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Review

Effects of dam construction on biodiversity: A review

Haipeng Wu [a, b, *], Jin Chen [a], Jijun Xu [a], Guangming Zeng [c, d, **], Lianhai Sang [a], Qiang Liu [a], Zhengjie Yin [a], Juan Dai [a], Dacong Yin [a], Jie Liang [c, d], Shujing Ye [c, d]

[a] Changjiang River Scientific Research Institute, Wuhan, 430010, PR China
[b] College of Life Sciences, Hebei University, Baoding, 071002, PR China
[c] College of Environmental Science and Engineering, Hunan University, Changsha, 410082, PR China
[d] Key Laboratory of Environmental Biology and Pollution Control (Hunan University), Ministry of Education, Changsha, 410082, PR China

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ABSTRACT

Wetlands (rivers, lakes, bogs, etc.), the biodiversity hotspots, provide habitats for biology on Earth and play an important role in biodiversity protection around the world. However, they are damaged by dam construction all over the world. Many studies have been conducted on the effects of dam construction on biodiversity, but a review about it is missing. The objectives of this review are: (1) to discuss the effects of dam construction on biodiversity in freshwater wetlands; and (2) to identify the future directions for research in this field. To achieve these objectives, 347 significant publications from 2000 to 2017 were selected (based on a rigorous screening processes and a systematic literature review approach) from the ISI Web of Knowledge database. Dam construction decreased the water fungal biomass and richness in reservoirs and downstream reaches, but increased the amount of soil microorganisms in downstream lake wetlands. The studies about effects of dam on benthos mainly focused on macroinvertebrate, periphyton and mussel. Most studies about the effects on macroinvertebrate claimed that dam construction caused increases in biomass and decreases in taxa richness in downstream reaches. The studies about effects of dam on plankton mainly focused on phytoplankton, zooplankton, planktonic microorganisms and ichthyoplankton. Effects of dam on fish (including aquatic mammals) included blocking migration route, habitat fragmentation, changing from lotic to lentic water in the impounded area, release of hypolimnetic cold water of reservoir, and changes of water flow in downstream reaches. Studies about effects of dam construction on botany mainly focused on the riparian plants, but there were few studies on floating plants and submerged macrophyte and effects of dam construction on botany in downstream lake wetlands. There were only few studies that examined these effects of dam on bird. We also pointed out the future directions for research in this field.

Contents

* Corresponding author. Changjiang River Scientific Research Institute, Wuhan, 430010, PR China.
** Corresponding author. College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China.
E-mail addresses: wuhaipeng0701@126.com (H. Wu), zgming@hnu.edu.cn (G. Zeng).

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1. Introduction

Wetlands (rivers, lakes, bogs, etc.) are critical to global ecology and highly sensitive to climate change (Dai et al., 2016; Vorosmarty et al., 2010). They provide habitats for biology on Earth and play an important role in biodiversity protection around the world (Adapa et al., 2016; Wu et al., 2015; Zeng et al., 2013). They occupy only about 1% of surface of the Earth, while providing suitable habitat for about 20% of the global species, especially the endangered and endemic species (Fang et al., 2006). When mammals (river dolphins, otters, platypus), aquatic reptiles (turtles, crocodiles), amphibians and freshwater fish (over 10,000 species, about 40% of global fish diversity) are considered, it is very clear that about one third of all vertebrate species live in freshwater wetlands (Dudgeon et al., 2006). Besides, in China, about half of the endangered bird species live in wetland ecosystems (Fang et al., 2006; Seuring and Muller, 2008).

However, these biodiversity hotspots and habitats are damaged by dam construction around the world. To meet water, energy and transportation needs, humans built over 300 giant dams (which have a height of over150 m, dam volume of above 15 million m^3 or reservoir storage of above 25 km^3) and a surprising number of smaller dams, leaving over half (172 out of 292) of the global large rivers fragmented (Chen et al., 2016; Nilsson et al., 2005). For example, more than 50,000 dams were built throughout the Changjiang (Yangtze River) River's watershed to minimize flooding, generate electric power, facilitate irrigation and store water since 1950 (Wu et al., 2017a), and Three Gorges Dam is the world's presently largest dam and is located about 44 km upstream of Yichang (the control point of upper Changjiang River basin) (Wu et al., 2015).

Dam construction has altered wetland ecosystems more extensively than other anthropogenic activities (Lees et al., 2016; Tang et al., 2008). It has global implications on natural wetlands (Nilsson et al., 2005). It unavoidably induces changes in river flow regimes, sediment regimes and wetland morphology and geomorphology (Donohue and Molinos, 2009; Wu et al., 2013). And global biodiversity in wetland ecosystems is generated and maintained by these factors (Cucek et al., 2012; Poff et al., 2007). Therefore, dam construction has global influences on biodiversity (Grumbine and Pandit, 2013; Vorosmarty et al., 2010).

