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Potential Impact of a Large-Scale Cascade Reservoir on the Spawning Conditions of Critical Species in the Yangtze River, China

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Abstract: Dam building and reservoir operations alter the downstream hydrological regime, and as a result, affect the health of the river aquatic ecosystem, particularly for large-scale cascade reservoirs. This study investigated the impact of the Gezhouba Reservoir (GR) and the Three Gorges Reservoir (TGR) on the spawning conditions of two critical taxa, i.e., the endemic four major carps and the endangered Chinese sturgeon in the Yangtze River. We analyzed the flow, sediment, and thermal regime in these two taxa spawning seasons and compared their features between the predam and postdam periods. Our results revealed that the GR and the TGR had altered the frequency distributions of flow, sediment, and water temperature to different degrees, with the impact by the GR on the carps and Chinese sturgeon ranked as water temperature > flow, sediment > water temperature > flow, and the effect of the TGR on these two taxa were ordered as flow > water temperature, sediment > flow > water temperature. For the GR, the satisfying degree of the suitable flow and water temperature of the carps increased, whilst the suitable flow, sediment, and water temperature for the Chinese sturgeon decreased. These changes in TGR showed a significant ascending (descending) trend in the suitable flow (water temperature) for the carps, and a clear decreasing trend in the flow, sediment, and temperature for Chinese sturgeon. Both the TGR and the GR had negative impacts on the spawning of these two taxa in terms of the rising/falling flow characteristics.

Keywords: Three Gorges Reservoir; Gezhouba Reservoir; flow; sediment; water temperature; Chinese sturgeon; four major carps

1. Introduction

Global river systems have undergone major changes due to intensive anthropogenic activities, such as land use/cover change, irrigation, water diversion, and dam building and operations. According to incomplete statistics, more than half of the 300 biggest river systems around the world are controlled by or under the impact of dams [1]. Up to now, ≈2.8 million dams (with reservoir areas >10^3 m^2) have been built and more than 3700 hydropower dams (>1 MW) are currently planned or under construction worldwide [2]. Undoubtedly, dams or reservoirs play an important role in contributing water for domestic use and agriculture, sustaining transportation corridors, and enabling power generation and industrial production. However, they also affect many fundamental processes and functional characteristics of healthy rivers, such as the flow regimes [3–5], sediment conditions [6–8], and thermal characteristics [9–11], thus leading to the rapid decline of aquatic biodiversity and essential ecosystem services [12–14]. The alterations of natural river conditions could influence the critical habits of species [15,16], since each species may have an "optimal environmental window" for reproductive success and recruitment maximization [17–19]. Spawning is a vital and sensitive time for most fish, and this period is thus often deemed as a representative pivotal habit for them, whose breeding is closely related to hydrological factors [20].

The Three Gorges Reservoir (TGR), located over the Yangtze River main stream, is the largest hydropower project in the world (Figure 1). It was built for flood control, navigation, and hydropower generation. It started operations in June 2003, with its dam bottom release and the normal reservoir water level being at 135 m. With its dam heightening and reservoir storing water level being upgraded to 175 m, the world's attention on the Yangtze River keeps increasing. The endangered Chinese sturgeon (CS) and the endemic four major carps (FMC) are the two critical taxa in the Yangtze River, whose propagation and nursing habitats are located mainly in the middle reach of the Yangtze. Take the CS for instance, its spawning takes place just downstream of the TGR. It is well known that both the CS and the FMC have strict spawning requirements. Since the FMC and the CS populations indicate the health status of the Yangtze River ecosystem, they have received much needed attention during the (quasi-)normal stage of the TGR. Wang et al. [5] pointed out that the TGR had well-documented negative impacts on the river ecosystem, especially for species of migratory carp in the Yangtze River. Xu et al. [21] investigated the spawning activities of FMC and their responses to the TGR operation and found that the flood amplitude and river transparency were significantly positively correlated with the egg abundance of the FMC. Yu et al. [22] examined the flow regime at four key hydrological stations along the Yangtze River and concluded that the operations of the Gezhouba Reservoir (GR) and the TGR had altered the water rising and falling regime to some degree, which is particularly crucial for the spawning of CS and FMC. Yi et al. [23] proposed that the minimum discharge needed for the FMC in the middle reach of the Yangtze River is 3000 m^3/s. Wang et al. [24] emphasized that only the cumulative temperature for gonad development and the minimum temperature for FMC spawning (18 °C) are both satisfied, and the occurrence of a flow increase would produce a successful spawning event. Chang et al. [25] found out that a delay in the decrease in water temperature caused by the TGR and the few numbers of reproductively mature individuals were suspected to have contributed to the failure in natural breeding of the CS. Shen et al. [26] disclosed that the water temperature increase from the TGR impoundment primarily induced the habitat degradation and spawning time delay of the CS, and the effect of the water temperature increase was eight times that of a decrease in discharge. Ban et al. [27] revealed that the discharge and water levels dominated the FMC reproduction when the change of sediment concentration was kept stable; however, the sediment concentration played a leading role in the spawning while the sediment decreased over a limited range.

It can be seen that many previous studies have assessed the impacts of the TGR on the FMC or the CS during a (quasi-)normal stage; however, due to data collection difficulties, most of those studies often focused on the relationship between the spawning and the flow discharge characteristics [5,28–30], some on the river thermal regime [24,25], a few on flow discharge–water temperature [26], or a few on flow discharge–sediment [27]. In fact, spawning of the FMC and the CS is sensitive and restricted to complex hydrological factors that include flow, sediment, and thermal conditions. It is clear that few studies have considered the three hydrological factors together to investigate the impact of the TGR on the FMC or the CS during their spawning seasons. Besides, almost related studies focused on the impact of the TGR only on the spawning of the FMC or the CS but not both of them. Since the spawning seasons of the FMC and the CS just fall within the rising–warming flow period and the falling–cooling flow period, respectively, it is of great significance to examine the impact of the TGR on the spawning of the FMC and the CS in the Yangtze River simultaneously. Additionally, the data series of previous studies were time limited. This paper, with the most updated data from 1950 to 2017, first presents a systematic investigation of the influences of the TGR on the spawning of the FMC and the CS from the flow–sediment–thermal integrated perspective.

The aim of the study was to: (1) quantify regime changes in flow, sediment, and water temperature due to dam regulation; and (2) assess the suitable hydrological conditions and their changes for the spawning of the FMC and the CS during pre- and post-dam periods. This paper is organized as follows. First is the brief introduction, second is the data and methodology, third is the results section, and last is the discussion and conclusions. It reveals that the impact of the TGR and the GR on their downstream hydrological regimes varied with reservoir storage capacities and operation modes, with the sediment regime being most significantly affected. The two reservoirs also had different degrees of impact on the spawning conditions of the CS and the FMC, and the present status of the sediment condition is no longer suitable for the reproduction of the CS.

