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Impacts of cascade reservoirs on Yangtze River water temperature: Assessment and ecological implications

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ABSTRACT

The natural hydrological regime of the Yangtze River has been influenced by dam construction over past decades. More reservoirs are being built and have been planned in the upper reach of the Yangtze River (URYR). To investigate the effects of reservoirs in the URYR and the Three Gorges Reservoir (TGR) on the water temperature regime, a reservoir water heat model combined with the Soil and Water Assessment Tool is used to simulate the water temperature change under different scenarios. The results show that the water temperature regime has been dramatically altered by reservoir operation, especially in spring and autumn. Reservoir operations impose a noticeable hysteresis effect on water temperature rising and falling processes, thereby resulting in a delay of the suitable temperature date for the Chinese Sturgeon (*Acipenser sinensis*) and four famous major carps. When more reservoirs are put into use, the delays in the target spawning times of these fishes will be further exacerbated. Modifying operation modes of these reservoirs and depth of water release is necessary during fish spawning seasons, which could facilitate a better balance between ecological and socioeconomic demands. We hope the results of this study will be useful to the river ecosystem health and stability.

1. Introduction

Rivers provide numerous goods and services for humankind, including a source of water for domestic, industrial and agricultural purposes, a means of power generation and waste disposal, routes for navigation, and sites for recreation and spiritual activities (Ripl, 2003). However, dams and reservoirs have changed river flow regimes, sediment regimes and water temperature regimes worldwide (Nilsson et al., 2005; Syvitski et al., 2005; Li, 2012; Kumum et al., 2010; Graf, 2006; Dai et al., 2014; Zhou et al., 2016; LeRoy and Zimmerman, 2010; Prats et al., 2012; Latrubesse et al., 2017; Wang et al., 2018, 2016). Alterations in the water temperature regime caused by reservoir operations have important consequences for river ecosystems (Preece and Jones, 2002; Caissie, 2006; Webb et al., 2008; Olden and Naiman, 2010; Kędra and Wiejaczka, 2018). Todd et al. (2005) indicated that the impact of the low temperature water released by reservoirs on post-spawning survival rates posed a significant threat to the viability of a Murray cod population.

In recent years, numerous studies have been conducted on river temperature (King et al., 1998; Steel and Lange, 2007; Webb et al., 2008; Wright et al., 2009; Piotrowski et al., 2015; Lewis and Rhoads, 2015; Toffolon and Piccolroaz, 2015; Dugdale et al., 2017; Ferencz and Cardenas, 2017; Graf et al., 2019; Zhu et al., 2020; Heddam et al., 2020). Many temperature models have been developed to predict stream water temperature. Prats et al. (2012) used a modeling approach to determine the equilibrium temperature and recuperation distance for different seasons and hydrological years in the Lower Ebro River (Spain). Toffolon and Piccolroaz (2015) developed a model to predict the daily average river water temperature as a function of air temperature and discharge, with discharge being more relevant in some specific cases. Piotrowski et al. (2015) compared four artificial neural network types and the nearest neighbor approach for short-term stream water temperature predictions in two natural catchments. Other studies have been done to assess the effects of climate change and human activity on river temperature (Wright et al., 2009; Dickson et al., 2012; Cai et al., 2018; Kędra and Wiejaczka (2018). Preece and Jones (2002) investigated the river water temperature change caused by the Keepit Dam on the Namoi River, Australia, and indicated that the change disrupted thermal spawning cues for select Australian native fish species. Olden and Naiman (2010) analyzed the ecological consequences of

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dam-induced modifications to riverine thermal regimes and suggested incorporating water temperature targets into environmental flows standards for water abstraction practices. However, few studies have been done to assess the impacts of the cascade reservoirs on river water temperature.

The Yangtze River is one of the most important rivers in the world, and has become one of the most highly impacted rivers due to human activity. Many studies have been implemented to assess the hydrological regime changes caused by dams and reservoirs (Zhang et al., 2009, 2012a; Dai and Liu, 2013; Ban et al., 2016; Wang et al., 2016, 2018). Zhang et al. (2012a) analyzed the long monthly streamflow and sediment load series change using a scanning *t*-test and F-test and indicated that the construction of water storage reservoirs exerted a massive influence on sediment load variations. Wang et al. (2018) assessed the impacts of cascade dam development in the upper reaches of the Yangtze River on its natural flows by using a hydrological model (the Soil and Water Assessment Tool). Cai et al. (2018) indicated that the thermal effect caused by the Three Gorges Dam TGD was large at Yichang station, immediately downstream of the dam, by using the air2stream model. However, the potential impacts of cascade hydropower development in the upper reaches of the Yangtze River on water temperature remain unknown.

More large dams are being built and have been planned in the upper reaches of the Yangtze River (URYR). These new reservoirs will further affect the water temperature of the middle and lower Yangtze River. Therefore, the objectives of this paper are to (a) examine water temperature regime changes caused by cascade reservoirs in the URYR and the TGR and (b) assess the potential ecological impacts of water temperature regime changes caused by reservoirs in the URYR and the TGR.

2. Materials and methods

2.1. Cascade reservoirs construction in the upper reaches of the Yangtze River

The Yangtze, which is 6,380 km long, is the longest river in Asia and the third-longest in the world. The upper reaches of the Yangtze River covers an area of 10.56×10^5 km^2, which is approximately 58.9% of the entire Yangtze River Basin (Fig. 1) and is rich in water resources, with large headwaters and abundant opportunities for hydropower (Wang et al., 2018). According to the major rivers cascade development plan in the URYR, the layout of major river cascade reservoirs in the URYR will be completed by 2020 (Zhang et al., 2012b). The capacity of reservoirs under construction is more than 700×10^8m^3 while the capacity of reservoirs that have been planned is more than $2{,}000 \times 10^8$m^3 (Wang et al., 2018). Water temperature regime has been influenced by dam construction (Wang et al., 2012a, 2014; Cai et al., 2018). Consequently, the water temperature regime will be further influenced by the cascade reservoirs construction in the URYR. In the present study, 38 reservoirs are considered in the URYR.

