RIVER TEMPERATURE VARIATIONS AND POTENTIAL EFFECTS ON FISH IN A TYPICAL YANGTZE RIVER REACH: IMPLICATIONS FOR MANAGEMENT

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Abstract. Operation of large reservoirs often alters the water temperature regimes in downstream reaches. Water temperature, a key environmental factor, affects the reproduction, growth, and distribution of most riverine fishes. This study reveals water temperature variations in the Yichang reach of the middle Yangtze River during 1956−2014 and the potential effects on the reproductive timing of the four major Chinese carp and Chinese sturgeon, *Acipenser sinensis*. Our results indicate that: 1) water temperature increased significantly in winters in the past 59 years and declined during spring in this century; 2) construction and operation of the Three Gorges Reservoirs has significantly altered the water temperature regime, i.e., delayed suitable spawning temperature; 3) changes in the water temperature regime have significantly affected the reproduction season of the four major Chinese carps and Chinese sturgeon in the reach. This study will be beneficial for national and local agencies developing adaptive management strategies, including mitigation measures in the face of increased hydropower station growth in the Yangtze River.

Keywords: *river temperature regime, natural reproduction, Acipenser sinensis, four major Chinese carps, Yichang Hydrological Monitoring Station*

Introduction

As a key environmental factor for most aquatic organisms, river water temperature plays an important role in the overall health and function of aquatic ecosystems (Caissie, 2006). It affects the growth, reproduction, and distribution of most species. All poikilothermic animals live and develop under the influence of fluctuating temperature, light, and oxygen levels, among other factors (Allan and Castillo, 2007). However, reproduction and development of any fish species only remains normal within a certain range of these fluctuating factors. For example, the four major Chinese carp (FMCC, black carp *Mylopharyngodon piceus*, grass carp *Ctenopharyngodon idella*, silver carp *Hypophthalmichthys molitrix*, and bighead carp *Aristichthys nobilis*) in the Yangtze River always begin to spawn when water temperatures exceed 18°C in spring (Yi et al., 1988). While the suitable water

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temperature range for spawning of another endangered fish, Chinese sturgeon *Acipenser sinensis*, in the river is 17−21°C, almost all spawning activities of *A. sinensis* takes place within this range (YARSG, 1988; Yang et al., 2007a).

The Yangtze River, the third largest river in the world, is very rich in both fish biodiversity and hydropower resources (Fu et al., 2003; Yang et al., 2007b). In the main stem of the river, approximately 30 dams have either been constructed or are planned, which will convert the natural river system into a man-made cascaded reservoir system. Huge impoundment by reservoirs and the strong regulating ability of high dams on river flow tend to significantly alter the thermal regime in downstream reaches. The Gezhouba Dam (GD), which is approximately 1678 km from the Yangtze Estuary, is the first and also the most downstream dam in the Yangtze main stem. Approximately 7 km downstream of the dam, there is a hydrological monitoring station called Yichang hydrological station. This station is one of the oldest hydrological stations on the Yangtze River and was built over 110 years ago. The location of the station is also regarded as the boundary of the upper and middle Yangtze River reaches. Most hydrological studies on the Yangtze River have used data from this station; it is one of the most important and representative hydrological stations in the Yangtze River (Yu and Lu, 2005).

Because the GD is lower than most dams in the Yangtze River main stem, it blocks many anadromous fish migration routes, such as the migratory fishes FMCC and Chinese sturgeon. Many brood fishes aggregate below the dam and usually end up spawning there. For instance, since the GD was closed in 1981, the only remaining Chinese sturgeon spawning area was immediately downstream area of the dam, a stretch of river approximately 7 km long (Zhang et al., 2011). Most adult Chinese sturgeon have to live below the dam for over 12 months before they spawn (Wang et al., 2012). The FMCC spawning area is also located approximately 5 km below the dam, this area produced 0.4 billion eggs and larvae in 2015 and occupied 37% of the Yangtze River (Duan et al., 2009, unpublished data). Therefore, the hydrological regime, including water temperature, below the GD is very important as it likely affects the gonadal development and spawning of brood fishes, which in turn affect fish population sustainability.

In this study, water temperature at Yichang Hydrological Station during 1956−2014 (59 years) was analyzed. Temperature variation trends and differences before and after the opening of GD and the Three Gorges Dam (TGD) were investigated. The IHA/RVA (indicators of hydrologic alteration/range of variability approach) method was also used to evaluate variations in water temperature after the TGD was opened. Furthermore, the potential influence of water temperature variation on the timing of FMCC and Chinese sturgeon spawning were tentatively explored. The aim of this study was to determine changes in the temperature regime and the potential effects of an altered temperature regime on fishes under heavy dam construction. The study has the potential to provide a reference for conservation not only for fish spawning but also for the whole life-history of fishes and possibly for the entire Yangtze River Basin aquatic ecosystem.

Materials and Methods

Study area

The Yangtze River is approximately 6397 km in length with a drainage area of 1.8 $\times 10^6$ km^2 (*Fig. 1*). The river has 437 tributaries, 22 of which are >10,000 km^2, with a watershed area > 1000 km^2. Several large tributaries drain into the Yangtze River main stem, and from the upstream to the downstream section there are the Yalong, Minjiang, Tuojiang, Chishui, Jialing, Wujiang, and Hanjiang rivers. Several large lakes, such as Dongting, Poyang, Hongze, and Tai lakes, are connected with the middle and lower Yangtze River reaches (Yu and Lu, 2005). Humans use the river resources for a variety of functions, including various hydro-dam constructions, heavy ship navigation, and intensive sand and gravel extraction. Thus, water pollution originating from rapidly growing settlements and industries along the river has become problematic (Yang et al., 2007b).

