Environmental Science and Pollution Research (2022) 29:8970–8979
https://doi.org/10.1007/s11356-021-16363-3

RESEARCH ARTICLE

Effects of cascade dam on the distribution of heavy metals and biogenic elements in sediments at the watershed scale, Southwest China

Kangkang He[1,2] · Jingfu Wang[2,3] · Peng Liao[2,3] · Qingqing Sun[4] · Xiaohong Yang[1,2] · Zuxue Jin[2,3] · Jingan Chen[2,3,5]

Received: 18 May 2021 / Accepted: 1 September 2021 / Published online: 8 September 2021

Abstract
Cascade dam has important effects on the magnitude and dynamics of sediment particles, heavy metals, and biogenic elements in reservoirs. However, systematic studies on the interception effect of cascade dam on the various elements that occur in rivers at the watershed scale are lacking. The aims of this study were to (1) assess the interception effect of a cascade dam on heavy metals and biogenic elements and (2) investigate the key factors of these effects of the cascade dam. Surface sediments were collected from 29 sites distributed in the Wujiang River Basin (WRB, a watershed scale in Southwest China), including from tributaries (7 sites), the main stream (13 sites), and cascade reservoirs (9 sites). In addition, the particle sizes, heavy metals (Fe, Mn, Zn, Cr, Cu, As, Pb, and Cd), and biogenic elements (TOC, TN, and TP) of sediments were analyzed. Compared with the tributaries, D50 (median particle size) was significantly reduced by 56.8% of cascade reservoirs. The proportion of 63–2,000 μm decreased from 13.78 to 1.34%, indicating that more coarse particles were intercepted in the cascade reservoirs. The contents of heavy metals (Fe, Zn, Cu, As, and Cd) declined significantly along the way. On the whole, the contents of TOC, TN, and TP were highest in the midstream and lower in the upstream and downstream. The hydrological condition (reservoir age, HRT, and flow) and the basin area and internal and external inputs of cascade reservoirs are important factors. The findings deepen the current understanding of the mechanisms by which cascade dam affects the river transport of heavy metals and biogenic elements at the watershed scale and provide an important reference for establishing hydropower developments along rivers and developing aquatic environment management strategies.

Keywords Cascade dam · Heavy metals · Biogenic elements · Hydraulic retention time · Reservoir age · Interception effect

Introduction

As important channels connecting the circulation of material from land to ocean, rivers can act as carriers transporting large amounts of carbon (including inorganic and organic C, 9.0×10^{14} g), dissolved inorganic nitrogen (2.3×10^{13} g), and dissolved inorganic phosphorus (1.6×10^{12} g) to the ocean annually (Cole et al. 2007; Sharples et al. 2017). Hydropower development (building dams and reservoirs) provides essential energy support for socio-economic development globally. Currently, more than 8.45×10^5 dams have been constructed on about 2/3 of rivers worldwide (Fuggle and Smith 2000; Van Cappellen and Maavara 2016).

It is well known that cascade dam is a more effective way than a single dam to utilize river water resources. The cascade development of Tennessee River (USA) is a classic case (Fox 2020), and China is also developing cascade reservoirs on a

Responsible editor: Philippe Garrigues

✉ Jingfu Wang
wangjingfu@vip.skleg.cn

✉ Jingan Chen
chenjingan@vip.skleg.cn

[1] College of Resource and Environmental Engineering, Guizhou University, Guiyang 550025, People's Republic of China

[2] State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, People's Republic of China

[3] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

[4] Institute of Surface Earth System Science, School of Earth System Science, Tianjin University, Tianjin 300072, People's Republic of China

[5] CAS Center for Excellence in Quaternary Science and Global Change, Xi'an 710061, People's Republic of China

large scale (Fang and Deng 2011). However, damming has brought fundamental physical changes to the continuity of rivers, and cascade dam can damage the connectivity of rivers more than a single dam (Duarte et al. 2020; Grill et al. 2019). The velocity of the river in front of the dam slows down and the water level rises, forming a new lake system (as a reservoir). Damming has resulted in 40% of the world's river water being intercepted by reservoirs (Vörösmarty et al. 2003) and led to chemical changes in reservoirs, such as the formation of a thermocline, which changes the water quality and affects the ecology of the aquatic environment (Winton et al. 2019). The effect of cascade dam on the water environment may be superimposed. Damming also changes the transport of sediment and the geochemical circulation of heavy metals and biogenic elements (C, N, P) by rivers (Grill et al. 2019; Maavara et al. 2015; Shi et al. 2020; Vörösmarty et al. 2003). For instance, reduced sediment transport in the Mississippi River (USA) was found to be related to the cascade dam (Meade 2004; Meade and Moody 2010). Due to the interception caused by damming, it is estimated that outputs of particulate organic C, particulate N, and particulate P from rivers have declined to 1.97×10^{14} g year^{-1}, 3.0×10^{13} g year^{-1}, and 9.0×10^{12} g year^{-1}, respectively (Beusen et al. 2005). The behavior of heavy metal elements, such as mercury, is affected by the presence of dams (Hahn et al. 2018; Liu et al. 2020). In addition, cascade dam has changed the water temperature, dissolved oxygen, pH, and migration of heavy metals in cascade reservoirs in China (Feng et al. 2018; Li et al. 2020; Wang et al. 2019). In one specific case, the total phosphorus (TP) transport pattern of the Lancang River Basin (Southeast Asia) was found to have altered owing to the construction of the cascade dam, and the flux of TP was reduced by more than 50% (Xu et al. 2020).

Existing studies on the interception effect of damming on elements (C, N, P, etc.)—especially large-area, global-scale investigations—have predominantly been based on estimates using mathematical models, the calculation errors of which (noted in the findings of these studies) need to be tested using large-scale field sampling and surveys (Maavara et al. 2017; Maavara et al. 2015; Rodriguez et al. 2020). However, the different interception effect of cascade dam on the various key elements and their key controlling factors are still unclear. To date, there have been about 1.0×10^5 reservoirs of various types constructed in China (MWR 2019), and more than 5.0×10^4 of these are located along the Yangtze River Basin (Yang et al. 2005). More specifically still, there is a high density of cascade hydropower developments in the Wujiang River Basin (WRB), which is the largest first-order tributary on the south bank of the Yangtze River (Wang et al. 2019; Yang et al. 2020a). By virtue of its abundant hydropower resources, construction of the cascade reservoir group on the main stream of the WRB commenced in the 1950s, including 12 cascade hydropower stations. Over the past four decades, the cascade dam has greatly changed the aquatic environment of the WRB (Wang et al. 2019; Yang et al. 2020a; Yin et al. 2010). In addition, compared with 1956–2015, the annual runoff of Wujiang River did not change significantly in 2019, but its sediment transport decreased by 91.6%, according to *The sediment bulletin of Yangtze River in 2019* (CERC 2020). This remarkable effect likely derives from the interception of the cascade dam.

