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ORIGINAL ARTICLE

Temporal and spatial characteristics of dissolved organic carbon in the Wujiang River, Southwest China

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Abstract River systems play an important role in the global carbon cycle. Rivers transport carbon to the ocean and also affect the carbon cycle in the coastal ocean. The flux from land to the ocean is thought to be a very important part of the land carbon budget. To investigate the effect of dam-building on dissolved organic carbon (DOC) in rivers, three reservoirs of different trophic states in the Wujiang basin, Guizhou Province, were sampled twice per month between May 2011 and May 2012. Temporal and spatial distributions of DOC in the reservoirs and their released waters were studied. It was found that different factors controlled DOC in river water, reservoir water, and released water. DOC in the rivers tended to be affected by primary production. For reservoirs, the main controlling factors of DOC concentration varied by trophic state. For the mesotrophic Hongjiadu Reservoir, the effect of primary production on DOC concentration was obvious. For the eutrophic Dongfengdu Reservoir and the hypereutrophic Wujiangdu Reservoir, primary production was not significant and DOC came instead from soil and plant litter.

Keywords Carbon cycle · Dissolved organic carbon · Dam-building effect · The Wujiang River

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1 Introduction

The carbon cycle in the surficial Earth system is of great significance for climate change (Catalán et al. 2016; Huntington et al. 2016; Bianchi and Allison 2009). Rivers carry weathering products from the land to the ocean in the form of dissolved substances and particulate matter, especially carbon. Dam-building is one of the most impactful human activities on the riverine system (Liu 2007), the effect of which is called the reservoir effect. The reservoir effect changes elemental cycles in rivers, especially the carbon cycle (Peng et al. 2014).

Guizhou Province is rich in water resources, including the Wujiang River. Guizhou Province is typically a karst area, and the coverage rate of forests is low. There are 12 reservoirs along the Wujiang River. The effect of dam-building on the transportation of carbon to the ocean is a critical component of the land-river system carbon cycle and warrants increased study. As an important component of the riverine carbon cycle, dissolved organic carbon (DOC) and changes in its export volume may reflect changes in the carbon cycle of the surficial land and river system (Pumpanen et al. 2014). DOC includes water soluble forms of amino acids, carbohydrates, organic acids, and alcohols, as well as fulvic and humic acids (Thurman 1985). DOC in the river system can come from allochthonous sources, such as decomposition of detrital organic matter, and from autochthonous sources, such as in situ production by aquatic plants and microbes. To determine the effect of dam-building on the sources of DOC in a dammed river, this study investigates temporal and spatial distributions of DOC in the Wujiang River basin. Three variously aged cascade reservoirs and their corresponding rivers within the drainage basin were sampled for analysis.

2 Study area

The Wujiang River is a right-bank tributary of the Changjiang River, and has a total length of 1037 km and a drainage area of 88,267 km^2. The Wujiang has a fall of 2124 m and is one of the main rivers in a west-to-east power transmission project. The study area is characteristic of the subtropical monsoon humid climate, with an average annual temperature of 12.3 °C and extremes of 35.4 °C in the summer and −10.1 °C in the winter. Average temperatures in January (the coldest month) and July (the hottest month) are 3.5 and 26 °C, respectively. Annual precipitation ranges from 1100 to 1300 mm, and precipitation from May to October accounts for about 75% of the total. The predominant lithological character of the Wujiang River basin is Pre-Jurassic strata, and carbonate rock is widespread in this area. Triassic carbonate rock, coal-bearing petrofabric, and basalt predominate in the upper reaches of the Wujiang River. Triassic limestone, dolomitic limestone, and dolostone are widespread in the middle reaches of the Wujiang River. Carbonatite petrofabric including mudstone, shale, and siltite cover much of the lower Wujiang River basin, with Sinian basic to ultra-basic pyroclastic rock and magmatite emerging in some regions.

The Hongjiadu, Dongfengdu, and Wujiangdu Reservoirs are located on the middle and upper reaches of the basin (Fig. 1), and were constructed in 2001, 1989, and 1971, respectively. The annual discharge at the Liuchong River site accounts for 87.2% of the total inflow to the Hongjiadu Reservoir, and represented the unimpacted river. The annual runoff of the Liuguang River accounts for 88.8% of the total inflow to the Wujiangdu Reservoir, and represented the impacted river affected by damming.

