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Effects of dams on riverine biogeochemical cycling and ecology

Fushun Wang[1]*, Stephen C. Maberly[2], Baoli Wang[3]*, Xia Liang[1]

[1]School of Environmental and Chemical Engineering, Shanghai University, Shanghai 200444, China

[2]Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Lancaster LA1 4AP, United Kingdom.

[3]Institute of Surface-Earth System Sciences, Tianjin University, Tianjin 300072, China

*Corresponding author: fswang@shu.edu.cn and baoli.wang@tju.edu.cn

Fushun Wang：

Address: School of Environmental and Chemical Engineering, Shanghai University, P.O. Box 144, 99 Shangda Road, Baoshan, Shanghai, 200444, China;

Phone: +86-21-66137502;

Fax: +86-21-66137787;

Email: fswang@shu.edu.cn

Baoli Wang：

Institute of Surface-Earth System Science Tianjin University, 92 Weijin Road, Nankai District, Tianjin 300072, China

Email: baoli.wang@tju.edu.cn

Abstract

Currently, dam construction is the main and growing global anthropogenic disturbance on rivers. Dams have major effects on the physics, chemistry and biology of the original river including altering water circulation and retention time, sedimentation, nutrient biogeochemical cycling including greenhouse gas emissions, and the amount and composition of the organisms. Among those, the effect of dams on riverine material cycle and ecology is especially concerning because of its close relationship with current global environmental problems such as climate change and ecological deterioration. This review thus mainly focuses on nutrient cycling and ecological changes in a regulated river. In the future, researches on a reservoir-river system should focus on: (1) processes and mechanisms of nutrient biogeochemical cycles; (2) interaction between these processes and ecological change such as phytoplankton succession; (3) developing mathematical functions and models to describe and forecast these processes and their interaction in the future.

Key words: dam; retention time; nutrient; greenhouse gas; ecosystem

1. Introduction

Rivers are the major links connecting the land to the ocean; they deliver fresh water, carbon, energy and nutrients to the estuary and coastal sea (e.g., Humborg et al.,1997; Jiao et al., 2007). Rivers also link the land with the atmosphere, exchanging heat and influencing the regional climate, and exchanging gases, affecting global biogeochemical cycles and the global climate (Lauerwald 2015). In the past decades, with the increasing demands of a growing human population, the natural river has been strongly disturbed by dam construction to generate hydropower, increase water supply and security, control floods, improve navigation and provide opportunities for recreation (Bednarek 2001). Thus, the natural connectance between the land, rivers and the ocean has declined and material cycling has been affected with important consequence for the biology of the altered ecosystems.

However, until the 1970s, the environmental impacts of dams were not widely taken into account. In 1972, the Scientific Committee on Problems of the Environment issued a report of man-made lakes as modified ecosystems (SCOPE Working Group on Man-made Lakes, 1972), which showed earlier concern about the physical, chemical, and biological impacts of dams on the downstream rivers. In 2000, the World Commission on Dams presented another report about dams and development: a framework for decision making (The report of the world commission on dams, 2000). In 2010, the International Hydropower Association proposed the hydropower sustainability assessment protocol. Gradually, the effect of dams on rivers and their connected ecosystems becomes a popular scientific topic (IHA, 2010). The Millennium Ecosystem Assessment noted the dramatic increase in dam construction and consequent water storage to the extent that flows in 60% of the World's large rivers are moderately or strongly affected and also noted some of the negative ecosystem consequences that this has caused (Millennium Ecosystem Assessment 2005).

Generally, dam construction has three consequences: i) altered river hydrological cycle, exacerbated by artificial regulation such as anti-seasonal storage; ii) altered biogeochemical cycles in the impounded river; iii) altered ecological conditions in the discontinuous river-reservoir system. These processes interact with each other, and their influences can have local, regional and global effects. The understanding of these processes is the scientific basis for explaining the environmental impacts of dam construction and producing sustainable management strategies for the impounded river. This brief review mainly focuses on these processes and, in addition, current hot topics about the impounded river are also discussed.