2.2. Important fishes

The Yangtze River is a major pool of fish resources, a major habitat for rare aquatic animals, and the cradle of Chinese freshwater aquaculture. For many years, the Yangtze River basin has produced approximately 60% of the freshwater fish in China (Li, 2001). Chinese sturgeon (*Acipenser sinensis*) is an anadromous protected species that migrates from brackish water or the water of the East China Sea to Jinsha River spawning grounds in the upper reaches of the Yangtze River (Fig. 2). Dam construction blocked their migration paths, and the spawning grounds have shrunk from a length of 600 km to only 30 km in the Yichang reach, downstream of the Gezhouba Dam (Wang et al., 2012b). Due to human activity and changes in environmental factors, the spawning rate of the fish dropped by 80%. Chinese sturgeon spawning occurs when the water temperature ranges from 15.3 °C to 20.0 °C during the spawning season (October to November). The best suitable water temperature is 18.0 °C to 20.0 °C for Chinese sturgeon spawning activity. In general, Chinese sturgeon begin to spawn when the water temperature drops to 20 °C in October (Wei, 2003). Four famous major carp species (FFMC) – black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idellus*), silver carp (*Hypophthalmichthys molitrix*), and bighead carp (*Aristichthys nobilis*). – are important freshwater fish resources in the Yangtze River (Fig. 2). Due to changes in the ecohydrological conditions required by the FFMC, the number of fry decreased from 6.7 billion in 1981 to only approximately 1.9 billion in 2001 (Liu et al., 2004). After the impoundment of the TGR, adult populations decreased by more than 50% (Wang et al., 2016). FFMC spawning occurs when water temperature is between 18 °C and 24 °C during the spawning season (April to June). FFMC begin to spawn when the water temperature rises to 18 °C in April (Yi et al., 1988).

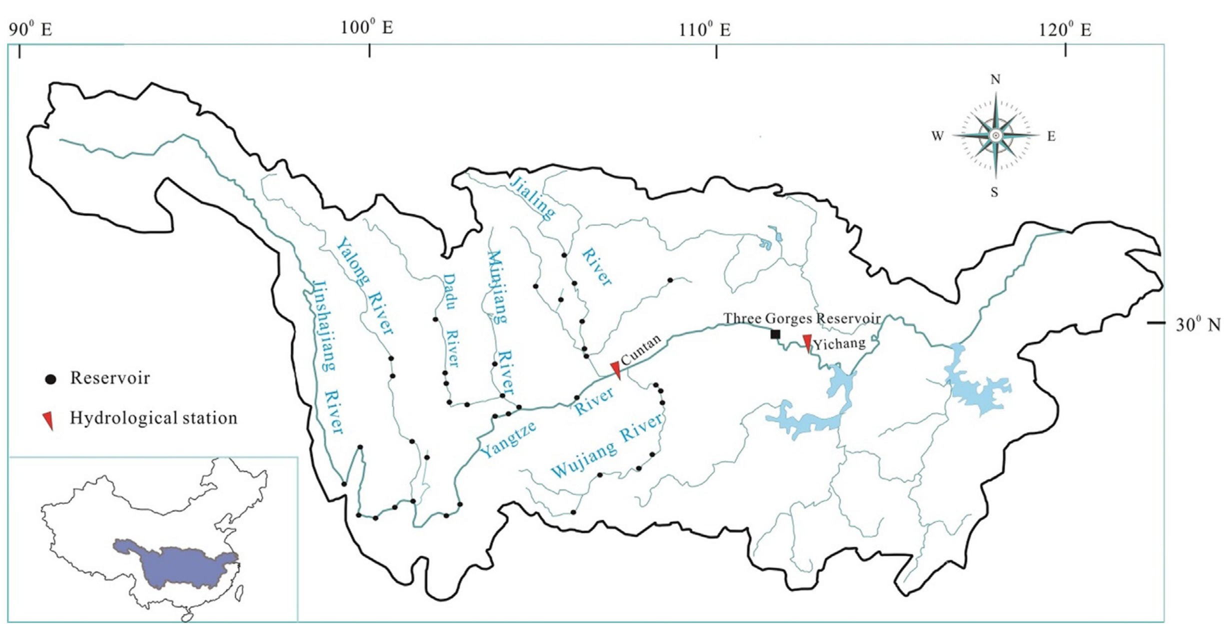
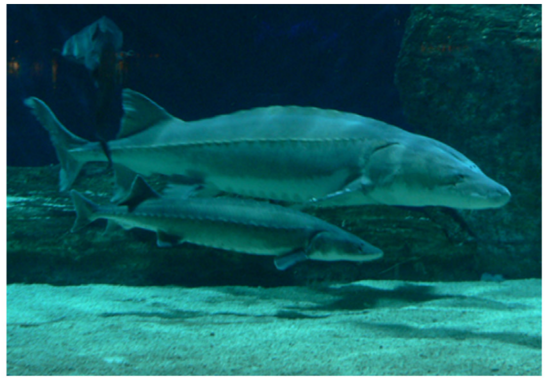


Fig. 1. Reservoirs and gauging stations in the study sites.



(a) Chinese sturgeon (Acipenser sinensis)

(b) Black carp (Mylopharyngodon piceus)

(c) Grass carp (Ctenopharyngodon idellus)

(d) Silver carp (Hypophthalmichthys molitrix)

(e) Bighead carp(Aristichthys nobilis)

* Pictures are from reference of Li 2012.

Fig. 2. Important fishes in the study sites.

2.3. Water temperature model

To investigate the impacts of hydropower cascade development in the URYR on the hydrological regime, the Soil and Water Assessment Tool (SWAT) was used to simulate the flow processes. The simulated discharge was used as the input of reservoir water heat model. The model is verified with the measured water temperatures downstream the TGR. The flow chart of model system is shown in Fig. 3.

