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Managing the Three Gorges Dam to Implement Environmental Flows in the Yangtze River

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The construction of the Three Gorges Dam, along with other development in the Yangtze River basin, has had profound consequences for the river's flow and sediment regime. This has had major impacts on the geomorphology and ecology of the river downstream of the dam, with related impacts on biodiversity, including fish populations, livelihoods, and water security in the middle and lower Yangtze. Changes to fish populations have included a fall of around 90% in the total number of fish fry for the four economically-important Chinese carp species, caused at least in part by alterations in the flow regime. In response, there has been increased research into the significance of flow regimes for Chinese carp, as well as other aspects of river health. A partnership between the Chinese Government, the dam operator, scientists, and conservationists has led to pilot environmental flow releases over a 5-year period in an attempt to mitigate some of these impacts. Subsequent monitoring has shown that numbers of fish fry are increasing from the low they had fallen to in 2008. Drawing on lessons from the pilot environmental flow releases, in October 2015 the official regulations that govern operations of the Three Gorges Dam were amended to incorporate additional objectives, including incorporating environmental flow releases as part of the routine operation of the dam. This paper describes the processes that led to the environmental flow program from Three Gorges, a review of monitoring data collected during the pilot environmental flow releases, the subsequent amendment of the dam operating rules, and prospects for expanding environmental flow implementation in the Yangtze River in coming years.

Keywords: dam re-operation, Three Gorges dam, environmental flows, river fisheries, Yangtze river

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INTRODUCTION

Environmental flows have become an important strategy for maintaining and restoring rivers and their social and environmental resources and values. Recent decades have seen major progress in the science that underpins environmental flow assessments. Although widespread implementation of environmental flows has been constrained by a number of challenges (Le Quesne et al., 2010), implementation of environmental flows has been seen in an increasing range of contexts (Harwood et al., 2017). In China, the concept of environmental flows has

gained currency in the river basin management discourse in the last decade (Chen et al., 2016), but examples of implementation remain rare (Sun et al., 2008; Li et al., 2009; Chen and Zhao, 2011). Nevertheless, recent shifts in policy priorities that emphasize the need for more environmentally sustainable approaches to socio-economic development have led to an increased focus on river restoration, including environmental flow implementation (Speed et al., 2016).

In this paper, we describe a program to implement environmental flow releases from the Three Gorges Dam on the Yangtze River (China)—by some measures, the largest dam in the world. We focus on the management, policy and institutional factors that contributed to environmental flow implementation because documenting these examples of application can provide insights for practitioners and managers in other parts of the world (Harwood et al., 2017).

Since 2003, the Three Gorges Dam has regulated flow on the Yangtze River, the third longest river in the world. Dam operations have modified the Yangtze's flow regime and affected flow-dependent processes such as the maintenance of wetlands and fish migration and spawning. The impact of the dam on Yangtze fisheries has been one of the most widely recognized consequences of the dam. For example, the annual harvest of four commercially important carp species dropped by 50–70% compared to the pre-dam baseline with even more dramatic declines in larvae and eggs below the dam (Xie et al., 2007).

Concern within government and the public led to discussions about how to mitigate the negative impact of the Three Gorges Dam on the downstream ecosystem. Researchers and conservationists, including international organizations such as Worldwide Fund for Nature (WWF) and The Nature Conservancy (TNC) recommended that the dam should be re-operated to help restore some of the Yangtze's crucial natural hydrological processes. In 2011, a program to release environmental flows from the dam was initiated and the dam operator [the China Three Gorges Corporation (CTG)][1] has released a flood pulse from the dam in May or June every year since. The primary purpose of these environmental flow releases has been to promote carp spawning. Drawing on lessons from the pilot flow releases, in October 2015 the regulations that govern operation of Three Gorges Dam were amended to incorporate additional objectives and operational requirements that now provide for environmental flow releases as part of the routine operation of the dam.

In this paper we will summarize: (1) the biophysical processes and relevant aspects of the biodiversity of the Yangtze River and how they were affected by the Three Gorges Dam, with a focus on changes to flow regime and populations of four Chinese carp; (2) the regulatory context for dam operations in China, including requirements to maintain fish populations; (3) the processes through which CTG, agencies and stakeholders planned environmental flow releases; (4) the annual flow releases and impacts on carp recruitment; and (5) recommendations for future research and adaptive management.