2. Historical and current states of river damming

Modern dam construction began in 1900 and boomed from about 1950 with the use of concrete and innovation of excavation (Fig.1). Currently, approximately 70% of the world's rivers are intercepted by dams (Kummu and Varis 2007), and in China, there were more than 80,000 reservoirs by the end of 2008, among which there were over 5000 dams with a height of over 30 m (http://www.chincold.org.cn). Dams are built to store water for various purposes. Accompanied with the rapid increase of dam construction (from 1948 to 2010), the global active storage capacity of reservoir grew from about 200 to over 5000 km^3, which is over 70% of the total global reservoir capacity (7000-8000 km^3) (Vörösmarty 1997; Zhou et al., 2016). The number of reservoirs will increase in the future with the restart of hydropower loan project by the World Bank (World Bank 2009) and the motivation to increase renewable energy sources (Hermoso 2017).

Globally, the extent of hydropower development is not balanced. In Europe, North America and Central America, more than 70% of the technically feasible hydropower has been utilized, while this value is less than 4% in Africa (Wang and Dong 2003, Home 2005). The developed countries have higher level of hydropower utilization than the developing countries. For example, in China, only about 24% of the hydropower resource has been exploited, much less than the average value of 60% in the developed countries. There are also large regional differences within China: eastern China has exploited 79.6% of its hydropower resources, but southwestern China, which has the richest hydropower resources, has only exploited 8.5% (Liu et al., 2009). With the development of the global economy, especially in the developing countries, it can be expected that the rivers will face large-scale dam construction, and human disturbance will be further intensified on the rivers (Zarfl et al., 2015; Hermoso 2017).

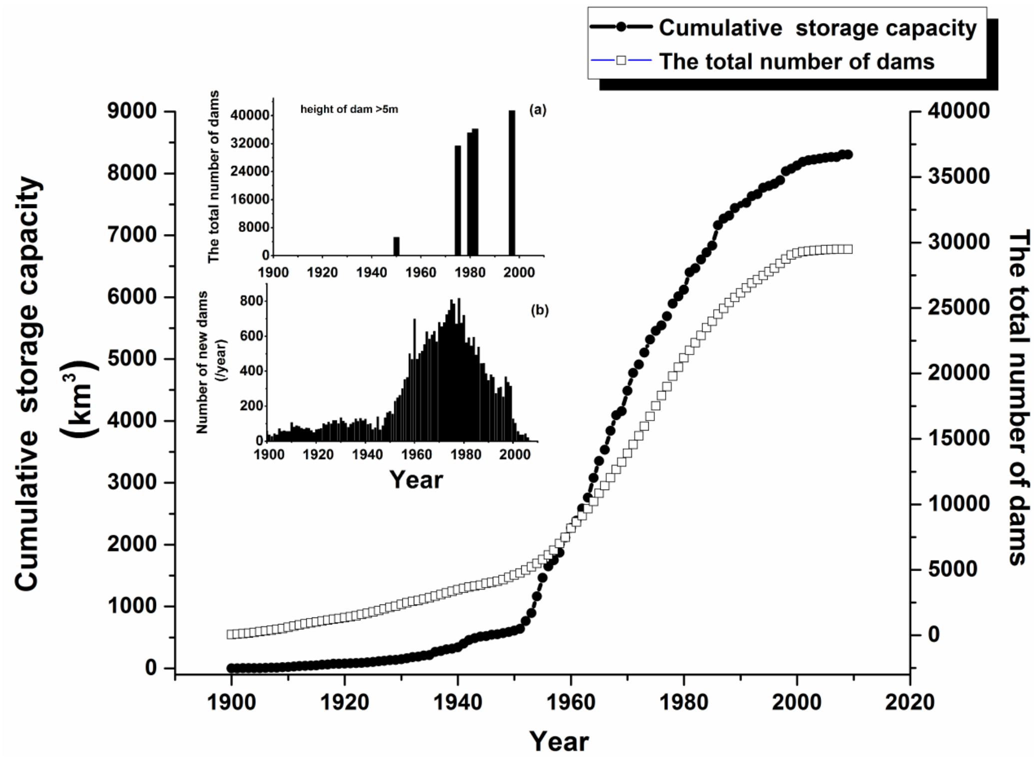

Figure. 1. Historical variation in the number and cumulative storage capacity of reservoirs (modified from (Chao et al., 2008; Jia et al., 2010). (a) Number of dams in the world with a dam height > 5 m (Liu et al., 2009; Jia et al., 2010); (b) The number of new dams constructed in the world each year and (c) The total number of dams and the cumulative storage capacity of reservoirs registered in the ICOLD (Chao et al., 2008).