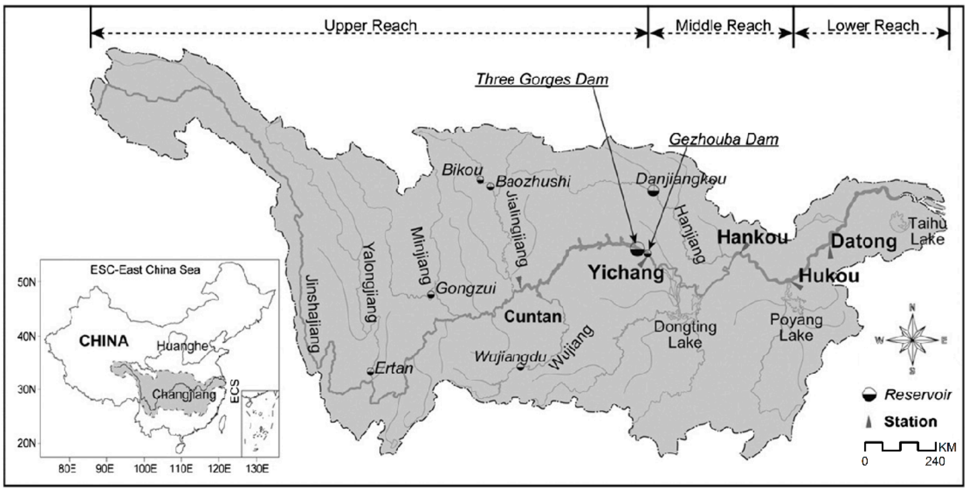


Figure 1. Sketch map of the Yangtze River basin.

2. Study Region

The TGR is located on the main stem 44 km above the end of the upper Yangtze River. Its operations were done in four stages: the initial stage began in June 2003, with the reservoir water level increased to 135 m above sea level; the transitional stage started in October 2006 with the water level increased to 156 m; the reservoir water level rose to 173 m in November 2008 during the quasi-normal stage; and then to the designed reservoir water level of 175 m in October 2010 during the normal stage with the total storage capacity of 39.3 billion m^3 [31]. According to the operational scheme of the Ministry of Water Resources [32], the TGR stores 22.15 billion m^3 of water to reach normal water level of 175 m from 145 m at the end of flood season (generally from 15 September to 31 October, lasting 47 days; it begins refilling from 10 September if the year is relatively dry). The GR, a run-of-river reservoir, located on the main stem of the Yangtze River, 38 km below the TGR. Its capacity is about of 1.58 billion m^3, partly operated in 1981. The spawning of CS takes place just downstream of the GR, and many spawning grounds of FMC also are also located in the downstream of the two reservoirs. To investigate the impacts of reservoir construction and operation on the spawning conditions of these two critical taxa, the two key hydrological stations of Cuntan and Yichang were selected as study sites (Figure 1). The Cuntan station, the farthest end of the backwater of the TGR, is located 608 km above the TGR. The Yichang station, an important monitoring station for outflow from the TGR, is immediately downstream of the TGR, approximately 44 km below the TGR.

3. Data and Methods

Due to the ≈86% runoff at Yichang that comes from Cuntan and the alteration of the flow regime by human activities being limited in the region between Cuntan and Yichang, the Cuntan station just above the TGR was selected as a reference station to investigate the impacts of the TGR on its downstream hydrological regime in the Yangtze River basin. Since the spawning of the FMC and the CS occurs primarily during May–June and October–November, respectively, the time series of daily discharge, sediment concentration, and water temperature during these two periods, both at Cuntan and Yichang, were obtained from the Changjiang Water Resources Commission (CWRC), China (Table 1). The data homogeneity and reliability have been firmly checked and assured by the CWRC before its release. It should be noted that the daily water temperature during 2001–2006 and 2010–2012 were averaged to a ten-day time scale for this analysis. Due to the scarcity of fish data, only annual numbers of the CS during 1981–2014 were collected from published references [33–40]. All these data for the CS were collected from the same spawning ground downstream of the GR during its spawning season.

Table 1. Data information during May–June and October–November.

Hydrological Item	Time Range	Time Scale	Unit
Flow discharge	1950–2017	daily	m^3/s
Sediment concentration	1953–2012	daily	kg/m^3
Water temperature	2001–2006, 2010–2012 1959–2000, 2007–2009	daily ten-day	°C

Based on the long-term historical data of the FMC (1997–2002) and the CS (1982–2006) from the Jianli river cross-section downstream of the GR in the Yangtze River, Guo [40] investigated the spawning characteristics of these two taxa in the Yangtze River, and concluded that the suitable discharge, velocity, and water temperature for the FMC's spawning fall within the range of 7500–12500 m^3/s, 0.2–0.9 m/s, and 18.6–25.5 °C, respectively; for the CS, the suitable discharge, velocity, sediment concentration, and water temperature fall within the ranges of 10,000–15,000 m^3/s, 1.0–1.2 m/s, 0.1–0.3 kg/m^3, and 18–20 °C, respectively.

To investigate the impacts of the GR and the TGR on the propagation of the FMC and the CS, the study period was divided into five sub-periods, i.e., pre-GR period (before 1981), post-GR period (1981–2002), post-TGR period (2003–2005 for the first stage, 2006–2008 for second stage, 2009–end for the third stage). Frequency distributions of the daily discharge, sediment concentration, and water temperature during May–June and October–November were found and compared among the different sub-periods. The satisfying degrees, i.e., the suitable daily discharge/sediment concentration/water temperature for the two taxa, and the flow rising characteristics during May–June, as well as the falling ones during October–November, were also examined. In addition, the flow rising (falling) difference between Yichang and Cuntan during different sub-periods was also tested using the two-sample *t*-test at a confidence level of 95% [41]. Definitions of frequency, satisfying degree, and flow rising and falling characteristics were provided as follows.

The frequency of the daily discharge/sediment concentration/water temperature was estimated according to the empirical frequency expectation formula [42,43]: $F(x_i) = \frac{m}{n+1} \times 100\%$, where x_i is the data from a given streamflow/sediment concentration/water temperature series and $F(x_i)$ is the frequency estimator of x_i; m is the rank of observations x_i arranged in rising order, and n is the number of data points.

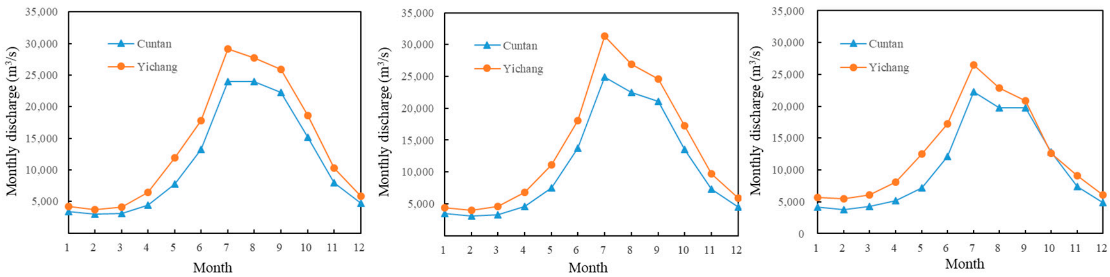
The satisfying degree (SD) was defined as: $SD = \frac{N_{\text{suitable}}}{N_{\text{total}}}$. For the FMC, the N_{suitable} was for the days of daily flow or water temperature within the range of 7500–1000 m^3/s and 18.6–25.5 °C, respectively, while the N_{total} is for the total days from May to June; for the CS, the N_{suitable} was for the days of daily discharge or sediment concentration or water temperature within the range of 10,000–15,000 m^3/s or 0.1–0.3 kg/m^3 or 18–20 °C, respectively, and N_{total} was for the total days from October to November.

