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Main issues in research and practice of environmental protection for water conservancy and hydropower projects in China

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Abstract

In this paper, we generally summarize the main issues in the operational period of water conservancy and hydropower projects in China over the past several decades. First, the adverse impacts of these projects since the technical guidelines were proposed in 2006 are analyzed. Then, combined with projects and experience from 2006 to 2014, the four main issues are summarized: (1) There exist many questions in the design and construction of fishways, which are useful for fish migration, and the migration effects are not as expected. (2) Temperature stratification affecting the downstream fish is the major impact of temperature, and alters fish spawning in the reproduction season. (3) Ecological base flow has been one of the primary questions of the last 30 years in China, the greatest related difficulty being quantification of the amount and flow process necessary to satisfy fish life history. (4) Fish habitat protection and restoration are popular topics in recent years with the development of river ecosystem restoration. Fish habitat loss due to the impacts of dam construction and habitat fragmentation has become more and more serious. These four issues are now the main difficulties in water project management, and interact with one another to bear combined effects on river ecosystems. The issues of eco-hydraulic consideration in the design period are the key factors. Finally, future priorities for research and practice of environmental protection for water conservancy and hydropower projects in China are proposed. The main purpose of this paper is to enhance the scientific research, monitoring, and assessment of operating effectiveness.

Keywords: Fishway; Temperature stratification; Ecological base flow; Fish habitat; Environmental protection

1. Introduction

China has exploitable hydropower resources of 542 million kW·h, and thus ranks highest in the world. Nevertheless, the installed capacity only accounts for 46% of the total exploitable amount (Li et al., 2015c). As is well known, the primary energy resource used in China is coal, and it is difficult to alter its primary status in the short term (Chang et al., 2010). The 12th Five-Year Plan states that, “On the condition that the ecological environment is protected and resettlements of the local people affected are properly handled, China will actively develop hydropower” (Hong et al., 2013). Hydropower is still the main driving factor supporting national economic development in the coming period. The distribution of developable hydropower potential across provinces is uneven (Li, 2012), due to the fact that hydropower projects in China are mostly implemented in the southeastern mountain areas where the natural environment is more sensitive, and the public holds varying opinions

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regarding hydropower development, especially regarding its impacts on the environment, such as the direct or indirect detrimental impacts on river ecosystems through alteration of the water flow pattern and restructuring of natural habitats (Chen et al., 2015). The development of hydropower must mitigate impacts on river ecosystems in order to alter current energy structures. The protection of fish species is attracting greater attention, as hydraulic power and the functions of rivers have been modified through dam construction activities, and the impacts of the changes on the fish fauna must be assessed for biodiversity conservation and fisheries management (Welcomme et al., 2006). Fish require different circumstances to complete breeding, feeding, wintering, and other activities, and the direct impacts of water conservancy and hydropower projects on fish are the obstructions and habitat fragmentation, with the natural river ecosystem being divided into discrete units (Zhao et al., 2008). Many spawning sites of migratory fish are lost, and their growth and reproduction are affected. In order to reduce the splintering of the river ecosystem, technological and engineering measures have been taken to ensure the effectiveness of the fishways and habitat restoration. However, this cannot significantly mitigate the effects of large dams (Orr et al., 2012). For example, fish have been seriously affected by large hydropower projects in the Yangtze River Basin, and the dams have cut off migration passages and have separated habitats. Some fish have been threatened and migrations have decreased due to the changes in connectivity between rivers and lakes (Yi et al., 2010b). In the Lancang-Mekong River Basin, the fish assemblages have changed greatly since the beginning of operation of the Xiaowan Dam (Li et al., 2013). Even for small-scale hydropower projects, the degradation of downstream ecosystem services caused by the periodic drying up of the river constitutes the largest portion of the ecological impact (Pang et al., 2015).

Some factors have indirect impacts on fish, including hydrologic regime alteration, influence of discharged cold water, minimum flow, and damage to the hydro turbine. Both the direct and indirect impacts on fish are among the main issues of environmental impact assessment of water conservancy and hydropower projects due to dam construction. In order to mitigate the impact of dam construction, fish engineering protection measures under environmental impact assessment must be integrated with the main project, and the protection measures must be taken after the operation begins. There are two main kinds of fish migration systems: the upstream and downstream fish migration systems. The upstream fish migration systems include fishways, fish ladders, fish barges, and so on. However, the downstream fish migration systems commonly pass through hydro turbines, which severely harm the downstream fish (Katopodis and Williams, 2012). Compared with the upstream passage of fish, the downstream passage has mostly been ignored. This harms fish by causing them to pass over the spillway and through the turbines. Over the past decade, many studies have described the injury mechanisms associated with the turbine passage, the response of various fish species to these mechanisms, and the probability of survival through specific dams under certain conditions (Richmond et al., 2014). Additionally, even if the fish successfully move upstream and downstream, the separated downstream habitats may move away from their original locations as a result of erosion, and the cold deep water released due to thermal stratification in the reservoir and the unnatural flow regime will also contribute to the habitat changes, especially the insufficient minimum discharge flow (Chang et al., 2011).

