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Jingan Chen
Chinese Academy of Sciences

Jingfu Wang
Chinese Academy of Sciences

Jianyang Guo
Chinese Academy of Sciences

Yan Zeng
Chinese Academy of Sciences

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Jingan Chen
Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China

Jingfu Wang
Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China

Jianyang Guo
Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China

Jia Yu
Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China; University of Chinese Academy of Sciences, Beijing, China

Yan Zeng
Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China

Haiquan Yang
Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China; University of Chinese Academy of Sciences, Beijing, China

Runyu Zhang
Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China

Abstract

China is home to 97,246 reservoirs, most of which are sub-deep water reservoirs characterized by seasonal stratification and multiple interfaces in the water body. The prominent eco-environmental problems, such as eutrophication and accidental deterioration in water quality, restrict reservoir construction. Compared to natural lakes, reservoirs have specific geologic backgrounds and eco-environmental characteristics, which manifest in the following aspects: (a) the origin of the water environment and ecological system of the reservoir is different from natural lakes; (b) sediment is rich in organic matter and nutrients; (c) water eutrophication and heavy metal pollution are tightly interlocked; (d) multi-interface and seasonal stratification control the key physicochemical and biological processes; (e) the cumulative effect of the material cycle has an important influence on the water environment and ecological security; (f) artificial regulation of water level leads to the ecological degradation of the hydro-fluctuation belt; and (g) the slow response of the aquatic ecosystem to the reduction of external load. Research on the eco-environment of sub-deep water reservoirs

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Corresponding author:
Jingan Chen, State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China.
Email: chenjingan@skleg.ac.cn

trails that of natural lakes in China. After describing the eco-environmental characteristics of reservoirs in China, we address potential challenges and propose future research directions to develop a full understanding of the complex biogeochemical processes prevalent in reservoirs.

Keywords
Reservoir, eco-environment, prospects, China

I Introduction

Shortages of energy and water resources, which were once primary barriers impeding the development of China, motivated the Chinese government to construct more dams and reservoirs. According to the first national census for water sources, there have been 97,246 reservoirs built in China as of 2011, with a total storage capacity more than 8.1×10^{11} m^3 (http://www.mwr.gov.cn). Meanwhile, the number of big dams in China has reached 23,842 accounting for almost half of the registered big dams worldwide (http://www.icold-cigb.org). Moreover, the number of reservoirs in China is still increasing due to the increasing demand for clean energy sources and the large number of potential hydraulic power sources (Liu et al., 2009). Construction of reservoirs greatly benefits socioeconomic development and quality of life, including drinking-water supply, power generation, flood control, irrigation, recreation, and fish farming. However, adverse effects exist, chiefly associated with eco-environmental issues. Searching for water resources and clean energy is not only a matter for China, but also a global issue. Therefore, China's challenges with hydroelectric power are also global concerns.

Development and utilization of water resources in China have experienced three historical periods: the technology-limited period, the fund-limited period, and the market-limited period (Wang, 2004a, 2004b). Currently, development is primarily limited by eco-environmental issues. The extensive anthropogenic activities in China have caused a variety of eco-environmental problems in reservoirs, which may directly endanger ecological safety and the drinking-water supply. For example, the Hongfeng reservoir (HF) and the Baihua reservoir (BH) are important drinking-water sources for Guiyang city in southwest China, but have repeatedly suffered algae blooms and accidental deterioration of water quality since 1990s, resulting in risks to the drinking-water supply and massive fish kills (Bai et al., 1995; Wan et al., 2010; Wang et al., 2005; Wang et al., 2012, 2016).

The physical properties of reservoirs, especially water depth and temperature, are important factors controlling the evolution of the aquatic environment and the shift in ecosystem regime (Genkai-Kato and Carpenter, 2005). The influence of water depth on the eco-environment of reservoirs has long been known. Therefore, we divide reservoirs into three categories based on water depth: (a) reservoirs without thermal stratification, with an average water depth usually less than 10 m; (b) reservoirs with seasonal thermal stratification, with an average water depth usually within the range of 10–50 m (hereinafter referred to as sub-deep water reservoirs); and (c) reservoirs with permanent thermal stratification, with an average water depth usually more than 50 m. Most reservoirs in China, especially southwest China, are sub-deep water reservoirs.

Unlike natural lakes, reservoirs have distinct characteristics, including geological background, material cycling, water pollution, and the associated mechanism. China has a large number of reservoirs belonging to different types with varying construction dates, thus providing ideal field sites for studying reservoirs' eco-environments. In this article, we describe the eco-environmental characteristics of reservoirs in China and stress the significance of understanding the evolution of reservoirs' eco-environments. The aims of the present work are to: (a) provide guidance for protecting the eco-environment and developing management strategies, and (b) propose directions for future research.

II Eco-environmental characteristics of reservoirs

Reservoirs are man-made aquatic environments, usually with mediate water depth and multiple interfaces. They normally have distinct eco-environmental characteristics different from natural lakes, which manifest in the aspects described below. Although some natural lakes may exhibit the following characteristics, they are typical features of sub-deep water reservoirs.