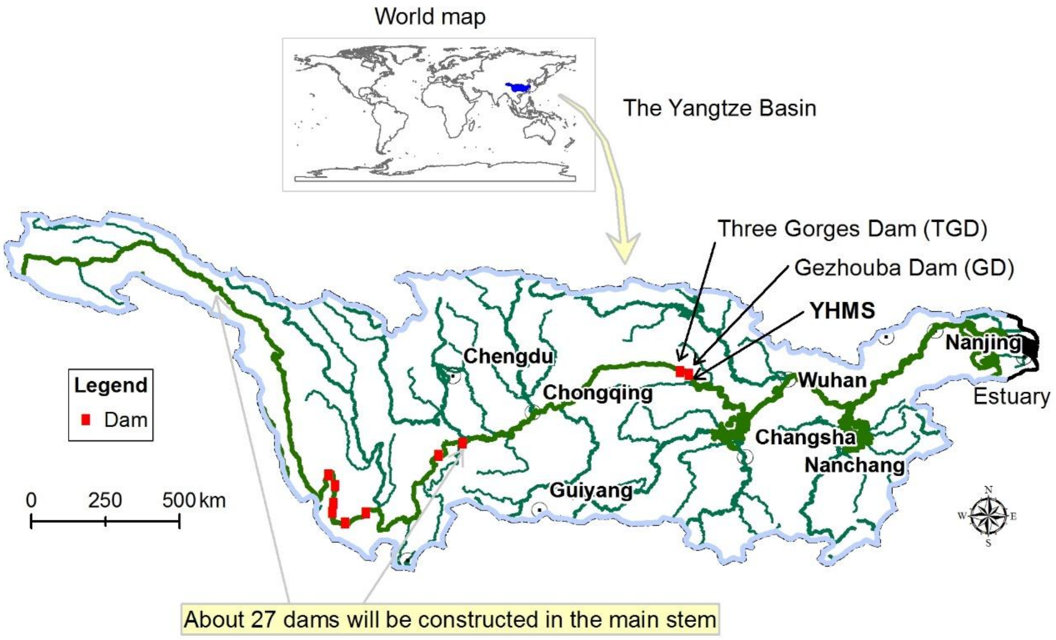

Figure 1. *Location of Yichang Hydrological Monitoring Station (YHMS) in the Yangtze Basin*

The GD, which was closed in 1981 and is approximately 1678 km from the Yangtze Estuary, is the first and lowest dam in the Yangtze main stem. The water temperature data used in this study was collected at the Yichang Hydrological Monitoring Station, which is approximately 7 km downstream of the dam. The annual average flow discharge in Yichang reach is approximately 13,900 m^3.s^{-1}, and the sediment content in the water averaged 1.129 kg.m^{-3} and 0.138 kg.m^{-3} before and after the TGD opened in 2002 (Zhang et al., 2012). The only known Chinese sturgeon spawning area is located in a 7-km reach immediately below the dam (Wei, 2003; Zhang et al., 2011), over the last 32 years (1981−2012) at least one spawning event has been observed there each year. This stretch is also an important spawning area for the FMCC. In 1981, this stretch produced 1−1.5 billion eggs and larvae (Yi et al., 1988). In 2015, this spawning area (5 km below the dam) produced 0.4 billion eggs and larvae and required 37% of the total Yangtze River production (Duan et al., unpublished data).

Water temperature measurement

Water temperature was monitored by the Bureau of Hydrology, Changjiang (Yangtze) Water Resources Commission, which is the only official agency to observe the hydrological elements in the Yangtze Basin. The water temperature was measured by mercury thermometer at 8:00 am each day, and this value was regarded as the daily baseline water temperature.

Data analysis

Trend test

Mann–Kendall trend tests (two-tailed) were used to test whether there was a variation trend in the average monthly and yearly water temperatures in the period 1956−2014 (59 years). The null hypothesis H_0 for these tests is that there was no trend in the series. The three alternative hypotheses, that there is a negative, non-null, or positive trend were chosen. The Mann–Kendall tests are based on the calculation of Kendall's tau measure of association between two samples, which is itself based on the ranks within the samples. In the particular case of the trend test, the first series is an increasing time indicator automatically generated for which ranks are obvious, this simplifies the calculations. The *S* statistic used for the test and its variance are given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sgn(x_j - x_i)$$

$$Var(S) = \frac{n(n-1)(2n+5)}{18}$$

where, n is the number of observations and x_i (i = 1n) are the independent observations. Sgn ($x_j - x_i$) is an indicator function that takes on the values 1, 0, or −1 according to the sign of $x_j - x_i$. The calculation was implemented by a complete statistical add-in XLSTAT 2015 (Addinsoft SARL, Paris, France) for Microsoft Excel 2013.

Homogeneity test

Pettitt's test (two-tailed) was used to test the homogeneity of monthly and yearly water temperature in the period 1956−2014 (59 years). Pettitt's test is a nonparametric test that requires no assumption about the distribution of data. It is an adaptation of the tank-based Mann–Whitney test that identifies the time at which the shift occurs. The two alternative hypotheses are H_0 and H_a. H_0: The T variables follow one or more distributions that have the same location parameter. H_a: There exists a time τ from which the variables change location parameter (two-tailed test). The statistic used for the Pettitt's test is computed as follows:

Let $D_{ij} = -1$ if $(x_i - x_j) < 0$, $D_{ij} = 0$ if $(x_i - x_j) = 0$, $D_{ij} = 1$ if $(x_i - x_j) > 0$

Then define:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=i+1}^{T} D_{ij}$$

Pettitt's statistic for the two alternative hypotheses is given by:

$$K_T = \max_{1 \le t < T} \left| U_{t,T} \right|, \text{ for the two-tailed case}$$

The p-value is then calculated and an interval around the p-value using the Monte Carlo method. The calculation was also implemented in XLSTAT 2015.

