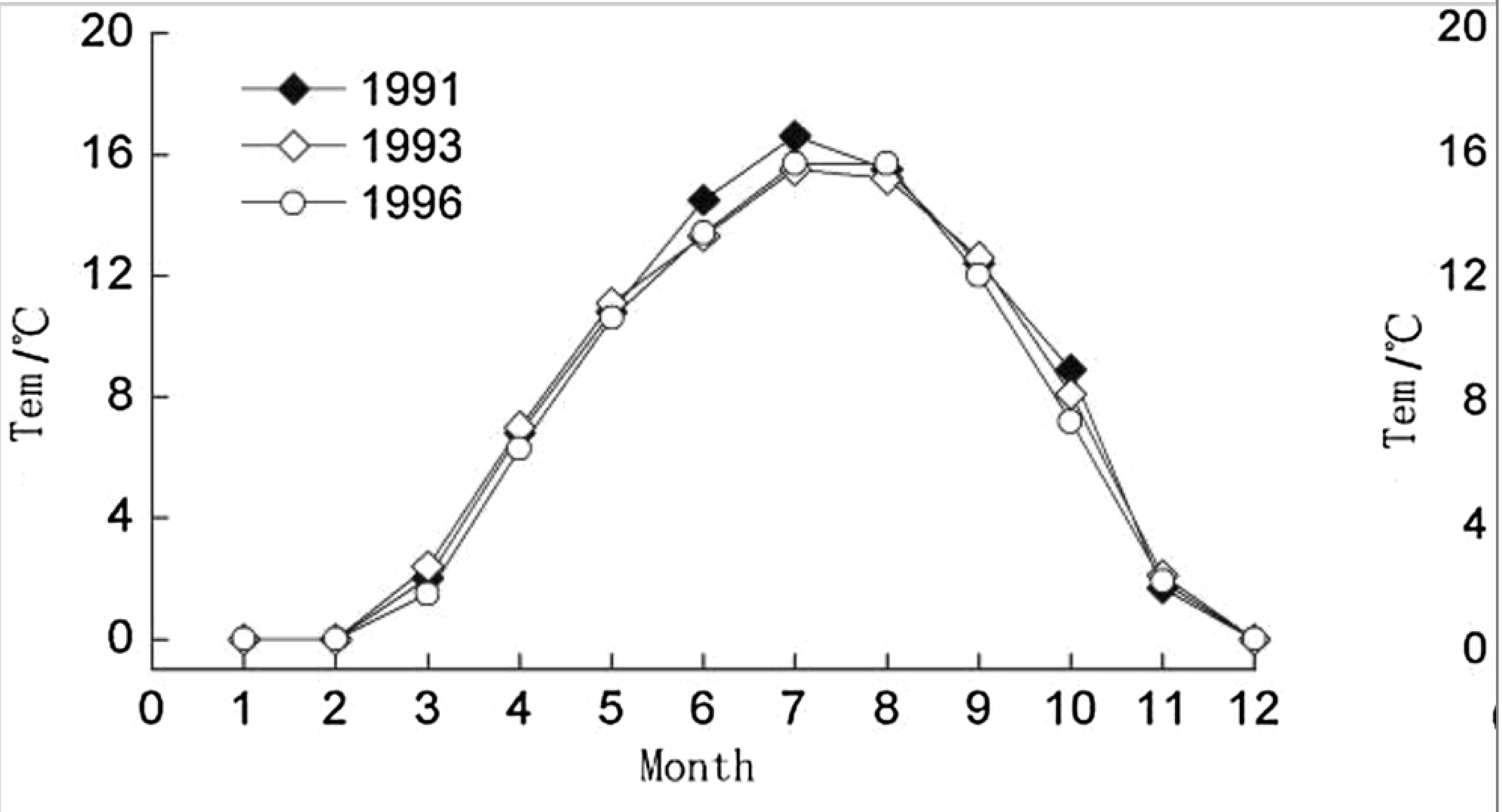
The vertical temperature distribution in front of the dam in different years



The monthly average water temperature data from the Tangnaihai hydrological station and data from the surface and discharge water in front of the dam were analyzed in three typical years from 1990 to 1996 (Fig. 3), and the differences among the 3 years were small. The changes in the features of the reservoir water temperature structure were defined by analyzing the inflow and discharge water temperature data from the 3 years. The results indicated that the vertical water temperature structure was stable in different periods in each year and that the surface temperature is low or exhibits a weak layered or isothermal distribution from December to March and a layered distribution from May to October. November and April are the turning points when the water temperature structure changes.

Fig. 3

Water temperature of Longyangxia Reservoir during a typical year



(a) Inflow water temperature

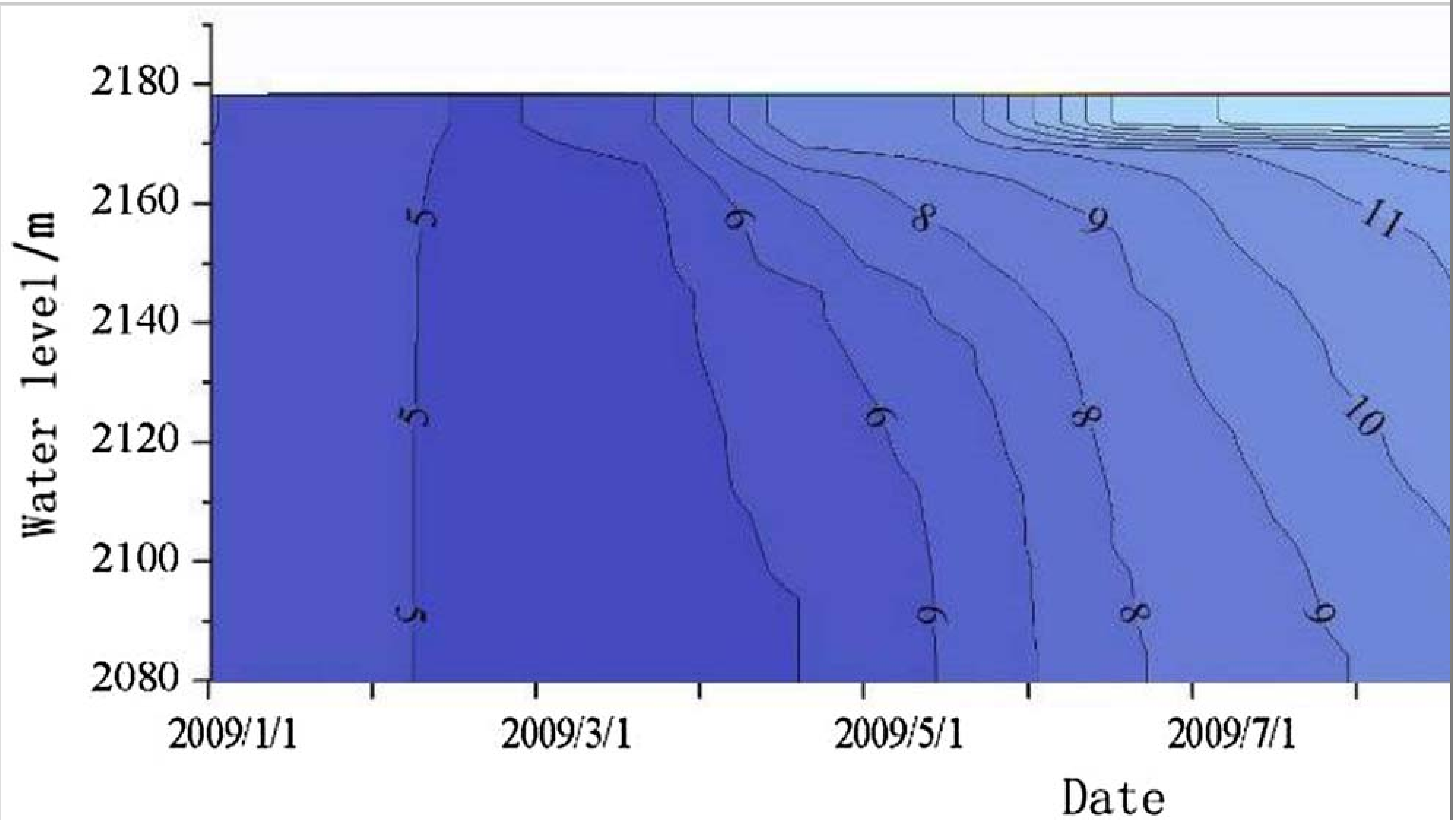
The surface water temperatures and discharge water temperatures are similar during the dry season from January to April in typical years when the reservoir releases water to the downstream and the variations in water flow are small. This result indicates that the external heat flux, which is determined by meteorological and inflow conditions, is insufficient for altering the nearly isothermal state of the reservoir. From May to September, the differences in heat inputs and outputs caused by the significant changes in the inflow, outflow and meteorological conditions, and particularly the operational differences of the reservoir, cause large variations in the reservoir temperature. Therefore, the water temperature stratification pattern is different from May to September. From October to December, the inflow water temperature is significantly lower, the difference between the surface and discharge temperatures decreases and the water variations are small. Thus, the effects of external heat inputs on the internal reservoir temperature are small, and the reservoir approaches an isothermal state. However, the reservoir exhibits different isothermal conditions throughout the years due to the internal heat differences.

