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Review article

The development of biodiversity conservation measures in China's hydro projects: A review

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ABSTRACT

The hydropower capacity of China ranks first in the world and accounts for approximately 20% of the total energy production in the country. While hydropower has substantially contributed to meeting China's renewable energy targets and providing clean energy to rural areas, the development of hydropower in China has been met with significant controversy. Ecologically, hydro projects alter the landscape, with potential impacts to the country's aquatic biodiversity. Over the past four decades in China, various mainstream opinions and misunderstandings have been presented concerning how to alleviate the negative impacts of hydro projects on aquatic ecosystems. This article reviews research concerning potential mitigation measures to enhance aquatic biodiversity conservation in hydro projects in China. Based on the academic attention such research has attracted, three technical measures for aquatic biodiversity conservation are considered: (1) fish passages, (2) restocking efforts and (3) river and lake renovations. This article provides a historical comparison of these three practices in China to demonstrate the advantages and disadvantages of each method. The article also reviews the relevant legislation, regulations and technical guidelines concerning China's hydro projects dating back to 1979. The dynamics in research, publications, and patents concerning these three mitigation measures are summarized to demonstrate their technological developments in the context of legislative and policy advances. Data were gathered through the China Knowledge Resource Integrated Database and the State Intellectual Property Office of the People's Republic of China. Based on the analysis provided, the article recommends an expansion of China's environmental certification system for hydro projects, more robust regional legislation to bolster the national framework, the cooperation between upstream and downstream conservation mechanisms, and better monitoring to determine the efficacy of mitigation measures.

1. Introduction

The negative impacts of high-intensity human activities on biodiversity have drawn global attention, making biodiversity conservation a central research focus in the 21st Century (Velasco et al. 2015). Impacts to aquatic biodiversity from the implementation of hydro projects have received considerable attention in China due to the country's dependence on hydropower as a significant source of energy production. Research on the relationship between hydro projects and aquatic biodiversity loss in China continues to grow (Shi et al. 2015). This article summarizes the history of protective measures for aquatic biodiversity conservation in China's hydro projects to evaluate their development and provide policy suggestions and guidance for the future.

Hydro projects include dam construction and operation, water utilization, river and lake renovation and aquatic ecosystem restoration and preservation. Since 2004, China has ranked first in the world in hydropower, with an installed capacity that exceeds 100 million kW (Shen 2008). Hydropower now accounts for 20% of China's total energy production (Shen 2008). As shown in Fig. 1 (Qian 2013), hydropower stations cover the country, with the highest concentration located in the southern part of China. There are > 6055 hydropower stations that are in operation or under construction in China, with a total installed capacity of 130.98 million kW and an annual power generation of 525.9 billion kWh (Qian 2013). Table 1 shows the distribution of the installed capacity and annual hydropower generation in ten river basins in China.

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Fig. 1. The distribution of China's hydropower stations (adapted from Qian 2013).

Table 1
The distribution of the installed capacity and annual hydropower generation in China (Qian 2013).

River basins	Installed capacity (ten thousand kW)	Annual hydropower generation (hundred million kWh)
Yangtze River basin	6972.71	2924.96
Yellow River basin	1203.04	464.79
Pearl River basin	1810.07	785.78
Haihe River basin	80.34	19.5
Huanhe River basin	31.03	9.58
Northeast river basins	639.68	151.74
Southeast coastal river basins	1165.37	363.08
Southwest river basins	932.27	442.77
Yalung Zangbo River and other Tibet river basins	34.66	11.55
Northern inland and Xinjiang river basins	229.02	85.1

Note: data on Hong Kong, Macau and Taiwan are not included in the table.

The development of hydropower in China has come with significant controversy. While these projects have contributed substantially to meeting China's renewable energy targets and providing energy to rural areas, they have also come with significant social and ecological consequences. In the most controversial cases, social consequences include the displacement and relocation of communities living within the designated flood basin of a project (Wang 2010; Liu et al. 2015). While acknowledging these potential negative social implications, this article focuses on the ecological impacts of hydropower.

Ecologically, hydro projects alter the landscape, affect the local aquatic biodiversity and change the productivity and balance of ecosystems. A healthy aquatic ecosystem is characterized by high biodiversity and complex structures and functions, including ample habitat, corridors, and buffering (Cai 2008). Positive impacts from hydro projects may include flood prevention and increased air humidity, both of which are beneficial to the growth of nearby plants (Liu and Jin 2012). Negative impacts to biological factors may include increased species invasion risk, habitat loss, impeded fish migration and eutrophication (Hu 2012; Xu et al. 2016). Negative impacts to nonbiological factors may include increased soil erosion, modified fluvial morphology and reduced habitat heterogeneity. The construction of dams and other types of hydro projects alter the original watercourse, potentially impeding the migratory pathway of fish (Jutagate et al. 2016) and the habitat of many aquatic species.

Countries around the world have taken aquatic biodiversity into account when engaging in hydro projects. In the United States, the hydropower licensing system, the Low-Impact Hydropower Certification standards (Sun et al. 2009) and the Endangered Species Act all play important roles in protecting aquatic species. Likewise, in Canada, comprehensive environmental assessments, public hearings, roundtable discussions, formal or informal meetings, information sessions and various funding committees are required to ensure the participation of all stakeholders in hydro projects (Sun et al. 2009). In Europe, considerable funding has been provided for research on the environmental impacts of hydropower projects. In both the pre-impoundment or post-impoundment periods of dams, European administrators are required to monitor the environmental impacts and mitigate potential adverse effects (Young et al. 2005). The situation is similar in India. In 2013, the Ministry of Environment in India established a panel of experts, including government representatives from the Indian Central Power Authority, the Indian Central Water Commission, and other government bodies, to study the environmental impacts of the existing and ongoing construction of hydro projects in India (Xu 2013). Japan also has an advanced legal code regarding this issue (including the River Law revised in 1997, the Environmental Impact Assessment Law, the Law for the Promotion of Nature Restoration of 2002 and the Invasive Alien Species Act of 2004). These laws are intended to reduce adverse impacts on the local ecosystems and require the restoration of biodiversity (Osugi et al. 2007).

China has been concerned with aquatic biodiversity conservation for > 20 years, but still lacks robust mitigation and monitoring techniques compared to the countries discussed above. The biodiversity conservation goals in China date back to 1992 when the United Nations Conference on Environment and Development (UNCED) adopted the Convention on Biological Diversity, and China established a national mechanism to fulfill its obligation under the Convention. Relevant activities and organizations include China's national biodiversity research (1995 to 1997), China's Biodiversity Conservation National Strategy and Action Plan (2007 to 2010) and China's biodiversity Conservation National Committee (established in 2011). China also issued major legislation and policy guidelines (see section 3) and undertook a number of additional activities to conserve aquatic biodiversity, including the investigation and cataloging of endangered species, controlling invasive species and encouraging ecological risk assessments (Xue et al. 2012). Currently, almost all of China's rivers have been developed, and the associated hydro projects have placed substantial pressure on China's attempts to conserve aquatic biodiversity. In particular, hydro projects contribute to water pollution, depletion of aquatic biological resources, migration route blockage or alteration, hydrological changes to water temperatures and flow rates and habitat loss (Chen et al. 2013). Researchers have also detected negative impacts from the isolation of river sections and habitat fragmentation caused by multiple hydropower projects in the Heilongjiang basin in China (Zenkova 2013).

