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PRIMARY RESEARCH PAPER

Different hydrodynamic conditions on the deposition of organic carbon in sediment of two reservoirs

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Abstract In regulated freshwater ecosystems, the deposition process of organic carbon (OC) in sediment could be affected by all the changes of physical, chemical, and biological factors. To assess different hydrodynamic conditions on the deposition of OC in sediment, the combination of elemental and stable isotope analyses was carried out in two reservoirs: the Huairou Reservoir (HR), which undergoes seasonal water level fluctuation (WLF) like natural lakes, and the Shisanling Reservoir (SR), which undergoes daily WLF for the operation of pumped storage power station. In general, OC concentration and its variation were comparable in the two reservoirs, whereas the OC distribution showed completely different features. The OC burial rate in SR was nearly two times more than in the HR, which reflect the impact of WLFs on the erosion of soil. For the relative contribution of phytoplankton-derived OC (P-OC), macrophyte-derived OC (M-OC), and terrestrial OC (T-OC) in sediment, the T-OC and M-OC in the SR were both higher than those of the HR, whereas the P-OC was markedly lower. Furthermore, the classification of nearshore and offshore sediments suggested that hydrodynamic conditions affected the T-OC import by physical processes and the in situ contributions of P-OC and M-OC with a spatial difference.

Keywords Hydrodynamic condition · Mixing model · Sedimentary organic carbon · Stable isotope · Water level fluctuation

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Introduction

The impounding process on natural rivers has dramatically changed carbon transportation, and the role of reservoir sediments in global and regional carbon cycles has received increasing attention (Cole et al., 2007; Downing et al., 2008; Tranvik et al., 2009). Previous studies have suggested that the amount of organic carbon (OC) accumulated in reservoir sediments was significant and could be used to explain part of the carbon missing in global budgets (Mulholland & Elwood, 1982). The OC burial rate in reservoir sediments was estimated to be in the range of 0.16–0.22 Pg a^{-1}, which was higher than the estimates of 0.02–0.07 Pg a^{-1} and 0.10 Pg a^{-1} in lake and marine sediments, respectively (Dean & Gorham, 1998;

Einsele et al., 2001; Cole et al., 2007; IPCC, 2007). Studies on OC in lake and marine sediments have been well documented in many aspects, including OC concentration, distribution, and sources in sediments, as well as the factors influencing the sedimentary OC accumulation (Viner, 1989; Tenzer et al., 1997; Brenner et al., 1998; Sobek et al., 2009; Gudasz et al., 2010). However, research on man-made reservoirs is still limited. Furthermore, previous studies on reservoir have mainly focused on OC content measurements and burial rate assessments (Hyne, 1978; Ritchie, 1989; Dean & Gorham, 1998; Pittman et al., 2013); only a few studies have investigated the impact factors (especially those factors that differ from lakes) on OC deposition (Downing et al., 2008; Thothong et al., 2011), and even fewer studies have determined the OC source in sediments.

In contrast with natural lakes, reservoirs are man-made water bodies that usually experience greater changes in hydrodynamic conditions depending on human demand. Several studies have reported that hydrodynamic conditions could affect not only the erosion and sedimentation but also the biotic communities, with both direct and indirect effects (Furey et al., 2004; Unger et al., 2009; Li et al., 2012). The direct effects include water disturbance and water level fluctuation, whereas the indirect effects work through environmental factors, i.e., transparency, temperature, dissolved oxygen, and conductivity (Sweerts et al., 1991; Hartnett et al., 1998; Gudasz et al., 2010). To date, the potential effects have been examined from the physical, species, and even ecosystem level (Hulthe et al., 1998; Leira & Cantonati, 2008), and these changes are associated with the concentration and sources of OC in sediments. Nevertheless, few studies have examined the hydrodynamic effects on sedimentary OC accumulation in regulated reservoirs.

In reservoirs, the distribution and source of sedimentary OC has significant implications for the depositional environment (Thothong et al., 2011; Sakai et al., 2013). Sedimentary OC can be allochthonous derived from terrestrial organic matter in the watershed or autochthonous produced in situ through photosynthesis by phytoplankton and macrophytes (Downing et al., 2008; Park et al., 2009). Organic matter from different sources deposited onto the sediment–water interface are partially mineralized into CO_2 and CH_4 by microbial activities and partially buried in the sediment as humus (Sobek et al., 2009). Sedimentary OC can reflect the trophic status of the reservoir and the vegetation in the watershed. Therefore, it is important to identify the sources of OC in reservoir sediments.

The atomic C/N ratio and stable isotope composition of bulk organic material have increasingly been used to quantify the contribution of several sources of mixed OC in sediments (Kikuchi & Wada, 1996; Phillips & Gregg, 2003). In general, based on the different mechanisms for CO_2 fixation, $\delta^{13}C$ values have been widely used to discriminate terrestrial C3 versus C4 plants (Collister et al., 1994). Meanwhile, macrophytes and phytoplankton also have distinct $\delta^{13}C$ values that reflect the usage degree of atmospheric CO_2 versus dissolved inorganic carbon for photosynthesis (Kendall et al., 2001). On the other hand, nitrogen (N) uptake pathways of different species also make it possible to employ $\delta^{15}N$ values as a tracer of organic materials (Kikuchi & Wada, 1996). Nevertheless, previous studies have mainly focused on estuarine sediments where the continental and marine OC sources are well discriminated (Thornton & McManus, 1994; Dubois et al., 2012) and lake sediments where allochthonous and autochthonous OC reveal large differences (Tenzer et al., 1997; Murase & Sakamoto, 2000; Sakai et al., 2013). However, there have been few studies that have addressed the allochthonous and autochthonous sources of OC in reservoir sediments (Hyne, 1978; Pittman et al., 2013).

