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ORIGINAL ARTICLE

Dissolved organic carbon concentration and its seasonal variation in the Huguangyan Maar Lake of Southern China

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Abstract The dissolved organic carbon (DOC) in the surface water of Huguangyan Maar Lake was continuously monitored based on once per week sampling frequency of 4 locations from June 2018 to May 2019. The DOC concentrations and its seasonal variation were discussed by correlating with the rainfall, water temperature, and pH of lake water. The results showed that the weekly DOC varied from 8.15 to 32.65 mg/L with an annual average concentration of 17.96 mg/L. There was a significant difference in the average DOC concentrations between the rainy and dry seasons as the monthly average DOC concentration was 21.72 mg/L for the wet season compared to the dry season concentration of 14.21 mg/L. The rainfall shows a significant effect on the DOC concentration of lake water, as DOC concentration was much high during the wet season. There were no significant spatial variations in the average monthly concentration among the four sampling locations except occasional variation during the wet season. The reason for the wet season DOC differences among four sampling locations is likely due to the uneven runoff and underground water inputs and the relatively slow circulation of lake water. Finally, the seasonal fluctuation of DOC concentration in this closed lake water suggests that dissolved soil organic matter inputs through the rainfall related to surface runoff and subsurface infiltration from the surrounding watershed land is important to the primary production and organic matter deposition in the lake sediments.

Keywords Dissolved organic carbon · Seasonal variation · PH value · Rainfall · Huguangyan Maar Lake

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1 Introduction

The water dissolved organic carbon (DOC) is one of the largest bioactive organic pools and plays an important role in the carbon cycle of the Earth's surface (Cole et al. 2007; Song et al. 2018). Although inland waters such as lakes occupy small proportions of the Earth's surface, they have been suggested to have a significant effect on the global carbon cycle (Aherne and Farrell 2002; Cole et al. 2007; Pan et al. 2010) by storing and decomposing large amount of organic matter (Yu et al. 2015). Lakes receive water from the surrounding landscape, connecting streams, rivers, etc., therefore store a large amount of terrestrially derived carbon in the form of particulates and most of this carbon would eventually be mineralized and released into the atmosphere as CO_2 and CH_4 (Song et al. 2018). In lakes, DOC indirectly controls the ecological functions by regulating the water transparency, penetration of UV radiations, and dissolved oxygen concentration (Eimers et al. 2008). DOC concentration also largely affects a lake's food web, metabolic activities in the water (Larsen et al. 2011), and may also mediate the chemical environment of the water through the generation of organic acids (Brooks and Lemon 2007) which influences the solubility and bioavailability of metals (Eimers et al. 2008) and nutrients in the water (Song et al. 2018). Moreover, the abundance of DOC in lake water is affected by the water acidity, as the decline of DOC may indicate an increase in acidity of the lake and vice versa (Evans et al. 2012; Keller et al. 2008; Yallop et al. 2010). There have been many studies around the world such as North America (Dean and Gorham, 1998), western Europe (Woszczyk et al. 2011), Asia (Song et al. 2018; Wang et al. 2012a, b), and other regions. These studies have explored the temporal variation of DOC in coastal and fresh inland waters (Fang et al. 2018; Kai et al. 2019; Tranvik et al. 2009; Wang et al. 2015; Wen et al. 2016; Zhao et al. 2017), aimed to a better understanding of the primary production and organic carbon storage in the various water bodies.

Maar lakes are a typical kind of volcanic lake that has a unique water system (Christenson et al. 2015) and are mostly closed with no inflow/outflow from rivers or streams (Fang et al. 2018). The water supply of Maar lake is mainly groundwater, rainfall, and runoff. Therefore, the ecosystem of Maar lake is climate-sensitive (Ortiz et al. 2013). Moreover, Maar lakes are mostly characterized by relatively small drainage basin and somewhat uniform geology (Martín-Serrano et al. 2009). These morphological features of Maar lakes promote the continual accumulation and preservation of sediments (Allen et al. 1999; Ortiz et al. 2013) which makes them important subjects for paleoenvironmental, geophysical, paleoclimate, and geochemical studies (Chen et al. 2021; Qiang et al. 2018). The Huguangyan Maar Lake (shortened for HG Lake) is such a unique lake that was developed from a volcanic crater and rimed by tephra (Christenson et al. 2015). HG Lake is one of the largest volcanic lakes in the world and is reserved as a tourist site (Fang et al. 2018). HG lake is regarded as a “twin lake” to Lake Eifel of Germany and was listed as a UNESCO geological park in 2006. The lake is located in the Leizhou peninsula which is affected by the East Asian monsoon climate (Wu et al. 2012). The monsoon exhibits seasonal variations in atmospheric circulations and precipitation and is characterized by a rainy season from March to August (summer and spring) and a dry season from September to February (winter and autumn) (Huang et al. 2010). Just like other Maar lakes, HG Lake is regarded as a unique water environment and its ecosystem has been affected solely by the regional climate changes, therefore bear scientific significance in studying the regional climate and environmental change (Fang et al. 2018). In particular, because the organic matter in the sediments bears valuable information for paleoclimate studies, the DOC concentration and its variation are significant to the understanding of sedimentary organic matter formation and related regional climate conditions. The HG lake has been drawing attention from geologists due to its unique geological background. The first sediment core samples of HG Lake obtained in 1997 (Mingram et al. 2004) provided key information about climate change since the last glaciations. To date, substantial re-constructional studies of the lake’s sediments have improved the understanding of Holocene climatic evolution, paleoclimate changes, etc (Liu et al. 2000; Mingram et al. 2004; Yancheva et al. 2007, and reference therein). The knowledge of surface water DOC may further be required to improve the effective assessment of the contributions of lakes to the contemporary carbon sink.

