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Influence of Three Gorges Dam and drought on particulate organic carbon flux and its source in the lower Yangtze River

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Abstract The Yangtze River basin regulated by the gigantic Three Gorges Dam (TGD) is the best location to study the impacts of intense anthropogenic modifications on the global biogeochemical cycles. However, frequent drought periods commencing from 2006 to 2011 may equally act as a strong factor influencing the particulate organic matter (POM) flux. To capture the distinctive role of TGD operations and drought severity on the POM, weekly sampling of total suspended matter (TSM) concentration was conducted at Nantong in the lower Yangtze basin. Biogeochemical parameters (POC% of TSM, PN% of TSM, C/N ratios, and $\delta^{13}C$), $CaCO_3$%, mean suspended sediment size, and drought parameters (mean temperature, solar radiation, relative humidity, wind speed, evapotranspiration, and rainfall) were evaluated. The inverse power-law correlation between TSM-POC% and TSM-PN% was observed and POC% during 2008–2009 was found to be higher than pre-dam values. The $\delta^{13}C$ and C/N range from − 25.6 to − 24.1‰ and 4.8 to 9.2, and moderate negative correlation between $CaCO_3$-POC% and POC%-$\delta^{13}C$ were observed. Principal component analysis stipulates that high temperature and solar radiation enhanced evapotranspiration and TGD operations were not found to promote drought in the lower Yangtze basin. The results evince the potential shift of POM source from terrestrial to aquatic biological activity was related to low discharge, low TSM concentration, and dry conditions. The study advances our understanding of the impacts of hydrological connectivity on the POM pool and accentuates the role of phytoplankton as a dominant source of POM in regulated river channels.

Keywords Yangtze River · Three Gorges Dam (TGD) · Drought · Particulate organic carbon · Particulate nitrogen

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Introduction

Human induced obstruction of river flows through dam and reservoir impact biogeochemical cycles. Out of ∼ 20 billion tons per year of fluvial sediment delivered to the oceans, reservoirs in the large river basins trap 4–5 billion tons of flux per year, thereby greatly affecting the primary production, transportation, oxidation, and sequestration of terrestrial carbon (Milliman and Syvitski 1992; Vorosmarty et al. 2003).

Large rivers of Asia are a significant component of the global carbon cycle exporting approximately 40–50% of total fluxes of C (Ludwig et al. 1996; Dai et al. 2012; Park et al. 2018). Among them, the Yangtze River basin represents the ideal location to study the river–reservoir–river continuum and a wide-scale effect of human-induced discontinuities on the riverine C cycle. The Yangtze is one of the most stressed river systems in terms of controlled water flow and rapid change of sediment load. The presence of many dams and notably the gigantic Three Gorges Dam (TGD) with a storage capacity of 39.6 km^3 has resulted in the entrapment of $\sim$ 60% of the upstream sediments during the year 2003–2006 (Zhang et al. 2014; Li et al. 2018;). Before the impoundment of the TGD, most of the sediment transported from the Yangtze to the adjacent continental shelf was sourced from the upper part of the basin, while the middle-lower part behaved as a sediment sink (Yang et al. 2007). However, this behaviour changed after the impoundment process begins in 2003. The massive entrapment of sediment flux leads to high channel erosion in the middle and lower part of the basin and converted the deltaic region from progradation to recession (Yang et al. 2007; Wang et al. 2019).

Previous studies have quantified and specified the substantial effects of TGD on the regional and global C cycle (Yu et al. 2011; Gao et al. 2012; Bao et al. 2014; Wu et al. 2018). The impact of discontinuities in the hydrologic pathways has resulted in a Particulate Organic Carbon (POC) burial flux of $\sim$ 2.1 Mt $year^{-1}$ in the TGD reservoir, which is $\sim$ 30% of the total POC sequestration within the Yangtze basin (Li et al. 2015). It has been found that from 1993 to 2010, soil organic matter was the prominent source of modern POC (Zhang et al. 2007; Wu et al. 2007, 2018; Yu et al. 2011; Gao et al. 2012). However, in the post-TGD time, alteration of downstream floodplain processes resulted in > 90% of the terrestrial organic matter sourced from the mid-lower part of the basin with tributaries and lakes acting as significant entities contributing high POC content (Bao et al. 2014).

However, apart from the TGD impact, frequent natural calamities, particularly floods and droughts, are an important phenomenon in the Yangtze River basin. Drought is a strong climatic factor that can significantly alter the transportation pathways, source to sink processes, and metabolism-sequestration flux ratio (Dai et al. 2008; Yu et al. 2011; Mosley 2015). By retaining the geochemical constituents in catchments, it can change the water composition of the river bodies (Worrall and Burt 2008). The period from 2006 to 2011 corresponds to the sequential impoundment of TGD and frequent drought events. Since drought events coincided with the early impoundment operations, TGD became the focus of controversy regarding environmental concerns (Li et al. 2018). The period showcases changes in the hydrological balances, particularly time-series changes in river runoff and sediment concentration. For instance, in 2006 (the year of severe drought) at Datong, the water level was historically low and sediment load was reported to be > 50% of the pre-dam values; thereby referring to the time as ‘no flood in the flood season (Yu et al. 2011; Wu et al. 2015).

Over the past 19 years, the focus in the Yangtze River basin is to quantify the damming effects on the river’s hydrological and biogeochemical processes. However, focussing only on the effects of TGD and undermining the role of climatic factors can lead to an inaccurate estimation of the cumulative impact of dams and reservoirs and over-and underestimation of other controlling variables. Therefore, with a motive to understand the changes in POM flux and sources and conceptualize the extent of TGD and drought control on the POC and PN content. We conducted continuous 1-year sampling (2008–2009) and collected total suspended matter (TSM) concentration near Nantong City in the lower Yangtze basin. The approach includes the amalgamation of biogeochemical indices (POC% of TSM, PN% of TSM, C/N ratios, and stable isotope of carbon $\delta^{13}C$) and drought climatic parameters (mean temperature, solar radiation, relative humidity, wind speed, evapotranspiration, and rainfall). Further, to get the overall picture, the present results were related to the previously published data of pre-dam and 2006–2011. The findings of the present research manifest the distinct impact of damming practices and climatic drivers on the C cycle and provide new insights into the factors controlling primary productivity in the Yangtze basin.

Materials and methods

River setting

The Yangtze is the largest river in Asia covering a basin area of $\sim$ 1.8 $\times$ 10^6 km^2 and flowing over $\sim$

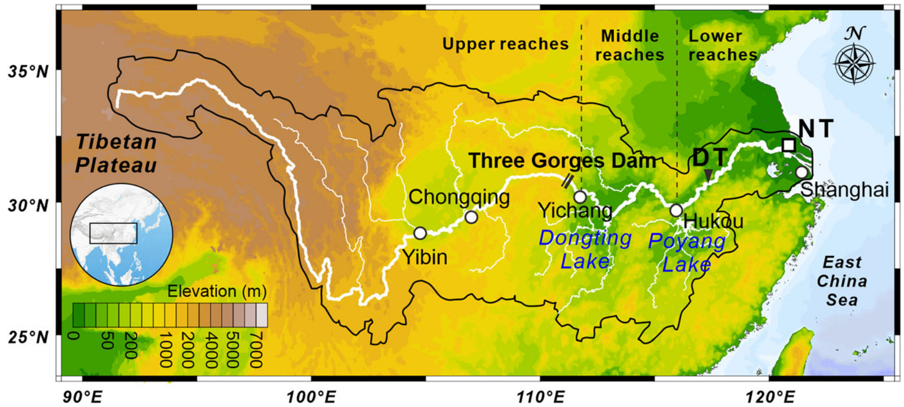

Fig. 1 A map showing the drainage basin of Yangtze River with the location of discharge data site, Datong (DT) and sample collection site, Nantong (NT)

6300 km in length. The river originates from the Qinghai-Tibet Plateau at an altitude of 5100 m above mean sea level and flows eastward to the East China Sea (Fig. 1). Physiographically, the river course is divided into three segments: (1) the upper reach (from the source area to the outlet of TGD at Yichang) covers a stretch of 4500 km. The river flows through high mountains and deep canyons and features high drainage density. Most of the major tributaries join the mainstem in this part; (2) the middle reach (from Yichang to Hukou), with a stretch of 950 km displaying meandering platforms. The Poyang and Dongting lakes contribute to the river discharge in this part of the river course; (3) the lower reach (from Hukou to the river mouth) consists of an 850 km long river stretch and a drainage area of 0.12×10^6 km^2.