BACKGROUND ON THE YANGTZE RIVER AND THREE GORGES DAM

The Yangtze River is Asia's longest river, flowing more than 6,000 kilometers from west to east. It sustains 416 fish species, including more than 178 endemic and ancient species, such as the Chinese Paddlefish (*Psephurus gladius*) and Chinese Sturgeon (*Acipenser sinensis*) (Ye et al., 2011). The Yangtze also supports high numbers of birds, especially in the productive wetlands at the river's middle section and mouth that serve as an important stopover and wintering ground for birds traveling Asia's north-south migratory route.

Two independent climate patterns drive the hydrology of the Yangtze River: the upper basin experiences the Indian summer monsoon and the middle parts of the basin experience the East Asian summer monsoon (Ding and Chan, 2005; Chen et al., 2014). Annual precipitation in the basin varies from nearly 900 mm in the upper basin to 1,500 mm in the lower basin (Zhang et al., 2010; Chen et al., 2014). Due to these patterns, flows in the middle reaches of the Yangtze River, including the region immediately upstream of the Three Gorges Dam, are greatest in July with average flow reaching ∼30,000 m^3/s. Flows then decline gradually to an average of ∼4,000 m^3/s in February before rising again in the spring to reach the July peak.

Spanning more than 3 million square kilometers, the Yangtze Basin is home to one-third of China's human population. Throughout history, the river has also supported the rise of early agricultural civilisations, the growth of some of China's largest cities and facilitated shipment of agricultural and industrial goods from the country's interior to the port of Shanghai and beyond (Normile, 1997; Yasuda et al., 2004). While the Yangtze has played a key role in the rapid development of China, the river's ecological functions have undergone dramatic declines resulting from pollution and other anthropogenic impacts.

In recent years, the Yangtze's flows have been harnessed to generate hydroelectric power for one of the world's fastest-growing economies. Hydropower expansion has been driven in part by goals to reduce emissions from coal-fired power plants. Twenty-nine major dams have been built or are planned on the mainstream of the Yangtze. Most of the hydropower sites in the Upper and Middle Yangtze have already been developed and almost all of the hydropower potential in the Jinsha River (the name of the upper mainstream of the Yangtze) is now under development.

The Three Gorges Dam is located at Sandouping, about 40 km upstream of the city of Yichang on the mainstem Yangtze River (**Figure 1**). First contemplated by Sun Yat-sen in the early twentieth-century and with design work undertaken as long ago as 1930s, construction of the dam began in December of 1994 and, by November of 1997, the river had been successfully cut off. In June 2003, the second phase of the dam was finished, and the water level in the reservoir rose to 135 m. Construction of the dam was completed in 2009 and water levels in the reservoir

[1] China Three Gorges Corporation official website, http://www.ctg.com.cn/english/