2.3.1. SWAT model

The SWAT is an ecohydrological model for the river basin scale incorporating over 30 years of model development at the co-located US Department of Agriculture and Texas A&M University laboratories at Temple, Texas. SWAT has undergone continuous review, testing, modification and enhancement, and has already been widely applied in the Yangtze River with promising results to represent hydrological processes (Wang et al., 2018). To investigate the impacts of hydropower cascade development in the URYR on the hydrological regime, the SWAT was used to simulate the flow processes. Calibration and verification of the SWAT were implemented from 1966 to 1985 based on field discharge from the Changjiang Water Resources Commission. Details on the calibration and verification procedures can be found in Zhang et al. (2012b) and Wang et al. (2018). Simulated discharges of the SWAT model are taken as the input of the reservoir water heat

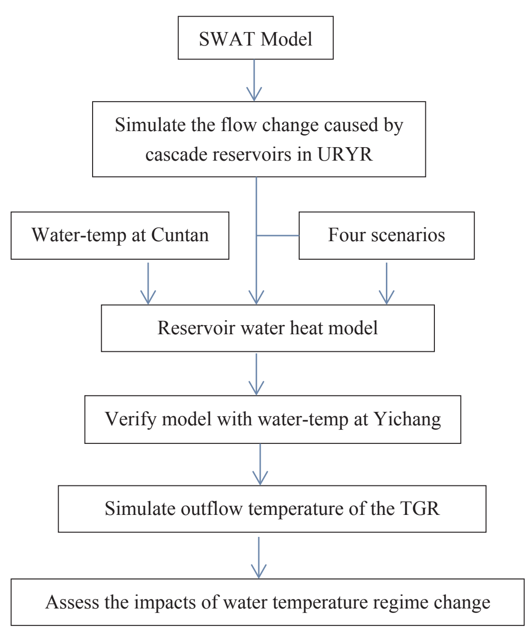


Fig. 3. Flowchart of river water temperature model system.

model.

2.3.2. Reservoir water heat model

The reservoir water heat model is applied to analyze the change of water temperature caused by the reservoir by comparing the water temperature of the inflow and outflow of the reservoir. This model focuses on the river water-heat changes caused by reservoirs in the longitudinal direction along the river, so the water - heat exchange in the vertical direction of the reservoir water body is not considered in the model (Zou, 2008).

The reservoir water balance equation can be expressed as:

$$I(\Delta t)\Delta t - O(\Delta t)\Delta t = \Delta S \tag{1}$$

where $I(\Delta t) = \frac{I(t-\Delta t)+I(t)}{2}$ represents the mean discharge of reservoir inflow from time $t - \Delta t$ to time t. $O(\Delta t) = \frac{O(t-\Delta t)+O(t)}{2}$ represents the mean reservoir outflow discharge from time $t - \Delta t$ to time t. ΔS represents the change of reservoir water volume. Δt is the time step, either in hours or days. In this study, time step Δt is set at 1 day.

The change of reservoir heat during Δt period can be expressed as:

$$T_I(\Delta t)I(\Delta t)\Delta t - T_O O(\Delta t)\Delta t = \Delta E \tag{2}$$

where ΔE represents the change of reservoir heat. $T_I(\Delta t) = \frac{T_I(t-\Delta t)+T_I(t)}{2}$ represents the mean water temperature of reservoir inflow from time $t - \Delta t$ to time t. $T_I(t - \Delta t)$ is the water temperature of inflow at time $t - \Delta t$. $T_I(t)$ is the water temperature of inflow at time t. $T_O(\Delta t) = \frac{T_O(t-\Delta t)+T_O(t)}{2}$ represents the mean water temperature of reservoir outflow from time $t - \Delta t$ to time t. $T_O(t - \Delta t)$ is the water temperature of outflow at time $t - \Delta t$. $T_O(t)$ is the water temperature of outflow at time t.

The product of the unit water volume and unit water temperature at a certain moment is called unit water body heat, which represents heat carried by the unit volume of water. Hence, ΔE can be defined as:

$$\Delta E = S(t)T_R(t) - S(t-\Delta t)T_R(t-\Delta t) \tag{3}$$

where $S(t)$ and $S(t - \Delta t)$ is the reservoir water storage volume at time t and $t - \Delta t$, respectively. $T_R(t)$ and $T_R(t - \Delta t)$ is the reservoir water temperature at time t and $t - \Delta t$, respectively.

Combining equations (2) and (3):

$$T_R(t) = \frac{I(\Delta t)T_I(\Delta t)\Delta t + S(t-\Delta t)T_R(t-\Delta t) - O(\Delta t)T_O\Delta t}{S(t)} \tag{4}$$

where $S(t) = I(\Delta t)\Delta t + S(t - \Delta t) - O(\Delta t)\Delta t$

Thus, the outflow water temperature can be obtained:

$$T_O(t) = T_R(t-\Delta t) \tag{5}$$

In this study, the SWAT model was applied to examine the effects of cascade reservoirs in the URYR on flow processes. The simulated discharge of SWAT was used as the inflow of the Three Gorges Reservoir to assess the impacts of flow change caused by the cascade reservoirs in the URYR on the water temperature regime via use of the reservoir water heat model proposed here. Due to limited measured data, the water temperature at Yichang station in 1983 was taken as the natural water temperature (Baseline) without any reservoir construction. The water temperature at Cuntan is taken as the inflow temperature of the Three Gorges Reservoir and the water temperatures at Yichang station is taken as the outflow temperature in 2012 in verification of the reservoir water heat model (Table 1). Daily water temperature at the two hydrological stations were provided by the Yangtze River Water Resources Commission.

Table 1
Information of the studied hydrological gauge stations.

Stations	Locations	Drainage area (10^4 km^2)
Cuntan	106°36′E 29°37′N	86.7
Yichang	111°18′E 30°42′N	100.6

Table 2
Scenarios setup in hydrological simulation.