This paper conducts a historical review of the mitigation measures implemented to protect aquatic biodiversity conservation in China during the era of hydropower project development in order to provide guidance for the future. For comparison, the hydro projects in this article refer to only projects involving dam construction/operation and the renovation of rivers and lakes. The article first reviews the history of three aquatic biodiversity conservation measures that have drawn much attention from researchers – fish passage facilities, restocking efforts and river and lake renovations. The pros and cons of each of these measures, as they have been historically implemented throughout China, are discussed. Following this historical review, the article reviews the relevant legislation, regulations and technical guidelines concerning China's hydro projects dating back to 1979. The dynamics of the research, publications, and patents concerning these three mitigation measures for aquatic infrastructures are summarized to demonstrate their technological development. Data were gathered from the China Knowledge Resource Integrated Database and State Intellectual Property Office of the People's Republic of China.

2. Main techniques for biodiversity conservation in China's hydro projects

The major biodiversity conservation measures in China's hydro projects include (1) fish passage facilities, (2) restocking efforts, and (3) the renovation of rivers and lakes. The first two measures provide direct protection to aquatic species, while the latter measure enhances the stability of the entire aquatic ecosystem, thereby indirectly contributing to biodiversity conservation.

2.1. Fish passage facilities

2.1.1. Description and categorization

Hydro-projects that involve dam construction block the flow of rivers and alter the entire hydrological system and associated fisheries. As a mitigation measure, these hydro projects typically utilize fish passage facilities to either open a waterway for fish travel or trap and transport fish up or downstream. In either case, the goal is to maintain the migratory fish patterns with as little interference as possible. As an increasing number of hydro projects has been conducted, their impacts on fisheries throughout China have become increasingly significant. The construction of fish passages and research concerning their efficacy has also risen concomitantly. Two general types of fish passages may be utilized – upstream or downstream – each with their own merits, as discussed below.

2.1.1.1. Upstream fish passage facilities. Located at water locks, dams or natural barriers, fishways – or fish ladders – are one of the most crucial upstream fish passage facilities used to mitigate the impacts to fisheries in China. This mechanism consists of a structure built on or around the barrier to facilitate the passage of fish. While fishways can be easily operated and maintained for a wide range of species, they are typically only applied to low dams (Bao 2013).

Fish lock and fish collection-transportation systems are two other types of upstream passage facilities used in China. Compared to fishways, fish locks have limited capacity, cannot run continuously and are therefore being phased out. The working mechanisms of a fish lock are similar to a ship lock. As fish pass the dams near the fish lock, they are drawn into a lower chamber that then closes, triggering both the water level in the culvert pipes and the fish to rise to an upper chamber that expels the fish into the reservoir before draining (Bao 2013). The fish collection-transportation system also has limited capacity and requires continual human intervention. Fish are gathered in a fish collection boat, which is driven to an area of water with high fish density and opened at both ends so that fish may swim in. The fish that are collected in the boat are then transferred to a fish transportation boat, which transports and releases the fish into suitable water areas. This system has been piloted by the Pengshui hydropower station in China and continues to be monitored for potential future use (Bao 2013).

The fish lift, a mechanism that lures fish into a large container and elevates the container upstream is similar to an elevator and has also been considered in China's hydro projects but has yet to be implemented (Qiao et al. 2013). As the fish lift is suitable for high dams, it has a wide potential for application. A fish lift was initially planned to be constructed at the Mamaya Hydropower Station in southwest China, but the plan was abandoned in favor of a fish collection-transportation system that was more appropriate for the deep valley landscape where the station is located (Zhao et al. 2011).

2.1.1.2. Downstream passage facilities. Fishways and fish collection-transportation systems could also be utilized as downstream passage facilities, despite the fact that the fishway system is designed primarily for upstream migration (Zhou et al. 2011) and the water inlet would probably not attract many migratory fish headed downstream (Rainey 1997). The more common downstream passage facilities in China include spillway passages and turbine passages. A spillway passage provides a conduit in the reservoir alongside the dam through which the fish can travel downstream as the reservoir water is discharged. This is an important passage system used in many dams worldwide. However, spillway passages often have adverse impacts on fish, such as gas bubble trauma (Backman et al. 2002), swim performance reduction and physical trauma from the dissipation of energy from the structure under the spillway (Zhu et al. 2015). A turbine passage draws fish into a pipe traveling in the direction of the flow towards the turbines and then provides a draft tube through which the fish can travel to the downstream area (Zhu et al. 2015). The primary drawback of this type of passage is the physical trauma to the fish from contact with the turbines (Schilt 2007).

Downstream fish passage technologies have developed more slowly than upstream methods. In fact, downstream methods have only recently been considered in hydro projects. This is likely because hydro projects present less of an imposition to downstream migration, as fish often travel downstream through routine spillways not specifically intended for fish migration. Moreover, downstream passage facilities have encountered a number of complexities and difficulties in their implementation. The remainder of this section discusses the historical development of the fishway (or fish ladder), China's most important fish passage facility.

2.1.1.3. Demerits of the fish passage facilities. Although fishways play an important role in alleviating the negative impacts of hydro projects on aquatic biodiversity, there are downsides to this type of fish passage facility. Fishways at power stations with high headwaters (with large height differentials) function inefficiently because the flow rates inside the fishways are too fast for fish to migrate. In addition, it is necessary to reduce the flow velocity inside the fishways so that it does not exceed the limiting velocity and impede fish migration. Multiple energy dissipation measures are therefore frequently adopted in fishways for dams with high headwaters, making the flow conditions within the fishway quite complex. Moreover, due to the improper design, construction and management of these early fishways, fish were often reluctant to, or could not enter the provided passage to migrate successfully. These potential problems associated with the fishway are outlined in Table 2, along with the main demerits of other fish passage facilities.

2.1.1.4. Successful international cases. Fish passage facilities have been recorded worldwide for over 300 years (Liu et al. 2010). Fishways are usually constructed at dams with low headwaters, while dams with headwaters > 10 m typically use fish lifts and fish locks (Clay 1994). By the 1960s, fish passage facilities had been created all over the world, including over 200 in the United States and Canada, over 100 in western Europe, approximately 35 in Japan, and over 15 in the former Soviet Union (Liu et al. 2010). In the late 1980s, Latin America successfully built fish locks and fish lifts on top of a 20-m-high barrier (Zheng and Han 2013). From 1939 to 1943, the Rock Island Dam in the lower reaches of the Columbia River used a fish collection-transportation system that successfully transported thousands of adult salmon to new spawning grounds (Clay 1994).

2.1.2. Development and history of fishways in China

Fishways are the most important type of fish passage facility utilized in hydro projects throughout China. The development of this fish passage mechanism has undergone three major stages: the beginning stage (1958–1983), the lag stage (1984–2001) and the culminating stage (2002-present) (Cao et al. 2010). The distribution, type and number of fishways constructed in each stage have been recently summarized (Figs. 2 and 3) (Shi et al. 2015). As discussed below, these figures demonstrate changes in the types of fishways used during the three stages, as well as an overall increase in the usage of fishways as mitigation mechanisms in hydro projects throughout China. In Fig. 2, the pool type fishway refers to a fishway that starts downstream from the dam, overcomes the water head difference through several pools, and extends upstream; the vertical type fishway has a vertical seam from top to bottom, the water flow is blocked by a plate on both sides, and water is discharged from a vertical seam in the middle or on both sides of the fishway.

2.1.2.1. Beginning stage (1958–1983). In 1958, China's first fishway was designed for the Qililong Power Station in Zhejiang Province. During this time and up until the mid-1980s, most of the fishways in China were built for coastal tide sluices or dams in the plains and all had relatively low headwater designs (in other words, small height differentials between down and upstream). Two hydropower stations in large rivers were constructed with fishways during this time, the Qililong PowerStation (constructed in 1958) in Zhejiang Province (Jin and Xuan 2007) and the Yangtangshuilunbeng Power Station (constructed in 1980) in Hunan Province (Bian 1984). These fishways (along with many others in China during this time) were designed and constructed using foreign standards. The flow rates inside these fishways were quite large and were suitable only for fish species with strong migratory abilities.