3 Sampling and analysis

The Liuchong River (LCH), the Hongjiadu Reservoir (HJD), the water released from the Hongjiadu Reservoir (HJD-R), the Dongfengdu Reservoir (DFD), the water released from the Dongfengdu Reservoir (DFD-R), the Liuguang River (LGH), the Wujiangdu Reservoir (WJD), and the water released from the Wujiangdu Reservoir (WJD-R) were sampled twice monthly (Fig. 1) between May 2011 and May 2012. Samples were collected from the surface (upper 0.5 m).

Water temperature (T), pH, and dissolved oxygen (DO) were measured in-situ with an automated multi-parameter profiler (model YSI 6600), and alkalinity (ALK) was determined by HCl titration in the field. Concentrations of chlorophyll (Chl) were measured with a Phyto-PAM (WALZ, Germany). Water samples were filtered through glass fiber filters (0.70 µm, Whatman GF/F) within 24 h. Water samples for DOC analysis were then added to concentrated saturated $HgCl_2$ and kept frozen until analysis. DOC was determined using an OI Analytical Aurora 1030 TOC analyzer with a detection limit of 0.01 $mg \cdot m^{-3}$. The analytical error based on replicate analysis was less than 0.3%.

4 Results and discussions

4.1 Temporal and spatial variations of basic physical, chemical, and biological parameters

The variable ranges and averages of temperature, pH, DO, Chl, dissolved inorganic carbon (DIC), particulate organic carbon (POC), and DOC for rivers, reservoirs, and released water are listed in Table 1, and a detailed description can be found in Peng et al. (2014). For rivers, reservoirs, and released water, temperature, DO, and POC showed clear seasonal variation. Temperature, Chl, and POC were generally higher in May-to-October (warm season) and lower in November-to-April (cold season); DO and DOC displayed an opposite trend. More specifically, average warm-season water temperatures of rivers, reservoirs, and released waters were higher by 33.5%, 40.0%, and 28.9%, respectively, than cold-season averages. Concentrations of Chl were higher by 8.3% and 57.9%, respectively, for rivers and reservoirs during the warm season than during the cold; concentrations of Chl in the released water showed less seasonal variation. POC concentrations were higher by 35.4%, 43.0%, and 5.6%, respectively, for rivers, reservoirs, and released water during the warm season. On the other hand, DO concentrations in rivers, reservoirs, and released water were lower during the warm season by 11.1%, 4.2%, and 15.8%, and DOC lower by 6.2%, 22.4%, and 9.3%, both respectively. Values of pH showed less seasonal variation.

4.2 Temporal and spatial variation of dissolved organic carbon

The ranges for DOC in rivers, reservoirs, and released waters are listed in Table 2. In rivers (both the Liuchong and the Liuguang), DOC concentrations showed seasonal variation, but different trends (Fig. 2a). The DOC concentration in the Liuchong River was 33% higher during

