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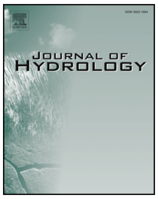

Research papers

Impact factors of dissolved organic carbon and the transport in a river-lake continuum in the Tibet Plateau of China

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ABSTRACT

As a significant fraction of carbon in inland waters, dissolved organic carbon (DOC) plays a crucial role in carbon cycling at a global scale. Understanding the linkages between variations in DOC and its dominant factors in lakes is critical for estimating its concentration on a larger scale. This study characterized the concentrations of DOC in the lakes of Tibet Plateau and explored the major underlying influencing factors. The overall mean concentration of DOC in these closed lakes had a mean value of 21.80 ± 30.82 mg/L (mean ± S.D.) and was higher than open lakes (F = 174.1, $p < 0.05$). The potential drivers for the concentration of DOC in the lakes of Tibet Plateau were conducted by the correlation analysis of DOC with the observed landscape, water quality variables, and climatic factors. The multiple regression model showed that 78% of DOC concentrations across the lakes could be explained by Shannon evenness index (SHEI) of landscape, slope, and landscape dominance index (LDI), of which SHEI explained the most substantial variations for the concentration of DOC. The changes in the concentrations of DOC in river-lake interaction were analyzed in Qinghai Lake watershed. The concentration of DOC in the Qinghai Lake water was higher than the surrounding rivers. Slope and the density of soil organic matter (SOM) in the Qinghai Lake watershed were responsible for the higher DOC in lake than rivers. The landscape had a significant influence on DOC in the lakes, and the dominant factor was SHEI. The results observed from this investigation further supplement the information of DOC in the inland waters with plateau lakes. Further, this study is expected to improve the understanding of the transport of DOC in the river-lake ecosystem.

1. Introduction

As a significant fraction of carbon in inland waters, dissolved organic carbon (DOC) plays a crucial role in carbon cycling on a global scale. It has a crucial influence on light penetration, secondary production, and nitrogen dynamics processes in aquatic systems (Cole et al., 2007; Mostofa et al., 2013; Song et al., 2018a). DOC in marine and freshwater systems account for the same amount of carbon as that of atmospheric intake (Siegenthaler and Sarmiento, 1993). Recent research has reported that the DOC stored in lakes and reservoirs of China reached 17.43 Tg C (Song et al., 2018a). To a greater extent, climate change and environmental conditions may be responsible for the variations in the concentrations of DOC in water (Godin et al., 2017; Liu and Chen, 2000; Xu et al., 2013). Therefore, it is of utmost importance in understanding the concentration of DOC in inland waters considering climate change. In recent decades, the concentrations of DOC in many of the lakes in boreal regions have increased, and notably, its concentrations in boreal lakes are predicted to increase by as much as 65% owing to the effects of climate change on terrestrial ecosystems (Larsen et al., 2011). A widespread increase in the concentrations of DOC was also observed in the surface waters of glaciated landscapes across northern and central Europe, which may be resulted from changes of sulfate deposition with precipitation and temperature (Gavin et al., 2018) and watershed soils acid sensitivity (Driscoll et al., 2016; Monteith et al., 2007). However, these temporal patterns in DOC dynamics are difficult to extrapolate from one region to another due to different environments and climates (Oni et al., 2011). Understanding the linkages between the variations of DOC and its dominant factor in waters is favourable in realizing the estimation of the concentration of DOC in a larger scale.

DOC in aquatic environment originates from allochthonous and autochthonous sources. The metabolism of phytoplankton and surrounding catchments decides the quality and quantity of DOC together (Sugiyama et al., 2004). As the lowest point in the surrounding

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landscape, lakes act as receivers in the landscape from terrestrial and river ecosystems (Williamson et al., 2014). The river-lake interaction is an integrated system with the mutual exchange of water, nutrients, pollutants, and organisms in river-lake systems (Gao et al., 2014). This relationship could be significantly impacted by natural and anthropogenic factors (Gao et al., 2014; Zhang et al., 2019). The carbon transport caused by the evolution of river-lake interactions has received more attention for better understanding the role of the river-lake ecosystem in a global carbon cycle (Xu and Xu, 2018; Yamada et al., 2018). Also, the primary source of DOC in most waters is from the surrounding terrestrial landscape (Williamson et al., 2014). Watershed landscape pattern plays a crucial role in the concentration of DOC in lakes (Lapierre et al., 2015; Lee et al., 2018; Oni et al., 2011), and lakes exhibit different trends of DOC in the regions with a different landscape. The different landscape processes could alter the quantity and quality of DOC exported from terrestrial ecosystems (Lee et al., 2018). Boreal peatlands are primary catchment sources of DOC and nutrients, and higher concentrations and fluxes of DOC were often observed in peatland catchments (Broder et al., 2017; Burd et al., 2018). The agricultural practices also have the potential to alter the DOC dynamics of water in a dominant agricultural watershed (Oh et al., 2013). The percentage wetland cover in the catchment could be used as the predictor of concentrations of DOC in lakes and rivers (Ritson et al., 2019; Xenopoulos et al., 2003). To clearly understand the changes in the concentration of DOC in lakes, it requires the identification of components of the landscape that are responsible for the transport of DOC to the lakes. For watershed scale, the physio-geographic factors such as runoff, slope and soil organic matter (SOM), are useful predictors for regulating the availability of DOC and substrate transport (Lee et al., 2019). However, few investigations pay attention to the concern of how landscapes effect DOC pools in the catchment scale.

The water volume in Tibet Plateau lakes is about 550 km^3, and 92% of which is present in saline lakes (Song et al., 2018a). Most of the saline lakes are located in endorheic watersheds, which are hydrological terminal, and the nutrients and organic matter tend to remain within the waters instead of exported to downstream (Duarte et al., 2008). Lakes in Tibet Plateau always have a high salt content or possessing a significant accumulation of DOC with the prolonged sunshine and arid environment (Song et al., 2016; Zhang et al., 2011). The storage of DOC is 13.39 Tg C in these alpine lakes, which is the most abundant storage of DOC in the five lake regions in China (Song et al., 2018a). Furthermore, Tibet Plateau has the highest alpine lakes in the world, where the landscapes in the catchments are different from other parts of lakes in the world, which merits further investigations to explore the characteristics of DOC and river-lakes continuums. In recent years, the climate change alters the balance of the carbon cycle of water ecosystems, and the consequent permafrost and glacier thawing induced by climatic warming could trigger the release of DOC preserved in the soil to river-lake ecosystems (Godin et al., 2017). Tibet Plateau is a sensitive area to climate change (Liu and Chen, 2000). Lakes in Tibet Plateau play a key role in terrestrial carbon cycling under the conditions of climatic warming, but the distribution of the concentration of DOC in these waters is not precise, which may help in fully understand the role of inland waters in terrestrial carbon cycling. In this context, we present the investigation of DOC concentrations in the lakes of Tibet Plateau, China. We hypothesize, here, that the land-use type within lake basins and rivers inflow into lakes all had an important influence on DOC concentrations in lakes in Tibet Plateau. We anticipate that the results from the study could further supplement the information on DOC in inland waters with plateau lakes. More significantly, this study is expected to assist in exploring the main influencing factors of the concentrations of DOC in lakes, and also may improve the understanding of the transport of DOC in the river-lake ecosystem. The objectives of this study are to (1) characterize the concentrations of DOC in the lakes of Tibet Plateau and exploring the primary underlying reasons; (2) explore the dominant influencing factors of the concentrations of DOC in the lakes of Tibet Plateau based on the water quality parameters, climatic factors, and catchment landscapes analysis; (3) reveal the variations in the concentrations of DOC in lake and the entering rivers to expound the impact of river-lake interaction on the concentrations of DOC, this river-lake continuum was selected in Qinghai Lake, which is the largest inland lake of China, is also the - largest saline lake of China.