2.1.2.2. Lag stage (1984–2001). Following the beginning stage, fishway development entered a twenty-year lag stage, in which very few new fishways were constructed or implemented. The lag in fish passage facility development was triggered by an incident that occurred in the 1980s. At that time, a great deal of research was conducted to protect the Chinese sturgeon (*Acipenser sinensis*) during the construction of the Gezhou Dam in China. That research concluded that restocking methods are better than fish passage facilities in preserving the Chinese sturgeon. As a result of this famous project, authorities in China advocated for restocking as a better conservation method than fish passage facilities. Taking note, Chinese practitioners almost ceased to consider the application of fish passage facilities (Cao et al. 2010) during this twenty-year lag stage, during which time most of the facilities were left idle or abandoned.

2.1.2.3. Culminating stage (2002-present). The growing number of hydro projects in the 21st century has ushered a renewed interest in utilizing fishways to preserve China's remaining fish populations. Severe fishery degradation has encouraged the designation and construction of a large number of new fish passage facilities, such as the Beijing Shangzhuang Reserve Fishway (Sun et al. 2006), the Tibet Shiquanhe Fishway (Yan et al. 2005), the Zhujiangchangtanshuniu Fishway and the Yangtze River Xiaonanhai Fishway (Cao et al. 2010).

Table 2
Demerits of fish passage facilities (adapted from Zheng and Han 2013).

Fish passage facilities	Demerits
Fishway	Fishways at power stations with high headwaters (with large height differentials) function inefficiently. Problematic measures in reducing the flow velocity inside fishways. Improper design, construction and management easily occur.
Fish locks	The fish are transported in batches instead of continuously, and the amount of fish transported in each batch is relatively small. The fish may fail to leave the locks in time and sustain injuries.
Fish lifts	The fish are transported in batches instead of continuously. Maintenance costs are relatively high. The fish may sustain injury due to overcrowding.
Fish collection-transportation system	The fish passage is not continuous. Maintenance and operating costs are relatively high. The fish may sustain injury or die during the transportation process.

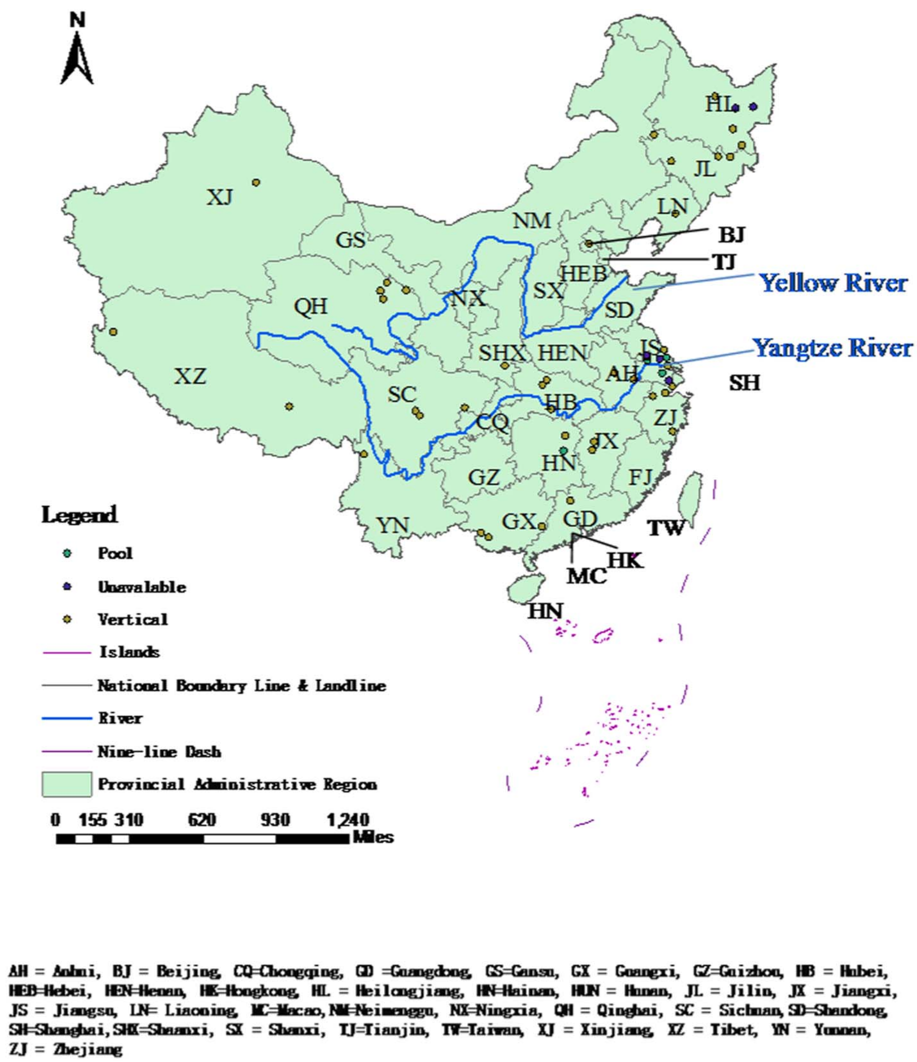

Fig. 2. Distributions and types of fishways built in the provinces of China from 1958 to present ("unavailable" refers to projects without records on their types, adapted from Shi et al. 2015).

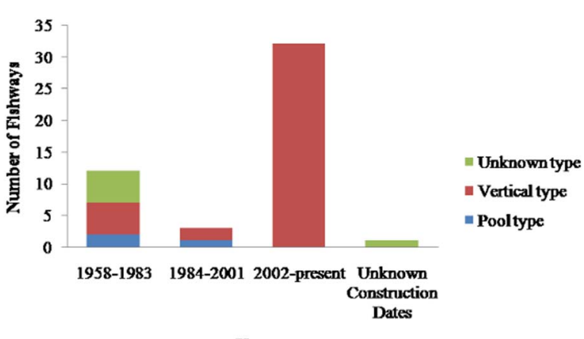

Fig. 3. Number and types of fishways built in China from 1958-1983, 1984–2001 and built or planned from 2002-present (adapted from Shi et al. 2015).

There are currently > 50 fishways built in China (Shi et al. 2015), and they are mainly distributed in the Jiangsu, Zhejiang, Shanghai, Anhui, Guangdong and Hunan provinces (Liu et al. 2010).

Despite the proliferation of fish passage facilities since 2002, significant design and implementation flaws remain. Due to a lack of mature theories and methods, the current designs of fish passage facilities are relatively rough and comprise only a small part of the overall hydro project design. Issues concerning the design phase include the lack of reliable and comprehensive biological data (migratory period, migratory behavior, etc.) and no designation of the water level for the controlling facilities, which results in insufficient water for the fishway (Liu et al. 2010). Following dam construction, the associated maintenance and management of fishways are insufficient. Research conducted by the Chinese Sustainable Development in Agriculture Group (CSDAG) revealed that the congestion of fishways had become a common phenomenon (CSDAG 2013), primarily due to low flow rates and suspended materials that block the fishway, thereby reducing the transportation of nutrients and causing negative impacts on the downstream environment.

Not all hydro projects in China have adopted fish passage facilities. Researchers investigated 25 of China's major hydro projects that did not contain passage facilities and found that the main reasons for not adopting passage facilities included (1) the lack of specific requirements for fish protection in the corresponding environmental impact assessments; (2) the lack of endangered or migratory fish in the project area; and (3) the existence of older hydro projects that had already adversely impacted the waterway, making the impacts of new hydro projects less severe in comparison and thus less in need of mitigation (Chen et al. 2013). Taken together, the authors conclude that the hydro projects that fail to use fish passage facilities typically cite a particular reason for doing so, although the reliability of their reasoning is doubtful.