Therefore, the effects of dam construction on biodiversity have attracted the attention of researchers, environmental activists and wildlife campaigners around the world (Jacobsen et al., 2012; Wu et al., 2015). Numerous studies about the effects of dam construction on microorganisms, benthos, plankton, fish (including aquatic mammals), botany and birds were reported (Rechisky et al., 2013; Wu et al., 2017a). However, the review about the effects of dam construction on biodiversity is still missing.

This review focuses on the effects of dam construction around the world on biodiversity in freshwater wetlands (Fig. 1). In this review we aim to: (1) discuss the effects of dam construction on biodiversity of benthos, plankton, microorganisms, fish (including aquatic mammals), botany and birds; and (2) identify the future directions for research in this field.

2. Methodology

Because of its comprehensiveness and high-quality records, the ISI Web of Knowledge database was used to bibliometric analysis (Binnemans et al., 2013; Zhang et al., 2017a). "Dam" (or "reservoir") and "biology" (or "biodiversity") was used to search subjects (titles, abstracts and keywords) of the documents (including journal articles, book, book chapters, editorial materials and conference articles). Then, publications were further selected, according to their titles and abstracts, by artificial screening. Altogether, 347 original publications (published from 2000 to 2017) were selected for

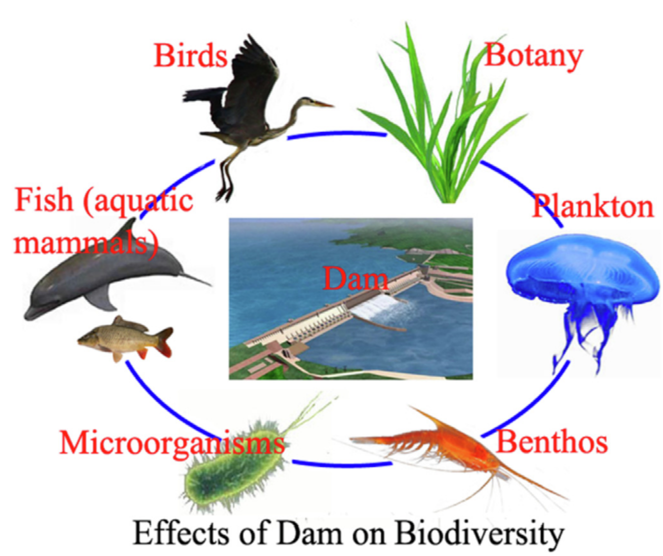

Fig. 1. The topic of this review: effects of dam construction on biodiversity of microorganisms, benthos, plankton, fish (including aquatic mammals), botany and birds.

further analysis. According to the research subject, all the papers were classified into 6 aspects: benthos, plankton, microorganisms, fish (including aquatic mammals), botany and birds. The time and categories distribution of the 347 publications are shown in Fig. 2.

The contents of these papers were further evaluated through descriptive dimensions (Seuring and Muller, 2008; Zutshi and Creed, 2015): 1) the distribution of papers across the time period; 2) the journals in which they are published; 3) the species they studied; 4) the research methodologies they used; 5) the conclusions they reported; and 6) the citing of these papers. Distributions of these papers in important journals (important journals are defined as the journals where at least 5 of these papers were published in the time period) are shown in Table 1. Endnote X6 was used in the management of these papers. Although 347 relevant publications were selected and analyzed, not all of these were cited in this article because some conclusions were similar. To ensure the objectivity of content analysis, we applied a structured and systematic approach (Rodrigues and Mendes, 2018; Tranfield et al., 2003). Finally, the future directions for research in this field were identified (Bocken et al., 2013; Ford and Despeisse, 2016).

3. Effects of dam construction on microorganisms

Microorganisms are sensitive to anthropogenic activities and environmental factors and play an important role in ecosystem (Dai et al., 2016; Wu et al., 2016; Zeng et al., 2015). Water or soil microorganisms would therefore be influenced by the changes of environment caused by dam construction.

3.1. Effects on water microorganisms

In general, dam construction decreased the water fungal biomass and richness in reservoirs and downstream reaches, probably because of flow reduction in reservoirs and cooler water below the dam (Colas et al., 2016; Menéndez et al., 2012; Xu et al., 2012). For example, Dam construction decreased abundance of nitrogen cycling *Betaproteobacteria* (e.g., *Limnohabitans*), abundance of functional genes and KEGG orthology groups involved in nitrogen cycling in backwater (reservoir) (Yan et al., 2015). But in some types of reservoir with other stresses (e.g. pollution), the fungal richness had no significant change (Colas et al., 2016; Mendoza-Lera et al., 2012; Zhou et al., 2014).