2. Materials and methods

2.1. Study area

Tibet Plateau in the west of China located between 74–98°E and 28–40° N is the largest and extensive plateau in the world with an area about 2.5 million km^2 (Zhang et al., 2011). It is referred to as “the Third Pole” of the Earth with the Earth’s largest ice store except for the north and south polar regions (Kotlia et al., 2017; Qiu, 2008). Because of its immense size and elevation, the Tibetan Plateau has a significant influence on the atmospheric circulation of the Northern Hemisphere (Kotlia et al., 2017). The altitude makes Tibet Plateau cold, and the cover of snow and ice could reflect sunlight, making it colder in winter. The year-round average temperature in this area is lower than 8 °C (Qiu, 2008). In the northwest of Tibet Plateau where the average elevation exceeds 5000 m, and the average temperature is -40 °C (Song et al., 2016). The annual precipitation in Tibet Plateau ranges from 100 to 1300 mm, and abundant snow takes place in winter. Also, there is intense solar UV radiation because of the dry and thin air with a low concentration of ozone, and the duration of total annual average sunshine is over 2600 h.

There are thousands of closed lakes in Tibet Plateau, and the total area of lakes accounts for more than half of China’s inland waters (Ma et al., 2011). Lakes in this region are mainly fed by precipitation, snow, and glacier melting, and are sensitive to global warming (Liu and Chen, 2000; Song et al., 2016). Despite the present-day aridity, the lakes with the surface area greater than 10 km^2 are still more than 300, which vary from fresh to hypersaline (Kong et al., 2011). The changes in the levels of lake and water stored in this area are the net result of precipitation, input from melting glaciers, outflow, and evaporation (Kong et al., 2011).

2.2. Water sampling and field measurements

Three field campaigns were conducted in the summer of 2014, 2015, and 2017 (Fig. 1a), and the field campaigns were all performed by the same research group. During these field campaigns, a total of 310 samples were collected from 80 lakes. To be specific, 87 samples were taken from 19 lakes in late summer 2014, and 94 samples were collected from 33 lakes in early summer 2015. In summer 2017, 93 samples were collected from 28 lakes, and 36 samples were collected from 12 previous sampling lakes. These lakes were selected based on their salinity gradients and areas, these lakes were selected based on their salinity gradients and areas. We ensured the selected lakes covered all trophic types, and the salinity of lakes was from fresh to hypersaline. These lakes are distributed in different land use patterns, including forest, grass, built-up land, arable land, sand, swamp, and unused land (Fig. 1a). The examined lakes, ranging in size from 1 to 4256 km^2, are situated at altitudes between 2000 and 4718 m above the sea level (Fig. 1b). Based on the electrical conductivity, these lakes are grouped into 33 freshwater (n = 115) and 47 saline waters (n = 195) (Duarte et al., 2008). The closed drainage in this area is marked in Fig. 1b.

Waters were taken as grab samples from approximately 0.5 m below the water surface. Water samples were collected at 3–5 sampling points from lakes on average, these sampling points were evenly distributed across the lake. The number of sampling stations in lake were linking to the area of the lake, it always had 3–4 points in the lake with area less than 100 km^2, 4–5 points in the lake with area between 100 and