The Environmental Protection Law (EPL) for trial implementation in the People's Republic of China, promulgated in 1979, provided the foundation for the environmental impact assessment (EIA) (Jin, 2015). After more than 20 years, the Law of the People's Republic of China on Environmental Impact Assessment was passed in 2002, and came into force in 2003. Over the past several decades, the EIA system has been expanded with consideration of dam construction activities, in China and other Asian countries (Erlewein, 2013). As mentioned in the EIA Law, 2002, post-project environmental appraisal for dam projects has been proposed in practice (Chen et al., 2014a). The new Environmental Protection Act took effect on January 1, 2015. The ecological protection demands for water conservancy and hydropower projects, especially the impacts of large dam construction on fish, were proposed in the EIA (Liu et al., 2013). In the EIA practice of water conservancy and hydropower projects, we found that there have been four major issues in water conservancy and hydropower projects over the past ten years, namely the design and construction of fishways; thermal stratification in deep reservoirs; the minimum released flow or otherwise designated ecological base flow; and fish habitat restoration. We collected as many related research results as possible, to summarize the issues in research and practice of environmental protection for water conservancy and hydropower projects in China, and we propose future directions in each field.

2. Fishways

2.1. Fishway status

In aquatic systems, in-stream structures, such as dams, weirs, and road crossings, can act as barriers to fish movement, particularly upstream movement, along waterways. A fishway, also known as a fish passage, fish-pass, or fish ladder, is a type of structure built on or around artificial and natural barriers (such as dams, locks, and waterfalls) to facilitate the natural migration of diadromous fish (Chen et al., 2014b; Keller et al., 2012). There are various types of fishways, including Denil fishways, pools and weir fishways, vertical slot fishways, and natural fishways (Katopodis and Williams, 2012). At present, the major types of fishways in China are vertical slot fishways and natural fishways.

The first fishway in the world was built in 1662, in France, as described by Chen et al. (2012). The first law to forbid the construction of weirs which would limit fish passing during the spring was passed in 1709, and then, although such laws or regulations were not promulgated, fishways were sometimes built (Katopodis and Williams, 2012). In the 19th century, many countries, such as Norway and Ireland, proposed laws, acts, or regulations to protect fish by requiring the construction of fishways at dams or otherwise impassable barriers. In the 20th century, the U.S. Federal Power Act of 1920 (passed in 1920), which was amended in 1935, prescribed fishways at all hydropower plants, and by the early 1960s over 200 fishways were in place. Then, the Endangered Species Act of 1973 and other acts focused on the further effectiveness of fishways. In the 21st century, related laws and technologies were strengthened, requiring efforts to be made to improve the effectiveness of fishways in Canada and the European continent, and natural fishways became the main concern. Fishway designs have been evaluated to examine the efficiency in physical models or numerical models (Foulds and Lucas, 2013; Gustafsson et al., 2013).

The first fishway facility built in China was in the Qililong Reservior on the Fuchunjiang River in 1958, and, according to statistics, there were more than 40 fishways constructed from 1958 to 1980 (Wang and Guo, 2005). Because it is difficult to assess the effectiveness of the fishways, a lag phase occurred from 1980 to 2000 and no fishways or other facilities were built even in large hydropower projects like the Gezhouba Dam. With the increasing development and evaluation of fishways throughout the world, China began to restore fishway construction in 2000, and researchers began to pay more attention to fishway design with both numerical simulations and physical experimental methods (Mao et al., 2012). This has required additional fishway engineering measures in new and reconstructed projects in the EIA process, in order to maintain biodiversity and mitigate impacts on the fish. According to assessment reports, since 2000, fishways or other facilities have been built in a total of 27 large water conservancy and hydropower projects.

2.2. Issues involved in fishway design

Recent eco-hydraulic studies on fishways have mainly been performed in the U.S., Canada, and Europe. Such studies have connected fish, fishways, and the correlation between movement of fish and turbulence (Santos et al., 2012). Compared to global achievements related to fishways, in China there are currently three main difficulties in fishway design:

(1) Modeling limitations in upstream passage simulation

Even though vertical slot fishways are widely used, many difficulties remain in ensuring the effectiveness of fishways. At present the major issue is the interplay between hydraulic and biological variables, and the hydrodynamic properties of the fishway must meet the requirements of the fish species (Puertas et al., 2012; Bian and Sun, 2013). One of the main factors that must be considered in the design is swimming performance, and there are still other factors such as the depth and flow velocities. Recently, fishway projects established in China have faced several difficulties, the main ones being theoretical limitations on fish physiology habits, emulation of foreign designs and empirical formulas, and lack of experimental verification or authentication. Fishway hydraulics may present barriers to fish in three places (the entrance, interior, and outlet) as the entrances and outlets of fishways are the places where the flow is distributed at the interface between the water flow in the fishways and other structures, and the pool creates dissipation difficulties related to the following hydraulic characteristics:

(a) Entrance flow characteristics

Flow and velocity distribution for fish at the entrances of fishways is the key to the success of the fishways. There are many factors that must be considered in the design stage, such as the biological habits of target species, long-term series of hydrological data, geographical location, terrain features, and other environmental factors. Quantitative tests have been performed to encourage European eels to pass through fishways, and the results have shown that a strong edge effect influences the route choices (Piper et al., 2012). Four major criteria were compared in the Han River in Korea to determine the best positions of fishways (Baek and Kim, 2014). Using lighting and other complementary measures to induce fish to enter fishways is the mostly widely used method in China. However, the fact is that it is difficult to find the entrance for most fish and thus many fish gather below the dam, indicating the deficiency of the design.

(b) Internal flow characteristics

The flow characteristics of internal pools mainly depend on the specific geometry, such as the slope, internal flow velocity, water depth, and other relevant factors (Bermúdez et al., 2010). Fishway internal flow characteristics are hydraulic conditions that attract the fish readily, and allow them to enter, pass through, and exit safely with minimum costs in time and energy. According to research performed outside China, there is a linear relationship between the discharge and average depth in a pool, and the turbulence is important for evaluating the biological efficiency of the design. This is because the fish become fatigued, and high turbulence levels confuse the fish when they are finding their way through the pools (Mao et al., 2012). Previous research has shown that there are minor differences in the turbulence distributions for different baffle types. The differences in the turbulence distributions are due to the variations in flow created by each baffle (Morrison et al., 2009; Yagci, 2010; Rodríguez et al., 2006). The turbulence distributions, in essence, are the traditional hydraulic dissipation difficulty, so we need to take a different energy dissipation approach within a predetermined length of fishways, and create suitable physical conditions. There have been an insufficient number of hydrodynamic studies performed regarding the pools of fishways, but with the results and findings, it is possible to determine the slope, the size of the pools depending on the target species and temperature, and the discharges that are available or suitable for these structures.

(c) Outlet flow characteristics

The outlet flow parameters mainly seek to prevent the fish from falling back downstream because of the high flow velocity, or to prevent the fish from getting lost in the pool due to the hydrostatic force in the reservoir (Alvarez-Vázquez et al., 2011). The development of fishways in some locations in the Pacific Northwest goes back nearly half a century, and has been greatly successful in allowing the large, strong-swimming, and highly motivated pre-spawning adult salmonids and non-native American shad to pass through (Schilt, 2007). However, important challenges remain in China against the backdrop of increasingly widespread hydropower development. The alteration of water level also affects the status of the fishway outlets, especially because of the operation of cascade reservoirs (Sui et al., 2013). The fishway outlets in China are often clogged by sand, driftwood, or large stones, and the power generation benefit is the first objective of the cascade reservoir operation, but the flow status in the fishway outlets is rarely considered.

(2) Threats of downstream passage

There are as of yet no effective measures for solving the downstream issues of fishways. As a rule, downstream migrants do not use fishways. Downstream options in other countries usually include turbines, juvenile bypass systems, spillways, sluiceways, and other routes on the surface, or transporting fish directly by barge or truck (Schilt, 2007). To avoid fish injuries, the most commonly used method is to prevent fish from entering turbines using racks, while at the same time accessing spill gates, and allowing them to proceed downstream at small- to medium-sized hydroelectric plants (Calles et al., 2012). However, the main downstream route for fish in China directly passes through the hydro turbines or spillways, which in recent years has resulted in significant harm to fish. Most fish in China are multiple-spawning fish. In contrast, fish like salmon and trout die after spawning in other countries such as the U.S. and Canada. This signifies that we must ensure the safety of parental fish passing through fishways for species protection and the sustainable development of fisheries.

(3) Determination of multi-species hydraulic parameters

Velocity is relatively insensitive to the variations of discharge. Traditional fishway designs mainly aim at one or two major kinds of fish, in accordance with a certain velocity, water depth, and other indicators of fish types. However, for some types of fish, due to the fish's different sizes, habits, and movement, the following two major problems exist in China:

(a) Velocity range determination

Calculation and determination of the velocities that allow different fish to pass through fishways is a technical difficulty. Too high of a velocity results in direct reduction in fish that pass through fishways, due to the increased energy demands, and too low of a velocity fails to encourage the fish to enter the pool (Puertas et al., 2012). The minimum velocity matching the swimming ability of one fish must take other fish into consideration.

(b) Multiple fishway necessity

On the other hand, whether or not it is necessary to build more than one fishway on account of the different fish species must also be discussed. Most of the projects carried out over the past ten years in China have involved construction of only one fishway, and some projects have involved other fish passages like lifts, though the effects have not been ideal. There still remain large challenges such as the fact that fish ladders and lifts have been evolving for a long time and are effective for many species, but the fish species in China are very different from those in other countries, and the hydraulic characteristics for species in China require further study.