The flow rising (falling) characteristics included the rising (falling) count, rising (falling) magnitude, and rising (falling) duration. The rising (falling) count was defined according to the following algorithms: $\Delta Q_i = Q_{t+i} - Q_{t+i-1}$. If ΔQ_i remained positive (negative) for at least three days in a row, then one rise (fall) was recorded; and the related rising (falling) magnitude for this rise (fall) was defined as $\sum_{i=1}^{i=m} \Delta Q_i$, while the m days is defined as the related rising (falling) duration for the rise (fall).

4. Results

4.1. Alterations in Flow, Sediment, and Water Temperature Frequency Distributions

Relative to the Cuntan station, it was clear that the effect of the TGR's regulation on the downstream discharge was very strong. The monthly discharge distribution remained relatively stable during the pre-GR and pre-TGR periods, whilst over the post-TGR period, a big drop during July–December occurred with the maximum reduction in September and October, along with an increase over January–June with the maximum increase occurring in May and June (Figure 2). Figure 3 shows the frequency distributions of the daily discharge in May–June and October–November during the pre- and post-dam periods. For discharge in May–June, no obvious change was observed during 1981–2002 in comparison with 1950–1980. Over 2003–2005, the Yichang-Cuntan discharge difference rose when the percentage was bigger than ≈80%; and it kept increasing for the frequencies higher than 97% during 2006–2008; after 2009, almost the whole frequency distribution remarkably increased. Comparing the decrease of discharge difference in May–June, the TGR impact on the flow in October–November was more significant, i.e., a pronounced reduction of flow occurred during 2003–2005; during 2006–2008 and 2009–2017, this decrease intensified and most of the frequency curve at Yichang was even overlapped by the one for Cuntan.



(**a**) 1950–1980 (**b**) 1981–2002 (**c**) 2003–2017

Figure 2. Impact of reservoir regulation on mean monthly discharge.

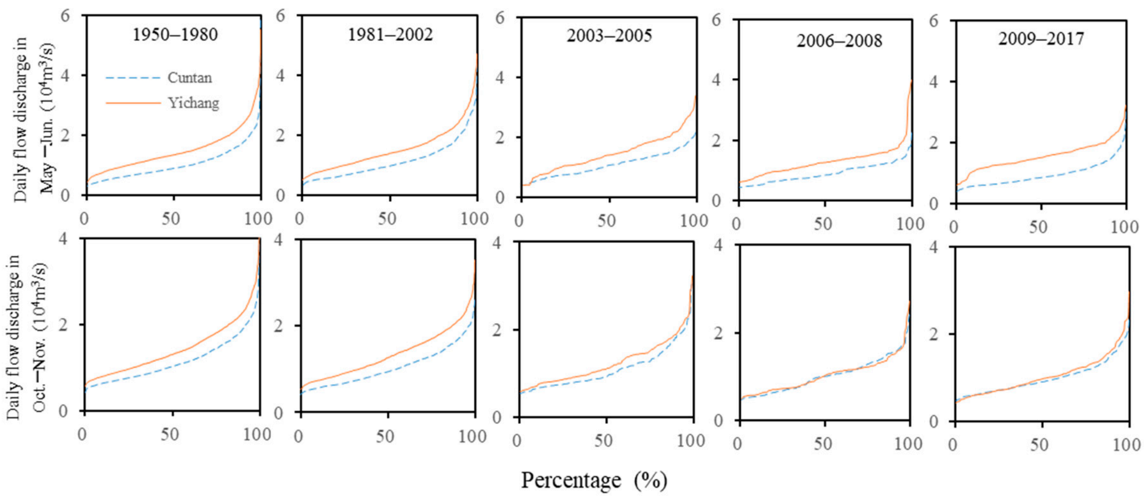
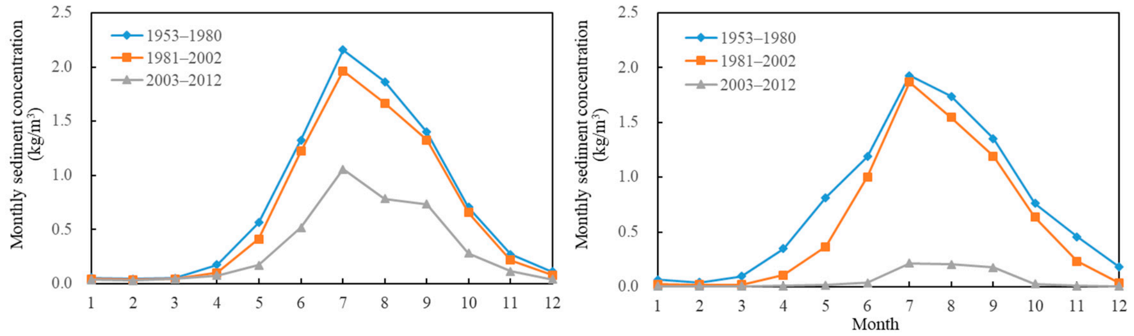


Figure 3. Daily discharge frequency distribution in May–June and October–November for different sub-periods.

Relative to Cuntan, significant changes in the monthly sediment concentration occurred at Yichang due to the GR and the TGR. Sediment concentration during January–May and November–December was reduced by 50–80% over 1981–2002; a reduction was also found during June–October (3–15%) (Figure 4). These changes were statistically significant at the 95% confidence level. After the TGR's implementation, sediment concentration in January–December substantially decreased (76–95%), with the decrease being more than 94% during April–June and October–November. The decrease during March–November was also found to be statistically significant at the 95% confidence level. Frequency distributions of daily sediment concentrations in October–November during pre- and post-dam periods are shown in Figure 5**.** The frequency curve at Yichang generally overlapped with that at Cuntan during 1981–2002, while the curve at Yichang was clearly above that at Cuntan during 1953–1980. During 2003–2005, the curve at Yichang was completely below that at Cuntan, particularly for the higher frequency part. The decrease in the higher frequency part for Yichang was exacerbated over 2006–2008. Since the sediment concentration at Cuntan was rather low after 2009, the decrease at Yichang was not as clear as that during the past two periods.



(**a**) Cuntan (**b**) Yichang

Figure 4. Impact of reservoirs on the monthly distribution of sediment concentration. Notes: the average monthly sediment concentration (kg/m^3) was calculated using the average monthly sediment discharge (kg/s) divided by the average monthly flow discharge (m^3/s) according to the Code of Hydrologic Data Compilation [32].