Moreover, it is particularly important that compared with a single reservoir, the interception effect and environmental impacts of cascade dam on the river basin may be considerably stronger. Indeed, cascade dam can aggravate river fragmentation, hydrological changes, sediment deposition, element accumulation, and ecological impacts (Duan et al. 2016; Kondolf et al. 2014; Wang et al. 2019; Yang et al. 2020b). In this study, surface sediments were systematically collected from the main stream, tributaries, and cascade reservoirs along the WRB. The aims of the study were to (1) assess the interception effect of the cascade dam on heavy metals and biogenic elements—especially how they differed for different elements—and (2) investigate the key factors controlling the interception effect of the cascade dam on elements.

Materials and methods

Study area and sample collection

As the largest first-order tributary on the south bank of the Yangtze River, the Wujiang River is 1037 km long and has a total runoff of 5.34×10^9 m^3 and a basin area of 1.1×10^5 km^2 (Huang et al. 2017). The WRB is located in a petrographic province dominated by carbonates (accounting for 70%), characterized by mainly calcareous soil and shrub vegetation upstream and yellow calcareous soil and arbor-shrub vegetation midstream and downstream (Han et al. 2010; Yang et al. 2020a). The WRB is subject to a subtropical humid monsoon climate, having a concentrated rainy season (accounting for 75% of annual precipitation) from May to October; average annual precipitation is 1100–1300 mm (Han et al. 2018; Li et al. 2019). According to measurement results released by hydrological departments, more than 60% of the sediments in the WRB derive from the upstream regions (Zhu 2005). There is a more concentrated distribution of sediment than water within the year, with the sediment discharge from May to October usually accounting for more than 90% of the total annual sediment discharge. The terrain of the WRB tilts from the southwest to the northeast, with a total elevation decline of 2,124 m.

In July 2020, surface sediments were collected using a Peterson grab (HL-CN, Wuhan Hengling, CHN) from 29 sites distributed in the WRB (25°56′–30°01′N, 105°09′–109°26′E: Fig. 1), including 13 sites in the main stream (labeled as M 1–

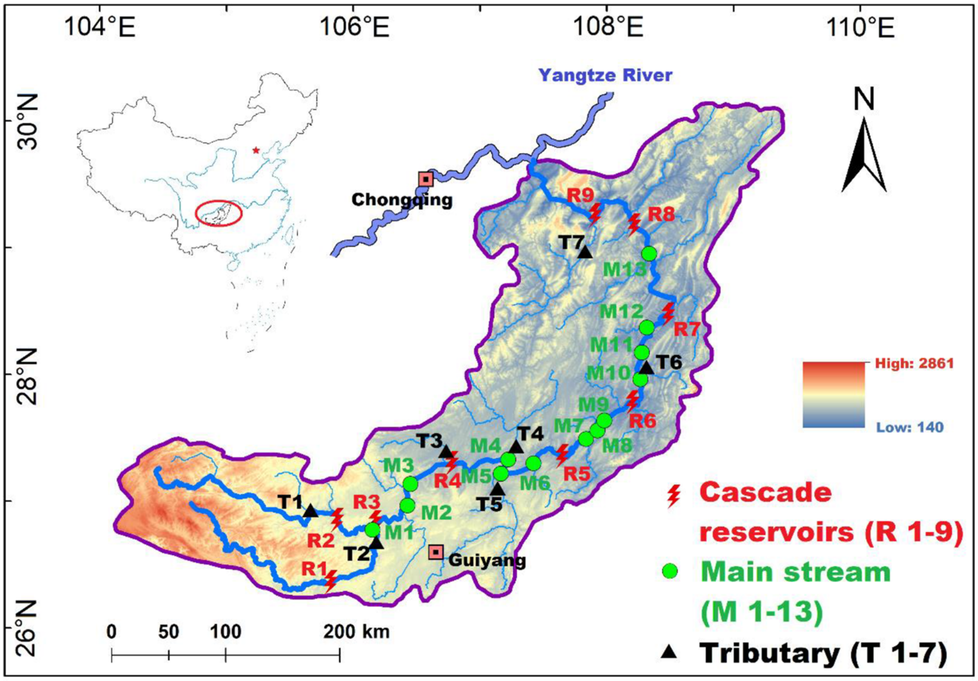

Fig. 1 Locations of sampling sites in the Wujing River Basin (WRB), southwest China

13), 7 sites in tributaries (labeled as T 1–7), and 9 sites in cascade reservoirs (labeled as R 1–9). Depending on sampling position, sampling sites were divided into three groups, i.e., upstream (T1, R2, R1, T2, M1, R3), midstream (M2, M3, T3、R4, T4, M4, T5, M5, M6, R5, M7, M8, M9, R6), and downstream (M10, T6, M11, M12, R7, M13, R8, R9, T7). When collecting samples, appropriate locations were selected on site, as follows: The sediment in front of the dam was collected in the cascade reservoirs, a position with stable velocity was selected for collection in the main stream between the cascade reservoirs, and tributaries close to the main stream were selected. Three parallel samples were collected at each point and mixed into 1–2 kg wet weight. The sediment was immediately stored in a wide mouth glass bottle in a refrigerator. Information on the cascade reservoirs is provided in Table 1.

Sample analysis

All samples were analyzed at the Institute of Geochemistry, Chinese Academy of Sciences. In the testing process for all physicochemical indices, one group of parallel samples was prepared for every ten samples. After removing impurities, sediments were freeze-dried at − 50 °C using a freeze dryer (FDU-2110, Tokyo Rikakikai, JPN). A total of 0.5 g of dry sediment was placed into a 50-mL centrifuge tube, and 10 mL of 30% H_2O_2 was then added to these suspensions to remove organic matter. Following 10 min of oscillation and resting for 12 h, the mixture was centrifuged (3000 r min^{-1}, 10 min), and the supernatant was discarded. Next, 15 mL of 20% HCl was added, and the mixture was stirred to enable a sufficient reaction and the removal of carbonates. After 12 h of standing still, the mixture was centrifuged, and the supernatant was discarded. The sample was then washed multiple times until a neutral pH was recorded. Ten milliliters of 0.05 mol L^{-1} $(NaPO_3)_6$ was then added to the sample, and the mixture was stirred before undergoing ultrasonic treatment for 5 min. Finally, particle size was measured using a laser particle size analyzer (Mastersizer 2000, Malvern, GBR). According to the testing range (0.02–2,000 μm) and particle characteristics, the samples were separated based on the following size fractionation: 0.02–4 μm (clay, fine particles), 4–63 μm (silt), and 63–2000 μm (sand, coarse particles) (Blott and Pye 2001). Moreover, the median particle size (D50) is the particle size corresponding to 50% of the total soil mass on the particle size distribution curve. It is an important index for particle size evaluation (Guo et al. 2020; Wang et al. 2020).