This study examined the characteristics of sedimentary OC in two reservoirs with contrasting hydrodynamic conditions. The objectives of the study were as follows: (1) determine the OC, N, and C/N ratio distribution in surface sediments of the two reservoirs; (2) estimate the relative contribution of potential sources to OC in sediments; and (3) evaluate the effects of different hydrodynamic conditions on the distribution and source of OC in nearshore and offshore sediments, respectively.

Materials and methods

Site description

This study was conducted in the Huairou Reservoir (HR) and the Shisanling Reservoir (SR), located north of Beijing, China (Fig. 1). The regional climate is characterized by a warm temperate, semi-humid continental monsoon climate, which is hot and humid

Fig. 1 Geographical and sampling map of the HR and SR in Beijing, China. **A** Location of the two reservoirs; **B** The water depth contour and distribution of sampling sites in the HR; **C** The water depth contour and distribution of sampling sites in the SR. Nearshore sediments (*triangle*), offshore sediments (*circle*), and soils (*square*)
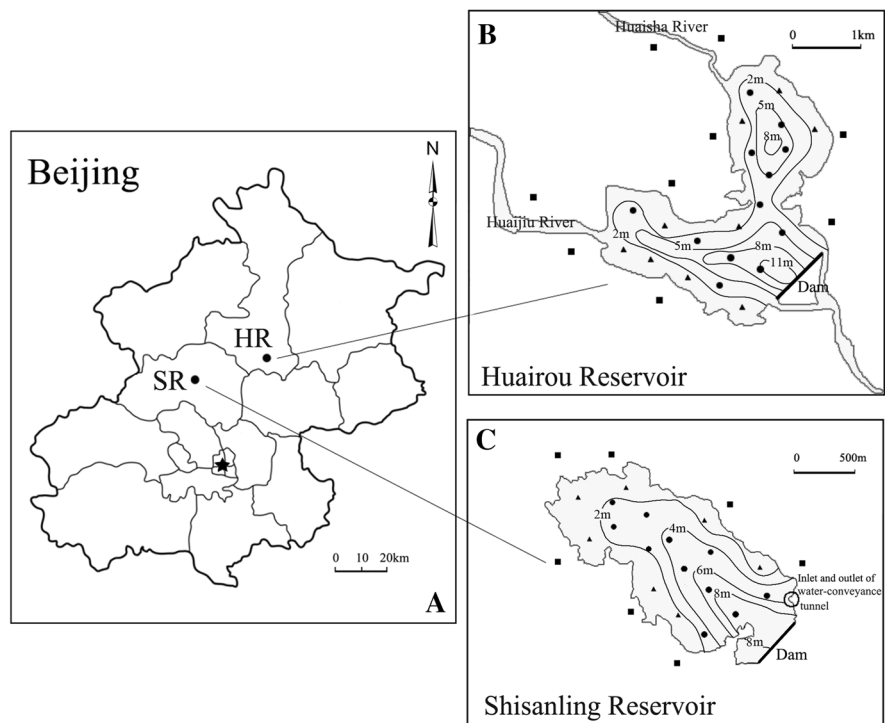
in summer and cold and dry in winter. The annual precipitation averages approximately 570 mm, and 70% of the rainfall occurs between June and August (Beijing Meteorological Bureau).

HR is located at the intersection of the Huaisha River and the Huaijiu River, 60 km northeast of Beijing city (Fig. 1B). HR has provided domestic water to Beijing since its inception in 1958. SR is 30 km west of the HR, and was also commissioned in 1958. SR was originally built for irrigation and flood control. Due to the regular shutoff of the upstream river since 1970s, the SR was altered to the lower reservoir of the Shisanling Pumped Storage Power Station (SPSPS, http://www.chincold.org.cn/news/li080321-10-Shisanling.pdf) in the 1990s. The upper reservoir of the SPSPS and SR is connected with a water conveyance tunnel, and the inlet and outlet of the tunnel in the SR is situated northeast of the reservoir (Fig. 1C). The installed capacity of the SPSPS is 800 MW, and water loss is supplemented by rainfall and pumping from the downstream reservoir. The main characteristics of the two reservoirs are shown in Table 1.

The HR and SR have contrasting hydrodynamic conditions caused by the different reservoir regulations, of which the HR undergoes seasonal water level changes, similar to unregulated natural lakes, and the SR is regulated daily to maintain the pumped storage power plant (Fig. 2). The SR experiences a daily water level fluctuation (WLF) of more than 0.5 m, whereas the HR has a modest daily WLF, which was estimated to be less than 0.05 m per day (Xing, 2011). To assess the impacts of different WLFs on sedimentary OC concentration and OC sources, the sampling sites of the two reservoirs were grouped into nearshore and offshore sites (Fig. 1). Specifically, nearshore sites are macrophytes dominated, and their altitudes are between the annual water level ranges of the two reservoirs. Offshore sites are phytoplankton dominated, and their altitudes are below the lowest water levels. Thus, nearshore sites emerge during low water level periods, and offshore sites are submerged year round. The main macrophyte species and phytoplankton divisions found in the two reservoirs are shown in Table 2.