Lijiaxia reservoir

Lijiaxia reservoir is a multiyear regulating reservoir, and vertical water temperature observations in front of the dam began in 2009 (Fig. 4). The data were collected 200 m from the dam during the middle of each month. The water temperature structure shows that Lijiaxia Reservoir has weak layering from April to July and that the maximum temperature difference between the surface and bottom water is approximately 8 °C and occurs in July. Because the temperature of the inflow water decreases in October, the vertical water temperature distribution of the reservoir gradually turns to an isothermal state. Due to the effects of the upstream reservoirs, the temperature of the inflow water is high in the winter because the thermal reservoirs store warm water; therefore, the temperature of the discharged water is high in the winter.

Fig. 4

Vertical distribution of the water temperature in Lijiaxia Reservoir in 2009

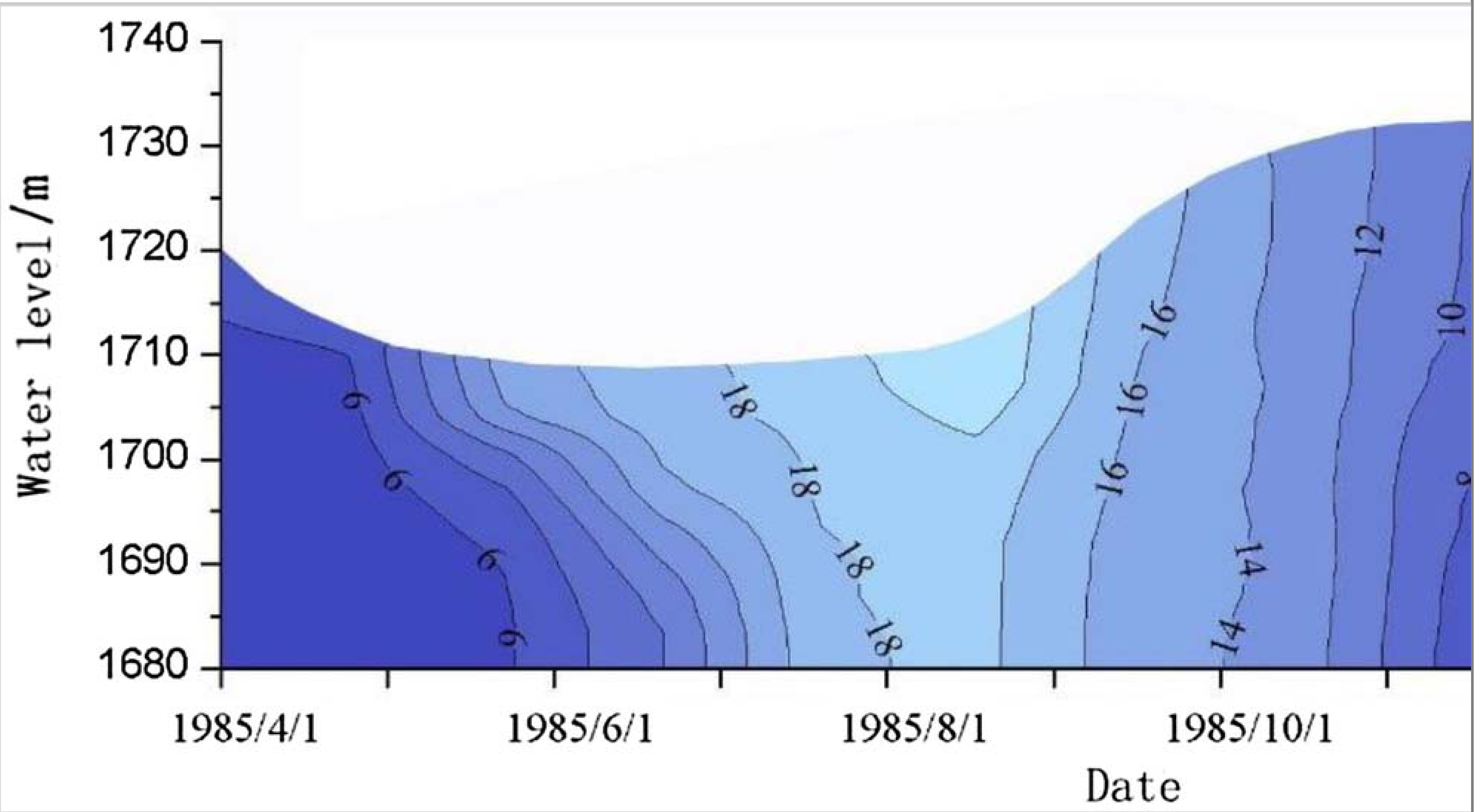


Liujiaxia reservoir

The water temperature in Liujiaxia reservoir was observed from April 1985 to March 1986. The data collected at 14 typical sections are presented and represent the vertical temperature distribution in the reservoir area each month. The typical canyon section that is in front of the dam was selected to present the vertical temperature distribution. (Fig. 5).

Fig. 5

Vertical distribution of water temperature in Liujiaxia reservoir



The water temperature in Liujiaxia reservoir is mixed most of the time. Stratification is weak from July to September, and typical stratification is observed in only May and June. This condition occurs because the Tao River, which has high sediment concentrations, flows into the upper reaches of the river, and the water temperature in the Tao River is higher than that in the main stream, which leads to sediment gravity flow and affects the water temperature distribution in the reservoir. Two factors lead to the abnormal water temperature distribution in Liujiaxia Reservoir compared to the typical distributions in other large reservoirs in the summer. First, the inflows are large from June to September when the reservoir operates at a low water level to satisfy the water and flood control requirements downstream. Then, the capacity is greatly reduced, which leads to mixing and water temperature variations when more water flows into the reservoir. Conversely, a large amount of sediment flows into the reservoir from May to August, and the dense sediment current carries hot water to the bottom of the reservoir, causing a uniform water temperature distribution in the upper and lower layers.

The impacts on downstream water temperatures

Longyangxia reservoir

The downstream reaches of the river that are affected by Longyangxia Reservoir are at the dam site following the tail section of Liujiaxia Reservoir, and only the Guide and Xunhua hydrological stations are in this reach. The course of the river in this reach was natural from 1988 to 1996. The statistics of the water temperature characteristics derived from the two hydrological stations (Table 1) can be used to analyze the water temperature changes along the river when it was influenced by only Longyangxia Reservoir.

Table 1

Characteristics of the downstream water temperature at the Guide and Xunhua stations, units: °C

Stations	Natural temperature	After impoundment	After impoundment/natural (Dec–Mar)	After impoundment/natural (May–Oct)

The natural water temperature references the data from 1960 to 1985, and the water temperature after impoundment references the data from 1988 to 1996.

