Effects of reservoir operation and climate change on thermal stratification of a canyon-shaped reservoir, in northwest China

Yang Li, Ting-lin Huang, Zi-zhen Zhou, Sheng-hai Long and Hai-han Zhang

ABSTRACT
Thermal stratification has a significant impact on water quality and ecological characteristics. Reservoir operation and climate change have an effect on the thermal regime. The Jinpen Reservoir is a large canyon-shaped reservoir located in Shaanxi Province with a strong thermal stratification, which resulted in an anaerobic condition in the hypolimnion. We used a hydrodynamic module based on MIKE 3 to simulate the thermal structure of the Jinpen Reservoir and study the relationship between the thermal regime, reservoir operation and climate change. Based on the daily hydrological and climatic data from 2004 to 2013, we made 13 hypothetical simulated conditions that included extreme change of inflow volume, water level, air temperature, radiation, inflow water temperature and selective withdrawal to explore the effect of different factors on the thermal regime. The results showed that the period of thermal stratification, water column stability and surface water temperature were influenced by these factors. With the increase of air temperature, the simulation results indicated a stronger thermal stratification and a higher surface water temperature, which could cause water safety problems. Deep withdrawal could decrease water column stability and prompt water column mixing early, which could be used by reservoir managers to optimize the reservoir operation.

Key words | climate change, numerical simulation, reservoir operation, thermal stratification

INTRODUCTION
Reservoirs play an important role in water supply, irrigation, flood control and electricity generation. Thus, the operation of reservoirs is very important (Huang et al. 2014). In tropical and subtropical zones, most of the reservoirs and lakes exhibit thermal stratification in the summer season (Zhang et al. 2015). Thermal stratification has a significant impact on the dynamics of water quality and ecological characteristics of lakes and reservoirs (Sahoo et al. 2015). Seasonal thermal stratification prevents dissolved oxygen (DO) transport from surface to deeper water layers, which could result in an anaerobic condition in the hypolimnion (Little & McGinnis 2001). Long-term exposure to anoxia leads to a significant deterioration of water quality because nutrients and metal substances continue to diffuse to the hypolimnion through sedimentation (Beutel 2006).

Changes in hydrological and climatic conditions have an effect on the thermal regime of reservoirs (Staben et al. 2015). Hydrological conditions, such as inflow and outflow volume and water level fluctuations, could regulate the structure of thermal stratification and outflow temperature (Moreno-Ostos et al. 2008). Different methods of reservoir operation could change hydrological conditions that include outflow volume and water level. Meanwhile, climatic conditions, such as air temperature and radiation, could have an impact on the thermal regime, mixing depth, heat budget and period of stratification of the reservoir (Winder et al. 2008).
& Schindler 2004). These effects have been widely investigated in several tropical and subtropical reservoirs and lakes (Leira & Cantonati 2008).

Field observations combined with numerical simulation are becoming increasingly important and widely used for exploring reservoirs. Measurements and simulations can be successfully used to illustrate the changes of the thermal regime and hydrological and climatic conditions. A series of hydrodynamic models have been used to study the thermal regime of lakes and reservoirs with useful conclusions (MacKay et al. 2009; Samal et al. 2012).

In this study, we used a three-dimensional hydrodynamic module based on the MIKE 3 software to simulate the thermal structure of a canyon-shaped reservoir and explore the relationship between the thermal regime, reservoir operation and climate change. We took into account the period of thermal stratification, water column stability and surface water temperature under extreme changes on this reservoir to provide management strategies for the reservoir managers.

METHODS

Study site

The Jinpen Reservoir (34°42’–34°13’ N; 107°42’–108°24’ E) is a large canyon-shaped reservoir located in a subtropical zone, approximately 86 km southwest of Xi’an in Shaanxi Province, northwestern China (Figure 1). Xi’an is the capital city of Shaanxi Province, with a population of 8.4 million people. The Jinpen Reservoir is the most important raw water source for Xi’an, providing a daily water supply of 8.0 × 10^5 m^3. When full, the reservoir has a surface area of 4.55 km^2, a total capacity of 2.0 × 10^8 m^3, and a mean and maximum depth of 44 m and 94 m, respectively. Generally, the normal high and minimum water levels are 594 m and 520 m above sea level (a.s.l.), respectively. Originating from the Qinling Mountain, the Heihe River, which drains a catchment area of 1,481 km^2, is the main tributary of the Jinpen Reservoir. Upstream and surrounding landscapes of the reservoir are largely unmodified hills covered with forests and showing little human activity.