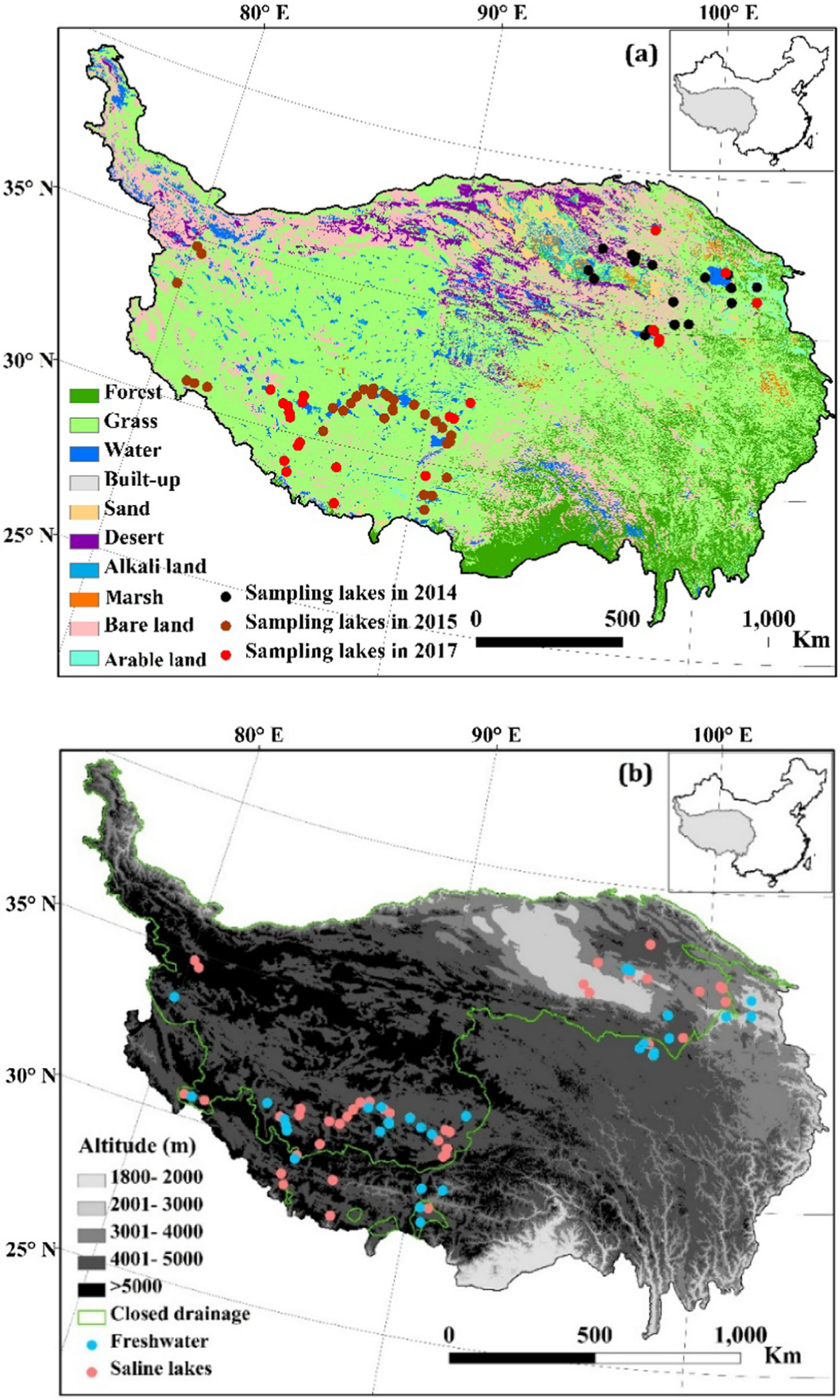


Fig. 1. Study area location and sampling lakes distribution, (a) sampling lakes distribution across the different land use patterns; (b) sampling freshwater and saline lakes distribution in different altitudes in Tibet Plateau, China.

1000 km^2, and 6 points in the lake with area over 1000 km^2. An exception was that Qinghai Lake had 37 sampling points with area of 4256 km^2, 20 of them was collected in 2013. During sample collection, Secchi disk depth (SDD) at each sampling site was measured and recorded using a black-and-white disk. Salinity and water temperature were also determined *in situ* using a portable multi-parameter water quality analyzer (YSI 6600, U.S) with the uncertainty of 0.01, and 0.001 K. Water samples were collected to amber coloured high-density polyethylene (HDPE) bottle, and were placed in a portable refrigerator at 4 °C for no more than 7 days before they were transported back to the laboratory. A part of the collected water samples was filtered through a 0.45 μm glass-fiber filter (Bandao Industrial Co., Ltd, China) within 24 h

Table 1
Classification and water quality characteristics of sampling lakes in Tibet Plateau, China.

Lake type	DOC (mg/L)	TN (mg/L)	TP (mg/L)	Chla (μg/L)	SDD (m)	Salinity	Samples
All lakes	0.27–164.80 (23.94 ± 34.34)	0.18–25.67 (3.79 ± 4.46)	0–6.79 (0.13 ± 0.32)	0–23.7 (2.30 ± 4.22)	0.18–13.90 (3.38 ± 4.76)	0.10–16.13 (6.04 ± 9.00)	310
Saline lakes	3.89–164.80 (34.78 ± 39.71)	0.09–25.67 (3.19 ± 4.34)	0–6.79 (0.19 ± 0.64)	0–14.7 (1.64 ± 3.97)	0.64–13.90 (5.13 ± 3.40)	0.17–16.13 (9.98 ± 5.87)	195
Fresh waters	0.27–15.45 (5.72 ± 4.23)	0.18–11.54 (2.07 ± 2.52)	0–0.10 (0.03 ± 0.03)	0–23.7 (1.48 ± 3.50)	0.45–12.50 (4.21 ± 3.08)	0.04–13.27 (0.59 ± 1.85)	115
Closed lakes	0.27–164.80 (21.80 ± 30.82)	0.09–25.67 (3.12 ± 4.11)	0–6.79 (0.10 ± 0.48)	0–23.7 (1.50 ± 3.61)	0.45–13.9 (4.96 ± 3.42)	0.04–16.13 (7.25 ± 4.27)	246
Open lakes	1.7–64.80 (16.29 ± 18.78)	0.28–7.90 (1.43 ± 1.43)	0–9.3 (0.18 ± 0.54)	0–2.51 (1.89 ± 4.34)	2.60–3.70 (3.18 ± 0.40)	0.10–16.13 (1.67 ± 4.25)	64

The values in brackets are the values of mean ± S.D.

of the water being got, and the filtrate was used for the analysis of DOC. The concentration of DOC was measured using a Shimadzu Total Organic Carbon Analyzer (TOC-VCPN, Shimadzu Corporation, Japan). The analysis of blanks and replications showed a detection limit of 0.3 mg/L, a precision of 5.0% at a concentration of 4 mg/L, and a precision of 3.4% at a concentration of 60 mg/L (Song et al., 2018b). The concentrations of DOC of all the samples were measured by the same instruments. The glass-fiber filter was used to extract Chlorophyll *a* (Chla) using a 90% buffered acetone solution, and the concentration of Chla was determined by spectrophotometry (UV-2600 PC, Shimadzu) (Jeffrey and Humphrey, 1975). In the laboratory, the raw water samples were used to test for the concentrations of total phosphorus (TP) using a continuous flow analyzer (SKALAR, San Plus System, the Netherlands). The concentration of total suspended matter (TSM) in raw water samples was determined gravimetrically using a pre-combusted 0.7 μm glass fiber Millipore filters (Whatman, GF/F 1825-047) (Cleveland and Weidemann, 1993). The analytical replicates for every parameter were double.

2.3. Data acquisition and analysis

According to the concentrations of SDD, TP, and Chla, the trophic state of each lake and sampling site were evaluated based on a modified Carlson's trophic state index (TSI) (Aizaki et al., 1981; Carlson, 1977). Based on the TSI value, the lakes are then classified as being eutrophic, mesotrophic, or oligotrophic: TSI $<$ 30 indicates an oligotrophic state, 30–50 indicates a mesotrophic state, and 50–100 indicates a eutrophic state.

The annual average temperature, annual average precipitation, wind speed, and humidity were all collected from National Meteorological Information Center (http://data.cma.cn/). GIS analysis (ArcGIS10.0 software package) was used to delineate the catchment areas based on fine resolution 10 m DEM data, and to derive the slope value. The data about catchment came from Lake-Watershed Science Data Center, National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://lake.geodata.cn). The density of soil organic matter (SOM) for the top 20 cm soils in Tibet Plateau derived the second national soil census (Song et al., 2018b). The computation of landscape indices was based on the 50 × 50 m^2 grid DEM for Tibet Plateau in China. The land use datasets obtained from the GLOBELAND 30, the address of which is (http://www.globallandcover.com/Chinese/GLC30Download/index.aspx). Shannon's diversity index (SHDI), Shannon evenness index (SHEI), and Landscape dominance index (LDI) were calculated by the following equations:

$$SHDI = -\sum_{i=1}^{m} (P_i \times lnP_i$$

$$SHEI = \frac{-\sum_{i=1}^{m} (P_i \times lnP_i)}{\ln m}$$

$$LDI = \text{lnm} + \sum_{i=1}^{m} (P_i \times lnP_i)$$

where, p_i is the area proportion of landscape i to the total area of all the landscapes; and m is the number of landscape types.