The annual water and sediment discharge of the Yangtze is ~ 900 km^3 $year^{-1}$ and ~ 500 Mt $year^{-1}$, respectively (Yang et al. 2015). The basin is characterized by a subtropical climate with a large spatial and temporal variability of precipitation. The average annual precipitation is ~ 1050 mm $year^{-1}$. The precipitation amount increases eastwards with < 300 mm $year^{-1}$ in the upper reaches to > 1000 mm $year^{-1}$ in the middle and lower basin (Wang et al. 2008). The basin receives ~ 80% of annual precipitation and the river carries 70% of water and 85% of sediment load during the wet season (i.e., May–October) (Yang et al. 2018). Three Gorges Dam (TGD) is the world's largest hydropower structure installed in the mainstream Yangtze. The TGD reservoir is 663 km long, 1084 km^2 with a total storage capacity of 39.6 km^3 (Li et al. 2018; Guo et al. 2020). The TGD operation began in 2003 and achieved full capacity in 2009 after three major impoundments (Wu et al. 2015). TGD has influenced the hydrology of the river by storing a large share of water and sediment load, plus several studies have linked the occurrence of recurrent droughts to water shortage (Li et al. 2018). The basin inhabits > 450 million people and possesses immense socio-economic importance, thereby holding utmost accountability for assessing natural and anthropogenic impacts at a regular interval.

Sample collection and analysis

From April 2008 to April 2009, fifty-one samples were collected from Nantong, Jiangsu province in China. The sampling location (31° 57′ 24″ N, 120° 51′ 54″ E) lies ~ 140 km from the river mouth (Fig. 1). The salinity of surface water was ~ 0 throughout the year, and hence samples can be considered as the end-member compositions of the Yangtze River. A 10 L water sample was collected in acid-cleaned containers from a depth of 0.3 m. Samples were filtered by pre-combusted (at 500 °C for 5 h) glass fiber filters of 0.45 µm pore size for the collection of suspended sediments. Filtration was conducted within the time frame of 4–5 h and stored immediately at < 4 °C before the analysis commenced.

Mean suspended sediment size (Mz), particulate carbon (PC), particulate organic carbon (POC), particulate nitrogen (PN), and stable carbon isotope ($\delta^{13}C_{org}$) of the suspended sediments were analyzed at the State Key Laboratory of Marine Geology, Tongji

University. Mz was measured following the pre-treatment method mentioned in Velozzi et al. (2004). For each 0.5 g of sediment sample, 10 ml of 10% H_2O_2 was added over 24 h to remove organic matter. Then 5 ml of 10% HCl was added for 1 h to remove calcium carbonate. To wash out the residual HCl, ultrapure water was added to make a 500 ml mixture. Sample solutions then went through two centrifugations at 3500 rpm for 6 min. Further, treatment of 120 s of ultrasonic dispersion was performed to disperse and homogenize the samples before analysis through the Laser Diffraction Particle Size Analyzer (Coulter LS230, US). The analytical error calculated by repetitive measurements was $< \pm 1\%$. POC% and PN% denoting the percentage of POC and PN in TSM were determined by CN Elemental Analyzer (Vario EL-Cube, Elementar Co., Germany) without acid treatment. Crystine and Sulphanilamide were used as standard (reference) compounds for the calibration of the instrument. The POC was determined after removing the carbonate fraction by using 1 N HCl. The leached residue was rinsed with deionized water and then dried at 40 °C. The calcium carbonate ($CaCO_3$) content was calculated as the difference between PC and POC, assuming that all inorganic carbon is incorporated as calcite or aragonite. The stable organic carbon isotope ($\delta^{13}C_{org}$) was analyzed by the Stable Isotope Ratio Mass Spectrometer (Deltaplus XP, Finnigan). The standard of carbamide yielded a precision of about 0.3%.

In the absence of Nantong's discharge data, water discharge data of the Datong gauging station was used. The Datong data was referred to considering the facts that till Datong, the river covers ~ 94% of the total basin area, and no major tributary and lakes are present in the course while traversing from Datong to Nantong. Therefore, the additional input or loss of water in this part of the river is minimal. Further, the POC and PN flux was calculated by multiplying POC% and PN% values with sediment load.

The severity of the drought was estimated based on reference evapotranspiration (ETo) values. ETo calculator developed by FAO (food and agriculture organization) was employed to calculate ETo values. ETo is based on the Penman–Monteith method. It incorporates climatic parameters and expresses the evapotranspiration power of the location at a variable time. It is a widely accepted method with high reliability and accuracy (Gentilucci et al. 2021). Daily climatic records were downloaded from the public domain database of CFSR (Climate Forecast System Reanalysis (CFSR) and MERRA (Modern-Era Retrospective analysis for Research and Applications). ETo was calculated using the maximum and minimum temperature (to calculate mean temperature as proposed in Chapter 3—Meteorological data on ETo methodology by FAO) and solar radiation from the CFSR database and relative humidity, wind speed data from the MERRA. For more detailed information on ETo data, refinement, and methodology, refer to the literature available on the FAO website (https://www.fao.org/land-water/databases-and-software/eto-calculator/en/).

To correctly process the multivariate dataset, Principal Component Analysis (PCA) was applied using the SPSS software. PCA is a statistical technique used to find underlying correlations without losing the dataset's originality. PCA holds the advantage of reducing the dimensionality of a large dataset and elucidates linear combinations between samples (represented by PC scores) and between variables (represented by PC loadings). PCA was run on varimax rotation, and following the Kaiser principle, eigenvalues > 1 were used to select significant components. The loading of > 0.7 was considered strong, 0.5–0.7 as moderate, 0.3–0.49 as weak, and < 0.3 as irrelevant for interpretation.