2 Materials and methods

2.1 Geography of HG lake

HG Lake is located in the Leizhou Peninsula (21°9′N 110°17′E) of Guangdong province as shown in Fig. 1 and is about 500 m away from the campus of Guangdong Ocean University. The water surface of HG Lake is about 2.1–2.25 km^2 with a maximum water depth of 20–21 m. HG Lake has a limited catchment area of 3.2 km^2 with no riverine input or output, and is almost immune to external water system interference (Fang et al. 2018), thus changes in the lake’s water depends mainly on the supply of rainfall and groundwater level (Chen et al. 2018). Furthermore, since the lake is surrounded by the rim formed by the volcanic eruption, the circulation of lake water is kind of slow. The lake is affected by monsoon climate and portrays seasonal fluxes in atmospheric circulation and precipitation propagated by EASM that increases the rain and accounts for over half of the annual average precipitation of the area (Jia et al. 2015) during the hot rainy months, i.e. from March to August (Huang et al. 2010; Li et al. 2012; Qiang and Yang 2008). The rainy season is accompanied by high atmospheric temperatures and weak winds that promote thermal stratification in the lake’s water column (Jia et al. 2015). However, during the dry and cold months i.e. from September to April (Huang et al. 2010; Li et al. 2012), the EAWM prevails and breaks up this thermal stratification resulting in increasing primary productivity as it promotes the mixing of bottom nutrient-rich waters with the surface waters (Wang et al. 2008, 2009). Affected by the monsoon climate, the surrounding site has a recorded average annual rainfall of about 1600 mm and a temperature of 23 °C (Jia et al. 2015; Shen et al. 2013; Wang et al. 2012a, b).

2.2 Lake water sampling and *in-situ* data acquisition

Surface water was taken using an amber high-density polyethylene (HDPE) bottle every Wednesday morning before 8 o’clock, starting from June 6, 2018, until May 29 of 2019, from four sampling locations (numbered 1, 2, 3,

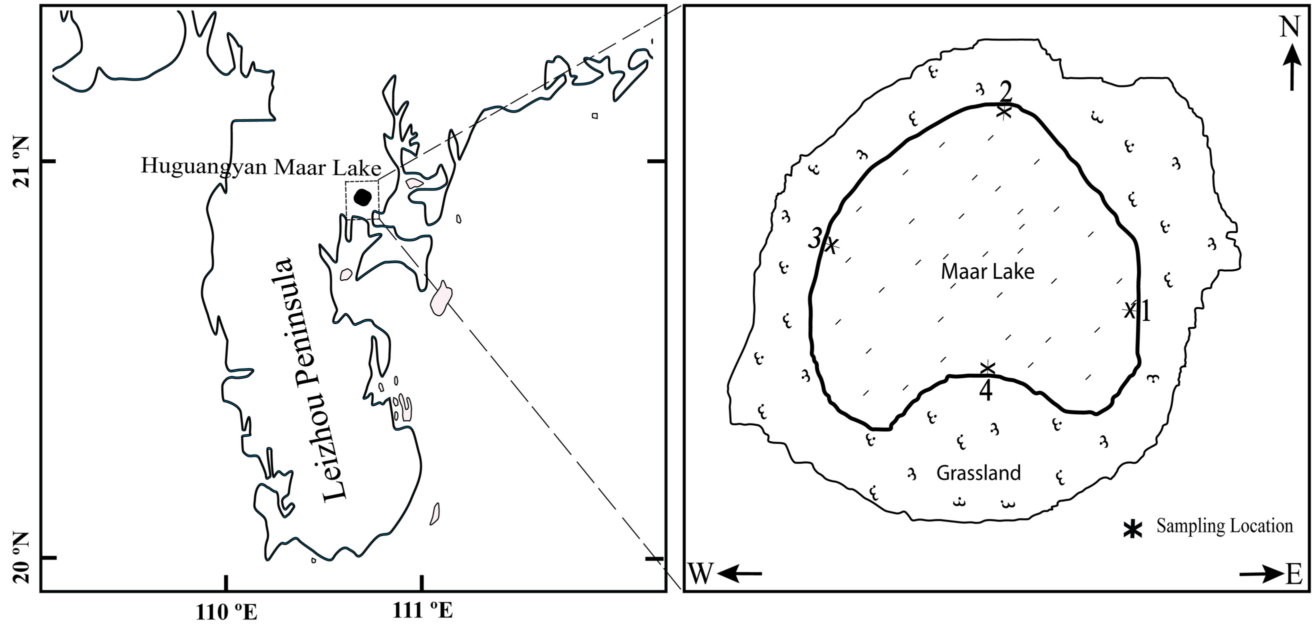

Fig. 1 The geographical location of the study lake

and 4) of the HG Lake (Fig. 1). The main consideration for the choice of four locations was based on the possible difference in the underground water supply and the effect of human activities. Thus, the sampling locations 1 and 2 are close to the main entrance area of the lake where more tourist activity was observed, while locations 3 and 4 are less-visited areas by the tourist.

A total of 208 surface water samples were collected during the 52 weeks of the sampling exercise. While taking the water samples, the surface water temperature and pH values were measured on-site using a Mercury thermometer and Mettler Toledo AG pH meter with LE438 probe, respectively. The pH meter was calibrated using standard Toledo technical buffer solution before each measurement. Daily rainfall data for the sampling period was obtained from a nearby meteorological field station monitored by the Zhanjiang Meteorological Bureau.

2.3 DOC measurements and data processes

After sampling, the water samples were immediately brought back to the laboratory (which is about 1 km away from the lake), filtered using a 0.45 µm Whatman GF/F filter, and stored in a fridge at temperatures of 4 °C for DOC and other analyses. The water DOC concentration was determined using a modern Total Organic Carbon Analyzer (Vario TOC Elementar manufactured by Elementar Company, Germany). The inorganic carbon was removed from the sample by automatic acidification of the water samples with non-oxidative acid of HCl. The TOC Elementar was calibrated according to the manufacturer's instructions, using the primary standard of potassium hydrogen phthalate (KHP). QA/QC KHP standards were run every 20–30 samples. All experiments were performed at the College of Chemistry and Environment laboratory of Guangdong Ocean University.

The DOC concentration of the water samples from all four sampling locations was averaged to obtain a mean DOC value which represented the weekly DOC content of the whole lake. And then the monthly DOC concentration was also calculated based on this mean weekly DOC concentration. The average weekly mean DOC was correlated with water temperature, pH values as well as rainfall to determine the influence of these factors on the DOC concentration.