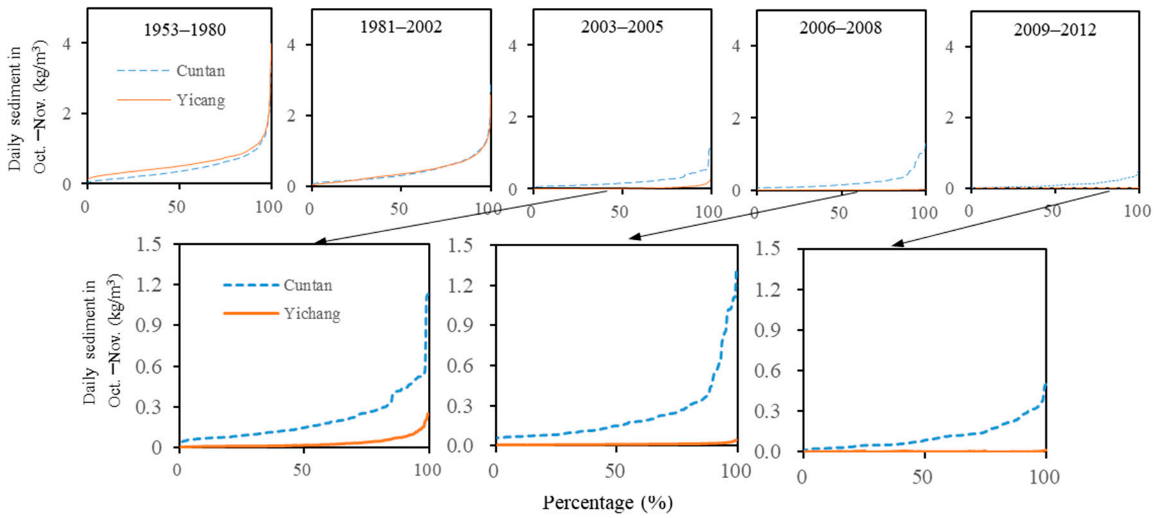


Figure 5. Frequency distributions of the daily sediment concentration in October–November during different periods. Notes: The three bigger graphs are the frequency distributions of daily sediment over periods of 2003–2005, 2006–2008, and 2009–2012, respectively, but with more details and a shorter y-axis scale.

Water temperature conditions at Cuntan did not change much, as seen by the distribution curves being very close during the three periods. However, water temperature at Yichang experienced a remarkable decrease from March to July and an increase from September to February after the TGR was implemented, while a very limited change occurred between pre- and post-GR periods (Figure 6). The changes during January, March to May, and October to December were all significant at the 95% confidence level. Frequency distributions of ten-day water temperature in May–June and October–November during pre- and post- dam periods are presented in Figure 7. No obvious change was found during 1981–2002, relative to 1959–1980, for both May–June and October–November periods. However, a significant decrease (increase) of water temperature at Yichang occurred during 2003–2005, with a very significant decrease (increase) for lower (higher and lower) frequency in May–June (October–November). The difference between Yichang and Cuntan during 2006–2008 kept increasing with a more significant decrease (increase) in the middle (lower and middle) frequency occurring during May–June (October–November). The most significant decrease (increase) at Yichang occurred after 2009 in May–June (October–November).

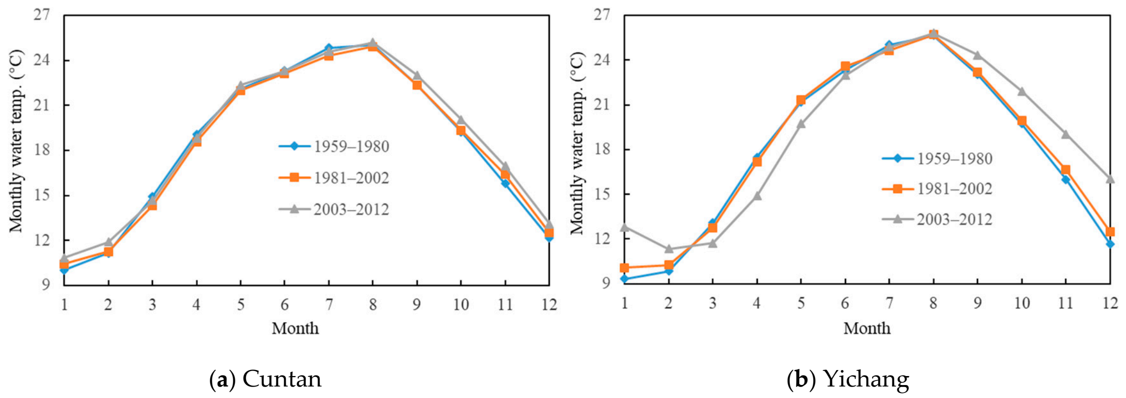


Figure 6. Impact of reservoirs on the monthly distribution of water temperature.

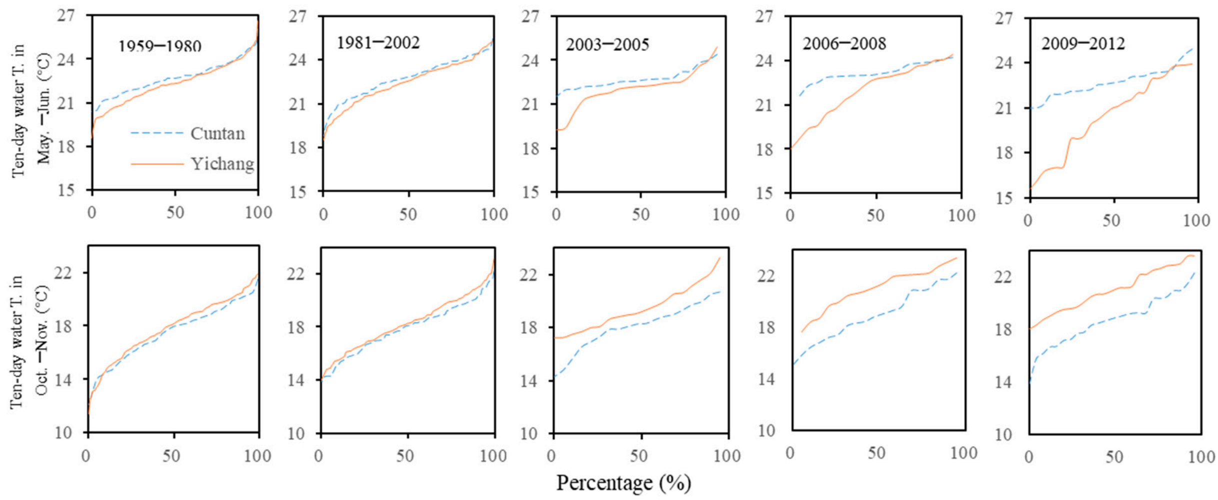


Figure 7. Frequency distributions of the daily water temperature in May–June and October–November during different periods.

4.2. Alterations in the Satisfying Degree of Suitable Spawning Conditions

For the suitable discharge of the FMC, the relative satisfying degree increased over 1981–2002 in comparison with that during 1950–1980; however, it reduced a lot during 2003–2005. The satisfying degree was enhanced again during 2006–2008 as a result of more water release relative to 2003–2005, which contributed to the increment of the daily discharge value being originally lower than 7500 m^3/s.

The satisfying degree kept increasing over the period of 2009–2017 with more water being released from the TGR with the increase of water storage during the period from the middle of September to early November. The lower flows continued to increase and finally fell within the range of 7500–10,000 m^3/s. In contrast, the relative satisfying degree of discharge for the CS showed an opposite behavior. It diminished slightly during 1981–2002 from the period of 1950–1980 whilst it improved significantly during 2003–2005. It is clear that the reservoir water storage decreased some daily flows to 10,000–15,000 m^3/s. Nevertheless, the satisfying degree declined again during 2006–2008. Although the daily flow higher than 15,000 m^3/s was reduced by the reservoir operation, some discharge falling within the suitable range was also reduced by the TGR. Unfortunately, the decreased days of suitable discharge was more than the increased days of high discharge. Thus, the relative satisfying degree of suitable flow significantly dropped during 2009–2017 (Table 2).