Sediments were passed through a 100-mesh size before being analyzed for heavy metals (Fe, Mn, Zn, Cr, Cu, As, Pb, Cd). As per the standard method proposed by the Chinese Ministry of Ecology and Environment (MEE 2016), 0.1 g was placed in a 100-mL conical flask and digested using 6 mL of aqua regia (prepared by mixing HCl and HNO_3 with a volume ratio of 3:1). Samples were digested using a hot plate for 2 h before being cooled to room temperature. The extract was filtered using quantitative filter paper into 50-mL volumetric flasks. The content of heavy metals was measured using an inductively coupled plasma mass spectrometer (ICP-MS, PerkinElmer, NexION 300X, USA).

After placing 1 g of sediment into a centrifuge tube, 1 mol L^{-1} HCl was added to remove carbonates; samples were left for 24 h for complete reaction. Each sample was then

Table 1 Information on the cascade reservoirs in the Wujiang River Basin (WRB), southwest China

Sites (n = 9)	Cascade reservoirs[a]	Location (latitude, longitude)	Year of construction[b]	Basin area (km^{2})[c]	Flow (m^{3} s^{-1})[d]	Hydraulic retention time (days)[e]
R1	Puding Reservoir	(26°22′54.47″N, 105°48′20.45″E)	1993	5871	123	40.6
R2	Hongjiadu Reservoir	(26°22′54.47″N, 105°48′20.45″E)	2004	9900	155	368.8
R3	Dongfeng Reservoir	(26°51′19.37″N, 106°9′19.54″E)	1994	18,161	343	28.1
R4	Wujiangdu Reservoir	(27°19′11.35″N, 106°45′39.91″E)	1979	27,790	502	49.3
R5	Goupitan Reservoir	(27°22′34.91″N, 107°37′54.28″E)	2003	43,250	717	89.8
R6	Silin Reservoir	(27°48′4.82″N, 108° 11′8.96″E)	2009	48,558	849	19.4
R7	Shatuo Reservoir	(28°29′36.57″N, 108°28′8.36″E)	2013	54,508	951	11.1
R8	Pengshui Reservoir	(29°11′54.84″N, 108°11′59.87″E)	2007	69,000	1300	10.0
R9	Yinpanm Reservoir	(29°16′40.88″N, 107°53′28.91″E)	2011	74,910	1380	2.0

[a] R1 is in Sancha River, the south source of the WRB; R2 is in Liuchong River, the north source of WRB; both flow into R3

[b] Data obtained from Liu et al. (2019), Xiang et al. (2016) and Zhao et al. (2017)

[c] Data obtained from Fan et al. (2017), Peng (2020), Xiang et al. (2016) and Yang et al. (2020a)

[d] Data obtained from Xiang et al. (2016) and Yang et al. (2020a)

[e] Data obtained from Li (2018), Xiang et al. (2016) and Yang et al. (2020a)

repeatedly flushed using Milli-Q until neutral; samples were then freeze-dried, ground, and passed through a 60-mesh size. An elemental analyzer (PE2400-II, Elementar, PerkinElmer, USA) was then used to determine total organic carbon (TOC) and total nitrogen (TN) contents. TP was tested using the Standards, Measurements and Testing method (Ruban et al. 1999). In brief, 0.2 g was ashed at 500 °C for 2 h, and then immersed in 20 mL of 3.5 mol L^{-1} HCl. After 16 h of oscillation, the mixture was centrifuged, and the extract was regulated until neutral. Testing was performed using the molybdenum-blue method (Murphy and Riley 1962), and the C/N ratio of the sediment sample was calculated.

Results and discussion

Spatial changes of the granularity in sediments

The cascade dam effectively intercepted the coarse particles in sediments, with the particle size distribution suggesting an obvious increase in fine-grained fractions ($p < 0.05$) and a decrease in coarse-grained fractions in sediments with distance through the WRB (Fig. 2a). Compared with the tributaries, main stream, and cascade reservoirs (Fig. 2b), D50 was also significantly reduced, by 56.8%, exceeding the reduction ratio along the way. The proportion of 63–2\000 μm decreased from 13.78 to 1.34%, indicating that more coarse particles were intercepted in the cascade reservoirs. In addition, the D50 of sediments occurred in the following order: upstream (14.5 μm) > midstream (9.7 μm) > downstream (6.6 μm) (Fig. 2c). Compared with upstream, the D50 of downstream declined by 54.7%. The proportion of fine particles increased from 32.0 to 38.3% and decreased from 9.9 to 1.9%, showing that coarse particles accumulated in the sediment along the way. Dams tend to intercept coarse particles more than fine ones (Dai and Liu 2013; Eiriksdottir et al. 2017). However, in the WRB, where cascading dams have been built, the interception may be even more serious (CERC 2020).

Spatial changes of heavy metals contents in sediments

In the WRB, the content of eight heavy metals in surface sediments decreased along the way. The average content of the heavy metals in the whole basin was ranked as follows: Fe (50,224 mg kg^{-1}) > Mn (1,863 mg kg^{-1}) > Zn (173.9 mg kg^{-1}) > Cr (143.27 mg kg^{-1}) > Cu (64.73 mg kg^{-1}) > As (43.37 mg kg^{-1}) > Pb (42.25 mg kg^{-1}) > Cd (1.37 mg kg^{-1}). The content of five heavy metals (Fe, Zn, Cu, As, Cd) declined significantly along the way (Fig. 3a–d: $p<0.01$). As and Cr decreased significantly in the sediments of the cascade reservoirs,