3. Impacts of river damming on the hydrological cycle and physical characteristics

3.1 Seasonal thermal stratification

Reservoir stratification conforms to the classical pattern of lake stratification especially hydroelectric reservoirs that are usually deep and thus usually develop seasonal thermal stratification. The densimetric Froude Number (F) has been suggested to estimate the stratification tendencies in a reservoir (Ledec and Quintero 2003). The stratification is expected when F is less than 1, the severity of which increases with a smaller F; while when F is greater than 1, stratification is not likely. For hydroelectric reservoirs, the extent of thermal stratification is influenced by the pattern and extent of water storage and discharge (Fig. 2). One consequence of thermal stratification is that if water is released from the bottom of the reservoir during stratification it will be very different to that at the surface with potential effects on the downstream river for tens of kilometers (Petts 1984). It has been suggested that this problem could be eliminated by artificially destroying thermal stratification (Lackey 1972; Elçi2008), or by releasing water from the surface or sub-surface.

A reservoir can also have an effect on the downstream river temperature with consequences for biogeochemical cycling and river ecology and particularly fish populations. In general, water released from the bottom of a reservoir will be cooler than it would be without the reservoir while water released from the surface of the reservoir will be warmer. However, in addition, reservoirs also dampen the temperature cycle at seasonal, daily and sub-daily timescales and, in a study of Canadian reservoirs, increased the mean water temperature in September (Maheu et al., 2016).

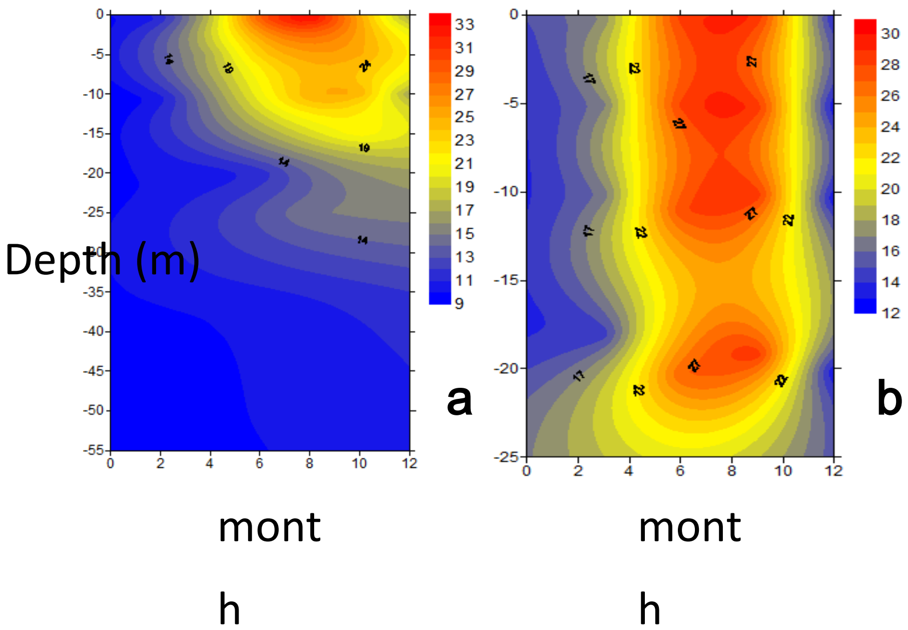

Figure. 2. Thermal stratification in different reservoirs (unpublished data).(a) The Xinanjiang Reservoir with a water retention time greater than one year; (b) The Wanan Reservoir with a water retention time less than two weeks.