IHA/RVA methods

The indicators of hydrologic alteration (IHA) method was used to compare the variations in water temperature between two time periods: pre- (1983−2002) and post-TGD (2003−2014). The IHA was developed by The Nature Conservancy (TNC) as an easy-to-use tool for calculating the characteristics of natural and altered hydrologic regimes. The method and software work on any type of daily hydrologic data, such as stream flow and river water temperatures. The power of the IHA method is that it can be used to summarize long periods of daily temperature data into a much more manageable series of ecologically relevant hydrologic parameters. The scientific basis behind the software and some sample applications are described in Richter et al. (1996, 1997, 1998), which are available on the website (http://conserveonline.org/workspaces/iha).

The IHA can calculate 67 statistical parameters. These parameters are subdivided into two groups, the 33 IHA parameters and the 34 environmental flow component (EFC) parameters. In this study, the 33 IHA parameters were included (*Table 1*): 1) Group 1: Magnitude of monthly water temperature conditions, subtotal of 12 parameters, 2) Group 2: Magnitude and duration of annual extreme water temperature conditions, subtotal of 11 parameters (the indicator "Number of zero days" was excluded in this study), 3) Timing of annual extreme water temperature conditions, subtotal of two parameters, 4) Frequency and duration of high and low temperature pulses, subtotal of four parameters, 5) Rate and frequency of water temperature changes, subtotal of five parameters. The non-parametric statistics (median and percentile) method was used for the analysis. The temperature parameters produced by the IHA were calculated and organized in the output tables by water year. The water year used in this study was January 1st–December 31st.

Table 1. *Evaluation of water temperature alterations at Yichang reach pre and post the Three Gorges Dam (TGD) were impacted by the IHA/RVA (Indicators of Hydrologic Alteration/Range of Variability Approach) method issued by The Nature Conservancy*

	Pre-TGD-impact period: 1983−2002 (n=20)			Post-TGD-impact period: 2003−2014 (n=12)			RVA boundaries (middle category) [a]		Temperature alteration factor (middle category) [b]
	Median ± Coeff. of dispersion	Min	Max	Median ± Coeff. of dispersion	Min	Max	Low	High	
Parameters group #1									
January	10.20±0.105	8.50	11.90	13.50±0.183	10.80	15.00	9.68	10.40	−1.000 (H)
February	10.05±0.114	7.80	11.95	11.60±0.115	9.40	12.40	10.00	10.77	−0.815 (H)
March	12.65±0.121	10.60	15.80	11.80±0.078	10.60	13.60	12.19	13.11	−0.583 (M)
April	16.98±0.075	14.65	19.90	14.50±0.125	12.80	18.00	16.68	17.21	−1.000 (H)
May	21.50±0.072	19.60	23.00	19.40±0.144	16.60	22.10	20.99	22.11	−0.167 (L)
June	23.68±0.044	22.60	24.65	23.25±0.059	21.40	23.95	23.19	24.00	0.296 (L)

July	24.50±0.052	23.30	26.40	24.90±0.072	23.20	26.80	24.20	24.82	−0.444 (M)
August	26.00±0.071	24.00	29.00	25.60±0.037	24.60	28.20	24.97	26.21	0.875 (H)
September	23.13±0.067	21.60	25.00	24.00±0.103	22.85	26.60	22.73	23.80	0.111(L)
October	20.20±0.074	18.80	22.00	22.15±0.087	20.60	23.00	19.49	20.60	−0.630 (M)
November	16.95±0.066	15.25	17.75	19.10±0.102	17.90	20.50	16.40	17.02	−1.000 (H)
December	12.65±0.105	10.80	14.70	16.70±0.127	13.80	18.00	12.19	12.81	−1.000 (H)
Parameters group #2									
1−day minimum	9.20±0.163	7.40	10.90	10.30±0.134	9.00	11.80	8.59	9.51	−0.792 (H)
3−day minimum	9.22±0.174	7.53	10.97	10.45±0.128	9.00	11.87	8.63	9.58	−0.792 (H)
7−day minimum	9.31±0.162	7.64	11.04	10.60±0.121	9.03	11.91	8.78	9.65	−0.792 (H)
30−day minimum	9.63±0.134	7.88	11.55	10.96±0.102	9.44	12.08	9.38	9.95	−0.792 (H)
90−day minimum	10.92±0.126	9.46	12.82	12.04±0.093	10.76	12.89	10.63	11.41	−0.375 (M)
1−day maximum	27.00±0.060	25.80	29.70	27.00±0.033	25.80	29.20	26.60	27.81	0.482 (M)
3−day maximum	26.87±0.068	25.57	29.50	26.92±0.032	25.77	29.20	26.58	27.50	0.667 (M)
7−day maximum	26.72±0.071	25.29	29.34	26.71±0.034	25.73	29.07	26.43	27.26	0.667 (M)
30−day maximum	26.11±0.054	24.56	28.82	26.04±0.031	25.30	28.44	25.64	26.38	0.458 (M)
90−day maximum	24.84±0.028	24.07	26.76	24.87±0.041	23.94	27.18	24.54	25.10	0.458 (M)
Base flow index	0.50±0.137	0.43	0.59	0.57±0.108	0.49	0.64	0.49	0.53	−0.583 (M)
Parameters group #3									
Date of minimum	30±0.065	5	56	60±0.088	16	75	23.58	34.28	−0.583 (M)
Date of maximum	223±0.057	177	243	235.5±0.060	204	257	212.9	228.1	−0.167 (L)
Parameters group #4									
Low pulse count	2±0.875	1	4	2±1.000	1	3	1	2	−0.222 (L)
Low pulse duration	54±1.280	1.5	114	31.75±2.260	1	81	41.29	85.14	0.042 (L)
High pulse count	3.5±0.857	2	12	1.5±1.833	1	5	3	6	−0.359 (M)
High pulse duration	12±2.250	2	58	59±1.610	3	121	5.43	21.42	−0.375 (M)
Parameters group #5									
Rise rate	0.2±0.000	0.2	0.3	0.2±0.000	0.2	0.3	0.2	0.2	−0.167 (L)
Fall rate	−0.2±0.000	−0.3	−0.2	−0.2±0.000	−0.3	−0.2	−0.2	−0.2	−0.216 (L)
Number of reversals	112±0.219	94	146	109.5±0.199	88	144	100.9	119.1	0.042 (L)