Sample collection and pretreatment

Surface sediment samples were collected at 21 sites in the HR and 18 sites in the SR during October 2012 (Fig. 1). These sites were evenly distributed in the nearshore and offshore zones of each reservoir, which was determined

Table 1 Characteristics of the Huairou Reservoir (HR) and the Shisanling Reservoir (SR)

	HR	SR
Location	40°19′07″N	40°15′20″N
	116°36′49″E	116°16′07″E
Impoundment year	1958	1958
Watershed soil type	Loam	Loam
Maximum dam height (m)	20	29
Mean depth (m)	6.0	3.0
Maximum reservoir surface (km^2)	12	3.11
Catchment surface area (km^2)	525	223
Maximum reservoir volume (km^3)	0.14	0.073
Mean annual discharge (m^3 s^{-1})	2.69	0.98
Water residence time (day)	158	11
Annual water level range above sea level (m)	84.0–86.0	56.0–58.0
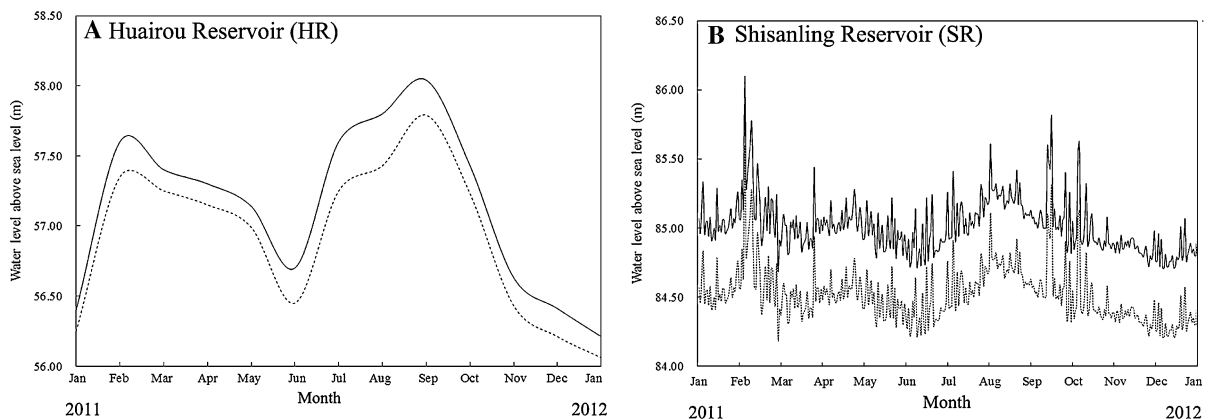
Fig. 2 The monthly water level variation of the HR (**A**) and daily water level variation of the SR (**B**) in the year 2011. The *solid line* is the highest water level, and the *dashed line* is the lowest water level

Table 2 The main macrophyte species and phytoplankton divisions in the Huairou Reservoir (HR) and Shisanling Reservoir (SR)

		HR	SR
Macrophyte			
	Emergent plants	*Phragmites australis*	*Phragmites australis*
		Typha angustifolia	*Typha angustifolia*
	Floating-leaved plants	*Marsilea quadrifolia*	Null
	Submerged plants	*Myriophyllum spicatum*	*Myriophyllum spicatum*
		Ceratophyllum demersum	*Ceratophyllum demersum*
		Potamogeton crispus	*Vallisneria asiatica*
Phytoplankton		*Chlorophyta*	*Chlorophyta*
		Cyanophyta	*Cyanophyta*
		Bacillariophyta	*Bacillariophyta*

References Chen (2008), Zhang et al. (2012), Lu et al. (2012)

by depth and water level when sampling. At each sampling site, a Multisampler (Eijkelkamp®, Netherlands) was used to collect sediment cores. The sampling strategy was to mix the top 5 cm of two to three cores of each site together, and the samples were stored in the dark. The depth from the water surface to the sediment

surface was measured with a Secchi disk on a metered rope, and the depth from the water surface to the underlying hard sandstones was measured with demountable metal rods (Brenner et al., 1998). The sediment thickness was estimated by subtracting the former from the latter.

To determine the stable isotope values of the potential OC sources in sediments, water (for phytoplankton-derived organic matter), macrophyte, and surrounding soil samples were collected. Water samples were taken 1 m below the surface using a plastic bottle at offshore sites, and the temperature was measured in the field. Macrophytes were sampled by hand at nearshore sites when present. According to the distribution map of soil subtype in Beijing (HR, Huairou County: http://www.hrzzzx.gov.cn/huairouweb/trfb. html and SR, Changping County: http://www.bjnjtg. com.cn/upload/changpingweb/trfb.html), seven to nine surrounding soil samples of each reservoir were taken using a gouge (Fig. 1). The locations of all sampling sites were recorded using a GPS unit (Garmin® GPSmap 60CSx, China).