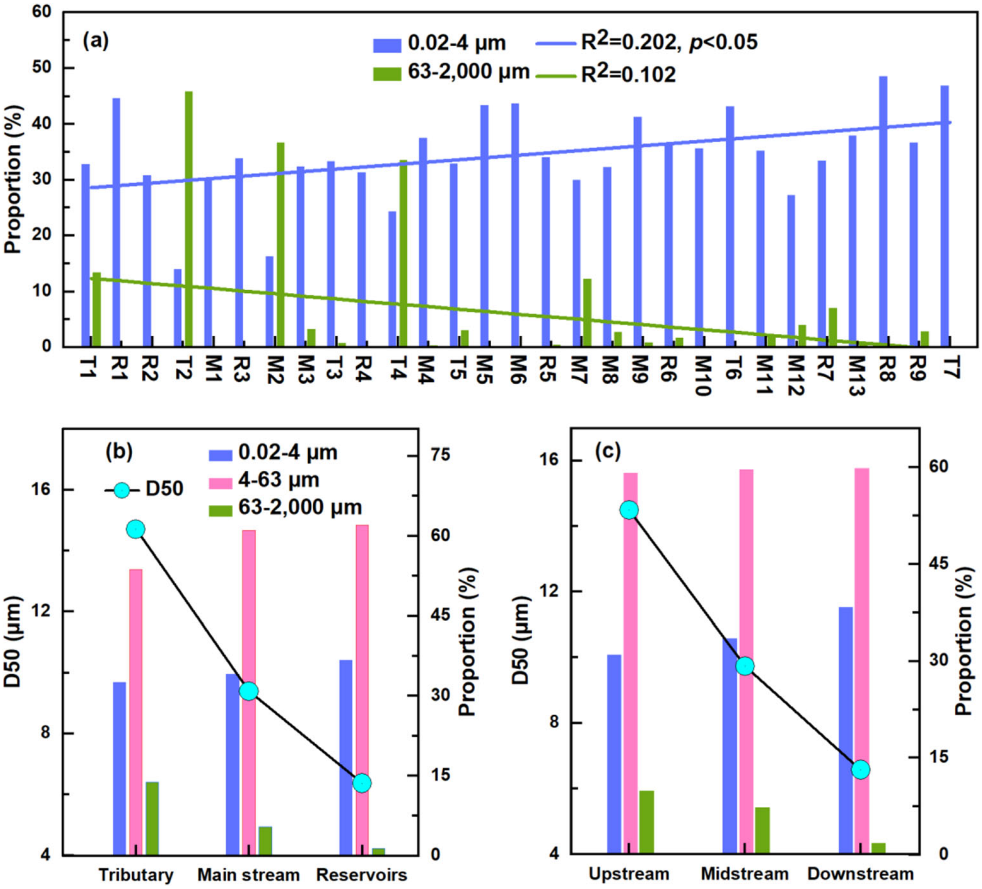

Fig. 2 Changes of sediment grain size in surface sediments of the WRB: a proportion of fine particles (0.02–4 μm) and coarse particle (63–2,000 μm) along the way of the WRB; b variation of sediment particle size in tributaries, the main stream and cascade reservoirs; c variation of sediment particle size in the upstream, midstream and downstream

indicating that their interception by the cascading dam was more obvious (Fig. 3 g and h, $p < 0.05$). However, the declining rates of Fe, Mn, Zn, Cu, Pb, and Cr in the cascade reservoirs sediments were lower than in the whole basin, indicating that the interception effect of the cascade dam on these elements was relatively low.

The hydrological condition of cascade reservoirs is an important factor affecting the distribution of heavy metals (Li et al. 2020; Zhao et al. 2017; Zhu 2005). In this study, the Spearman correlation between the important factor (HRT) and corresponding heavy metals in surface sediments was calculated (Table 2). The results showed that the contents of heavy metals (Fe, Zn, Cu, Cr, and As) increased significantly with the increase in hydraulic retention time (HRT, $p < 0.05$). However, As and Cd were negatively correlated with basin area and flow ($p < 0.05$). In the WRB, due to the large amount of particulate mercury captured by sediments, the total mercury concentration decreased from upstream to downstream (Zhao et al. 2017). Similarly, As and Li in the sediments of cascade reservoirs in the Luan River Basin in Northeast China are more upstream due to dam interception (Li et al. 2020).

However, heavy metals are not decreasing in all cascade reservoirs. Anthropogenic emission is an important factor interfering with the distribution of heavy metals. Due to chemical fertilizer and mineral exploitation, the contents of Cu, Pb, and Zn are higher in the reservoir downstream of Luan River Basin (Li et al. 2020). At the downstream of the Cantareira system reservoirs (São Paulo, Brazil), the contents of Mn and Cu in Paiva Castro reservoir increase due to urban sewage and algicide (copper sulfate) (Cardoso Silva et al. 2017).

Spatial changes of C, N, and P contents in sediments

The cascade dam altered the distribution of biogenic elements in the sediments. Compared with the tributaries, main stream, and cascade reservoirs, the distribution of biogenic elements was quite different. The average TOC content in the cascade reservoirs was the highest, but TN and TP presented the following order: tributaries < reservoirs < main stream (Fig. 4a). On the whole, the spatial distributions of C, N, and P contents are highest in the midstream, lower in the upstream, and lowest in the downstream (Fig. 4b). From a spatial distribution perspective, the TOC, TN, and TP contents were high in midstream sediments (R4), mainly because this reservoir is the oldest (41 years). The TOC at R5 was as high as 8.14%; however, this reservoir is only 16 years old. This result is probably because, in the initial period after reservoir