2.2. Restocking

2.2.1. Description and categorization

Restocking involves supplementing the existing fish (or other aquatic species, such as shrimp and shellfish) populations with individuals raised in aquaculture to increase fishery production. The restocked aquatic species are normally larvae or adult fish that are ready for immediate reproduction. The growth and reproduction of the restocked fish are intended to recover or increase the fishery population size to retain or improve the community structure of the aquatic ecosystem. Restocking typically involves either stock enhancement, which aims to maintain fish populations at a stable level, or multiple releases, which aims to increase both new recruits and the spawning biomass (Stottrup and Sparrevohn 2007).

The main technologies related to restocking include large-scale breeding technologies; operational process technologies; and tagging, tracking and assessment techniques. Large-scale breeding technologies lay the foundation for the development of restocking. While the technology is different from artificial breeding for general aquaculture, the species used for restocking are usually more sensitive to changes in the environment, and it requires more effort to achieve the breeding outcomes ideal for restocking (Pan et al. 2010). During the operational process, species selection should be based on the main purpose of restocking and the characteristics of the local aquatic environment; the species need to be tested by quarantine institutions before release, and the species need oxygenated transportation via fully enclosed live fish cars or plastic bags (MAQTS 2012). Then, the tagging, tracking and assessment technologies should be used to assess the effectiveness of the work, which include in vitro and in vivo methods (Pan et al. 2010). In vitro tagging, tracking and assessment methods mark the fish using fin-cutting and branding, or make use of special substances such as fluorescent chemicals (Catalano et al. 2001; Miller and Able 2002). A representative in vivo method is satellite tracking, which is mainly used for fish with large individuals and long life cycles (Pan et al. 2010).

Aprahamian et al. (2003) divided restocking efforts into six categories based on their stated purpose. These categories include (1) *mitigation*, a long-term restocking effort that compensates for hydro projects and other activities that pose adverse impacts on fish migration and reproduction; (2) *restoration*, a one-time restocking effort that addresses mass mortality caused by temporary incidences; (3) *enhancement*, which increases fish populations that lack fully developed productive capacities or have unsustainable population sizes; (4) *conservation*, which prevents the fish stock from becoming endangered or locally extinct; (5) *research and development*, which investigates certain fishery management techniques; and (6) *the creation of new fisheries*, which introduces new species into an aquatic area to improve the structure of the aquatic ecosystem. In practice, the restocking of aquatic species is often used as a method to achieve a variety of these purposes simultaneously.

2.2.1.1. Demerits of restocking. The potential negative effects of restocking include the loss of genetic diversity, spread of diseases and other potential ecological imbalances (Yang et al. 2013). The loss of genetic diversity stems mainly from the fact that most released populations originate from limited progeny, resulting in a significant lack of diversity (Chen et al. 2001). Smaller populations are more susceptible to genetic drift, and artificially raised populations may lose their ability to survive in the natural environment (Yang et al. 2013). In general, restocked populations have lower heterozygosity and allele richness than wild populations (Blanchet et al. 2008). Releasing a large number of larvae has the potential to reduce the genetic diversity in wild populations. Furthermore, artificially raised populations are vulnerable to disease outbreaks and other disasters (Yang et al. 2011) and may contribute to the spread of exotic diseases and parasites (Yang et al. 2013). Lastly, restocked species may be exotic or may have the potential to bring invasive species to the aquatic ecosystems into which they have been introduced. Failing to comprehensively consider the potential impacts of fish introduction may threaten ecological security (Xu et al. 2015). To meet the diversified needs of the market, many countries have introduced alien species, which leads to the demise of the indigenous populations. Two examples include the decreased diversity of coastal species in Indonesia and accelerated genetic degradation in the Philippines (Han and Du 2015). Similar cases have also occurred in China (Xu et al. 2015).

2.2.1.2. Successful International Cases. Over 94 countries have conducted restocking projects across the world (Li et al. 2009). Japan has long participated in the restocking of aquatic biological resources, and now the country has nearly 30 species with restocking amounts exceeding one million individuals (Kitada 2006). The United States has released > 20 species into natural waters, and the Russian government's annual investment in the restocking of salmon has increased the salmon populations such that they now maintain stable high levels (Li et al. 2009).

2.2.2. Development and history of restocking efforts in China

The restocking of aquatic species in China has developed rapidly since its inception in the late 1950s. This is primarily because local governments and administrative fishery departments held a wide variety of resource proliferation activities to encourage the practice (Yang et al. 2009). Currently, all provinces, autonomous regions and municipalities directly under the central government have conducted restocking projects in inland water bodies (Li 2011). Fig. 4 shows the hydro projects that have conducted restocking (Chen et al. 2013).

Restocking efforts in China have demonstrated considerable benefits in recent years. In terms of conservation, restocking has the potential to control algal blooms and other environmental disasters. For example, the release of phytoplanktivorous fishes to Poyanghu Lake, Chaohu Lake, Liangzihu Lake and other inland lakes has a significantly alleviated eutrophication. Moreover, according to scientific monitoring and accounts from fishers, the populations of *Fenneropenaeus chinensis*, *Rhopilema esculenta* and *Portunid* have increased in the Bohai Sea and the northern Huanghai Sea, while wild populations of *Pseudosciaena crocea* have reappeared in coastal waters. In these cases, restocking efforts have thus contributed to biodiversity conservation goals (Wu 2009). In terms of economic benefits, the incomes of fishers and overall piscatorial profits have increased (Wu 2009). According to surveys conducted by the Fishery Department (located within the Ministry of Agriculture), China invested 710 million yuan in restocking efforts in 2010 to augment > 220,000 tons of fishing yield, generating 3 billion yuan of output value and befitting approximately 1.5 million fishers (FDMA 2010). The total national investment in restocking has increased annually, along with the amount and diversity of released aquatic species (Fig. 5) (Chang 1999). By 2007, > 105 species had been released, including 96 economic species and 9 endangered species. The released economic species include 59 species of fish, 7 species of shrimp and crab, 16 species of shellfish and 14 other species (Yang et al. 2009). In the Shandong Province, for example, the recapture of released fishes has become the primary economic activity during the autumn months, constituting an important source of income for approximately 800,000 fishermen owning > 20,000 small and medium fishing boats. The recapture rate of the *F. schinensis* is > 8% (Liu et al. 2008) and > 1000 tons of *F. schinensis* have been recaptured each autumn since 2005 (Zhang et al. 2009). In terms of social benefits, restocking efforts have increased the social awareness of aquatic conservation goals (Wu 2009). Various forms of restocking activities have helped the public understand aquatic biological resource conservation and fishery management and pay attention to aquatic ecosystem protection (Sun 2009).

In recent years, the Chinese government has become aware of the ecological risks that restocking may bring (as mentioned above) and has taken measures to avoid these risks. In 2009, China's Ministry of Agriculture promulgated the Regulations on Restocking of Aquatic Species, which prohibit the restocking of exotic, hybrid, or genetically modified species and other aquatic species that do not meet certain ecological requirements. In addition, the Department of Fishery Administration has organized and carried out scientific research and

Fig. 4. Hydro project-related restocking efforts and combined fish passage facilities in China (adapted from Chen et al. 2013).

provided technical guidance on the restocking. Moreover, sign releasing, tracking and monitoring and social investigation measures have been taken to evaluate the effects and impacts of restocking.

The application of restocking in China, however, still has limitations. Uniform standards and scientific guidance are urgently needed. The disorderly release of fish and the release of exotic species still occur in some places. Basic issues, such as species type, amount, time and location, as well as how to properly evaluate the results of release studies, all require further research.