3.2. Effects on soil/sediment microorganisms

In general, dam construction increased the soil microorganisms in downstream lake wetlands. For example, (1) decrease of grain-sizes of sediment (mainly caused by 50,000 dams of Changjiang River) could increase soil microbial biomass and bacterial community diversity in Dongting Lake wetland (Wu et al., 2013); (2) the impound of Three Gorges Dam caused early dry season in downstream wetlands, and caused increases of soil microbial biomass and bacterial community diversity (less drastic change would not have caused such a significant change in diversity) (Wu et al., 2015).

Although there were some studies on effects of dam construction on microorganisms, these studies were far too less in number to mark the significance of microorganisms in the research field (Wu et al., 2017b). Dam construction would change water flow, water temperature, water transparency, sediment regime and nutriment. And all these would affect the water or soil microorganisms.

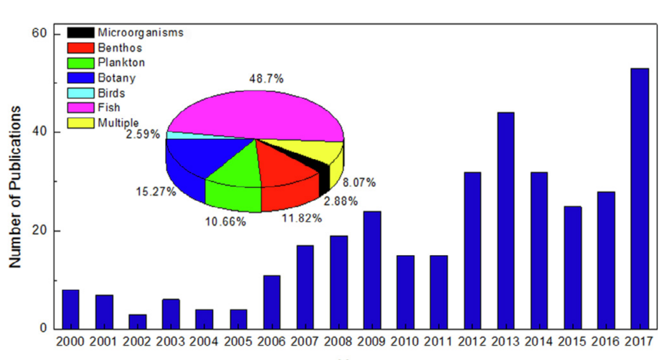

Fig. 2. The time and categories distribution of the publications.

4. Effects of dam construction on benthos

Dam construction could affect benthos with changes in flows, temperature, water quality, substrate, food availability and other water physicochemical parameters in reservoirs and downstream reaches (Chen et al., 2015a; Smolar-Žvanut and Mikoš, 2014). The affected benthos are mainly macroinvertebrate, periphyton and mussel.

4.1. Effects on macroinvertebrate

The effect on macroinvertebrate is one of the hotspots in the research field of effects of dam construction on biodiversity. Most study found that dam construction caused the increases of biomass and the decreases of taxa richness in downstream reaches. For instance, the study found that the average macroinvertebrate density increased from 1000/m^2 to 10000/m^2 and genera declined from above 70 to below 30 after the dam's closure (Vinson, 2001). Besides, some studies also focused on changes of chironomids (a key component of macroinvertebrate). Dam lowered their total density and diversity in upstream reaches (Głowacki et al., 2011), and raised their total density and diversity in downstream reaches (Głowacki et al., 2011). However, dam could not raise density of all kinds of macroinvertebrate in downstream reaches. For example, dam possibly reduced the densities of downstream snails (*Neotricula aperta*) to an undetectable level in Laos, due to decreased calcium levels and silting (Attwood, 2012).

Dam construction also changed the macroinvertebrate community structure. In general, those tolerant taxa (species that are capable of exploiting various habitats, and tolerant of pollution) increased in numbers, while those intolerant taxa (species that are sensitive to disturbance and pollution) declined in numbers (Mantel et al., 2010). For example, there were relatively more *Chironomidae* larvae, *Mollusca* and *Oligochaeta* and fewer *Plecoptera*, *Trichoptera* and *Ephemeroptera* in the sites below the dams and in reservoirs than those in control sites" (Vaikasas et al., 2013). Besides, some studies demonstrated that the distribution of the functional feeding groups of macroinvertebrate was also affected by dam construction, collector-filterers, scrapers and predators increased whereas collector-gatherers and shredders decreased (Vallania and Corigliano Mdel, 2007).

4.2. Effects on periphyton

Dam construction generally caused the increases of periphyton biomass and species in downstream reaches. For example, there were thicker biofilms, more Chlorophyll-a concentration, higher photosynthetic efficiency, higher respiration capacity and more active metabolically (Ponsatí et al., 2015). Another study found a consistent trend towards higher cell numbers and species richness in downstream reaches (Mueller et al., 2011). This is the combined

Table 1
Distributions of papers in important journals.

Journal	Total publications	Total citations	IF 2017
River Research and Applications	23	475	2.067
Hydrobiologia	16	258	2.165
Environmental Biology of Fishes	12	237	1.514
Ecological Engineering	9	150	3.023
Freshwater Biology	9	381	3.767
Neotropical Ichthyology	8	47	1.216
Brazilian Journal of Biology	7	210	0.784
Science	6	1556	41.058
Ecological Indicators	6	80	3.983
PNAS[a]	5	726	9.504
Conservation Biology	5	437	5.890
Journal of Applied Ichthyology	5	27	0.774
Transactions of the American Fisheries Society	5	83	1.406

[a] PNAS: Proceedings of the National Academy of Sciences of the United States of America.

results of the lack of sediment supply from upstream reaches, prolonged periods of reduced flows and changes in physicochemical variables in downstream reaches, which were caused by dam construction (Smolar-Žvanut and Mikoš, 2014).