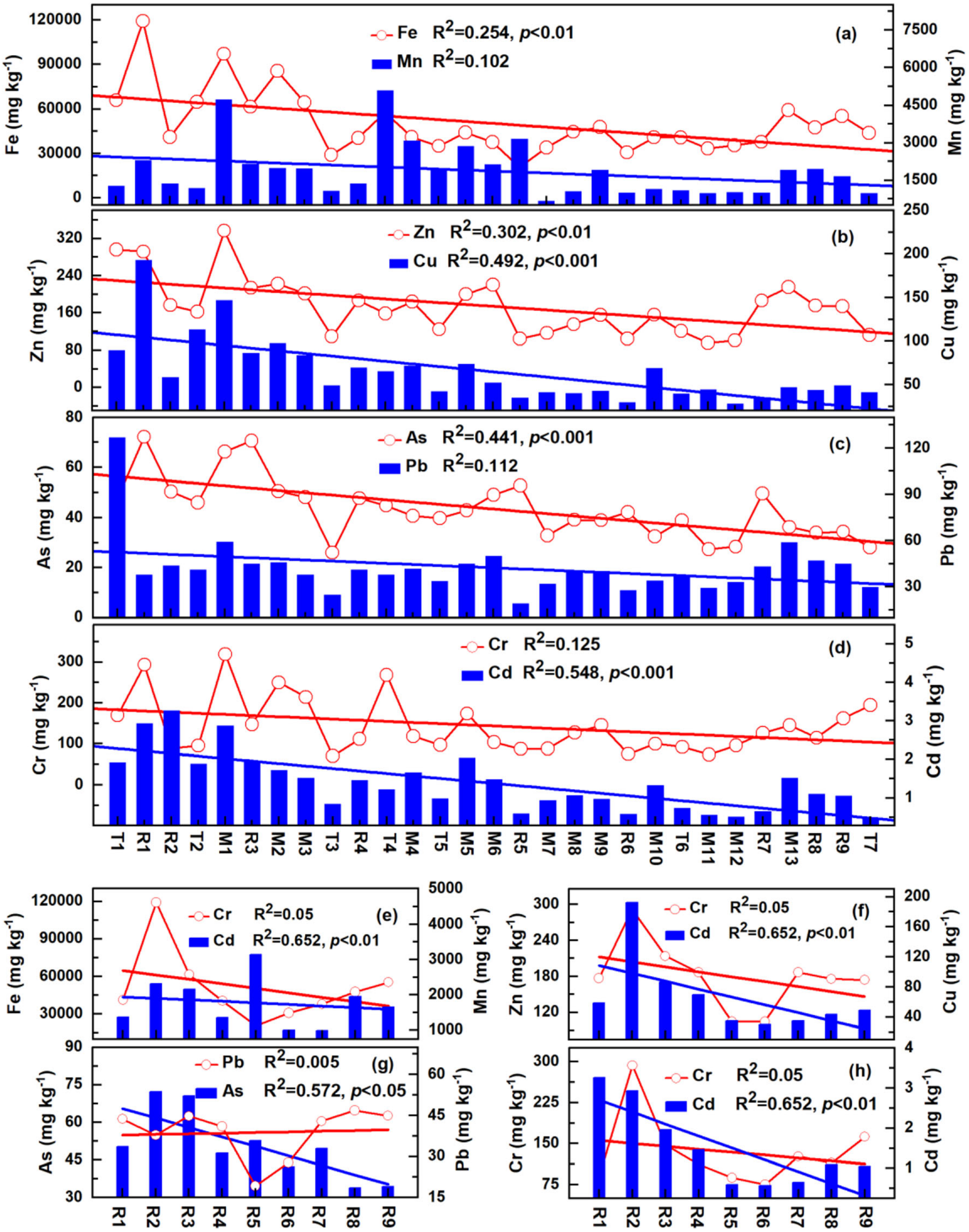

Fig. 3 Content variations of eight heavy metals in surface sediments along the way and in the cascade reservoirs of the WRB. The contents of Fe, Zn, Cu, As, and Cd were significantly and negatively correlated along the way ($p < 0.01$), and the decreasing trends in heavy metal contents (As and Cd) were highly significant in the cascade reservoirs of the WRB

construction, the nutrient concentrations in the water were greatly affected by an intense internal release due to the degradation of soil organic matter in flooded farmland and grassland. According to existing studies, the main cause of rising nutrients in the initial period after reservoir construction is the nutrients released by rotten vegetation in the hydro-fluctuation belt (e.g., Chang and Wen 1997).

The average C/N ratio was ranked as follows: upstream (9.81) > midstream (9.77) > downstream (7.35) (Fig. 4c). The results showed that from upstream to downstream, the main source of the organic matter of sedimentary species in the basin changed from terrigenous to internal. In non-karst areas, the interception rates of eight cascade dams for TN and TP in the upstream of the Yellow River (northern China) were found to reach 97.4% and 83.6% (Wei et al. 2011), showing that the interception effect of cascade dam on biogenic elements can be very significant. In particular, changes in the particle size of sediments can cause marked changes in the migration behaviors of elements (Eiriksdottir et al. 2017; Liu et al. 2020). Biogenic elements transported in the form of particles can be easily retained in reservoirs, causing changes in the ratios between biogenic elements in downstream rivers and coastal waters. Compared with rivers in Europe, most rivers in China have higher sediment contents, so the effect of a cascade dam in retaining biogenic elements is more significant (Zhu 2005). The Wujiang River is also a major contributor of nutrients to the Yangtze River, contributing 1/3 of the TP transported by the Yangtze River (Zhou et al. 2018). About 80% of the TP flux in the Wujiang River is particulate P distributed in the WRB, so P can be easily intercepted by reservoirs together with particles (Liu et al. 2009). However, due to the lack of an anaerobic layer at the bottom of many reservoirs in the WRB, P can be easily adsorbed by oxidized particles and stored in sediments, thus increasing the interception effect of P retention (Yin et al. 2010).

A significant positive correlation was found between the biogenic element contents and reservoir ages in the WRB: the higher the reservoir age, the higher the TOC, TN, and TP contents (Table 2, $p < 0.01$). Rivers with larger basin areas tend to receive more sediments and nutrients (Straskraba et al. 2013), and downstream areas far from the dam are affected not only by sediment inputs from the upstream but also by terrigenous inputs in the catchment area (Li et al. 2011). By analyzing the correlation between the basin area of the cascade dam and the contents of TOC, TN, and TP, an obvious declining trend with basin area was detected (Table 2). The WRB is divided into several sections by the cascade dam, resulting in

Table 2 Spearman correlations between influencing factors and the contents of biogenic elements and heavy metals in surface sediments of cascade reservoirs

Factors	Reservoir age	Basin area	Flow	HRT
Fe	-	-	-	0.817
Zn	-	-	-	0.665
Cu	-	-	-	0.911
Cr	-	-	-	0.827
Mn	-	-	-	-
As	-	-0.793	-0.807	0.783
Cd	-	-0.804	-0.768	-
Pb	-	-	-	-0.700
TOC	0.976	-0.762	-0.762	0.786
TN	0.967	-0.833	-0.833	0.700
TP	0.817	-0.733	-0.733	0.733

The influencing factors are reservoir age, basin area, and hydraulic retention time (HRT); orange means significant at the 0.01 level, and blue means significant at the 0.05 level

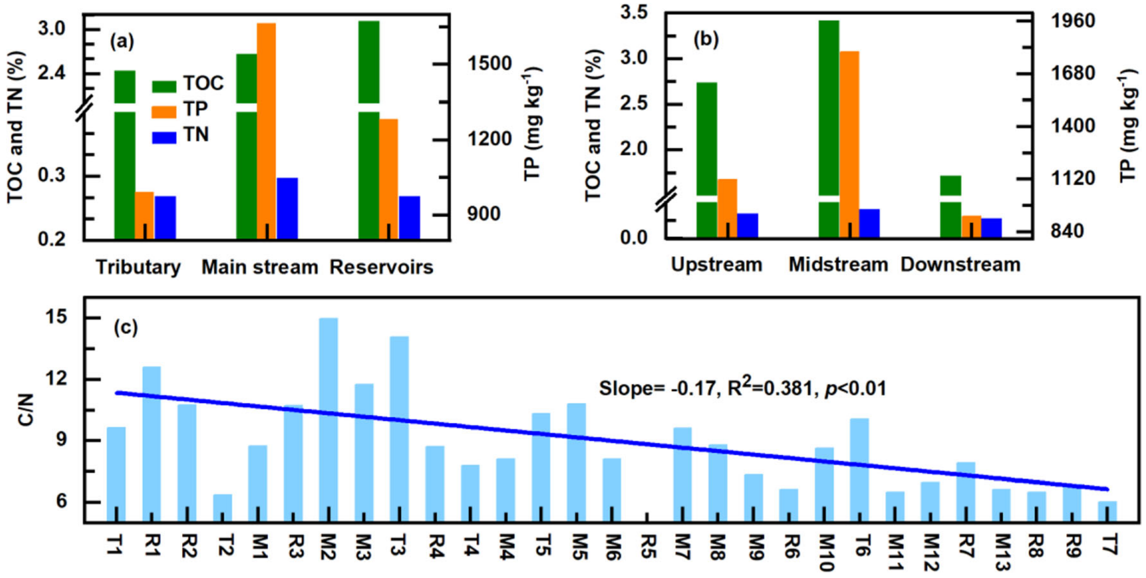

Fig. 4 Variational trend of TOC (total organic carbon), TP (total phosphorus), TN (total nitrogen), and C/N ratio in surface sediments of the WRB. The mean C/N ratio of the whole basin ranged from 6.0 to 33.6 and presented a significant declining trend along the way (except for R5, $p < 0.01$). The C/N ratio of sediments at R5 peaked at 33.6, suggesting that the shift in the organic matter source from external to internal and the influence of tributary inputs in the upstream was greater

serious damage to the connectivity of the river. The previous part of the material is transferred to the next part through the dam, and the dam will affect the transfer of material. As a result of interception in the sediments of the upper reservoir, the quantities of TOC, TN, and TP flowing to the next reservoir are reduced. In this study, it is considered that the source of material in the water body comes more from the partial basin area, which is actually controlled by the dam. In addition, the more TOC, TN, and TP are stored in the cascade reservoirs, the lower the flow and higher the HRT (Table 2: $p < 0.05$).