2.3. Issues involved in management system

The main issues involved in the management system include the following:

(1) Issues in adaptive management

Multidisciplinary studies of the management of fishways include hydrology, hydraulics, and ecology, and these must be considered in the construction of fishways. Related laws and regulations must also be considered in management. At the same time, the effectiveness assessment of fishways is a broader study of whether there is evidence that fish populations are benefiting from the fishways (Dan et al., 2014). Establishing an adaptive management mechanism for fishways can ensure their normal operation and maintenance. The adaptive management cycle of fishways includes six main steps: (1) assessment of the problem and specification of the objectives; (2) modeling of existing knowledge; (3) assessment of the potential management options; (4) implementation of the chosen options; (5) monitoring of the changes; and (6) review and adjustment of the actions (Humphries and Walker, 2013). The adaptive management of fishways lacks the monitoring and review period, which is important to improving the efficiency of fishways. Furthermore, the monitoring often requires a long period of time. The life of the fishways should be continuously monitored in order to maintain the functionality of the fishways, but in China this is also an unsubstantial step.

(2) Insufficient understanding of related concepts

At present, the main problem is the misunderstanding of fishways. Fishways in China were originally designed for precious migratory fishes to help their feeding migration, reproductive migration, and wintering migration. At the same time, fishway construction in China realized the goal of aquatic protection, for the protection of both precious and endemic fish, or connectivity protection of benthic organisms and organic materials. The fishway construction was initially based on the techniques used in Europe and the U.S. The fishway effectiveness in China has not been ideal, because the fishways were not designed for the local fish species, and did not consider their habits and behavior characteristics. During the fishway efficiency evaluation and review, not only should the target of the original fish be assessed, but the integrity of aquatic organisms and the river connectivity should also be comprehensively evaluated.

(3) Lack of fundamental surveys

Fishways should be monitored in real time to verify the efficiency of the fishways and identify the existing problems of fish passage design. At the same time, it will be indispensable in the design and development of future fishways to gather technical and biological information. A lack of survey and monitoring data within the regional ecological environment is the most common problem. To effectively evaluate the fishway performance, studies must directly address clearly defined passage objectives (Roscoe and Hinch, 2010). China has more than 3800 kinds of endemic fish species on record, but the behavioral studies of fish are mainly based on Chinese sturgeon and four major Chinese carp, while there have been fewer studies on the behavior and swimming ability of the vast majority of fish. Another difficulty is that the requirements of fishways and other facilities are generally presented in the EIA period, during which both the operation time and monitoring time are too short, so it is difficult to ensure a complete monitoring cycle in the design period and during work related to fish resources surveys, fish behavioral testing, and model testing. Earlier watershed planning in China had no requirements for fishway facility construction, and the monitoring and management lacked supervision after the reconstruction of fishways. In addition, with the development of artificial propagation and other facilities, it is not easy to distinguish the effects of fishways from those of other facilities.

(4) Lack of sound legal norms

Many legislatures require the construction of fishways (Farnham, 1904). Developed countries have published laws, regulations, or guidelines to improve the effectiveness of fishways, such as *Fishway Guidelines for Washington State*. In Africa there have been guidelines such as *Guidelines for the Planning, Design and Operation of Fishways in South Africa*. At present, fishway construction in China is less prevalent, and there are rarely specific guidelines to follow. There are two major regulations for fishway design and management: the *Executive Summary of Aquatic Biological Resource Conservation in China*, issued by the State Council in 2006, and the *Technical Guide for Environmental Impact Assessment of River Ecological Flow, Cold Water, and Fish Passage Facilities for Water Conservation Construction Projects (Trial)*, issued by the State Environmental Protection Administration in 2006. This shortage of fishway guidelines has greatly limited the construction and development of fishways, and there is an urgent need for the composition and publication of guidelines for fishway design for water conservancy and hydropower projects, fishway design regulations, etc. The mechanism of fishway compensation has not been established yet, and the costs of fishway operation, management, and maintenance vary with different companies. The hydropower loss in the operation of fishways has no relationship with the duty of the companies, so there is no enthusiasm for the companies to strengthen the management.

3. Temperature stratification

3.1. Impacts of cold water release

The differences in temperature between reservoir water and a natural river channel will impact the river ecosystem, and the aquatic ecosystem, water quality, and crops will be influenced by the cool water released from the reservoir (Yang et al., 2012; Fan et al., 2009). In northern China, the minimum flow of many reservoirs is too low to maintain the life cycle for downstream fish (Zhang et al., 2006).