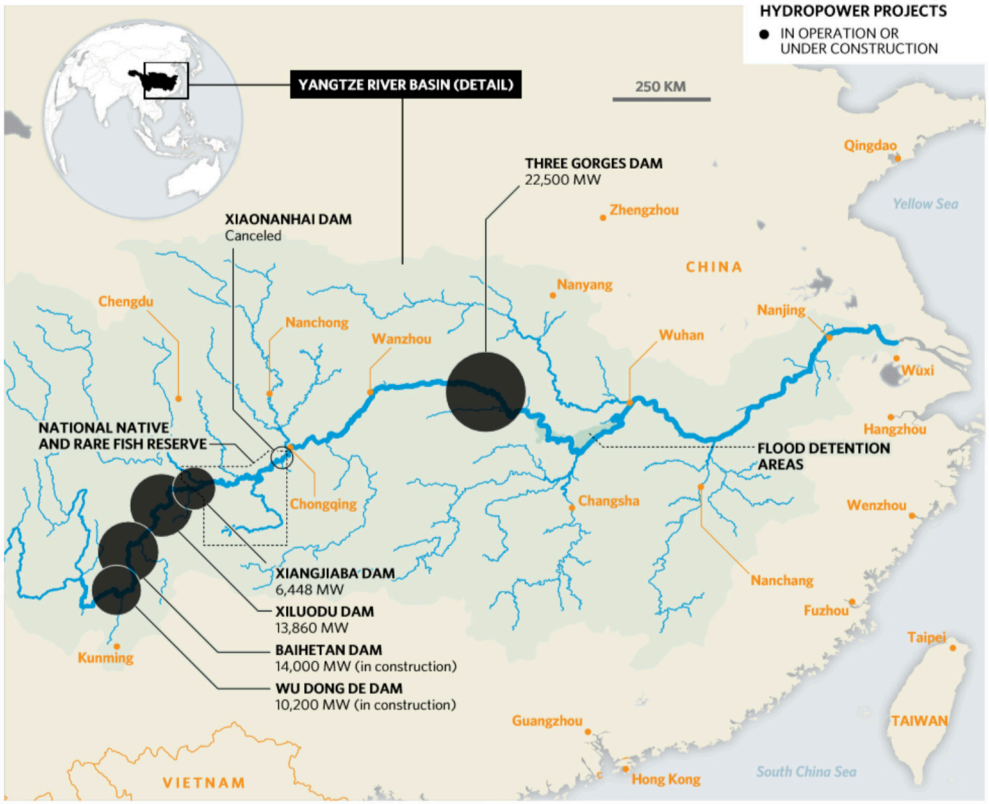

FIGURE 1 | The Yangtze River and the hydropower development in the main stem. Reproduced from (Opperman et al., 2017) with permission from The Nature Conservancy.

rose to the design level of 175 m in November of that year. The dam has a length of 2,309 m at crest elevation 185 m, and a total storage capacity of 39.3 billion m^3 including flood control storage of 22.2 billion m^3. This flood storage can effectively control most floods originating from upstream and significantly reduce flood risk for cities and agriculture in the Yangtze's valley downstream. The hydropower plant of the Three Gorges Dam includes 32 turbines of 700 MW each, with a total installed capacity of over 22,000 MW and an average annual energy output of 84.7 TWh, which would be sufficient to meet the average electricity demand of Pakistan (CIA, n.d. and CTG official website http://www.ctg.com.cn/english/)[2]

CARP IN THE YANGTZE RIVER AND ENVIRONMENTAL CHANGES FROM THREE GORGES DAM

The Yangtze River supports four species of carp, which are among the most important freshwater commercial fish species in China: the Silver Carp (*Hypophthalmichthys molitrix)*; the Bighead Carp (*Aristichthys nobilis*); the Grass Carp (*Ctenopharyngodon idella)*, and the Black Cgarp (*Mylopharyngodon piceus*). In the Yangtze, adult fish of all these species migrate upstream to the middle and upper reaches to spawn during the rising flow levels of the spring (Anonymous, Fish Research Laboratory, Institute of Hydrobiology of Hubei Province, 1976; Yi et al., 1988).

Carps have specific hydrological requirements for spawning. Water temperatures must exceed 18°C, with spawning most effective between 21 and 24°C. Spawning is triggered by the rising water temperatures and increases in flow that occur during the late spring. Adults spawn in the open water and eggs and larvae drift downstream. Larval fish float until they have developed in size and are capable of moving into nursery habitats along the river's edge. These nursery habitats include floodplain lakes and seasonal wetlands that are hydrologically connected to the Yangtze, including Dongting Lake and Poyang Lake (Zhang et al., 2000; Chen et al., 2009). This period of development generally requires at least 100 km of river distance with flowing water because the eggs can sink if flow velocity is below 0.2 m/s.

Fish numbers in the Yangtze River and associated fishery harvests have been declining due to overfishing, illegal fishing, and water pollution from industrial waste discharge, agricultural chemical runoff, aquaculture, and community sewage (Cao et al., 2008; Ye et al., 2014). The changes of fish early resources since 1997 have shown in **Figure 2**. Fish have also been negatively impacted by habitat loss and degradation from dredging and

[2]CIA n.d. CIA World FactBook, Pakistan, Available online at https://www.cia.gov/library/publications/the-world-factbook/geos/pk.html (viewed 1/3/18).

from the disconnection of floodplain lakes and wetlands from the main river (Fang et al., 2006; Cheng et al., 2014). The disconnection the lakes to the river prevents fish from accessing both spawning and nursery habitats. Further, the extensive construction of dams and reservoirs in the Yangtze Basin—more than 5,000 total with a storage capacity >100,000 m^3—has resulted in extensive barriers to migration and changes in the natural flow regime (Li et al., 2016).