Implications

Cascade dam blocks the transport of water and sediments by natural rivers and further changes the granularity, chemical compositions, and distribution of sediments (Guo et al. 2020; Wang et al. 2020). Damming increases the average water depth and HRT and gradually transforms the ecosystem from a riverine one into a plankton-based autotrophic one (Winton et al. 2019). Also, the spatial distribution of particle size characteristics of sediments is affected by many factors, such as sediment supply and hydrodynamic conditions (Costigan et al. 2014; Rodriguez et al. 2020). In the present study, the tributaries downstream of the dam presumably provide more sediments and water, which helps the river to return to a more "natural" state.

When estimating the interception efficiency of a dam, full consideration should be given to dynamic changes in the hydrological conditions of reservoirs, such as spatial and temporal disparities in HRT, reservoir operation mode, reservoir age, and internal and external inputs (Wei et al. 2011). Changes in the intensities of provenance and hydrodynamics produce differential sedimentary environments, which can in turn be reflected by the parameter combinations of the constituents and particle sizes of sediments (Qiao et al. 2010).

Because the accumulation of sediments, heavy metals (Pb) and biogenic elements (TOC, TN, TP) in cascade reservoirs was not obtained in this study, and evidence of terrestrial sources in the WRB was also lacking, the interception efficiency and contribution of material sources of the cascade dam could not be quantified. Although, most global estimates of the impacts of dams on river nutrient fluxes rely on very simple approximations (Akbarzadeh et al. 2019; Maavara et al. 2017; Maavara et al. 2015). In this study, from the surface sediments, it was found that the material in the basin is significantly intercepted by the cascade dam, which is of great significance to the study of the impact of human activities on the surface material cycle. In the future, sediments and element contents in water bodies and point-source inputs of industry, agriculture, and major towns in the whole basin should also be investigated, therefore accurately quantifying the effects of the cascade dam on the transport of sediments and different elements.

Conclusions

In this study, the multi-parameter spatial distribution of surface sediments of the WRB was analyzed, and the interception effect of the cascade dam on sediment, heavy metals, biogenic elements and their influencing factors were explored. A clear and significant effect of the cascade dam in terms of intercepting sediments, heavy metals, and biogenic elements was found, as well as an obvious increase in fine-grained fractions and a decrease in coarse-grained fractions in sediments along the way of the WRB (i.e., the cascade dam of the WRB apparently intercepts coarse particles in sediments). In addition, the contents of heavy metals and biogenic elements in sediments decreased significantly along the main stream in the WRB, and, significantly, the contents of heavy metals (Fe, Zn, Cu, Cr and As) declined along the way. The contents of TOC, TN, and TP were highest in the sediments of the main stream and cascade reservoirs. Moreover, the contents of heavy metals were significantly affected by the HRT. The distribution of biogenic elements was affected by the reservoir age, partial basin area, and HRT. The reduction of the C/N ratio showed the main source of the organic matter of sediments in the basin changed from terrigenous to internal along the way, which was a vital factor in the interception effect of the cascade dam in the WRB. The findings of this study provide a scientific foundation for water resource management and protection of the aquatic environment along rivers with cascade dam. In the future, more work needs to be done to better understand the impacts of cascade dams on material transport processes.

Author contribution Conceptualization: Jingfu Wang, Peng Liao; Formal analysis: Kangkang He, Qingqing Sun, Xiaohong Yang, Zuxue Jin; Funding acquisition: Jingan Chen, Jingfu Wang; Investigation: Kangkang He, Xiaohong Yang, Zuxue Jin; Methodology: Jingfu Wang, Peng Liao; Project administration: Jingfu Wang, Jingan Chen; Supervision: Jingfu Wang, Peng Liao, Jingan Chen; Writing—original draft: Kangkang He, Xiaohong Yang; Writing—review and editing: Kangkang He, Jingfu Wang, Peng Liao. All the authors read and approved the final manuscript.

Funding This work was supported by the Strategic Priority Research Program of CAS [No. XDB40020400], a Chinese NSF Joint Fund Project [No. U1612441], a Chinese NSF project [No. 41773145, 41977296], the Youth Innovation Promotion Association of CAS [No. 2019389], and the CAS Interdisciplinary Innovation Team.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Akbarzadeh Z, Maavara T, Slowinski S, Van Cappellen P (2019) Effects of damming on river nitrogen fluxes: a global analysis. Global Biogeochem Cy 33(11):1339–1357. https://doi.org/10.1029/2019GB006222

Beusen AHW, Dekkers ALM, Bouwman AF, Ludwig W, Harrison J (2005) Estimation of global river transport of sediments and associated particulate C, N, and P. Global Biogeochem Cy 19(4). https://doi.org/10.1029/2005gb002453

Blott SJ, Pye K (2001) Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf Process Landf 26(11):1237–1248. https://doi.org/10.1002/esp.261

Cardoso-Silva S, Meirelles ST, Frascareli D, López-Doval JC, Rosa AH, Moschini-Carlos V, Pompêo M (2017) Metals in superficial sediments of a cascade multisystem reservoir: contamination and potential ecological risk. Environ Earth Sci 76(22):756. https://doi.org/10.1007/s12665-017-7104-9

CERC (2020) The sediment bulletin of Yangtze River in 2019. In: Changjiang Water Resources Commission, The Ministry Of Water Resources (ed). Changjiang Press, Wuhan. http://www.cjw.gov.cn/zwzc/bmgb/. Accessed 1 Jan 2021

Chang SP, Wen CG (1997) Changes in water quality in the newly impounded subtropical Feitsui Reservoir,Taiwan. J Am Water Resour As 33(2):343–357. https://doi.org/10.1111/j.1752-1688.1997.tb03514.x

Cole JJ, Prairie YT, Caraco NF, McDowell WH, Tranvik LJ, Striegl RG, Duarte CM, Kortelainen P, Downing JA, Middelburg JJ, Melack J (2007) Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. Ecosystems 10(1):172–185. https://doi.org/10.1007/s10021-006-9013-8

Costigan KH, Daniels MD, Perkin JS, Gido KB (2014) Longitudinal variability in hydraulic geometry and substrate characteristics of a Great Plains sand-bed river. Geomorphology 210:48–58. https://doi.org/10.1016/j.geomorph.2013.12.017