In the laboratory, water samples were gently filtered through GF/F filters and then stored at −80°C. Macrophyte samples were cleaned with deionized water, dried in an oven at 50°C for 12 h, and then powdered using a ball mill. Soil and sediment samples were dried at 105°C for 8 h, sieved to pass through a 0.2-mm screen to eliminate the influence of debris, and then crushed to a particle size until they could be sieved to pass through a 0.075-mm screen according to the manual of the organic carbon analyzer. The water content of the sediment and soil samples were measured by weighing samples both before and after drying, and dry bulk density was measured using ring samplers. All soil, sediment, and plant samples were sealed in plastic bags and stored in the dark at room temperature before conducting measurements.

Organic carbon and nitrogen analysis

Organic carbon (OC) concentration was determined by subtracting inorganic carbon (IC) from total carbon (TC), both of which were measured in an organic carbon analyzer (Shimadzu® TOC-V attached with SSM-5000A, Japan): TC was measured by combustion at 900°C in an oxygen-rich atmosphere, and IC was measured by reaction with phosphoric acid at 200°C. Total nitrogen (N) content was determined by dry combustion at 950°C using an elemental analyzer (Euro Vector® EA3000, Italy) according to standard procedures. Each sample was analyzed in duplicate and the average value was reported. The accuracy limit of the instrument is estimated at 0.001% by mass, and the relative standard deviation is within 5%. Moreover, the distribution map of OC and N concentrations and C/N ratios in sediments were drawn using the kriging function of the spatial analysis tool in ArcMap 10.0 (ESRI®, USA).

Organic carbon accumulation rate

The Organic carbon accumulation rate (OCAR, g m^{-2} year^{-1}) of the two reservoirs was calculated based on the followings: organic carbon concentration (OC, mg g^{-1}), dry bulk density (DBD, g cm^{-3}), sediment thickness (d, cm), and the impoundment year (T, year) (Mulholland & Elwood, 1982; Dean & Gorham, 1998; Gui et al., 2013). The equation is shown as below:

$$OCAR = OC \times DBD \times d \times 10/T.$$

Stable isotope analysis

Stable isotope (C and N) analyses of all samples were performed using an elemental analyzer coupled with an isotope ratio mass spectrometer (Thermo Fisher® Delta V Advantage EA-IRMS, German) following the methods of Maki et al. (2010) and Dubois et al. (2012). Data are reported as δ in parts per thousand (‰) relative to Vienna Pee Dee belemnite for $\delta^{13}C$ and atmospheric N$_2$ for $\delta^{15}N$:

$$\delta R = (X_{sample}/X_{standard} - 1) \times 10^3 (‰),$$

where R is ^{13}C or ^{15}N (‰) and X is the isotope ratio (^{13}C to ^{12}C or ^{15}N to ^{14}N). Carbonate content was eliminated by soaking in 0.1 M HCl for 24 h before stable carbon isotope measurements (Murase & Sakamoto, 2000; Sakai et al., 2013), because a preliminary analysis on inorganic carbon content in sediments accounted for 20 to 50% of the total carbon (Table 3). Reproducibility in the analyses was within ±0.2‰. In addition, published data of the terrestrial C3 and C4 plants in Beijing were also referenced (Lu et al., 2012).

Source of organic carbon

In this study, phytoplankton, macrophytes, soil organic matter, and terrestrial C3 and C4 plants are all the potential sources to OC in sediments (Kendall et al., 2001; Lu et al., 2012). An indicator parameter C/N ratio, which is determined by the source of organic materials, is used for the qualitative analysis of the OC sources in sediment. The lignin and cellulose of terrestrial plants and macrophytes contain relatively low N in contrast to N-rich proteins of freshwater phytoplankton (Hyne, 1978; Tenzer et al., 1997). Thus, it was generalized that terrestrial plants (15–30) and macrophytes (10–30) have high C/N ratios, whereas phytoplankton (5–8) has low values (Meyers & Ishiwatari, 1993; Kendall et al., 2001). However, the C/N ratio was not a useful index to quantitatively calculate the OC sources in sediment due to the similar values of macrophyte- and terrestrial C3 and C4 plant-derived organic matters.

An isotopic mixing model with δ^{13}C and δ^{15}N is used to quantitatively calculate the relative contribution of potential sources to OC in sediments. The model can limit the sources that may not contribute, and show high accuracy when determining the n + 1 different sources with n different isotope elements (Phillips & Gregg, 2003; Sakai et al., 2013). In order to improve the estimation accuracy, we limit the number of potential OC sources in sediments. Terrestrial C3 and

C4 plants are the primary producers for allochthonous OC in sediments. However, we did not include them in the model directly but instead through soil OC for the following reasons. First, we did not need to classify the contribution of C3 and C4 plants in allochthonous sedimentary organic carbon in this study. Second, the δ^{13}C and δ^{15}N values of the soil can reflect the terrestrial plants growing in the soil (Kendall et al., 2001). Live terrestrial C3 and C4 plants cannot directly contribute to the OC in sediments, whereas the leaves and debris of terrestrial plants mainly decompose in the soil before being transported to the reservoir by surface runoff. In addition, considering the observation of macrophyte residues in sediment of the two reservoirs, M should be considered as an end member. Consequently, three end member OC sources, phytoplankton (P-OC), macrophytes (M-OC), and terrestrial soil (T-OC) were considered in this study, and their relative contribution was estimated by the following equations:

$$\delta^{13}C_{sediment} = \delta^{13}C_P \cdot f_P + \delta^{13}C_M \cdot f_M + \delta^{13}C_T \cdot f_T$$

$$\delta^{15}N_{sediment} = \delta^{15}N_P \cdot f_P + \delta^{15}N_M \cdot f_M + \delta^{15}N_T \cdot f_T$$

$$f_P + f_M + f_T = 1,$$

where $\delta^{13}C_{sediment}, \delta^{13}C_P, \delta^{13}C_M, \delta^{13}C_T$, and $\delta^{15}C_{sediment}, \delta^{15}N_P, \delta^{15}N_M, \delta^{15}N_T$, are the δ^{13}C and δ^{15}N