Stations	Natural temperature	After impoundment	After impoundment/natural (Dec–Mar)	After impoundment/natural (May–Oct)
Guide	0–17.0	3.3–14.5	4.3/0.9	12.2/14.2
Xunhua	0–18.1	2.9–16.0	3.9/1.3	13.4/15.3
The natural water temperature references the data from 1960 to 1985, and the water temperature after impoundment references the data from 1988 to 1996.				

The water temperature along the river was warmer during the warm season and cooler during the cold season after reservoir impoundment. From December to March, the water temperature at the Xunhua station is 0.4 °C lower than that at the Guide station, but a heating process occurred along the reach before reservoir impoundment. The water temperature at the Xunhua station is 1.2 °C higher than that at the Guide station from May to October, but a cooling process occurred before reservoir impoundment.

The annual water temperature data from Guide and Xunhua (Table 2) were used to analyze the characteristics of the water temperature changes due to the impoundment of Longyangxia Reservoir. Notably, heating occurred from the Xunhua station to the Guide station before Longyangxia Reservoir impoundment. The water temperature patterns are opposite before and after impoundment. Specifically, cooling occurs from November to February, heating occurs from April to September, and there are few changes during other months.

Table 2

Water temperatures before and after the impoundment of Longyangxia Reservoir

Period stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Before impoundment												
Guide	0.0	0.3	3.3	9.0	12.9	15.1	17.0	16.8	13.9	9.2	3.0	0.1
Xunhua	0.1	0.4	4.4	9.6	13.7	16.4	18.2	18.2	15.0	10.3	3.6	0.1

Period stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Difference	0.1	0.1	1.1	0.6	0.8	1.3	1.2	1.4	1.1	1.1	0.6	0.1
After impoundment												
Guide	4.3	3.2	3.6	5.2	8.0	10.5	12.7	14.2	14.3	12.0	9.4	6.2
Xunhua	3.4	3.1	4.4	7.1	10.1	13.0	15.1	16.2	15.3	12.1	8.7	5.2
Difference	− 0.9	− 0.1	0.8	1.9	2.1	2.5	2.4	2.0	1.0	0.1	− 0.7	− 1.0

Lijiaxia reservoir

Lijiaxia reservoir is located between the Guide and Xunhua stations, and the inflow water temperature is affected by Longyangxia Reservoir. The data observed during the different periods during Lijiaxia Reservoir construction were used to analyze the impacts of the reservoir on the downstream river temperature. The data from 1988 to 1996 were observed before the impoundment of Lijiaxia Reservoir, and the data from 1988 to 1996 were after the reservoir was built. In addition, we compared the water temperature data from a typical year and multiple years at the Guide and Xunhua stations (Table 3).

Table 3

Water temperatures at the Guide and Xunhua stations in different years

Period stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1988–1996												
Guide	4.3	3.2	3.6	5.2	8.0	10.5	12.7	14.2	14.3	12.0	9.4	6.2
Xunhua	3.4	3.1	4.4	7.1	10.1	13.0	15.1	16.2	15.3	12.1	8.7	5.2
Difference	− 0.9	− 0.1	0.8	1.9	2.1	2.5	2.4	2.0	1.0	0.1	− 0.7	− 1.0

Period stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997–2003												
Guide	3.7	3.1	3.7	5.5	8.5	10.8	12.5	13.3	13.6	12.2	9.5	6.2
Xunhua	3.8	3.4	4.7	6.6	9.5	12.0	14.1	15.3	14.8	13.3	10.1	6.7
Difference	0.0	0.3	1.0	1.1	1.0	1.2	1.6	2.0	1.2	1.1	0.6	0.5

The changes in the multiyear average water temperatures at the Guide and Xunhua stations are small during the two periods. The water cools along the river reach due to the influence of Longyangxia Reservoir from November to February. The combined operations of the Longyangxia and Lijiaxia Reservoirs have an attenuated impact on water temperature, and the water temperature is particularly low in May. Similarly, the water temperatures are high in autumn and winter, and the temperature of the discharge water is also high.

Liujiaxia reservoir

Liujiaxia Reservoir began operation in 1969 and was operated from 1969 to 1985 before the other reservoirs began operation. The water temperature data observed at the Shangquan hydrological station before and after the reservoir was built and during isolated operation (Table 4) were used to analyze the effects of the reservoir on the downstream water temperature.

Table 4

Water temperatures at the Shangquan station before and after Liujiaxia Reservoir impoundment

Period	Parameters	Dec–Mar	Apr	May–Oct	Nov
1956–1967	Mean temp/°C	1.4	10.4	16.4	4.4
	Range/°C	0.8–2.3	9.0–12.3	15.9–17.0	1.9–3.8

Period	Parameters	Dec–Mar	Apr	May–Oct	Nov
	Monthly temp range/°C	0.2–4.6	/	11.0–19.7	/
	Highest/lowest temp/°C	7.2/0	/	21.3/10.1	/
	Highest/lowest temp time/month	3/1	/	7/10	/
1969–1985	Mean temp/°C	3.0	7.0	15.9	9.1
	Range/°C	2.0–3.9	6.2–9.0	14.9–16.5	7.9–10.0
	Monthly temp range/°C	1.9–4.5	/	11.6–19.3	/
	Highest/lowest temp/°C	5.6/1.6	/	20.5/10.1	/
	Highest/lowest temp time/month	12/2	/	8/5	/

The data collected at the Shangquan station reflect the temperature of the river water after the impoundment of Liujiaxia Reservoir. The average water temperature from December to March is two times higher after impoundment than before impoundment, and the average temperature from May to October is 0.5 °C lower after impoundment than before impoundment. The range of water temperature decreases throughout the year. An increase in water temperature is evident in the winter, when there is less of a reduction in the peak water temperature, and a large reduction occurs in the spring. The warming and cooling periods delay the changes in the natural water temperature.

Discussion

Water temperature characteristics of the reservoirs

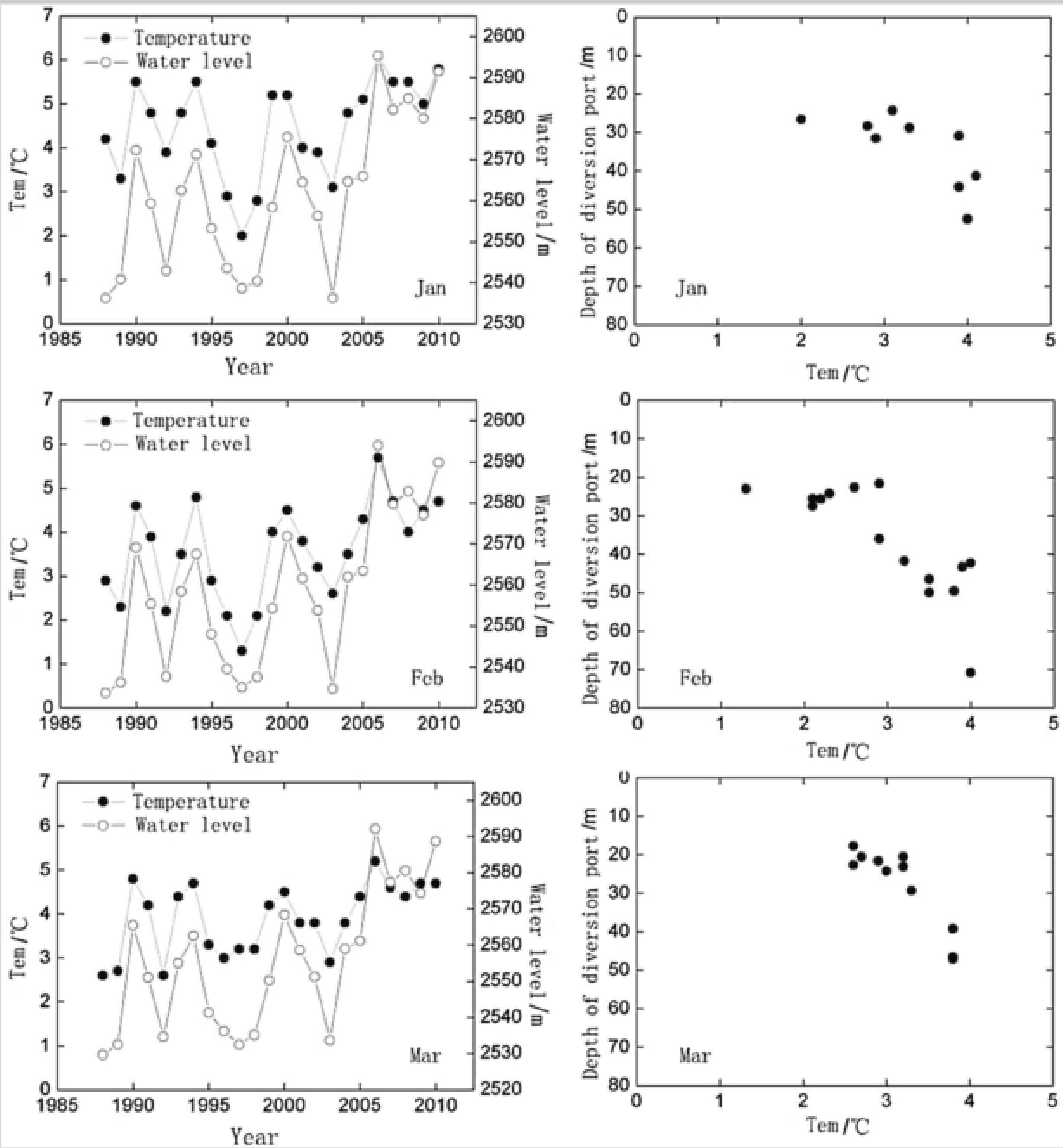
Water temperature inversion in the winter