Results

Temporal variation in suspended sediment characteristics

The seasonal hydrological changes in the Yangtze River basin result in temporal variations in physical and biogeochemical characteristics (TSM concentration, Mz, $CaCO_3$, POC%, PN%, and $\delta^{13}C$ composition) of sediment flux as shown in Table 1. The TSM concentration varied from 13 to 213 mg l^{-1} with an average of 85.2 mg l^{-1} and 42.2 mg l^{-1} respectively in the wet and dry season. TSM is mainly composed of clayey silt, with Mz ranging from 4.4 to 8.7 μm and an average of 6.1 μm, thereby exhibiting somewhat large variation but without a clear seasonal trend. The average contents of PN and POC in the TSM were 0.2 ± 0.06% and 1.2 ± 0.21%, respectively. The POC contents yield large fluctuations in the wet

Table 1 Statistics of biogeochemical characteristics of particulate sediment samples collected from Nantong in the year 2008–2009 (Qw = discharge, TSM = Total suspended matter, POC% is particulate organic carbon % in TSM, PN% is particulate nitrogen % in TSM, Mz = mean suspended sediment size, ETo is reference evapotranspiration, calculated using FAO calculator based on Penman–Monteith method)

	Qw ($m^3\ s^{-1}$)	TSM (mg l^{-1})	POC %	PN %	C/N	$\delta^{13}C$ (‰)	$CaCO_3$ (%)	Mz (µm)	POC flux (TgC)	PN flux (TgC)	ETo (mm day^{-1})
Yearly											
Minimum	10,900	13.00	0.78	0.10	4.78	− 25.63	0.01	4.36	0.02	0.01	1.02
Maximum	46,900	213.14	1.80	0.39	9.24	− 24.13	9.62	8.67	0.74	0.09	3.87
Mean	27,280	63.31	1.16	0.19	7.34	− 24.71	5.29	6.08	0.18	0.03	2.54
Standard deviation	10,617	46.71	0.21	0.06	0.92	0.37	2.19	1.09	0.16	0.02	0.77
Coefficient of variation, CV	0.39	0.74	0.19	0.30	0.13	− 0.01	0.41	0.18	0.90	0.80	0.30
Wet season (May–October)											
Minimum	21,200	16.01	0.78	0.10	6.32	− 25.40	0.01	4.46	0.05	0.01	1.86
Maximum	46,900	213.14	1.80	0.28	9.24	− 24.13	9.62	8.67	0.74	0.09	3.87
Mean	34,568	85.24	1.08	0.17	7.71	− 24.47	5.87	6.09	0.26	0.04	3.15
Standard deviation	7837	54.93	0.23	0.05	0.80	0.27	2.58	1.16	0.18	0.02	0.55
Coefficient of variation, CV	0.23	0.64	0.21	0.28	0.10	− 0.01	0.44	0.19	0.68	0.60	0.17
Dry season (November–April)											
Minimum	10,900.00	13.00	0.90	0.14	4.78	− 25.63	1.30	4.36	0.02	0.0	1.02
Maximum	38,300.00	103.16	1.60	0.39	8.58	− 24.46	7.18	8.43	0.31	0.0	2.98
Mean	20,273.08	42.21	1.23	0.21	6.98	− 24.95	4.72	6.07	0.09	0.0	1.95
Standard deviation	7894.18	22.88	0.18	0.06	0.90	0.30	1.59	1.03	0.07	0.0	0.43
Coefficient of variation, CV	0.39	0.54	0.14	0.27	0.13	− 0.01	0.34	0.17	0.76	0.7	0.22

season (May–October) and dry season (November–April), ranging from 0.8 to 1.8% and 0.9 to 1.6% respectively. The POC% and PN% were lowest in August–September with high values in March–April (Fig. 2). The C/N ratio varies between 4.8 and 9.2, showing higher values in the flood season than in the dry season. The δ^{13}Corg values vary between − 25.6 and − 24.1‰ demonstrating higher values in the wet season. The weight percentages of $CaCO_3$ vary from 0.01 to 9.62%, showing a significant drop in the dry season.

Variation in climatic factors

Climatic parameters such as reference evapotranspiration (ETo), temperature, and precipitation are important drivers that can explain most of the variations in TSM, POC% and PN% and their fluxes in the river channel. The seasonal variation in the ETo is mentioned in Table 1. ETo ranges between 1.0 and 3.9 mm day^{-1} with an average ETo rate of 3.15 mm day^{-1} in the summer months (May–October).

Discussion

Controlling factors impacting POM flux

The drought in 2008 characterized as mild to moderate in severity lasted for 3 months (May–July) (Zhang et al. 2015; Sun et al. 2018). Still, TSM concentration was found to be higher in the wet season, with a peaked value in September (Fig. 2). The results contrast with Wu et al. (2015) (which was based on monthly samples collected from Xuliujing, ~ 60 km away from our sampling point) that mentioned the

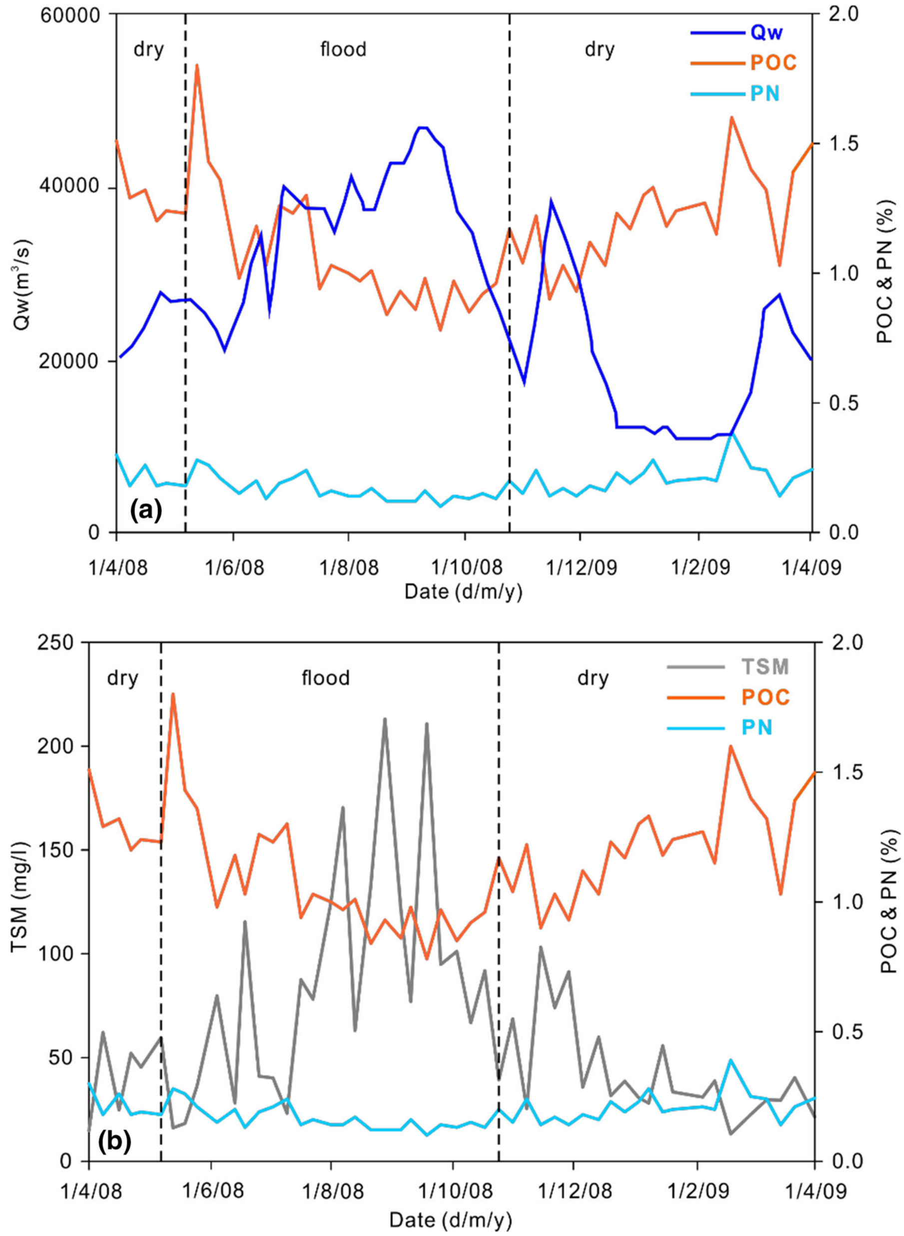

Fig. 2 Seasonal variations in POC%, and PN% in relation with **a** Qw (discharge), **b** TSM concentration

occurrence of high TSM during the dry season rather than in the flood season of 2006, 2008, and 2009. The limited number of monthly samples during 2008 maybe were unable to exhibit the dynamic conditions as captured by a continuous sampling plan. Contrary to TSM, the striking observation was POC% (mean 1.2% ± 0.2%) and PN% (mean 0.2% ± 0.06%) were higher in the dry season than in the flood season (Fig. 2).