3.2 Storage pattern

Artificial regulation of reservoir water, such as storing or releasing water, changes the flood pulse of the original river, affects the water balance of the basin and the hydrological condition of the river bank（Liu et al., 2009）. After interception by a dam, a significant reduction in the maximum flow is found in the downstream river (Fig. 3a). In addition, large and medium-sized reservoirs often have anti-seasonal storage to reduce reservoir water level in flood season to cope with flood peaks (e.g., Fig. 3b). This is totally different from a lake; where water level changes corresponding to the input or river water minus evaporation. When cascade reservoirs are constructed, competitive water storage among the reservoirs will occur. This will enhance the disadvantage of requirement of water in the downstream reaches of the river.

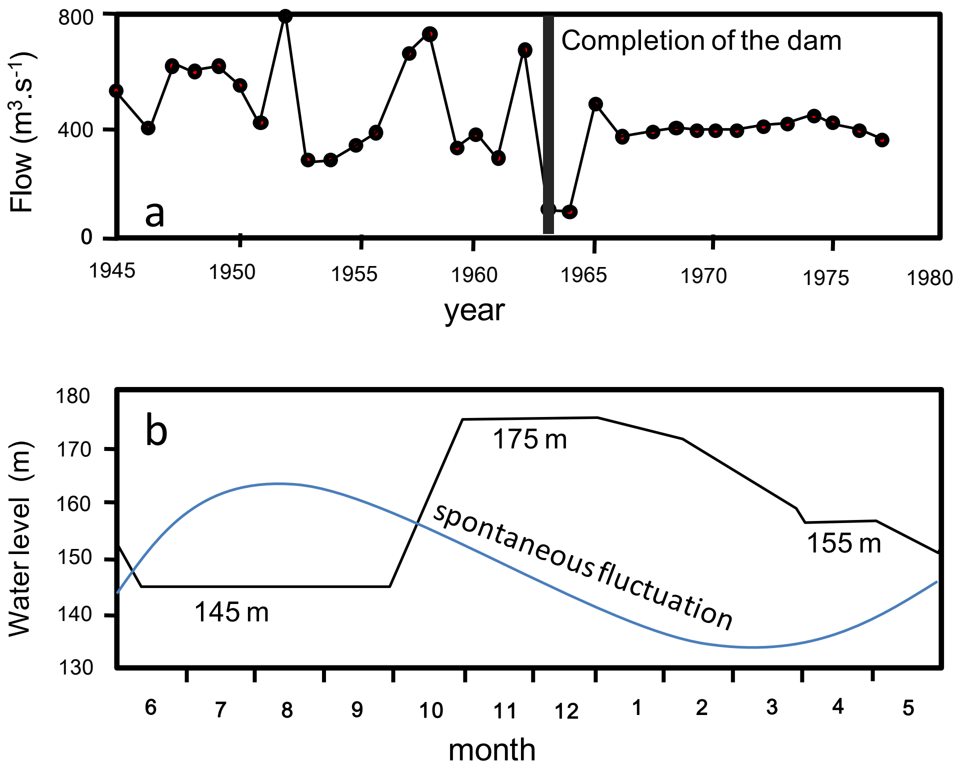

Figure. 3. Changes in river flow and water level after river damming. (a) Effects of an upstream reservoir (Lake Powell) on the maximum annual flow of downstream (Modified from Thornton et al., 1996). (b) Water level change after the Three Gorge Reservoir closure.

3.3 Hydrological retention time

Dam construction obviously changes the retention time of the corresponding river. Within one reservoir, the retention time can vary between one day and several years, greatly prolonging that of the natural river. For continental runoff in free-running river channels, the average residence time varies from <16 to 26 days, while the discharge weighted global average value is almost 60 days (Vörösmarty and Sahagian 2000). In some strongly regulated river basins, the value can be higher. For example, the water retention time of the Huanghe River (upstream of Lijin station, i.e. the whole basin taking into account the 2816 reservoirs), increased from one year to 4 years after dam construction, ranking the Yellow River in the top three in terms of residence time and flow regulation among large river systems in the world (Ran and Lu 2012). The increase of the water retention time has a profound effect on the reservoir thermal stratification, riverine elemental cycle, and phytoplankton ecology (e.g., Duras and Hejzlar 2001; Soares et al., 2012).