3 Results and discussion

3.1 The DOC concentration of the surface water of HG lake

All weekly DOC concentration of the lake's surface water from the four sampling locations is depictured in Fig. 2. The weekly DOC concentration of the water samples from the four sampling locations 1, 2, 3, and 4 ranged from 7.02 to 49.61 mg/L, 8.32 to 43.69 mg/L, 6.89 to 41.99 mg/L, and 6.63 to 38.68 mg/L respectively. As shown in Fig. 2, there are significant seasonal variations in the DOC concentration during the sampling period. The spatial variation in DOC of the lake water from the four locations was insignificant. However, the DOC concentration displayed

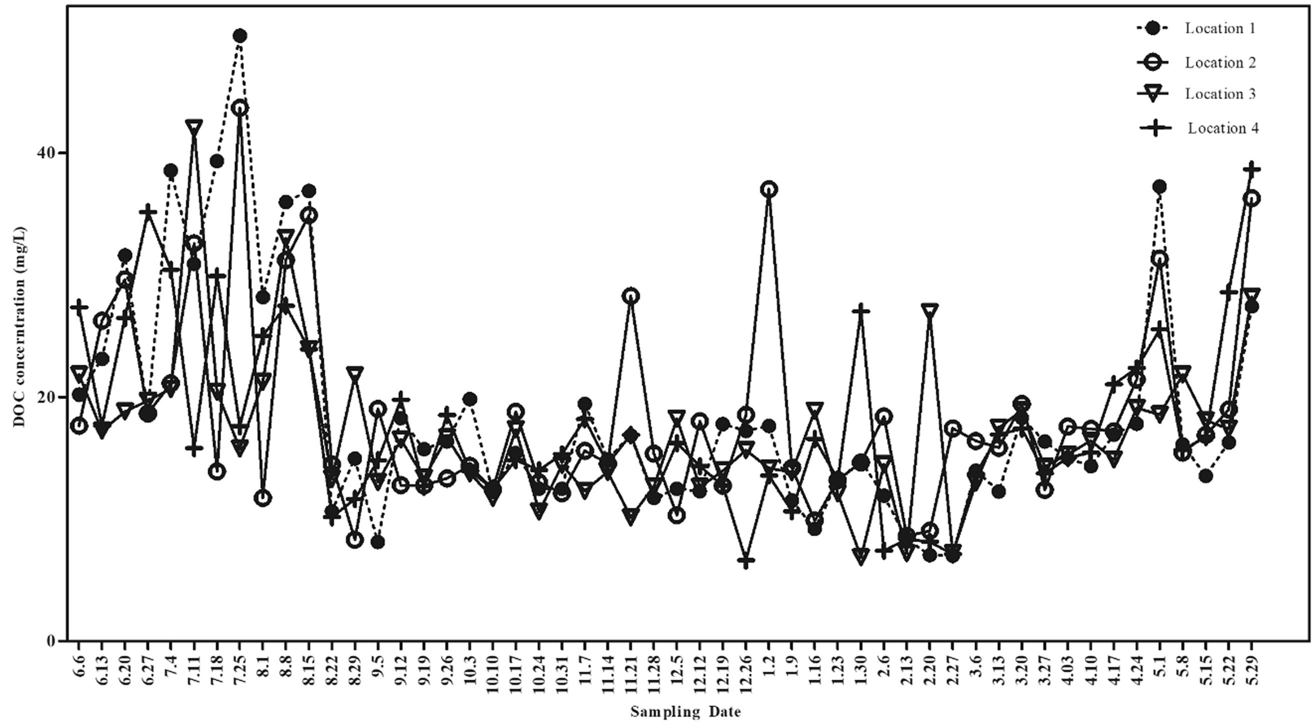

Fig. 2 The weekly variation in DOC concentrations (mg/L) of the surface water of HG Maar Lake based on four location sampling measurements monitored from June 6, 2018, to May 29, 2019

obvious spatial variation among the four locations during the high DOC concentration period i.e. from May to August, while less variation during the dry season of September to April when the DOC concentration is low. These fluctuations among the four sampling locations in DOC concentrations could be due to the spatial variations in the geographical condition such as the uneven underground water and surface runoff inputs as well as the relatively weak circulation of the lake (Keller et al. 2008).

The annual average DOC concentration of the lake's surface water from the four sampling sites named 1, 2, 3, and 4 were 18.63, 18.57, 16.97, and 17.69 mg/L respectively (see in the supplementary table). The annual differences in the average DOC concentration among these four locations were also insignificant, suggesting that DOC is homogeneously distributed in the surface water of this lake. However, despite exhibiting insignificant annual variation in DOC concentration, the higher average annual DOC concentrations of sampling sites 1 and 2, compared with the other sampling locations (3 and 4), is likely due to their location in the lake which is in the north side, (Fig. 1). Thus, sampling locations 1 and 2 may receive more sunshine during the day resulting in the thrive of microorganisms subsequently increasing primary production. Also, the watershed area of the north side is much large than that of the south side of the lake which may indicate much high underwater input through runoff and filtration. Moreover, these two locations are close to the entrances of the lake thus, have increased proximity to frequent human disturbances during visits (Li et al. 2012) such as the feeding of fishes which may introduce organic substances contributing to the DOC loads (Table 1).

Averaging from the weekly DOC content of these four sampling locations, the weekly DOC concentration of the whole-lake displayed great variation ranging from 8.15 to 32.65 mg/L with an average annual concentration of 17.96 mg/L. By comparison to the surface water of other lakes, streams, and reservoirs in China and other parts of the world, HG Maar Lake shows a higher DOC concentration range (Table 2). The higher surface water DOC concentration of the HG Lake is likely due to its relatively closed water system (Fang et al. 2018) that makes the lake water less prone to dilution from external water sources (Sobek et al. 2007). This is similar to previous findings where closed lakes of the endorheic regions of the Tibet plateau exhibited significantly higher DOC concentrations than the open lakes due to no flow export of the water DOC (Wen et al. 2019). However, compared to the eutrophic lakes in Northeast and Inner Mongolia-Xingjiang limnetic regions, and lakes in boreal regions, peatland catchments in the UK, Canada, North, East America, etc. (Evans et al. 2005; Skjelkvåle et al. 2005; Wen et al. 2019) the mean DOC concentrations of the HG Lake is lower. This observed phenomenon could be due to the difference in