4.3. *Effects on mussel*

Dam construction could also affect the growth of mussel. The mussels of immediately downstream from the dam grew faster than that of both up- and downstream populations, which was because of substantial increase in water temperatures (Singer and Gangloff, 2011).

In general, most of studies in the research field of effects of dam construction on benthos were completed by comparing the rivers with dams and rivers without dams, and few was completed by comparing the key statistics before and after dam construction. There are many other factors that can affect the authenticity of the results from studies that compared rivers with dams and rivers without dams. Therefore, there is need for more studies which are completed by comparing the river before and after dam construction.

5. Effects of dam on plankton

Plankton is sensitive to changes of environment in rivers and lakes. Dam construction could affect plankton by changes in sediment charge, flows, temperature, water quality, food availability and other water physicochemical parameters.

The affected plankton are mainly phytoplankton, zooplankton, planktonic microorganisms and ichthyoplankton: 1) Phytoplankton: damming generally lead to the increase in abundance and biomass of phytoplankton assemblages in reservoir areas (Li et al., 2013), and the significant changes in proliferating patterns (especially, *Microcystis aeruginosa* and *Stephanodiscus hantzschii*) (Jeong et al., 2007), composition and abundance of phytoplankton (Li et al., 2013); 2) Zooplankton: damming give rise to exponential decline of copepods and cladocerans in downstream reaches with distance from main-stem dams and less abundant of rotifers in the inter-reservoir zone (Havel et al., 2009); 3) Planktonic microorganisms: damming caused a significant decline in *Bacteroidetes*, *Betaproteobacteria*, and *Gammaproteobacteria* in downstream sites, whereas the total bacteria, *Actinobacteria* and *Alphaproteobacteria* observably increased (Ruiz-Gonzalez et al., 2013); 4) Ichthyoplankton: there were decline in densities and number of taxa of ichthyoplankton (especially migratory species), and formerly common migratory species were disappearing in dammed rivers (Sanches et al., 2006). Besides, another study also reported that the effect of dam on plankton was more significant in dry season than that in wet season, because of the altered water dynamics (Jiang et al., 2012).

More attention should be given to effects of dam on plankton, because plankton (especially algae) is related to eutrophication, and is sensitive to water quality and temperature changes.

6. Effects of dam on fish (including aquatic mammals)

Effects of dam on fish (including aquatic mammals) had drawn great attention around the world, and were researched in many studies. The effects include blocking migration route, habitat fragmentation, changing from lotic to lentic water in the impounded area, release of hypolimnetic cold water from reservoirs, and changes of water flow in downstream reaches (Fig. 3 and Table 2).

6.1. *Blocking migration route*

Blocking migration routes (Fig. 4) is one of the key influences of dam on fish and aquatic mammals. Dam blocked upstream migration routes of migration fish and aquatic mammals (such as Striped bass (*Morone saxatilis*), American shad (*Alosa sapidissima*), salmon, Chinese sturgeon (*Acipenser sinensis*), and Chinese paddlefish (*Psephurus gladius*).) (Hilborn, 2013; Mann and Plummer, 2000; Xie, 2003). In general, it would have a negative impact on spawning and cause the decreases in abundance and biodiversity of fish and aquatic mammals throughout the river (particularly upstream reaches of the dam). For example, the dams currently under construction (in the upper Yangtze River) would block migration routes for 35 migration fish species, increase risk of extinction of *Corieus guichenoti*, and reduce the likelihood of successful recruitment of *Acipenser dabryanus* and *Psephurus gladius* (Cheng et al., 2015). In the Mekong River basin, the biggest inland fishery site in the world, the 78 dams on tributaries would have catastrophic impacts on fish biodiversity and productivity (Ziv et al., 2012).

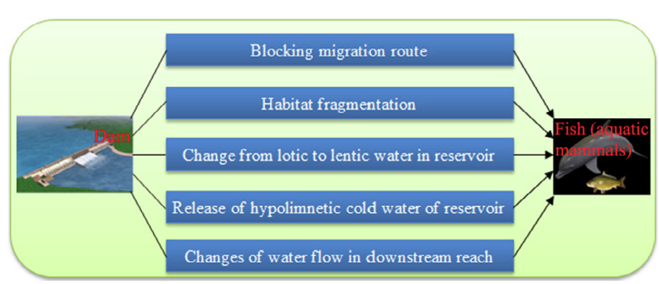

Fig. 3. The effect of dam construction on biodiversity of fish (including aquatic mammals).

