**Hydrological processes and permafrost regulate magnitude, source and chemical characteristics of dissolved organic carbon export in a peatland catchment of northeastern China**

Yuedong Guo1 , Changchun Song1,\*, Wenwen Tan1, Xianwei Wang1, Yongzheng Lu 1

1Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130012, China

Tel: 86-431-85542211

Fax: 86-431-85542298

Address:

Northeast institute of Geography and Agroecology, Chinese Academy of Sciences. No.4888, Shengbei Road, Changchun, Jilin Province, China, 086-130102

**Abstract**

Permafrost thawing in peatland has the potential to alter the catchment export of dissolved organic carbon (DOC), thus influencing carbon cycling in linked aquatic and ocean ecosystems. However, peatland along the southern margins of Eurasian permafrost are seldom examined in spite of the presence of considerable risks associated with permafrost degradation due to climate warming. This study examines dynamics of DOC export from a permafrost peatland catchment located in northeastern China during the growing seasons of 2012 to 2014. The estimated DOC loads varies greatly between 3211 to 19022 Kg yr-1 with a mean DOC yield of 4.7 g m-2 yr-1. The floods contribute to the majority of DOC loads, which derived mainly from riparian peat pore water stored in the upper organic layer. The peat catchment shows a transport-limited process in DOC export regarding to the strong linkages between discharge and DOC concentrations in both wet and fry years. DOC source and chemical characteristics, as indicated by three fluorescence indexes, change sensitively during rainfall-runoff events owing to flowpath-shifts. Interaction between the flowpath and DOC source is greatly influenced by the seasonal thawing of the soil active layer, and the deepening of the active layer due to climate warming should elevate proportions of microbial-originated DOC in baseflow discharge.

**1. Introduction**

Permafrost soils have acted as sinks for atmospheric carbon (C) since at least the late Pleistocene and serve as key sources of dissolved organic carbon (DOC) for linked aquatic and ocean ecosystems (Opsahl et al., 1999; Kicklighter et al., 2013). As changes in the quantity and quality of exported DOC could greatly alter the energy cycles of linked oceans, considerable advances have been made in recent years to better evaluate potential changes DOC export patterns from permafrost regions (Townsend-Small et al., 2011; Vonk et al., 2013;). However, uncertainties remain regarding to main driving factors involved and the fate of DOC due to complex interactions between hydrological and thermal dynamics and bio-chemical drivers (Olefeldt and Roulet, 2012; Kicklighter et al., 2013).

Significant losses of near-surface permafrost have been observed over the past century and such outcomes have induced considerable changes in hydrological processes and soil thermal regimes (Lyon et al., 2009; Lessels et al., 2015), in turn altering the magnitude and timing of terrestrial DOC export processes. Flow pathway is an important and well-documented regulator of DOC export from permafrost regions (Ågren et al., 2010; Guo et al., 2015). Owing to increased levels of hydrological access to previously frozen soils following permafrost degradation, DOC export is forecasted to increase in Siberian rivers along a latitudinal transect (Frey and MacClelland, 2009). However, permafrost degradation also increases the likelihood of interactions between subsurface flows and mineral soils, which should lead to considerable DOC absorption by fine soil particles and in turn decrease in DOC export magnitude (Petrone et al., 2006; Striegl et al., 2005). There are significant disparities in DOC export concentrations and seasonal patterns between surface- and subsurface-dominated runoff processes in permafrost catchments (Laudon et al., 2011). Studies have proven that capacities for DOC export from permafrost soils are closely related to lateral subsurface flows (Striegl et al., 2007; Lyon et al., 2010). Therefore, alterations in flow pathways during permafrost freeze-thaw cycles are some of the most important factors to consider in evaluating DOC export potential.