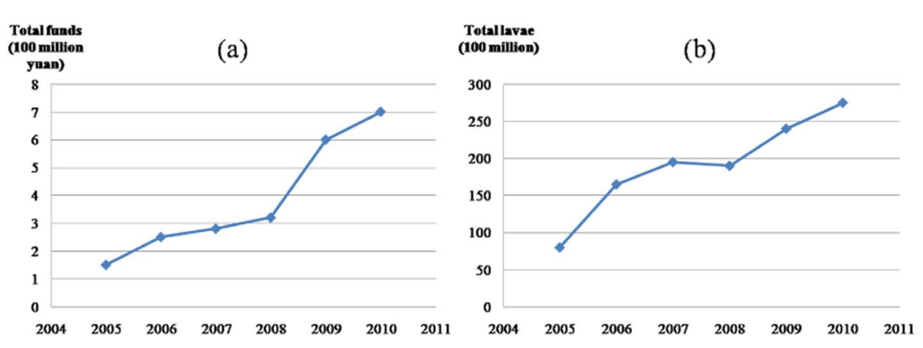

Fig. 5. The total investment funds (a) and amount of larvae (b) used for China's restocking efforts (2005–2010). Data source: Ministry of Agriculture, State Environmental Protection Administration, China's Piscatorial Ecological Environment Bulletin (in Chinese).

2.3. Renovation of rivers and lakes

2.3.1. Description and categorization

Rivers and lakes have multiple functions including water supply, flood control and drainage, tourism and entertainment, urban heat island effect reduction, beautification of the environment and natural ecology maintenance (Zeng 2001; Li et al. 2015). In the face of rapid urban development and the demand for water resources, the deterioration of water quality has become an increasingly prominent issue. At the same time, citizens have higher expectations of environmental quality. Under such circumstances, the renovation of rivers and lakes presents an increasingly appealing route to secure China's water resources. The effective renovation of rivers and lakes can purify water quality, regulate water temperature, reconnect rivers and lakes that are disconnected by hydro projects, and potentially increase biodiversity and improve the overall aquatic ecosystem.

The renovation of rivers and lakes can be divided into two stages – remediation and ecological restoration (Lu et al. 2014). However, in practice, the two stages are often carried out simultaneously. Remediation refers to the treatment of severely polluted rivers and lakes to reduce the concentration of water pollutants. Ecological restoration, designed for both remediated and lightly polluted water bodies, aims to gradually form a healthy aquatic ecosystem and restore its self-purification and self-sufficient capacities.

The renovation of rivers and lakes involves physical, chemical, biological and ecological methods (Lu et al. 2014). The physical methods for renovating rivers and lakes include interception, desiltation, water diversion and flushing (Xue et al. 2002), aeration (Zhou et al. 2001), mechanical algae removal (Huang et al. 2008) ultrasonic algae removal (Chi et al. 2012) and river-lake reconnection projects (Zenkova 2013). Interception refers to intercepting sewage before it enters rivers and lakes and diverting the sewage to treatment facilities (Lu et al. 2014). Desiltation refers to the removal of sludge from the bottom of lakes (Lu et al. 2014). Water diversion and flushing can increase flow rates and prevent the emergence of black and odorous water resulting from excessive hydraulic retention times (Xue et al. 2002). Aeration refers to the artificial oxygenation of rivers and lakes in anoxic (or anaerobic) states, which supplements the dissolved oxygen in the water and enhances the self-purification capacity of the water (Zhou et al. 2001). Mechanical and ultrasonic algae removal make use of specific equipment to quickly remove algae to avoid the deterioration of water quality caused by the toxins secreted by dead algae (Huang et al. 2008; Chi et al. 2012). In contrast to the measures mentioned above, river-lake reconnection projects are not measures used for water purification but are used for habitat conservation (Zenkova 2013). The construction of hydro projects may artificially disconnect many lake floodplains from the main river stems and adjacent lakes. River-lake reconnection projects reconnect the fragmented rivers and lakes that were disconnected by hydro projects.

Chemical methods include chemical flocculation, chemical algae removal and chemical fixation of heavy metals (Wu 2007). All chemical methods involve adding chemical agents to rivers and lakes. They are usually simple to conduct, and the respective chemical reactions are fast (Lu et al. 2014).

Biological methods include the addition of biological strains, biocarrier technologies, and seepage biofilm purification technologies (Zhang 2009). Biological strains refer to artificially cultured microorganisms that rapidly proliferate and degrade pollutants after introduced into the water (Lu et al. 2014). Bio-carrier technology refers to the addition of highly efficient microbial carriers made of polyester fibers to the water, which enriches the number of microorganisms on the surface of the carrier so that they can reproduce rapidly and enhance the self-purification abilities of rivers and lakes (Lu et al. 2014). Seepage biofilm purification technology refers to the use of pebbles, waste bricks, ceramsite or zeolite as fillers to build seepage biofilm purification beds on lake shores or river banks. The purification beds not only degrade organics but also filter pollutants (Tang et al. 2004).

Ecological methods include aquatic plant technologies, ecological floating islands (Huang et al. 2011), and ecological embankments. Aquatic plant technology uses plant growth to absorb pollutants from the water and uses plant roots to provide living areas for microorganisms that enhance the water quality (Lu et al. 2014). Ecological floating islands are constructed by growing artificially selected emergent aquatic plants on the surface of floating bodies in rivers and lakes (Huang et al. 2011). Ecological embankment technology is a combination of geosynthetic, vegetation bank protection and side slope treatment engineering technologies, which together can reduce the impacts of surface runoff and other non-point pollution in rivers and lakes (Lu et al. 2014).

2.3.1.1. Demerits of river and lake renovations. Although the primary goal of river and lake renovation is to enhance environmental quality, these projects have the potential to cause significant ecological harm. For example, blindly straightening river channels without regard for the habitat decreases the diversity of the landscape and reduces microhabitats (Li et al. 2013). Using concrete to reinforce the river bank, slope and bottom also destroys species habitat and has significant deleterious effects on the ecosystem (Zhang 2012). In addition, when using chemical methods, the biological enrichment and biological amplification caused by chemical agents may have negative impacts on the aquatic ecosystem, and long-term use can also lead to the resistance of aquatic organisms (Lu et al. 2014). For biological methods, exotic microorganisms need time to adapt and compete with the native microorganisms, which requires repeatedly adding artificially cultured strains, thus increasing the cost of maintenance (Lu et al. 2014).

2.3.1.2. Successful international cases. Since the mid-20th century, many countries across the world have conducted river and lake renovation projects (Wang 2005). For instance, after > 20 years of treatment, the portion of the Thames River flowing through London has changed from a polluted river to one of the cleanest waterways in the world, harboring > 100 species of fish (Jiang 1999). In Europe, the Rhine Action Plan was proposed in 1987, and the coastal countries of the Rhine River have invested tens of billions of dollars in renovating the river. By 2000, the Rhine River fully achieved the ecological target with clean water and dense forest along the river bank (Xu et al. 2008). In addition, the oxidation sewage treatment pond in Morehead, North Carolina in the United States, the biological park around Xiapu Lake in Japan, and the raising of fish for an algae control project in Wariak Lake in Poland are all successful river and lake renovation examples (Xu et al. 2008).

2.3.2. Development and history of river and lake renovation in China

Interception, dredging and aeration are the major measures China has utilized over the country's history of river and lake renovation. Some cities with abundant water resources have also adopted water diversion and flushing technologies, such as the projects in the Suzhou River in Shanghai and the Nei River in Fuzhou (Lu et al. 2014) (Fig. 6).