In general, the reservoir water temperature distribution is characterized by higher surface water temperatures and lower bottom water temperatures, but the reservoirs in the study area exhibit different water temperature structures in the winter. Specifically, the surface water temperature is low, and the bottom water temperature is high. This layering phenomenon is called an inversion profile. The reservoirs in the study area are located at an altitude of 3000 m. The part of the river upstream of the Jungong hydrological station freezes for an average of 124 days. The data from this hydrological station show that the average temperature in the winter (December to February) ranges from − 12.3 to 8.7 °C. A large area of Liujiaxia Reservoir froze for the first time in the past 30 years in mid-January 2008. During this freeze period, the average temperature observed at a nearby hydrological station was − 10 °C. Based on this information, we can assume that reservoirs in the Upper Yellow River freeze in the winter and display significantly inverted water temperature distributions.

The water level and temperature data from the Guide station from January to March 1988–2010, when the discharge water temperature was similar to that in the river, were used to analyze the thickness of the inversion layer in the reservoir (Fig. 6).

Fig. 6

Water level and water temperature of Longyangxia Reservoir



Temperature
Water level
Tem /℃
Water level /m
Year
Jan
Feb
Mar
Depth of diversion port /m
Tem /℃

Longyangxia Reservoir operated at a low water level during the winter when the river water temperature was low. When the water temperature was less than 4 °C, an inversion layer formed in the reservoir above the outfall location. The temperature of the river is lowest in the winter in February; thus, we can determine that the maximum thickness of inverse stratification is approximately 50 m below the surface.

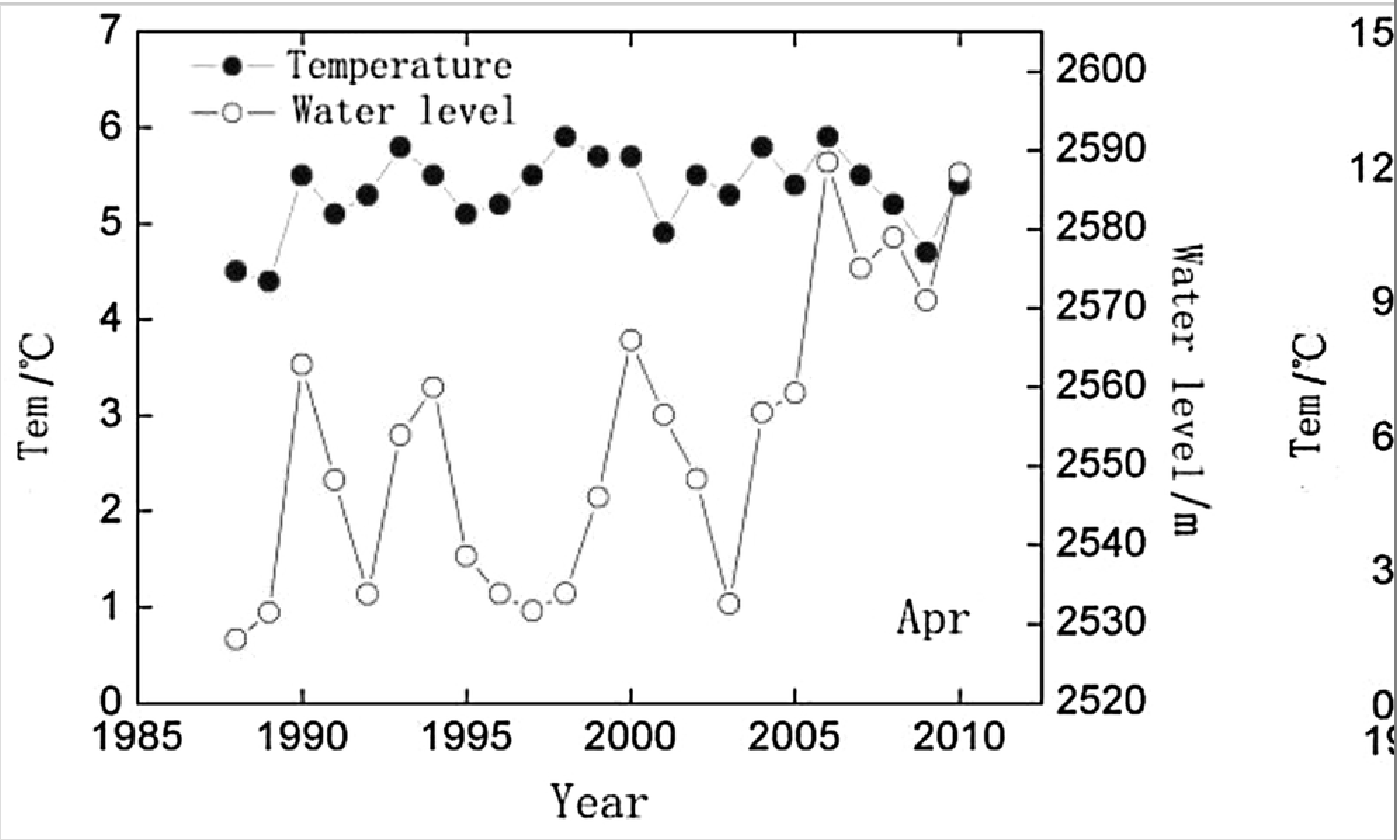
Moreover, the lowest average water temperature of the discharge water was only 2.5 °C in February from 1976 to 1985 when Liujiaxia Reservoir was the only reservoir in operation. The water outlet is 50 m below the water surface. Therefore, the thickness of the temperature inversion layer was determined to be greater than 50 m during this period, and the monthly average minimum temperature of the discharge water was less than 2.5 °C in the winter.

Changes in the reservoir water temperature structure

The water temperature data from the reservoirs in study area indicate that most of the reservoirs exhibit similar seasonal change characteristics, except Liujiaxia Reservoir. The water is mixed or inversely stratified from December to March and is typically stratified or weakly stratified from May to October, and the transition periods occurred in April and November. Analyses of the water level of Longyangxia Reservoir in April and November from 1988 to 2010 and the water temperature at the Guide station (Fig. 7) can be conducted to determine the structural change characteristics of the water temperatures in the reservoirs of the study area. The results suggest that the water temperature increases along the river in April by an average of 0.8 °C. This finding indicates that the temperature of the intake water is approximately 4–5 °C. Although both the air and water temperatures obviously increased, and stability of the water temperature was not significantly correlated with the different reservoir operations. Therefore, we can estimate that the temperature distribution changed in early April.