4. Effect of dams on riverine material cycling

4.1 Sedimentation

Sedimentation within reservoirs is a complex process. The sediment load delivered to the reservoir is controlled by the sediment yield in a basin, and reservoir sedimentation is mainly influenced by the hydraulics of the river, the geometry of the reservoir and ratio at the entrance to reservoir (width to depth ratio). The distribution of sediment types in a reservoir is shown in Table 1. The reduction in downstream sediment load by reservoir construction may be greater than 75%, as seen in the case studies of Sao Francisco River in Brazil, the Chao Phraya River in Thailand, and the Yellow River in China (Walling 2006). Kummu and Varis (2007) reported that the operation of dams on the Mekhong main channel had approximately halved the sedimentation from 150-170×10^9 to 81×10^9 kg annually. The magnitude of global suspended sediment flux to the ocean is still unclear and has been estimated to be in the range of 9.3 Gtyr^{-1} (Judson 1968), to more than 58 Gtyr^{-1} (Holeman1968) with recent studies converging around 15-20 Gtyr^{-1}(e.g.,Milliman and Meade 1983; Meybeck 1988; Ludwig et al., 1996; Vörösmarty et al., 2003).

Table 1 A typical distribution of deposited sediment in a reservoir (USACE 1987**)**.

Particle size	Inlet (%)	Mid-reservoir (%)	Outlet (%)
Sand	5	<1	0
Silt	76	61	51
clay	19	38	49

4.2 Nutrient retention

The geochemical behaviors of nutrient elements such carbon (C), nitrogen (N), silicon (Si), and phosphorus (P) are obviously influenced by dam construction. After damming a river, particulate nutrients are partially impounded and their fluxes through the river thus decrease.

In addition, biological activity such as photosynthesis and respiration modifies the dissolved nutrient content and species in the reservoir. These modified nutrients are then transported to the downstream river, and finally influence the ecosystem of the estuary and marginal sea (e.g., Humborg et al., 1997; Jiao et al., 2007).

The first concern on the consequences of dams on nutrient retention was about Si. Dam construction resulted in a great deal of Si retention and a significant decrease in the flux of dissolved Si (DSi) to the sea (Humborg et al., 1997, 2006; Wang et al., 2010; Maavara et al., 2014). At the global scale, the retention of DSi in lakes and reservoirs is 163 Gmol yr^{-1} (9.8 Tg SiO_2 yr^{-1}), and the total active Si retained is 372 Gmol yr^{-1} (22.3 Tg SiO_2 yr^{-1}) (Maavara et al., 2014).

Recently, Maavara et al.(2015, 2017) estimated the global P and organic C (OC) retention by river damming. Total P (TP) trapped in the global reservoirs was estimated to be 22 Gmol yr^{-1}in 1970 and 42 Gmol yr^{-1} in 2000, and active P was 9 Gmol yr^{-1}in 1970 and 18 Gmol yr^{-1} in 2000; however, the global river TP load to the ocean in the same period, only changed from 312 to 349 Gmol yr^{-1} (Maavara et al., 2015). The rapid increase of total and active P retention was mainly caused by the rapid expansion of dam construction between 1970 and 2000, and the volume of reservoirs increased from about 3,000 in 1970 to almost 6,000 km^3 in 2000 (Lehner et al., 2011). By 2030, about 17% of the global river TP load will be sequestered in reservoir sediments, and the main increase is from Asia and South America, especially in the Yangtze, Mekong, and Amazon drainage basins (Maavara et al., 2015). As for global OC, its mineralization in reservoirs exceeds C fixation, and about 75% of OC in reservoir sediments is allochthonous. OC burial in reservoirs is estimated to be about 4.3 Tmol yr^{-1} by 2030, a fourfold increase relative to 1970, and OC mineralization is around 2.6 Tmol yr^{-1} in the same time. The total value (6.9 Tmol yr^{-1}) accounts for about 19% of total OC carried by rivers to the oceans by 2030 (Maavara et al., 2017). Comparatively little is known about N retention in impounded rivers, perhaps because of the more complex N cycle in the reservoir-river system. A case study in a regulated Mediterranean river indicated that river reaches below dams acted as net sinks of total dissolved N, unlike dissolved P or OC, and this high net uptake by organisms (autotrophs and heterotrophs) below dams could reduce N export to downstream ecosystems (von Schiller et al., 2016).