Table 1 The monthly average DOC concentration (mg/L), water temperature (°C), rainfall (mm), and pH values and their standard deviations (SD) of the HG Maar Lake monitored from June 6, 2018, to May 29, 2019

Sampling date	DOC concentration (mg/L) Mean ± SD	Rainfall (mm)	Temperature (°C)	pH
June	23.14 ± 2.97	95.58 ± 65.66	29.30 ± 1.41	8.46 ± 0.08
July	28.75 ± 6.89	109.85 ± 85.80	30.30 ± 1.29	8.39 ± 0.19
August	21.95 ± 2.61	77.44 ± 53.35	30.29 ± 0.68	7.73 ± 0.22
September	15.13 ± 0.9	74.28 ± 73.48	27.68 ± 0.91	7.35 ± 0.19
October	14.10 ± 0.3	24.32 ± 41.74	29.44 ± .0.83	7.33 ± 0.19
November	15.46 ± 2.53	9.75 ± 11.39	25.06 ± 0.95	7.39 ± 0.09
December	14.51 ± 1.25	8.53 ± 12.27	21.14 ± 1.72	7.28 ± 0.10
January	15.11 ± 2.28	0.00 ± .0.00	18.72 ± 0.66	7.51 ± 0.12
February	10.93 ± 3.1	6.75 ± 7.84	21.76 ± 0.63	7.57 ± 0.15
March	15.67 ± 0.3	24.03 ± 35.33	23.01 ± 0.64	7.50 ± 0.11
April	17.34 ± 1.2	10.4 ± 12.91	27.56 ± 1.52	7.74 ± 0.17
May	22.95 ± 1.8	20.26 ± 10.25	28.21 ± 1.74	7.86 ± 0.13

Table 2 Comparison of the surface water DOC concentrations in the Huguangyan Maar Lake with other studied water bodies (lakes, rivers, reservoirs and streams) in China and other parts of the world

Study sites	Average DOC concentration range in mg/L	References
Huguangyan Maar Lake, China	8.15–32.65	Present study
Hongjiadu reservoir, China	0.77–29.04	(Peng et al. 2017)
Donfengdu reservoir, China	0.43–30.61	
Wujiangdu reservoir, China	1.19–31.61	
Liuchong river, China	0.81–20.02	
Headwater streams of Wuyi, China	4.03–5.06	
Northern Poyang Lake, China	1.60–2.82	(Xu et al. 2015)
Dee Valley, Scotland (56 Gauged and ungauged watersheds)	1.4–12.2	(Aitkenhead-Peterson et al. 2007)
North America (headwater stream in north central Massachusetts)	1.8–14	(Xu et al. 2012; Liu et al. 2014a, b)
Irish streams (55 studied streams)	0.9–25.9	(Liu et al. 2014a, b)

lake trophic status, lake type, and the watershed landscape pattern of the lakes (Lee et al. 2018; Oni et al. 2011; Wen et al. 2019).

3.2 The monthly and seasonal variation in DOC concentration

As shown in Table 1, the monthly mean DOC concentrations of the HG Lake ranged from low values of 10.93 mg/L in February to high values of 28.75 mg/L in July. The DOC concentrations were high from June to August (weeks 6.6–8.15). On the other hand, the DOC concentrations were significantly lower from September to May (week 9.5 to 5.29) (Figs. 3, 4, and 5). This revealed a typical seasonal pattern with the highest mean concentration of 24.45 mg/L during the summer (June, July August), followed by 18.98 mg/L during spring (March, April, and May), low concentration of 14.83 mg/L during autumn (September, October, and November), and the lowest concentrations of 13.59 mg/L during the winter season (December, January, and February), (Table 1). Both weekly and monthly average DOC concentrations indicated therefore that, the DOC concentration of the surface water of HG Lake was high in the rainy season but low in the dry season.

Seasonal variation in surface water DOC concentration of lakes or reservoirs has also been reported from several inland water bodies in China including Lake Bosten of the Xinjiang Province, Wulixia reservoir, Shuibuya reservoir over the Qingjiang river basin, Nam Co, and inflowing rivers of Tibet Plateau (Fang et al. 2018; Lu et al. 2018; Kai et al. 2019; Wang et al. 2014; Zhao et al. 2017). Seasonal changes are often associated with changes in land-use, climate change, temperature variation, changes in rainfall amounts, etc. and all these factors could cause short