Table 2. Satisfying degree of SF for the FMC and the CS during different stages.

Fishes	Stations	Before 1980	1981–2002	2003–2005	2006–2008	After 2009
FMC	CT	0.390	0.329	0.404	0.470	0.432
	YC	0.341	0.326	0.311	0.415	0.177
	YC/CT	0.875	0.991	0.770	0.884	0.406
CS	CT	0.298	0.292	0.273	0.404	0.350
	YC	0.348	0.312	0.339	0.410	0.271
	YC/CT	1.168	1.069	1.240	1.014	0.776

Notes: SF—suitable flow discharge, FMC—four major carps, CS—Chinese sturgeon; CT, YC—satisfying degree of suitable flow at Cuntan and Yichang respectively, YC/CT—ratio of the satisfying degree of suitable flow at Yichang to that at Cuntan.

Since no publicly admitted information of the suitable sediment concentration for the FMC is available, only the suitable sediment concentration for the CS was examined. Analysis of sediment data showed (Table 3) that the relative satisfying degree of the suitable sediment concentration decreased during 1981–2002 relative to the period of 1950–1980, and it continued to decline significantly during 2003–2005. What is more concerning is that the satisfying degree even dropped to zero during both 2006–2008 and 2009–2012.

Table 3. Satisfying degree of SSC for Chinese sturgeon during different stages.

Fishes	Stations	Before 1980	1981–2002	2003–2005	2006–2008	After 2009
CS	CT	0.751	0.775	0.699	0.645	0.451
	YC	0.724	0.701	0.060	0.000	0.000
	YC/CT	0.964	0.905	0.086	0.000	0.000

Notes: SSC—suitable sediment concentration, CS—Chinese sturgeon; CT, YC—satisfying degree of suitable sediment concentration at Cuntan and Yichang respectively, YC/CT—ratio of the satisfying degree of suitable sediment concentration at Yichang to that at Cuntan.

The relative satisfying degree of the suitable water temperature for the FMC remained relatively stable during 1981–2002 compared with 1950–1980, and it began declining during 2003–2005, with the decreasing trend persisting during both 2006–2008 and 2009–2012 (Table 4). For the CS, a clear decrease in the relative satisfying degree was observed during 1981–2002, and it dropped further during the next later two periods; however, it increased during 2009–2012. The significant increase during 2009–2012 could be attributed to the strong hysteresis cold effect during October–November from the TGR. The water temperature at Yichang increased above 18 °C throughout 2009–2012, while the lower temperature at Cuntan decreased further during the same period. Nevertheless, the average satisfying degree for the three periods after TGR was still significantly lower than that during 1981–2002.

Table 4. Satisfying degree of SWT for the FMC and the CS during different stages.

Fishes	Stations	Before 1980	1981–2002	2003–2005	2006–2008	After 2009
FMC	CT	0.993	0.997	1.000	1.000	0.996
	YC	0.985	0.996	0.989	0.940	0.717
	YC/CT	0.992	0.999	0.989	0.940	0.720
CS	CT	0.387	0.397	0.546	0.339	0.348
	YC	0.387	0.348	0.426	0.208	0.328
	YC/CT	1.000	0.876	0.780	0.613	0.941

Notes: SWT—suitable water temperature, FMC—four major carps, CS—Chinese sturgeon; CT, YC—degree of suitable water temperature at Cuntan and Yichang respectively, YC/CT—ratio of the satisfying degree of suitable water temperature at Yichang to that at Cuntan.

4.3. Alterations in Discharge Rising/Falling Characteristics

During the post-GR period, there was an obvious increase in annual falling counts and a mild increase in annual falling/rising duration and rising/counts, along with a remarkable reduction in annual rising/falling magnitude, observed in comparison with those during the pre-GR period (Figure 8). A *t*-test indicated that only the annual falling magnitude and counts were statistically significant at the 95% confidence level. Since the falling magnitude and counts showed opposite changing trends, it can be considered that the contributions from the changes of these two factors had counteracting effects on the downstream CS's spawning. However, the falling duration showed a moderate increase during the post-GR period; thus, it seems that the GR had a negative impact on the downstream CS's propagation. The GR also had negative influences on the downstream FMC's propagation due to the obvious decrease in rising magnitude since the increase of rising duration and counts was small. It should be noted that the conclusion obtained from the above was based on the assumption that the flow falling/rising magnitude, counts, and duration contributed equally to the spawning of the CS and FMC.

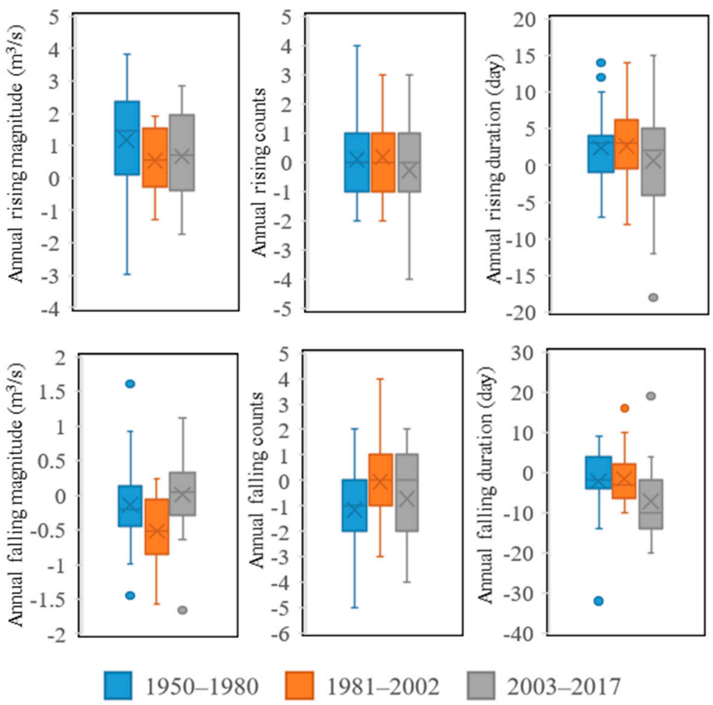


Figure 8. Boxplots of flow rising/falling characteristic difference between Yichang and Cuntan during May–June/October–November. The upper and lower parts of the boxes represent the 75th and 25th percentiles, respectively; the whiskers indicate the 90th and 10th percentiles; and the lines within the boxes are the median values.

Comparison of flow characteristics between the post-TGR and pre-TGR period shows a clear increase in annual falling magnitude, but a pronounced decrease in the annual rising magnitude, rising/falling counts, and duration (Figure 8). A two-sample *t*-test indicated that only the falling magnitude and duration were statistically significant at the 95% confidence level. These results also suggest some trade-off between the changes in falling magnitude and duration in contributing to CS's reproduction because of their counteracting tendencies. Therefore, the TGR had a negative effect on the downstream CS's propagation due to remarkable decline in falling counts. Additionally, the TGR also had a negative impact on the downstream FMC's spawning since the annual rising counts and duration decreased much more than the rising magnitude.