The deep water of a stratified reservoir is typically low-temperature and anoxic. The cold water released to the downstream river ecosystem will have an influence on fish and crops (Yang et al., 2012; Milstein and Feldlite, 2015). After the construction of dams, the annual regulation, uncompleted annual regulation, and seasonal regulation, are formulated for them. The water temperature changes in the vertical direction during the operation of dams, and the trends are approximately as follows: Isothermal distribution occurs in winter, and the temperature of the release flow is higher than the temperature of the natural environment. The surface water temperature is higher and the bottom water temperature is lower than the water temperature at the same location in spring and summer, and the temperature of the release flow is lower than the natural water temperature. From the typical examples collected around the world, the temperature of the release flow is as much as 10°C lower than the natural water temperature in spring and summer. Numerical models are commonly used in hydro-environmental simulations for water quality, water temperature, and hydraulic characteristic recognition (Wang et al., 2014), but there are still problems related to thermal stratification because of the impacts on the fish.

High water temperatures in summer have led to increased juvenile fish stress in fish passage facilities (Politano et al., 2008). Fish are also threatened by the cold water at the deep bottom. There are several adverse impacts of dissolved oxygen and chemical composition changes due to the cold water release on the downstream fish (Zhang et al., 2015a). As a result, the composition of the fish fauna has changed. Research has shown that temperature stratification is one of the dominant factors influencing the vertical distribution and fish avoidance behavior (Sajdlová et al., 2015). In general, the fish spawning period is from April to August, during which the lowest endured temperature of spawning fish is generally 18°C. Though the increased water temperature in winter has some advantages, the released warm water directly leads to the extension of the growth and breeding season of the fish, reduction of the growth time of the juveniles, and decrease of the growth rate. The impact of the cold water release on spawning sites is another limitation, as some spawning sites disappear during the construction, their scale becomes smaller, and they migrate during the operation period. The scale of the spawning sites downstream, farther away from the dam, may expand, but, in general, the total number of fish spawning sites is reduced after the dam construction.

3.2. Difficulties in multi-level intake practices

Difficulties in multi-level intake practices mainly include the following:

(1) Lack of sufficient water intake measures

Design, construction, operation, and management experience from around the world suggest that there are no technical limitations to setting the water intake. However, construction has become more difficult due to the topographic and geologic conditions, and surface water release increases the head loss in the reservoir operation period. Theoretically, each multi-level intake measure has certain effects on the recovery of water temperature, but, in fact, the effectiveness depends on the fitting of the recovered water temperature and the growth of the critical temperature of aquatic organisms.

Furthermore, the lack of consideration of downstream aquatic organisms in conventional reservoir designs has led to fish reduction and ecosystem integrity destruction in many areas. To mitigate the adverse effects of cold water release downstream and to protect the river ecosystem, multi-level intake measures must be considered in the design of deep water reservoirs.

(2) Lack of sufficient monitoring data of release flow temperature

Compared with the empirical discriminant method, numerical models have many advantages, such as higher accuracy and wider range of application. However, numerical models also have some limitations, i.e., the models must go through calibration and validation to meet the accuracy demands for forecasting. Most numerical studies on temperature dynamics in reservoirs are based on one- or two-dimensional models. Over the past two decades, the models for reservoir water simulation have developed from one-dimensional (1D) to three-dimensional (3D) (Lee et al., 2013; Han et al., 2000; Diao et al., 2015), and today the most commonly used models are EFDC, MIKE 21, MIKE 3, and FLUENT. There are also some new models, such as a holistic water depth simulation (HWDS) and time to empty (TE) model for small reservoirs (Alia et al., 2015). Therefore, when using the numerical models, it is preferable to add field observations or laboratory measurements to ensure the model accuracy. However, it is very difficult to monitor the temperature of the released cold water, and the lack of monitoring temperature data, especially the lack of temperature data in deep-water reservoirs where multi-level intake buildings have been constructed, limits the development of numerical models.

(3) Limitations of empirical discriminant method

The empirical discriminant method is based on observed data from many reservoirs, and the discrimination results have been reasonable. Nonetheless, this method is not suitable for some narrow-deep reservoirs in mountains, due to the neglect of the morphology, climatic conditions, operation mode, and so on. Due to the limitations of the empirical discriminant method, for important projects the preferable choice is a more sophisticated numerical method.

(4) Limitations of validation of water intake measures

For large reservoirs with thermal stratification, the hydraulic characteristics and hierarchical structures are more complex. A study on a large dam showed that the temperature decreased rapidly in both the surface and bottom zones from June through October (Ma et al., 2015). Another example is the Fenhe Reservoir, where the simulated temperature of discharged water is consistent with the measured data, and the difference in temperature between the discharged water and the natural river channel under the current operating conditions is less than 3°C (Fan et al., 2009). However, although multi-level intake measures have been designed, the temperature of the surface water still cannot be determined, and the measures require further research and validation.