[a] RVA boundaries (middle category) were defined as the range of the 34th to 67th percentiles of observed water temperature values.

[b] Temperature alteration factor (TAF) = (observed frequency – expected frequency) / expected frequency. An absolute value of TAF larger than 0.67 was defined as high level alteration (H), between 0.34 and 0.67 was medium alteration (M), and less than 0.34 was low alteration (L).

The range of variability approach (RVA) described in Richter et al. (1997) was implemented to evaluate changes in temperature after the TGD opened. In the RVA analysis, the full range of pre-impact data (1983−2002) for each parameter was divided into three categories. The boundaries between categories were based on percentile values (for non-parametric analysis). In this study, the default in non-parametric RVA analysis, which places the category boundaries 17 percentiles from the median, was used. This yielded an automatic delineation of three categories of equal size: the lowest category contains all values ≤ the 33rd percentile; the middle category contains all values falling in the range of the 34th to 67th percentiles; and the highest category contains all values > 67th percentile. The temperature alteration factor (TAF) was then calculated by:

$$\text{TAF} = (\text{observed frequency} - \text{expected frequency}) / \text{expected frequency}$$

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The absolute TAF value > 0.67 was defined as high level alteration (H), between 0.34 and 0.67 was medium alteration (M), < 0.33 was low alteration (L).

Temperature suitability evaluation

The temperature suitability index for the FMCC was imported from Wang et al. (2014). Based on previous studies (Yi et al., 1988), when the water temperature increased to 15°C (minimum temperature for adult carp gonad development), the suitability index was defined as 0.5. When the water temperature increased to 18°C (minimum temperature for spawning of these carp), the suitability index was defined as 1 (*Table 2*).

Table 2. *Definition of temperature suitability index for gonad development and spawning of the four major Chinese carps, and spawning of Chinese sturgeon*

Fish	Water temperature (T, °C)	Reason	Suitability index
Four major Chinese carps	$15 \le T < 18$	Minimum temperature for adult gonad development	0.5
	$18 \le T$	Minimum temperature for spawning	1
Chinese sturgeon	$17 < T \le 18$	Spawning frequency 6	0.6
	$18 < T \le 19$	Spawning frequency 10	1
	$19 < T \le 20$	Spawning frequency 10	1
	$20 < T \le 21$	Spawning frequency 4	0.4

To develop a temperature suitability index for Chinese sturgeon spawning, 10 temperatures during spawning in historic spawning areas (YARSG, 1988) and 20 temperatures in recent spawning areas (Wei, 2003) were included in the analysis. As in many years only one spawning run was observed, and the first spawning run was commonly included in the main spawning activity with some events having more than one spawning run. Only the temperature in the first spawning run was included in the analysis. A frequency statistic was first conducted using a 1°C temperature scale. The temperature range with the highest frequency of runs was regarded as suitability index 1, and thereafter an index of other temperature ranges was obtained by calculating the ratio of its frequency to the highest frequency. The suitability index for Chinese sturgeon spawning is shown in *Table 2*.

Last, the suitability index of daily water temperature for FMCC gonad development and spawning, and Chinese sturgeon spawning in 2003−2014 was evaluated in Visual Basic for Applications in Microsoft Excel® 2013.

Results

Water temperature trend

The water temperature profiles from 1956 to 2014 are shown in *Fig. 2* and the trend analysis is given in *Table 3*. Water temperature decreased in spring, with a statistically significant decrease in Mar and Apr, approximately −0.216°C and −0.391°C, respectively. In summer (Jun, Jul, and Aug), water temperature was comparatively stable, no statistically significant trends were observed. In autumn (Sep, Oct, and Nov), significant increases were observed, approximately 0.245°C, 0.467°C, and

0.615°C, respectively. Significant increases were also observed in winter (Dec, Jan, and Feb), 0.650°C, 0.680°C, and 0.472°C per year, respectively. Increasing trends were also observed in the average yearly temperature, with an increase of roughly 0.518°C per year.