5. Discussion

Generally, the GR exerted no obvious effects on the frequency distribution of the downstream discharge in both May–June and October–November, whereas the TGR decreased its downstream flow significantly during May–June and October–November. What is more important is that the influence from the TGR was more pronounced in October–November, relative to May–June, since the TGR began storing water from the middle of September to the end of October or early November. Generally, the higher water storage in the TGR reservoir led to a larger decline, with the maximum impact during the TGR's normal stage in May–June and October–November. The GR and the TGR also affected the downstream flow rising and falling characteristics, with a larger impact on the falling characteristics than the rising ones. Correspondingly, the TGR and the GR had negative impacts on the spawning of the CS and the FMC.

Significant trapping of sediment was induced both by the GR and the TGR, particularly by the TGR during the refilling operations due to the higher water level. For instance, the average daily sediment concentration at Yichang reduced from 0.406 kg/m^3 over 1981–2002 to 0.032 kg/m^3, 0.010 kg/m^3, 0.004 kg/m^3 during the first stage, second stage, and third stage, respectively, of the post-TGR period. The low sediment in the clear water with high energy can trigger serious riverbed scouring and riverbank collapse in the downstream channels [8,44,45]. In addition, low sediment may also harm the spawning of Chinese sturgeons as they are rather sensitive to the sediment condition during their propagation. The present study suggested that the sediment condition in the downstream of the TGR was not suitable anymore for the spawning of the CS after 2006. A similar conclusion for the FMC by Ban et al. [27] disclosed that the sediment concentration played the leading role in the spawning while its reduction was beyond the limited range. It is worthy to note that the dramatic decline of sediment could also be partly attributed to the sediment trapping above the Cuntan station since several other large reservoirs (i.e., Xiluodu reservoir, Xiangjiabang reservoir, Pubugou Reservoir) were built in recent years. This is one of the most important reasons that the Cuntan was chosen as a reference station to investigate the impact of the TGR and the GR on their downstream hydrological regimes.

The GR had a very mild thermal hysteresis effect on its downstream water temperature for both the May–June and October–November periods. Comparatively, the hysteresis impacts of the TGR were much more significant, i.e., hindering the warming trend in water temperature in the warm season of May–June and impeding the cooling trend in the cooling season of October–November. The thermal hysteresis effects were amplified significantly with increasing reservoir storage volumes. The larger the reservoir capacity, the longer the residence time of the water inside the reservoir, as a result of more severe stratification of the water. Since the spawning of the FMC and the CS are closely associated with the water temperature, the lower temperatures in the water released from the TGR, as a result of the cooling effect, delayed the FMC spawning timing to middle May, and the spawning period was shortened from April–July to May–June [46]. Du et al. [47] also reported that the timing of the water temperature reaching 20 °C (the upper limit of the optimal water temperature for the CS) was postponed by 27 days.

The population of adult CS may directly reflect the ecological health degree of their spawning conditions. The number of the adult CS downstream of the GR spawning site significantly reduced from 1131 during 1981–2002 to 295 during 2003–2005, with a peak population of ≈2200 in 1984. The population kept decreasing to 153 during 2006–2008, and further dropped to 111 during 2009–2014, with a historical minimum of 57 in 2013 (Figure 9). Moreover, the Ministry of Agriculture (MOA) also reported that no CS spawning activity was detected in 2013 and 2014 [48]. This evidence implies that integrated changes/variations in flow, sediment, and water temperature regime due to dam construction and operation have severely affected the CS spawning ground and habitat, leading to a significant reduction in the Chinese sturgeon population. It is worth noting that due to difficulties in fish data collection, only the annual population of adult CS was obtained from different publications. Although these data series may not be very homogenous, they are from the same CS spawning ground during the spawning season, and their variation could serve as a reliable reference for the change in CS spawning habitat between the pre and post-dam construction.

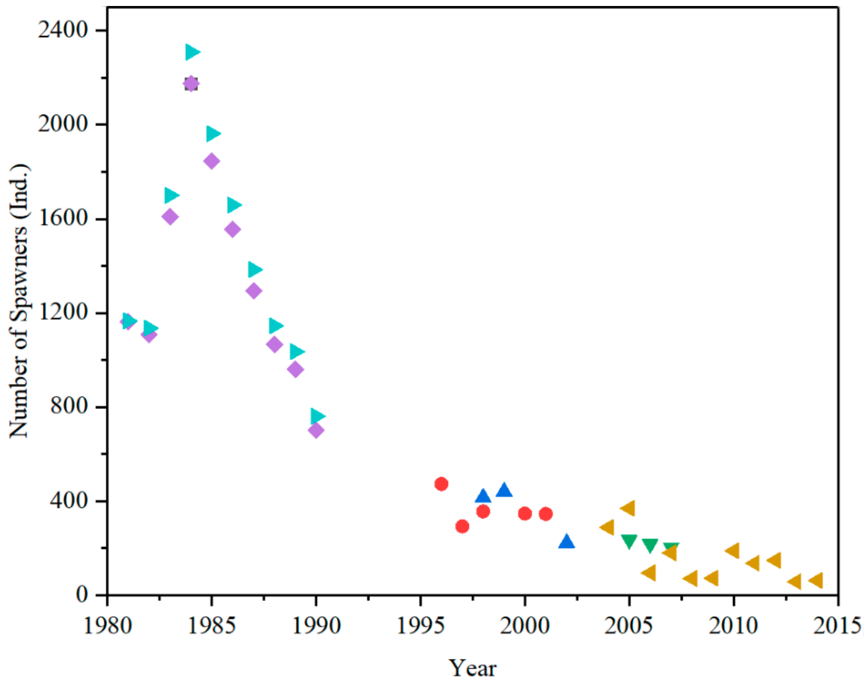


Figure 9. Temporal variations of adult CS population at the Gezhouba spawning site in the Yangtze River. Note: Blue square represents the data collected from Ke et al. [33], red dot from Wei et al. [34], blue triangle from Qiao et al. [35], green inverted triangle from Tao et al. [36], purple diamond from Huang et al. [37], left brown triangle from Wu et al. [38], right green triangle from Huang et al. [39].

To alleviate the adverse effects of dam regulation, the TGR has advocated releasing an experimental flow increase process to simulate the natural flow in duration, magnitude, and daily increasing rate during the spawning season to enhance the natural population of the FMC since 2011 [23]. These ecological experimental operations have been launched continuously over the past seven years and the 11th ecological operation test was carried out by the Changjiang Flood Control and Drought Relief Headquarter on 19 May 2018 [49]. It was reported that the water temperature and rising characteristics were considered reasonable during this experimental operation. For the spawning of the CS, there is not as much information of ecological experimental operations as that for the FMC. However, the spawning condition of the CS is much more complicated and sensitive to the environment than that of the FMC. Since the CS is in a near-extinct condition, the ecological operation for the CS's spawning should be the highest priority and should at least take flow, sediment concentration, water temperature, and flow falling characteristics into account simultaneously. Therefore, an urgent ecological operation, including at least three sub-operations, i.e., ecological flow, sediment concentration, and thermal condition, is necessary for the GR and the TGR in the near future. Furthermore, we also emphasize the need for long-term monitoring of the FMC and the CS after the TGR commenced operation in order to understand the ecological health responses to hydrological alterations for effective resource management in regulated rivers [50].