Non-parametric test was employed to test the difference of DOC concentrations between fresh and saline lakes using SPSS 22.0 software. The analysis method is Two-Sample Kolmogorov-Smirnov Test. Spearman's rank correlation analysis is used to characterize the relationship in the concentrations of DOC with environmental variables, including land use type characteristics, meteorological factors, and water quality characteristics in SPSS statistics 19.0 software. The relationships between DOC concentrations and environmental variables were explored using the multivariate regression analysis with stepwise selection model in SPSS statistics 19.0 software. The dependent variable was DOC concentrations, and the predictors were SHEI, slope, humidity, precipitation, salinity, TP, and LDI.

3. Results

3.1. DOC concentration and variability in water quality

In all the field surveys conducted over the 80 lakes with the diverse land use patterns, a vast diversity of lakes with different water qualities was encountered (Table 1). The transparency and trophic status of these lakes were analyzed, and it has been found that 36.51% of the studied lakes in Tibet Plateau were oligotrophic lakes, 44.44% of the studied lakes were mesotrophic lakes, whereas the proportion of eutrophication of these lakes was only 19.05%. These lakes had good transparency (SDD) with the median/mean ± standard deviation of 2.45/3.68 ± 5.02 m. The salinity of these lakes ranged from 0.04 to 113.23. Many lakes located in the closed area and the salinity in these lakes were higher than the lakes in the open area.

The concentration of DOC varies significantly among the 80 lakes. The overall mean DOC concentration of these sampling lakes was 23.94 ± 34.34 mg/L (mean ± S.D.), ranging from 0.27 to 164.80 mg/L (Table 1). The minimum value was observed in the Shibu Co, and the maximum value was noted in the Hajiang lake (Fig. S1). The concentrations of DOC in several major lakes were compared as shown in Fig. 2. The Qinghai Lake showed the highest mean DOC concentration (72.97 ± 52.40 mg/L), and the lowest DOC concentration was in Nam Co with 4.63 ± 1.79 mg/L.

An analysis of the whole land use type in Tibet Plateau reveals that it is a grass -dominated area, accounting for 58.8% of land mass use (Fig. 3), followed by forest (10.6%). The land use patterns in several main lake basins also demonstrated the grass-dominated pattern. Moreover, the proportions of bare land and swamp showed the highest

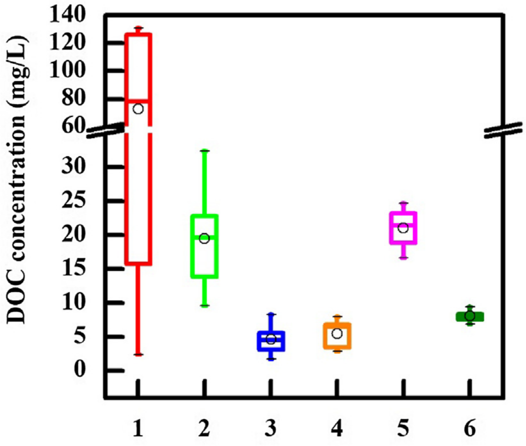


Fig. 2. Difference in the concentration of DOC among different lakes in Tibet Plateau. 1-Qinghai Lake (n = 37), 2-Siling Co (n = 13), 3-Nam Co (n = 16), 4-Zhari Namco (n = 7), 5-Tangra Yumco (n = 14), and 6-Yamzho yumco (n = 12). The top and the bottom lines represent denote the maximum and minimum value, respectively. The horizontal top and bottom edges of the boxes denote the 75th and 25th percentiles. The solid line in box represents the median values, the hollow circles represent mean values.

values in Qinghai Lake than other lake watersheds in this study (Fig. 3).

DOC concentrations in fresh and saline lakes were compared. The concentration of DOC in these saline lakes was significantly different from that of the fresh lakes (F = 222.1, $p < 0.001$). As shown in Fig. 4a, in terms of either the mean or median value, the saline lakes exhibited higher concentration of DOC than the fresh lakes. A broad range in the concentration of DOC (3.89–284.40 mg/L) was encountered for these saline lakes. A higher mean DOC concentration was observed (34.07 mg/L) with some modest variation (S.D., 40.02 mg/L). The concentrations of DOC in fresh lakes ranged from 0.27 to 15.45 mg/L, and the mean value in fresh lakes was much lower (5.72 ± 4.23 mg/L).

The concentrations of DOC in closed lakes were different compared to open lakes (F = 174.1, $p < 0.05$). The lakes in the closed area displayed higher mean DOC concentration (21.80 ± 30.82 mg/L) compared to the open area (16.29 ± 18.78 mg/L).

3.2. DOC versus environmental factors in Tibet Plateau

The correlation analysis reveals the strongest correlation of DOC concentration with the SHEI of land use type with a Spearman's rank correlation coefficient (r_s) of 0.73 and a weakly negative correlation with LDI and the mean slope in the catchment ($r_s = -0.39$, $r_s = -0.33$, $p < 0.05$). The climate parameters analysis showed that only humidity and precipitation were weakly correlated to the concentrations of DOC ($r_s = 0.21$, $r_s = 0.22$, $p < 0.05$). The correlation analysis with water quality variables reveals good correlations of DOC with salinity and concentration of TP ($r_s = 0.51$, $p < 0.01$) but no relationship to all other parameters ($r_s < 0.2$, $p > 0.05$) (Fig. 5).

The multiple regression analysis showed that SHEI, slope, and LDI had an impact on K_d(PAR) (Table 2), and the relationship could be expressed as follows: $\text{DOC} = 542.42 \times \text{SHEI} - 16.22 \times \text{slope} + 48.64 \times \text{LDI} - 338.91$ ($R^2 = 0.78$, $p < 0.001$). The multiple regression model indicated that these variables could explain 78% of the variance in the concentrations of DOC across the lakes. The standardized coefficient of independent variables indicated that SHEI had the most significant impact on the concentration of DOC, followed by the slope. However, the water quality parameters (salinity and TN concentration) and climate characteristics cannot sufficiently explain the spatial differences in the concentrations of DOC, which were excluded in the building up of the multiple regression model.

3.3. DOC concentrations in the Qinghai Lake and the inflow rivers

DOC concentrations in the Qinghai Lake basin were analyzed in detail (Fig. 6). The DOC concentration in the Qinghai Lake water was higher than the surrounding rivers (Fig. 6a). The mean DOC concentration in the lake water was 72.97 ± 52.40 mg/L, and the DOC concentrations in the influent rivers ranged from 1.55 to 5.80 mg/L. The Daotang River was originally the outflow river of Qinghai Lake, and the DOC concentration in this river was 12.45 mg/L. The eastern waters showed the highest DOC concentration in Qinghai Lake (Fig. 6b). The DOC concentrations inside the lakes were higher than in the outer locations (Fig. 6b). The slope analysis of this basin showed that Qinghai Lake was in the downgrade position (Fig. 6c). The SOM density in Qinghai Lake basin ranged from 0.3 to 8%, and closer to the lake shore it was lower.

