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Review

Review of fishway research in China

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ABSTRACT

Fishways play an increasingly important role in restoring free passages in rivers for aquatic organisms, especially fishes. Effective fishway operations are the prerequisite for the restoration of fragmented habitats. Research has shown that most existing fishways in China are not functioning correctly. In order to facilitate the successful operation of fishways, this paper discusses several key issues, such as swimming capabilities and behaviors of migratory fishes, fishway entrance position and structure type, downstream migration, and fishway siltation. In addition, the author provides directions for future fishway research in China.

1. Introduction

The construction of dams, *Research significance* weirs, sluices, and other hydraulic structures in rivers has rapidly increased due to the development of water conservancy and the increasing demands for flood control, irrigation, and the generation of power. China's total water resource is the sixth highest in the world, estimated at 2,795.79 billion m^3 (The Ministry of Water Resources of the People's Republic of China, 2013a). However, the amount of water resource per capita is only 2300 m^3, a quarter of the world's average. Therefore, China has the lowest per capita water resource worldwide, while consuming the most water globally. For example, in 2012, the consumption of freshwater in China reached 549.7 billion m^3, approximately 13% of the total global consumption. In addition to excessive water use, the temporal and spatial distribution of precipitation is extremely uneven in China. Therefore, China is a country with severe drought and water shortages, and imminently requires a consistent water resource. As such, the development of water conservancy in China is rapidly growing with increased construction of dams, weirs, sluices, and other hydraulic structures. The number of hydropower stations in China has reached 46,758 as of 2013 (The Ministry of Water Resources of the People's Republic of China, 2013b), which is the most quantity in the world.

Fish rely on migrations to satisfy their requirements with regard to the structure of the biotope during juvenile fish, during their growing phase, find their optimal habitat in areas with gentle currents and fine grained substrates (Gross et al., 1988; Dugan and Winemiller, 2010). However, the construction of hydraulic structures causes a series of ecological problems by breaking down the connectivity between rivers and waterways. Fish habitat is an important component of riverine ecosystems (Li et al., 2015). The anthropogenic barriers block upstream migration, effectively fragmenting the fish habitat. The disruption to the natural migration patterns could result in a population decrease for many fish species. In addition, the hydraulic structures alter the physical river environment such as the water level, flow rate, and water temperature, properties that have been shown to significantly affect fish behavior. As habitat quality is directly related to ecosystem biodiversity, habitat fragmentation has significant negative impacts on biodiversity (Vannote et al., 1980). Therefore, the restoration of fish migration passages is vital in protecting river biodiversity. The construction of fishways has been an effective tool used to restore fish migration passages, and bridge fragmented habitats. The purpose of a fishway is to assist fish in smoothly bypassing an obstacle and alleviate the negative effects of the hydraulic structure. More importantly, fishways prevent the extinction of fishes, by protecting river connectivity and biodiversity (Food Agriculture Organization, 2002). Therefore, well-functioning fishways have ecological, economic, and engineering significance. The Ministry of Environmental Protection of the People's Republic of China (2012) enacted a statute on "Further strengthening environmental protection of hydropower", asked for hydropower projects to strengthen the construction of fishway.

2. Retrospection of fishway research

In 1662, the Beaune Province in France released the first fishway regulation that required the construction of fishways in dams or weirs to facilitate fishes' upstream or downstream migration passages (Food Agriculture Organization, 2002). Since then, with the rapid development of water conservancy projects, the construction of fishways has become essential. After their initial development, fishways have become more advanced, current types of fishways include: baffle fishways (Rajaratnam and Katopodis, 1984; Katopodis et al., 1997; Mallen-

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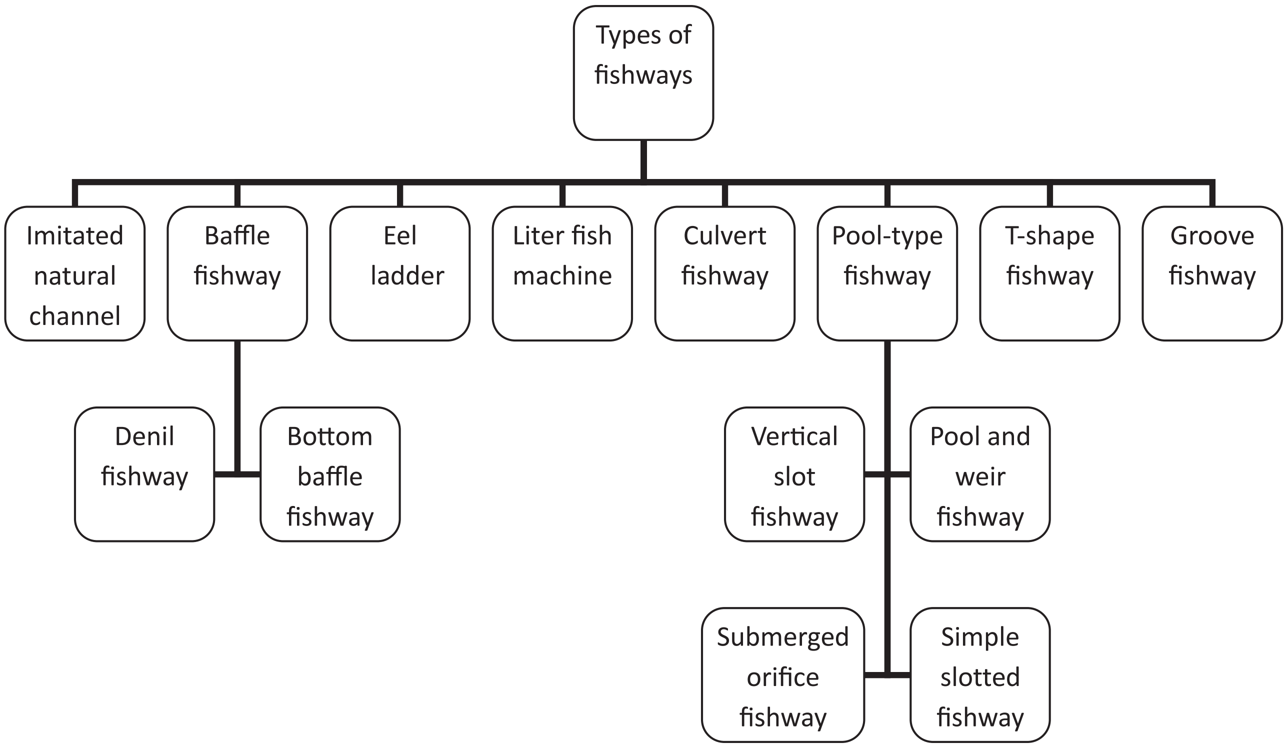