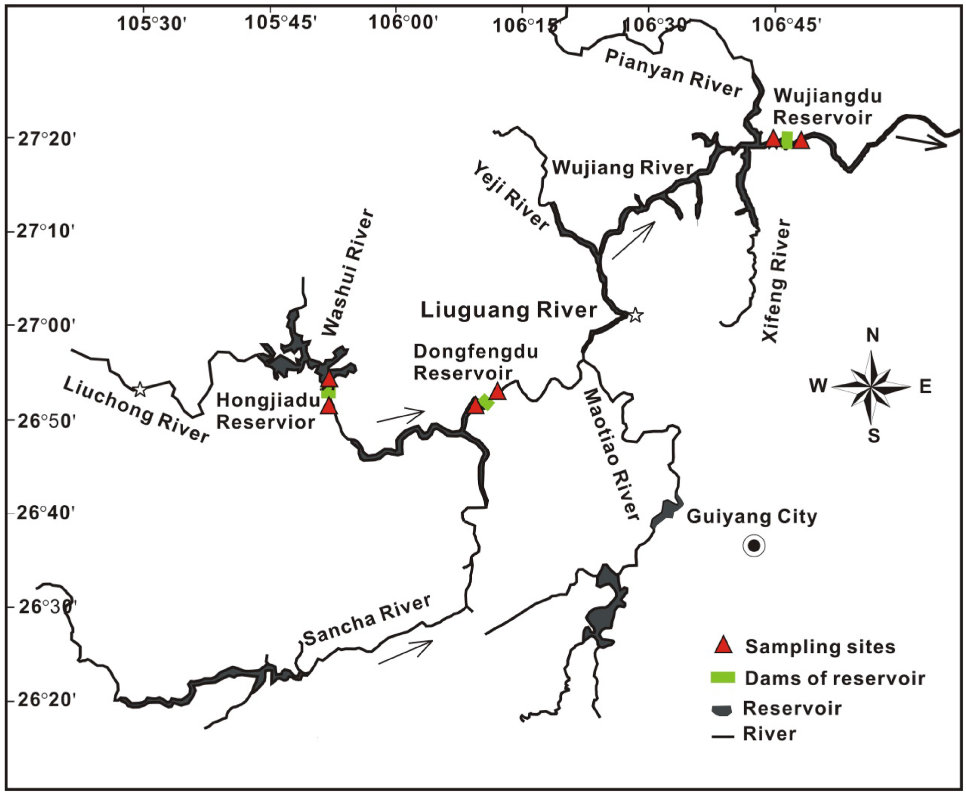

Fig. 1 Regional map showing the sampling sites

Table 1 Statistics of basic physical, chemical, and biological parameters

	Types	Minimum	Maximum	Average	Std.
Temperature (°C)	Rivers	8.1	24.4	17.0	4.5
	Reservoirs	9.1	29.7	18.9	5.6
	Released water	9.2	24.6	15.8	4.2
pH	Rivers	7.7	8.6	8.1	0.2
	Reservoirs	7.5	8.5	8.1	0.3
	Released water	7.4	8.1	7.8	0.2
DO (mg/L)	Rivers	7.4	11.1	9.2	0.9
	Reservoirs	3.8	12.4	8.2	1.8
	Released water	3.2	11.8	7.8	1.7
Chl (mg/L)	Rivers	0.9	7.6	1.9	1.0
	Reservoirs	1.4	40.6	6.1	7.1
	Released water	1.1	4.9	2.1	0.7
DIC (mmol/L)	Rivers	1.39	2.64	1.84	0.28
	Reservoirs	0.52	2.33	1.71	0.30
	Released water	1.61	2.65	1.92	0.22
POC (mg/L)	Rivers	0.02	1.17	0.26	0.21
	Reservoirs	0.11	1.84	0.40	0.34
	Released water	0.09	0.36	0.18	0.06

the warm season than during the cold season; in contrast, the DOC concentration in the Liuguang River was 32% lower during the warm season. For reservoirs, the Hongjiadu and Wujiangdu showed clear seasonal variation, but the Dongfengdu showed less seasonal variation (Fig. 2b). DOC concentrations in the Hongjiadu Reservoir and the Wujiangdu Reservoir were 32% and 47% higher, respectively, during the warm season than during the cold season. The released water from the Hongjiadu Reservoir showed clear seasonal variation, but the released water from the Dongfengdu and the Wujiangdu Reservoirs did not (Fig. 2c). The DOC concentration in the released water

Table 2 Statistics of dissolved organic carbon in rivers, reservoirs, and released water

Type	Sample	Minimum	Maximum	Average	Std.
Rivers		0.50	44.59	7.52	7.35
Reservoirs		0.43	31.61	8.18	6.69
Released water		0.16	41.24	8.15	7.75
Rivers	LCH	0.81	20.02	6.85	4.99
	LGH	0.50	44.59	8.20	9.18
Reservoirs	HJD	0.77	29.04	7.24	5.93
	DFD	0.43	30.61	8.34	7.37
	WJD	1.19	31.61	8.36	7.29
Released water	HJD-R	0.16	23.20	6.88	5.25
	DFD-R	0.52	31.88	7.86	6.51
	WJD-R	0.58	41.24	9.77	10.62

from the Hongjiadu Reservoir was 36% higher during the warm season than during the cold season.