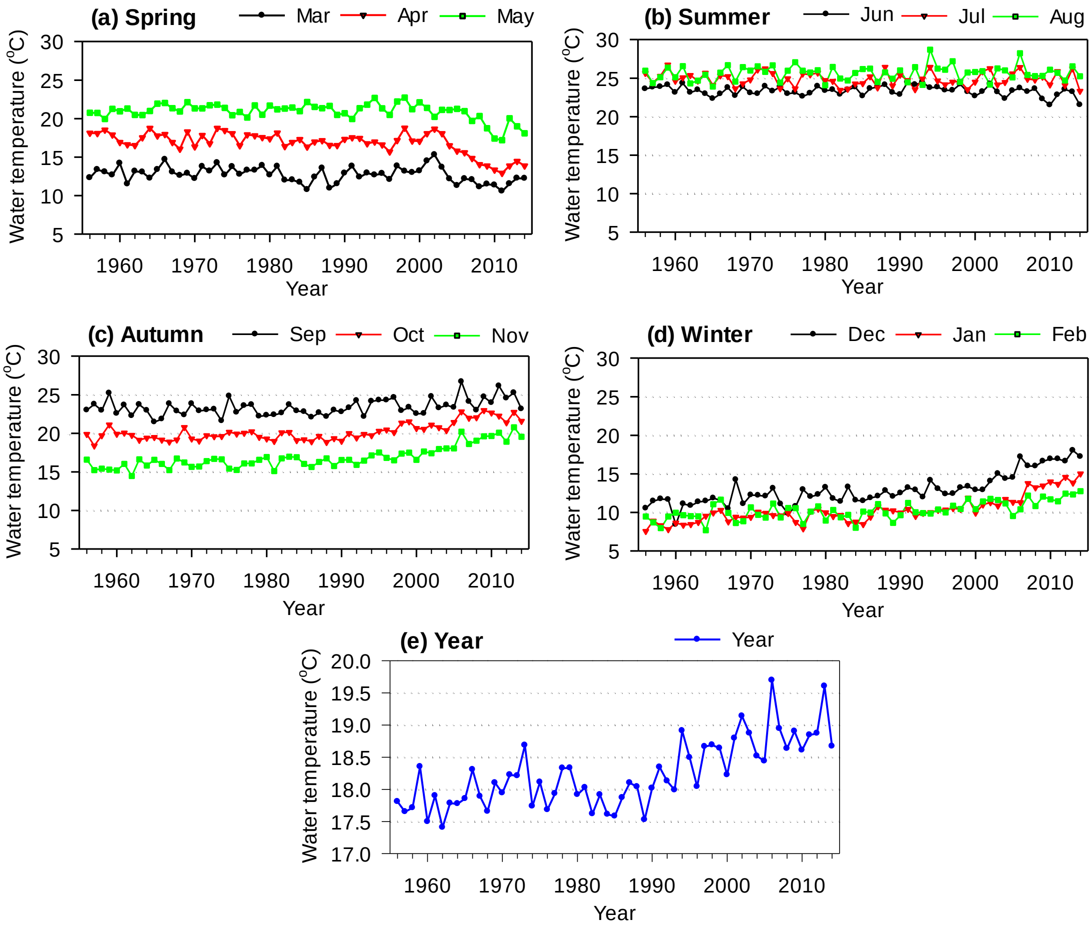

Figure 2. *Variations of month and year average water temperature at Yichang reach from 1956 to 2014*

Table 3. *Summary statistics and trend analysis on water temperature at Yichang reach during 1956−2014 (n=59)*

Season	Month	Min	Max	Mean ± SD	Trend	Kendall's tau	P-value (Two-tailed)	Sen's slope [95 % Confidence interval]
Spring	Mar	10.59	15.30	12.73±1.00	Yes	−0.216	0.016	−0.020 [−0.023, −0.015]
	Apr	12.93	18.80	16.86±1.43	Yes	−0.391	<0.0001	−0.048 [−0.053, −0.040]
	May	17.21	22.73	20.91±1.11	No	−0.160	0.075	−0.014 [−0.019, −0.009]
Summer	Jun	21.51	24.47	23.35±0.64	No	−0.096	0.289	−0.005 [−0.008, −0.003]
	Jul	23.31	26.74	24.89±0.89	No	−0.072	0.425	−0.005 [−0.009, −0.002]
	Aug	23.91	28.70	25.66±0.98	No	0.036	0.690	0.003 [−0.001, 0.006]
Autumn	Sep	21.47	26.69	23.36±1.06	Yes	0.245	0.006	0.022 [0.018, 0.027]
	Oct	18.39	22.99	20.22±1.13	Yes	0.467	<0.0001	0.044 [0.040, 0.048]
	Nov	14.47	20.79	16.88±1.42	Yes	0.615	<0.0001	0.063 [0.058, 0.067]

Winter	Dec	8.42	18.02	12.93±2.05	Yes	0.650	<0.0001	0.094 [0.088, 0.101]
	Jan	7.56	15.03	10.31±1.74	Yes	0.680	<0.0001	0.077 [0.071, 0.083]
	Feb	7.69	12.76	10.26±1.17	Yes	0.472	<0.0001	0.046 [0.042, 0.050]
Year		17.41	19.70	18.23±0.52	Yes	0.518	<0.0001	0.021 [0.019, 0.022]

Homogeneity of water temperature

Fig. 3 and *Table 4* show the homogeneity results for water temperatures during two time periods according to the operation status of the dams: before the TGD opened (1956−2002) and after the GD closed (1981−2014). The average yearly temperature was nonhomogeneous during 1956−2002, the changes occurred in 1989, and the average water temperature before and after then were 17.92°C and 18.47°C, respectively. No statistical difference was found between the months Mar, Apr, May, Jun, Jul, Aug, and Sep, while Oct, Nov, Dec, Jan, and Feb were heterogeneous with the changes occurring from 1976 to 1990. During 1981−2014, the average yearly temperature was also heterogeneous, a change occurred in 1993, and the average temperature before and after then were 17.91°C and 18.77°C, respectively. Temperatures remained the same Jul and Aug, while changes occurred in other months from 1993 to 2003.