Since the 1980s, Chinese scholars have shown increasing interest in developing and applying ecological methods (Huang et al. 2011) to maintain water quality by building a stable aquatic ecosystem to preserve the local biodiversity. Aquatic plant technologies have been widely used at Dong Lake in Wuhan, Xi Lake in Huizhou, Xuanwu Lake in Nanjing and Wenruitang River in Wenzhou, as well as other project locations (Lu et al. 2014; Wu et al. 2001) (Fig. 6). Specifically, a large-scale enclosed system was built at Dong Lake. Submerged macrophytes have been introduced to significantly improve water quality (Wu et al. 2001). Moreover, instead of introducing one single species during the construction of an ecological floating island, a combination of plants, fish and shellfish have been applied to artificial floating-island ecosystems. In the Bailianjing River, Shanghai (Du et al. 2010), scholars have used three different combinations in artificial floating-island

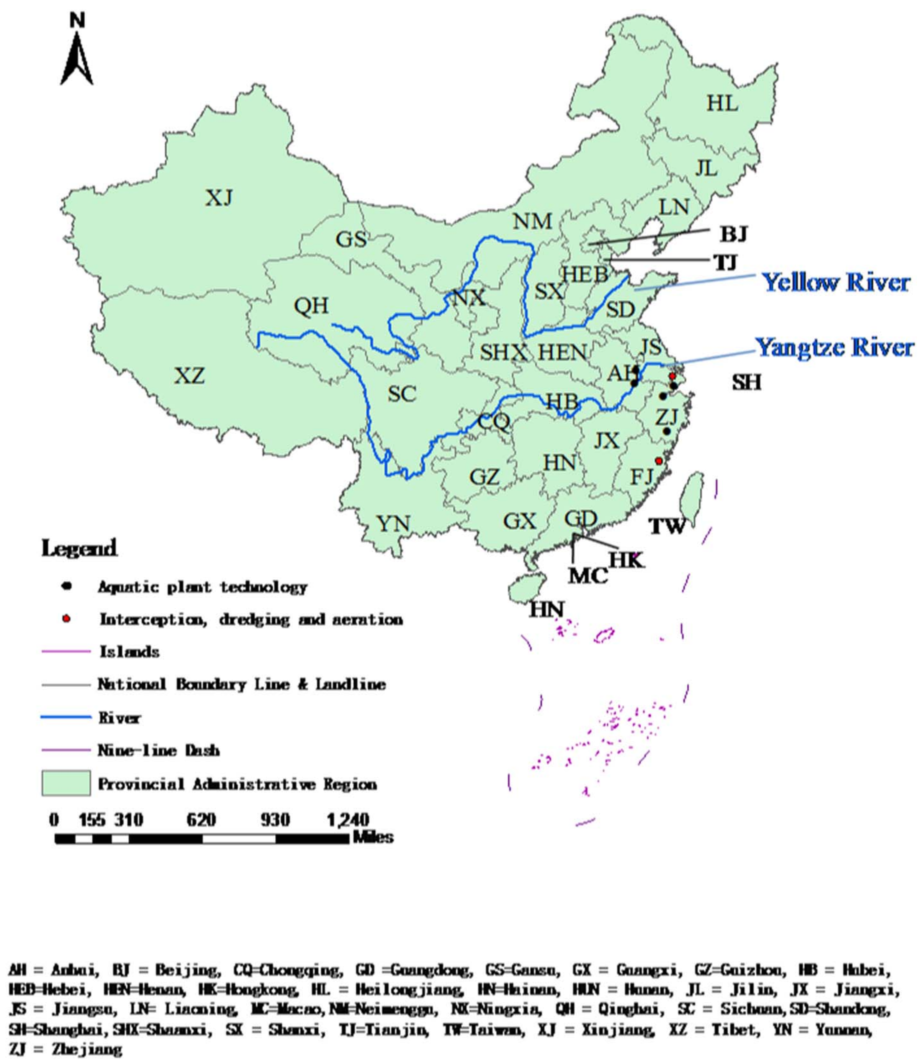

Fig. 6. Rivers and lake renovations discussed in this article.

ecosystems: *Acorus gramineus* Var. *Pusillus* + filter-feeding fishes + *Hyriopsiscumingii (Lea)*, *Imperata cylindrical red baron* + filter-feeding fishes + *Hyriopsiscumingii (Lea)* and *Acoruscalamus linn* + filter-feeding fishes + *Hyriopsiscumingii (Lea)* (Fig. 6). Experiments have demonstrated that the proportion of *Hypophthalmichthys molitix* and *Aristichthys nobilis* chosen for the combination of fish, benthic animals and aquatic plants can significantly affect water quality (Chen et al. 2016). Diverse ecological materials have been developed to replace the traditional concrete used for embankment projects. These materials include natural materials (wood, bamboo, and stone), geotextiles, Gabion boxes (boxes filled with rocks, concrete, or sometimes sand and soil) and planting concrete that has continuous porosity (Zhang 2012).

According to the post-intervention impact assessments, the renovations of rivers and lakes in China have had positive results. For example, the three abovementioned combinations used in the Bailianjing River (Du et al. 2010) could all reduce the concentrations of total phosphorus from class III class to class II, total nitrogen from the inferior class V to class IV, and permanganate from class IV to class III. In Beijing, enhancements to water quality and transparency have been observed after river renovations. The renovation of Dianchi Lake augmented a vegetation zone along the bank, restored the riparian habitat, strengthened the connection and interaction among species and greatly promoted the reproduction of the local populations.

However, there have been misunderstandings about the implementation of river and lake renovations in China, which have led to negative historical impacts. Some cities in southern China have continuously increased the heights of the flood prevention riverbanks, which results in vertical river slopes and further decreases the space that is used to support the reproduction of aquatic species. The over-construction of ecological wetlands and inappropriate breeding of aquatic species are two other problems that are frequently involved in renovation work (Li et al. 2013). Recently, to more effectively renovate rivers and lakes, practitioners in China have paid more attention to avoid these problems, using ecological materials for river banks and adopting designations that mimic the natural ecosystem.

3. Policies for hydro projects in China

The public policies implemented by the Chinese government have played significant roles in encouraging and guiding the practices of biodiversity conservation in hydro projects. Before 1979, there were few official documents related to the conservation of China's biodiversity in hydro projects. In 1979, the Chinese government began to gradually refine the relevant laws, guidelines, rules and regulations (Table 3). At this beginning stage, most government documents related to biodiversity included basic laws on fish husbandry, water and wildlife protection. There were also some general rules and regulations on biodiversity conservation at the national level, but they were not designed specifically for hydro projects.

From 2002 to 2003, the government issued the Regulation of Calculations (Estimations) on Environmental Protection Design for Hydraulic and Hydro-power Projects and the Guide for Environmental

Table 3
China's official documents related to biodiversity conservation in hydro projects

Year of issuing	Names of laws, technique guidelines, rules and regulations	Classification
1979–2000	Wildlife under the Special State Protection List (1989)	Rules and regulations
	China's National Biodiversity Conservation Strategy and Action Plan (1994)	
	Fish Husbandry Law (1986)	Laws
	Water Law (1988)	
	Wildlife Protection Law (1988)	
	Environmental Protection Law (1989)	
	Water and Soil Conservation Law (1991)	
2002–2003	Regulation of Calculations (Estimations) on Environmental Protection Design for Hydraulic and Hydro-power Projects (2002)	Technique guidelines
	Guide for Environmental Impact Assessment of Hydraulic and Hydro-power Projects (2003)	
	China's Red Data Book of Endangered Animals and Fishes (2003)	Rules and regulations
	The Law ofthe People's Republic of China on Appraising Environmental Impacts (2003)	Laws
2006–2007	Guidelines for Environmental Impact Assessment of River Water, Low-Temperature Water and Fish Passage Facilities in Hydraulic and Hydro-power Projects (2006)	Technique guidelines
	China's Aquatic Biological Resource Conservation Action Outline (2006)	Rules and regulations
	Regulation of Environmental Impact Assessment on River Basin Planning (2006)	
	The National Program for Resource Protection and Utilization of Biological Species (2007)	
2010–present	National Plans on Restocking of Aquatic Species (2010)	Rules and regulations
	The Notification by the Ministry of Agriculture on Further Standardizing Restocking (2013)	
	The Notification on Strengthening Environmental Protection in Hydro projects (2014)	
	Design Specifications for Environmental Protection in Hydro-projects (2011)	Technique guidelines
	Regulations on Feasibility Study Report of Hydro-projects (2013)	
	Guidelines for the Designing of Fishways in Hydro-projects (2013)	

Impact Assessment of Hydraulic and Hydro-power Projects (Table 3). These regulations and guidelines provide guidance specifically for biodiversity conservation in hydro projects. The Law of the People's Republic of China on Appraising Environmental Impacts also plays an important role as it requires the administrators of development projects to take biodiversity conservation into consideration.