Table 2 shows the variation in the pre-TGD and post-TGD periods. POC% value of 2008–2009 (0.8–1.8% of TSM, mean = 1.2 ± 0.21) was higher than the pre-dam value of 1.0% in 1997 to 0.92% in 2003 (Wu et al. 2007; Yu et al. 2011) but lower than

Table 2 Temporal variation in POC% in the lower Yangtze River basin

Year	Average POC%	References
1997	1.0	Wu et al. (2007)
2003	0.9	Yu et al. (2011)
2006	1.7	Yu et al. (2011)
2006–2007	2.8	Zhang et al. (2014)
2007–2008	1.8	Li et al. (2015)
2008–2009	1.2	Our result
2009–2010	1.6	Gao et al. (2012)

those reported during the frequent drought period commencing from 2006 to 2011. However, the annual POC flux (2.0 TgC) was less than 1993 and more than that of the most severe drought of 2006–2007 (1.88 TgC at Datong, Zhang et al. 2014) and 2009 (1.52 TgC at Datong, Wang et al. 2012) (Fig. 3).

Before the operation of TGD in 2003, a positive linear relationship between TSM and POC% was observed (Wu et al. 2007). However, in the post-TGD time, the retention of sediment within the reservoir, disturbed the delicate balance between discharge and sediment load, thereby inducing significant changes in the positive relationship between TSM and POC% in the mid-downstream reaches. Yu et al. (2011) mentioned the occurrence of inverse linear correlation ($R^2 = -0.74$, p-value ≤ 0.01) between TSM and POC% as also observed by Gao et al. (2012), Bao et al. (2014), Zhang et al. (2014) (For the entire Yangtze basin, POC% = $-$ 2.52 ln(TSM) + 11.72, $R^2 = 0.67$) and Wu et al. (2018). In the present study, an inverse power-law correlation between TSM-POC% and TSM-PN% was observed (Fig. 4a). The power-law correlation is a common feature across the world rivers. It represents the nonlinear reduction in POC% and PN% with an increase in TSM that may result from catchment heterogeneity or change in sediment source. In the Yangtze basin, it can relate to

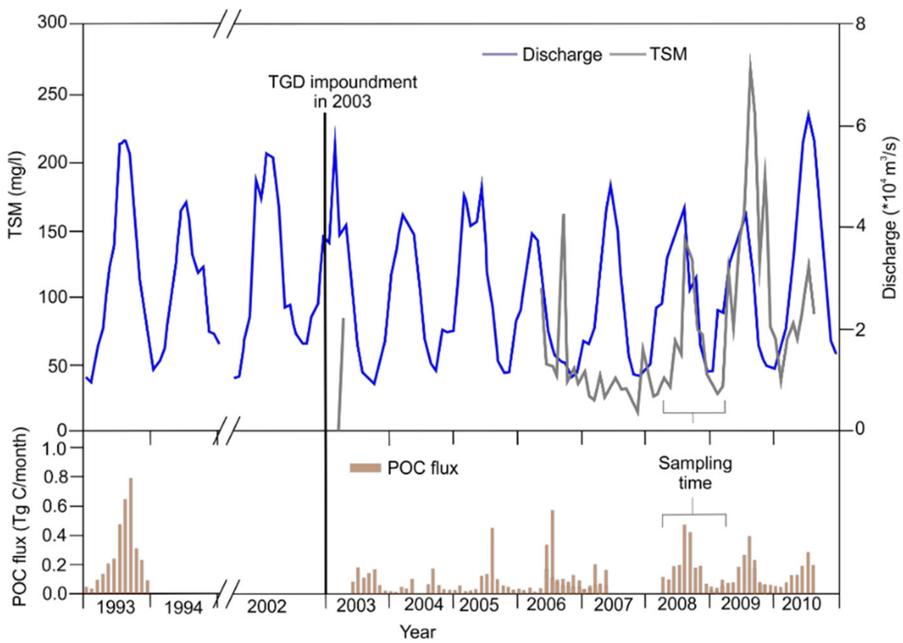

Fig. 3 Variations in monthly TSM concentration, discharge and POC fluxes in the lower Yangtze River (1993–2010). Discharge data of Datong hydrological station is cited from Gao et al. (2012). TSM concentration is cited from Wu et al. (2018) (from lower reaches of Yangtze at different months in 2003 to 2010), Zhang et al. (2014) (May 2006–May 2008, Datong), Wang et al. (2012) (Jan–Dec 2009, Datong), Gao et al. (2012) (Sep 2009–Aug 2010, Datong). POC flux is cited from Cai and Han (1998) (Jan–Dec 1993, Datong), Lin et al. (2007) (Jun 2003–May 2004, Aug 2004–Oct 2006, Xuliujing), Wang et al. (2011) (Jun 2006–May 2007, Datong), Zhang et al. (2014) (Jun 2006–March 2007, Datong); Wang et al. (2012) (Jan–Dec 2009, Datong), Gao et al. 2012 (Sep 2009–Aug 2010, Xuliujing)