Field observations

Weekly sampling campaigns were started in July 2012. Three sampling sites were located in the reservoir (S1, S2) and the inlet (S0) of the Heihe River. Vertical profiles of temperature, DO and turbidity were measured using Hydro-lab DS5 (Hach, USA). Samples from S0 were taken about 0.5 m below the surface. Samples from sites within the reservoir (S1, S2) were taken every 10 m from the surface (0.5 m below the surface) to the bottom (0.5 m above the sediments). All samples were stored at 4 °C immediately after collection. The total nitrogen (TN) and total phosphorus (TP) were measured within 24 h using the official recommended methods (SEPA of China 2002).
Daily hydrological and climatic data included inflow and outflow water level and temperature, air temperature, radiation, precipitation and evaporation from 2004 to 2013, which were obtained from the Jinpen Reservoir Administration Bureau and the automatic weather station.

**Numerical simulation and data analysis**

We used a three-dimensional hydrodynamic module based on MIKE 3 to simulate the thermal structure of the Jinpen Reservoir. MIKE 3 was developed by the Danish Hydraulic Institute (DHI) and had been successfully used for many reservoirs and bays (Liu et al. 2007; Wei et al. 2013; Zeinoddini et al. 2013). The simulated domain included the Heihe River and the Jinpen Reservoir from the sampling site S0 to the reservoir dam. We measured the bathymetry of the domain and generated the unstructured triangular meshes with a maximum area of 0.02 km$^2$ and a Minimum Angle of 30 degrees. To enhance the computational efficiency, we used a variable vertical grid divided by a combined sigma z-level method, which contained 20 layers. The total cells of this numerical model were 4905. The computation period was 365 days from 1 July 2012 to 30 June 2013.

Numerous thermal stratification indexes were used to evaluate the strength of the thermal stratification such as the Schmidt stability index, Wedderburn Number and Lake Number (Idso 1973; Read et al. 2011; Xiao et al. 2011). In this study, we used the Schmidt stability index (Idso 1973), which was set at a threshold value of 49 J/m$^2$ to determine the start and end of stratification (Winder & Schindler 2004):

$$S = \frac{g}{A_0} \int_0^{Z_{max}} A_z (Z - z^*) (\rho_z - \bar{\rho}) dz$$  \hspace{1cm} (1)

where $A_0$ is the surface area of the lake (m$^2$), $A_z$ is the lake area at depth $z$ (m), $\rho_z$ is density as calculated from the temperature at depth $z$ (m), $\bar{\rho}$ is the lake’s mean density, $z^*$ is the depth where the mean density occurs, $dz$ is the depth interval and $g$ is the acceleration due to gravity (m/s$^2$).

The density of water was calculated as (Li & Shen 1990):

$$\rho = 1000 - 1.9549 \times 10^{-2} |T - 4|^{1.68} + 0.623 \times S$$  \hspace{1cm} (2)

where, $T$ is the water temperature and $S$ is the concentration of suspended solids (SS).

**RESULTS AND DISCUSSION**

**Variation of hydrological and climatic data**

The annual mean water level varied between 588.28 m and 569.59 m with a decreasing trend (Figure 2(a)). The annual total inflow volume was roughly equal to an annual total outflow volume in the range of $3.55 \times 10^8$ m$^3$ to $8.05 \times 10^8$ m$^3$ and $3.07 \times 10^8$ m$^3$ to $7.92 \times 10^8$ m$^3$, respectively.
(Figure 2(a)). It showed that variations in the inflow and outflow volumes were evident in the past 10 years.

The annual total radiation varied between $4.07 \times 10^3$ MJ/m$^2$ and $4.80 \times 10^3$ MJ/m$^2$ and had small oscillations (Figure 2(b)). The inflow water temperature changed with air temperature with an increasing tendency and had a range of $10.10 \degree C$ to $12.10 \degree C$ and $12.70 \degree C$ to $15.40 \degree C$, respectively (Figure 2(b)).