6. Conclusions

This study investigated the impact of the GR and the TGR on their downstream spawning of the FMC and the CS in the Yangtze River using frequency distribution, satisfying degree, and rising/falling characteristics of hydrological conditions. Results revealed that the GR had no obvious impacts on the frequency distribution of its downstream discharge, a weak impact on water temperature in the spawning season of the FMC and the CS, but a significant impact on the sediment concentration in the CS spawning season. Due to GR operations, the satisfying degree of the suitable discharge and water temperature for the FMC propagation increased, while that of the suitable flow, sediment concentration, and water temperature for the CS decreased. The TGR significantly reduced the downstream flow and sediment concentration in the spawning season of these two species, with a very dramatic decrease in the CS's season. The TGR had a significant hysteresis effect on the downstream water temperature by hindering the warming trend of the water temperature during the FMC spawning season while impeding the cooling trend in the CS's season. During the post-TGR period, the satisfying degree change showed a pronounced ascending tendency in the suitable flow while displaying a remarkable descending trend in the water temperature for the FMC; the satisfying degree change presented a significant decreasing trend for the suitable discharge, sediment concentration, and water temperature for the CS, and the importance of each effect on the decrease was ranked as sediment concentration > flow discharge > water temperature. The TGR and the GR had negative impacts on the spawning of the CS and the FMC in terms of the rising/falling characteristics. The impact of the TGR was generally much more significant than that of the GR, and the impact of the TGR increased with the reservoir storage.

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References

1. Nilsson, C.; Reidy, C.A.; Dynesius, M.; Revenga, C. Fragmentation and flow regulation of the world's large river systems. *Science* **2005**, *308*, 405–408. [CrossRef] [PubMed]
2. Grill, G.; Lehner, B.; Thieme, M.; Geenen, B.; Tickner, D.; Antonelli, F.; Maced, H.E. Mapping the world's free-flowing rivers. *Nature* **2019**, *569*, 215. [CrossRef] [PubMed]
3. Wiatkowski, M. Influence of Słup dam reservoir on flow and quality of water in the Nysa Szalona river. *Pol. J. Environ. Stud.* **2011**, *20*, 469–478.
4. Tebakari, T.; Yoshitani, J.; Suvanpimol, P. Impact of large-scale reservoir operation on flow regime in the Chao Phraya River basin, Thailand. *Hydrol. Proc.* **2012**, *26*, 2411–2420. [CrossRef]
5. Wang, Y.; Zhang, N.; Wang, D.; Wu, J.; Zhang, X. Investigating the impacts of cascade hydropower development on the natural flow regime in the Yangtze River, China. *Sci. Total Environ.* **2018**, *624*, 1187–1194. [CrossRef] [PubMed]
6. Li, Q.; Yu, M.; Lu, G.; Cai, T.; Xia, Z.; Ren, L. Impacts of the Gezhouba and the Three Gorges reservoirs on the sediment regime of the Yangtze River. *J. Hydrol.* **2011**, *403*, 224–233. [CrossRef]

7. Shokri, A.; Haddad, O.B.; Mariño, M.A. Reservoir operation for simultaneously meeting water demand and sediment flushing: Stochastic dynamic programming approach with two uncertainties. *J. Water Res. Plan. Manag.* **2012**, *139*, 277–289. [CrossRef]
8. Yang, H.F.; Yang, S.L.; Xu, K.H.; Milliman, J.D.; Wang, H.; Yang, Z.; Chen, Z.; Zhang, C.Y. Human impacts on sediment in the Yangtze River: A review and new perspectives. *Glob. Planet. Chang.* **2018**, *162*, 8–17. [CrossRef]
9. Carron, J.C.; Rajaram, H. Impact of variable reservoir releases on management of downstream water temperatures. *Water Resour. Res.* **2001**, *37*, 1733–1743. [CrossRef]
10. Liu, B.; Yang, D.; Ye, B.; Berezovskaya, S. Long-term open-water season stream temperature variations and changes over Lena river basin in Siberia. *Glob. Planet. Chang.* **2005**, *48*, 96–111. [CrossRef]
11. Li, Q.; Li, H.; Yu, M. Impacts of Three Gorges-Gezhouba reservoir cascade on the heat flux regime of the Yangtze River. *Concept. Model. Stud. Integr. Groundw. Surf. Water Ecol. Syst.* **2011**, *345*, 207–212.
12. Suen, J.P.; Eheart, J.W.; Herricks, E.E.; Chang, F.J. Evaluating the potential impact of reservoir operation on fish communities. *J. Water Res. Plan. Man.* **2009**, *135*, 475–483. [CrossRef]
13. Wu, H.; Zeng, G.; Liang, J.; Chen, J.; Xu, J.; Dai, J.; Ye, S. Responses of landscape pattern of China's two largest freshwater lakes to early dry season after the impoundment of Three-Gorges Dam. *Int. J. Appl. Earth Obs. Geoinf.* **2017**, *56*, 36–43. [CrossRef]
14. Han, X.; Feng, L.; Hu, C.; Chen, X. Wetland changes of China's largest freshwater lake and their linkage with the Three Gorges Dam. *Remote Sens. Environ.* **2018**, *204*, 799–811. [CrossRef]
15. Zalewski, M. Ecohydrology—Process oriented thinking for sustainability of river basins. *Ecohydrol. Hydrobiol.* **2012**, *12*, 89–92. [CrossRef]
16. Wang, H.; Brill, E.D.; Ranjithan, R.S.; Sankarasubramanian, A. A framework for incorporating ecological releases in single reservoir operation. *Adv. Water Resour.* **2015**, *78*, 9–21. [CrossRef]
17. Cury, P.; Roy, C. Optimal environmental window and pelagic fish recruitment success in upwelling areas. *Can. J. Fish. Aquat. Sci.* **1989**, *46*, 670–680. [CrossRef]
18. Roy, C.; Cury, P.; Kifani, S. Pelagic fish recruitment success and reproductive strategy in upwelling area: Environmental compromises. *S. Afr. J. Mar. Sci.* **1992**, *12*, 135–146. [CrossRef]
19. Baumgartner, G.; Nakatani, K.; Gomes, L.C.; Bialetzki, A.; Sanches, P.V.; Makrakis, M.C. Fish larvae from the upper Parana River: Do abiotic factors affect larval density? *Neotrop. Ichthyol.* **2008**, *6*, 551–558. [CrossRef]
20. Gao, X.; Li, M.Z.; Lin, P.C.; Duan, Z.H.; Liu, H.Z. Environmental cues for natural reproduction of the Chinese sturgeon, *Acipenser sinensis* Gray, 1835, in the Yangtze River, China. *J. Appl. Ichthyol.* **2013**, *29*, 1389–1394. [CrossRef]
21. Xu, W.; Qiao, Y.; Chen, X.J.; Cai, Y.P.; Yang, Z.; Liu, H.G. Spawning activity of the four major Chinese carps in the middle mainstream of the Yangtze River, during the Three Gorges Reservoir operation period, China. *J. Appl. Ichthyol.* **2015**, *31*, 846–854. [CrossRef]
22. Yu, M.; Li, Q.; Lu, G.; Cai, T.; Xie, W.; Bai, X. Investigation into the Impacts of the Gezhouba and the Three Gorges Reservoirs on the Flow Regime of the Yangtze River. *J. Hydrol. Eng.* **2013**, *18*, 1098–1106. [CrossRef]
23. Yi, Y.; Wan, Z.; Yang, Z. Impact of the Gezhouba and Three Gorges Dams on habitat suitability of carps in the Yangtze River. *J. Hydrol.* **2010**, *387*, 283–291.
24. Wang, J.N.; Li, C.; Duan, X.B.; Luo, H.H.; Feng, S.X.; Peng, Q.D.; Liao, W.G. The relationship between thermal regime alteration and spawning delay of the four major Chinese carps in the Yangtze River below the Three Gorges Dam. *River Res. Appl.* **2014**, *30*, 987–1001. [CrossRef]
25. Chang, T.; Lin, P.C.; Gao, X.; Liu, F.; Duan, Z.H.; Liu, H.Z. Using adaptive resolution imaging sonar to investigate Chinese sturgeon (*Acipenser sinensis* Gray, 1835) behaviour on its only spawning ground in the Yangtze River. *J. Appl. Ichthyol.* **2017**, *33*, 681–688. [CrossRef]
26. Shen, Y.; Wang, P.; Wang, C.; Yu, Y.; Kong, N. Potential causes of habitat degradation and spawning time delay of the Chinese sturgeon (*Acipenser sinensis*). *Ecol. Inform.* **2018**, *43*, 96–105. [CrossRef]
27. Ban, X.; Chen, S.; Pan, B.Z.; Du, Y.; Yin, D.C.; Bai, M.C. The eco-hydrologic influence of the Three Gorges Reservoir on the abundance of larval fish of four carp species in the Yangtze River, China. *Ecohydrology* **2017**, *10*, e1763. [CrossRef]
28. Ban, X.; Du, Y.; Liu, H.Z.; Ling, F. Applying instream flow incremental method for the spawning habitat protection of Chinese sturgeon (*Acipenser sinensis*). *River Res. Appl.* **2011**, *27*, 87–98. [CrossRef]