Specific impacts of the Three Gorges Dam include its effects on habitat, connectivity, and the flow regime. The consequences of these changes for carp have been closely studied. According to a hydrological analysis at Yichang Station, downstream of the dam site, the construction and operation of the dam has resulted in changes in flow patterns, including more erratic flows and increased flow variability during April and May. These changes are likely the result of releases to create storage space in the reservoir in anticipation of the upcoming flood season. This modified flow regime is significantly less effective in stimulating spawning behavior of the carps. Thus, since the completion of the Three Gorges Dam, the change of the flow pattern and the decline of the average flooding period are the key factors affecting the natural spawning of the four carp species (Yangtze River Fisheries Research Institute, 2011). It is possible that these pressures have acted synergistically to impact fish populations.

Since the Three Gorges Dam started impounding water in 2003, populations of the four carp species in the Jianli section of the Yangtze (~350 km below the Three Gorges Dam) have declined rapidly. The number of egg and larvae in surveys had already dropped from 7 to 8 billion in the 1960 to 1–2 billion by the 1980s and 1990s (Survey Team of Spawning Grounds of Domestic Fishes in Chanjiang River, 1982; Yi et al., 1988), but the completion of Three Gorges Dam led to an even more dramatic decline. The number of egg and larval fell from 1.9 billion in 2002 to 400 million in 2003 following closure of the dam and to 42 million in 2009 (Yangtze River Fisheries Research Institute, 2011; **Figure 2**).

DRIVERS THAT LED TO ENVIRONMENTAL FLOW IMPLEMENTATION FROM THREE GORGES DAM

Beginning in the 1970s, fishery managers within the Chinese government were aware that the Yangtze's fishery resources would be seriously affected by proposed dams on the main stem of the Yangtze—first Gezhouba (a smaller dam ~40 km downstream of Three Gorges, completed in 1988) and then Three Gorges Dams (**Figure 1**). The social and environmental impacts of the Three Gorges Dam received considerable attention—both within China and globally—since the dam's planning stages in the 1990s. Subsequently, the dramatic decline of the four carp species, described above, received widespread media attention within China, prompting the public and conservation organizations to apply pressure to regulators and CTG to find solutions to address the issue.

Evolving regulatory requirements for environmental protection provided the strongest driver for dam operators to seeks solutions to mitigate impacts on the carp. Following decades of rapid economic growth, the Chinese government has begun to strengthen environmental protections to address the negative impacts of that growth. In 2005, China's State Environmental Protection Administration (the precursor to the Ministry of Environmental Protection) required that hydropower projects release environmental flows to support a range of other downstream resources and values, including social and environmental benefits. This has included releases to support fisheries and to maintain water quality. This requirement was repeated and detailed in a series of subsequent policies by government agencies including the Ministry of Water Resources (MWR), Ministry of Environmental Protection (MEP), Ministry of Agriculture (MOA), and National Energy Administration (NEA) (Chen et al., 2016). These requirements on flows were built into the Optimized Operation Scheme of the Three Gorges Dam (guidelines for the dam's operations), issued by The State