Based on the daily hydrological and climatic data from 2004 to 2013, we made 13 hypothetical simulated conditions (SC0-SC12) to research the effects of different factors on the thermal regime of the Jinpen Reservoir. SC0 was a baseline in the Jinpen Reservoir and the hydrological and climatic data were equal to the average value from 2004 to 2013. The other simulated conditions (SC1-SC12) represented the extreme change within the range that occurred from 2004 to 2013 (Table 1).

### Seasonal characteristics of water quality

The Jinpen Reservoir had a long period of stratification with a maximum temperature of 24.62 $\degree C$ at the surface (August 2012, Figure 7(b)) and a minimum temperature of 5.84 $\degree C$ during mixing (February 2013, Figure 7(f)). During the stratified period, the transfer of DO from the upper to deeper water was limited. With the consumption of DO by organic matter in sediments and suspension in water bodies, the available DO in the hypolimnion was rapidly diminished. Generally, the anoxic condition in the hypolimnion occurred in August 2012, October 2012 and from April to June 2013 (Figure 3). Field observations were conducted in the Jinpen Reservoir to ascertain the water quality and structure of phytoplankton and zooplankton communities, and the results showed a mesotrophic condition (Ma et al. 2013).

The turbidity varied between 2 NTU and 495 NTU with a great change width (Figure 3). In a stratified reservoir, the inflow water would flow into a layer with an equivalent density. The water density was thought to be primarily determined by water temperature and SS (Fan & Kao 2008). Previous research had shown that the effect of SS could be ignored if its concentration was lower than 0.8 kg/m$^3$ (Yang et al. 2010). In this study, we established a relationship between the turbidity and SS concentration in the Jinpen Reservoir (Figure 4). The maximum turbidity value was 495 NTU, which corresponded to 0.3 kg/m$^3$. Therefore, we concluded that water temperature is the main factor influencing water density.

### Table 1 | Description of hypothetical simulated conditions

<table>
<thead>
<tr>
<th>Simulated conditions</th>
<th>Simulated factors</th>
<th>Inflow volume ($\times 10^8$ m$^3$)</th>
<th>Water level (m)</th>
<th>Air temperature ($\degree C$)</th>
<th>Solar radiation (MJ/m$^2$)</th>
<th>Inflow water temperature ($\degree C$)</th>
<th>Withdrawal depth (m a.s.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC0</td>
<td>Baseline</td>
<td>4.98</td>
<td>579.54</td>
<td>14.10</td>
<td>4.48</td>
<td>10.90</td>
<td>554.00</td>
</tr>
<tr>
<td>SC1</td>
<td>High inflow</td>
<td>8.05</td>
<td>579.54</td>
<td>14.10</td>
<td>4.48</td>
<td>10.90</td>
<td>554.00</td>
</tr>
<tr>
<td>SC2</td>
<td>Low inflow</td>
<td>3.55</td>
<td>579.54</td>
<td>14.10</td>
<td>4.48</td>
<td>10.90</td>
<td>554.00</td>
</tr>
<tr>
<td>SC3</td>
<td>High water level</td>
<td>4.98</td>
<td>588.28</td>
<td>14.10</td>
<td>4.48</td>
<td>10.90</td>
<td>554.00</td>
</tr>
<tr>
<td>SC4</td>
<td>Low water level</td>
<td>4.98</td>
<td>560.59</td>
<td>14.10</td>
<td>4.48</td>
<td>10.90</td>
<td>554.00</td>
</tr>
<tr>
<td>SC5</td>
<td>High air temperature</td>
<td>4.98</td>
<td>579.54</td>
<td>15.40</td>
<td>4.48</td>
<td>10.90</td>
<td>554.00</td>
</tr>
<tr>
<td>SC6</td>
<td>Low air temperature</td>
<td>4.98</td>
<td>579.54</td>
<td>12.70</td>
<td>4.48</td>
<td>10.90</td>
<td>554.00</td>
</tr>
<tr>
<td>SC7</td>
<td>High radiation</td>
<td>4.98</td>
<td>579.54</td>
<td>14.10</td>
<td>4.82</td>
<td>10.90</td>
<td>554.00</td>
</tr>
<tr>
<td>SC8</td>
<td>Low radiation</td>
<td>4.98</td>
<td>579.54</td>
<td>14.10</td>
<td>4.01</td>
<td>10.90</td>
<td>554.00</td>
</tr>
<tr>
<td>SC9</td>
<td>High inflow water temperature</td>
<td>4.98</td>
<td>579.54</td>
<td>14.10</td>
<td>4.48</td>
<td>12.10</td>
<td>554.00</td>
</tr>
<tr>
<td>SC10</td>
<td>Low inflow water temperature</td>
<td>4.98</td>
<td>579.54</td>
<td>14.10</td>
<td>4.48</td>
<td>10.10</td>
<td>554.00</td>
</tr>
<tr>
<td>SC11</td>
<td>Shallow withdrawal</td>
<td>4.98</td>
<td>579.54</td>
<td>14.10</td>
<td>4.48</td>
<td>10.90</td>
<td>564.00</td>
</tr>
<tr>
<td>SC12</td>
<td>Deep withdrawal</td>
<td>4.98</td>
<td>579.54</td>
<td>14.10</td>
<td>4.48</td>
<td>10.90</td>
<td>544.00</td>
</tr>
</tbody>
</table>
Field investigations conducted from 2012 to 2013 showed that TP was significantly correlated with turbidity \((R = 0.938, P < 0.01)\) but was not strongly correlated with TN \((R = 0.272, P > 0.01)\) (Figures 3 and 5). This suggested that the major components of phosphorus are particulates. The vertical distribution of TN changed slightly, but TP had an intense oscillation and was abundant in a deep layer most of the year (Figure 5).