Table 2
Effects of dam on fish (including aquatic mammals).

Kind of effects	General effects	Other effects (particular case)
Blocking migration route	Have a negative impact on spawning and cause the decreases in abundance and biodiversity of fish and aquatic mammals	Could increase hydrologic connectivity between upstream and downstream river so to facilitate fish migration when the reservoir flooded natural barriers (such as waterfall)
	Might destroy bi-directional gene flow in the fish populations and develop a new interpopulational structure, with increased risk of reduced genetic diversity and stochastic extinction	
Habitat fragmentation	Would cause fragmentation of fish populations, with larger stream fragments supporting larger fish populations which has greater range of fish sizes and higher species diversity	
	Many effects occur gradually over several generations rather than immediately	
Change from lotic to lentic water in the impounded area	Affects fish growth, population and assemblage structures in the impounded area	
	Lentic adapted species would colonise the reservoir, fish species richness usually increases immediately after reservoir's formation	Fish richness in the impounded area would decreases as reservoirs age
	Would cause the loss of spawning grounds and habitats in the impounded area due to flooding	
Release of hypolimnetic cold water of reservoir	Would delay and reduce upstream migration, inhibit fish spawning and embryonic development, weaken growth and swimming performance, decrease survival of early life stages, and affect fish assemblage structures and biodiversity	
Changes of water flow in downstream reaches	Affect fish spawning, swimming, upstream migrant, digging and other behaviors, and also have an impact (generally a negative impact) on the population and structure of fish assemblage	

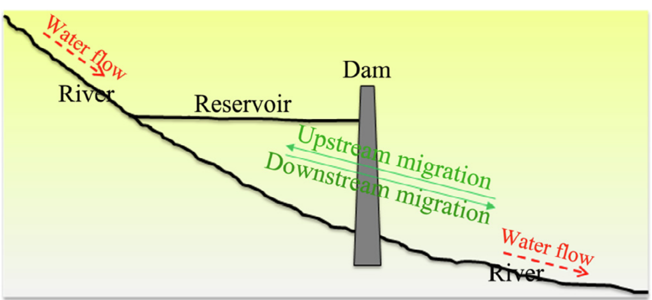

Fig. 4. The blocking of migration routes of migration fish. Solid arrow: the direction of migration; Dashed arrow: the direction of water flow.

Besides, blocking migration routes might destroy bi-directional gene flow in the fish populations and develop a new interpopulational structure, with increased risk of reduced genetic diversity and stochastic extinction (Esguícero and Arcifa, 2009; Winans et al., 2014). For instance, segregation caused by the Gavião Peixoto Dam had led to fragmentation and interpopulational structuring of *Salminus hilarii* (Esguícero and Arcifa, 2009). Furthermore, different types of dams also lead to different levels of blockade of migration routes. For example, low-head dams had lower blocking efficiency (because bottom release gates may allow fish passage under some conditions) than that of high-head dams (Zigler et al., 2004).

Although almost all researches supported that dam blocked migration routes of migration fish and aquatic mammals, in a particular case, dam could increase hydrologic connectivity and migration fish between the upper and lower river when the reservoir flooded natural barriers (such as waterfall) (Fukushima et al., 2014; Vitule et al., 2012). For example, in the Paraná River (south-eastern South America), the Itaipu reservoir flooded a natural barrier and caused the functional homogenization of large-bodied *Siluriformes* (catfish) (Vitule et al., 2012).

In contrast many studies focused on blocking of upstream migration routes, there were few studies focused on blocking of downstream migration routes. The impacts of large dam construction on downstream migration (Fig. 4) of fish (and aquatic mammals) and its technical solutions need further study. The blocking of downstream migration routes was easy to overlook, because discharge of dam can help fish to move through it (particularly the low-head dams) to downstream regions (Pracheil et al., 2015). However, recent studies indicated that downstream passage of adults and young fish is nil or minimal with large dams (Pelicice et al., 2015). This was because large reservoirs forced a different kind of barrier to migratory fish: impoundment created diffuse gradients of hydraulic/limnological conditions and was an extensive environmental filter (discourages downstream movements), and there is no technical solution to solve this problem (Pelicice et al., 2015). Besides, Multiple blockings of downstream migration routes (caused by dam) was believed to reduce the subsequent survival of Chinook salmon in Snake River, but the existing research had not found any evidence to support this viewpoint (Rechisky et al., 2013).

6.2. Habitat fragmentation

Habitat fragmentation is one of the most serious impacts of dam construction (particularly multiple dams cascade) (Kitanishi et al., 2012; Morita et al., 2009). This is because that larger stream fragments support a greater range of fish sizes, more abundant populations, and higher species diversity (Cooper et al., 2016; McCluney et al., 2014; Musil et al., 2012). For example, Redhorse (*Moxostoma spp.*) species richness was positively correlated to river fragment size in Canada, and they were absent from the highly fragmented river (Reid et al., 2006).