Table 3 Summary data of measurement results in the two reservoirs

| | Huairou Reservoir (HR) | | Shisanling Reservoir (SR) | |
	Mean	Range	Mean	Range
Site number (N vs. O)[a]	21 (9 vs. 12)		18 (7 vs. 11)	
Sediment thickness (cm)	24	14–50	33	11–76
Water content (%)	29.6	24.3–35.8	27.2	25.0–32.8
Dry bulk density (g cm^{-3})	0.91	0.81–1.38	0.97	0.73–1.36
Organic carbon (mg g^{-1})	15.7	7.1–29.7	17.2	6.9–27.7
Inorganic carbon (mg g^{-1})	7.8	4.3–10.4	5.6	2.2–10.6
Total nitrogen (mg g^{-1})	1.9	0.6–4.7	1.5	0.9–2.8
C/N ratio (mol mol^{-1})	10.8	7.5–13.9	13.2	8.9–16.8
δ^{13}C (‰)	−25.5	−28.5 to −22.3	2.9	1.7–4.0
δ^{15}N (‰)	−23.9	−25.2 to −22.9	2.2	1.1–3.2
Organic carbon accumulation rate (g m^{-2} year^{-1})	62.3	36.4–129.9	100.1	33.4–230.5

Variables include Number of nearshore and offshore sites, sediment thickness, water content, dry bulk density, organic carbon (OC); inorganic carbon (IC), total nitrogen (N), atomic C/N ratio, δ^{13}C, δ^{15}N, and organic carbon accumulation rate

[a] N versus O indicates the number of nearshore and offshore sites

values for phytoplankton, macrophytes, and terrestrial soil, respectively; and f_P, f_M, f_T are the relative contributions of P-OC, M-OC, and T-OC to OC in the sediments, respectively.

Results

Organic carbon in sediments

The concentration of OC in the HR varied from 7.1 to 29.7 mg g^{-1} with an average value of 15.7 ± 6.3 mg g^{-1} (average $\pm$ standard deviation). Meanwhile, the mean value of sedimentary OC concentration in the SR was 17.2 ± 6.3 mg g^{-1} and varied from 6.9 to 27.7 mg g^{-1} (Table 3). Both the OC concentration and its variation were comparable in the two reservoirs. The mean OC ARs were 62.3 g m^{-2} year^{-1} in the HR and 100.1 g m^{-2} year^{-1} in the SR over the past 55 years (Table 3).

Figure 3 illustrates the distribution of OC in the surface sediments of the two reservoirs. In the HR, high values were observed in offshore sites near the dam, and low values were found in sites near the mouths of the Huaijiu River and the Huaisha River. However, the horizontal distribution of the OC concentration in the SR showed a completely different pattern. The high OC concentrations occurred in nearshore sediments far from the dam, whereas the low OC content sediments were collected near the inlet and outlet of the water-conveyance tunnel (Fig. 1C).

Nitrogen and C/N ratio in sediments

In contrast with OC, the concentration of N in sediments showed obvious variation in the HR (0.6–4.7 mg g^{-1}), whereas SR exhibited slight fluctuations (0.9–2.8 mg g^{-1}). The average value of the HR (1.9 ± 1.1 mg g^{-1}) was approximately 30% higher than that of the SR (1.5 ± 0.5 mg g^{-1}). This indicates the different trophic status of the two reservoirs.

The spatial gradients of sedimentary N in the two reservoirs were analogous to those of the OC patterns (Appendix 1—Supplementary material). Further, a plot of the N versus OC concentrations in the nearshore and offshore sediments is shown in Fig. 4; there was a positive correlation of sedimentary N versus OC contents in the HR ($R^2 = 0.74$, $p < 0.01$) and the SR ($R^2 = 0.75$, $p < 0.01$), thus indicating that the nitrogen within the sediments was predominantly from organic sources. The slopes of the regression lines confirmed that the state and source of sedimentary OC were different in the two reservoirs because the slope of regression line was equivalent to an important index, the C/N ratio, which reflects the OC sources in sediment. The C/N ratio in sediments showed a wide variation, of which the HR values ranged from 7.5 to 13.9, and the SR ranged from 8.9 to 16.8 (Table 3). The two reservoirs also showed a completely different distribution of C/N ratio (Appendix 2—Supplementary material). The HR showed a decreasing trend as the water depth increased, while the SR was positively correlated with the distance from the inlet and outlet of the tunnel.