Scenario	Reservoir of URYR
1	No reservoir
2	Reservoirs that have been built
3	Reservoirs that have been built and are under construction
4	All reservoirs

To assess the impacts of cascade reservoirs in the URYR and the TGR on the water temperature regime, according to the hydropower development plan of the Yangtze, four hypothetical scenarios are developed in the present study (Table 2).

Scenario 1: No reservoir in the URYR, but the TGR is considered.

Scenario 2: Reservoirs that have been built in the URYR and TGR are considered.

Scenario 3: Reservoirs that have been built and are under construction in the URYR and TGR are considered.

Scenario 4: All reservoirs in the URYR and TGR are considered.

3. Results and discussion

3.1. Verification of the reservoir water heat model

The verification of the model was carried out with the observed data. Measured water temperatures at the Yichang hydrological station in 2012 were used in the model's verification. The relative root mean square error of the final calibration is 1.11 °C. The agreements between the measured and simulated values in Fig. 4 are a strong measure of the accuracy of the simulation, and, as such, the output of the model proposed here is adoptable.

3.2. Water temperature changes caused by cascade reservoirs

Fig. 5 shows the water temperature below the TGR in four different scenarios based on the reservoir water heat model. The water temperature below the TGR varies greatly when more reservoirs are involved in the operation. The water temperature has been influenced dramatically throughout the whole year. In spring (March to May), water temperatures in scenarios 1, 2, 3, and 4 are higher than those of the inflow of the Three Gorges Reservoir. This means that the reservoirs' operation alters the water temperature processes. The water temperatures in scenarios 2, 3, and 4 are also higher than those in scenario 1, which means that more reservoirs built in the upper reaches of the Yangtze River will further influence the water temperature. In summer (June to August), there are no noticeable changes in the four scenarios, which can be attributed to operation rules. For flood control, the Three Gorges Reservoir runs at the flood control limit water level in summer, which means that the outflow is equal to the inflow of the reservoir. Hence, reservoir operation will not impose effects on water temperature below the reservoir. In autumn, reservoir operation decreased the water temperature regime. From Fig. 4, the outflow water temperatures of the TGR have changed greatly. Outflow water temperatures are less than inflow temperatures in the four scenarios, because the reservoir starts storing water in the middle of September until the reservoir level reaches 175 m. In winter (December to February), the outflow water temperatures are also less than the inflow temperatures because of reservoir operation.

Fig. 6 shows the water temperature changes in the four different scenarios compared to the water temperature without the Three Gorges Reservoir (Baseline). The water temperature change in the spring for scenarios 1, 2, 3, and 4 varied from 0.2 °C to −2.1 °C, from 0.5 °C to −2.6 °C from 0 °C to −3.1 °C, and from 0.4 °C to −3.5 °C, respectively. The water temperature change in summer for scenarios 1, 2, 3, and 4

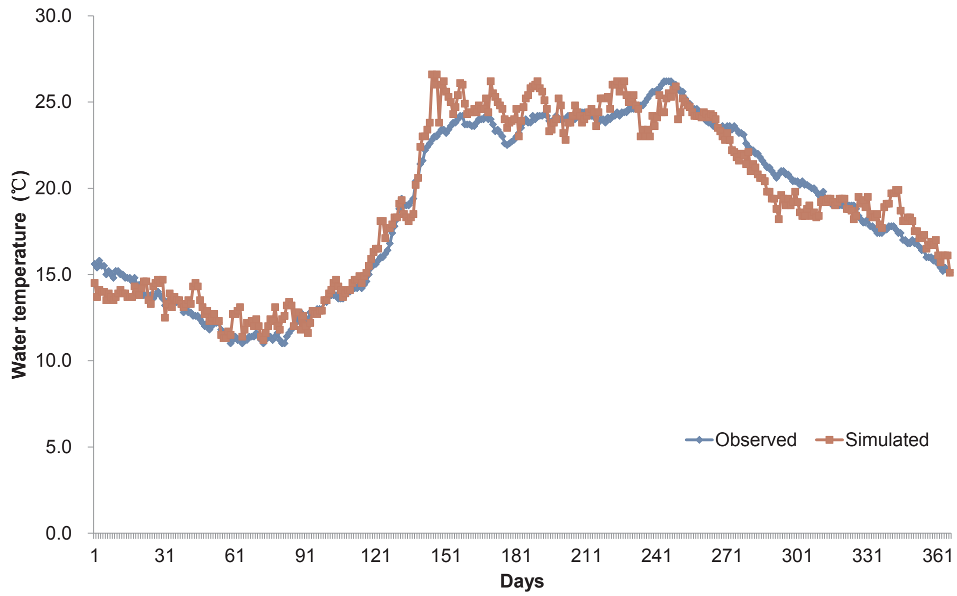


Fig. 4. Comparison between observed and simulated water temperatures at Yichang station in 2012.

varied from −1.8 °C to 0.7 °C, from −1.7 °C to 1.0 °C, from −1.9 °C to 0.6 °C, and from −1.9 °C to 1.2°, respectively. The water temperature change in autumn for scenarios 1, 2, 3, and 4 varied from −0.2 °C to 2.5 °C, from −0.1 °C to 2.4 °C, from 0.1 °C to 2.5 °C, and from −0.2 °C to 3.0 °C, respectively. The water temperature change in winter for scenarios 1, 2, 3, and 4 varied from 2.1 °C to 5.9 °C, from 2.9 °C to 6.9 °C, from 3.4 °C to 6.7 °C, and from 4.1 °C to 7.3 °C, respectively.