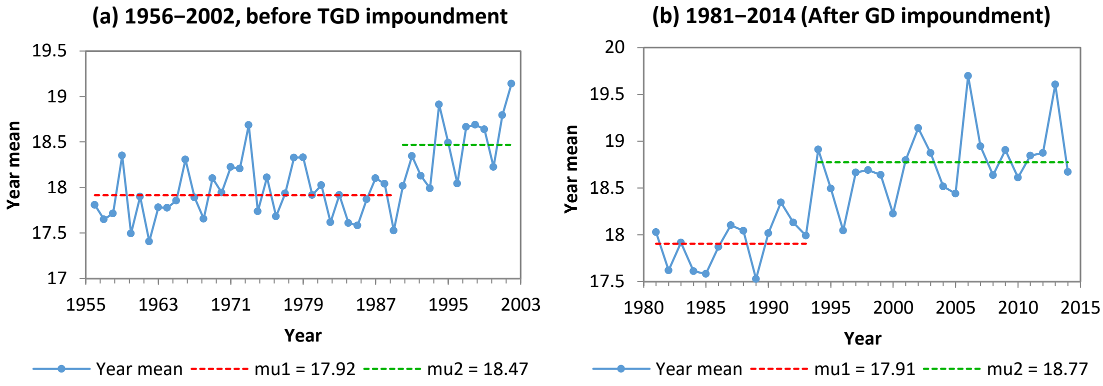

Figure 3. *Homogeneity analysis of year average water temperature at Yichang reach, (a) during 1956−2002, before the Three Gorges Dam (TGD) began operation, (b) during 1981−2014, after closure of the Gezhouba Dam (GD)*

Table 4. *Homogeneity analysis on water temperature at Yichang reach during two periods (1956−2002 and 1981−2014) based on the operational status of dams*

Season	Month	1956−2002 (Before TGD impoundment)					1981−2014 (After GD impoundment)				
		Homogeneity	t[a]	P-value (Two-tailed)	mu1[b]	mu2[b]	Homogeneity	t	P-value (Two-tailed)	mu1[b]	mu2[b]
Spring	Mar	Yes	1981	0.467	12.97	12.97	No	2003	0.016	12.83	11.66
	Apr	Yes	1981	0.176	17.39	17.39	No	2003	<0.0001	17.21	14.47
	May	Yes	1964	0.145	21.25	21.25	No	2001	<0.0001	21.43	19.63
Summer	Jun	Yes	1985	0.292	23.47	23.47	No	1998	0.026	23.65	22.98
	Jul	Yes	1979	0.293	24.88	24.88	Yes	1987	0.541	24.76	24.76
	Aug	Yes	1966	0.654	25.62	25.62	Yes	1993	0.849	25.72	25.72
Autumn	Sep	Yes	1990	0.323	23.12	23.12	No	1993	0.002	22.83	24.06
	Oct	No	1990	0.006	19.56	20.43	No	1997	<0.0001	19.60	21.66

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	Nov	No	1981	0.002	15.93	16.72	No	2000	<0.0001	16.56	18.98
Winter	Dec	No	1976	0.000	11.39	12.62	No	2001	<0.0001	12.54	16.12
	Jan	No	1986	<0.0001	9.17	10.43	No	1996	<0.0001	9.76	12.33
	Feb	No	1990	0.027	9.67	10.68	No	1996	<0.0001	9.89	11.40
Year		No	1989	0.001	17.92	18.47	No	1993	<0.0001	17.91	18.77

[a] t is the year when the alterations can be detected, the P-value indicates whether they are homogeneous (P>0.05) or not (P<0.05).

[b] mu1 and mu2 are the average values of the two distinct periods.

Assessment of changes in temperature regime

The changes in water temperature in Yichang reach before and after the TGP are given in *Table 1*. Thirty-two indicators were evaluated. For magnitude of monthly water temperature conditions (Group 1), six (50%) months had high alterations, three (25%) had medium, and three (25%) had low. For magnitude and duration of annual extreme water temperature (Group 2), four (36.4%) had high and seven (63.6%) had medium alterations. For timing of annual extreme water temperature (Group 3), one had a medium alteration and the other had low. For frequency and duration of high and low temperature pulses (Group 4), two had low and two had medium alterations. For rate and frequency of water temperature changes (Group 5), all three indicators had low alterations.

The RVA analysis on water temperature (*Table 5*) indicated that in the middle RVA category (34–67th percentiles), 10 (31.3%) of 32 indicators had high alterations, in the high RVA category (< 67th percentile), 25 (78.1%) had high alterations, and in the low RVA category (≤ 33rd), 18 (56.3%) had high alterations, which implies that the temperature regime in Yichang reach has been altered obviously since the TGD opened in 2003.

Table 5. *Range of Variability Approach (RVA) analysis on water temperature at Yichang reach post the Three Gorges Dam (TGD) was impacted in 2003−2014 (n=12), using the water temperature during 1983−2002 (n=20) as non-impacted period (Table 1)*

	Middle RVA category (range of the 34th to 67th percentiles)			High RVA category (greater than the 67th percentile)			Low RVA category (less than or equal to the 33rd)		
	Expected	Observed	TAF	Expected	Observed	TAF	Expected	Observed	TAF
Parameters group #1									
January	5.4	0	−1.000 (H)	3.0	12	3.000 (H)	3.6	0	−1.000 (H)
February	5.4	1	−0.815 (H)	3.6	10	1.778 (H)	3.0	1	−0.667 (M)
March	4.8	2	−0.583 (M)	3.6	1	−0.722 (H)	3.6	9	1.500 (H)
April	4.8	0	−1.000 (H)	3.6	1	−0.722 (H)	3.6	11	2.056 (H)
May	4.8	4	−0.167 (L)	3.6	0	−1.000 (H)	3.6	8	1.222 (H)
June	5.4	7	0.296 (L)	3.0	0	−1.000 (H)	3.6	5	0.389 (M)
July	5.4	3	−0.444 (M)	3.6	6	0.667 (M)	3.0	3	0.000 (L)
August	4.8	9	0.875 (H)	3.6	2	−0.444 (M)	3.6	1	−0.722 (M)
September	5.4	6	0.111 (L)	3.0	6	1.000 (H)	3.6	0	−1.000 (H)
October	5.4	2	−0.630 (M)	3.0	10	2.333 (H)	3.6	0	−1.000 (H)
November	5.4	0	−1.000 (H)	3.6	12	2.333 (H)	3.0	0	−1.000 (H)
December	4.8	0	−1.000 (H)	3.6	12	2.333 (H)	3.6	0	−1.000 (H)
Parameters group #2									
1−day minimum	4.8	1	−0.792 (H)	3.6	11	2.056 (H)	3.6	0	−1.000 (H)
3−day minimum	4.8	1	−0.792 (H)	3.6	11	2.056 (H)	3.6	0	−1.000 (H)

