Journal of Environmental Management 217 (2018) 391–402

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Quantification of dissolved organic carbon (DOC) storage in lakes and reservoirs of mainland China

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ARTICLE INFO

Article history:
Received 5 February 2018
Received in revised form
23 March 2018
Accepted 29 March 2018

Keywords:
DOC
Lake
Reservoir
Brackish
Freshwater
Carbon storage

ABSTRACT

As a major fraction of carbon in inland waters, dissolved organic carbon (DOC) plays a crucial role in carbon cycling on a global scale. However, the quantity of DOC stored in lakes and reservoirs was not clear to date. In an attempt to examine the factors that determine the DOC storage in lakes and reservoirs across China, we assembled a large database (measured 367 lakes, and meta-analyzed 102 lakes from five limnetic regions; measured 144 reservoirs, and meta-analyzed 272 reservoirs from 31 provincial units) of DOC concentrations and water storages for lakes and reservoirs that are used to determine DOC storage in static inland waters. We found that DOC concentrations in saline waters (Mean/median ± S.D: 50.5/30.0 ± 55.97 mg/L) are much higher than those in fresh waters (8.1/5.9 ± 6.8 mg/L), while lake DOC concentrations (25.9/11.5 ± 42.04 mg/L) are much higher than those in reservoirs (5.0/3.8 ± 4.5 mg/L). In terms of lake water volume and DOC storage, the Tibet-Qinghai lake region has the largest water volume (552.8 km^3), 92% of which is saline waters, thus the largest DOC (13.39 Tg) is stored in these alpine lake region; followed by the Mengxin lake region, having a water volume of 99.4 km^3 in which 1.75 Tg DOC was stored. Compared to Mengxin lake region, almost the same amount of water was stored in East China lake region (91.9 km^3), however, much less DOC was stored in this region (0.43 Tg) due to the lower DOC concentration (Ave: 3.45 ± 2.68 mg/L). According to our investigation, Yungui and Northeast lake regions had water storages of 32.14 km^3 and 19.44 km^3 respectively, but relatively less DOC was stored in Yungui (0.13 Tg) than in Northeast lake region (0.19 Tg). Due to low DOC concentration in reservoirs, especially these large reservoirs having lower DOC concentration (V > 1.0 km^3: 2.31 ± 1.48 mg/L), only 1.54 Tg was stored in a 485.1 km^3 volume of water contained in reservoirs across the entire country.

1. Introduction

Dissolved organic carbon (DOC) is a broad classification for organic molecules of varied origin and composition within aquatic systems (Findlay and Sinsabaugh, 2003; Tranvik et al., 2009). Many researchers use the term "dissolved" for compounds below 0.45 μm, which is practically defined by determination of all substances that pass through a GF/F filter (Findlay and Sinsabaugh, 2003). DOC in marine and freshwater systems is one of the greatest cycled reservoirs of organic matter on Earth, accounting for the same amount of carbon as the atmosphere and up to 20% of all organic carbon (Siegenthaler and Sarmiento, 1993). Organic carbon compounds are a result of decomposition processes from dead organic matter such as plants in the catchment, and algae and macrophyte within waters. When water contacts highly organic soils, these components drain into rivers and lakes as DOC (Findlay and Sinsabaugh, 2003; Pacheco et al., 2013). Climate change alters the balance of the carbon cycle of water ecosystems, and climate change-related mechanisms may become increasingly responsible for variations in the inputs of allochthonous DOC concentrations in water (Godin et al., 2017). Thawing of permafrost induced by warming could trigger the release of old organic carbon presently preserved in frozen soil and alter soil permeability. DOC could be released from the soil organic pool into streams and inland waters

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https://doi.org/10.1016/j.jenvman.2018.03.121

(Godin et al., 2017). Climate extremes due to climate change also affected the DOC concentration and components in waters (Shin et al., 2016). However, there are several environmental concerns associated with the increasing DOC levels in water. High DOC concentration may enhance "color" of natural waters, and then block the sun's radiation from penetrating to reach deeper ecosystems. The excessive DOC can also increase the bioavailability of pollutants or make natural waters more acidic (Mierle and Ingram, 1991). Understanding the reserves of DOC in natural waters is necessary in the face of a variable and changing climate.

Inland waters play a vital role in global carbon cycling, and about 2.9 Pg C from terrestrial landscapes are discharged into lakes or reservoirs via streams or rivers, in which about 0.6 Pg C was buried in the sediments, 1.4 Pg C was released into atmosphere via outgassing, and about 0.9 Pg C was transported in the ocean annually (Cole et al., 2007; Tranvik et al., 2009). DOC along with dissolve inorganic carbon (DIC), and particulate organic carbon (POC) are the major forms of carbon in inland waters (Weyhenmeyer et al., 2015), in which DOC is about 50% of total carbon stored in the water column (Tranvik et al., 2009). Numerous studies have proven that most inland waters are CO_2 supersaturated by showing higher partial CO_2 (pCO_2) in the water-air interface (Kling et al., 1991; Cole et al., 1994; Tranvik et al., 2009; Wen et al., 2016, and references therein). It has been proven that the minimization of DOC via biological or photochemical processes is one of the main sources of outgassing CO_2 (Tranvik et al., 2009; Weyhenmeyer et al., 2015; Wen et al., 2016). Investigations also indicated that lakes with different trophic status in various climatic regions may present different pCO_2 features (Wen et al., 2017). To date, several investigations have demonstrated that saline waters tend to contain higher concentration of DOC due to the evaporative condensed effect (Curtis and Adams, 1995; Song et al., 2013, 2017; Wen et al., 2016). However, a systematic examination of DOC characteristics and storage in saline lakes is urgently needed.