1 Intensive material exchange at the newly formed sediment–water interface

Natural lakes have existed for a long time, and material exchange has reached a relatively stable, balanced state at the sediment–water interface (SWI). However, the SWI in reservoirs is newly formed and may exhibit intense material exchange; therefore, the origin of reservoirs' water environment and ecosystem evolution differ from that of natural lakes. On the one hand, dissolution of nutrients and harmful substances from the submerged soils directly leads to an increase in the pollutant load of reservoirs. Meanwhile, degradation of organic matter (OM) in the submerged soils not only releases nitrogen (N), phosphorus (P), and other nutrients, but also promotes the release of heavy metals from sediment (Campo and Sancholuz, 1998; Jossette et al., 1999; Porvari, 1995). Both processes result in an increased load of nutrients and heavy metals in the upper water column. On the other hand, endogenous OM produced by the photosynthesis of aquatic plants gradually accumulates at the bottom of reservoir during its operation. Therefore, during the early stages of a reservoir, attention should be paid to possible eutrophication and heavy metal pollution. As the reservoir ages, the biological, chemical, and physical features of the lake will evolve. Endogenous OM produced by algae and hydrophyte increasingly accumulates in the sediment. Because endogenous OM is unstable and degrades preferentially during early diagenesis, N and P are activated in the OM and then migrate back to the overlying water. Usually, the environmental risks related to nutrient release from sediment increase with the extension of a reservoir's running time. Thus, it is very important to understand the eco-environmental characteristics of a reservoir at different stages to develop effective prevention and control measures.

2 Sediment rich in nutrients and OM

Compared with most lakes, the sediment of reservoirs is usually more abundant in nutrients and OM as a result of the following facts: (a) the newly submerged land, such as woodland, grassland, or farmland, is often rich in nutrients and OM; (b) once the reservoir is formed, the water flow will slow, which favors the growth of algae and other aquatic organisms, resulting in the accumulation of endogenous OM and nutrients in sediment; and (c) a reservoir is usually hypoxic in the bottom water or at the SWI. This would slow the degradation rate of OM, which is conducive to the burial of OM and nutrients in sediment. As illustrated in Figure 1, the total organic matter (TOM) and total nitrogen (TN), as well as total phosphorus (TP) in sediments from reservoirs are statistically higher than that in sediments from natural lakes, based on the available data from 21 natural lakes and 24 reservoirs in China. Taking HF as an example,

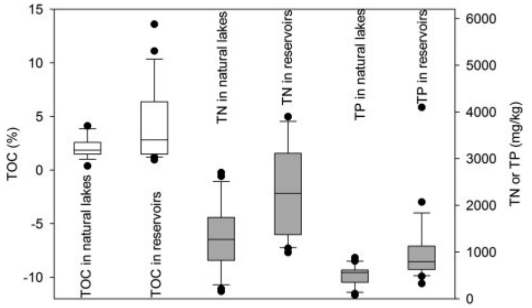

Figure 1. Comparison of TOC, TN, and TP between reservoirs and natural lakes (collected data were from 21 natural lakes and 24 reservoirs in China).

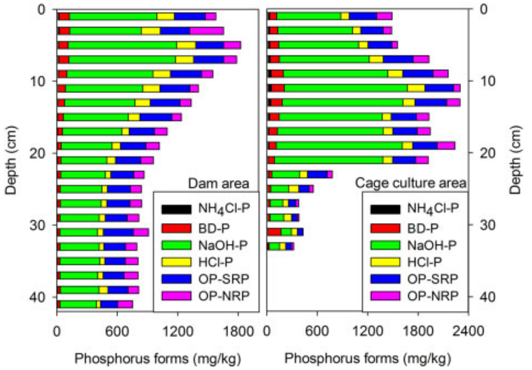

Figure 2. Vertical profiles of geochemical forms of P in sediments from HF.

based on a comprehensive survey using a grid-sampling strategy, the maximum values (mean values in parentheses) of TOM, TP, and TN in sediment can be up to 32% (3.2%), 1.0% (0.12%), and 1.03% (0.31%), which are 2–4 times higher than those in Taihu Lake (Chen et al., 2009; Wang et al., 2015).

As mentioned above, endogenous OM is prone to degradation during early diagenesis. Along with the degradation of OM, organic phosphorus (OP), and iron-bound P (Fe-P) can be released into the pore water and then into the overlying water. This provides an "endless" supply of P and imposes a second contamination. For example, the release of P from sediment is estimated to be approximately 6.3–8.0 tons during the summer in HF, accounting for approximately 22–28% of TP in the whole body (Luo et al., 2015). Worse, P in sediment from HF is rich in active components, including Fe-P, OP, and exchangeable P, collectively accounting for more than 80% of TP in sediment (Figure 2). This is probably the main reason for the accidental eutrophication in HF historically.

3 Synergistic effect of eutrophication and heavy metal pollution

In addition to the possible eutrophication, reservoirs may also suffer from serious heavy metals contamination. If these happen simultaneously, the effects may be even worse because under certain conditions a synergistic effect between the two environmental issues could occur. For example, aggravated eutrophication in the water body leads to aggregation of OM in the sediment and hypoxia in the bottom water. This will greatly promote the methylation of Hg and enlarge its ecological risk. In fact, accelerated methylation of Hg in the sediment has often been found in reservoirs with anoxic conditions caused by eutrophication in the bottom water (He et al., 2008, 2010).