**Numerical simulation verification**

S1 and S2 were located in the reservoir and had the same trend of water temperature variation. Therefore, in this study we chose one of these two sampling sites (S2) to discuss the simulation results. The simulation results were compared with the measurements (Figures 6 and 7). The position of the thermocline and the period of the stratification were predicted accurately, which suggested that the simulation method was effective. There was a large seasonal fluctuation in water level \((544.9–592.5\text{ m a.s.l.})\), and a seasonal thermocline variation between 510 m and 550 m a.s.l. during the stratified period (Figure 7).

**Results of different simulated conditions**

The results indicated that the hydrological and climatic factors had a different impact on the thermal regime (Table 2), which had an obvious effect on the mixing period. Conditions
Figure 5 | Vertical distribution of total phosphorus (TP) and total nitrogen (TN) at S1.

Figure 6 | (a) Simulated and (b) measured temperature variation at S2.
with high inflow (SC1), low water level (SC4), low air temperature (SC6), low radiation (SC8), low inflow water temperature (SC10), and deep withdrawal (SC12) had a longer mixing period than the baseline (SC0). The other six simulated conditions (i.e. SC2, SC3, SC5, SC7, SC9, and SC11) had shorter mixing periods than the baseline.

The Jinpen Reservoir is a canyon-shaped reservoir and has a huge water volume that exhibits significant water column stability. The results showed that high inflow (SC1) could cause early mixing in late autumn and reduce water column stability in spring and autumn significantly (Figure 8(a)) because high inflow strengthens turbulence and causes vertical mixing. Low inflow (SC2) caused obviously higher water column stability in summer (Figure 8(a)) and delayed the end of thermal stratification compared with the baseline (SC0). Seasonal rainfall events