Fig. 7

Water level and water temperature of Longyangxia Reservoir



Impact of reservoir operation on water temperature

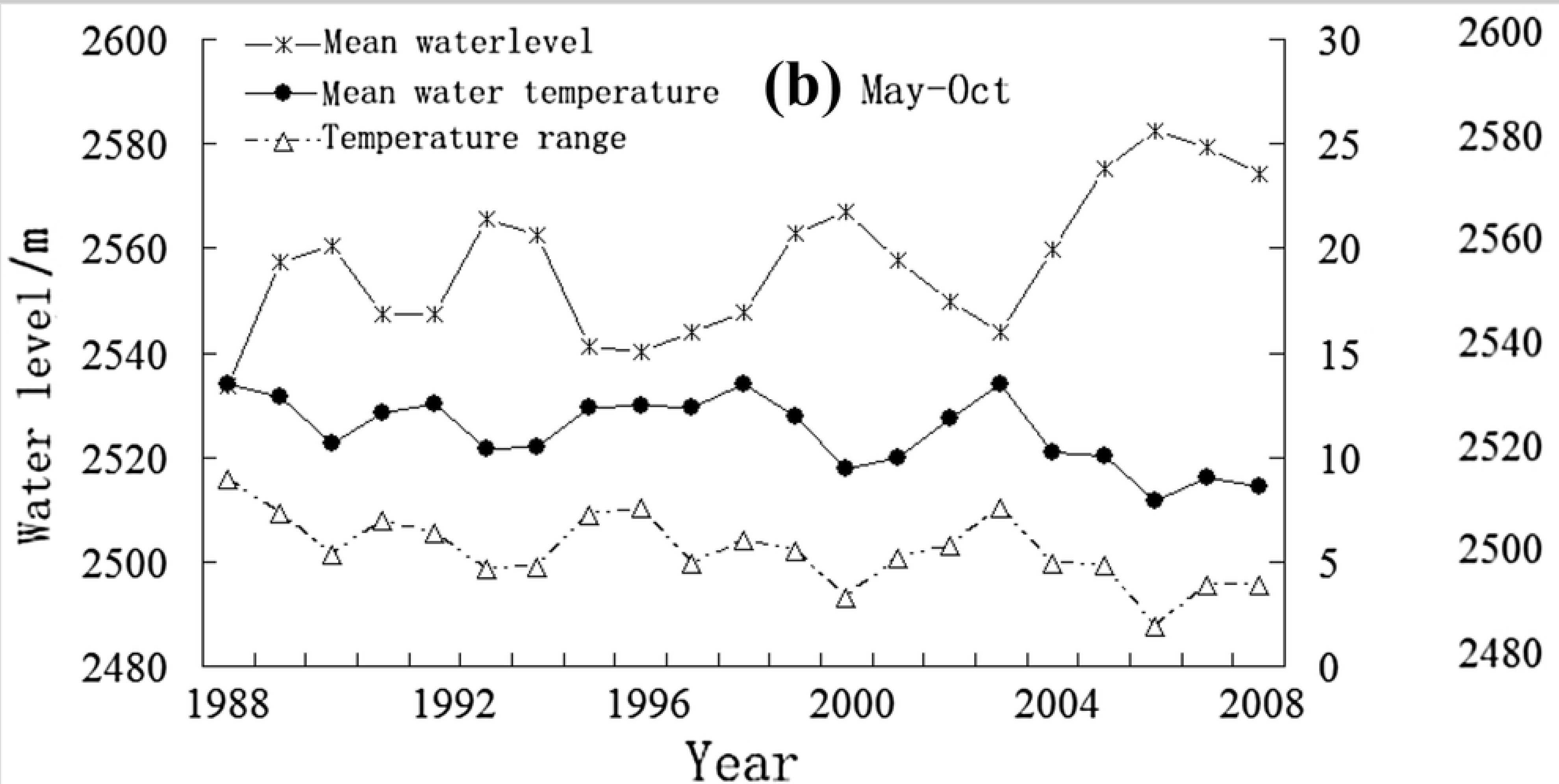
Reservoir operation affects both the water temperature structure and downstream water temperature. A case study of Longyangxia Reservoir indicated that the different reservoir operations are the root causes of the changes in the structure of the reservoir water temperature.

There were two water temperature structures in Longyangxia Reservoir from 1988 to 2010. First, there were three similar cyclical interannual variations with large water level ranges from 1988 to 2002. In each cycle, the layering was weak during the years with low water levels, and stratification was significant during years with high water levels from May to October. Second, the reservoir operated differently from 2003 to 2010, and the water levels were normal in 2003 and 2005 when temperature hysteresis layers were observed.

The monthly mean temperature data from the Guide station from 1988 to 2008 (Fig. 8) were selected according to the operating conditions and water temperature distribution of Longyangxia Reservoir to analyze the influence of the different reservoir operating conditions on the downstream water temperature.

Fig. 8

Water level and downstream water temperature of Longyangxia Reservoir



The data show that the river water temperature displays an in-phase relationship with the water level and an antiphase relationship with the magnitude of the river water temperature from December to March. When the water level is high, low water exchange leads to more heat storage and small river water temperature fluctuations. Conversely, from March to October, the water temperature exhibits an antiphase relationship with the water level and an in-phase relationship with the magnitude of the river water temperature, as the water level is high during this period, and the water temperature at the bottom of the reservoir is low. The low water storage leads to low water temperatures.

A statistical indicator of the water level of Longyangxia Reservoir and the river water temperature was created, and the corresponding river temperature classification levels are shown in Table 5.

Table 5

The downstream temperatures and reservoir water levels from 1988 to 2008

Period parameters	**Water level/m**			
	$E < 2540$	$2560 > E \geq 2540$	$2580 > E \geq 2560$	$E \geq 2580$
Dec–Mar				
Mean/°C	3.5	4.2	5.1	5.9
Range/°C	2.9–4.1	3.3–5.2	4.2–5.6	5.4–6.2
Indicator value	5	6	8	2
May–Oct				
Mean/°C	13.5	12.2	10.1	8
Range/°C	13.5	10–13.5	8.6–12	8
Indicator value	1	11	8	1

Longyangxia Reservoir operated from May to October at a water level of 2540–2580 m for 19 years, and the average river water temperature decreased by 2 °C per 20 m decrease in water level. The water level was above 2540 m from December to March, and the average river water temperature increased by 1 °C per 20 m increase in the water level.

Influence of low discharge temperatures

The data from the Longyangxia, Lijiaxia and Liujiaxia Reservoirs (Table 6) were analyzed to determine the influence of low discharge temperatures from the reservoirs in the study area in the spring.