Because it is one of the largest low-temperature metallogenic domains in the world, southwest China not only hosts many cascade reservoirs but also has high background levels of many toxic heavy metals (e.g., Hg, Sb, Pb, Zn, As, and Tl). If combined with heavy metals contamination, the frequently occurring eutrophication in these cascade reservoirs could increase the adverse ecological impacts on the aquatic environment. This has been proven by the fact that, along the cascade reservoirs located in the Wujiang River, total Hg in discharged water was less than that in inputted water, which is the opposite for methylmercury (Feng et al., 2009; Guo et al., 2008; Yao et al., 2011).

4 Seasonal stratification

Most reservoirs in China are sub-deep water reservoirs with a depth of 10–50 m (Table 1). Their distinct eco-environmental characteristic is seasonal stratification in the water column. As the ambient temperature increases from late spring to early summer, a temporary thermal stratification (a physical layer characterized by significant variation in water temperature and density) will develop, resulting in a significant decrease in mass transfer between the upper and lower layers, with the hypoxia in the bottom water accelerating the release of P and heavy metals from sediment. Along with the thermal stratification, the water column is also biologically stratified (with autotrophic organisms dominant in the upper layer and heterotrophic organisms dominant in the deeper layer) and chemically stratified (with dissolved oxygen and nutrient content). The seasonal stratification not only controls the distribution of algae and zooplankton among the surface water, thermocline, and bottom water, but also affects the physicochemical processes in different water layers, including the adsorption and desorption, precipitation and dissolution, oxidation and reduction, degradation and mineralization of OM (Liu et al., 2009; Stumm, 1985; Wang et al., 2012; Wetzel, 2001).

In deep water reservoirs, the bottom water is usually abundant in nutrients and reducing substances, which is also true for sub-deep water reservoirs during the period of thermal stratification. The abundance of nutrients and reducing substances in bottom water is a potential risk. The whole water body would face a serious deterioration in water quality if the temporary stratification was broken. This possibility is unlikely in deep water reservoirs due to the existence of permanent thermal stratification but can happen in sub-deep water reservoirs because the water body is not deep enough to form a permanent stratification; seasonal exchange or sudden convective mixing between the bottom water and the surface water may occur.

If the temporary stratification is broken, nutrients and reducing substances would flow into the upper water column, resulting in disastrous consequences such as accidental deterioration in water quality and harmful algae blooms. A lack of oxygen and increase in reducing substances (H_2S, for example) in surface water could lead to large fish kills, as has repeatedly occurred at BH since the 1990s (Bai et al., 1995; Wan et al., 2010). In addition, a rapid increase in nutrients in the surface water can cause algae blooms if the ambient temperature is high enough (Wang et al., 2012). Once this happens, the water body is difficult to restore using submerged plants because the submerged plants are difficult to grow in reservoirs where the water is too deep (>10 m).

In sub-deep water reservoirs, seasonal stratification is the most important factor influencing physicochemical and biological processes, material cycling, and evolution of the eco-environment, as well as the spread of aquatic organisms. The unique material cycling and contamination processes in sub-deep water reservoirs indicate that the ecosystem of sub-deep water reservoirs is more vulnerable than that of shallow or deep water reservoirs. To fully understand their environmental evolution and shifting ecosystem, sub-deep water reservoirs must be researched as a separate category of reservoirs.

5 Multiple interfaces

A sub-deep water reservoir usually has multiple interfaces (Figure 3). The typical interfaces include the following.

1. The water–air interface, which is an interface between the surface water and the above atmosphere, with rapid and

Table 1. Sub-deep water reservoirs in China.

Reservoir	River system	Location	Catchment area (km^2)	Normal (DWL) altitude (m)	Mean (max.) depth (m)	Storage capacity (10^8 m^3)	Date constructed
Dongfeng	CJR	N 27°02′57″, E 106°58′34″	18,161	970 (936)	25 (76)	10.25	1995
Hongfeng	CJR	N 26°32′43″, E 106°26′03″	1596	1240 (1228)	10.5 (40)	7.53	1960
Baihua	CJR	N 26°39′29″, E 106°32′02″	1895	1195 (1188)	10.5 (45)	2.51	1966
Hongjiadu	CJR	N 26°55′58″, E 105°50′20″	9900	1140 (1076)	60 (130)	49.5	2004
Suofengying	CJR	N 26°59′48″, E 106°25′41″	21,862	837 (822)	21 (80)	2.01	2006
Wujiangdu	CJR	N 27°16′23″, E 106°36′45″	27,790	760 (720)	33 (95)	23.00	1983
Goupitan	CJR	N 27°22′17″, E 107°38′07″	43,250	630 (615)	35 (>100)	55.65	2009
Yinzidu	CJR	N 26°34′07″, E 106°08′17″	6422	1086 (1052)	32.5 (>100)	5.31	2001
Puding	CJR	N 26°22′13″, E 105°45′47″	5871	1145 (1126)	17.5 (40)	4.01	1995
Silin	CJR	N 27°48′02″, E 108°10′44″	48,558	440 (431)	22 (60)	16.54	2007
Shatuo	CJR	N 29°08′445″, E 108°16′36″	54,508	365 (353)	30 (>100)	7.71	2013
Shuanghekou	ZJR	N 25°34′58″, E 106°31′25″	2200	530 (545)	20 (50)	1.70	2008
Huanghuazai	ZJR	N 25°40′26″, E 106°27′07″	2163	795 (770)	24 (85)	1.63	2010
Guanyinyan	CJR	N 26°26′02″, E 104°39′46″	941	599 (577)	20 (75)	1.23	2013
Sanbanxi	CJR	N 26°37′43″, E 109°02′41″	11,051	475 (425)	45 (>100)	40.94	2003
Baishi	CJR	N 26°57′26″, E 109°28′12″	16,530	300 (294)	18 (70)	4.20	2012
Yangtou	CJR	N 27°39′10″, E 109°08′07″	3780	230 (227)	10 (45)	1.15	1991
Hongjiadu	CJR	N 26°55′47″, E 105°49′26″	9900	1140 (1076)	41 (>100)	49.47	2001
Wanfenghu	ZJR	N 24°54′21″, E 105°04′24″	50,139	780 (731)	45 (>100)	102.57	2000
Guangzhao	ZJR	N 25°37′34″, E 105°15′00″	13,548	745 (695)	40 (>100)	32.45	2009
Dongjin	ZJR	N 25°31′57″, E 105°45′05″	26,557	490 (485)	35 (>100)	9.55	2010
Songbaishan	CJR	N 26°24′11″, E 106°34′11″	127	1179 (1162)	12 (40)	0.48	1987