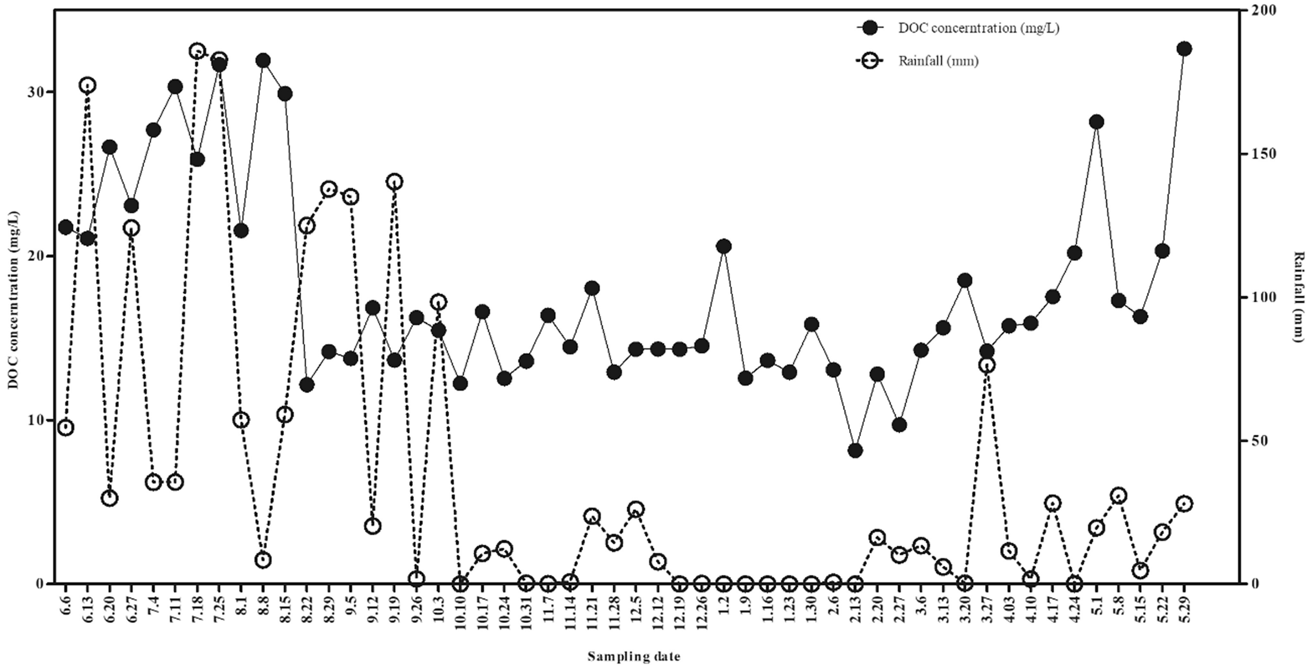

Fig. 3 Temporal variation of the weekly rainfall (mm) and the average DOC concentrations (mg/L) in the surface water of HG Maar Lake drawn from the four location sampling measurements monitored from June 6, 2018, to May 29, 2019

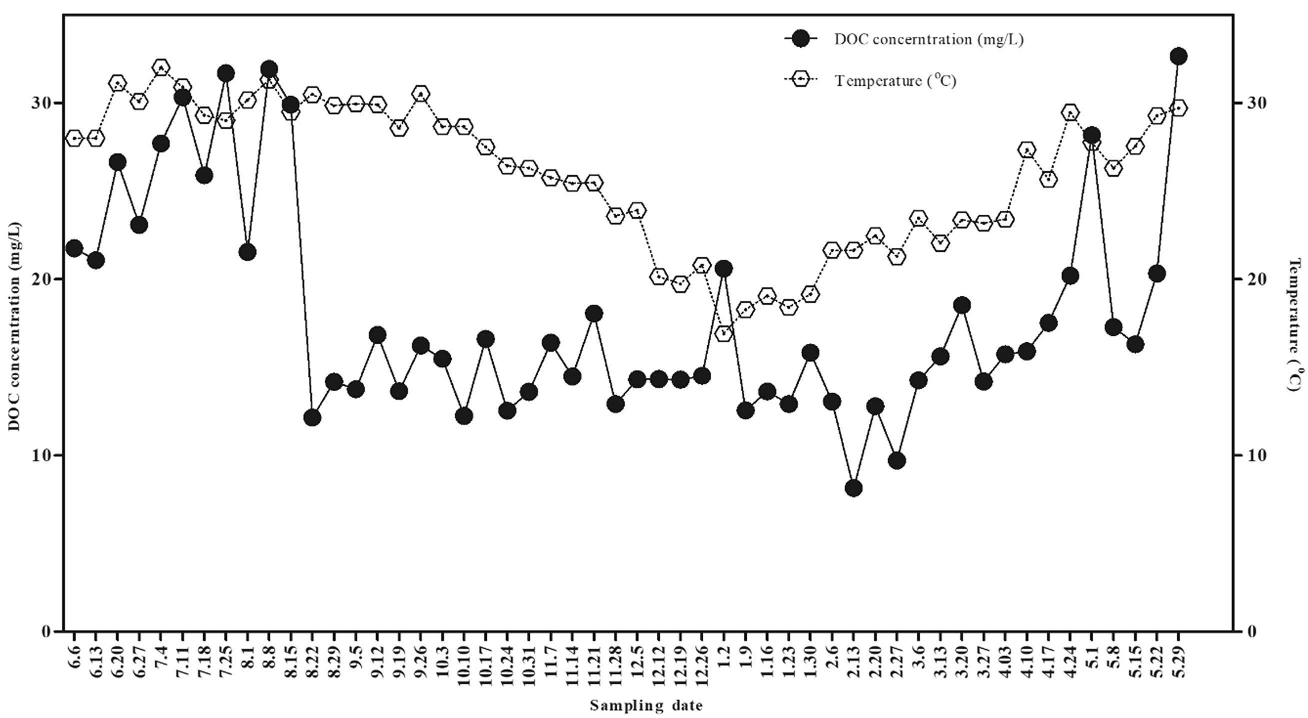

Fig. 4 Temporal variation in the weekly average DOC concentrations (mg/L) and surface water temperature (°C) of HG Maar Lake drawn from the four location sampling measurements monitored from June 6, 2018, to May 29, 2019

term variations in the DOC concentration of lakes (Erlandsson et al. 2008; Evans et al. 2006; Valinia et al. 2014; Weyhenmeyer and Karlsson 2009; Yallop et al. 2010). Lake Bosten is one of the biggest inland freshwater lakes in China (Yao et al. 2018) and it showed an average DOC of 9.3 mg/L during the summer season and 10.3 mg/L during spring and autumn (Wang et al. 2014). The DOC concentration of 55 Irish streams was reported to be higher in