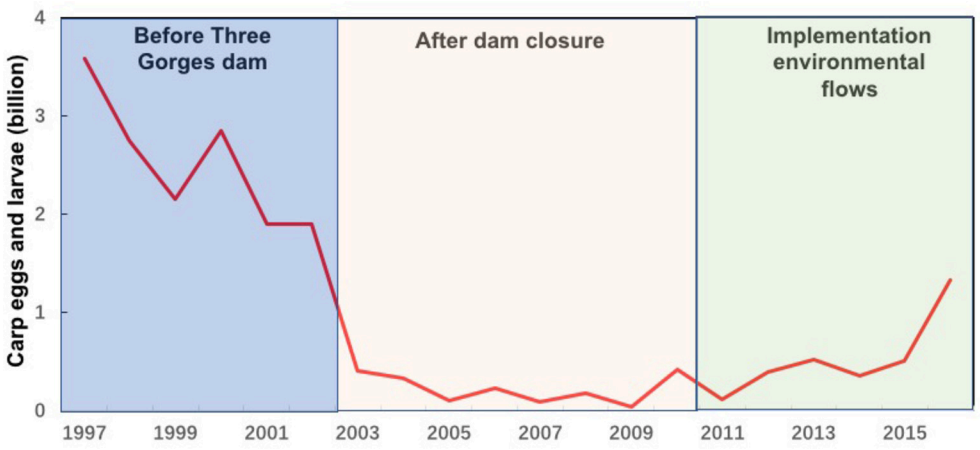

FIGURE 2 | Annual results of monitoring of carp egg and larvae in the Yangtze downstream of Three Gorges Dam during three periods: before the dam, after dam closure, and during the period of environmental flow operation.

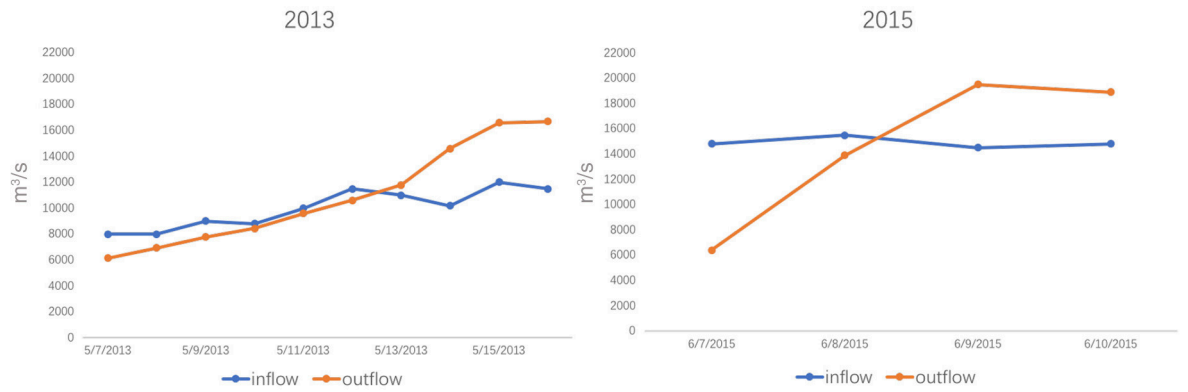

FIGURE 3 | Examples of environmental flow releases (m^3/s) from Three Gorges Dam (2013 and 2015).

Council. The Operation Guideline of the Three Gorges Dam and Gezhouba, approved by the MWR, requires that the dam operation should "maintain river health" by controlling certain flows and water levels in the reservoir and below the dam.

Scientists understanding of the carps' spawning requirements suggested that an environmental flow should mimic the Yangtze's natural flood pulse to promote spawning. However, the Three Gorges Dam is a multi-purpose project that has major functions of flood control, electricity production, navigation, and drought alleviation. The implementation of environmental flows needed to be integrated into the operational requirements that encompass these multiple purposes and thus required engagement with diverse stakeholders.

A range of stakeholders and agencies came together to determine how to provide improved flow conditions for carp, including CTG, the Changjiang (Yangtze) Water Resources Commission (CWRC) under MWR, the Yangtze Fishery Resources Management Committee (YFRC) under the MOA, and the power grid. This consultation process addressed barriers to reoperation, complemented by a research program. For example, the MOA (which is responsible for fishery resources management in China) and CTG funded a research program, including field surveys, analyses of hydrologic and fish biology data, and modeling of operations. The research focused on the relationship between flows and spawning, including identifying hydrologic indicators and thresholds, and how changes to flows would affect other major purposes, such as flood control. This research program is ongoing to monitor the effects of environmental flow operation and analyze further potential improvements to operations.