(continued)

Table 1. (continued)

Reservoir	River system	Location	Catchment area (km^2)	Normal (DWL) altitude (m)	Mean (max.) depth (m)	Storage capacity (10^8 m^3)	Date constructed
Aha	CJR	N 26°32′27″, E 106°38′51″	190	1110 (1090)	13 (24)	0.87	1960
Huaxi	CJR	N 26°26′40″, E 106°37′43″	325	1140 (1120)	24 (48)	0.31	2003
Yujianhe	CJR	N 27°02′06″, E 106°39′53″	42.6	1057 (1027)	35 (70)	0.11	2003
Leigongtan	ZJR	N 25°23′38″, E 106°40′56″	5385	410 (409)	8 (20)	0.15	2006
Hongqi	CJR	N 27°01′49″, E 108°15′53″	2120	508 (499)	16 (50)	0.58	1981
Fengshutun	CJR	N 26°19′07″, E 109°03′55″	39.5	557 (538)	11 (76)	0.17	2009
Liangchahe	CJR	N 26°57′54″E 107°43′58″	256	724 (710)	10 (22)	0.63	2000
Taixiong	CJR	N 26°38′10″, E 108°16′47″	127	710 (677)	14 (30)	0.25	2008
Daotianhe	CJR	N 27°19′21″, E 105°15′49″	256	1557 (1537)	11 (21)	0.19	2004
Shengtian	CJR	N 27°27′53″, E 106°16′13″	58.3	966 (933)	26 (48)	0.13	2008
Daxinqiao	CJR	N 26°42′12″, E 105°46′43″	42.3	1476 (1458)	12 (40)	0.12	2008
Xiangshui	ZJR	N 26°22′50″E 104°41′11″	4834	1150 (1133)	13 (30)	0.34	2006
Zhelun	ZJR	N 24°56′21″, E 105°20′43″	86.9	1301 (1283)	9 (25)	0.15	2007

Note: CJR represents the Changjiang River and ZJR represents the Zhujiang River.

frequent exchange of materials and energy.

2. The photic zone–aphotic zone interface, which is an interface between the photic zone and the aphotic zone. The photic zone is a water column where light can reach and the net primary productivity is zero. Phytoplankton is abundant in the photic zone but is scarce in the aphotic zone;
3. The thermocline is a transition layer between the upper water and the bottom water (also an important chemical and biological interface), where water temperature and density decrease sharply from top to bottom.
4. The oxidation–reduction interface (ORI) is a chemical interface whose position varies depending on the hydrochemical properties between water and sediment.
5. The SWI, a stable geological interface between sediment and overlying water.

The processes by which interfaces develop reflect complex interactions between physical, chemical, and biological effects (Wan, 1988; Wan et al., 2001).