3.3. *Water temperature changes during the Chinese sturgeon spawning season*

Reservoir operation changes the water temperature below the dam while altering the downstream flow processes. According to the modeling results (Fig. 7), the temperatures in four scenarios increase greatly compared to those without built reservoirs. In general, Chinese Sturgeon begins to spawn when the water temperature drops to 20.5 °C. The water temperature drops below 20.5 °C in the middle of October, and then Chinese Sturgeon start to lay eggs in the spawning ground when there is no reservoir in the upper reaches of Yangtze River and the Three Gorges Reservoir. From Fig. 6 the water temperature is still above 22 °C in the middle of October. The water temperature did not fall below 20.5 °C until the beginning of November. This kind of water temperature delay phenomenon can be attributed to the operation of the TGR and reservoirs in the upper reach of the Yangtze River. The water temperatures of scenarios 1, 2, 3, and 4 begin to drop below 20.5 °C on the 1st, 3rd, 3rd, and 9th, November, respectively. Compared to the baseline, the suitable spawning water temperature for Chinese Sturgeon is postponed for 14, 16, 16 and 22 days. When more reservoirs in the upper reaches of Yangtze River are put into operation, the longer the delay of the suitable spawning water temperature.

From Fig. 8 the water temperature frequencies with a temperature of 20.5 °C in scenarios 1, 2, 3, and 4 are 50%, 46%, 47%, and 36%,

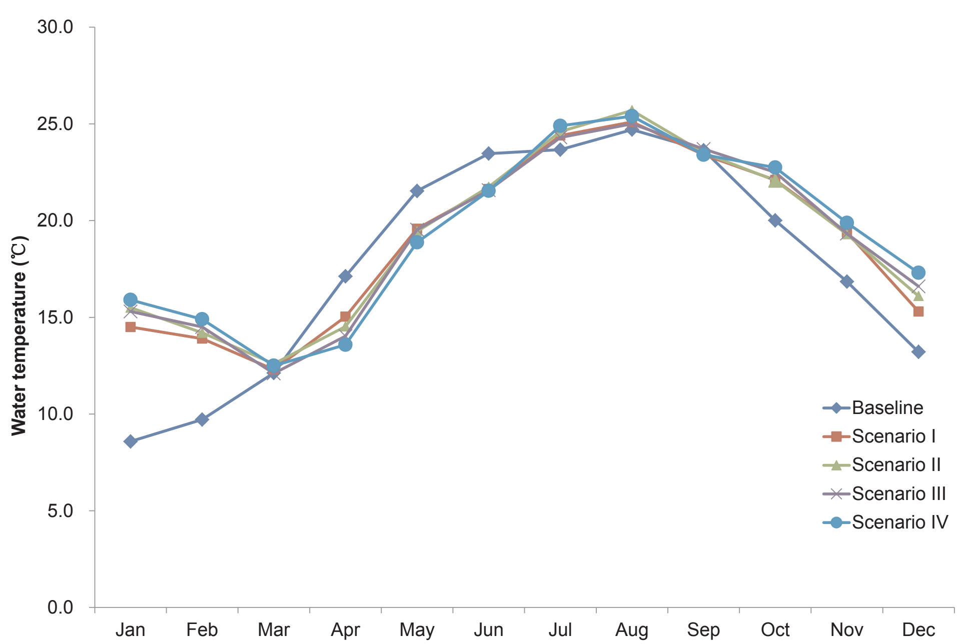


Fig. 5. Monthly water temperatures in four scenarios.

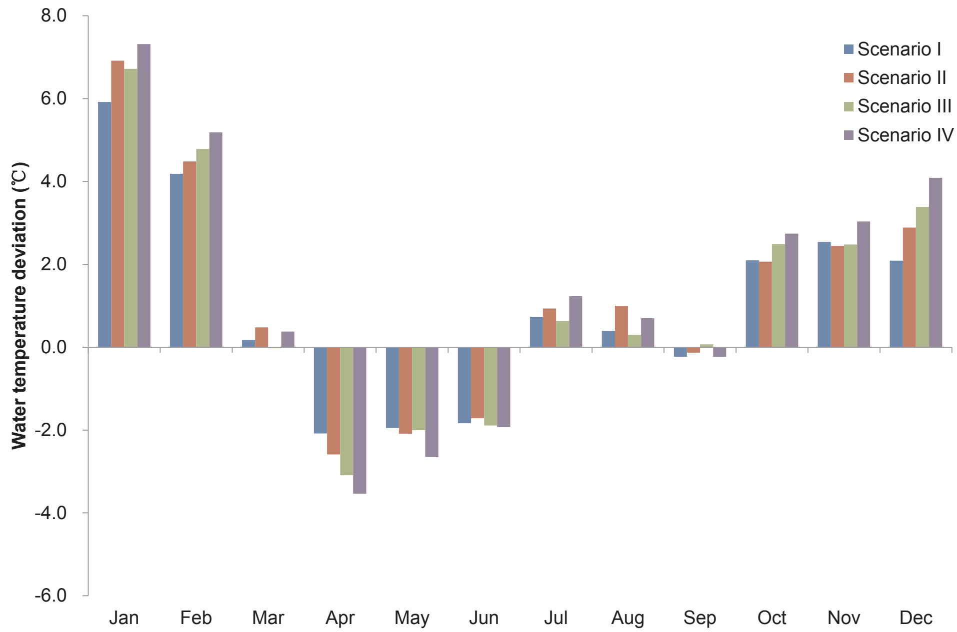


Fig. 6. Monthly water temperature deviation in four scenarios compared to baseline.

respectively. These results are less than those during a natural period with a frequency of 80%. This implies that the downstream water temperature regime was has been altered by the impoundment of TGR and upstream reservoirs during the Chinese Sturgeon spawning season. For scenario 1, only the TGR was put into operation without any reservoirs in the upper reaches of the Yangtze River, and the water temperature downstream has been altered greatly. When more reservoirs in the upper reaches of Yangtze River are considered the water temperature will be further influenced under scenarios 2, 3, and 4. These analyses suggest that the reservoirs in the upper reaches of the Yangtze River and the TGR greatly imposed significant impacts on the water temperature regime during Chinese Sturgeon spawning time.