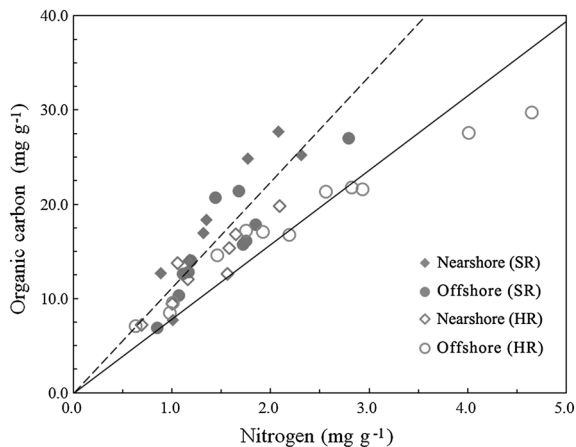Fig. 3 Spatial distribution of organic carbon in sediments
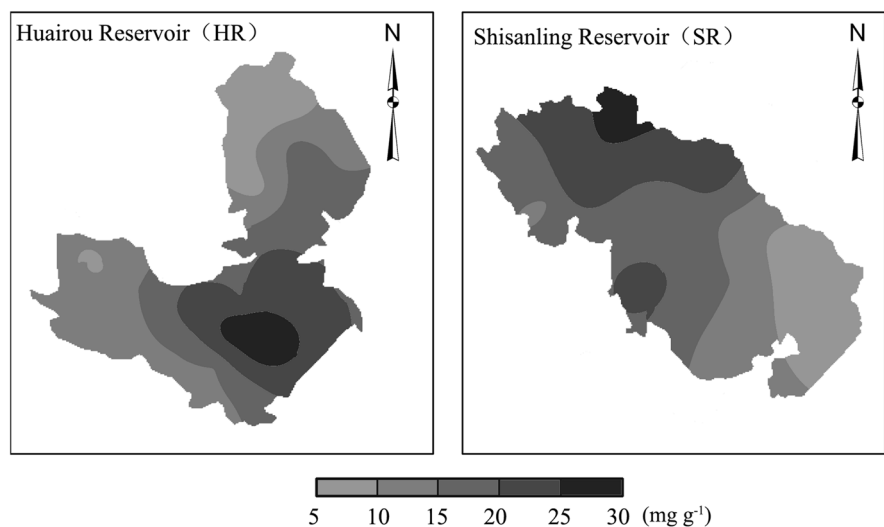
Fig. 4 Relationship between nitrogen and organic carbon concentrations in sediments. The *solid line* is the least squares regression with the zero intercept of the Huairou Reservoir (HR) ($R^2 = 0.74$, $n = 21$, $p < 0.01$), and the *dashed line* is the least squares regression with the zero intercept of the Shisanling Reservoir (HR) ($R^2 = 0.75$, $n = 18$, $p < 0.01$)

Stable isotopes of potential organic carbon sources and sediments

The $\delta^{13}C$ and $\delta^{15}N$ of potential OC sources are shown in Table 4. In this study, we assumed that the isotope signatures of OC sources to sediments were the same in the two reservoirs because there were identical results for the phytoplankton, macrophyte, and surrounding soil samples. In addition, the watersheds of the two reservoirs are characterized by the same terrestrial plants (Lu et al., 2012). The results showed that the isotope signatures of the potential OC sources

ranged from $-33.0‰$ (phytoplankton) to $-11.3‰$ (terrestrial C4 plant) for $\delta^{13}C$, and from $-2.8‰$ (terrestrial C3 plant) to 8.0‰ (phytoplankton) for $\delta^{15}N$. There was a clear discrimination among the potential sources (Fig. 5).

The isotope signatures in sediments varied within the ranges of the OC sources (Fig. 5), suggesting that the OC of different origins was mixed during the accumulation process. In the HR, remarkable regional differences in the isotope signatures were observed. The $\delta^{13}C$ in the offshore sediments exhibited lighter values (-28.5 to $-25.3‰$) than the nearshore sediments (-23.8 to $-22.3‰$), whereas the $\delta^{15}N$ content showed heavier values in the offshore sediments (2.3–4.0‰) than the nearshore sediments (1.7–2.8‰). By contrast, the isotope signatures in the SR maintained relatively constant values throughout the reservoir ($\delta^{13}C$, -25.2 to $-22.9‰$; $\delta^{15}N$, 1.1–3.2‰), which were also similar to the values of the nearshore sediments in the HR (Fig. 5).

Spatial variations of organic carbon sources

The relative contribution of P-OC, M-OC, and T-OC to OC in sediment was estimated by using a three sources mixing model with $\delta^{13}C$ and $\delta^{15}N$ values. As shown in Fig. 6, the mixing model showed good results at most sites, except for one site near the mouth of the Huaijiu River (HR), where other OC sources that were not considered may have had a contribution. The three components P-OC, M-OC, and T-OC to OC varied among sites in the two reservoirs. At the

Table 4 Stable isotope values of potential sedimentary OC sources in the Huairou Reservoir (HR) and Shisanling Reservoir (SR)