4. Ecological base flow

4.1. Origins and impacts of ecological base flow

The impact of ecological base flow on fish is currently a major issue. The ecological base flow sustains fish through life stages and the river course. Many cutoff rivers have been created after construction and the beginning of operation of dams, in particular diversion hydropower stations. Insufficient ecological base flow can cause a reduction in habitat availability and fish reproduction, the most serious impact falling in the fish spawning period, which is the most important period in fish life history. Dams greatly affect river hydrology, primarily through changes in the timing, magnitude, and frequency of high and low flows (Magilligan and Nislow, 2005). For both large and small rivers in China, dam construction has modified hydrologic regimes on a nationwide scale. Since the Three Gorges Dam (TGD) went into regular operation in 2006, its impacts on the flow regime in the middle and lower Yangtze River reaches have received attention worldwide, and the overall impact of dams on the flow regime have included the decrease of high-flow magnitudes and, at the same time, the increase of low-flow magnitudes over time (Gao et al., 2013; Zhang et al., 2015b). To assess the effects of dam operation, a number of hydrologic indices were recognized to describe the different characteristics of flow regimes, and the most commonly used indicators are the indicators of hydrologic alteration (IHA) (Gao et al., 2009).

With the intensification of human activities in river ecosystems, ecological base flow studies have become active once again, aimed at the concepts, methods, practices, or guidelines, and legal systems. The effectiveness of flow releases mainly depends on how they are managed (Mackie et al., 2013). However, due to the diversification of river ecosystem services, in China, there are still many difficulties in ecological base flow research, or, more accurately, ecological flow demand research. For example, the definitions and implications have yet to be unified, and the implications have expanded greatly (Chen and Zhao, 2011). At the same time, calculation methods have not been formed, and it is difficult to transplant the research results, due to the significantly different characteristics of regional watersheds (Deitch and Mathias Kondolf, 2012). The insufficiency of a legal system is the third factor that limits the development of ecological flow demand, along with ecological protection measurements, especially in the design and planning period of water conservancy and hydropower projects.

The greatest difficulty in ecological flow demand research is setting the threshold value against the background of significant differences in different regions, and different functions associated with the flow values for ensuring the ecosystem services are not clearly defined. Presently, the most urgent task is to set the criteria for ecological base flow in China. This will provide technical support for decision making in studies. The study of ecological base flow is relatively mature in developed countries, while in China it is still insufficient. Specific criteria have been developed to ensure the minimum released flow from dams in most countries. China has also promulgated a series of guidelines or regulations, including the *Technical Guide for Environmental Impact Assessment of River Ecological Water, Cold Water, and Fish Passage Facilities for Water Conservation Construction Projects (Trial)*, published in 2006, which states that the ecological base flow is 10% of the annual average flow. Since then, a number of related guidelines have been promulgated over the past several decades, which have enriched the system of laws and regulations. However, in the operation and implementation processes, the *Technical Guide* is still the main basis for determining the ecological base flow in the planning, design, and operational periods of most water conservancy and hydropower projects. Although it is convenient and simple to execute operations described in the *Technical Guide*, lack of consideration of the temporal characteristics of ecological base flow has led to the appearance of many drying areas in river courses as well as excessive discharged flows, which are not conducive to the sustainable development of river ecosystems.

4.2. Difficulties in research and practice

Over the past decade, the main difficulties related to ecological base flow may be summarized as follows:

(1) Lack of united concepts and calculation methods

There are many concepts or definitions related to the ecological base flow around the world, including environmental flow, instream flow, minimum flow, minimum acceptable flow, ecological and environmental water demand, sensitive ecological water demand, and minimum ecological flow (Carvajal-Escobar, 2008). There are also many differences between different concepts, and the implications continue to expand, thereby satisfying most ecosystem service functions. Studies have combined hydro-ecological response model outputs and nonmarket economic values (Akter et al., 2014). It is becoming increasingly difficult to determine the threshold value of ecological base flow. The development progress of ecological base flow outside China began from the minimum flow for maintaining shipping and fishing, evolved then to sufficient flow for maintaining the normal life cycle of aquatic organisms, then to sufficient flow for preserving the river and landscape patterns, and finally to flow that maintains the sustainable development of the river ecosystem. In China, ecological base flow research began from research on the minimum flow in the northwestern region in the 1970s. Later, studies turned to the Yellow River and Yangtze River basins. After nearly 40 year of development, the sub-regional ecological flow results had been obtained.

At the same time, it is difficult to select a suitable method from various calculation methods for determining the ecological base flow. There are many methods for calculation, but they usually require accurate long-term hydrological flow records, which are sometimes unavailable (Alcázar et al., 2008). Under this condition, the hydrological models are important for runoff simulation (Olsen et al., 2013). In summary, there are currently more than 200 methods, which can be divided into the categories of hydrological methods, hydraulic methods, habitat methods, and synthesis methods (Tharme, 2003). All of the methods are established on the basis of specific regions, and similarities of the natural environmental and community compositions in different regions play a very important role in the successful application of the methods (Li et al., 2009). Hydrological methods are most widely used, including the Tennant method and RVA method utilized in China and other countries (Gippel, 2001; Babel et al., 2012; Gippel and Stewardson, 1998). The habitat and synthesis methods are mostly used in the U.S., the U.K., and other developed countries, while most of these methods have also been introduced to China. The ecological limits of hydrologic alteration (ELOHA), which is a new framework for developing regional ecological base flow standards, was proposed in 2007 (Poff et al., 2010). Aside from the previously introduced methods, researchers in China have developed several methods suitable for rivers in China, including the hydrological index method, ecological hydraulic method, and water quality numerical model method.