The information gained from the research program was then integrated into the decision processes for the operation of the Three Gorges Dam. Operations of the dam during flood and drought seasons is determined by the Yangtze River Flood Control and Drought Relief Headquarters (YFDH). The operational plan is drafted based on a structured decision-making (SDM) process involving relevant agencies (Gregory et al., 2012), which is then submitted to the YFDH for approval. A number of government agencies are consulted during this process, including CWRC and YFRC, and those concerned with environmental protection, land and resources, the electricity grid, and navigation. Following the direction set by the YFDH, the operational department of the CTG oversees operations of the Three Gorges Dam. The operational guidelines for the dam clearly stipulate that flood control takes priority over water resources operation (water released for downstream economic production, human needs, and environmental needs), which has priority over electricity production and navigation. For example, in order to cope with salt water intrusion in the Yangtze River estuary in 2014, the reservoir released more water (1.73 billion m^3) and lost electrical generation of 160 MWh.

The evolving regulatory requirements for dam operators to maintain river health along with a period of stakeholder consultation and research resulted in changes to the operations of the Three Gorges Dam in 2011. Operational changes included both those aimed at water management to benefit social and economic values downstream (flow releases to mitigate droughts and saltwater intrusion) and flows to promote carp spawning. Drawing on the lessons from the pilot environmental flow releases, in October 2015 these requirements were subsequently incorporated into the official joint regulation of the Three Gorges Dam/Gezhouba cascade released by the MWR.

IMPLEMENTING ENVIRONMENTAL FLOWS AT THREE GORGES DAM

Dam operation was first modified in 2011, for two purposes: drought mitigation during the early part of the year; followed by a flow release in May to mimic the Yangtze's natural flood pulse and promote carp spawning. Under this operating mode, flows can be released during periods of drought, between January and April, with discharges up to 6,000 m^3/s, which is 1,500 m^3/s (25%) higher than the typical inflow discharges during that time of year. Flow releases to promote carp spawning have been made in the early flood period (late May to June), and have lasted for 3–10 days, continuously increasingly the flow during the spawning period of the carps. During these releases, the

usual base flow (6,160–14,700 m^3/s) is increased by an additional 1,000–6,000 m^3/s. These environmental flow releases have now been implemented for seven consecutive years. Examples of environmental flow releases from Three Gorges Dam in 2013 and 2015 were shown in **Figure 3**.

A monitoring program samples carp eggs and larval fish in the water column below the dam before, during and after the period of environmental flow release. Monitoring results available to date indicate that carp reproduction has increased with these new flow releases. The average number of carp eggs and larvae sampled at Jianli station was 230 million per year between 2003 and 2010 (before implementation of environmental flows) and 540 million between 2011 and 2016, during the period that environmental flows have been implemented (data from Yangtze River Fisheries Research Institute, 2016) (**Figure 2**). In June 2014, the average density of eggs and larvae in the reach from Yichang to Yidu was three times higher after the environmental flow release than before, and the density on the third day of operation was seven times higher than before the release began (Chen and Li, 2015).

While these results show that carp reproduction appears to be increasing after a period of significant decline (between 2003 and 2010), it is not yet possible to fully attribute that increase to the environmental flow program. The relevant authorities would need to publish more rigorous statistical analyses that control for other factors (water quality, habitat, fishing pressure, background hydrology) before firm conclusions can be drawn on the extent to which the environmental flows can explain the increases.

CONCLUSIONS

Although the full analysis of impacts has yet to be published, the re-operation of Three Gorges Dam to promote carp spawning provides an important example of how regulations, stakeholder engagement, and science can be combined to inform re-operation of a major dam and to broaden the range of objectives for dam management in China and, potentially, beyond. A combination of environmental, socio-economic, and political pressures and opportunities stimulated policies, processes and institutional interactions that led to the re-operation program. An understanding of how this situation unfolded can provide insights that might be useful in other contexts.

This case study is particularly valuable as it involved one of the largest dams in the world and occurred within a country with extremely limited examples of environmental flow implementation. The environmental flows program of the Three Gorges Dam can serve as a precedent for the re-operation of other dams in China—the country with the most dams in the world. Further, Chinese companies and investors have achieved substantial market shares in the construction of hydropower dams around the world. A high-profile example of dam management for environmental objectives could influence how dams are planned, designed and operated in other countries.