Habitat fragmentation would cause fragmentation of fish populations. For example, the dams currently under construction in the upper Yangtze River would fragment the populations of 134 species (Cheng et al., 2015). Habitat fragmentation would also cause ongoing loss of alleles, which negatively impacts genetic structure (Kitanishi et al., 2012). Besides, Many effects of habitat fragmentation caused by dam construction occur gradually over several generations rather than immediately (Morita et al., 2009).

6.3. Change from lotic to lentic water in the impounded area

In the impounded area, the main influence of dam construction on fish is the change from lotic to lentic water, which affects fish growth, population and assemblage structures (Pelicice et al., 2015; Sá-Oliveira et al., 2015). For example, *Cyprinella venusta* inhabiting reservoir had a deeper body, smaller head, a shorter dorsal fin base, a more ventral eye position and a more anterior dorsal fin than that in stream, and the *Cyprinella venusta* shape in reservoirs is significantly correlated with reservoir size (Haas et al., 2010). *Labeobarbus aeneus* exhibited slow growth, delayed maturity and longevity, most likely resulting in slow population growth rates in reservoir (Ellender et al., 2016).

For fish assemblage structures, lentic adapted species (such as Hoplosternum littorale and Hoplias malabaricus) would colonise the reservoir, thus fish species richness usually increased immediately after reservoir formation (Agostinho et al., 2008; Cooper et al., 2016). However, fish richness would decrease as reservoirs age (Agostinho et al., 2008).

Besides, change from lotic to lentic water in the impounded area would generally cause the loss of spawning grounds and habitats of some species due to flooding. For example, 4 spawning grounds for the grass carp, black carp, silver carp and bighead carp in the Ganjiang River (in China) were flooded and lost after the construction of the Wan'an Dam (Hu et al., 2014); and critical habitats for 46 endemic species would lost due to the impoundments of several adjacent dams in the upper Yangtze River (Cheng et al., 2015).

6.4. Release of hypolimnetic cold water of reservoir

Release of hypolimnetic cold water of reservoir is also one of the impacts imposed by dams. In general, it would delay and reduce upstream migration, inhibit fish spawning and embryonic development, weaken growth and swimming performance, decrease survival of early life stages (Clarkson and Childs, 2000), and affect fish assemblage structures and biodiversity (Cooper et al., 2016). For example, in the first 34 km section immediately downstream from the Três Marias dam, *Astyanax fasciatus* and *Astyanax bimaculatus* were less abundant and the females had smaller body weight, total length, gonadosomatic index and fecundity values than those in 34–54 km section downstream from the dam, which were consistent with the changes of water temperature (Normando et al., 2013). The low water temperatures associated with hypolimnetic discharges of dams in the upper Yangtze River would postpone the start of annual spawning for 13 fish species by more than 1 month, and decrease fish spawning and growth opportunities (Cheng et al., 2015). And the introduction of selective withdrawal abilities to access near-surface water maybe is an effective resolution for the release of hypolimnetic cold water of reservoir (Sherman et al., 2007).

6.5. Changes of water flow in downstream reaches

Changes of water flow in downstream reaches is anothor impact imposed by dams. It would affect fish spawning, swimming, upstream migrant, digging and other behaviors, and also have an impact (generally a negative impact) on the population and structure of fish assemblage (Tiffan et al., 2009; Wang et al., 2014a; Welsh et al., 2016). For example, a discharge that is too large or small had a negative impact on carps spawning (Yi et al., 2010); Change of the flow, caused by several adjacent dams in the upper Yangtze River, had a negative impact on the recruitment of 26 species which have drifting eggs (Cheng et al., 2015). In general, natural flood pulses (including rise rate and duration of flow increase) are important to maintaining the persistence of fish populations (Gubiani et al., 2007; Wang et al., 2014a). Besides, this problem can be minimized through altering fluctuations of dam discharge (Harnish et al., 2014).

In total, the studies about the effects of dam on fish (including aquatic mammals) took up 50% of the total number of studies about the effects of dam on biodiversity (Fig. 2). But three types of research are obviously lacking in this field: 1) the impacts of large dam construction on downstream migration of fish (and aquatic mammals) and its technical solutions need further study; 2) the combined or long-term influences of dam construction (especially cascading dams) on fish (including aquatic mammals) should be given more attentions; and 3) there is need for more studies which completed by comparing the key statistics before and after dam construction, rather than by comparing key statistics of the rivers with dams and rivers without dams.