Fig. 1. Classification of Fishways.

Cooper and Stuart, 2007), pool-type fish channels (Rajaratnam et al., 1988; Kim, 2001; Yagci, 2010; White and Pennino, 1980; Rajaratnam et al., 1986; Wu et al., 1999; Mao et al., 2012b), culvert fishways (Powers and Bates, 1997), T-shape fishways (Mao et al., 2012a), imitated natural channels (Clay, 1995; Hyde and Chirgwin, 2004; Calles and Greenberg, 2005), liter fish machines (Holst and McDonald, 2000), groove fishways (Mao et al., 2011), and eel ladders (Whitfield and Kolenosky, 1978), as shown in Fig. 1.

The quantity statistics showed that there are primarily three common categories of fishways used in engineering (Bell, 1973; Food Agriculture Organization, 2002): 1) Denil fishways, 2) pool and weir fishways, and 3) vertical slot fishways. Research has primarily been concerned with the structure of the fishways themselves, and exhaustively explores the hydraulic problems of the fishways from different perspectives. For example, the Denil fishways initial design purpose was to overcome small or medium height gaps over a short distance. Therefore, the Denil fishway was designed as a linear passage, in which baffles are arranged obliquely against the water flow direction at fixed and short intervals. The initial design prototype was dramatically improved using U-shaped section baffles, this modification had the best function and is referred to as the standard Denil fishway (Rajaratnam and Katopodis, 1984; Katopodis et al., 1997; Mallen-Cooper and Stuart, 2007). Pool and weir fishway, were created to accommodate the volumetric dissipation rate of salmonid species, although these fish have a strong endurance capacity, the volumetric dissipation rate can reach 200 W/m^3— while an ideal rate is less than 150 W/m^3 (Larinier et al., 2002). Lastly, the vertical slot fishway was designed based on the in-depth model experiment of 18 structural types of vertical slot fishways (Rajaratnam et al., 1986). It was discovered that when the length:width ratio was equal or close to 10:8, the water flow pattern in a pool was conductive to the upstream migration of fishes. As a result, the length:width ratio of a vertical slot fishway is typically designed equal or close to 10:8. The design was further modified when it was discovered that a vertical slot fishway with a slope of less than 10% created a water flow pattern with obvious two-dimensional characteristics (Wu et al., 1999). The importance of a < 10% slope was further verified using numerical simulation software to analyzed the hydraulic characteristics of water flow in different ipsilateral vertical slot fishways (Barton and Keller, 2003). These results offer a hydraulic analysis of the elements of fishways and have been significant in guiding the preliminary design.

In summary, the characteristics of the three common types of fishways are summarized as follows: 1) The Denil fishway occupies less space and is not constricted by space; however is susceptible to water level fluctuation, and is easily blocked by sediments and debris. This design requires a higher water level than other types of fishways. 2) The pool and weir fishway has smaller water-flow cross-sections in a pool. This design can easily accumulate sediments and debris; making the orifice is vulnerable to blockage, seriously affecting the water level. This type of fishway is inadaptable to large water level fluctuations; and does not allow fish passing across the entire cross section. 3) The vertical slot fishway is adaptable to large and frequent water level fluctuations. It has a spacious interior room and provides fishes with gliding places. The design allows fish to pass across the entire cross section and is not prone to be blockage. This type of fishway is not only applicable to low-flow creeks but also large-flow mountain rivers, and is also easy placed in narrow valleys.

Therefore, among the three common types of fishways, the vertical slot fishway is most favored (Food Agriculture Organization, 2002; Zhang et al., 2014). Since first available, this design has been widely used in many countries and is effective in fish passing. For example, the Bergerac vertical slot fishway in France's Dordogne River was built in 1984. Large salmonids, the economically significant allis shad (*Alosa alosa*) and cyprinids have been discovered in the river since its operation. It has a high fish-passing rate and excellent operation effectiveness (Food Agriculture Organization, 2002). Another example is the new Lübbenau vertical slot fishway in Germany's Spree River, which was built in 1992. It operates well and successfully passes a considerable number of successful migratory fishes. During 1993 and from April to May in 1994, the total number of upstream-migrating fishes exceeded 10,000. During the peak, the daily number exceeded 1800 (Food Agriculture Organization, 2002).