3.4. Water temperature changes during spawning season for four famous major carp

Fig. 9 shows the results of the water temperature simulations of four different scenarios during the FFMC spawning season. The water temperatures in the four scenarios are altered dramatically after reservoirs are put into operation. FFMC starts to spawn when the water temperature rises to 18 °C in Mid-April before these reservoirs built in the upper reaches of Yangtze River are put into operation. After the reservoirs are built, reservoirs begin to release water for flood control during this period. From Fig. 10 the water temperature does not rise as it did within the natural period. The water temperature did not rise to 18 °C until the middle of May. This kind of water temperature delay phenomenon can be attributed to the operation of TGR and reservoirs in the upper reaches of the Yangtze River. The hysteresis effect on water temperature rising processes was caused by released water of TGR and reservoirs in the upper reaches of the Yangtze River. The water temperatures of scenarios 1, 2, 3, and 4 begin to rise to 18 °C on the 15th, 17th, 16th, and 21th, May, respectively. Compared to the baseline, the suitable spawning water temperature for FFMC was postponed for 28, 30, 29 and 34 days. From this analysis we observe that the date of

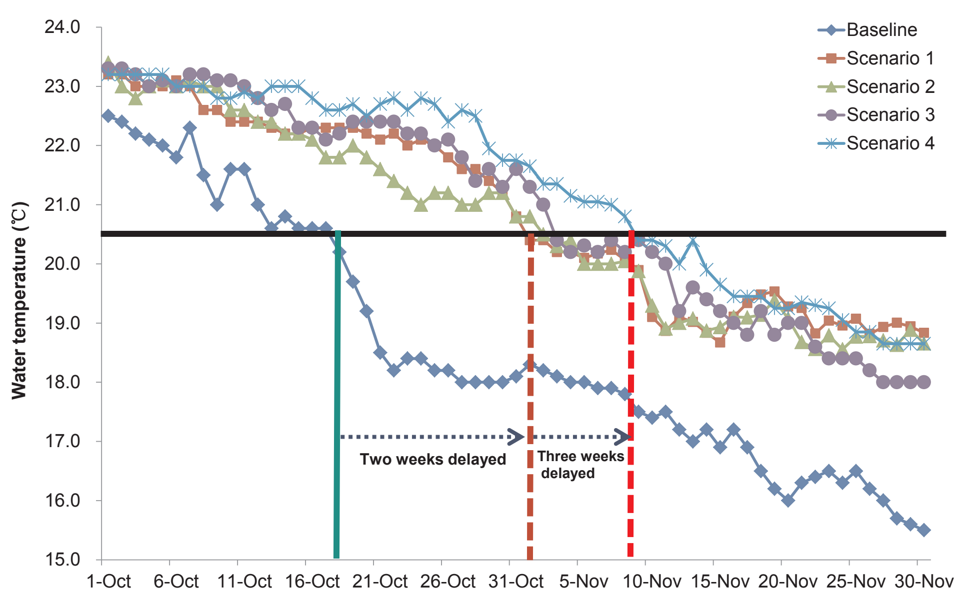


Fig. 7. Water temperature comparisons during the Chinese Sturgeon spawning season in four scenarios.

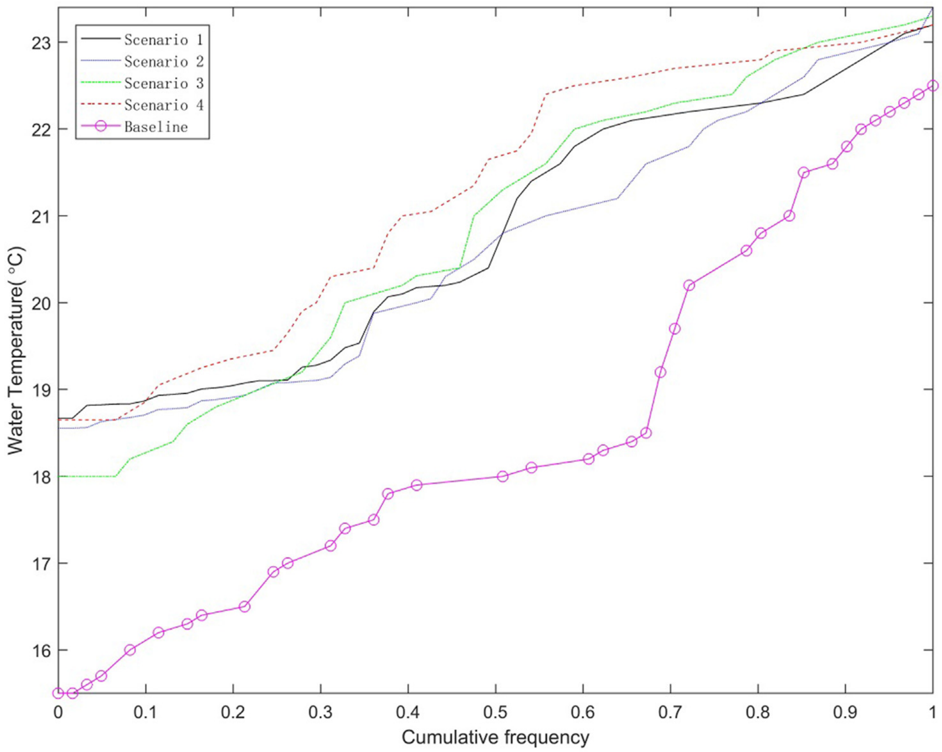


Fig. 8. Water temperature distributions during the Chinese Sturgeon spawning season in four scenarios.

spawning water temperature suitable for FFMC will be delayed by approximately 4 weeks after the TGR is put into use; thus, reservoirs being built and planned in the upper reaches of the Yangtze River will further impose influences on the water temperature regime downstream.

From Fig. 10 the water temperature frequencies with a temperature of 18.0 °C in scenarios 1, 2, 3, and 4 are 47%, 49%, 50%, and 51%, respectively. They are higher than those during the natural period with a frequency of 18%. This indicated that the downstream water temperature regime became increasingly dominated by lower water temperatures after the reservoirs were put into use, including TGR, during the FFMC spawning season. The water temperature downstream is altered greatly after the Three Gorges Reservoir is put into operation without any reservoirs in the upper reaches of the Yangtze River. As more reservoirs in the upper reaches of Yangtze River begin to release water during this period, the water temperature will be further affected. Hence, the optimal water temperature for the FFMC spawning will be further delayed.