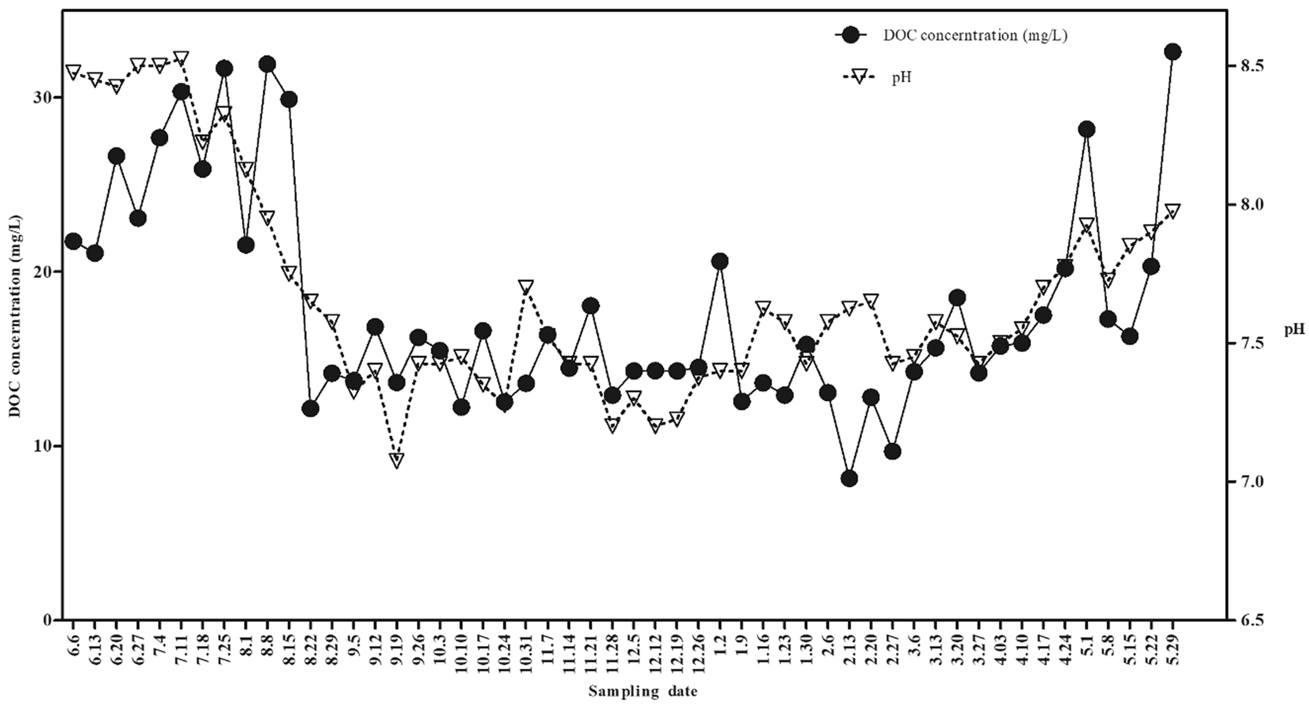

Fig. 5 Temporal variation in the average weekly DOC concentrations (mg/L) and pH values of HG Maar Lake drawn from the four location sampling measurements monitored from June 6, 2018, to May 29, 2019

autumn than in summer and winter (Liu et al. 2014a, b). In the Xijiang River of South China, a higher DOC concentration of 1.40 mg/L was recorded during flood seasons but a low concentration of 1.18 mg/L during the non-flood season (Tao et al. 2011). DOC concentration of northern Poyang Lake was found to be relatively low during the wet season (Xu et al. 2015). The seasonal variation of DOC concentration in HG Lake is different from the temporary pattern of these other water bodies in China and around the world. Several factors may explain this difference including divergences in climatic, geopedological, topographical landscape conditions (Song et al. 2018) and as well as the lake type. As large freshwater reservoirs, most of these lakes have external water input through connecting streams, rivers, etc. The external water input would increase during the wet season (Lu et al. 2018) and therefore may have diluted the DOC concentration and resulted in a low DOC concentration of their lake water (Hudson et al. 2003; Sobek et al. 2007). But for the HG Lake, there is no riverine input or output and their watershed area is also small (Fang et al. 2018).

3.3 Correlation between the DOC concentration and rainfall

It has been reported that the DOC concentration was lower during the raining season than that of the dry season in the Wulixia reservoir, China's third-largest body of freshwater, the Xijiang River of South China, the northern Poyang Lake, etc. due to the dilution factor of massive river input during the wet season (Liu et al. 2014a, b; Lu et al. 2018; Tao et al. 2011). While the HG Maar Lake would receive most of its water inputs through runoff and infiltration during the wet season and these processes may dissolve and transport more soil organic matter into the lake. Furthermore, studies on the evolution of both EASM and EAWM of HG Lake have shown that the lake is sensitive to Asian monsoon winds as thermal stratification of the water column builds up during EASM. Conversely, the emerging winds of the EAWM break up this thermal stratification of the water and facilitate the mixing of nutrient-rich bottom waters with the surface water which could then increase the DOC concentration during the dry season (especially in winter) (Jia et al. 2015; L. Wang et al. 2012a, b, 2008). In a recent study by (Jia et al. 2015) to better understand the evolution of both EASM and EAWM during the Holocene, a high sedimentary TOC concentration during the dry season but low concentrations during the wet season of the HG Lake was found. However, this was not the case for the surface water DOC concentration of the HG Lake, as DOC concentrations were higher in the rainy season but low in the dry season. This could be explained by the timing and amount of rainfall which had a significant impact on the surface water DOC concentration of the HG Lake (Strock et al. 2017; Valinia et al. 2014).

As shown in Fig. 3, during the rainy season, DOC concentration was higher during March to the middle of August which is generally the rainy season of Leizhou Peninsula, while the DOC concentrations are much lower during the dry season of low rainfall months from the middle of August to February. There was also a positive correlation between weekly rainfall and DOC concentration of the lake's surface water. The average DOC concentration was 21.72 mg/L during the rainy season compared to the rather low value of 14.21 mg/L for the dry season. The statistical data in the region of HG Lake during the sampling period showed a total of 123.63 mm rainfall in the dry season compared to a total of 337.56 mm rainfall in the rainy season (Table 1). Because lakes are often surrounded by high lands as a watershed, the high rainfall would have subsequently increased surface runoff and therefore increasing the terrestrial supply of organic matter into the lake water (Jia et al. 2015; Strock et al. 2017; Valinia et al. 2014; Wu et al. 2012). This is comparable with previous findings from eight headwater catchments in Muskoka of central Ontario, lakes in the boreal ecozone north of Toronto, Ontario, where DOC concentration of lake waters increased during warm and high flow periods but declined in cold and low flow periods (Eimers et al. 2008; Hudson et al. 2003; Koehler et al. 2009; McGlynn and McDonnell 2003). Moreover, the increased rainfall may lift the groundwater table to levels that come in contact with high organic matter containing soils and thus, the increase in DOC transport to the lake's water by infiltration process (Valinia et al. 2014; Bragée et al. 2015; Strock et al. 2017). On the other hand, less rainfall during the dry season may result in fewer amounts of DOC being transferred into the lakes through runoff and groundwater infiltration, thus lower DOC-levels. Giving the fact that HG Maar Lake is a closed water system without riverine input and that the high DOC concentration corresponded with the high rainfall suggests that rainfall and its related infiltration inputs are a major source of DOC to the surface water of HG Lake.