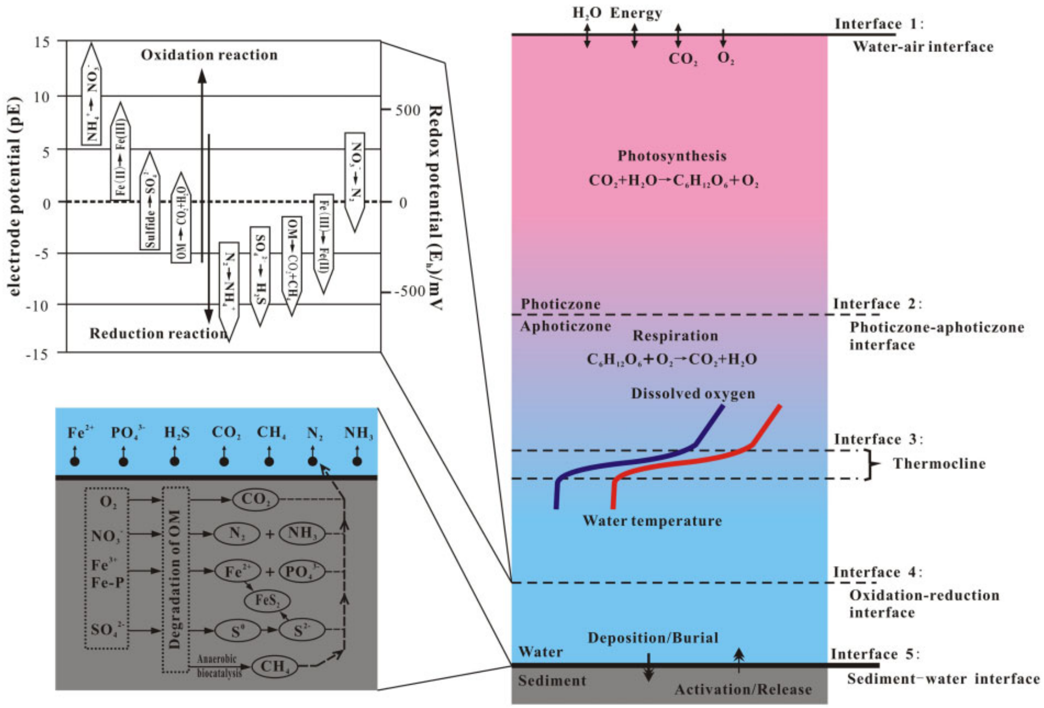

Figure 3. Multiple interfaces in deep water reservoirs.

The evolution of an eco-environment is controlled by physicochemical and biological processes, as well as frequent material and energy exchanges that occur at or near the interfaces (Wan, 1987). In the early1980s, a conceptual model was developed and applied to explain the geochemical behaviors of iron (Fe) and manganese (Mn) in water (Davison, 1993; Furrer and Wehrli, 1993; Stumm, 1985). However, this model emphasizes the significance of redox conditions and overlooks the geological constraints of the SWI on the cycling of Fe and Mn. Meanwhile, the influence of aerobic decomposition of OM during the early diagenesis on the shift of ORI was usually neglected (Wan et al., 2001). In fact, the cycling of Fe and Mn in an aquatic environment is jointly controlled by the SWI and ORI (Wan et al., 1997, 2001). In addition to the cycling of Fe and Mn, biogenic elements and the distribution of aquatic organisms are also controlled by the coupling effects of multiple interfaces. Presently, our understanding of the processes that occur at interfaces is still limited; we are especially lacking comprehensive knowledge about the coupling effects of multiple interfaces on material cycling and biological processes.

6 Cumulative effect of material cycling

Damming on the river greatly weakens hydrological strength, causing the so-called hydrostatic effect, leading to enhanced sedimentation, and promoting the growth of aquatic plants. As a result, more particulates would settle to the bottom and more biogenic elements would be retained in the reservoir, forming a cumulative effect along the river. Namely, the lower reach the downstream, the fewer the particulates in water. This is also the case for biogenic elements, such as C, N, P, and Si (Maavara et al., 2015; Paul, 2003; Teodoru and

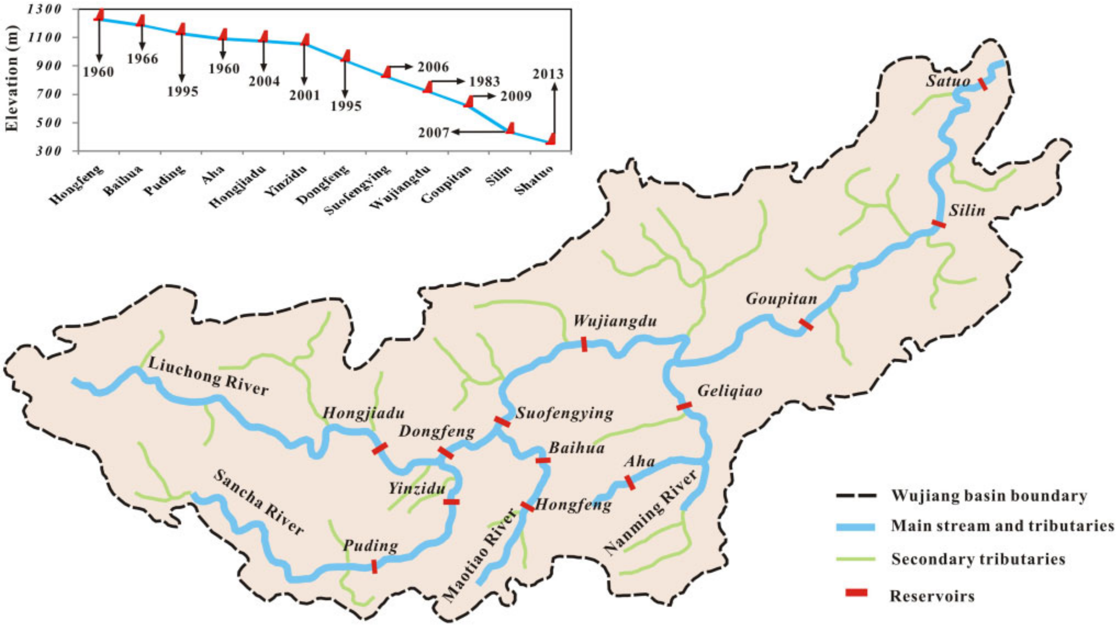

Figure 4. Cascade reservoirs along the Wujiang River, Southwest China.