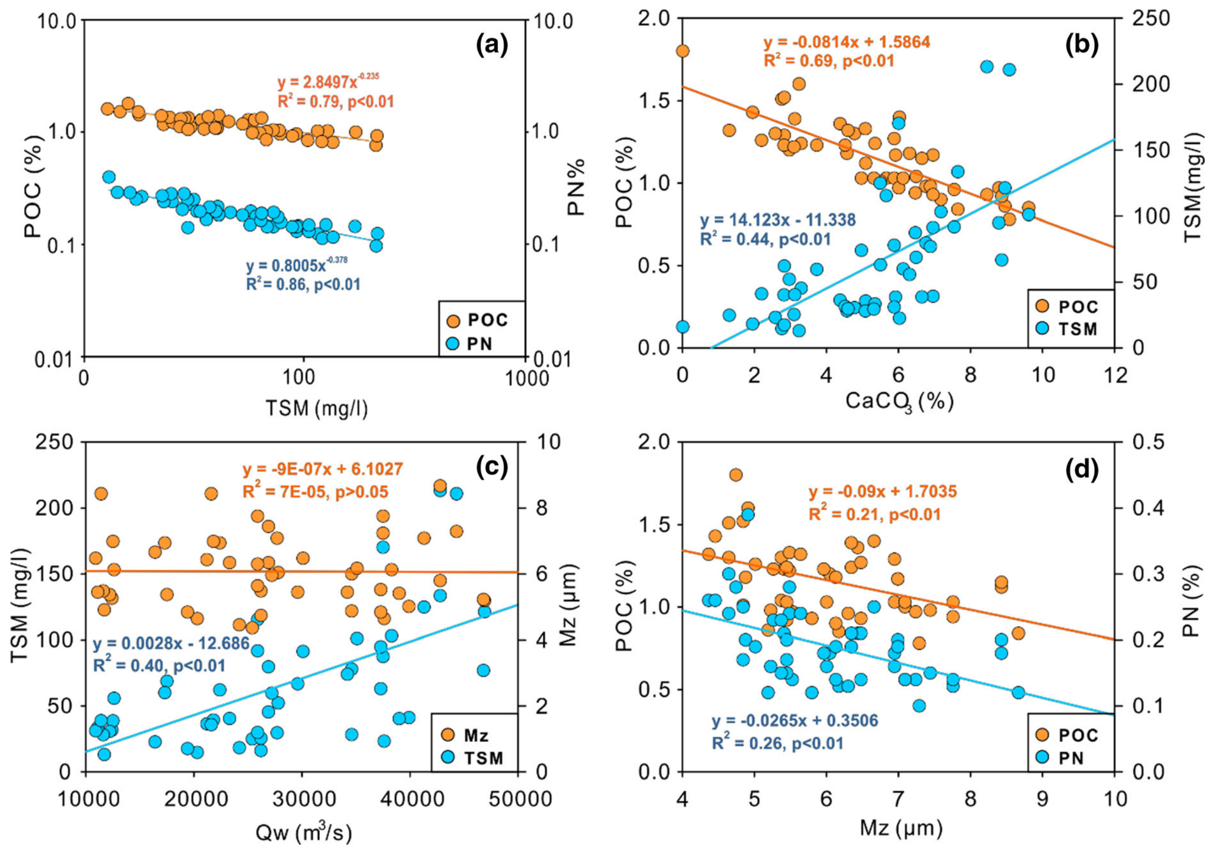

Fig. 4 **a** Log verses log scale plot showing inverse power-law relation between TSM and POC% and PN%, **b** correlation between TSM, $CaCO_3$, and POC%, **c** Qw, TSM, and Mz, **d** Mz, POC%, and PN%

the following processes: (i) the dilution of riverine POC with the mineral matter coming from the scouring of terrigenous soils and carbonate outcrop downstream of TGD. Severe bed scours and bank erosion has been reported even 1500 km downstream of the TGD (Guo et al. 2020). Further, Fig. 4b shows $CaCO_3$% varies conversely with POC% (as also reported by Liu et al. 2013) but shows a moderately positive linear correlation with TSM, thereby affirming the influence of inorganic carbon on the sediment load composition. (ii) the high TSM concentration can suppress primary production from phytoplankton and algal biomass resulting in low POC, as evidenced by Chai et al. (2006) and Tang et al. (2020) in the lower stretch of the Yangtze River and its estuary.

Further, the regression equation analysis shows that the power-law constant for POC is 2.8 and PN is 0.80, indicating POC% was affected much by the TSM concentration than PN% (Fig. 4a). Since exponent value (− 0.23, − 0.38 respectively for POC% and PN%) represents the rate at which a change in the TSM concentration occurs, which is dependent on discharge, Qw (as shown by the positive relationship between Qw and TSM, Fig. 4c) it can be postulated that in the lower Yangtze River, TSM and Qw are sensitive parameters influencing POC% and PN%. Additionally, the coefficient of variation ratio, $CV_{POC}/CV_{Qw} = 0.48$, $CV_{PN}/CV_{Qw} = 0.76$, $CV_{POC}/CV_{TSM} = 0.25$ and $CV_{PN}/CV_{TSM} = 0.40$ indicate that variation in PN% is much affected by the variation in Qw and TSM concentration.

However, the absence of a significant correlation between Qw and mean suspended sediment size, Mz (as was also observed in the year 2006 by Yu et al. 2011), Mz-POC%, and Mz-PN% was observed (Fig. 4c, d). Further, though Qw values in 2006 were among the lowest reported in the Yangtze basin (Wu et al. 2015) still Mz in that year was not the smallest. The Mz in 2006 was 14.76 µm as compared to mean values for the years 2003 and 2008, i.e., 6.77 µm and 6.08 µm (Table 1 and Yu et al. 2011). Thus, the presence of very fine silt to fine silt of suspended sediments and decrease in mean values from 2003 to 2008 cannot be explained solely by Qw.

Studies mentioned that water loss to TGD accounts for only 5–9% of the annual discharge and reduced water level (resulting due to scouring caused by clear water released by the dam) in the middle and lower reaches has a more significant influence on the hydrological behaviour (Dai et al. 2008; Lai et al. 2014; Zhang et al. 2016; Wang et al. 2020; Guo et al. 2020). The generalized data outline that TGD impoundment occurred in three stages from 2003 to 2010 (Period 1, May 2003–September 2006—reservoir water level rose to 139 m; Period 2, October 2006–September 2009—156 m; Period 3, October 2009–October 2010—175 m) (Wu et al. 2015). With each rising stage, in the reservoir region, POC% varied from $< 2\%$ in 1997 and 2003 to 9–21% in the spring of 2006 and 2008 (Zhang et al. 2014). However, coinciding with the time, POC% in the lower Yangtze River varied from 0.92% in 2003 to 1.73–2.78% in 2006 (Yu et al. 2011; Zhang et al. 2014), 0.8–1.8% in 2008–2009 (our results), 1.21–1.6% in 2009 (Wang et al. 2012; Gao et al. 2012), thereby limiting to decipher a clear trend in the lower section. However, apart from TSM concentration, Qw, and water level, multiple factors such as land cover (agricultural practices, sand mining, Lai et al. 2014; Bao et al. 2014), contribution of water and sediment discharge by the tributaries and lakes in the middle and lower reaches (as discussed by Yu et al. 2011), and drought conditions (from 2006 to 2011) (Dai et al. 2008; Yu et al. 2011; Gao et al. 2012; Li et al. 2015) can also influence the POM in the lower Yangtze. 'Natural drought versus artificial TGD control' explicates and distinguishes the role of climate and anthropogenic factors controlling POC% and PN% using a large number of parameters.

Source of organic matter

The terrestrial organic matter in the lower Yangtze River is documented to be sourced from multiple sources including, autochthonous freshwater aquatic life, terrestrial vegetation, pre-aged soil, and fossil organic matter (Zhang et al. 2007; Wu et al. 2007, 2018; Yu et al. 2011; Bao et al. 2014). Wu et al. (2018) mention that regardless of hydrological conditions, 9–15% of the POC is derived from the modern biomass (comprising of fresh higher plant detritus and aquatic production) and 17–56% is sourced from the pre-aged soil. Previous studies have documented $\delta^{13}C$ ranging from − 30.60 to − 24.25‰, and C/N ratios from 4.87 to 13.50, (10–20 in the estuarine area) and signified soil may constitute up to 50% of POM in the Yangtze basin (Fig. 5) (Cai and Han 1998; Zhang et al. 2007; Wu et al. 2007, 2018; Yu et al. 2011; Bao et al. 2014; Wang et al. 2012). However, after 2003, the decline in sediment load due to TGD storage promoted propagation of in-situ production and strong signatures of autochthonous organic matter from the mid-lower reaches of the river were reported (Yu et al. 2011; Bao et al. 2014; Wu et al. 2018). The $\delta^{13}C$ value from 2003 to 2010 varied from − 25.3 to − 24.4‰ in the lower reaches of the river (Wu et al. 2018). During the years 2003 and 2006, the average value was − 24.9‰ (Yu et al. 2011), 2007–2008 was − 24.48‰ (Li et al. 2015), and between 2003 and 2011 was − 25.7‰ (Wu et al. 2015). Therefore, considering the subsequent increase in POC% and PN% with low TSM concentration and previous data highlighting soil-originated POM signatures (Figs. 2, 5), we expected an enhanced contribution from both soil matter and phytoplankton.