4.3 Greenhouse gas emissions

Reservoir greenhouse gases (GHGs) based on carbon, CO_2 and CH_4, are derived from OC mineralized in the reservoir or direct input of CO_2 produced in the catchment (Maberly et al., 2013), and their emission occurs by diffusion across the air-water interface and, especially for CH_4, ebullition. GHG production and emission fluxes from a reservoir are closely related to reservoir age, latitude, and retention time (Barros et al., 2011; Ometto et al., 2013; Wang et al., 2015; Deemer et al., 2016). The reservoir surface is usually dominated by the diffusive flux of CO_2, even in cases in which bottom anoxia leads to high CH_4 production because of conversion of upwardly-diffusing CH_4 to CO_2 by methanotrophic bacteria. However, when water is released from the bottom of the dam, CH_4 emissions can be very high. It is suggested that this source contributes 50 to 90% of total CH_4 emissions from tropical or temperate hydroelectric reservoirs (Abril et al., 2005; Kemenes et al., 2007; Maeck et al., 2013).

Rates of surface diffusion of GHGs among reservoirs have been shown to vary along broad geographic gradients, low-latitude tropical reservoirs typically emitting GHGs at greater rates per unit area than high-latitude temperate and boreal reservoirs (Barros et al., 2011). Average emissions of 3500 mg m^{-2} d^{-1} of CO_2 and 300 mg m^{-2} d^{-1} of CH_4, have been found in tropical reservoirs compared to 387~1400 mg CO_2 m^{-2} d^{-1} and 2.8~55 mg CH_4 m^{-2} d^{-1} from temperature reservoirs (mostly hydroelectric reservoirs) (St. Louis et al., 2000; Soumis et al., 2005; Lima et al., 2008; Barros et al., 2011). Chanudet et al. (2011) estimated diffusive fluxes to the atmosphere from two Southeast Asian sub-tropical reservoirs to be -466~1680 mg m^{-2} d^{-1} for CO_2 and 12.8~190 mg m^{-2} d^{-1} for CH_4, comparable to other tropical reservoirs. Few studies have focused on reservoir N_2O emission. A case study in the Wujiang cascade reservoirs showed that the average flux of N_2O emission from the reservoir surface was about 0.64 μmol m^{-2} h^{-1}, comparatively to the natural lake (Liu et al., 2011).

It has been estimated that hydropower reservoirs account for 30%- 62% of all reservoirs globally (Lehner et al., 2011; Varis et al., 2012). Lima et al. (2008) first estimated that CH_4 emission from the global hydroelectric reservoirs are 100 Tg CH_4-C yr^{-1}; however, Barros et al. (2011) suggested this value was 3 Tg CH_4-C yr^{-1}, with CO_2 emission of 48 Tg CO_2-C yr^{-1} in the hydroelectric reservoirs. While the values from Herwich (2013) were 76 Tg CO_2-C yr^{-1} and 7.3 Tg CH_4-C yr^{-1}, respectively. The large range in published estimates could be caused by the different estimate of global reservoir surface (Mendonça et al., 2012; Teodoru et al., 2012; Mosher et al., 2015). Perhaps high heterogeneity of CO_2 and CH_4 fluxes along the long and narrow reservoirs also contributes to these differences.

5. Effect of dams on riverine ecology

5.1 River continuum concept

The river continuum concept (RCC) describes the longitudinal gradient of physical conditions such as geomorphological and hydrological factors in pristine rivers (Vannote et al., 1980; Tornwall et al., 2015). Biological communities are adapted to these gradients, and vary along the river from the headwaters to the mouth in a predictable manner. The headwater regime is strongly heterotrophic (the ratio of photosynthesis to respiration (P/R) <1), and has coarse particular matter and invertivores as the main biological species. The mid-regime is autotrophic (P/R>1), and has fine particular matter and piscivorous, invertivorous, and planktivorous species. Finally, the downstream regime gradually return to heterotrophy due to turbidity (Fisher 1977; Vannote et al., 1980). Dams interrupt the river continuum altering geomorphology, water quality, temperature regime, and flow regime, and result in upstream–downstream shifts in biotic and abiotic patterns and processes. The serial discontinuity concept (SDC) views impoundments as major disruptions to longitudinal resource gradients along river courses (Ward and Stanford 1983, 1995). The impacts under impoundment have been studied with respect to geomorphology, temperature, flow, invertebrates, and fish (e.g. Kondolf 1997; Jakob et al., 2003; Poff and Zimmerman 2010; Jones 2011; Winemiller et al., 2017). Usually, periphyton biomass recovers quickly within 5 km downstream, while benthic invertebrate richness varies considerably, with both increases and reductions observed at near-dam sites and varying in recovery downstream (Ellis and Jones 2013, 2016).