Wehrli, 2005; Wang et al., 2010). In addition, most reservoirs with high dams discharge the bottom water during power generation. The discharged water is often abundant in soluble and reducing substances, which is contrary to the chemical properties of received water (usually abundant in particulate and oxidizing substances). These chemical properties greatly influence the mass transfer and chemical species of nutrients and the physicochemical properties of the river downstream (Chen et al., 2015; Dynesius and Nilsson, 1994; Humborg et al., 2000; Petts, 1984; Santos et al., 2016; Silva et al., 2005; Teodoru and Wehrli, 2005; Wang et al., 2011).

Southwest China hosts many cascade reservoirs along the Wujiang, Lancang, Ru, and Jinsha rivers. The Wujiang River, for example, has many cascade reservoirs, as illustrated in Figure 4. These cascade reservoirs could face serious challenges associated with eutrophication, due to the following facts: (a) the extensive socio-economic activities within its catchment lead to a large quantity of pollutants entering and settling into the reservoir; (b) the interception effect of the dam leads to the accumulation of pollutants (such as N and P) in sediment, enhancing the release of internal pollutants; and (c) the hydrostatic effect of dam promotes the growth of algae in the reservoir. This will increase the burial of OM and the probability of algae blooms. The increase in OM may lead to hypoxia in the bottom and promote the release of N and P, resulting in the increase of N and P loading and accelerating eutrophication in the upper water column. This would form a positive feedback mechanism of "increase in N and P in water body → algae bloom → hypoxia in the bottom water → enhanced release of N and P from sediment → increase in N and P in water body" (Conley et al., 2002), which also described elsewhere (Howarth et al., 2011; Jilbert et al., 2011; Rabalais et al., 2010; Slomp and van Cappellen, 2007).

The eco-environment of cascade reservoirs may be worse due to eutrophication in the water

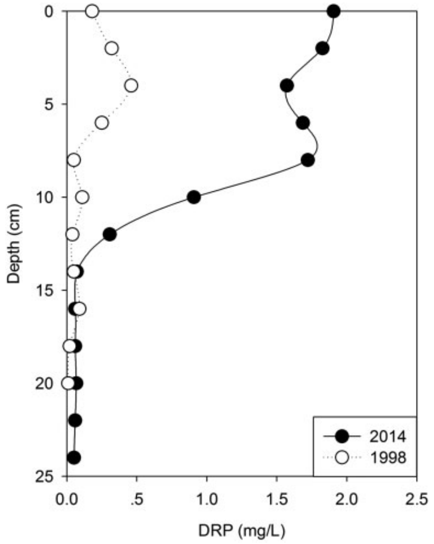

Figure 5. Dissolved reactive P in pore water of HF in 1998 and 2014.

body and hypoxia at the bottom. The influence of material exchange at the SWI on the aquatic environment and ecosystem would escalate with time. Results from a comparative study conducted at the Wujiangdu reservoir (built in 1974) and the Dongfeng reservoir (built in 1992) suggested that the longer the running time, the stronger the influence of the materials released from sediment on quality of the water environment. This is supported by the vertical profile of PO_4^{3-} in HF, where the PO_4^{3-} level in pore water in 2014 was 5–10 times that in pore water in 1998 (Figure 5). Hypoxia and the degradation of OM in bottom water not only accelerate the release of nutrients but also stimulate the release of heavy metals from sediment. The increase in soluble and hazardous substances in bottom water (such as H_2S and methylmercury) will increase the inputs and risks of these hazardous substances downstream. For example, 40 years after the establishment of the Aha reservoir, accumulation of pollutants in sediment and the release of hazardous substances directly led to odor, hypoxia, and the extinction of aquatic animals, as well as a unique white turbidity event in the lower reaches of the river (Chen et al., 2015).

7 Artificial regulation of water level

Unlike the natural fluctuation of water levels in lakes, reservoirs are usually subject to intensive anthropogenic disturbance, and their water levels are frequently artificially regulated to meet the requirements of drinking-water supply, flood control, and power generation. Traditionally, reservoirs in China are operated with the strategy of "eliminating flood peak and compensating dry season, storing clear water and releasing the muddy water." In detail, during the flood season, muddy water will be discharged as necessary to maintain the water level provided that it can ensure the drinking-water supply and power generation. During the dry season, the received water will be retained as much as possible to guarantee a water level high enough to ensure shipping, power generation, and the drinking-water supply.

The artificial regulation of water level, characterized by "reservoir bank exposure in summer and submergence in winter," could provoke a series of unprecedented eco-environmental problems. The negative effects include increasing erosion due to heavy rainfall and strong surface runoff during the rainy season, fragmentation of vegetation habitats within the hydro-fluctuation belt (HFB), ecological deterioration, reduced biodiversity, poor efficiency in interception of pollutants, possible geological disasters (landslides) and the challenges of land use at the HFB, as well as the deterioration in water quality (Bao et al., 2015; Wu et al., 2003; Yang et al., 2015; Zhang and Lou, 2011). Fully understanding the eco-environmental characteristics resulting from the artificially controlled water level would help maintain the ecological functions of the HFB, such as conservation of both soil and moisture, and improvement of water quality. The damaged ecosystem at the

HFB should be restored for the maintenance of a healthy reservoir ecosystem.