7. Effects of dam on botany

The effects of dam on botany, which is sensitive to the changes of hydrological period, caused worldwide extensive concern because botany could provide food and habitat to microorganisms, benthos, plankton, fish, animals and birds (Chen et al., 2015b; Wu et al., 2017a). Many studies, which are listed in the Table 3, reported the effects of dam on plants in reservoir area, downstream channel and downstream lake.

7.1. Botany in reservoir area

As shown in Fig. 5, there are four kind effects on plants in reservoir area: 1) dam operation caused the submerging of most surrounding land, and also made the distribution of plants have the characteristic of sub-lacustrine habitat (Ceschin et al., 2015); 2) the species diversity and functional richness were significantly decreased (compared to the former riparian zone) (Liu et al., 2013; Wang et al., 2014b). For example, the number of vascular plant species in Three Gorges reservoir decreased from 175 to 127 after the full impoundment (Wang et al., 2014b); 3) the relative species number and relative cover were both negatively related to elevation and slope (Liu et al., 2013); and 4) apart from the immediate habitat loss caused by the building of dams, habitat fragmentation and persistent edge effects associated with dams also had large negative influences on animal–plant mutualistic networks (Emer et al., 2013).

7.2. Botany in downstream channel

In downstream channel, dam generally caused the expanding of herbaceous plant (such as reed and grass) to mudflat/water zone in lower altitude locality (because the boundary of inundated region generally moves down towards the thalweg due to incision processes) (Bombino et al., 2014), and recruitment of macrophanerophyte (such as cottonwood) was suppressed in higher altitude locality, where riparian vegetation tends to a terrestrial character (Bombino et al., 2014; Burke et al., 2009). Besides, another study also found dam could decrease riparian plant species richness by cutting off hydrochory (plant dispersal by water) of propagules (Merritt et al., 2010).

7.3. Botany in downstream lake

The lake wetlands, especially the large lake wetlands, are biodiversity hotspots around the world. In downstream lake, dam generally caused the expanding of riparian vegetation to mudflat/water zone (Feng et al., 2016; Wu et al., 2017a). For example, early

Table 3
Studies about the effects of dam on botany. In this table, riparian plants include emerged plants, because of some same species of them.

Study area	Species	Reference
Reservoir area	Riparian plants	Ceschin et al. (2015); Cunha and Ferreira (2012); Denneler et al. (2008); Doubek and Carey (2017); Emer et al. (2013); Keken et al. (2015); Kellogg and Zhou (2014); Li et al. (2012); Liu et al., 2013; Moser et al. (2014); New and Xie (2008); Silva et al. (2017); Su et al. (2012), 2013; Tombolini et al. (2014); Urruth et al. (2017); Wang et al. (2014b); Xiao et al. (2015); Zhang et al. (2017b)
	Floating plants	No studies
	Submerged macrophyte	No studies
Downstream channel	Riparian plants	Asaeda and Rashid (2012); Benjankar et al. (2012); Bombino et al. (2014); Brown and Chenoweth (2008); Burke et al. (2009); Casado et al. (2016); dos Santos Junior et al. (2012); Douglas et al. (2016); Egger et al. (2012); Ferreira et al. (2013); Gordon and Meentemeyer (2006); Herbison and Rood (2015); Johnson and Waller (2013); Li et al. (2012); Liu et al., 2013; Lucas et al. (2016); Mallik and Richardson (2009); Merritt et al. (2010); Moser et al. (2014); Nakamura et al. (2017); Rood et al. (2009); Sitzia et al. (2016); Takahashi and Nakamura (2010); Tealdi et al. (2011)
	Floating plants	No studies
	Submerged macrophyte	Benítez-Mora and Camargo (2014); Głowacki et al. (2011)
Downstream lake	Riparian plants	Fang et al. (2006); Feng et al. (2016); Liu et al. (2016); Shi et al. (2017); Wang et al. (2007); Wu et al. (2017a); Xie et al. (2015)
	Floating plants	No studies
	Submerged macrophyte	No studies

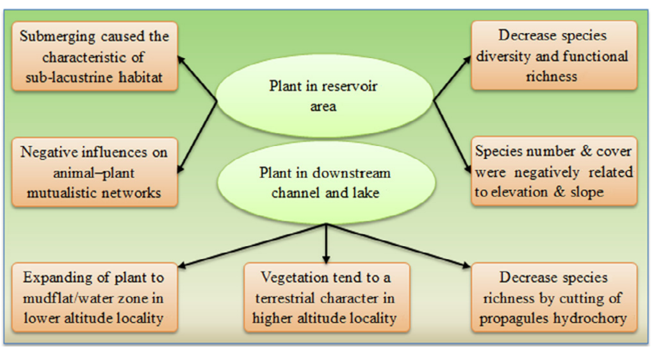

Fig. 5. Effects of dam on plant in reservoir area and downstream channel and lake.