(2) Significant differences in temporal and spatial characteristics

The greatest difficulties of ecological base flow research are the significant regional and functional differences of rivers, and the fact that the threshold values of the ecological base flow in different regions differ according to river ecosystem services. The lack of regional guidelines protecting the ecological values of rivers, especially when the flows must be determined at many locations in large basins, has led to the establishment of very simplistic criteria to fix the flow needs in rivers (Alcázar and Palau, 2010). The threshold value is also affected by the types and functions of different reservoirs. The diversity of sub-region characteristics in China has led to differences in the ecological base flow in different sub-regions, including not only differences in the ecological base flow between the northern rivers and southern rivers in China, but also differences in the ecological base flow between the upstream and downstream sections of the same river.

Most of the calculation methods used in China have taken the distribution process of runoff into consideration, and the threshold value of the ecological base flow has been a single value, or two threshold values in two different periods according to the Tennant method. Compared to rivers without protected aquatic organisms, the ecological base flow requirements that meet different conservation objectives in different periods vary greatly for rivers with protected aquatic organisms. Although there have been some studies that take the operation rules into consideration, it is still very difficult to use one set of rules for different rivers with different aquatic organisms, periods, and flow alterations.

(3) Inadequate system of laws and regulations

The ecological base flow has been guaranteed by specific criteria in most developed countries, such as *Water Law* and *Fisheries Law*, published by France in 1992, which stipulates 10% of the measured runoff as the minimum instream flow, and that the runoff series should be based on at least 10 years of data (Bethune et al., 2005). The U.S., Canada, Australia, and other countries have also published ecological flow standards. In addition, there are countries that have not yet recommended a standard (Benetti et al., 2004). International experience regarding setting the threshold value is valuable. China has promulgated a series of regulations and guidelines that lack legal protection, so there is a greater arbitrariness in the actual implementation process. Another problem is the possibility of ecological base flow. The water-supply guaranteed rate for residential areas is generally above 95%, and for industrial areas it is above 90%. Currently, the released ecological base flow is based on the threshold value, in most cases when the inflow is greater than the perspective threshold value, but turns into the inflow under other conditions. Therefore, the current ecological base flow standard needs to be revised.

5. Fish habitat restoration

5.1. Fish habitat protection in China

River restoration is currently a major issue in many countries, and the assessment of fish habitats in a water body is a basic approach for strategically planning ecological conservation and EIA (Maeda, 2013). Fish habitats include spawning grounds, feeding grounds, wintering grounds, and migration routes, with the spawning grounds being the most important and sensitive places for fish to complete their propagation process. The mechanical characteristics of fish habitats in the breeding season, such as the suitable water depth and flow velocity, are unique. The fish habitats also require suitable and stable sediment, along with appropriate water temperature and dissolved oxygen. During feeding, they require suitable sediment to satisfy the organisms and sufficient organic supply. They must also provide protection sites, shelter, diversity of flow types, and shoals.

There have been few studies on the hydraulic characteristics of fish habitats in China. One of the major studies aimed at protecting the four major Chinese carp and Chinese sturgeon, by describing different hydraulic parameters. There is no hydraulic index system for fish habitats, and the commonly used indicators are water depth, flow velocity, and Froude number (*Fr*). Most of the methods are based on fuzzy habitat suitability and the modeling of different river scales (O'Hanley et al., 2013; Marsili-Libelli et al., 2013; Yi et al., 2014). Studies on fish habitats are generally seen from one of two aspects: the distribution of various fish habitat locations in the river, and the distribution of flow from the surrounding water (Li et al., 2015a, 2015b). The influence of hydraulic characteristics on habitat conditions is mainly divided into direct and indirect effects. The direct effects involve the hydraulic indices, which affect fish over their life period; for example there is a significant correlation between the spawning time and water level. The indirect effects are wider, and the hydraulic conditions affect not only the oxygen content and water temperature, but also the terrain of the habitat. In the U.S., the hydrology and geomorphology of large rivers reflect the pervasive influence of an extensive water control infrastructure, including more than 75000 dams (Graf, 2006). In addition, the altered terrain also has effects on hydraulic indices.

5.2. Difficulties in fish habitat restoration

Difficulties in fish habitat restoration mainly include difficulties in fish habitat research and management.