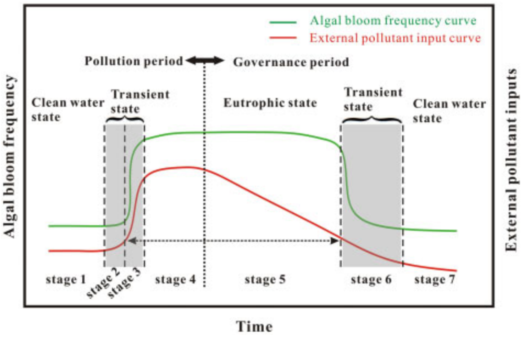

Figure 6. Responses of reservoirs to inputs of nutrients from watershed.

8 Slow response of the aquatic ecosystem to external load

Considering the continuous eco-environmental investigation, we propose a conceptual model of the aquatic ecosystem responsible to the external loading of nutrients (Figure 6), which can be divided into seven stages.

1. The external inputs of nutrients are limited and the water is clear in the reservoir.
2. Although the external inputs of nutrients have increased, the reservoir has a limited capacity for self-purification and can maintain a state without algae blooms.
3. The external inputs of nutrients increased rapidly and the self-purification capacity of the water body is insufficient to prevent algae blooms.
4. The external inputs of pollutants are no longer increased, yet algal blooms happened frequently.
5. The external inputs of nutrients begin to decline, while the internal nutrients are highlighted, resulting in a steady state of eutrophication without an obvious decline in algae blooms.
6. The external inputs of nutrients continued to decline and water began to clear, accompanied by a decline in frequency of algae blooms.
7. Both external and internal nutrients are under control and water in reservoir has returned to clear.

This model covers the whole process of eutrophication, from its occurrence to its development and disappearance. The slow response of the aquatic ecosystem to the external load helps us to understand why the external inputs of nutrients can be reduced substantially but the reservoir still persists in a state of eutrophication. This proves the importance of controlling internal release of nutrients during the restoration of reservoirs from eutrophication.

III Prospects

Unlike most natural lakes, reservoirs are usually multifunctional, providing a drinking-water supply, power generation, and flood control. To achieve its social functions, a reservoir must first have a sound eco-environment. Developing an effective control theory and technologies, which is critical to ensuring a sound environment, ecological security, and sustainable development, requires knowledge of how a reservoir's eco-environment evolves.

1 Evolution of the eco-environment and its controlling factors

A reservoir is usually formed by damming a river; the river–reservoir ecosystem is very complex due to its large space, unclear boundary, and complicated eco-environmental controlling factors. Long-term monitoring and field investigation is hard enough, not to mention elaborating the intrinsic mechanisms and controlling factors of eco-environmental evolution. The Wujiang River, one of the rivers first developed for hydropower, exemplifies in miniature the hydropower development in southwest China. Along the river, there are many cascade reservoirs with varying construction dates and thus in different stages of eco-environmental evolution. By a contrastive observation of these cascade reservoirs that replaces time with space, deep insight into the eco-environmental evolution of river–reservoir ecosystem can be achieved. This method is also helpful to explore the key processes, mechanisms, and controlling factors associated with the influence of hydropower development on the water environment. The results could provide a simplified model and valuable experience for understanding the eco-environmental evolution in larger river–reservoir ecosystems, such as those on the Yangtze, Jinsha, Lancang, and Nu rivers.

2 Material cycling and biological processes

As mentioned above, there are five typical interfaces in deep or sub-deep water reservoirs. These interfaces, with spatial position varied according to environmental conditions, play an important role in material cycling and distribution of aquatic organisms. Presently, our understanding of these interfaces remains limited, along with their coupled effects on the biogeochemical cycling of substances in deep or sub-deep water reservoirs, due to lack of large-scale simulating systems and in situ monitoring techniques. Fortunately, the development and application of advanced techniques, such as diffusive gradients in the thin-film technique, the microelectrode technique, and the planar optoelectronic technique, made it possible for in situ, synchronous, and high-resolution observation at different interfaces. These techniques can help us develop an open, large-scale simulating and in situ monitoring system, and ultimately obtain a better understanding on the biogeochemical cycling of materials and its intrinsic impetus.

3 Coupled cycling of C–N–P–Si and its effects on the eco-environment

Biogenic elements play an important role in the process of eutrophication and are usually carried by OM during their biogeochemical cycling in the water body (Bratkič et al., 2012). In sub-deep water reservoirs, the biogeochemical cycling of biogenic elements is closely related to the primary production and degradation of OM. Growth of phytoplankton is in fact a process of absorption and utilization of C, N, P, and Si and the formation of OM, while sedimentation and early diagenesis is a process of degradation and mineralization of OM accompanied by the release of C, N, P, and Si back into water. Though activated simultaneously during the mineralization of OM, C, N, P, and Si are not released in equal proportions. Previous studies have revealed that hypoxia in bottom water can promote a greater release of P than C (Jilbert et al., 2011; Rabalais et al., 2010; Viktorsson et al., 2013a, 2013b). The effects of primary productivity and mineralization of OM on the cycling of biogenic elements are key points for a better understanding of the coupling processes and mechanisms of biogenic elements in reservoirs. These effects are also helpful to clarify whether, similar to marine ecosystems (Conley et al., 2002), there exist positive feedback effects of “hypoxia in bottom water → increase in the release of nutrients from sediment → algae blooms → increase in primary productivity → increased hypoxia in the bottom water” in sub-deep water reservoirs.