4. Discussion

4.1. Analysis in the concentration of DOC in Tibet Plateau lakes

The total mean DOC concentration of these sampling lakes in Tibet Plateau was 11.28/23.94 ± 34.34 mg/L (median/mean ± S.D.) with the range of 0.27–164.80 mg/L (Table 1). Compared with the lakes in

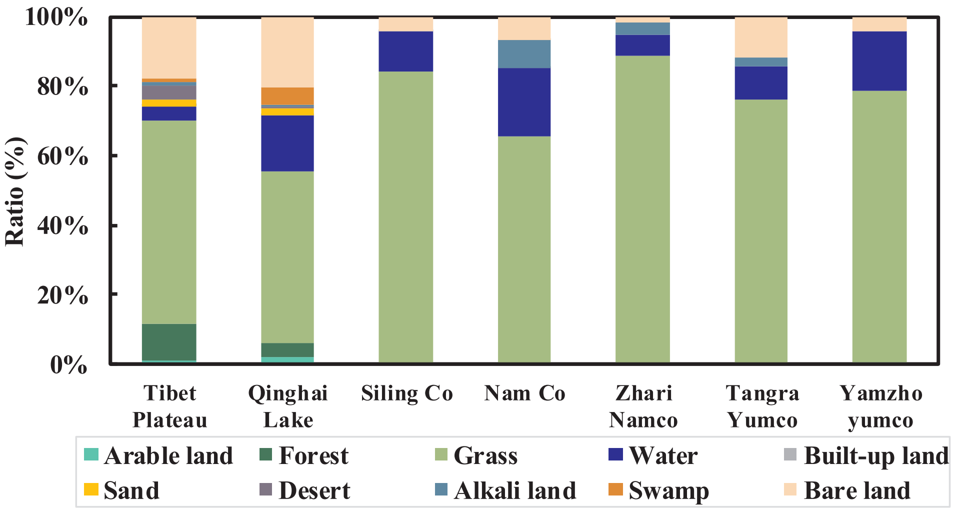


Fig. 3. Land-use type in Tibet Plateau and the main lake basins.

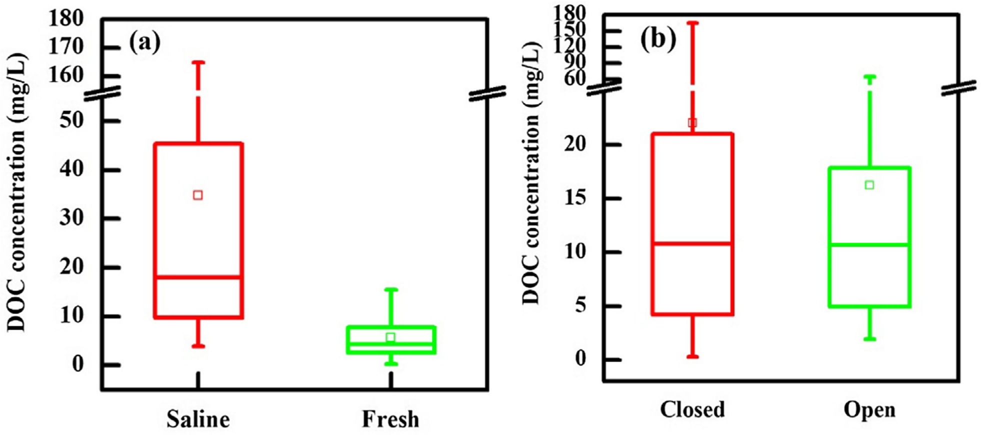
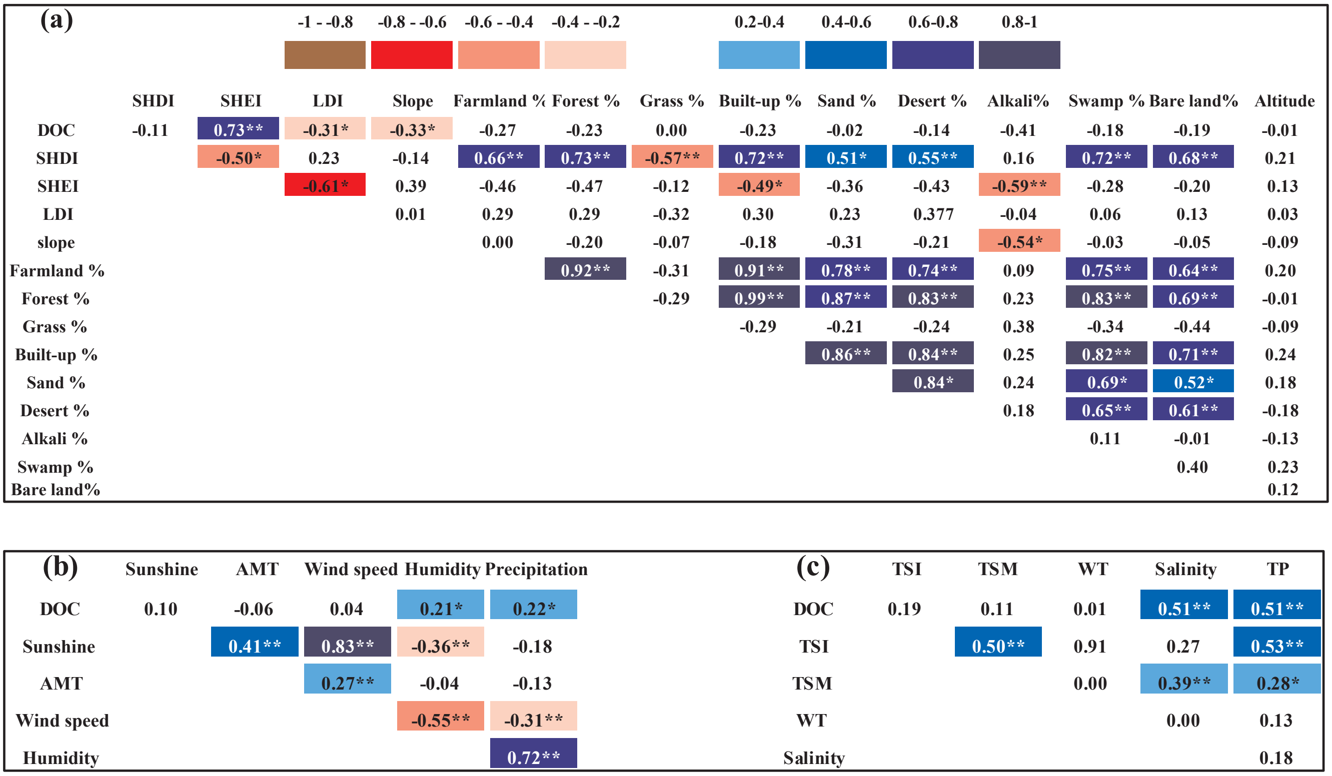


Fig. 4. Box plots of the concentration of DOC in different types of lakes in Tibet Plateau: (a) in fresh (n = 115) and brackish lakes (n = 195) (b) in closed (n = 246) and open lakes (n = 64). The top and the bottom lines represent denote the maximum and minimum value, respectively. The horizontal top and bottom edges of the boxes denote the 75th and 25th percentiles. The solid line in box represents the median values, the hollow squares represent mean values.