The changes in DOC content of lake water are also related to the soil mineralization rates of the surrounding catchment, as organic matter in soils is transported into the lake by runoff and other processes (Larsen et al. 2011; Monteith et al. 2007). However, the mineralization and decomposition of organic matter in soils are sensitive to moisture as well as temperature variations (Eimers et al. 2008; Rey et al. 2005). This could also further explain the variations in DOC concentrations between the dry and wet seasons, as heavy rainfall and high temperatures (Table 1) in the raining season may have increased the solubility of soil organic matter and therefore increased soil export processes, leading to increased DOC concentration of the lake's water in the wet season compared with the dry season.

The DOC in lakes and other freshwater bodies are subjected to loss through photo-mineralization (Hudson et al. 2003; Saros et al. 2015; Selvam et al. 2019). The photo-mineralization of DOC is induced by UV sunlight irradiations which oxidizes DOC into CO_2, carbon monoxide (Selvam et al. 2019), etc. A balanced study of 12 years of data in Dorset lakes estimated the photo-decomposition process as the major potential loss pathway of allochthonous DOC (Molot and Dillon 1997). Likewise, lake Terjevann of Norway was reported to have lost 33% of its organic matter to photo-decomposition processes (Andersen and Gjessing, 2002). However, the loss of DOC through this process is influenced by several factors including the DOC loads (Hanson et al. 2011; Reche et al. 2000). The increase in DOC concentration would reduce the UV penetration and subsequently slow down the photo-mineralization processes (Hanson et al. 2011; Hudson et al. 2003; Obernosterer and Benner, 2004; Reche et al. 2000). With regards to this, the increased transport and subsequent increases in DOC concentration during high rainfall season may have also reduced the UV light penetration hence prevented the photo-oxidation and excess loss of DOC in the lake. The photo-mineralization processes could also well explain the low DOC concentration of HG Maar Lake during the dry season.

3.4 Correlation between the DOC concentration and water temperature

Temperature has been identified as a potential driver of DOC concentration in lake waters (Erlandsson et al. 2008; Evans et al. 2006; Weyhenmeyer and Karlsson, 2009), as DOC concentration may decrease as temperature decreases and vice versa (Pan et al. 2010). The measured weekly water temperature (which is measured before 8 a.m. of each Wednesday during the sampling period) of the HG Maar lake, varied from 16.90 to 31.13 °C with an annual average of 25.95 °C. As shown in Fig. 4, the high DOC concentration was somehow associated with the higher water temperature suggesting that water temperature may have had a positive effect on the DOC concentration. These results agree with findings from other lakes and inland waters which suggest that during high temperatures, DOC concentration is likely to be increased. Examples of such findings include; the DOC concentration in the rivers of Tibet Plateau which peaked in late spring and summer but were low in winter (Kai et al. 2019). Results from multiple linear regression models indicated that an increase in temperature resulted in increased DOC export to lakes of Boreal Shield in Ontario (Keller et al. 2008). It is also found that an increase of 0.66 °C at the upland catchments in the United Kingdom would cause about a 65% increase in the DOC concentration of the stream (Freeman et al. 2001).

Lake's microbial activities are a major source of autochthonous DOC in the water (Koehler et al. 2009). Higher water temperature will enhance these microbial activities and accelerate primary production and therefore increase the DOC concentration (Freeman et al. 2001). On the other hand, a low water temperature would reduce or slow the microbial activities and therefore result in a declined DOC concentration in the lake (Eimers et al. 2008; Li et al. 2012). This could partly explain the low DOC concentration during the dry season compared with the high DOC concentrations in the rainy season. However, the correlation between the DOC concentration and water temperature is somehow complicated as in Fig. 6; it is shown that there is a positive but not a linear correlation but an inverted L shape between DOC versus Temperature. This suggests that water temperature may have a more complicated influence on the DOC concentration of HG Maar Lake. At higher water temperatures the solubility of organic matter in the water may increase but the primary production could be lower and this could result in a relatively low DOC concentration in the lake water during the hot and dry season (Laudon et al. 2012; Toming et al. 2020). Anyway, the water temperature may not be an independent factor affecting the water DOC of this lake.

3.5 Correlation between DOC concentration and pH values

Previous studies have shown that acidification is a controlling factor of the DOC concentration in lakes (Bragée et al. 2015; Monteith et al. 2007; Valinia et al. 2014). Acidification of surface water would reduce the DOC concentration through accelerated photo-degradation of organic matter in the water (Hudson et al. 2003). Acidification of a lake's water could be caused primarily by acid rain which brings a significant amount of airborne sulfur (S) and nitrogen (i.e. NO_x and SO_2). Pregitzer et al. (2004) had proposed a positive correlation between nitrogen deposition and DOC leaching. The freshwater in Swan lakes of the Sudbury showed significant long-term changes in DOC as a result of variations in pH (Keller et al. 2008). DOC concentrations of some lakes studied in southern Sweden were found to be low due to its lower pH value caused by high sulfur deposition (Valinia et al. 2014).