4 Mechanisms and technology for in situ inactivation

Eutrophication is one of the biggest and most frequently encountered challenges in river–reservoir ecosystems. Excessive P in the water body is the most likely culprit. To reduce the level of P in the water column, inputs of external P must be intercepted (Cooke et al., 2005;

Lürling et al., 2016). Nevertheless, this interception is insufficient (Cooke et al., 2005; Mehner et al., 2008; Søndergaard et al., 2007). During the restoration of reservoirs from eutrophication, increasing evidence has confirmed that there is no significant decline of PO_4^{3-} contents in the water body despite substantial reduction in inputs of external P (Jiang et al., 2008; Søndergaard et al., 1999, 2003). The release of internal P is believed to be the main cause, especially during seasonal stratification (Burger et al., 2007; Carpenter et al., 1999; Luo et al., 2015; Søndergaard et al., 2003). Without mitigating the release of internal P, the reservoir has little chance of being quickly restored from eutrophication (Carpenter et al., 1999; Mehner et al., 2008).

Mitigating the release of internal P is of great importance during the restoration of the river–reservoir ecosystem from eutrophication. Among the available techniques, sediment dredging is probably a simplest but most effective technique. However, adverse environmental effects associated with dredging are apparent (Bormans et al., 2016; Palermo, 2001). Bioremediation is thought to be a good alternative to sediment dredging, thanks to its cost-saving and environmentally friendly properties (Muñoz and Guieysse, 2006). Nevertheless, like sediment dredging, bioremediation is also exclusively suitable for shallow water body. Hypolimnetic aeration is a promising technique for reducing the internal release of P (Bormans et al., 2016; Singleton and Little, 2006), but is mainly applied to deep water bodies; its applicability to sub-deep water reservoirs needs further verification (Bormans et al., 2016). In situ passivation, a technique that can reduce the release of P to overlying water via the formation of a passivation layer on the sediment surface, is one of the most popular techniques, with many advantages (in situ, cost-effective, and eco-friendly). A large suite of passivators have been proposed, but it is not easy to find an ideal passivator considering that it must be efficient, safe, cheap, and easy to use (Lürling et al., 2016). Further efforts should be focused on the mechanism of in situ passivation of nutrients and the controlling factors of different passivators under different environmental conditions. This is of great importance for developing an effective technique suitable to control internal P in sub-deep water reservoirs.

5 Management of water quality: forecast and criteria

The environmental issues of reservoirs in China are mainly manifested in the frequently occurring incidents of water quality deterioration, such as algae blooms and "black tide." These events seriously endanger ecological security and the drinking-water supply. Due to lack of long-term and high-resolution observation, our understanding of these incidents is too limited to achieve a real-time forecast and/or early warning. Presently, the most urgent task is to strengthen the long-term observation at fixed points, which comprise the monitoring of meteorological factors (including sun-light, wind speed, ambient temperature, and rainfall), water environment parameters (including water temperature, dissolved oxygen, pH, and nutrients), and aquatic ecology (including species and abundance of phytoplankton), especially during the sensitive period of thermal stratification. Based on these gathered data, the basic law of seasonal thermal stratification may be revealed, along with insight into the development and mechanism of water quality deterioration. Together with a dynamic reservoir-simulating model, we hope to develop an early warning system that can predict water quality and possible incidents. This early warning system is conducive to proposing coping strategies for possible emergencies, reducing adverse ecological effects, and decreasing the frequency of water quality deterioration.

Another purpose of water quality management is to develop local matched water quality criteria (WQC). WQC include the maximum dose or concentration of a specific pollutant in water that poses no harmful or adverse effects on humans or other organisms (Environmental Protection Agency, 1980; Meng et al., 2006). WQC have distinct regional characteristics because they were developed on the basis of the natural background and evolution of the local water environment. In addition, the environmental behaviors and toxicological effects of a specific pollutant may vary in different regions (Wu et al., 2008). There are significant differences between natural lakes and reservoirs, including the climate, geological and geographical background, material cycling, flora and fauna, etc. Pollutants in reservoirs have their own characteristics relevant to their migration, transformation, and ecotoxicological effects. It is not advisable to indiscriminately imitate the WQC of other countries or regions. For example, various investigations have confirmed that reservoirs in southwest China usually have a high background level of TN (Feng et al., 2011), which is evidently higher than that of the environmental quality standard for surface water recommended by the Chinese government (GB3838-2002). In southwest China, reservoirs may be overprotected, and socioeconomic development could be restrained by its catchment if the management activities are based on the criteria of GB3838-2002. Further efforts should focus on the evolution of the reservoirs' environment under natural conditions (or anthropogenic activities) to obtain detailed information on the biogeochemical processes and a precise evaluation of the ecotoxicological effects of various pollutants in reservoirs. This would provide critical information on environment management and pollution control and is helpful for developing a local matched WQC.

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Data availability statement

All data generated or analyzed during the current work are available from the corresponding author on reasonable request.

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