dry season in Dongting Lake caused expanding of *Carex* to *Phalaris* zone, and *Phalaris* to mudflat zone, while that in Poyang Lake caused expanding of *Phalaris* to mudflat zone after the impoundment of Three-Gorges Dam (Wu et al., 2017a). In the Nanjishan Wetland National Nature Reserve of the Poyang Lake, approximately 30% of total area changed from water to emerged vegetation during 2003–2014, and the changes in the Normalized Difference Vegetation Index also showed that the vegetation in the center regions flourished in dry seasons, while vegetation in the off-water areas was stressed (Feng et al., 2016). Few studies about the effects of dam construction on floating plants and submerged macrophyte were found in this field.

From Table 3, we could found that most of studies in the research field of effects of dam construction on botany focused on the riparian plants. And there were few studies about the effects of dam construction on aquatic botany (especially floating plants and submerged macrophyte), which have become an important food resource, refuge or nesting habitats for aquatic fauna (Ceschin et al., 2015). Besides, the studies about the effects of dam construction on botany in downstream lake wetlands were also insufficient, although lake wetlands (especially large lake wetlands) are biodiversity hotspots around the world.

8. Effects of dam on bird

Damming could cause changes in plants and other biology, which provided habitat and food to birds, and further affect population and diversity of birds (Wu et al., 2017a). However, there were only few studies looked at this effects of dam on bird. The existing research found reservoir was a vital staging and wintering area for geese, ducks, grebes, gulls, cormorants, waders and coots (Ali et al., 2011), but reservoir could decrease the absolute abundance of former steppe birds in winter and breeding seasons (more evident in the breeding season) (Figueiredo and Pereira, 2009). There was also a study which claimed that birds were sensitive to hydrological change and also were affected by dam operation for this reason (Wang et al., 2013). Wetlands are important for birds, about half of the endangered bird species of China live in wetland ecosystems (Fang et al., 2006; Seuring and Muller, 2008). However, the research in this field is very inadequate, especially on the effects of dam on migratory birds.

9. Conclusion and future research

Wetlands (rivers, lakes, bogs, etc.), the biodiversity hotspots, provide habitats for biology on the earth and play an important role in biodiversity protection. However, they are damaged by dam construction around the world. Little is known about the comprehensive effects of dam construction around the world on biodiversity, and the review about it is also missing. Dam construction could affect the biodiversity of microorganisms, benthos, plankton, fish (including aquatic mammals), botany and birds. Dam construction decreased the water fungal biomass and richness in reservoirs and downstream reaches, but increased the soil microorganisms in downstream lake wetlands. The studies about effects of dam on benthos mainly focused on macroinvertebrate, periphyton and mussel. Most study about the effect on macroinvertebrate found that dam construction caused increases in biomass and decreases in taxa richness in downstream reaches. The studies about effects of dam on plankton mainly focused on phytoplankton, zooplankton, planktonic microorganisms and ichthyoplankton. And more attention should be given to effects of dam on plankton for its relationship with eutrophication. Effects of dam on fish (including aquatic mammals) included blocking migration route, habitat fragmentation, changing from lotic to lentic water in the impounded area, release of hypolimnetic cold water of reservoir, and changes of water flow in downstream reaches. Studies about effects of dam construction on botany mainly focused on the riparian plants, but there were few studies on floating plants and submerged macrophyte and effects of dam construction on botany in downstream lake wetlands. There were only few studies which studied the effects of dam on bird. The studies about of effects on microorganisms and birds are sorely lacking.

Based on the above reviews, following is recommended for the future research.

1. The combined or long-term influences of dam construction on biodiversity need further research, and the existing researches mainly focus on the influences of one aspect of blocking migration route, habitat fragmentation, changings in flows, temperature, water quality, sediments regime, substrate, food availability and other water physicochemical parameters in reservoirs and downstream reaches, and short-term influences.
2. Effects of cascading dams should be given more attention. The effects of cascading dams on aquatic biology and ecosystem were more complex and serious than the effects of single dam. However, there are few studies focusing on the effects of cascading dams.
3. Many studies were completed by comparing the rivers with dams and rivers without dams. The other factors, between rivers with dams and rivers without dams, can affect the authenticity of the results. Therefore, there is need for more studies which are completed by comparing the river before and after dam construction.
4. The blocking of downstream migration routes of fish (including aquatic mammals), caused by dam construction, and its solutions need further study.
5. The ecological flow regime, fishway and other measures for protection of biodiversity need further study to reduce the environmental impact of dams.
6. The effects of dam construction on floating plants and submerged macrophyte in wetlands, and aquatic botany in lake wetlands need further study.
7. The effects of dam construction on microorganisms and birds need further study.

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