29. Chen, Y.B.; Wu, B.F. Impact analysis of the Three-Gorges Project on the spawning of Chinese sturgeon *Acipenser sinensis*. *J. Appl. Ichthyol.* **2011**, *27*, 383–386.
30. Li, Q.; Yu, M.; Zhao, J.; Cai, T.; Lu, G.; Xie, W.; Bai, X. Impact of the Three Gorges reservoir operation on downstream ecological water requirements. *Hydrol. Res.* **2012**, *43*, 48–53. [CrossRef]
31. Yang, S.L.; Milliman, J.D.; Xu, K.H.; Deng, B.; Zhang, X.Y.; Luo, X.X. Downstream sedimentary and geomorphic impacts of the Three Gorges Dam on the Yangtze River. *Earth-Sci. Rev.* **2014**, *138*, 469–486. [CrossRef]
32. MWR (Ministry of Water Resources). *Code of Hydrologica Data Compilation*; China Water Conservancy and Hydropower Press: Beijing, China, 1999.
33. Ke, F.E.; Wei, Q.W.; Zhang, G.L.; Hu, D.G.; Luo, J.D.; Zhuang, P. Investigation in the structure of spawning population of Chinese sturgeon (*Acipenser sinensis* Gray) and the estimate of stock. *Freshw. Fish.* **1992**, *4*, 7–11.
34. Wei, Q.W. Reproductive Behavior Ecology of Chinese Sturgeon (*Acipenser sinensis* Gray) with Its Stock Assessment. Ph.D. Thesis, Chinese Academy of Sciences, Beijing, China, 2003.
35. Qiao, Y.; Tang, X.; Brosse, S.; Chang, J. Chinese sturgeon (*Acipenser sinensis*) in the Yangtze River: A hydroacoustic assessment of fish location and abundance on the last spawning ground. *J. Appl. Ichthyol.* **2006**, *22*, 140–144. [CrossRef]
36. Tao, J.P.; Qiao, Y.; Yang, Z.; Chang, J.B.; Dong, F.Y.; Wan, L. Estimation on the spawning population and spawning sizes of Chinese sturgeon (*Acipenser sinensis*) and trend analysis of their change in recent years. *J. Hydroecol.* **2009**, *2*, 38–43.
37. Huang, Z.L. A New Method of Estimation on Populations of Chinese Sturgeon in the Yangtze River by Using Existing Fishing Data. *Sci. Technol. Rev.* **2013**, *31*, 18–22.
38. Wu, J.M.; Wang, C.Y.; Zhang, H.; Du, H.; Liu, Z.G.; Shen, L.; Rosenthal, H. Drastic decline in spawning activity of Chinese sturgeon *Acipenser sinensis* Gray 1835 in the remaining spawning ground of the Yangtze River since the construction of hydrodams. *J. Appl. Ichthyol.* **2015**, *31*, 839–842. [CrossRef]
39. Huang, Z.L.; Wang, L.H.; Ren, J.Y. Study on the spawning population fluctuation of Chinese sturgeons around the closure of Gezhouba Dam. *Sci. Sin. Tech.* **2017**, *47*, 871–881. (In Chinese)
40. Guo, W. Research on Reservoir Ecological Operation Model for River Health. Ph.D. Thesis, Hohai University, Nanjing, China, 2008.
41. Cressie, N.A.C.; Whitford, H.J. How to Use the Two Sample t-Test? *Biom. J.* **1986**, *28*, 131–148. [CrossRef]
42. Haan, C.T. *Statistical Methods in Hydrology*; The Iowa State University Press: Iowa, IA, USA, 1977.
43. Huang, Z.P. *Hydrological Statistics*; Hohai University Press: Nanjing, China, 2003.
44. Lai, X.; Yin, D.; Finlayson, B.L.; Wei, T.; Li, M.; Yuan, W.; Yang, S.; Dai, Z.; Gao, S.; Chen, Z. Will river erosion below the Three Gorges Dam stop in the middle Yangtze? *J. Hydrol.* **2017**, *554*, 24–31. [CrossRef]
45. Sun, G.; Yang, Y.; Jiang, W.; Zheng, H. Effects of an increase in reservoir drawdown rate on bank slope stability: A case study at the Three Gorges Reservoir, China. *Eng. Geol.* **2017**, *221*, 61–69. [CrossRef]
46. Cai, Y.P.; Yang, Z.; Xu, W. Effect of Water Temperature Variation After Impoundment of the Three Gorges Reservoir on Natural Reproduction of the Four Major Chinese Carps. *Adv. Eng. Sci.* **2017**, *49*, 70–77.
47. Du, L.X.; Niu, L.H.; Huang, T. Variations of the water temperature in Three Gorges Reservoir and its influences. *Exp. Water Resour. Hydrop.* **2017**, *38*, 58–63.
48. MOA (Ministry of Agriculture). *Chinese Sturgeon Rescue Plan (2015–2030)*; Ministry of Agriculture of the People's Republic of China: Beijing, China, 2015.
49. A new round of ecological dispatch test for the Three Gorges Reservoir. Available online: http://www.gov.cn/xinwen/2018-05/19/content_5292134.htm (accessed on 27 September 2019).
50. Gao, X.; Fujiwara, M.; Winemiller, K.O.; Lin, P.; Li, M.; Liu, H. Regime shift in fish assemblage structure in the Yangtze River following construction of the Three Gorges Dam. *Sci. Rep.* **2019**, *9*, 4212. [CrossRef] [PubMed]