4.3 Controlling factors of dissolved organic carbon in different types water

DOC in river systems can come from decomposition of detrital organic matter, organics from external sources, and in situ production by aquatic plants and microbes. Damming alters the hydrologic condition of the river, decreasing flow speed and increasing retention time (Wetzel 2001). Compared with river and released water, temperature, DOC, and Chl were all higher in the reservoir water. Lower velocity in the reservoir leads to higher water temperature and higher primary productivity. Thus, compared with rivers and released water, DO in the reservoirs is a little higher. The main controlling factors of DOC concentration can vary in rivers, reservoirs and released water due to the different physical, chemical, and biological conditions. Principal components analysis was carried out for temperature, pH, DO, Chl, DIC, POC, and DOC. For river water, there were good relationships between DOC concentration and Chl concentration ($N = 52$, $p < 0.5$), and between DOC concentration and POC concentration ($N = 52$, $p < 0.5$) (Fig. 3a). It can be concluded that in the Liuchong and Liuguang Rivers, DOC concentration is affected by Chl concentration, indicating the strength of primary production. There are good relationships in reservoirs between DOC concentration and DO ($N = 78$, $p < 0.05$), and between DOC concentration and DIC concentration ($N = 78$, $p < 0.05$) (Fig. 3b). It can be concluded that in reservoirs DOC concentration was less affected by primary production than by other factors, such as erosion of soil. There were good relationships in released water between DOC concentration and POC concentration ($N = 78$, $p < 0.5$), between DOC concentration and pH ($N = 78$, $p < 0.5$), and between DOC concentration and DO ($N = 78$, $p < 0.5$) (Fig. 3c). It can be concluded that for released water, DOC concentration was less affected by primary production than by the decomposition of organic matter in the reservoir.

For different reservoirs, the main factors controlling DOC concentration were different. There were good relationships in the Hongjiadu Reservoir between DOC concentration and DO ($N = 26$, $p < 0.5$), and between DOC concentration and Chl concentration ($N = 26$, $p < 0.5$) (Fig. 3d). For the Hongjiadu Reservoir water, DOC concentration was affected by primary production. There were good relationships in the Dongfengdu and Wujiangdu Reservoirs between DOC concentration and DO ($N = 26$, $p < 0.5$), and between DOC concentration and DIC concentration ($N = 26$, $p < 0.5$) (Fig. 3e, f). For the Dongfengdu and Wujiangdu Reservoirs, DOC concentration was less affected by primary production. The three reservoirs were built in different years, and currently exhibit different trophic states: the Hongjiadu Reservoir is mesotrophic, the Dongfengdu eutrophic, and the Wujiangdu hypereutrophic (Wang et al. 2008). For the Dongfengdu and Wujiangdu Reservoirs, he contribution of primary production to DOC may be reduced due to accumulation of DOC from many sources, such as erosion of soil and decomposition of organic matter. The DOC in reservoirs from soil and plants increases as the age of the reservoir increases. In contrast, the contribution of primary production to DOC decreases with increasing reservoir age.

For released water, the main factors controlling DOC concentration varied. There were good relationships in the released water from the Hongjiadu Reservoir between DOC concentration and DO ($N = 26$, $p < 0.5$), and between DOC concentration and POC concentration ($N = 26$, $p < 0.5$) (Fig. 3g). For the released water from the Hongjiadu Reservoir, DOC concentration was less affected by primary production. Good relationships were found in the released water from the Dongfengdu Reservoir between DOC concentration and Chl ($N = 26$, $p < 0.5$), and between DOC concentration and POC concentration ($N = 26$, $p < 0.5$) (Fig. 3h). For the released water from the Dongfengdu Reservoir, DOC concentration was affected by primary production. There were good relationships in the released water from the Wujiangdu Reservoir between DOC concentration and pH ($N = 26$, $p < 0.5$), between DOC concentration and DO ($N = 26$, $p < 0.5$), and between DOC concentration and POC concentration ($N = 26$, $p < 0.5$) (Fig. 3j). For the released water from the Wujiangdu Reservoir, DOC concentration was less affected by primary production.