Dai ZJ, Liu JT (2013) Impacts of large dams on downstream fluvial sedimentation: an example of the Three Gorges Dam (TGD) on the Changjiang (Yangtze River). J Hydrol 480:10–18. https://doi.org/10.1016/j.jhydrol.2012.12.003

Duan WX, Guo SL, Wang J, Liu DD (2016) Impact of cascaded reservoirs group on flow regime in the middle and lower reaches of the Yangtze River. Water 8(6):218. https://doi.org/10.3390/w8060218

Duarte G, Segurado P, Haidvogl G, Pont D, Ferreira MT, Branco P (2020) Damn those damn dams: Fluvial longitudinal connectivity impairment for European diadromous fish throughout the 20th century. Sci Total Environ 761:143293. https://doi.org/10.1016/j.scitotenv.2020.143293

Eiriksdottir ES, Oelkers EH, Hardardottir J, Gislason SR (2017) The impact of damming on riverine fluxes to the ocean: a case study from Eastern Iceland. Water Res 113:124–138. https://doi.org/10.1016/j.watres.2016.12.029

Fan KX, Guo W, Zhang J (2017) Research on flood control operation effect of cascade reservoirs in Wujiang River during “2014.07” Flood (In Chinese, with English abstract). Yangtze River 48(05):8–12. https://doi.org/10.16232/j.cnki.1001-4179.2017.05.002

Fang Y, Deng W (2011) The critical scale and section management of cascade hydropower exploitation in Southwestern China. Energy 36(10):5944–5953. https://doi.org/10.1016/j.energy.2011.08.022

Feng XB, Meng B, Yan HY, Fu XW, Yao H, Shang LH (2018) Biogeochemical cycle of mercury in reservoir systems in Wujiang River Basin, Southwest China. Science Press and Springer Nature, Beijing and Singapore

Fox CA (2020) River basin development. In: Kobayashi A (ed) International Encyclopedia of Human Geography, 2nd edn. Elsevier, Oxford, pp 1–8. https://doi.org/10.1016/B978-0-08-102295-5.10023-X

Fuggle R, Smith WT (2000) Experience with dams in water and energy resource development in the People’s Republic of China. Paper presented at the World Commission on Dams, https://www.rina.org/en/wcd-world-commission-on-dams

Grill G, Lehner B, Thieme M, Geenen B, Tickner D, Antonelli F, Babu S, Borrelli P, Cheng L, Crochetiere H, Ehalt Macedo H, Filgueiras R, Goichot M, Higgins J, Hogan Z, Lip B, McClain ME, Meng J, Mulligan M et al (2019) Mapping the world’s free-flowing rivers. Nature 569(7755):215–221. https://doi.org/10.1038/s41586-019-1111-9

Guo XJ, Zhu XS, Yang ZJ, Ma J, Xiao SB, Ji DB, Liu DF (2020) Impacts of cascade reservoirs on the longitudinal variability of fine sediment characteristics: a case study of the Lancang and Nu Rivers. J Hydrol 581:124343. https://doi.org/10.1016/j.jhydrol.2019.124343

Hahn J, Opp C, Evgrafova A, Groll M, Zitzer N, Laufenberg G (2018) Impacts of dam draining on the mobility of heavy metals and arsenic in water and basin bottom sediments of three studied dams in Germany. Sci Total Environ 640-641:1072–1081. https://doi.org/10.1016/j.scitotenv.2018.05.295

Han GL, Tang Y, Xu ZF (2010) Fluvial geochemistry of rivers draining karst terrain in Southwest China. J Asian Earth Sci 38(1):65–75. https://doi.org/10.1016/j.jseaes.2009.12.016

Han Q, Wang BL, Liu CQ, Wang FS, Peng X, Liu XL (2018) Carbon biogeochemical cycle is enhanced by damming in a karst river. Sci Total Environ 616-617:1181–1189. https://doi.org/10.1016/j.scitotenv.2017.10.202

Huang QB, Qin XQ, Liu PY, Zhang LK, Su CT (2017) Impact of sulfuric and nitric acids on carbonate dissolution, and the associated deficit of CO_2 uptake in the upper–middle reaches of the Wujiang River, China. J Contam Hydrol 203:18–27. https://doi.org/10.1016/j.jconhyd.2017.05.006

Kondolf GM, Rubin ZK, Minear JT (2014) Dams on the Mekong: cumulative sediment starvation. Water Resour Res 50(6):5158–5169. https://doi.org/10.1002/2013wr014651

Li QF, Yu MX, Lu GB, Cai T, Bai X, Xia ZQ (2011) Impacts of the Gezhouba and Three Gorges reservoirs on the sediment regime in the Yangtze River, China. J Hydrol 403(3-4):224–233. https://doi.org/10.1016/j.jhydrol.2011.03.043

Li SQ (2018) Influence of dam interception on nutrient and inorganic nitrogen cycling in Wujiang River Basin (In Chinese, with English abstract). Tianjin University. https://doi.org/10.27356/d.cnki.gtjdu.2018.002210, Beijing

Li YY, Gao B, Xu DY, Peng WQ, Liu XB, Qu XD, Zhang M (2020) Hydrodynamic impact on trace metals in sediments in the cascade reservoirs, North China. Sci Total Environ 716:136914. https://doi.org/10.1016/j.scitotenv.2020.136914

Li ZW, Xu XL, Zhu JX, Xu CH, Wang KL (2019) Effects of lithology and geomorphology on sediment yield in karst mountainous catchments. Geomorphology 343:119–128. https://doi.org/10.1016/j.geomorph.2019.07.001

Liu CQ, Wang FS, Wang YC, Wang BL (2009) Responses of aquatic environment to river damming-from the geochemical view (In Chinese, with English abstract). Resources and Environment in the Yangtze Basin 18(4):384–394

Liu F, Cao Y, Wang W, Sun JY, Jiang HS, Li W (2019) A preliminary study on the distribution pattern and diversity of wetland plants in the riparian ecotone of Cascade Reservoirs along the Wujiang River

(In Chinese, with English abstract). Earth Environ 47(06):760–767. https://doi.org/10.14050/j.cnki.1672-9250.2019.47.141

Liu MD, He YP, Baumann Z, Zhang QR, Jing X, Mason RP, Xie H, Shen HZ, Chen L, Zhang W, Zhang QG, Wang XJ (2020) The impact of the Three Gorges Dam on the fate of metal contaminants across the river–ocean continuum. Water Res 185:116295. https://doi.org/10.1016/j.watres.2020.116295

Maavara T, Lauerwald R, Regnier P, Van Cappellen P (2017) Global perturbation of organic carbon cycling by river damming. Nat Commun 8(1):15347. https://doi.org/10.1038/ncomms15347

Maavara T, Parsons CT, Ridenour C, Stojanovic S, Dürr HH, Powley HR, Van Cappellen P (2015) Global phosphorus retention by river damming. P Natl Acad Sci USA 112(51):15603–15608. https://doi.org/10.1073/pnas.1511797112

Meade RH (2004) Engineering works and their effects on movement and storage of sediment in Mississippi river and its major tributaries. Tsinghua University Press, Beijing