3.5. Further discussion

This study demonstrates that water temperature regimes are significantly influenced by reservoirs in the upper stream of the Yangtze

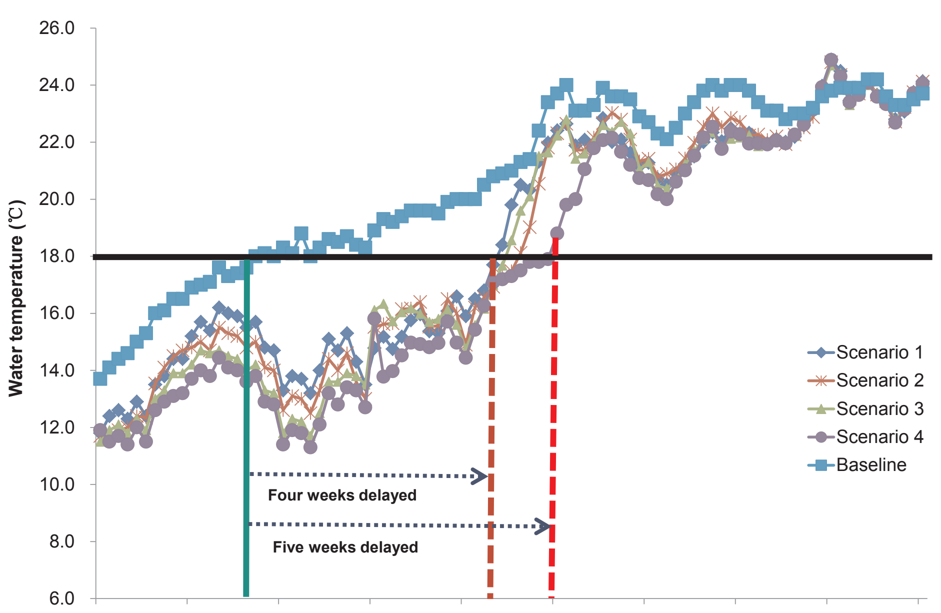


Fig. 9. Water temperature comparisons during the FFMC spawning season in four scenarios.

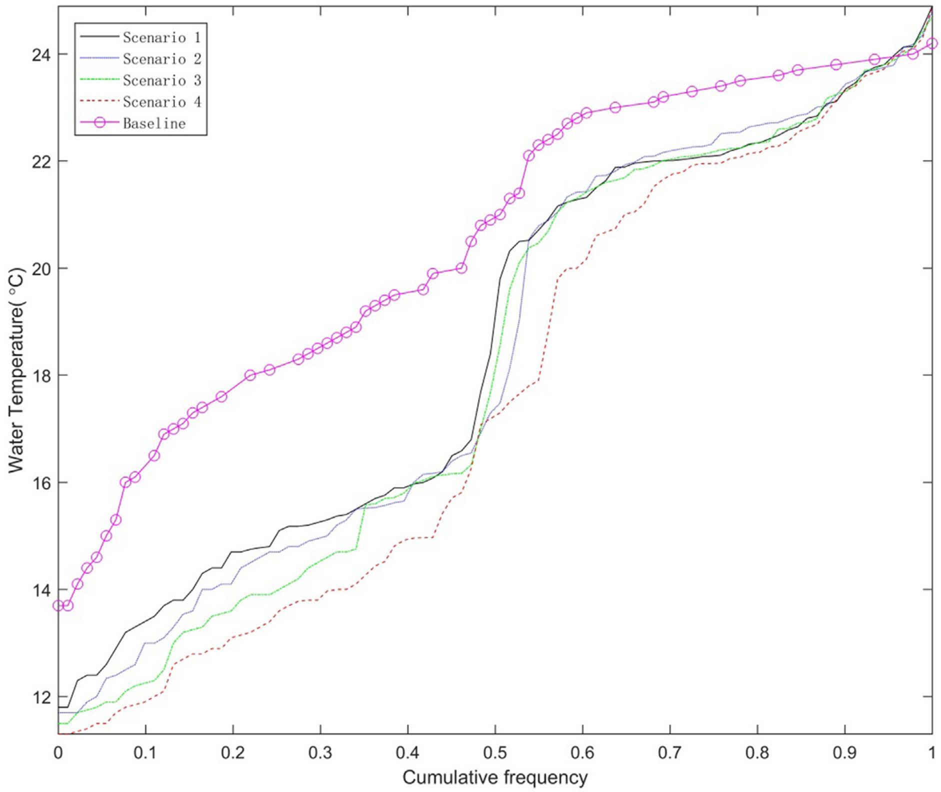


Fig. 10. Water temperature distributions during the FFMC spawning season in four scenarios.

River and the TGR. Water temperature processes changed throughout the entire year (Figs. 5 and 6). Water temperature is one of the crucial factors in almost all ecological processes in rivers, and its alteration likely leads to biological behavior changes, such as fish spawning activity delays. The magnitude of temperature modification in the river immediately below the dam can cause adverse ecological impacts (Preece and Jones, 2002).

Reservoirs have the hysteresis effect on temperature falling processes (Fig. 7). Water temperature characteristics during the Chinese Sturgeon spawning period have been altered due to reservoir operations (Figs. 7 and 8). These temperature modifications in spawning grounds lead to a delay in Chinese Sturgeon spawning behavior. Gao et al. (2014) found that the first spawning dates were significantly correlated with the date of the water temperature reaching 20 °C, the October mean discharge (Oct. discharge), and the discharge change from October to November (Oct-Nov discharge). The date for the beginning of Chinese Sturgeon spawning was gradually delayed by the impoundment of the TGR. The later spawning periods may relate to a change in the original water temperature rhythm in the Yichang spawning reach (Xiao and Duan, 2011). The findings of this study indicate that the suitable spawning water temperature date for Chinese Sturgeon would be postponed for two weeks. When all reservoirs are put into use, it will be postponed for three weeks.