	SHDI	SHEI	LDI	Slope	Farmland %	Forest %	Grass %	Built-up %	Sand %	Desert %	Alkali%	Swamp %	Bare land%	Altitude
DOC	-0.11	0.73**	-0.31*	-0.33*	-0.27	-0.23	0.00	-0.23	-0.02	-0.14	-0.41	-0.18	-0.19	-0.01
SHDI		-0.50*	0.23	-0.14	0.66**	0.73**	-0.57**	0.72**	0.51*	0.55**	0.16	0.72**	0.68**	0.21
SHEI			-0.61*	0.39	-0.46	-0.47	-0.12	-0.49*	-0.36	-0.43	-0.59**	-0.28	-0.20	0.13
LDI				0.01	0.29	0.29	-0.32	0.30	0.23	0.377	-0.04	0.06	0.13	0.03
slope					0.00	-0.20	-0.07	-0.18	-0.31	-0.21	-0.54*	-0.03	-0.05	-0.09
Farmland %						0.92**	-0.31	0.91**	0.78**	0.74**	0.09	0.75**	0.64**	0.20
Forest %							-0.29	0.99**	0.87**	0.83**	0.23	0.83**	0.69**	-0.01
Grass %								-0.29	-0.21	-0.24	0.38	-0.34	-0.44	-0.09
Built-up %									0.86**	0.84**	0.25	0.82**	0.71**	0.24
Sand %										0.84*	0.24	0.69*	0.52*	0.18
Desert %											0.18	0.65**	0.61**	-0.18
Alkali %												0.11	-0.01	-0.13
Swamp %													0.40	0.23
Bare land%														0.12

(b)	Sunshine	AMT	Wind speed	Humidity	Precipitation
DOC	0.10	-0.06	0.04	0.21*	0.22*
Sunshine		0.41**	0.83**	-0.36**	-0.18
AMT			0.27**	-0.04	-0.13
Wind speed				-0.55**	-0.31**
Humidity					0.72**

(c)	TSI	TSM	WT	Salinity	TP
DOC	0.19	0.11	0.01	0.51**	0.51**
TSI		0.50**	0.91	0.27	0.53**
TSM			0.00	0.39**	0.28*
WT				0.00	0.13
Salinity					0.18

Fig. 5. Spearman's rank correlation matrix; a, DOC concentration with the land use type; b, DOC concentration with the climatic factors; c, DOC concentration with water quality parameters. *represents the correlation is significant at the level, $p < 0.05$, ** is $p < 0.01$.

Table 2
Results of the multiple regression analysis.

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	F	Adjusted R^2	Std. Error
	β	Std. Error	β					
Constant	−338.908	55.303	/	−6.128	0.000	20.063	0.781	20.662
SHEI	542.418	70.735	1.108	7.668	0.000			
Slope	−16.222	5.525	−0.389	−2.936	0.012			
LDI	48.643	21.885	0.287	2.223	0.045			

Dependent Variable: DOC; redictors in the Model: Constant, SHEI, Slope, LDI.

Yungui and East limnetic regions in China, the median/mean concentrations of DOC in Tibet Plateau lakes were all much higher (Fig. S2) (Song et al., 2018a). Most of the lakes in the TQR are located in endorheic regions (Fig. 1, Fig. S3), whereas Yungui and East limnetic regions are located in the outflow regions. The previous study has pointed out that the closed lakes exhibited significantly higher DOC concentrations than the open lakes (Song et al., 2018a; Song et al., 2013). Because of no flow export, the DOC gradually accumulated in these closed lakes with the prolongation of water residence times and strong evapoconcentration (Song et al., 2013). Moreover, the DOC in