OC source	$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)		References
	HR	SR	HR	SR	
Phytoplankton	−30.1	−29.8	5.2	4.8	This study
	(−33.0 to −25.9)	(−32.8 to −25.4)	(2.8–8.0)	(3.0–7.7)	
Macrophytes	−20.8	−20.0	5.5	5.8	This study
	(−23.8 to −19.3)	(−23.0 to −18.3)	(3.8–6.2)	(4.0–6.9)	
Terrestrial					
Soil OC	−23.3	−24.0	0.3	0.3	This study
	(−26.2 to −22.2)	(−27.2 to −21.6)	(−2.2 to 2.0)	(−2.2 to 2.8)	
C3 plants	−28.0		−1.8		Lu et al. (2012)
	(−28.9 to −26.3)		(−2.8–0.6)		
C4 plants	−13.7		4.4		Lu et al. (2012)
	(−17.4 to −11.3)		(1.4–7.0)		

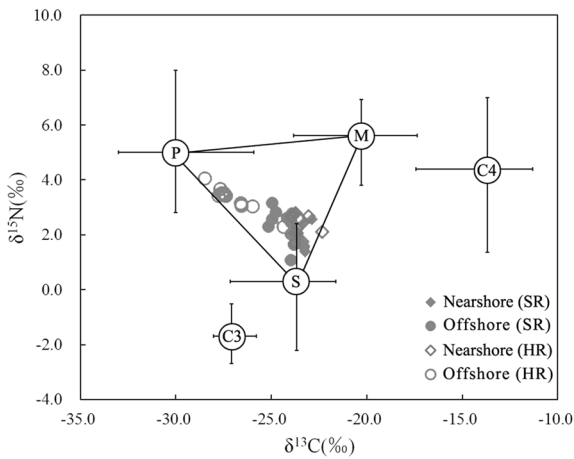**Fig. 5** Organic carbon and nitrogen isotope signatures (δ^{13}C vs. δ^{15}N) in sediments of the Huairou Reservoir (HR) and Shisanling Reservoir (SR) and their potential organic matter sources (phytoplankton, macrophytes, terrestrial soil, C3 and C4 plants). *Each plot* indicates the average value, and the *vertical* and *horizontal bars* of potential organic matter sources indicate the ranges

reservoir scale, allochthonous T-OC played the most important role in the HR ($47 \pm 15\%$) and SR ($62 \pm 11\%$). However, the proportions of autochthonous P-OC and M-OC in HR were different from those of the SR. That is, the M-OC contributed less in the HR ($13 \pm 12\%$) than in the SR ($23 \pm 6\%$), whereas the P-OC contributed much more in the HR ($40 \pm 24\%$) than SR ($15 \pm 10\%$). For the spatial distribution of the two reservoirs, the higher T-OC and M-OC values

were mainly observed in nearshore sites, whereas the offshore sites usually exhibited a higher contribution of P-OC (Fig. 6). However, the comparisons between the two reservoirs are clearly marked in two cases, of which nearshore and offshore sediments were mainly different in the concentration and contributions of the three sources, respectively (Appendix 3—Supplementary material). The details will be discussed in the following.

Discussion

Comparison of organic carbon distribution between the two reservoirs

The distribution of OC in HR was similar to the results of other reservoirs (Fig. 3), which reported that the sedimentary OC concentration increased from the river inflow toward the dam (Hyne, 1978; Pittman et al., 2013). The large amount of silt (mainly inorganic sediment) imported by rivers, as well as the associated high sedimentation rates in estuaries, is likely to dilute the OC concentration in sediments (Hyne, 1978), whereas high OC values are attributed to the anoxic sedimentary environment (Sobek et al., 2009). However, the distribution gradient in the SR could be dependent upon the hydrodynamic effects caused by the operation of the Shisanling pumped storage power plant. The increased water disturbance, caused by the high flow speed of the tunnel, had

Fig. 6 Spatial variation in the concentrations of the three components P-OC, M-OC, and T-OC to sedimentary OC. *Transparent circle* indicates site where the relative contributions could not be estimated
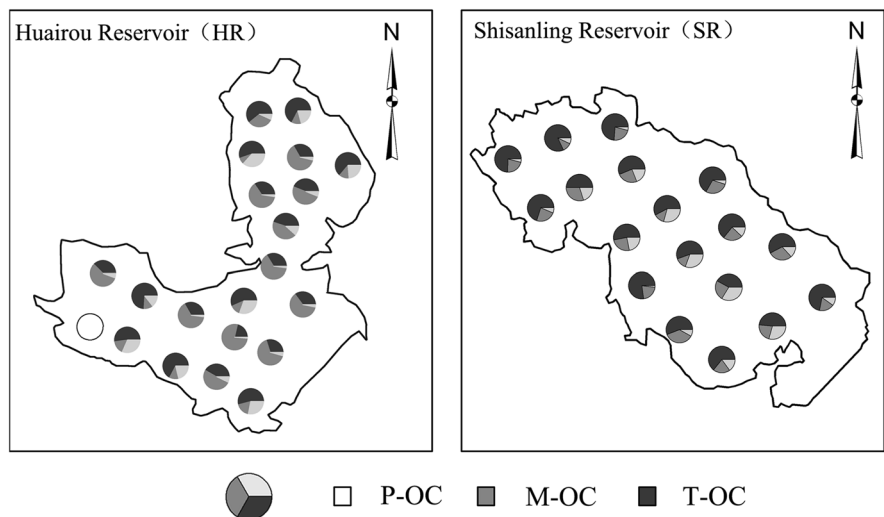
negative effects on the growth of phytoplankton and the settling of small particles. The smaller particles, which are expected to better adsorb organic matter due to a higher relative surface area (Sfriso et al., 2005; Manning et al., 2010), demonstrated settlement difficulties near the tunnel. This effect was positively related to the distance from the inlet and outlet of the tunnel. In addition, enhanced shoreline erosion near the tunnel also resulted in the dilution of OC in local sediments by inorganic particles from soil.