From 2006 to 2007, China's regulations and guidelines began to treat biodiversity conservation as an independent issue, rather than as a small part of environmental protection. These guidelines have also become more comprehensive and elaborate over time (Table 3). However, further improvements are still necessary when considering future policies. Table 4 demonstrates the lacunae in the existing policies, the social conflicts surrounding policy implementation, and the specific areas requiring immediate attention.

4. Dynamics of scientific research on aquatic biodiversity conservation in China's hydro projects

Achieving aquatic biodiversity conservation measures in hydro projects requires the development of relative theories and testing these theories through academic research, as well as the establishment of relevant research organizations and financial support. This section assesses the development of research concerning aquatic biodiversity conservation in hydro projects in terms of the following four aspects: number of publications, research fields, research organizations and funding sources.

4.1. Number of publications

Information on the number and content of research articles

Table 4
Information on possible improvements to future policies (Chen et al., 2013).

Content	Description
Lacunae in existing policies	Lack of incorporation of biodiversity impact assessments into China's environmental impact assessments. China's National Plan of River Basins lacks specific plans for species habitats influenced by hydro projects and biodiversity conservation. No specific or detailed guidelines on ecological risk assessments in hydropower projects. No green hydropower certification system currently exists. Public participation mechanisms in the environmental impact assessments of hydro projects remain limited.
Social conflicts surrounding policy implementation	In January 2005, the Ministry of Environmental Protection announced the suspension of 30 projects including some hydro projects. The main reason for suspension is a missing or incomplete Environment Impact Assessment. At the same time, hydro projects on some large rivers have aroused considerable social concern, including the Three Gorges Hydropower Projects and the Nujiang Hydropower Projects.
Specific areas requiring immediate attention	Incorporate more ecological protection requirements into the designation and operation of hydro projects. Transition from the mitigation of adverse environmental impacts to the protection and improvement of aquatic ecosystems.

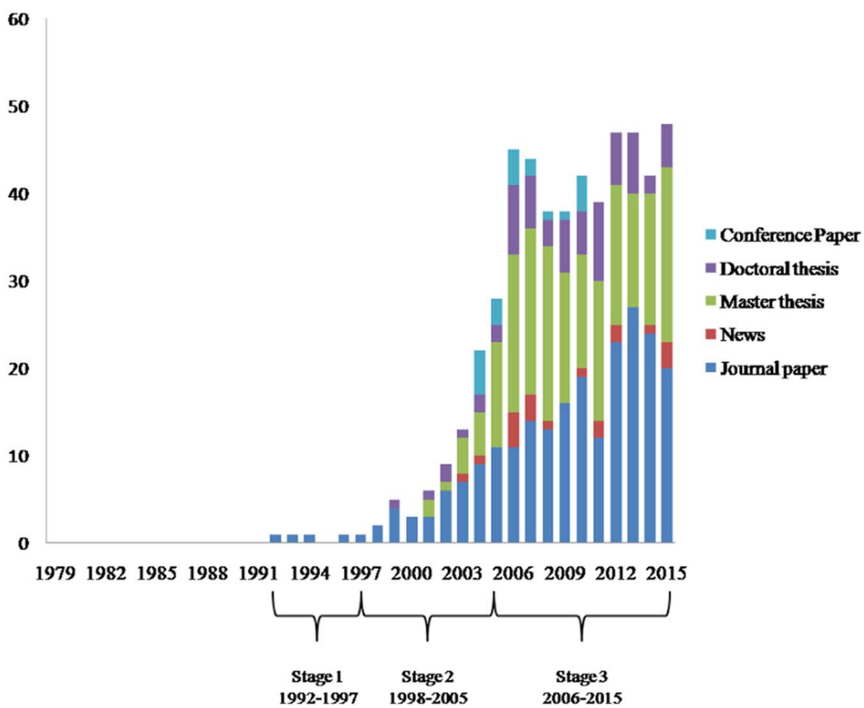

Fig. 7. Number of publications related to biodiversity conservation in China's hydro projects from 1979 to 2015. Data source: www.cnki.net.

concerning hydro projects and aquatic biodiversity was extracted from China's Knowledge Resource Integrated Database (www.cnki.net). As illustrated in Fig. 7, during the first stage, aquatic biodiversity conservation in hydro projects did not receive much attention, with only a small amount of research conducted each year in this field. During the second stage from 1998 to 2005, the number of annual research publications proliferated. During the third stage, there was an average of approximately 40 articles per year published in China. The publication of the "Regulation of Calculations (Estimations) on Environmental Protection Design for Hydraulic and Hydro-power Projects" and the "Guide for Environmental Impact Assessment of Hydraulic and Hydropower Projects" in 2002 and 2003 likely triggered an increase in environmental research regarding hydro projects. Similarly, the publication of the Guidelines for Environmental Impact Assessment of River Water, Low-Temperature Water and Fish Passage Facilities in Hydraulic and Hydro-power Projects and other relevant regulations in 2006 and 2007 likely triggered another increase in publications on hydro project research. Since this time, the number of publications concerning hydro projects and the environment has remained relatively high, averaging approximately 40 publications per year.

4.2. Patents

To explore the impact of academic research on the development of technology, information on the number of patents related to aquatic biodiversity conservation in hydro projects was collected from the State Intellectual Property Office of the People's Republic of China. Based on the three mitigation measures discussed in this article (fish passage facilities, restocking and river and lake renovation), six technology categories were investigated: fishways, restocking, river and lake dredging, river and lake aeration, ecological banking and floating islands. Fig. 8 shows the changes in the number of patents related to these six technologies. In general, the number of patents in all categories increased after 2007. This increase in patents corresponds to the third stage (2006–2015) of academic research discussed above. The correspondence suggests that increased academic research may lay a strong foundation for innovative technology development.