Inland waters play a key role in terrestrial carbon cycling, but the total storage of DOC in inland waters is not clear, knowing this may help in fully understanding the carbon storage for terrestrial ecosystems. Inland waters in China, particularly these situated in the Northeast, East and Southeast region, are severely polluted by showing high nutrients and eutrophic status (MEPC, 2015), which also changes the inner sources of DOC from algae. In addition, anthropogenic discharge also carries a large amount of dissolved organic matter, including DOC, into lakes and reservoirs in these regions (Tong et al., 2017). The objectives of this study are to: (1) characterize the DOC concentrations for five limnetic regions in China and examine major underlying reasons; (2) assemble average water volume information through census and other different sources of information; (3) quantify DOC storage through water volume coupled with DOC concentration using both field surveys and meta-analysis. The results are the further supplement of the DOC storage information in inland waters with different geographic environments. The study is expected to help improve our understanding of DOC in inland waters with different trophic status, it may also provide the theory basis for estimation of carbon stock in saline and fresh waters.

2. Materials and methods

2.1. Study area

China is the largest country in Asia, having a complex terrain, it is high in the west and low in the east, thus the major rivers generally flow eastward. The surface features of the country may be grouped at three levels (Fig. S1). China's climate is mainly dominated by dry seasons and wet monsoons, and differs from region to region because of the highly complex topography. Precipitation in China generally decreases from the southeast to the northwest (Fig. S2a), while temperature pattern is controlled by latitude, elevation and land surface features (Fig. S2b).

China's lakes and reservoirs densities vary significantly across its vast territory, and are mainly controlled by its terrain and hydrology, reservoirs are also governed by precipitation and geology. Generally, lakes in China are divided into five limnetic regions (Wang and Dou, 1998), and they are the Northeast Lake Region (NLR), East China Lake Region (ELR), Inner Mongolia-Xingjiang Lake Region (MXR), Yungui Lake Region (YGR), and the Tibet-Qinghai Lake Region (TQR). In the NLR, lakes are mainly distributed in the Songnen Plain (60%), while reservoirs are mainly situated in the Changbai Mountain, the Daxing'an Mountain and the Xiaoxing'an Mountain ranges. For the ELR, the lake and reservoir (area> 1 km^2) area totaled 25171.6 km^2, which accounts to 25.3% of the total inland water in China. The lakes and reservoirs (area> 1 km^2) amount to 23,700 km^2 in the MXR, which is about 22.1% of the total water surface area in China. The YGR is located in the southwest of China, there are 65 lakes in this region with area >1 km^2 totaling to 1399.4 km^2. Thousands of closed lakes with high salinity have developed in the TQR, the total area is approximately half of the lake area in China (Ma et al., 2011), and most of these are sensitive to global warming.

2.2. Field surveys and water sampling

A total of 31 field surveys covering the whole country was conducted during 2009–2016. In the NLR, 1017 samples were taken from 216 water bodies from late August 2011 to August 2016 for spatially characterizing dissolved carbon in 18 field campaigns (Table S1). Five field surveys were conducted and 279 samples were collected in MXR, 54 lake and reservoirs from Inner Mongolia were sampled in late August 2013 and late October 2014, and 26 lakes and reservoirs over two weeks from late July to early August 2015 in Xinjiang Uygur Autonomous Region. In total, four field campaigns were carried out in the ELR in September 2012, October 2014, and October 2015, and 232 and 154 samples were collected over 65 lakes and 44 reservoirs, respectively. In the YGR, two field campaigns were conducted in October 2011 and October 2015, and 299 samples were collected from 52 lakes and reservoirs in this region. As for the highest lake region in the world, two field campaigns were carried out in September 2014 (Qinghai Province) and July 2015 (Tibet Autonomous Regions) across the TQR, and 171 samples were collected from 40 lakes and 3 reservoirs. The sampling stations for each lake and reservoir in China are demonstrated in Fig. 1. Surface water samples were collected at each station approximately 0.5 m below the water surface, generally from the middle of water bodies. Water samples were collected in amber HDPE bottles, and kept in a portable refrigerator at 4 °C before they were returned to a laboratory. Water temperature, turbidity (NTU), water turbidity, and total dissolved solid (TDS, in mg/L) were determined using YSI 600 (YSI Inc., Yellow Spirings, OH). Water transparency was determined through measuring Secchi disk depth (SDD, in meter) for each station.

2.3. Laboratory measurements

2.3.1. Water quality determination

In the laboratory, electrical conductivity (EC, μS/cm) was measured with DDS-307 EC m at room temperature (20 ± 2 °C). Chlorophyll-a (Chl-a) concentration for each water sample was determined using a Shimadzu UV-2660 PC spectrophotometer, and the procedures were detailed in Jeffrey and Humphrey (1975). Water samples were filtered through pre-combusted 0.45 μm