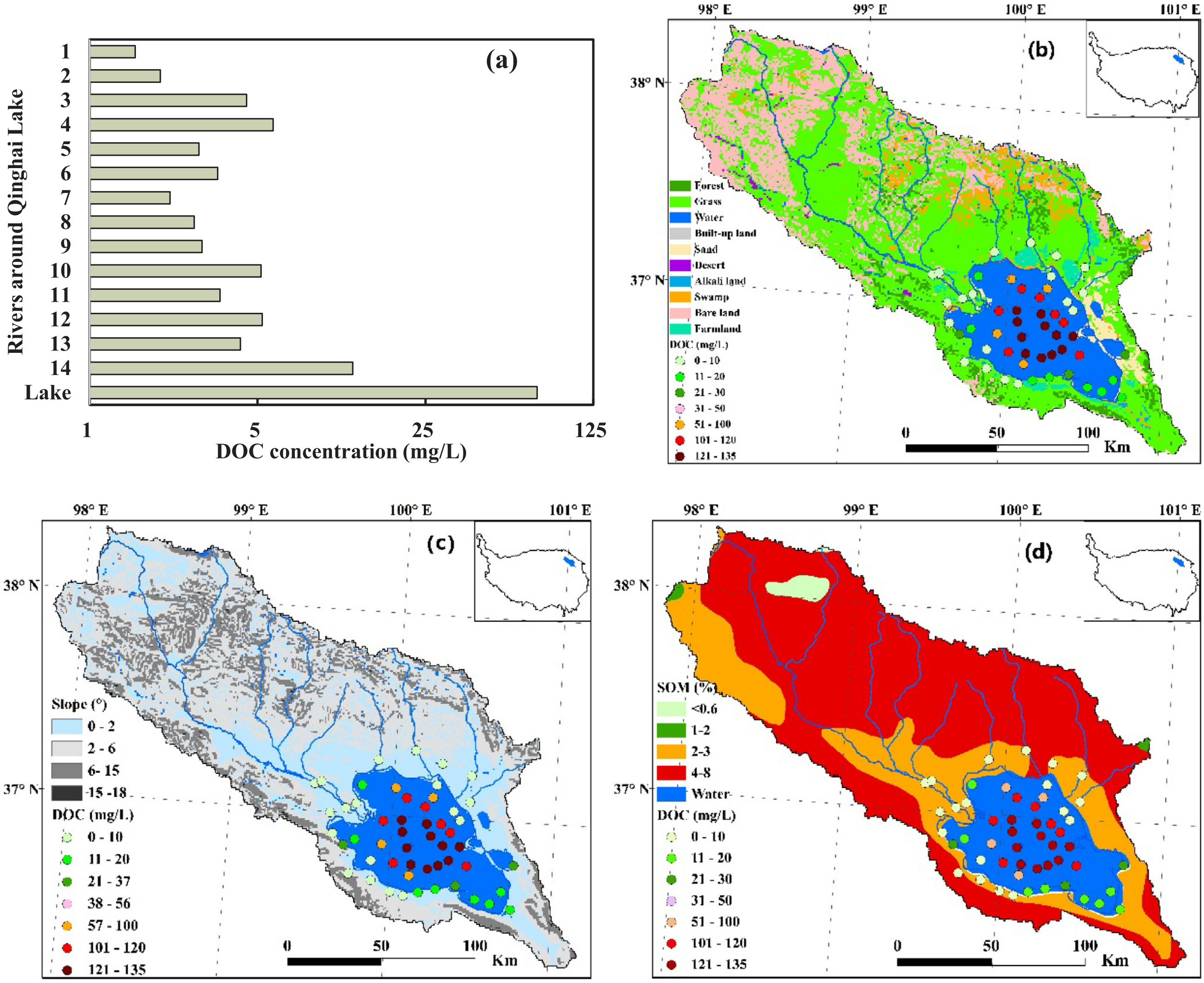


Fig. 6. DOC concentrations and environmental analysis in Qinghai lake watershed. (a) DOC concentrations in Qinghai lake and inflow rivers, (b) landscapes in Qinghai lake watershed, (c) slope in Qinghai lake watershed, (d) SOM distribution in Qinghai lake watershed.

lakes is related to the watershed SOM concentrations, and the allochthonous DOC is likely to be transported into lakes (Lee et al., 2018). In Tibet Plateau, SOM in the watershed is relatively higher than the Yungui and East limnetic regions (Fig. S2). Compared to the lakes in Northeast and Inner Mongolia-Xingjiang limnetic regions, the median/mean DOC concentrations in Tibet Plateau lakes were lower (Fig. S3). The trophic status may be responsible for the observed phenomenon. Many studies have shown that eutrophic waters tend to have higher DOC concentrations than mesotrophic and oligotrophic waters (Shang et al., 2018; Song et al., 2018a; Yoshioka et al., 2002; Zhang et al., 2010). Eutrophication generally results in algal blooms, thereby higher production of autochthonous DOC by phytoplankton and macrophyte (Pacheco et al., 2014; Sobek et al., 2007; Zhang et al., 2018). Although most of the northeast limnetic region is located in the outflow region (Fig. S4), the proportion of eutrophic lakes among surveyed lakes in this limnetic region reached to 44% and is about 33% in the inner Mongolia-Xingjiang limnetic region. In Tibet Plateau, most of the lakes were oligotrophic and mesotrophic, and in this study, the proportion of eutrophication of the studied lakes was only 15% (Fig. S5). The autochthonous DOC accumulation in the Tibet Plateau lakes might be inhibited by limited nutrients, even in the growing season.

Remarkably a higher concentration of DOC was found out in the saline lakes than fresh lakes in Tibet Plateau (Fig. 4a). Similar results have been found out in the lakes of semi-arid area of Northern China (Wen et al., 2018), in the semi-humid/semi-arid areas of Northern China (Song et al., 2013), in the east-central Alberta, Canada (Curtis and Adams, 1995), and in the Canadian prairies (Waiser and Robarts, 2000). The evapoconcentration has an essential effect on the elevated concentration of DOC in the saline lakes (Anderson and Stedmon, 2007). An increase in the concentration of salt would result in a decreased osmotic potential, which has adverse effects on the microbial activity (Mavi et al., 2012). DOC can accumulate in the terminal lakes with a lower microbial activity (Wen et al., 2016). The intense ultraviolet (UV) radiation in TQR has photobleaching and photodegradation effects on DOC. Studies have shown the photoinduced degradation of dissolved organic matter in the natural waters generally convert substances of high molecular weight to low molecular weight. The photoproduction, such as H_2O_2, has been found to increase with salinity linearly in natural waters (Mostofa et al., 2013; Nieto-Cid et al., 2006). This is evidence that more DOC may be produced in saline lakes through photorespiration or photo-assimilation.

4.2. Effect of environmental factors on the concentration of DOC

Many studies have shown that different landscape processes could alter the quantity and quality of DOC exported from terrestrial landscapes (Lee et al., 2018; Mao et al., 2018), and the primary type of land use in catchment had an important impact on the concentration of DOC in lakes (Broder et al., 2017; Oh et al., 2013; Xenopoulos et al., 2003). The above studies mainly analyzed the relationship between a specific land use type and the output loading of DOC in the surface water, and a little is known about how these relationships vary when considering the whole complex landscape. In this study, the results presented that the concentration of DOC in Tibet Plateau lakes was positively correlated to the landscape SHEI, which indicates that in Tibet Plateau, the more heterogeneous and straightforward landscape is shown in the catchment and a lower DOC concentration in the lakes. The land use patterns in Tibet Plateau and several main lake watersheds were all the grass-dominated pattern, followed by forest (10.6%) (Fig. 3). Soils with different land covers exhibited substantial differences in their DOC concentrations. In some grassland systems, the organic layers are small or missing, which is the major source of DOC (Don and Schulze, 2008). This appearance may lead to the lower exportation of DOC to rivers and lakes from grass soil than peatland and agricultural land (Eze et al., 2018). Studies have proven that the concentration of DOC in forest soil water increased with precipitation, and it was correlated with the concentrations of DOC in the nearby outflowing rivers (Rasilo et al., 2015). This study area located in the arid region and the precipitation in summer was only 200–300 mm during the sampling period. These may be responsible for the weakly positive correlation between the concentration of DOC and landscape LDI observed in this study.

The dominant landscape had an impact on the final result, but this influence was not decisive. DOC is a readily available substrate for microorganisms. Whether DOC is mineralised depends on environment characteristics (pH, texture, aggregation), the composition of the decomposer community, and the contact time between DOC and decomposer (Don and Schulze, 2008). In forested covered catchments, the DOC of surface waters is primarily from the allochthonous source (Lofgren and Zetterberg, 2011), and the DOC from the vegetation litter in woodlands was relatively recalcitrant to microbial degradation (Ritson et al., 2019). The DOC bioavailability is different in various land soils, this could affect the final DOC concentration in the surface water within watershed. Although the grassland and forest dominated most of the catchments in Tibet Plateau, there were also covered with many landscapes including agriculture, desert, marsh, and urban areas (Fig. 1a). The multiple land use pattern acts together to control the variations in the concentration of DOC in the lakes. Many Studies concerning the catchment scale influences on the concentration of DOC in waters admitted the integral effect of catchment landscape (Oni et al., 2011; Sliva and Williams, 2001). The concentration of DOC in the mixed land-use area was significantly higher than the peaty headwaters in the River Exe, UK ($p < 0.001$) (Ritson et al., 2019), which also indirectly proved the effect of the evenness of landscape might be before the dominant landscape.