Meade RH, Moody JA (2010) Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940-2007. Hydrol Process 24(1):35–49. https://doi.org/10.1002/hyp.7477

MEE (2016) Soil and sediment-determination of aqua regia extracts of 12 metal elements-inductively coupled plasma mass spectrometry. In: Ministry of Ecology and Environment, The People's Republic of China (ed). China Environmental Press, Beijing. http://english.mee.gov.cn/Resources/standards/Soil/Method_Standard4/201607/t20160704_357088.shtml. Accessed 20 Jul 2020

Murphy J, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. Anal Chim Acta 27:31–36. https://doi.org/10.1016/S0003-2670(00)88444-5

MWR (2019) 2018 Statistic Bulletin on China Water Activities. In: Ministry of Water Resources, The People's Republic of China (ed). China Water & Power Press, Beijing. http://www.mwr.gov.cn/sj/tjgb/slfztjgb/201912/t20191210_1374268.html. Accessed 25 Dec 2020

Peng T (2020) Study on flood resource utilization of cascade reservoirs in the middle and lower reaches of the Wujiang River (In Chinese, with English abstract). Water Resour Power 38(08):59-61+103

Qiao SQ, Shi XF, Wang GQ, Yang G, Hu NJ, Liu KF, Liu YG, Zhu AM, Li CX (2010) Discussion on grain-size characteristics of seafloor sediment and transport pattern in the Bohai Sea (In Chinese, with English abstract). Haiyang Xuebao 32:139–147

Rodriguez AB, McKee BA, Miller CB, Bost MC, Atencio AN (2020) Coastal sedimentation across North America doubled in the 20th century despite river dams. Nat Commun 11(1):3249. https://doi.org/10.1038/s41467-020-16994-z

Ruban V, López-Sánchez FJ, Pardo P, Rauret G, Muntau H, Quevauviller P (1999) Selection and evaluation of sequential extraction procedures for the determination of phosphorus forms in lake sediment. J Environ Monit 1(1):51–56. https://doi.org/10.1039/A807778I

Sharples J, Middelburg JJ, Fennel K, Jickells TD (2017) What proportion of riverine nutrients reaches the open ocean? Global Biogeochem Cy 31(1):39–58. https://doi.org/10.1002/2016gb005483

Shi WQ, Chen QW, Zhang JY, Liu DS, Yi QT, Chen YC, Ma HH, Hu LM (2020) Nitrous oxide emissions from cascade hydropower reservoirs in the upper Mekong River. Water Res 173:115582. https://doi.org/10.1016/j.watres.2020.115582

Straskraba M, Tundisi J, Duncan A (2013) Comparative reservoir limnology and water quality management, vol 77. Springer Science & Business Media, Berlin

Van Cappellen P, Maavara T (2016) Rivers in the Anthropocene: global scale modifications of riverine nutrient fluxes by damming. Ecohydrol Hydrobiol 16(2):106–111. https://doi.org/10.1016/j.ecohyd.2016.04.001

Vörösmarty CJ, Meybeck M, Fekete B, Sharma K, Green P, Syvitski JPM (2003) Anthropogenic sediment retention: major global impact from registered river impoundments. Glob Planet Chang 39(1):169–190. https://doi.org/10.1016/S0921-8181(03)00023-7

Wang BL, Zhang HT, Liang X, Li XD, Wang FS (2019) Cumulative effects of cascade dams on river water cycle: evidence from hydrogen and oxygen isotopes. J Hydrol 568:604–610. https://doi.org/10.1016/j.jhydrol.2018.11.016

Wang XX, Zhou J, Wu YH, Bol R, Wu Y, Sun HY, Bing HJ (2020) Fine sediment particle microscopic characteristics, bioavailable phosphorus and environmental effects in the world largest reservoir. Environ Pollut 265:114917. https://doi.org/10.1016/j.envpol.2020.114917

Wei OY, Hao FH, Song KY, Zhang X (2011) Cascade Dam-Induced hydrological disturbance and environmental impact in the upper stream of the Yellow River. Water Resour Manag 25(3):913–927. https://doi.org/10.1007/s11269-010-9733-6

Winton RS, Calamita E, Wehrli B (2019) Reviews and syntheses: dams, water quality and tropical reservoir stratification. Biogeosciences 16(8):1657–1671. https://doi.org/10.5194/bg-16-1657-2019

Xiang P, Wang SL, Lu WQ, Yang YX, Huang QS (2016) Distribution and retention efficiency of nitrogen and phosphorus in cascade reservoirs in Wujiang River Basin (In Chinese, with English abstract). Earth Environ 44(05):492–501. https://doi.org/10.14050/j.cnki.1672-9250.2016.05.002

Xu B, Li Y, Han F, Zheng Y, Ding W, Zhang C, Wallington K, Zhang Z (2020) The transborder flux of phosphorus in the Lancang-Mekong River Basin: Magnitude, patterns and impacts from the cascade hydropower dams in China. J Hydrol 590:125201. https://doi.org/10.1016/j.jhydrol.2020.125201

Yang MD, Li XD, Huang J, Ding SY, Yi YB (2020a) Damming effects on river sulfur cycle in karst area: a case study of the Wujiang cascade reservoirs. Agric Ecosyst Environ 294:106857. https://doi.org/10.1016/j.agee.2020.106857

Yang N, Li Y, Zhang WL, Lin L, Qian B, Wang LF, Niu LH, Zhang HJ (2020b) Cascade dam impoundments restrain the trophic transfer efficiencies in benthic microbial food web. Water Res 170:115351. https://doi.org/10.1016/j.watres.2019.115351

Yang SL, Zhang J, Zhu J, Smith JP, Dai SB, Gao A, Li P (2005) Impact of dams on Yangtze River sediment supply to the sea and delta intertidal wetland response. J Geophys Res-Earth 110(F3). https://doi.org/10.1029/2004jf000271

Yin R, Wang FS, Mei HY, Yao CC, Guo MY (2010) Distribution of phosphorus forms in the sediments of cascade reservoirs with different trophic states in Wujiang catchment (In Chinese, with English abstract). Chinese J Ecol 29(1):91–97. https://doi.org/10.13292/j.1000-4890.2010.0051

Zhao L, Guo YN, Meng B, Yao H, Feng XB (2017) Effects of damming on the distribution and methylation of mercury in Wujiang River, Southwest China. Chemosphere 185:780–788. https://doi.org/10.1016/j.chemosphere.2017.07.077

Zhou T, Cheng TY, Yu NX, Wang FS (2018) Nitrogen and phosphorus retention in cascade reservoirs along the upper reaches of Wujiang River (In Chinese, with English abstract). Chinese J Ecol 37(03):707–713

Zhu J (2005) Eefets of dams on the biogeoehemical cyeles of nutrients in the Wujiang River (In Chinese, with English abstract). Graduate School of Chinese Academy of Sciences (Institute of Geochemistry), Beijing