Flow pathways also determine chemical compositions of DOC export from permafrost catchments, which in turn have considerable impacts on downstream DOC mineralization levels and carbon emissions from streams, lakes and oceans (Mann et al., 2012; Cory et al., 2014). DOC compositions can be altered to a certain degree according to flow pathways of the organic-mineral soil layer. Mineral soil particles preferentially absorb dissolved organic matter high in aromatic components with large molecular weights or acidic functional groups, and aromatic structures (Kalbitz et al., 2005). Meanwhile, hydrophilic fatty microbial products with low molecular weights are desorbed and released (Striegl et al., 2005). To date, some theoretical framework or methods have been developed to evaluate alterations in DOC chemical characteristics following permafrost degradation (Spencer et al., 2015). But uncertainties still exist in the comprehensive effects of hydrological processes on the magnitudes and chemical characteristics of DOC exported from permafrost catchments.

Given the high spatial heterogeneities of peatland and complexities of hydrological processes in permafrost regions, it is important to understand magnitudes and regulations on DOC export in different permafrost regions and especially in the south part of the [Eurasian continent](http://dict.cnki.net/dict_result.aspx?searchword=%e6%ac%a7%e4%ba%9a%e5%a4%a7%e9%99%86&tjType=sentence&style=&t=eurasian+continent) where limited research has been performed. This study focuses on dynamics of DOC release from the Fukuqi River, a tributary of the Amur River positioned along northern slopes of the Great Xing’an Mountains in northeastern China. The Great Xing’an Mountains form an important barrier from Siberian cold air masses and monsoons of East Asia. The mean annual temperature of the area has on average increased by 0.3 ℃ every 10 years over the last 50 years, and the thickness of the active layer has increased by 20-40 cm on the southern slopes of the Great Xing’an Mountains from 1970s to 2000 (Jin et al., 2000). However, few studies have focused on possible effects of permafrost degradation on this region to date. This work thus investigates potential changes in DOC export patterns by answering the following questions:

(1) How much is the DOC load transported by discharge for the whole catchment?

(2) What is the relationship between runoff processes and concentrations, sources, and chemical characteristics of DOC?

**2. Approach and methodology**

**2.1. Study area**

Northern sections of the Great Xing’an Mountains in China are located along the southern margins of the continuous permafrost zone in Eurasia. The area represents the most remote region of the East Asia monsoon of the East Eurasian continent. The region includes approximately 8.245 × 103 km2 of natural wetland, representing a major proportion cold temperate wetlands and an important reservoir of soil carbon and usable water resources for northeastern China.

The Fukuqi River, a second order branch of the Amur River, is located at continuous permafrost zones of the northern section of the Great Xing’an Mountains (Fig. 1). The catchment extends across an area of 287 km2 with an annual mean temperature of −4.2 °C and a mean annual precipitation level of 425 mm (1959-2013). Peatland covers throughout the flat river valley with an altitude range between 500 to 580 m. Upland mountains surround the peatland and have a much larger slope than the peatland in the cross profile (Fig. 1). The peat layer, which is approximately 0.3-0.4 m thick, is composed of typical organic soil with organic matter levels ranging from 40% to 60% and with porosity levels ranging from 60% to 20% from the surface. According to previous field survey, the peatlands accounts for more than 90% of the total carbon stock in the catchment although it covers only about one-third of the total area. The maximum thaw depth of the active layer, ranging from 60 to 80 cm, occurs usually in early August. Below the peat soil layer, there covers mineral soil with much lower organic content (< 5%) and soil porosity (< 10%) than the upper soil. The plants usually grow from May until late September. The Sphagmum mosses (*S.capillifolium, S. magellanicum*) and sedges (*Eriophorum vaginatum*) are the dominant vegetation. The upland mountains on both sides of the valley are extensively covered by mineral soil and gravels with little organic content due to the continuous logging and frequent fires during the past 60 years. To date, the original coniferous forest has been already replaced by young *Pinus sylvestris var. mongolica*. The maximum thaw depth of the upland ranges from 80 to 100 cm, which is slightly deeper than the peatland.