Furthermore, the concentration of DOC in the lakes is the combined effect of a series of processes including surface runoff, soil infiltration, photolysis, biological metabolism, and sedimentation (Jones et al., 2016). Thus, the topography and surficial geology seem to be of particular importance to DOC flux and export from the surrounding terrestrial ecosystems (Sliva and Williams, 2001). The watershed slope represents physical watershed characteristics that are primarily independent of land use. Comparing with worldwide surface waters, the watershed slope is highlighted as a controlling factor of the DOC transport of terrestrial-surface water (Connolly et al., 2018; Lee et al., 2019; Sliva and Williams, 2001). The allochthonous DOC is likely to be transported by the surface runoff and rivers into lakes. During this transfer process in the subtropical small mountainous rivers, the slope could restrain the generation of DOC due to shallow soil depth and fast runoff velocity (Lee et al., 2019). In the lakes of Tibet Plateau, the watershed slope also showed a negative relationship with DOC in the lakes (DOC = 542.42 × SHEI-16.22 × slope + 48.64 × LDI-338.91). DOC in the lakes is related to the watershed SOM concentrations, which depends on the soil saturation and water flow from land to lakes (Lee et al., 2018). The gentle watershed slope brings about a longer water residence times, which is beneficial to the leaching of DOM from watershed soil, and DOM is then transferred to the lakes by the permeation or the stream and river networks (Creed et al., 2008; Winn et al., 2009). The significant relationship between SOM and watershed slope has been proven in many of the watersheds (Harms et al., 2016; Winn et al., 2009).

4.3. DOC transport in rivers- Qinghai Lake continuum

Lakes in Qinghai Lake watershed exhibited a high SOM density (Fig. 6d). The density of SOM in the surrounding landscape played an important role in the concentration of DOC in surface water (Lee et al., 2019; Song et al., 2018b). The closer to the Qinghai Lake, the lower SOM it presented in the soil (Fig. 6d), which means that the SOM in the soil around the lake may be transported to the water. Soils have been reported as the main source of riverine DOC, and the transport of DOC in river includes the production of DOC in soils and the transportation to drainage networks (Evans et al., 2007). Riverine DOC can represent a significant carbon loss pathway in temperate and boreal soil ecosystems (Billett et al., 2004; Finlay et al., 2006). The rivers could export this terrestrial carbon to the nearby lakes, which indicates that the SOC stock dominates the DOC supply. Several studies have stated that rivers and lakes should be considered as a combined conduit and reactor for the transport of terrestrial carbon across the waterscapes (Cole et al., 2007; Tranvik et al., 2009). Studies also proposed that DOC increases in the surface water of the UK may be linked to the carbon losses of soil (Bellamy et al., 2005). The destabilization of soil carbon is as a part of anthropogenic influence (Davidson and Janssens, 2006; Evans et al., 2007). Thus, the anthropogenic activity also had an essential influence on the concentration of DOC derived from soil to lakes.

Qinghai Lake was fed with more than forty rivers and with no effluent (Evans et al., 2007; Xu et al., 2013). The different concentrations of DOC were shown in the water of the studied river (Fig. 6a). Changes in the concentrations of DOC among these rivers were generally related to contrasts in the organic matter content of soil and water flow through soils among drainage basins (Judd and Kling, 2002; McGuire et al., 2005). In the warm-wet seasons, the riverine concentration of DOC is likely due to the melting of surface soils, which could increase the inflow of dissolved organic material (Xu et al., 2013). This study was conducted in summer, and thus the dissolved organic material in the soil had an important influence on the concentration of DOC in rivers. The concentration of DOC in the rivers is also closely linking with the landscapes in the watershed. Studies also exhibited that the operation management could affect the carbon balance in the agricultural grasslands, which may be a driver for soil depletion (Franzluebbers et al., 2000; Soussana et al., 2004). Forests are also significantly influencing on carbon loss. The different land use type around Qinghai Lake determined various concentrations of DOC in the rivers (Fig. 3). Besides, earlier studies have demonstrated that the watershed slope could be as a promising indicator of variations in the concentration of fluvial DOC in Arctic region with a strong negative relationship (Connolly et al., 2018; Harms et al., 2016; Inamdar et al., 2006). In Qinghai Lake watershed, this negative relationship was also presented between the concentration of lake DOC and watershed slope ($r_s = -0.33, p < 0.05$) (Fig. 5). Qinghai Lake was in the downgrade position and played the receiving function of DOC (Fig. 6c). However, the slope in the south shoreline region was steeper than the north shore, presenting a higher concentration of fluvial DOC (Fig. 6c). This indicates that the linkage between watershed slope and concentration of fluvial DOC also depends on soil saturation and water flow from land to rivers (Creed et al., 2008). The SOM in south shore was higher than north shore (Fig. 6d), which may be a reason for the higher concentration of fluvial DOC. The leaching of DOC from soil to river networks is a complicated process, demonstrating the biogeochemical connectivity among soil, rivers, and lakes which can assist us to understand their ecological and environmental impacts within a drainage basin (Xu and Xu, 2018).

There is a connectivity between the DOC of rivers and lakes in a river-lake continuum, which is an integral entity for carbon transport. In this study, the DOC in the inflow rivers-Qinghai Lake was analyzed to assess the transport of DOC in such a river-lake continuum. The concentration of DOC in Qinghai Lake water was higher than the surrounding rivers (Fig. 6a). This may be due to that the lake received the inflow fluvial DOC without any outflow, and DOC was accumulated in Qinghai Lake as a terminal aquatic environment via runoff and rivers passing through various landscapes (Song et al., 2013). Although DOC in Qinghai Lake can be lost through sedimentation or being transformed into dissolved inorganic carbon, the accumulation may be conducted in waters at a much higher rate than the lost. The elevated concentrations of DOC in the lake could also be attributed to evaporation, which would be expected to be stronger in the arid environment.

5. Conclusions

The main aim of this study was to identify the distribution of the concentration of DOC in the lakes of Tibet Plateau. Mean DOC concentration of 21.80 ± 30.82 mg/L in the closed lakes was higher than open lakes ($F = 174.1$, $p < 0.05$). However, due to the oligotrophic and mesotrophic status, the concentration of DOC in the lakes of Tibet Plateau was lower than some of the lakes in the outflow region. The potential analysis of drivers for the concentration of DOC in the lakes of Tibet Plateau showed that 78% of the changes in the concentration of DOC across the lakes could be explained by SHEI, slope, and LDI, where SHEI had the most significant impact on the concentration of DOC. The concentration of DOC in Qinghai Lake water was higher than the surrounding rivers. The slope and SOM density in Qinghai Lake watershed might be responsible for the observed phenomenon. Overall, this study is believed to be beneficial to understand the linkages between the variations in DOC and its dominant factor in lakes, which is favorable in realizing the estimation of the concentration of DOC in a larger scale.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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