5.2 Phytoplankton

As the main primary producers, river phytoplankton succession after damming is an important issue. Dams can result in major changes in the phytoplankton community in the river, estuary and adjacent sea (e.g., Humborg et al.,1997; Jiao et al., 2007). In a river-reservoir unit, the dominant Bacillariophyta (diatoms) in river water changes to co-existing Bacillariophyta, Chlorophyta (green algae), and Cyanophyta (blue-green algae) in mesotrophic reservoirs, and then shifts to dominance by Cyanophyta in eutrophic reservoirs (Wang et al., 2013). Phytoplankton succession in the impounded river is not directly caused by the physical obstruction of the dam, but can be attributed to changes in hydrological and geochemical conditions after damming. For example, phytoplankton community succession in karst cascading reservoirs was influenced by Si and P stoichiometry (Wang et al., 2014a), while in a tributary of the Three Gorges Reservoir, phytoplankton diversity was controlled by hydraulic retention time and nutrient limitation (Xiao et al., 2016). Phytoplankton dynamics in the impounded river is non-linear, and the mechanisms responsible need further research. Generally, the study of the effects of dams on riverine ecology is still at an initial stage, especially in the aspect of the coupling of ecological shifts and nutrient biogeochemical cycle.

5.3 Fish

The effect of dams on fish ecology (e.g. spawning, migration, and diversity) has always been a concern. Globally, dam obstruction decreases fish biodiversity, and taxa such as lampreys (*Lampetra* spp.), eels (*Anguilla* spp.), and shads (*Alosa* spp.) are at particular risk of species loss (Fu et al., 2003; Liermann et al., 2012). Regionally, the construction of the Three Gorges Reservoir, for example, resulted in a substantial decline in carp larval abundance of the middle Yangtze River (Wang et al., 2014b).

6. Perspectives

The construction of dams for various purposes, but particularly hydropower, is booming (Zarfl et al., 2015) and is likely to accelerate further. Given the complex interactions between land, rivers, the estuary and the atmosphere, the consequences of dam building will inevitably have complex knock-on, ecological and social effects. International initiatives such as the Paris Agreement reached at the COP21 in December 2015 are encouraging countries to move towards a greater reliance on renewable energy production. Hydropower currently accounts for more than 80% of renewable energy (Zarfl et al., 2015). Hermoso (2017) pointed out that while this might prove beneficial for global carbon emissions it would be likely to prove detrimental to local freshwater ecosystems and consequently there is a requirement for international guidance and legislation in order to evaluate the benefits of construction of a new dam compared to the ecological and societal costs. For example, proposals to increase dam construction on the Amazon River led Latrubesse et al. (2017) to introduce a 'Dam Environmental Vulnerability Index' based on: (1) the vulnerability of the basin to run-off and erosion that may transport nutrients and pollutants to the river, (2) modification to the hydrological regime and transport of sediment, (3) quantification of the extent of the river system affected. Clearly, there is a growing and urgent need for robust scientific evidence to make this kind of evaluation. Currently, while numerous case-studies exist at specific sites, it is difficult to take account of regional heterogeneity in conditions in order to produce advice at a global scale. In the area of the role of reservoirs in global biogeochemical cycling, future research should focus on the following aspects: (1) processes and mechanisms of nutrient biogeochemical cycles; (2) coupling these cycles with ecological conditions such as phytoplankton succession; (3) developing mathematical functions and models to describe and forecast these processes and their interaction in the future

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