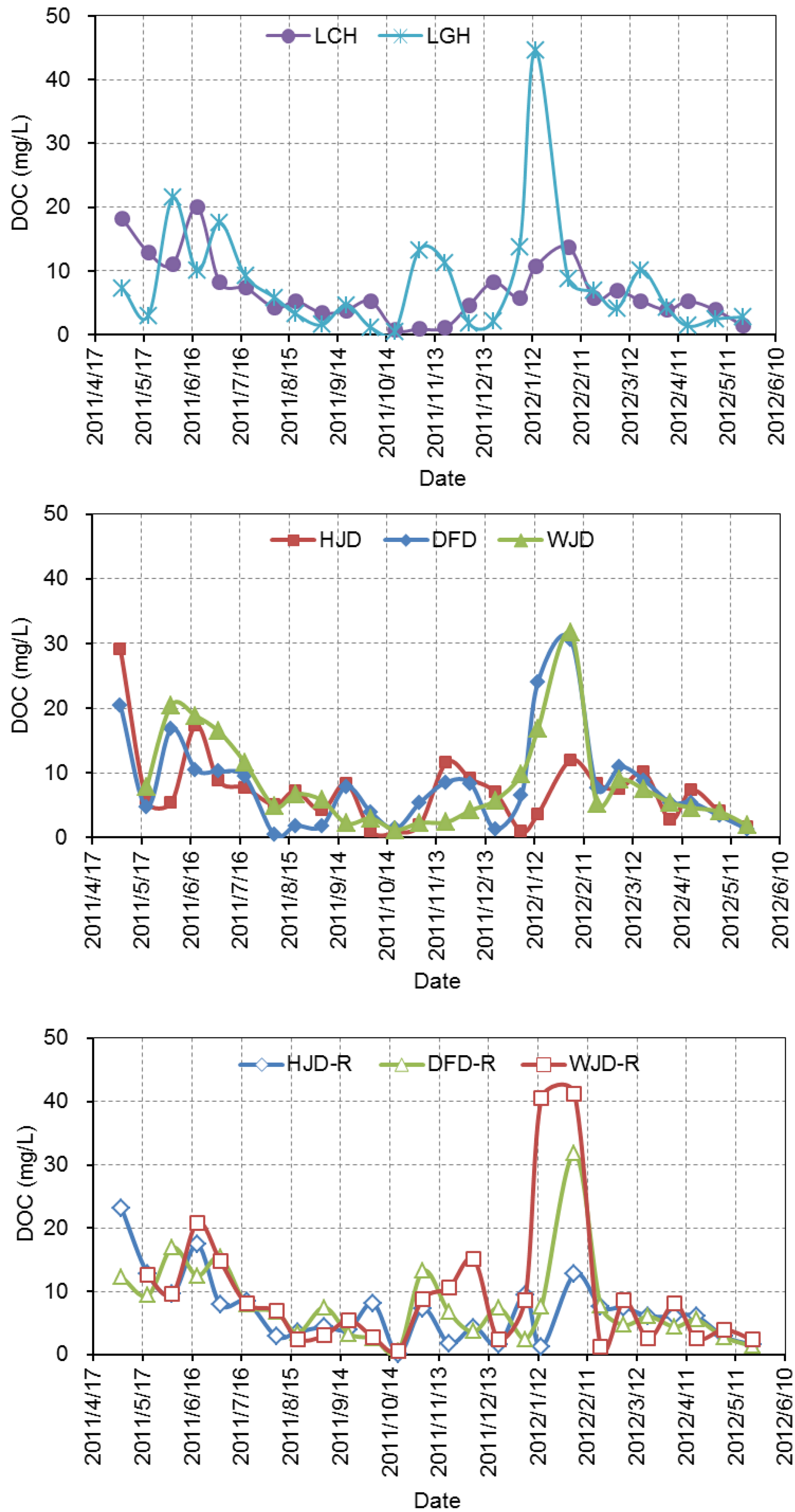

Fig. 2 Temporal and spatial variations of dissolved organic carbon in the Liuchong (LCH) and Liuguang (LGH) Rivers; the Hongjiadu (HJD), Dongfengdu (DFD), and Wujiangdu (WJD) Reservoirs; and released water from Hongjiadu (HJD-R), Dongfengdu (DFD-R), and Wujiangdu (WJD-R) Reservoirs