Keys factors for achieving environmental flow implementation included:

- *Public and agency support for mitigating negative impacts.* The public, conservation organizations, and various agencies recognized that Three Gorges Dam had caused considerable adverse environmental impacts and they advocated for solutions to mitigate these impacts.
- *Regulatory requirements to maintain river health.* China's evolving environmental regulations reflected and amplified the concerns described above. The State Environmental Protection Agency published policies requiring hydropower projects to release environmental flows to support downstream resources and these requirements were supported by further guidance from the MWR and the MOA. These agency actions provided a regulatory driver for CTG to pursue reoperation of Three Gorges Dam to support an expanded range of management objectives.
- *Science to inform environmental flow implementation.* The spawning requirements of carp are relatively well known and the environmental flow program has included considerable investment in further research. Fish biologists and hydrologists collaborated to identify the locations of spawning grounds of four Chinese carp. They also identified the critical hydrologic indicators (water temperature, discharge before the flow rise, daily rate of flow rise, and duration of flow rise) that trigger spawning behavior. The research institutions have also conducted ongoing monitoring that can provide the foundation for understanding the environmental outcomes from environmental flows and to inform adaptive management.
- *Collaboration among a range of agencies and stakeholders.* First, government institutions led environmental flow implementation at the Three Gorges Dam. The YFDH and the CWRC coordinated and managed the comprehensive operation of the dam including the environmental flow operation, and the MOA's Office of Fisheries Law Enforcement for the Yangtze River Basin actively promoted the environmental flow implementation for Chinese carp. Second, a multi-institutional interdisciplinary team funded by the CTG contributed to the development of environmental flow plans and objectives, including the science program described above. Third, international conservation organizations, such as WWF and TNC, supported the dam's environmental flow program. For instance, in 2008, WWF collaborated with relevant institutions to establish the Expert Working Group of Environmental Flows in China to promote environmental flow research and improvements to practice. This Working Group collaborated closely with CTG and other stakeholders in the environmental flows program of the Three Gorges Dam and other initiatives, including reconnection of river and lakes, measures to aid carp breeding, and ecological operational guidelines.

Below we provide several recommendations (drawn in part from Harwood et al., 2017) about how environmental flows program at the Three Gorges Dam could be improved and how this case study can be used to inform and promote implementation of environmental flows in China and globally.

- *Continue adaptive management and expand research.* The various agencies and stakeholders should continue collaborating to pursue adaptive management for the environmental flow program. Additionally, data collection and analysis should be expanded to better understand the relationship between changes in the flow regime and the response of carp reproduction. This can improve understanding of the effectiveness of the flow releases, in terms of biological outcomes, and inform adaptive management.
- *Coordinate flows throughout the Yangtze basin and embed environmental flows within broader management to conserve Yangtze fisheries.* Environmental flows can only address part of the management objectives for fish in the Yangtze and so the flow program should be embedded within a larger program focused on water quality, habitat, and fisheries management. Additionally, the current flow program is focused on carp but other taxa, especially those which are protected or threatened (such as Chinese sturgeon), merit further attention, as does the relationship between river flows and linked freshwater habitats, such as lakes and wetlands. Beyond the Three Gorges Dam, the Yangtze basin contains thousands of dams, including hundreds of large dams. Management of these dams could be coordinated at the basin scale to promote broader environmental flow regimes, consistent with the Chinese government's recent support to focus on environmental restoration for the Yangtze basin. This basin-scale management of flows could be coordinated with management of the major floodplain lakes, including managing lake levels and connectivity with the Yangtze River.
- *Use the precedent of re-operating the world's largest dam to influence environmental flow implementation throughout China and globally*. Chinese agencies can continue to learn from the environmental flow program at Three Gorges Dam and apply these lessons to broader application of environmental flows in China. The insights and publicity from re-operating such a high-profile dam can be used by advocates, within and outside of government, to influence Chinese policies on dam operations within China and also the policies and practices that govern how Chinese companies and others plan, design, and operate dams elsewhere around the world.

AUTHOR CONTRIBUTIONS

LC organized the overall paper, collected data, information, and related documents, and was a primary contributor to writing the paper. JO conducted the main data analysis, contributed to the framework of the paper and made the largest contribution to writing text. DT suggested the framework of the paper and contributed to writing and revisions. RS drafted the abstract and contributed to revisions. QG provided background information and joined the discussion of the paper's framework. DC provided the essential data for paper writing and contributed to revisions.

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