Table 6

Reservoir characteristics and low discharge water temperatures in the spring

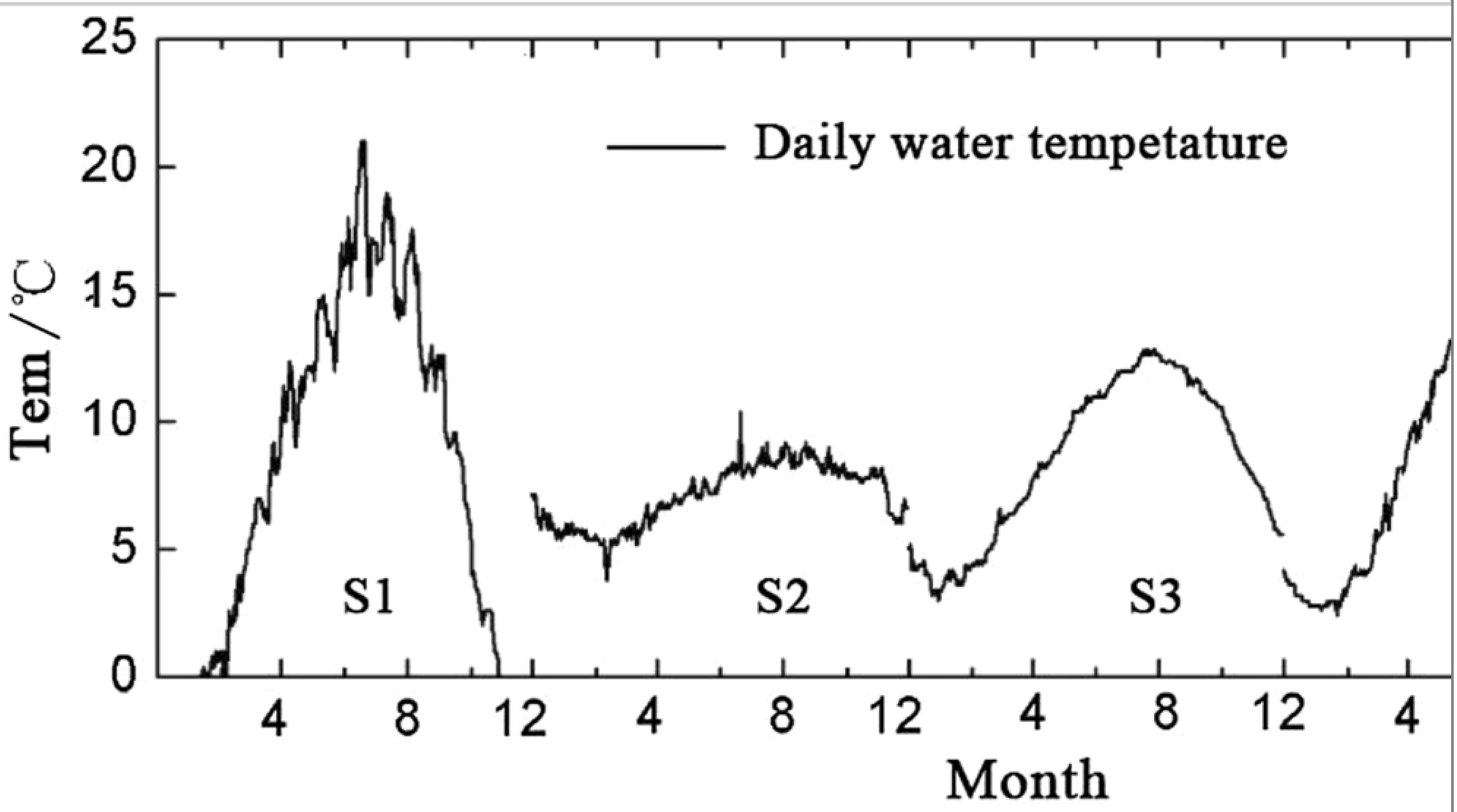
Reservoirs	Storage (billion m^3)	Water level (m)	Depth of outfall (m)	Max difference (°C)
Longyangxia (1987)	0.99–2.87	2495–2514	15–34	2.9 (Apr)
Longyangxia (1988)	4.84–5	2528–2529	46–47	4.6 (May)
Lijiaxia (2003)	1.65	2179.3	50	2.2 (May)
Liujiaxia (1976–1985)	3.6–2.3	1730–1720	50–40	3.7 (Apr)

The water temperatures of all three reservoirs are lower than the natural temperatures. In summary, the temperature differences between the discharge water and the natural water are approximately 2–4 °C, and these differences occur in April and May.

The water temperature data from the Tangnaihai (S1), Guide (S2), Xunhua (S3), Xiaochuan (S4) and Shangquan (S5) hydrological stations in 2006 are selected for further analysis, and the monthly mean temperatures and monthly amplitudes of the water temperature are analyzed to show the changes in water temperature throughout the year under the influences of the reservoirs (Fig. 9).

Fig. 9

Water temperatures at the stations in 2006



Compared with that at the Tangnaihai station, the water temperature at the Guide station is significantly more stable. The average monthly water temperature at the five stations ranged from 5.2 to 8.7 °C, and the peak water temperature exhibited an obvious delay of approximately two months. The delay in the peak water temperature at the Xunhua station is also apparent. The water temperatures at the Xiaochuan and Shangquan stations recovered to natural conditions, and the peak delay was only 15 days.

A decrease in water temperature can affect the hatching of fish eggs. The temperature of the water discharged from several dams in the Murray–Darling valley in Australia in the summer is approximately 10 °C below the natural temperature, and this decrease led to a significant increase in the death rates of native fish eggs (Lugg 2000). Cold water from the Glen Canyon dam on the Colorado River can impact areas up to 400 km downstream of the dam and significantly decrease the abundance of native fish (Holden and Stalnaker 1975). The protected fishes in the study area are Schizothoracinae fishes, which usually reach sexual maturity at 3–6 years old and spawn in April or May. The main breeding seasons of other key fish species, such as *Gymnodiptychus pachycheilus*, is from May to June, and spawning requires water temperatures between 6 and 11 °C. The water temperature of the *Gymnocypris eckloni* spawning grounds is approximately 10 °C, and the temperature of the *Platypharodon extremus* spawning grounds ranges from 6 to 10 °C. *Chuanchia labiosa* spawn in May, and the breeding period of *Schizopygopsis pylzovi* is from late April to mid-May. The spawning period of *T. scleroptera* is from late March to mid-April, and the water temperatures of the spawning grounds for this species are between 4 and 5 °C (Edinger and Buchak 1975).

The delay of the peak water temperature and the change in the water temperature pattern of the river will inevitably postpone the spawning period of cold water fish. Thus, the reproduction or population structure of the fish in the study area will be affected.

Alleviation of low water temperatures by stratified intake

We believe that appropriate measures should be taken to address or mitigate the effects of low water temperatures. Currently, a new reservoir named Maerdang is being constructed in the upper reaches of Longyangxia Reservoir. The water level of Maerdang is 3275 m, the storage capacity is 1.48 billion m^3, the dam height is 211 m, and the inlet elevation is 3220 m. Based on analyses of the water temperature characteristics and the effects of releasing low-temperature water from reservoirs, we simulated and predicted the influence of low water temperatures and the ability of stratified intake mechanisms to alleviate these impacts using a 3-D water temperature model.The simulation results (Figs. 10, 11) show that there is significant temperature inversion stratification in the reservoirs from January to March. The winter temperature exhibits a mixed distribution to 4 °C in April and December and is typically stratified form from May to November. The temperature of the discharge water in April to June is obviously lower than the natural water temperature, and a maximum temperature drop of 3.4 °C occurs in May. This result is consistent with the previous conclusions of this study.