7−day minimum	4.8	1	−0.792 (H)	3.6	11	2.056 (H)	3.6	0	−1.000 (H)
30−day minimum	4.8	1	−0.792 (H)	3.6	11	2.056 (H)	3.6	0	−1.000 (H)
90−day minimum	4.8	3	−0.375 (M)	3.6	9	1.500 (H)	3.6	0	−1.000 (H)
1−day maximum	5.4	8	0.482 (M)	3.6	1	−0.722 (H)	3.0	3	0.000 (L)
3−day maximum	4.8	8	0.667 (M)	3.6	1	−0.722 (H)	3.6	3	−0.167 (L)
7−day maximum	4.8	8	0.667 (M)	3.6	1	−0.722 (H)	3.6	3	−0.167 (L)
30−day maximum	4.8	7	0.458 (M)	3.6	2	−0.444 (M)	3.6	3	−0.167 (L)
90−day maximum	4.8	7	0.458 (M)	3.6	3	−0.167 (L)	3.6	2	−0.444 (M)
Base flow index	4.8	2	−0.583 (M)	3.6	10	1.778 (H)	3.6	0	−1.000 (H)
Parameters group #3									
Date of minimum	4.8	2	−0.583 (M)	3.6	9	1.500 (H)	3.6	1	−0.722 (H)
Date of maximum	4.8	4	−0.167 (L)	3.6	7	0.944 (H)	3.6	1	−0.722 (H)
Parameters group #4									
Low pulse count	9.0	7	−0.222 (L)	3.0	5	0.667 (M)	0.0	0	
Low pulse duration	4.8	5	0.042 (L)	3.6	0	−1.000 (H)	3.6	7	0.944 (H)
High pulse count	7.8	5	−0.359 (M)	1.8	0	−1.000 (H)	2.4	7	1.917 (H)
High pulse duration	4.8	3	−0.375 (M)	3.6	7	0.944 (H)	3.6	2	−0.444 (M)
Parameters group #5									
Rise rate	9.6	8	−0.167 (L)	2.4	1	−0.583 (M)	0.0	3	
Fall rate	10.2	8	−0.216 (L)	0.6	3	4.000 (H)	1.2	1	−0.167 (L)
Number of reversals	4.8	5	0.042 (L)	3.6	5	0.389 (M)	3.6	2	−0.444 (M)

[a] RVA boundaries were delineated by three categories of equal size: the lowest category contains all values less than or equal to the 33rd percentile; the middle category contains all values falling in the range of the 34th to 67th percentiles; and the highest category contains all values greater than the 67th percentile.

[b] Temperature alteration factor (TAF) = (observed frequency – expected frequency) / expected frequency. An absolute value of TAF larger than 0.67 was defined as high level alteration (H), between 0.34 and 0.67 was medium alteration (M), and less than 0.34 was low alteration (L).

Suitability of water temperature for fish spawning

The suitability index of daily water temperature for FMCC gonad development and spawning, and Chinese sturgeon spawning in 2003−2014 is shown in *Fig. 4*. Note that the curves for the first half of the year from Jan 1st to Jun 30th are the FMCC data because they spawned in spring, the curve for the last half of the year from Jul 1st to Dec 31st are Chinese sturgeon data because they spawned in autumn. Temperatures suitable for the commencement of FMCC gonad development and spawning activity shifted gradually during the period from 2003 to 2014. Overall, the Chinese sturgeon spawning window, which is 40−50 days, did not change during that period. However, the results also revealed that the spawning window gradually shifted from mid-October in 2003 to early November in 2014, it was delayed by approximately 20 days.