4.3. Research fields, organizations and funding sources

Fig. 9 illustrates the disciplines engaged in biodiversity conservation research as it relates to hydro projects throughout the three stages discussed above. The disciplines as classified by the China's Knowledge Resource Integrated Database are listed, as are the disciplines that were

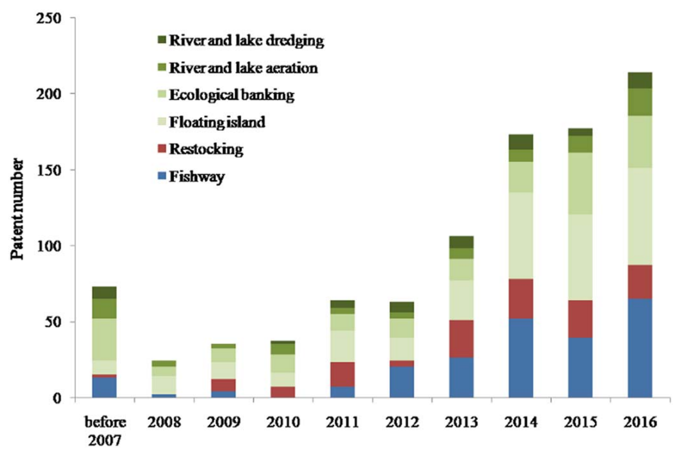

Fig. 8. Number of patents related to six technologies for biodiversity conservation in China's hydro projects. Data source: State Intellectual Property Office of the People's Republic of China.

reclassified into more general categories, such as environmental science, ecology and biology, engineering, economy and management, and tourism. The categorized results indicate that environmental science and ecology and biology have consistently been the major disciplines among the publications on biodiversity conservation and hydro projects in China. The percentage of publications in the engineering discipline has increased. There was also a slight recovery in the number of relevant publications in the economy and management discipline after the substantial decrease in the second period.

Fig. 10 shows changes in the organizations engaged in biodiversity conservation in China's hydro projects. The figure demonstrates a consistent increase in the proportion of research initiated by universities, matched by a decrease in the proportion of research lead by the Chinese government. Since 1998, companies and other institutions have increasingly participated in research concerning biodiversity conservation and hydro projects, while the proportion of research conducted by the Chinese Academy of Sciences has sharply decreased.

As depicted in Fig. 11, the amount of funding for research concerning biodiversity conservation and hydro projects increased significantly over the three stages, including a concomitant trend of diversification in funding sources. During the third stage, ministries and commissions, local governments, the central government and international organizations all provided financial support to ongoing research on the topic, although the central government continues to be the dominant source of funding. This demonstrates that the Chinese

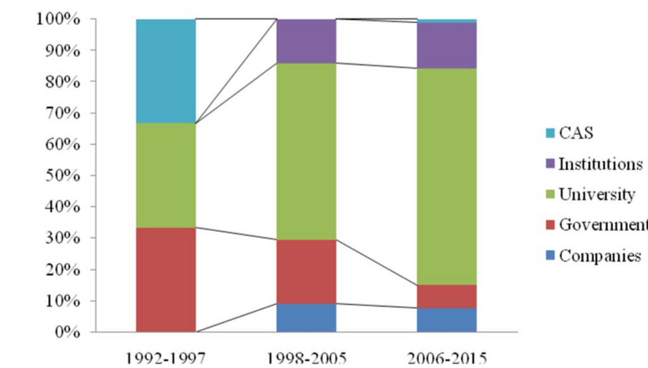

Fig. 10. Changes in the proportion of research organizations conducting research concerning biodiversity conservation in China's hydro projects. CAS refers to the Chinese Academy of Sciences. Data source: www.cnki.net.

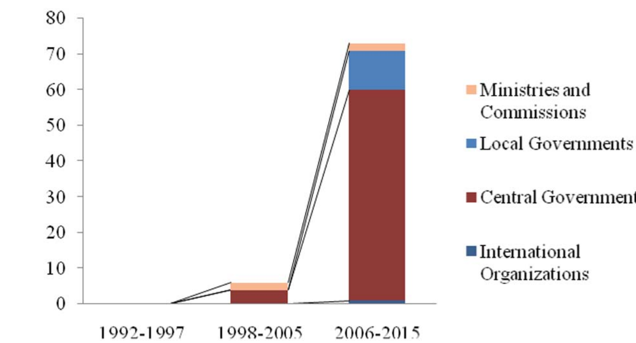

Fig. 11. Changes in the number of organizations funding research concerning biodiversity conservation in China's hydro projects. Data source: www.cnki.net.

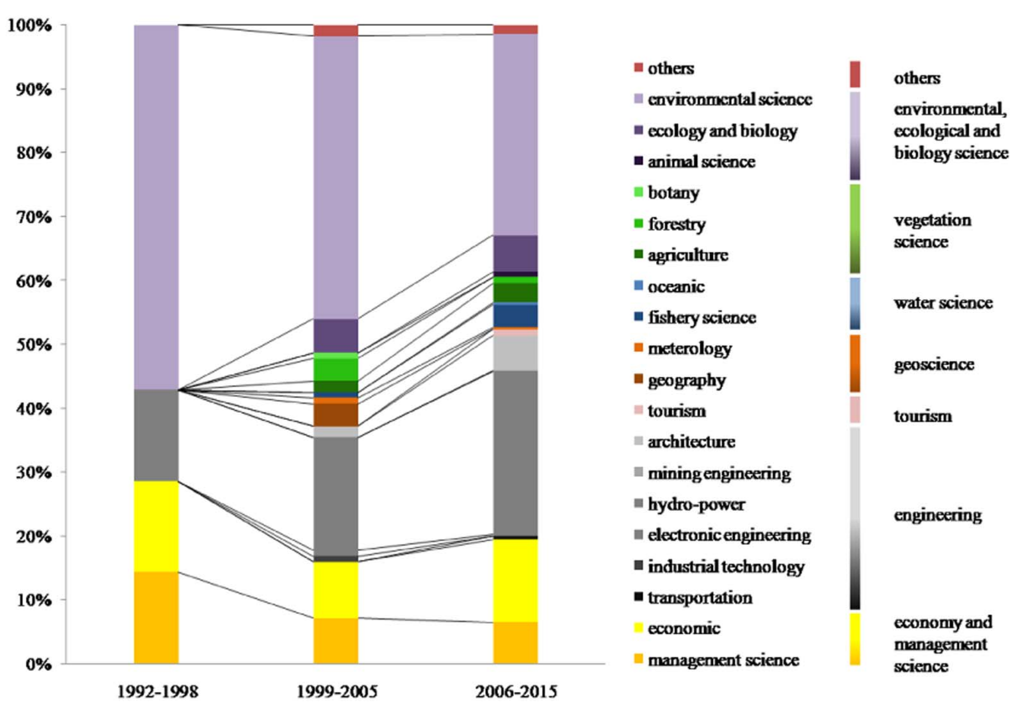

Fig. 9. Changes in the disciplines conducting academic research concerning biodiversity conservation in China's hydro projects. Data source: www.cnki.net.

government has made great efforts to support biodiversity conservation in hydro projects, not only through policy development but also through funding research on the topic.

5. Conclusions and suggestions

In terms of policy, research and implementation, China has demonstrated remarkable achievement in establishing aquatic biodiversity conservation measures in the country's major hydro projects. Despite these advances, there is still much room for improvement. Indeed, given the significant role of hydropower as a source of energy production in China and the monumental environmental impacts of hydro projects implemented thus far, China still faces daunting challenges in the pursuit of addressing aquatic biodiversity conservation concerns.

Based on the historical review presented in this article, we recommend the following areas for potential improvement. First, China's environmental certification system for hydro projects should be expanded to encourage hydro project managers to take effective measures to minimize the negative impacts of their projects on the environment. Second, the legislative framework regarding conservation measures in hydro projects, while robust at the national level, is lacking in terms of regional specifications. Regional legislation and, more specifically, public participation within the process of regional legislative development would bolster the national framework. Third, there is significant room for improvement regarding the cooperation between upstream and downstream conservation mechanisms to achieve more comprehensive conservation measures. As discussed, upstream and downstream approaches are often implemented in isolation, occasionally to counterproductive effects. Fourth, greater monitoring of fish populations after conservation measures have been implemented is needed to determine the efficacy of these measures. Lastly, new conservation measures specifically geared towards maintaining ecological flow and species habitats should be developed. Ecological methods must take precedence over high-impact approaches that significantly alter the landscape and ecosystem.

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