Fig. 10

Vertical distribution of the water temperature

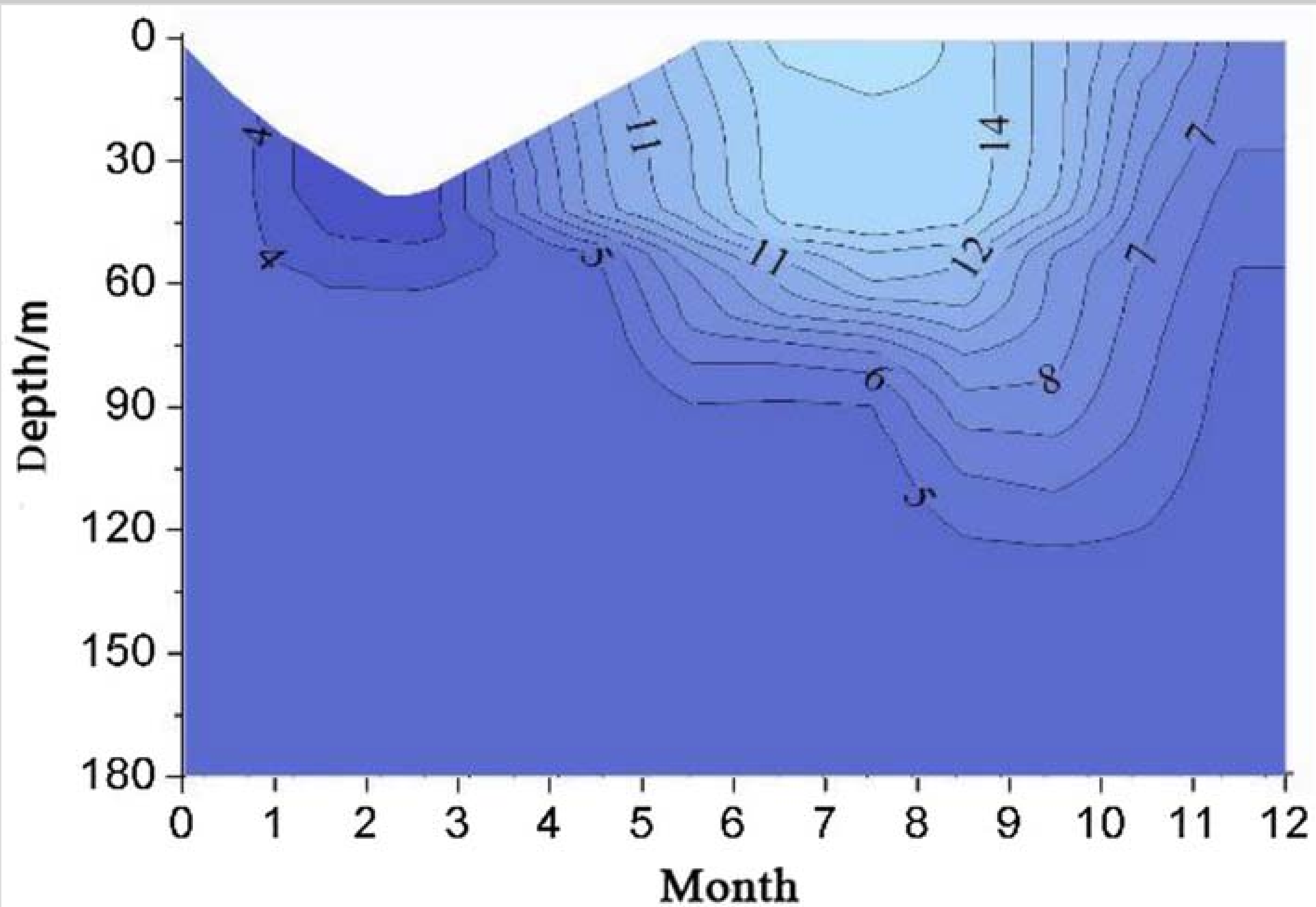
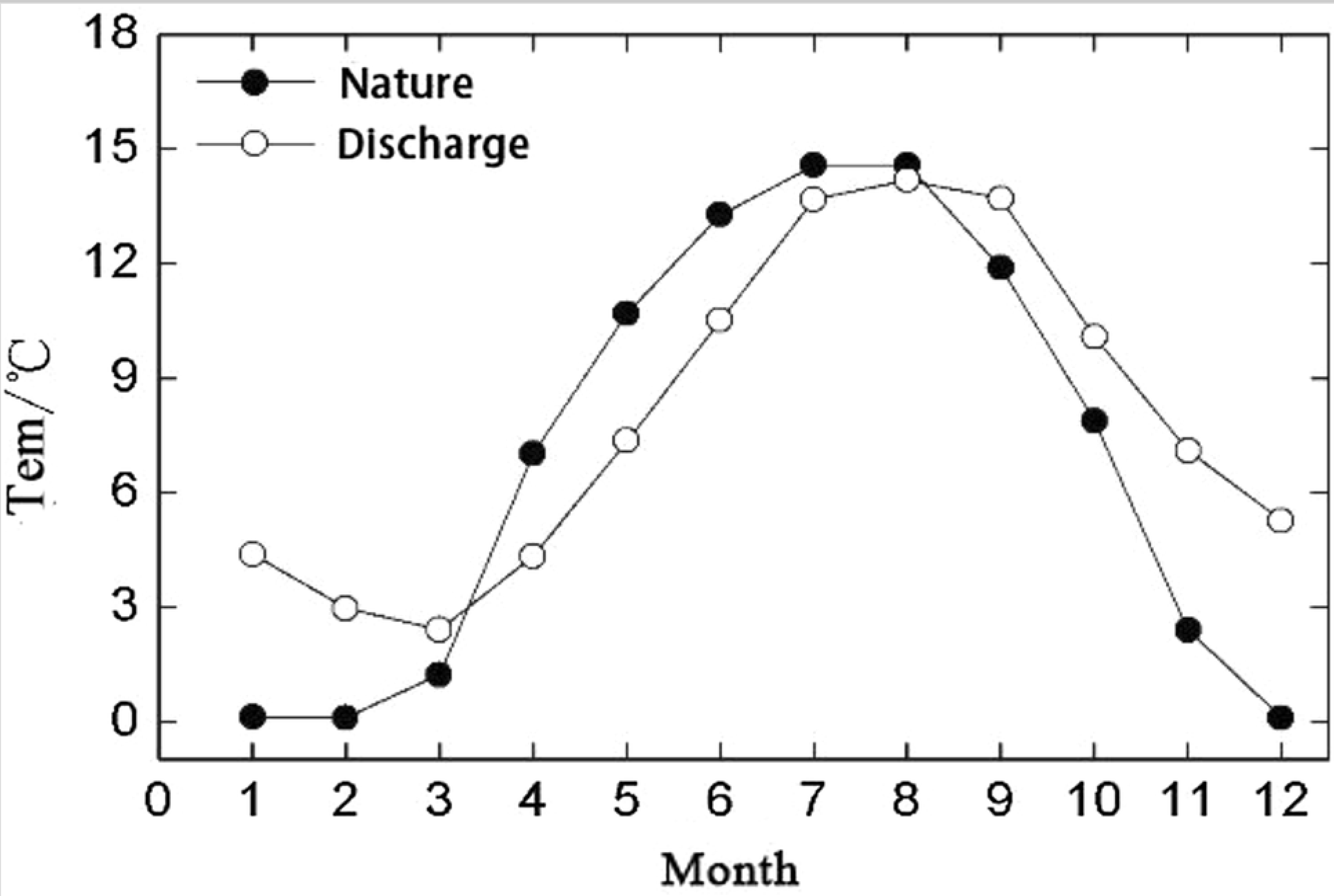