Our results showed a relatively confined narrow range of $\delta^{13}C$ varying from − 25.6 to − 24.1‰ and is within the range of C3 vegetation and surface soil of the mid and upper Yangtze basin (− 28.9 to − 24.3 ‰ and − 26.1 to − 24.6‰) (Goñi and Eglinton 1996; Wu et al. 2007). The range of C/N ratio for aquatic phytoplankton varies from 4 to 8 (Kendall et al. 2001) and highly degraded soil organic matter for the world's large river varies from 8.1 to 12.9, respectively (Ittekkott and Zhang 1989). In our database, C/N ratios vary from 4.8 to 9.2 and display an annual average of 7.3. From May to Oct and Nov to Apr, C/N varied from 6.3 to 9.2 and 4.8 to 8.6 respectively indicating significant contribution from both phytoplankton and soil similar to that observed in the year 2006 by Yu et al. (2011). The association of high C/N ratios and enriched $\delta^{13}C$ values found during flood season, large $\delta^{13}C$ and high C/N values with an increase in TSM and Qw, and weak to moderate

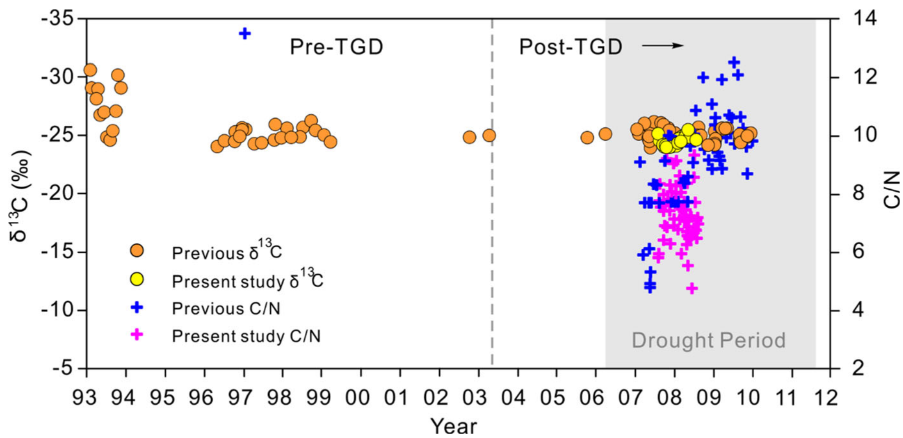

Fig. 5 Variations of $\delta^{13}C$ and C/N during pre-TGD and post-TGD impoundment periods. The $\delta^{13}C$ and C/N data were cited from Cai and Han (1998) at Datong (Jan–Dec 1993), Wu et al. (2002) at Nantong (Jul 1996–Jul 1999), Wu et al. (2007) from lower reaches (average C/N value of four samples collected in Apr–May 1997), Yu et al. (2011) from lower reaches (average April–May 2003 and Oct–Nov 2006), Bao et al. (2014) from lower reaches (Jan 2008), Wang et al. (2012) from Datong (Jan–Dec 2009), Wu et al. (2018) from lower reaches (2003–2010), Li et al. (2015) from Nanjing (Oct 2007–Sep 2008), Gao et al. (2012) from Xuliujing (Sep 2009–Aug 2010)

coefficient of determination implies the addition of allochthonous OM during the flood season (Fig. 6a–c). However, the contribution of phytoplankton to POC flux seems to be quite significant throughout the year. 78% samples show C/N value of < 8 and average annual value, average value during the flood and dry season were 7.3, 7.7, and 7.0 respectively. The annual average, average value during the flood and dry season of $\delta^{13}C$ was − 24.7, − 24.5, and − 24.9 than expected for terrestrial organic matter (− 27‰). Additionally, the negative correlation between TSM-POC% and $CaCO_3$-POC% also suggests POC controlling processes were not strongly related to terrestrial origin (Figs. 2 and 4). Further, the strong linear relationship between POC% and PN% indicates that the two had a common source and organic nitrogen majorly constitutes the PN% in TSM (Fig. 6d) (Meyers 1997; Ji et al. 2016).

Hein et al. (2003) elucidate that allochthonous POM is controlled by the extent of the hydrological exchange. At a medium–low connectivity level, allochthonous POM is expected to decrease and autochthonous organic matter dominates the POM pool. The strong phytoplankton signatures in 2008–2009 can be related to the impoundment activity and dry condition in the basin. In comparison to the year 1997 (TSM = 68.9 mg l^{-1} in the lower basin, Wu et al. 2007) and 2003 (TSM = 82.16 mg l^{-1}, Yu et al. 2011), TSM was 53.95 mg l^{-1} and 63.3 mg l^{-1} in the year 2006 and 2008. The occurrence of drought from May to July and increase in percentage area of drought conditions (dry area in WNW, NE, and ENW China) in 2008 may have supported the reduction of discharge and sediment contribution (Yu et al. 2014). Therefore, it can be speculated that reduced water discharge and occurrence of drought in the summer further supported a decrease in turbidity and render light availability promoting phytoplankton as a dominant source of POM even during the high sediment yield period. As extensive growth of phytoplankton results in the depletion of $\delta^{12}C$ and enrichment of $\delta^{13}C$ (Wu et al. 2008). The high ^{13}C values in the summer months and a moderate negative correlation between $\delta^{13}C$ and POC% can be asserted to primary productivity (Fig. 6d). Further, the decrease in POC% and C/N ratio in comparison to other drought events (2006–2011) can also be implied to increase in autochthonous production.

As river flow affects water age (water residence time), it is a good parameter to reveal hydrological disturbances that define biotic interactions and propagation of phytoplankton communities (Schagerl et al. 2009). The high water age due to the gentle terrain slope in the lower part of the Yangtze basin as well as in the dry period than the wet conditions has already been postulated to favour accumulation of algal