Comparison of organic carbon sources between the two reservoirs

Nearshore sediments

The contribution of P-OC, M-OC, and T-OC to OC in the nearshore sediment exhibited little difference in the two reservoirs. In both sites, the T-OC accounted for over half of the total, and the M-OC accounted for approximately one quarter; however, the proportion of P-OC was quite small (Appendix 3A). Because the OC concentration was generally higher in the SR than the HR, the concentrations of the three components in nearshore sediments were different from the ratios. On the whole, the M-OC and T-OC content in the SR were higher (1.4 and 5.4 mg g^{-1}, respectively) than those in the HR, whereas the P-OC was lower (0.7 mg g^{-1}) (Appendix 3B). There are three possible mechanisms which could explain the different results reported for SR and HR. One mechanism is associated with the WLF caused by the reservoir regulations. The daily WLF of the SR has synergistically enhanced soil erosion, resulting in an increased terrestrial contribution to OC in the nearshore sediments. Another mechanism is the productive environment in shallow waters, which was also related to the WLF. Macrophytes (especially emergent plants) occur in riparian habitats, which are sensitive to moist conditions and may be short-lived and rapidly replaced (Tabosa et al., 2012). That is to say, the WLF in the SR provided a more productive environment by completing the lifecycle rapidly and reestablishing young plants. This inference can be confirmed by field observation of the two reservoirs, where the macrophyte residues in the nearshore sites of SR (30–70 cm) were generally much thicker than that of the HR (10–30 cm). In the final mechanism, microbial communities were sensitive to water disturbance (Unger et al., 2009). The daily WLF induced considerable changes in the microbial communities and synergistically increased soil respiration (Hulthe et al., 1998; Wilson et al., 2011). The increased oxygen exposure time and microbial activities were beneficial to the humification of the refractory organic matter of cellulose in macrophyte residues.

Offshore sediments

By contrast, offshore sediments were composed of various proportions of three components in the two reservoirs. In the HR, the ratios of the P-OC, T-OC, and M-OC to OC in offshore sediments were 57.8, 37.5, and 4.7%, respectively. It is noteworthy that the P-OC was much higher than the T-OC, indicating higher phytoplankton productivity in the water. On the other hand, the ratio of P-OC in SR (20.6%) was much lower than in the HR, whereas the ratios of T-OC (58.4%) and M-OC (21.0%) were both higher (Appendix 3A). The average OC content in offshore sites of the two reservoirs were nearly equal, and the concentrations of the three components showed similar characteristics with the relative contributions (Appendix 3B). The following explanations are possible for the observed differences between the sites. The HR experienced a lake-type environment for OC accumulation due to seasonal WLF and long water residence time (Table 1). Several studies on natural lakes have reported that they were dominated by autochthonous OC and derived mainly from phytoplankton (e.g., Tenzer et al., 1997; Park et al., 2009). In addition, the SR experienced a river-type environment mainly due to the operation of the power plant. During the process of daily WLF, the M-OC and T-OC in offshore sediments were largely influenced by the transportation, resuspension, and deposition of terrestrial- and macrophyte-derived organic matters. At the same time, short water residence time caused the low productive state of phytoplankton in the SR compared to HR.

Conclusion

The concentration and distribution of organic carbon (OC) in sediments were investigated in two reservoirs: the Huairou Reservoir (HR), which is used as a domestic water supply, and the Shisanling Reservoir (SR), which is used for hydroelectric power generation. The data revealed that OC concentration and its variation were comparable in the two reservoirs, of

which the HR was 15.7 ± 6.3 mg g^{-1} and the SR was 17.2 ± 6.3 mg g^{-1}; however, the OC, N, and C/N ratio distributions showed contrasting features, of which the HR was positively related to water depth, whereas the SR was positively related to the distance from the inlet and outlet of the tunnel. The distribution patterns reflect the impact of WLFs on the sedimentation of organic matters. Furthermore, the mean OC ARs were 62.3 g m^{-2} year^{-1} in the HR and 100.1 g m^{-2} year^{-1} in the SR over the past 55 years.

The mixing model with stable isotopes offered an important tool for estimating the relative contribution of potential sources to the sedimentary OC. The spatial variation of OC composition indicated that the relative importance of three components (P-OC, M-OC, and T-OC) to OC varied among the sediments. The sedimentary OC in the HR mainly consisted of T-OC (47%) and P-OC (40%), whereas the M-OC (13%) contributed little. By contrast, the T-OC (62%) and M-OC (23%) in the sedimentary OC in the SR were both higher than those of the HR, whereas the P-OC (15%) was markedly reduced. Furthermore, the comparison of nearshore and offshore sediments between the two reservoirs demonstrated that the hydrodynamic conditions affected not only the distribution of sedimentary OC and its T-OC import by physical processes, but also the in situ contributions of P-OC and M-OC. These provide evidence for the indirect effects on the lifecycles of biotic communities and also the potential bias of allochthonous and autochthonous OC buried in regulated freshwater ecosystems, which could induce changes in the regional carbon cycle.

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