Fig. 11

Natural temperature and discharged water temperature at the reservoir site


Nature
Discharge
Tem/℃
Month
0
3
6
9
12
15
18
1
2
3
4
5
6
7
8
9
10
11
12

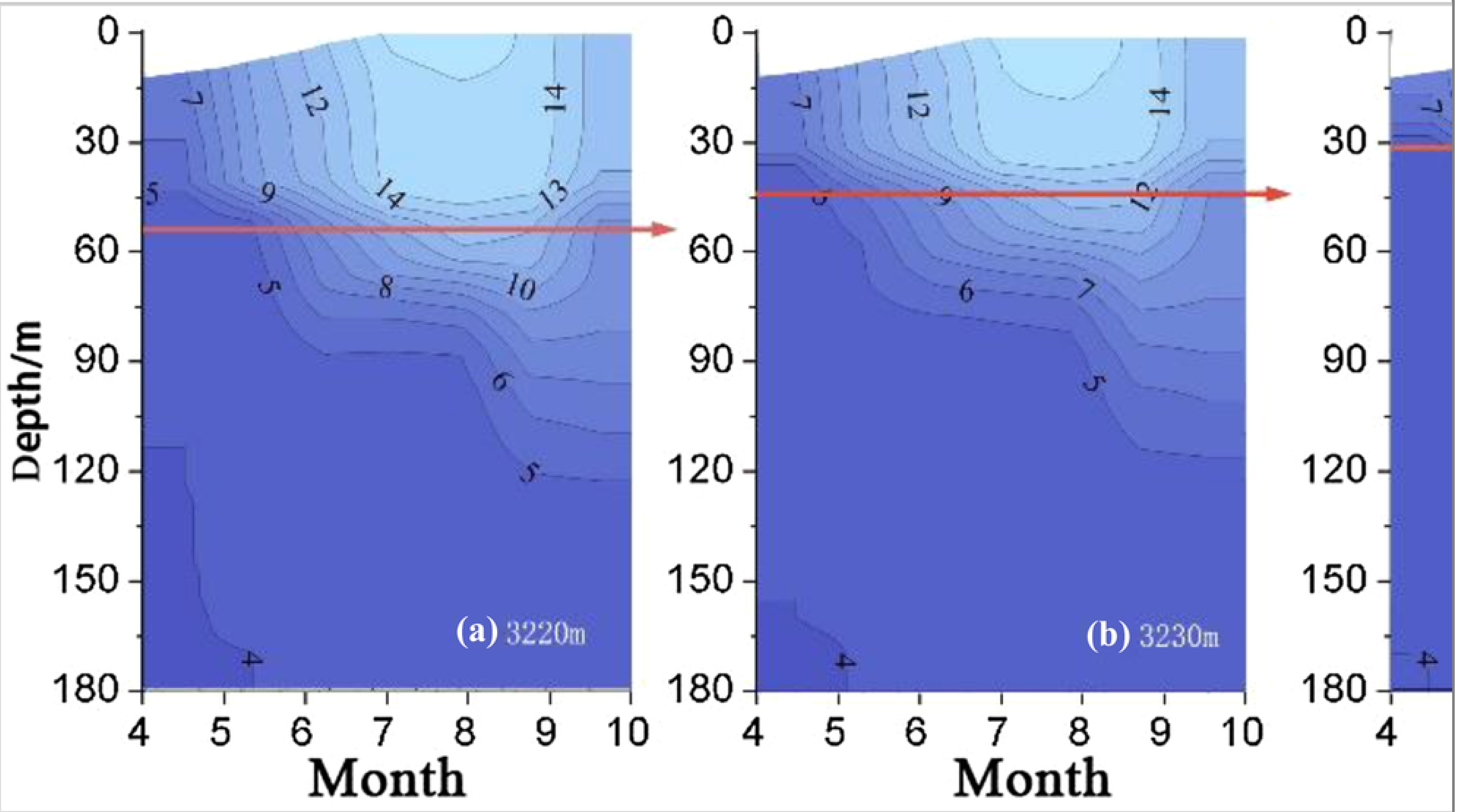
Currently, there are two main types of measures to mitigate the effects of low water temperatures in a reservoir. One measure is to change the operation of a reservoir to meet the water temperature targets of the downstream area. The other measure is to use temperature control device (TCD) technology to control the discharge water temperature. The second method has become an important measure in the ecological restoration of rivers (Dionne and Therien 1997; Jackson and Gibbins 2007; Jager and Smith 2008). For example, stratified intakes can mitigate both cold and warm water pollution. Stratified intake occurs when water is drawn from different areas of the reservoir based on the temperature stratification structure of the reservoir, and this technique can be used to meet downstream water temperature requirements. Research on stratified intake methods considers the comprehensive goals of regulating water temperatures, improving water quality, maintaining downstream river flow, saving endangered fish and restoring habitat (Craya 1949; Gelhar and Mascolo 1966; Grace 1971; Bohan and Grace 1969). Moreover, stratified intake can improve the quality and temperature of discharge water (Walter and Shelton 1970; Fontane et al. 1981; Vermeyen 1999; Rakesh and Steven 2007).

In addition to the design of water diversion outlets at 3230 m, three more outlets at 3230 m, 3240 m and 3260 m were established to simulate stratified intake. A simulation time from April to October was chosen to determine the impacts of low water temperatures. Changes in water intake elevations were implemented by establishing stacked doors at different heights in front of the dam.

The simulation results (Fig. 12) show that the thermocline significantly moves upward in the water column as the height of the water diversion outlet increases. When the water diversion position is deeper, the isothermal water body at the surface is thicker, and the temperature of the water in the deeper part of the reservoir is higher. When the water diversion position is near the surface, the process of surface temperature warming is weakened, the effect of vertical convection is reduced, and the water temperature below the inlet is lower.

Fig. 12

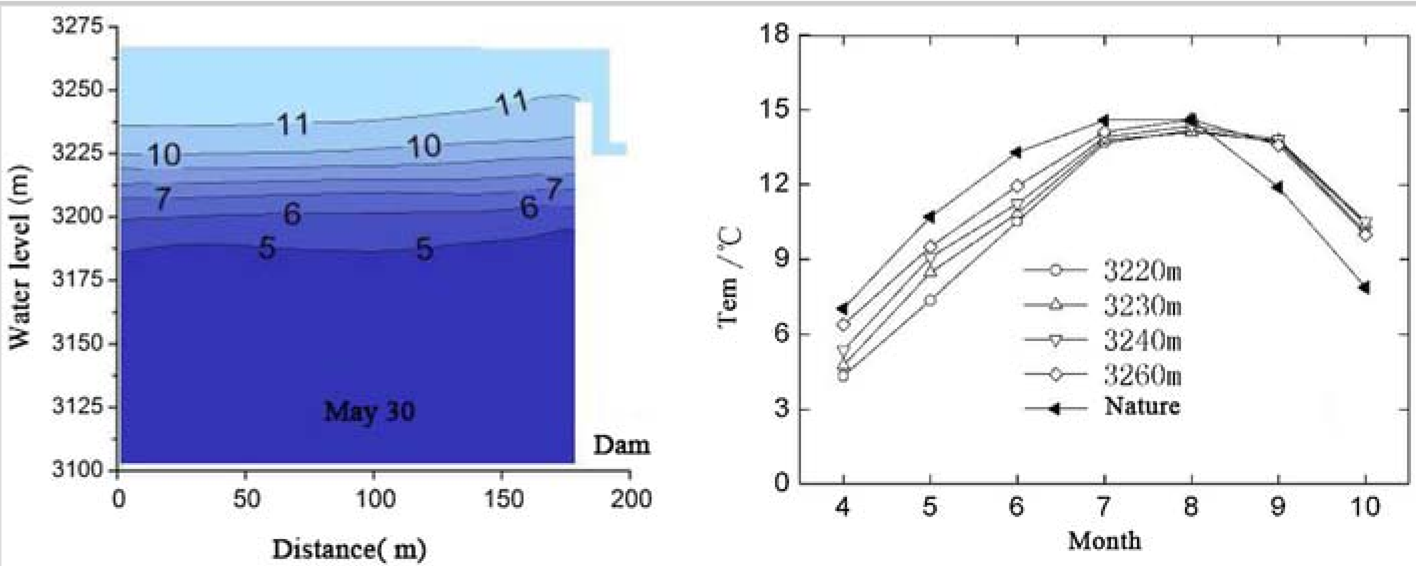
Vertical distribution of water temperature in the reservoir at different diversion locations



The discharge temperatures at the different water intake positions and the natural water temperatures of the dam site vary (Fig. 13). When the height of the water inlet is 3220 m, the maximum temperature difference between the discharge water and the natural condition is 3.3 °C in May, and this difference decreases to 1.2 °C when the height of the water inlet increases to 3260 m. That is, as the elevation of the water inlet increases, the temperature difference between the discharged water and the natural water obviously decreases from April to July. On the other hand, Most of the fish in the study area began to breed at 6 °C. The natural water temperature in the river reached 6 °C on April 6. The simulation results showed that the discharge temperature reached 6 °C on April 27 after the reservoir was impounded, and it reached 6 °C on April 11. When the stratified water intake measure was taken (3260 m). Which is about 20 days earlier than that when the stratified intake was not used, which suggests that stratified intake can effectively mitigate the influence of low water temperatures.

Fig. 13

Discharged water temperature at different diversion locations



Conclusions

This study shows that the water temperatures of reservoirs in the high and cold region of the upper reaches of the Yellow River are mixed to 4 °C in mid-April and that the conditions then change from mixed to stratified. Likewise, the temperature patterns of the reservoirs will change from stratified to mixed in November. Inversion profiles of water temperature will appear, and stratification will return in winter. The temperature of the released water is approximately 2–4 °C lower than the natural water temperature in the spring, which will affect fish spawning in the area. A water temperature model was established to simulate the effects of stratified intake for a new reservoir in the area. The simulation results show that stratified intake can increase the temperature of released water in the spring, the delay time for fish breeding in the study area is reduced from 21 days to 5 days and the maximum temperature difference between the discharge water and the natural condition decreases from 3.3 to 1.2 °C in May. This study can help future studies determine the water temperature structure of reservoirs in cold regions and the associated impacts, which can help managers establish proper reservoir management systems or take appropriate measures to reduce the ecological impacts of reservoirs.

Publisher's Note

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