The pH value of the surface water in HG Maar Lake ranged from 7.2 to 8.5 with an annual average of 7.6 (Fig. 5), and therefore the lake water is slightly alkaline. The pH values and range are similar to that of Sihailongwan Maar lake (Fang et al. 2018). Figure 5 showed that most of the high pH values were associated with the high DOC concentration, while Fig. 7 displayed a slightly positive correlation between DOC concentration and pH values. These also suggest that pH value has a positive effect on the DOC concentration of HG Maar Lake, i.e. the higher the pH value the higher the DOC concentration. However, the reason for the positive effect of the higher pH value on the DOC concentration may be complicated because the

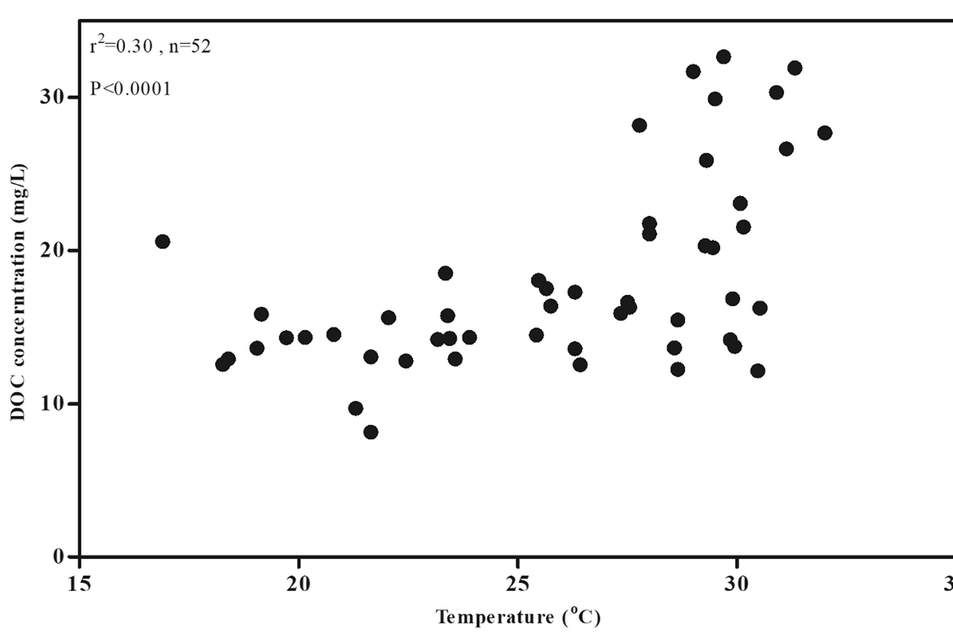

Fig. 6 A correlation of the weekly average DOC concentrations (mg/L) and water temperature (°C) of the surface water of HG Maar Lake based on four location sampling measurements monitored over the period of June 6, 2018,–May 29, 2019

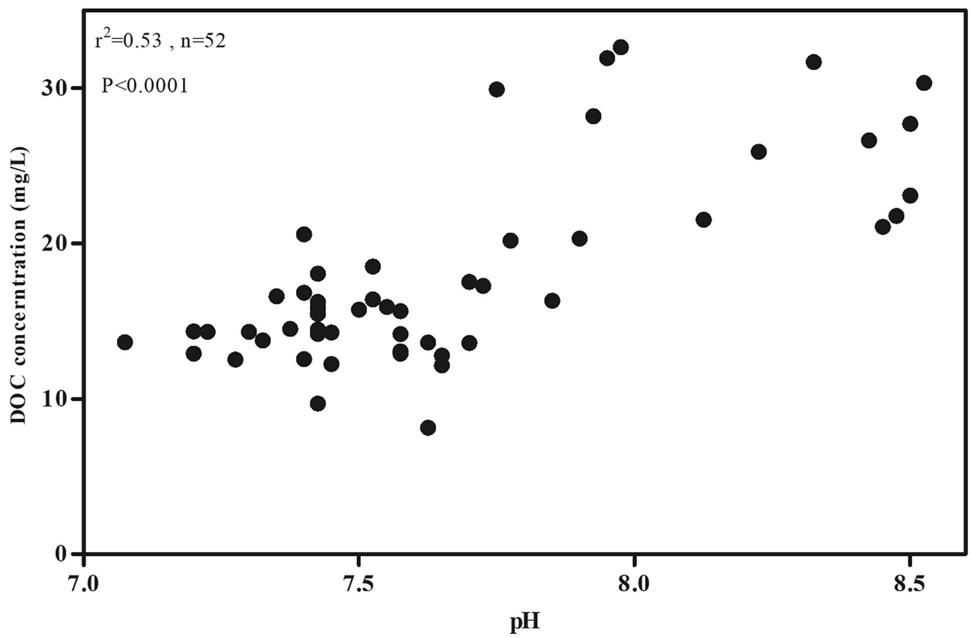

Fig. 7 A correlation of the weekly average DOC concentrations (mg/L) and pH values of the surface water of HG Maar Lake based on four location sampling measurements monitored from June 6, 2018, to May 29, 2019

high pH value is also associated with the high amount of rainfall (Table 1). Because the HG Maar Lake is not far from the coast of the South China Sea, Fig. 1, which is characterized by high salinity seawater, therefore, it is expected that the East Asian monsoon would bring high salinity rainfall which would contain a higher amount of alkaline ions. So, it is questionable if the positive correlation between the pH value and the DOC concentration is a coincidence or causation, and this needs further investigation.

4 Conclusions

By investigating the DOC concentration of surface water and its seasonal changes in the Huguangyan Maar Lake over a year, the following major points could be concluded:

(1) The weekly average DOC content of the whole-lake varied from 8.15 to 32.65 mg/L during the sampling period with an average annual concentration of 17.96 mg/L. In general, the DOC concentration showed no significant variation among the four sampling locations except seasonal-related occasional changes.
(2) There was a clear seasonal variation in the DOC concentration between the rainy and dry seasons, as the average monthly DOC concentration of the wet season was 21.72 mg/L compared to the DOC concentration of 14.21 mg/L for the dry season.
(3) The higher DOC concentration in the rainy season corresponded with high rainfall, higher water temperature, and pH value and vice versa in the dry season. However, the correlation between DOC, water temperature, and pH values appears to be complicated and requires further studies.
(4) There was occasional significant spatial variation in the DOC concentration among four sampling locations during the wet season and the reason for this is likely due to the uneven underground water and surface runoff inputs, and the weak circulation of lake water.
(5) The seasonal fluctuation of DOC concentration in this closed lake suggests that the soil organic matter inputs, which are mainly regulated by the rainfall-related surface runoff and subsurface infiltration from the surrounding watershed land, may play a significant role in the ecosystem of the lake.

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

Declaration

Conflict of interest We declare that there is no conflict of interest of any form that could inappropriately influence this work.

Consent for publication All authors are aware of the intended publication.

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