(1) Difficulties in fish habitat research

Hydrology is a primary control for the ecological quality of river systems, through its influence on the flow, channel geomorphology, water quality, and habitat availability. Although there have been numerous studies on the hydraulic conditions of fish habitat, some problems remain. Research on fish habitat protection and restoration is an interdisciplinary endeavor involving a variety of hydraulic parameters and terrain conditions. Reservoir operation results in downstream river channel erosion, which can detrimentally alter the physical habitat. Restoring stream habitat connectivity is also one of the objectives (O'Hanley et al., 2013). For example, the Gezhouba Dam and Three Gorges Dam are the two largest hydraulic projects in the middle reaches of the Yangtze River, and have changed the physical habitat and reduced the connectivity of the river (Yi et al., 2010a). Studies on water temperature have been limited to several endangered species or species with high economic value, while the majority of common species have not received attention. Yet another difficulty is that there are different water temperature requirements for different life cycles, while there are few studies on the water temperature requirements of different kinds of fish. The traditional river geomorphological indicators are defined from the perspective of an abiotic environment and do not meet the fish habitat requirements. Specific research on landscape patterns has not been conducted.

Research on suitable fish habitat demands is still weak, and the methods of technical assessment of fish habitat quality remain under discussion. The lack of monitoring data restricts the development of habitat models. Effective methods requiring fewer data and less expertise can be suitable for the assessment of restoration potential, and monitoring of rehabilitation activities and excessive data requirements for assemblage information render many current assessment models expensive and limit their wide use (Zhao et al., 2015). Fish habitat restoration also meets the ecological requirements and conforms to the natural river erosion trends. Therefore, it is restricted by basic techniques, which lead to obviously artificial landscape patterns, especially in downstream river courses and natural rivers.

(2) Difficulties in fish habitat management

Difficulties in fish habitat management include the following:

(a) Lack of protection and management funds

Government agencies and stakeholders agree that river restoration is necessary for sustainable development. However, many projects involving river restoration have failed, and river ecosystems continue to deteriorate (Choi and Choi, 2015). The infrastructures of the planned fish habitats in China are inadequate mainly due to the lack of management funds. This affects the capacity of basic construction and management of endemic and unique fish in the habitat area. At the same time, lack of government funds also leads to the interruption of routine patrolling and monitoring.

(b) Lack of concern for potential habitats

Fish habitats are gradually shrinking due to the delays in habitat protection and restoration, coupled with frequent economic activities in the habitats. In addition, there are no agencies for specific fish habitat protection, and very few stations for fish protection. There have only been special surveys or observations.

6. Conclusions

As hydropower development in China continues, the demands of environmental protection have become stricter than before due to the fragile river ecosystem in regions under exploitation. Therefore, river ecosystems and fishery resources must be protected, in order to allow research and facilitation of fishways, multi-level water intakes, ecological base flow, and fish habitat restoration. Because new practical problems have arisen over the past several decades, studies and practices on the monitoring of basic data and assessment of operating results must be enhanced. Therefore, we put forward the following four prospects integrated with the main problem:

(1) Fishway efficacy is affected by many factors, requiring full observation and survey of fish species, as well as their physical characteristics, habits, and distribution. On the basis of analysis of hydrology and hydraulic characteristics, the physical model and numerical model can be used to determine the fishway type and size of the various fishway elements. Through adaptive management and integrated operational observation, the fishway effectiveness, fishway type, and operational management can be improved.

(2) The traditional method of water release leads to the decrease of downstream water temperature, which in turn affects the downstream environment and aquatic organisms. The adverse impacts on the downstream river course can be reduced by taking multi-level water intake measures, and by controlling the temperature of the released water. The key point is to reinforce the monitoring of released flow water, which can provide basic data for the numerical models. In the planning and design of high dams, multiple objectives, such as project safety, economic benefits, operability, and reliability, must be taken into consideration to achieve the maximum socio-economic benefits and fulfill the needs of water temperature in downstream river courses.

(3) There are still no specific methods or standardized indices for ecological base flow in China, which results in some difficulties in the EIA of water conservancy and hydropower projects. The currently used method, which stipulates 10% annual average flow as the ecological base flow threshold value, must be refined. In addition, an index system of ecological base flow and regionalization of the limit line must be developed in the future, and a reasonable assessment standard must be established by filtering the representative factors and taking the ecological base flow characteristics into account. Most importantly, the ecological base flow sub-region, grading standard, and regionalization method of the red-line constraint zoning can be proposed to draft a nationwide ecological base flow constraint zoning map, which can provide technical support for determining the ecological base flow threshold values in the EIA of water conservancy and hydropower projects.

(4) There is an urgent need to launch continuous monitoring of fish habitats in the near future, and to perform research on the correlation between biological behavior and hydrology, and hydraulics characteristics. It is imperative to further study the habitat assessment and numerical simulation technology, in order to carry out post-environmental impact assessment and fish habitat management.

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