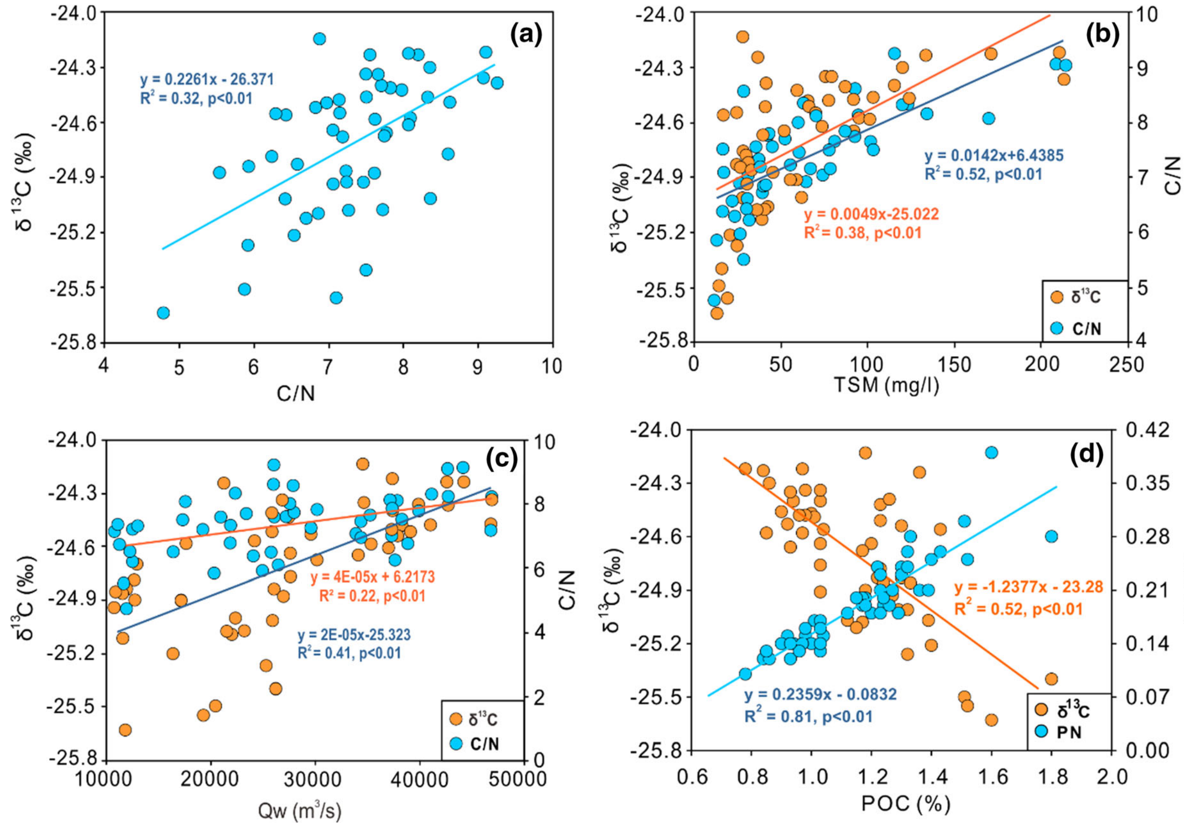

Fig. 6 Correlation between **a** $\delta^{13}C$ and C/N ratio, **b** TSM-$\delta^{13}C$ and TSM-C/N, **c** Qw-$\delta^{13}C$ and Qw-C/N, **d** POC%-$\delta^{13}C$ and POC%-PN%

biomass by Liu et al. (2018). Here, it can be inferred that in 2008–2009 key factors influencing the phytoplankton biomass were low flow (in drought time and dry season increasing the residence time of soluble and particulate matter), low TSM (resulting in improved water clarity for increased light penetration), low water level (due to scouring in the mid-lower reaches of the channel, Zhang et al. 2016; Guo et al. 2020), and high water age (due to moderate river discharge and dry climate, Liu et al. 2018; Wang et al. 2019). The impact of water age affecting the algal biomass in the Xiangxi Bay, Three Gorges Reservoir region, and mid-lower reaches of Hanjiang River has already been signified but it needs to be studied in the lower part of the basin (Gao et al. 2018; Tang et al. 2020). Further, in the drought period (characterized by high temperature and evapotranspiration resulting in low runoff and less terrestrial nutrients, Chen et al. 2014) anthropogenic effluents (as the mid-lower Yangtze basin is highly populated and industrialized) may have aided inhibition of nutrient limited conditions and favoured production and sustenance of phytoplankton and algal life throughout the year (as indicated by previous studies, Mosley 2015; Zhang et al. 2016; Liu et al. 2018; Gao et al. 2018; Tang et al. 2020; Wang et al. 2020).

Natural drought versus artificial TGD control

The strong dominance of in-situ aquatic productivity as a result of low TSM and regulated Qw indicates that TGD played a significant role in controlling the organic matter concentration. However, drought also seems to play a vital role in influencing in-situ productivity. Even for instance, in 2006 (an extreme drought year) in the lower reaches of Yangtze, the impact of drought was found to be stronger than TGD in influencing the TSM and OC flux (Yu et al. 2011).

To understand the impact of drought in 2008–2009, we first need to understand its causes and severity. As drought affects the hydrological balance of the basin and evapotranspiration process gets magnified during the time. Reference evapotranspiration (ETo) was estimated to understand the diurnal severity of drought in the lower Yangtze basin. The ETo is based on the Penman–Monteith method and expresses the atmosphere's evaporating power irrespective of soil conditions, crop types, and management practices. ETo is independent of the land cover and is affected only by the climatic parameters (mean temperature, solar radiation, relative humidity, and wind speed). Therefore, it is quite a useful parameter to compare the seasonal climatic changes in the highly complex Yangtze basin. ETo values in 2008–2009 varied from 1.02 to 3.87 mm day^{-1}, with a standard deviation of 0.77. Low values (less than the average) were witnessed mostly in the cold days with a mean of 1.91 mm day^{-1}, while high values coincided mostly with spring and summer months with a mean of 3.14 mm day^{-1} (Fig. 7). As the drought period coincided with the flood season (May–July), rainfall data were also included to determine the climatic control on the POC%, PN%, and their source.

To handle and investigate the inter-correlations between multiple variables in the special time of drought occurrence and TGD impoundment, PCA has been used. Table 3 shows the rotated component matrix. The first four principal components (PCs) showed eigenvalues > 1 and explained $\sim$ 82% of the variance in the data set. The four extracted component constitutes a unique source of variance that discern the role of controlling factors impacting POC% and PN%.

PC1 explains 42% of the variance and shows strong negative loading (> 0.9) for POC% and PN% and positive loading (> 0.75) for $CaCO_3$, TSM, and C/N, indicating their strong influence. The moderate loading for $\delta^{13}C$ and Mz and weak loading for Qw. The results reflect positive control of Qw on TSM, C/N, and $\delta^{13}C$ and negative control of $CaCO_3$, TSM, Mz, and $\delta^{13}C$ on POC% and PN% as also revealed by the linear regression analyses in sections 'Controlling factors impacting POM flux' and 'Source of organic matter'. PC2 explains 20% of the total variance. It delineates strong positive loading (> 0.9) for solar radiation, temperature, and ETo (> 0.8), moderate positive loading (0.53) for Qw, and weak positive loading (0.35) for $\delta^{13}C$. PC3 accounts for 13% of the dataset's variance, displaying positive loading for relative humidity, rainfall, Qw, and $\delta^{13}C$. The PC4 explains only 7.5% of the variance and indicates the positive loading between wind speed, Mz, rainfall, and C/N.

The following inferences can be deduced from the PCA analysis: (i) PC1–PC4 delineates the absence of significant control of climatic variables on the POC%, PN%, $CaCO_3$ and TSM (ii) PC1 explaining the largest variance delineates the absence of climatic control on the Qw, TSM, $CaCO_3$, Mz, $\delta^{13}C$, C/N, POC%, and PN%. It also indicates that the same conditions influence the POC% and PN% content, (ii). PC1, PC2, and PC3 delineate the control of Qw in controlling the carbon fractionation. (iii) PC2 indicates temperature, solar radiation, and Qw were the most significant factors inducing high ETo and abetting water stress in the basin. It also indicates that temperature and Qw determine $\delta^{13}C$ value. (iv) PC3 that explains $\sim$ 13% of the variance indicates rainfall has some control on Qw and $\delta^{13}C$. (v) PC1–PC4 highlights the absence of a significant relationship between ETo and rainfall indicating the water stress was not related to less rainfall in the basin but majorly related to temperature and solar radiation (PC2).

Few studies have documented that monthly and annual precipitation in the Yangtze basin from 2003 to 2018 has not been changed significantly but the temperature has increased by 0.9 °C in the lower catchment from 2003 to 2008 (Zhang et al. 2016; Li et al. 2018; Wang et al. 2020). The increase in temperature without significant change in precipitation has increased the evapotranspiration, thereby drought severity (the strong positive loading > 0.85 between temperature and evapotranspiration in PC2) as also observed by Chen et al. (2014).