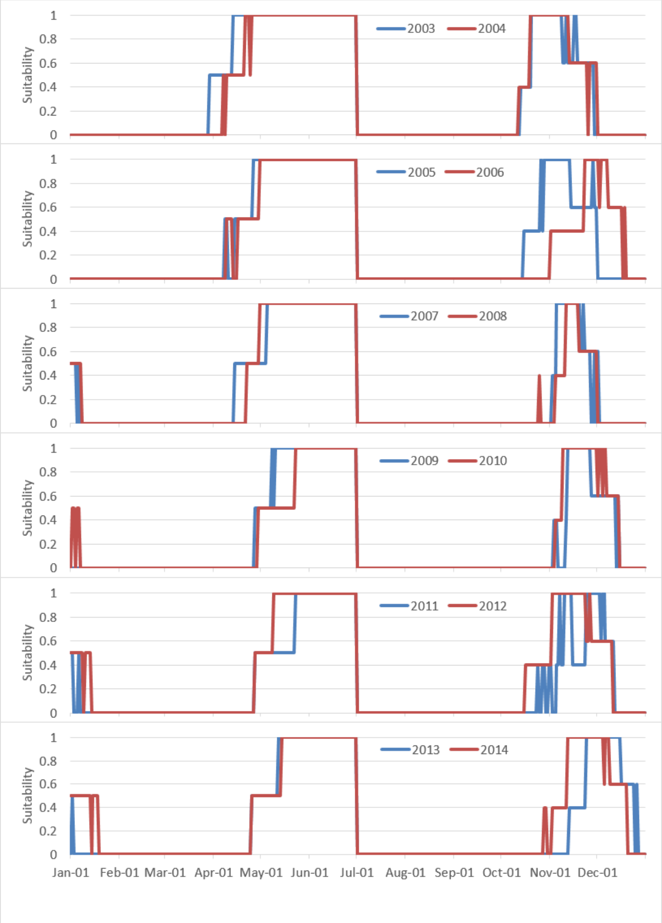

Figure 4. *Suitability index of water temperature for gonad development and spawning of the four major Chinese carps (the first half year from Jan 1 to Jun 30), and Chinese sturgeon spawning (the last half year from Jul 1 to Dec 31) at Yichang reach, as identified during the Three Gorges Dam (TGD) construction phase (2003−2009) and thereafter (2010−2014) when the TGD became fully operational*

Discussion

The temperature data used in this study was obtained over a long observation period from 1956 to 2014. In the mid-1900s, there was no strict standard on river temperature measurements available (first related standard issued in 1991 in China), and the commonly used thermometers may not always have been properly calibrated and, therefore, not sufficiently accurate to be fully comparable with present temperature readings. However, it is reasonable to assume that these potential errors will not seriously affect the results on the long-term trend changes. The temperature regimes at the Yichang Hydrological Monitoring Station were taken as the temperature reference points in the flow regimes that FMCC and Chinese sturgeon were exposed to. However, the fishes may have been some distance from the monitoring station (Yang et al., 2006; Wang et al., 2012), and, therefore, the temperature regime the fishes were actually exposed to may have differed somewhat from that measured at the station. The potential effect of very small differences has been ignored in this study because the water temperatures in that particular reach of the Yangtze main stem are usually very stable.

Many factors affected the water temperature in Yichang reach. 1) The main reason is the opening of the TGD in 2003, the total capacity of which can reach 39.3 km^3, the IHA/RVA analysis on water temperature in this study partly supports this conclusion. 2) Many small reservoirs have been operating in the upstream area since 1970, the total combined capacity of which is 17.0 km^3. These reservoirs impound water in summer and release it in winter. Water flow regulations tend to affect the water temperature regime (Li et al., 2007). 3) Global warming and subsequent variations in metrological and hydrological conditions (Singh, 2012). 4) The intrinsic variations in temperature regimes at various times under natural conditions (Guo et al., 2008). 5) Various of anthropogenic activities, such as deforestation, in the upper Yangtze Basin. Therefore, many factors can alter water temperature, and consequently, the variations are very complicated; the trend and homogeneity analysis results reflect this. At present, it is hard to say which factors, besides the TGD, are more important. However, it is undeniably clear that the water temperature regime in the Yichang reach has been altered.

Water temperature is important for both fish gonad development and spawning. In the Yangtze River, gonad development commences in most fishes at 15°C (Zeng, 1990). Natural or artificial wintering (vernalization of 2−4 months at a lower temperature) is necessary for sturgeon to reach the final maturation stage required for successful spawning (Chebanov and Galich, 2013), the Chinese sturgeon is thought to be similar. The timing of the spawning events is thought to be related to the hatching of eggs, because the fish want to choose a favorable environment for this. At Yichang, the favorable temperature windows for FMCC and Chinese sturgeon spawning were delayed year by year (*Fig. 4*), which may have adversely effected the populations. Wu et al. (2015) reported that Chinese sturgeon spawning was interrupted in Yichang reach in 2013, where spawning has taken place for over 30 years. No spawning occurred in that area in 2014, however, the occurrence of juveniles in the Yangtze Estuary the following year suggested that spawning took place elsewhere in the river (Zhao et al., 2015; Zhang et al., 2016). In 2015, no spawning was observed in Yichang reach, and no juveniles were observed in the estuary until the end of September 2016 (Wei et al., unpublished data). It is thought that the interruption in Chinese sturgeon spawning was mostly induced by changes in the water temperature regime.

The temperature regime in Yichang reach (particularly the shifts in the annual profile) has been drastically altered. Under natural conditions, the temperature regime varies at different time scales (Guo et al., 2008). However, because of the hydro-dams and subsequent changes in retention times (flow disruptions) (Wang et al., 2016), further influenced by global warming, changes in the temperature regime have become much more obvious than in the periods prior to river fragmentation (e.g., the historic natural status). Twenty-seven dams will be constructed in the near future in the upper Yangtze reach (Yang et al., 2007b), and these will likely affect the temperature regime in downstream reaches. The temperature regime will be further altered along with the cascade hydropower development. These changes may not only affect FMCC and Chinese sturgeon reproductive modes, but they will influence the reproductive capacity of many other commercially and ecologically important Yangtze fish species (Zeng, 1990). There may even be further effects on the entire aquatic ecosystem.

Major mitigation measures to regulate the temperature regime during sensitive periods could use the stratified water temperature profile in the man-made reservoirs to feed the downstream stretches with waters from a selected reservoir depth that exhibits the required temperatures. This strategy has been widely used and proven useful elsewhere.

However, the situation in the Yangtze River is complicated; at that large a scale and with the many high volume cascades, specific research will be necessary to solve the management problems to address both the operational requirements for hydropower generation and the ecologically required river flow and temperature profile. Regulating the temperature regime should be of utmost importance for research and management to develop strategies that meet the ecological requirements for the entire river basin ecosystem and the effective use of this important water resource. In this context the FMCC and Chinese sturgeon can be considered model species to optimize water resource management in the Yangtze River (Wang et al., 2012; Wang et al., 2014).

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