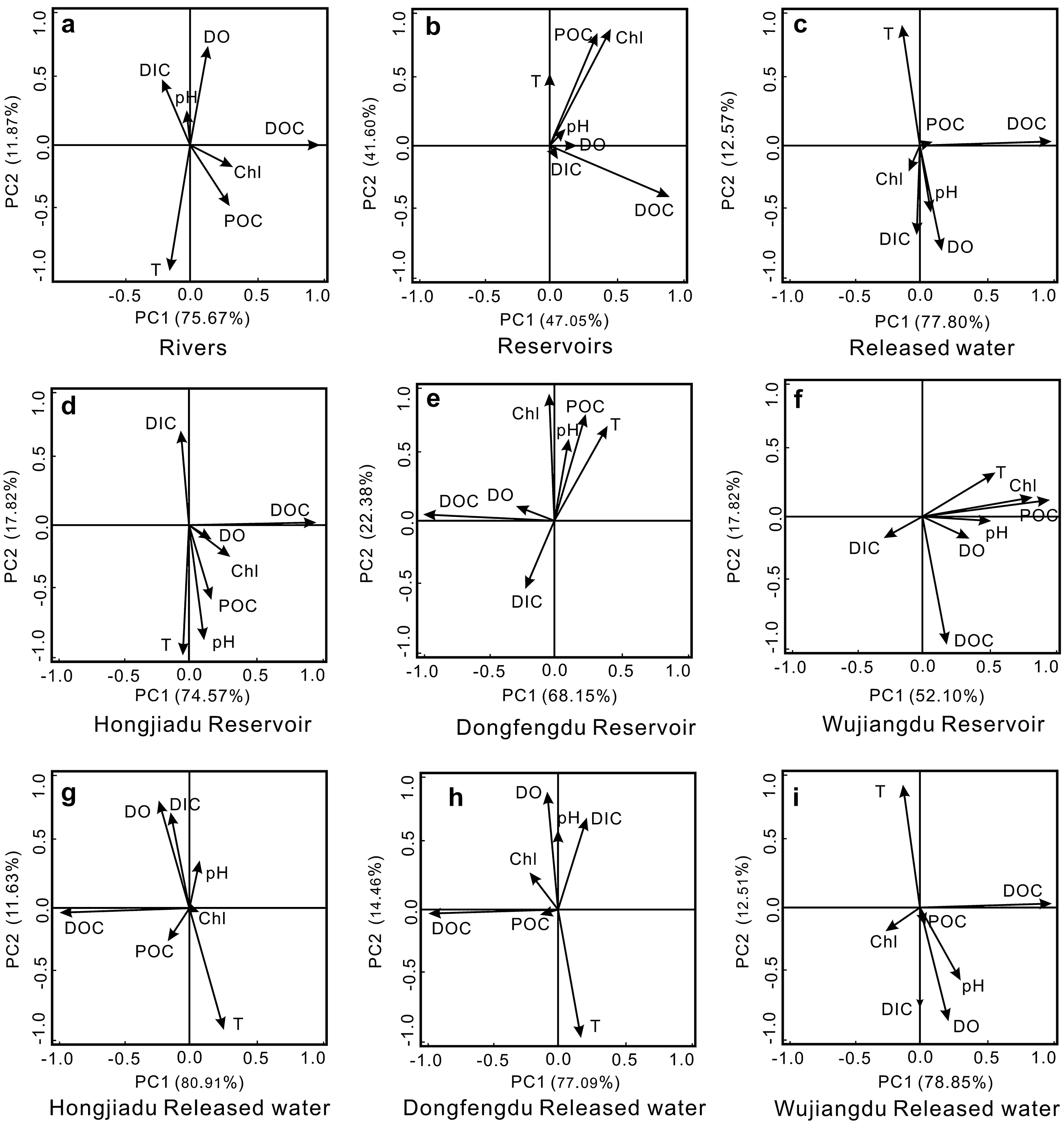

Fig. 3 Principal components analysis for data from different types of water. Rivers include data from the Liuchong and Liuguang Rivers. Reservoirs include data from the Hongjiadu, Dongfengdu, and Wujiangdu Reservoirs. Released water includes data of released water from the Hongjiadu, Dongfengdu, and Wujiangdu Reservoirs

5 Conclusions

Temporal and spatial variations of DOC in the dammed Wujiang River were studied and analyzed. Dams alter the physical, chemical, and biological conditions of the Wujiang River. The geochemical behavior of DOC in the Wujiang River is affected by the dams. The main controlling factors of DOC were different for rivers, reservoir water, and released water. DOC in the rivers tends to be affected by primary production. For reservoirs, the main controlling factors of DOC concentration were different due to different trophic states. For the mesotrophic reservoir, the effect of primary production on DOC concentration was obvious. For the eutrophic and hypereutrophic reservoirs, the effect of primary production on DOC concentration was not significant.

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