The hysteresis effect in temperature rising processes also occurred due to the release of low temperature water by reservoirs (Fig. 10). A decline in the abundance of several native fish species in sections of the basin has been attributed to a disruption of thermal spawning cues by the release of unseasonably cold water from deep-release reservoirs during spring and summer (Harris, 1997; Preece and Jones, 2002; Todd et al., 2005; Webb et al., 2008). The TGD has lowered the water temperature and lowered food availability in the river section above Jianli, which has dramatically decreased the suitability of this river section for the spawning of the four major Chinese carps (Song et al., 2018). Zhang et al. (2012c) indicated that the initiation of the spawning season was delayed by approximately 1 month compared to pre-TGD records. Our study demonstrated that the suitable spawning water temperature for FFMC would be postponed for four weeks. When all reservoirs are put into use, it will be postponed by approximately five weeks.

The effects of dam construction on water temperature, and subsequent effects on other fish, have also been reported in other river systems worldwide (Preece and Jones, 2002; Todd et al., 2005; Olden and Naiman, 2010). Preece and Jones (2002) assessed the impacts of Keepit Dam on the thermal regime of the Namoi River, indicated that Keepit Dam has modified the thermal regime of the Namoi River. The annual maximum daily temperature was approximately 5.0 °C lower and occurred three weeks later than the pre-dam condition. This change was sufficient to disrupt thermal spawning cues for selected Australian native fish species. Todd et al. (2005) investigated the impact of altered thermal regimes on the population viability of Murray cod in the Mitta Mitta River downstream of Dartmouth Dam, and found that cold water releases significantly threaten the post-spawning survival of Murray cod. The operation of Flaming Gorge Dam on the Green River decreased spring–summer tailwater temperatures to nearly 6, which contributed to the extirpation of several native species (Olden and Naiman, 2010). The findings in the present study show that reservoirs in the upper reach of the Yangtze River disrupt thermal spawning cues for Chinese sturgeon and FFMC in the Yangtze River, resulting in two to five weeks delay of spawning season. In addition, some endemic fish species are near extinction, such as the finless porpoise (*Neophocaena phocaenoides asiaorientalis*), the Chinese river dolphin (*Lipotes vexillifer*), Dabry's sturgeon (*Acipenser dabryanus*), long spiky-head carp (*Luciobrama macrocephalu*), and Chinese shad (*Tenualosa reevesii*) (Jiang, 2011). The water temperature alterations documented in this study are likely contributing to the ecological threats on these species of the Yangtze River.

Historical data analysis between pre- and post-dam periods have been widely implemented to assess the impacts of a single dam on thermal regime (Caissie, 2006; Olden and Naiman, 2010). However, we less research about how to qualify the impact of cascade reservoirs to the thermal regime, therefore, we proposed a framework to address the issue of water temperature change caused by cascade reservoirs. We also coupled the reservoir water heat model with the Soil and Water Assessment Tool as a useful tool to provide insight into how cascade reservoirs influence the water temperature regime in Yangtze River and a potential quantitative method for evaluating human activities (e.g. hydropower development) influence on water temperature regime in other regulated rivers.

Many process-based models have been developed and widely used in evaluation of river temperature change (Webb et al., 2008; Dugdale et al., 2017). Unfortunately, these models generally have high demand of input data including stream geometry, vegetation cover, land use, and meteorological conditions. Lack of those input data makes it impossible for the authors to run those models and compare them to the proposed model, leading to one of the limitations of this study. Another limitation of this study is that air temperature is not taken into consideration, though it has been found to be one of factors influencing river water temperature (Toffolon and Piccolroaz, 2015). Neglecting the impact of air temperature may result in inappropriate assessment of water temperature change induced by reservoir operation. Thus, air temperature effect will be included in the model in the future.

Although this study investigated the impacts of reservoirs on the water temperature in the Yangtze River, the possible effects caused by climate changes are not considered. Climate change will affect the hydrologic and thermal regimes of rivers, thus having a direct impact on freshwater ecosystems and human water use (Van Vliet et al., 2013). To acquire a comprehensive understanding of the water temperature change of the Yangtze River and its possible ecological effects, climatic and dam-induced impacts should be assessed simultaneously. This could be implemented via a combination of hydrological models, reservoir scheduling models, and climate change in further study.

Since 2011, to facilitate the spawning success of four famous major carp species of the Yangtze River, the TGR has implemented ecological scheduling experiments for their natural regeneration for six consecutive years. All the experiments were conducted when water temperature rises to 18° (Chen, 2018). Due to the reduction in suitable water temperature time, its effect is limited. A change in the operational rules for water temperature compensation during the fish spawning season is thus necessary.

4. Conclusions

This study established the reservoir water thermal model to investigate the influence of reservoirs in the upper reaches of the Yangtze River and the TGR on the water temperature regime in different scenarios based on the SWAT simulation. The results show that the water temperature regime has been dramatically altered by reservoir operations. Water temperatures in the spring increased after the reservoirs are put into use. There is no obvious change in summer due to the operation rule of flood control during this period. Compared to the period prior to reservoir operation, water temperatures in autumn decreased greatly, which can be attributed to the impoundment of reservoirs. Water temperatures in winter showed similar patterns of variation, with the water temperature being higher than that of the predam period. The release of reservoirs has significantly influenced the water temperature during the Chinese Sturgeon and FFMC spawning seasons. The hysteresis effect on water temperature rising processes and falling processes resulted in delays of the suitable temperature date for Chinese Sturgeon and FFMC by 2–3 weeks and 4–5 weeks, respectively. Therefore, optimizing the current operation rules of these reservoirs is necessary to minimize the negative effects of water temperature on river ecosystem integrity.

CRediT authorship contribution statement

Yuankun Wang: Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Nan Zhang:** Conceptualization, Validation, Data curation. **Dong Wang:** Writing - review & editing, Project administration. **Jichun Wu:** Investigation, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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