### Table 2 | Result of different simulated conditions

<table>
<thead>
<tr>
<th>Simulated conditions</th>
<th>Start of thermal stratification</th>
<th>End of thermal stratification</th>
<th>Total mixing days (d)</th>
<th>Mean Schmidt stability (J/m²)</th>
<th>Mean surface temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC0</td>
<td>03/12</td>
<td>10/23</td>
<td>141</td>
<td>1,675.7</td>
<td>16.5</td>
</tr>
<tr>
<td>SC1</td>
<td>03/26</td>
<td>10/15</td>
<td>163</td>
<td>1,307.4</td>
<td>17.0</td>
</tr>
<tr>
<td>SC2</td>
<td>03/11</td>
<td>11/01</td>
<td>131</td>
<td>1,884.3</td>
<td>16.2</td>
</tr>
<tr>
<td>SC3</td>
<td>03/09</td>
<td>10/25</td>
<td>136</td>
<td>1,898.5</td>
<td>16.8</td>
</tr>
<tr>
<td>SC4</td>
<td>03/13</td>
<td>10/14</td>
<td>151</td>
<td>1,463.1</td>
<td>16.2</td>
</tr>
<tr>
<td>SC5</td>
<td>03/05</td>
<td>10/26</td>
<td>151</td>
<td>1,867.1</td>
<td>17.4</td>
</tr>
<tr>
<td>SC6</td>
<td>03/12</td>
<td>10/12</td>
<td>152</td>
<td>1,505.7</td>
<td>15.5</td>
</tr>
<tr>
<td>SC7</td>
<td>03/10</td>
<td>10/23</td>
<td>139</td>
<td>1,751.9</td>
<td>16.8</td>
</tr>
<tr>
<td>SC8</td>
<td>03/16</td>
<td>10/23</td>
<td>145</td>
<td>1,541.6</td>
<td>16.0</td>
</tr>
<tr>
<td>SC9</td>
<td>03/10</td>
<td>10/25</td>
<td>137</td>
<td>1,786.5</td>
<td>16.7</td>
</tr>
<tr>
<td>SC10</td>
<td>03/15</td>
<td>10/21</td>
<td>146</td>
<td>1,539.2</td>
<td>16.3</td>
</tr>
<tr>
<td>SC11</td>
<td>03/10</td>
<td>10/26</td>
<td>136</td>
<td>1,778.7</td>
<td>16.8</td>
</tr>
<tr>
<td>SC12</td>
<td>03/17</td>
<td>10/13</td>
<td>155</td>
<td>1,424.2</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Figure 7 | Vertical distribution of measured and simulated water temperature at S2.
were influenced by the monsoon climate, and more than 60% of the annual precipitation was recorded during July–September for the Jinpen Reservoir (Huang et al. 2014). High inflow (SC1) caused 22 and 32 mixing days more than baseline (SC0) and low inflow (SC2), respectively (Table 2). High water level (SC3), which meant low discharge, was associated with greater stability in summer and autumn (Figure 8(b)). The influence of the low water level (SC4) was more obvious in spring when the reservoir was at its lowest level (Figure 8(b)). Changes in air temperature had an evident influence on water stability in spring and summer (Figure 8(c)) when the higher air temperature (SC5)
was associated with greater stability, and had 10 mixing days fewer than the baseline (Table 2). Lower air temperature (SC6) caused obviously lower water column stability in spring and summer (Figure 8(c)) and had 11 mixing days more than the baseline (Table 2). For radiation and inflow water temperature, the effects were not as obvious (Figure 8(d) and 8(e)). The high radiation (SC7) and high inflow water temperature (SC9) caused 2 and 4 mixing days fewer than the baseline, respectively, whereas the low radiation and low inflow water temperature caused 4 and 5 mixing days more than the baseline, respectively. The total annual radiation varied little in the past 10 years. In the dry season, the inflow volume was very small, so the inflow water temperature had little effect on the water column stability. However, the increase in intake had an evident effect on the thermal regime. Deep withdrawal could weaken the water column in autumn and promote water mixing to advance. The mixing days of deep withdrawal (SC12) were 14 days more than the baseline (SC0) (Table 2), and 19 days more than the shallow withdrawal (SC11). In spring and summer, water levels were low in the Jinpen Reservoir. Shallow withdrawal might bring phytoplankton from the upper layer of the water column into the water treatment plant, which could make the water unsafe for drinking and increase the cost of water treatment. Therefore, selective withdrawal is an important strategy for the reservoir’s operation.