The absence of significant correlations between climatic factors (ETo and rainfall) and TSM, POC%, and PN% (indicated by all four PCs, explaining $\sim$ 82% variance in the data, Table 3), control of Qw on TSM, POC%, PN%, $CaCO_3$, Mz, $\delta^{13}C$ and C/N (PC1) and Qw on $\delta^{13}C$ (PC2–PC3) specify that discharge is major factors that influence the organic

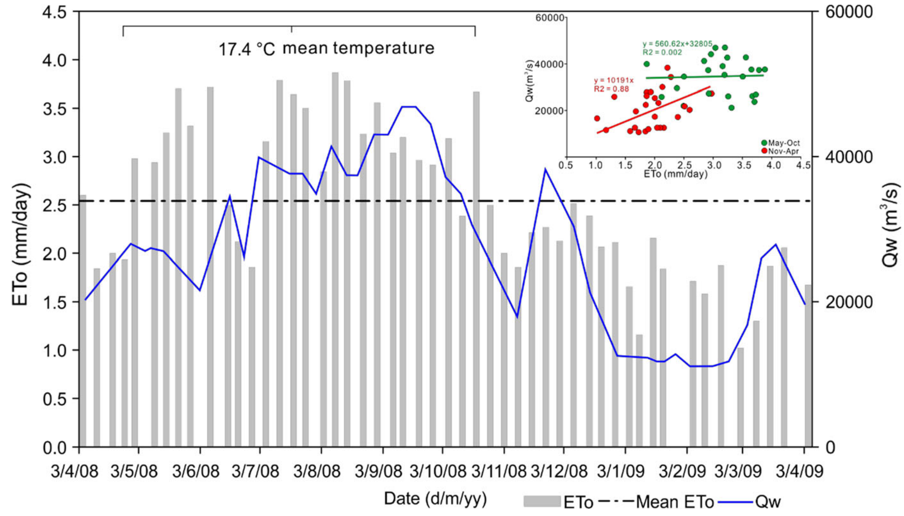

Fig. 7 Variations of reference evapotranspiration (ETo) and river water discharge (Qw). The correlation between ETo and Qw during the wet season (May–Oct) and dry season (Nov–Apr). The Qw is from Datong hydrological station

Table 3 Varimax rotation PCA loading matrix (factor loading > 0.3 is given in bold)

Rotated component matrix				
	Component			
	1	*2*	*3*	*4*
PN%	**− 0.933**	− 0.172	− 0.141	− 0.030
POC%	**− 0.917**	− 0.033	− 0.230	0.180
$CaCO_3$%	**0.858**	− 0.189	0.046	− 0.235
TSM (mg l^{-1})	**0.806**	0.239	0.258	0.031
C/N	**0.765**	0.298	0.049	**0.353**
Mz (μm)	**0.636**	− 0.106	− 0.184	**0.498**
$\delta^{13}C$ (‰)	**0.629**	**0.345**	**0.464**	− 0.119
Solar radiation (MJ m^{-2})	− 0.075	**0.952**	− 0.091	0.000
Mean temperature (°C)	0.068	**0.941**	0.108	− 0.029
Average ETo (mm day^{-1})	0.280	**0.879**	0.090	− 0.155
Relative humidity (%)	0.244	− 0.121	**0.850**	0.040
Rainfall (mm)	− 0.002	0.129	**0.781**	**0.410**
Qw (m^3 s^{-1})	**0.407**	**0.532**	**0.600**	− 0.094
Wind speed (m s^{-1})	− 0.113	− 0.160	0.273	**0.766**
Eigen value	5.877	2.758	1.821	1.057
Variance (%)	41.980	19.700	13.008	7.548
Cumulative variance (%)	41.980	61.680	74.688	82.236

matter content and its source in the lower Yangtze River. However, TGD impoundment operations and drought can both influence river discharge.

Considering the role of droughts in the year 2006 inducing a 45% loss of water flux at Datong Station in comparison to 9% loss due to TGD impoundment (Dai et al. 2008). The increment in the percentage area of drought conditions (which increased to up to 90% in 2008) can be one of the major reasons for low discharge in the Yangtze River (Yu et al. 2014). The drought in 2006 and 2008 both occurred in the summer season. In comparison to year 2003 (TSM 82.16 mg l^{-1}, POC% 0.92 ± 0.06), TSM and POC% were 53.95 mg l^{-1} and 1.73% ± 0.23% in 2006, and 63 mg l^{-1} and 1.2% ± 0.2% in 2008, thereby indicating higher organic carbon production in drought years (Yu et al. 2011). The high (0.879) loading of ETo and moderate to weak positive loading value of Qw (0.532) and $\delta^{13}C$ (0.345) in PC2 indicate the role of dry conditions in blooming the phytoplankton and algae (Table 3). Further, Fig. 7 indicate that ETo influenced Qw during the non-monsoon months (Nov–April) and not during monsoon months (May–Oct). In 2008, TGD impoundment took place from 28 September 2008 to 5 November 2008 (for 38 days); and from December until June, the TGD's operation increased the water level in the downstream rivers and lakes by discharging more water than the natural inflow to the TGD (Li et al. 2013). Therefore, it can be concluded that high evapotranspiration in the basin was not due to TGD operations rather it was due to high temperature and solar radiance in the lower part of the basin (as indicated by positive loadings in PC2). Therefore, PCA results specify that TGD was not the prime factor responsible for the drought event that occurred from May to July in 2008.

Our results show that the occurrence of frequent droughts and riverbed scouring induced low water levels provided favourable climatic conditions for phytoplankton to evolve as a major organic matter source. Algal blooms and eutrophication are environmental issues in the parts of the Yangtze River network (Gao et al. 2018; Tang et al. 2020). Phytoplankton growth and evolution is an extremely complex process governed by many different processes and mechanisms as displayed by the presence of power-law correlations, absence of Mz control on POC% and PN%, and not so strong terrestrial signatures. The positive loading for $CaCO_3$, $\delta^{13}C$, and C/N (PC1) and rainfall and $\delta^{13}C$ and C/N (PC3 and PC4) support the discussion to study the terrestrial sources with more biogeochemical proxies. Additionally, in addition to TGD, the role of small cascade dams in the upper Yangtze basin, the contribution of OM flux by lakes and tributaries, channel erosion in the mid-lower part of the basin, anthropogenic effluents acting as an important nutrient source during the dry season and POM processes in post-drought recovery phase also need to be studied, in detail.

Conclusions

From 2006 to 2011, the combined effect of TGD impoundment and drought conditions embrace uncertainties in the carbon budget of the Yangtze basin. The absence of seasonal variability of suspended sediment size and the presence of an inverse power-law correlation between TSM concentration and POC% and TSM and PN% at Nantong was witnessed. The $\delta^{13}C$, C/N ratio, negative correlation between TSM-POC% and $CaCO_3$-POC% points to primary productivity as a dominant source of organic carbon. PCA analysis indicates that rainfall was not the major factor determining Qw but temperature and solar radiation enhanced evapotranspiration induced water stress in the basin. Further, PCA results highlight that TGD was not the prime factor responsible for the drought event in 2008. The absence of significant correlations between climatic factors (ETo and rainfall) and TSM, POC%, and PN% and linear correlation of Qw and TSM with C/N and $\delta^{13}C$ specify that discharge and TSM concentration influences the organic carbon balances. Riverbed scouring induced low water levels and dry conditions aid in-situ productivity. However, there are still several uncertainties to unravel in future studies including more terrestrial signatures, the role of temperature (an important factor influencing aquatic ecosystems and climate change) on the POM transportation process, and recognition of dominant phytoplankton communities.

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Data availability The data used in the study is compiled in Supplementary file1. Further, the MERRA (Modern-Era Retrospective analysis for Research and Applications) and CFSR (Climate Forecast System Reanalysis (CFSR) database used to generate results is available in the public domain at websites http://www.soda-pro.com/web-services/meteo-data/merra and https://globalweather.tamu.edu/.

Code availability NA.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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