As artificial structures, the thermal regimes of reservoirs are influenced by anthropogenic and natural factors. In the Jinpen Reservoir, the hydrological and climatic data showed a decreasing trend of annual mean water level and an increasing trend of annual mean air temperature and inflow water temperature (Figure 2(a) and 2(b)). This might be due to the rapid development of Xi’an and global warming. It has been proved that global warming could change the thermal structure of lakes and reservoirs, delay water mixing, and decrease the thermocline depth in autumn (Naselli-Flores & Barone 2005; Coats et al. 2006). These changes would accelerate the consumption of DO in the hypolimnion and cause nutrients to be released from sediments (Beutel 2006; Huang et al. 2014). The changes in climate that occurred from 2004 to 2013 might lead to strong variations of annual total inflow volume (Figure 2(a)). However, changes in radiation were not obvious, and the simulation results suggested that it had little effect on the thermal regime of the Jinpen Reservoir.

Because of the undercurrent, changes in inflow volume had little effect on surface water temperature except in summer and autumn (Figure 9(a)). The air temperature was the main factor that affected the surface water temperature. A higher air temperature (SC5) led the mean surface water temperature to be about 0.9°C higher than the baseline and about 1.9°C higher than the low air temperature (SC6), respectively (Figure 9(c)). Surface water temperature can be influenced greatly by an increase in air temperature (Figure 9(c), Table 2). Previous studies showed that the surface water temperature was the key parameter of water-atmosphere interactions involving the energy exchange between the water and atmosphere (Fedorov & Philander 2001). A continuous surface water temperature increase could cause a longer thermal stratification with anoxic conditions and water quality problems (Beutel 2006). A high air temperature could lead to a longer thermal stratification, causing the surface water temperature to rise, which had a negative effect on the aquatic ecosystem in the Jinpen Reservoir. Variations of water level, radiation and inflow water temperature have almost no effect on surface water temperature (Figure 9(b), 9(d) and 9(e)). Deep withdrawal (SC12) had a stronger impact on surface temperature than on the shallow withdrawal (SC11) in late autumn because deep withdrawal caused heat exchange between the upper and deep layers.

In many reservoirs, thermal stratification could cause an anoxic condition in the lower water levels and promote nutrients to be released from sediments (Beutel et al. 2008; Zhang et al. 2015). In our study, the seasonal anoxic conditions occurred in the deeper layer of the water column of the Jinpen Reservoir (Figure 3). The simulated conditions with high inflow volume, low water level, low air temperature, low radiation, low inflow water temperature and deep withdrawal were associated with a longer mixing period than the baseline. On the contrary, the remainder of the simulated conditions had a shorter mixing period than the baseline. In the future, we should continue to monitor water quality and collect hydrological and climatic data to improve the simulated model. As an effective method, reservoir managers could use the deep withdrawal at the right time to optimize the operation of the Jinpen Reservoir.
CONCLUSIONS

The Jinpen Reservoir is a canyon-shaped reservoir in the subtropical zone, northwest China, with a long period of thermal stratification. Ten years of hydrological and climatic data showed that the water level of the Jinpen Reservoir displayed a decreasing trend because of the increasing water demand in this region. The annual total inflow volume showed intense oscillations along with the extreme weather that has occurred in recent years. The annual mean air
temperature and annual mean inflow water temperature showed an increasing trend because of global warming. However, the radiation changed little in these years.

By comparing the simulation with the measured temperature data, the simulation accurately predicted the position of the thermocline and period of stratification. Based on the hydrological and climatic data from 2004 to 2013, we investigated 15 simulated conditions. The results suggested that high inflow and low water level, low air temperature, low radiation, low inflow water temperature and deep withdrawal caused lower water column stability and a longer mixing period than the baseline. However, the other six simulated conditions strengthened the thermal stratification and caused a shorter mixing period than the baseline.

The simulation results indicated that the water column stability was more sensitive to hydrological and climatic changes in spring. The inflow volume, water level and air temperature were more important than other factors for water column stability. Deep withdrawal could decrease water column stability in autumn and prompt water column early mixing, which could be used by reservoir managers to optimize reservoir operations. The increasing trend of air temperature led to strengthening of the thermal stratification, whereas the surface water temperature rise caused water safety problems.

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REFERENCES


Yang, Z., Liu, D., Ji, D. & Xiao, S. 2010 Influence of the impounding process of the Three Gorges reservoir up to water level 172.5 m on water eutrophication in the Xiangxi Bay. Science China Technological Sciences 53 (4), 1114–1125.


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