**Fig. 1** Geographic location of the study area.

**2.2. Sampling and monitoring program**

Monitoring was conducted from early May to late September of 2012, 2013 and 2014. A gauging profile for DOC concentrations and hydrological parameters was set for the lower reaches of the Fukuqi River (Fig. 1). Water samples were collected from the stream profile every 1–5 days with 200 ml polyethylene bottles, and a higher sampling frequency was applied during flood events while a lower sampling frequency was applied during low water periods. The collected water samples were filtered through a 0.45-µm glass fibre membrane, and stored in 4℃ in dark for at most seven days before measured using a DOC analyser (C-VCPH, Shimadzu, Japan) (Guo et al., 2014). After September, the river frozen completely and no groundwater flow under ice is detectable.

To assess chemical DOC characteristics of the active layer and to determine sources of DOC in the discharge, peat soil pore water was collected from three sites located 50-100 m away from the main river channel in the growing seasons of 2013 and 2014 (Fig. 1). For each site, 3-5 sample points were used repeatedly for each sampling procedure. When sampling, 100 ml samples of soil pore water drawn from different depths at 10 cm intervals in the active layer were collected using ceramic soil pore water samplers (SIC20, Germany). Due to the gradual thawing of the active layer throughout the growing season, maximum sampling depths varied. Meanwhile, rainfall samples were collected during the two growing seasons. The depletion of stable oxygen isotopes (δ18O‰) for the discharge samples, peat soil pore water, local rainfall were analysed with an isotope mass spectrometer (Finnigan Delta plus XP, USA) at the Key Laboratory of Wetland Ecology and Environment, Chinese Academy of Sciences. The mean values of the triplicate analysis were used in the study, and replicate analysis of the samples reached a precision better than ±0.4‰.

To evaluate the discharge through the gauging profile, water level and mean flow velocity was automatically measured (Q) by a water level monitor (Odyssey, New Zealand, accuracy: ±2 mm) and a flow meter (Argonaut-ADV, USA, accuracy: ±0.01 m s-1) respectively. Air temperature and soil temperature at 0–1.0 m depth were also recorded by an automatic microclimate gauging tower (CS3000, Campbell, USA) set in the center part of the peatlands. The standing water levels in the site nearby the gauging tower were successively recorded by the same Odyssey monitor. The thaw depth of the peatland active layer was manually surveyed weekly with a 1.0-m stainless steel ruler (accuracy: 0.1 cm) at the same three sites. Information of the temperature (°C), electrical conductivity (mS cm-1), and turbidity (NTU) in the sampling profile is automatically obtained by a multi-parameter water quality sonde (6600EDS, YSI, USA). About one-fifth of the water quality data was lost because of power lose due to the excessively low temperature in the stream. All the gauging data were recorded once every six hours during the growing seasons.

**2.3. Fluorescence measurements**

Excitation-emission matrixes (EEMs) of the water samples were measured using a Hitachi F-7000 fluorescence spectrometer (Hitachi High Technologies, Japan) with a 50 W ozone-free Xenon arc lamp and R928P photomultiplier tube fitted as a detector. The spectrometer was set to collect signals using a 5-nm bandpass on excitation and emission monochromators at a canning speed of 3,200 nm min-1. EEMs were recorded for excitation spectra of between 220 and 400 nm and for emission spectra of between 300 and 500 nm. To eliminate the inner-filter effect, samples were diluted with deionized water to a decadal UV absorbance at λ= 254 nm of 0.2 absorbance units (cm-1). Milli-Q water blank EEMs were subtracted from the sample EEMs to eliminated Raman scatter peaks. Then, the EEMs were normalized to the area under the Raman scatter peak (excitation wavelength of 350 nm) of a Milli-Q water sample run the same day. The fluorescence intensities measured were reported in Raman Units (RU) in this study.

Three spectral indexes calculated from the EEMs were measured to quantify chemical characteristics of the dissolved organic matter: 1) humification (HIX) defined as the ratio of the sum of λem = 435–480 nm to the sum of λem = 300–345 for excitation at 254 nm and quantifying the complexity and aromaticity of dissolved organic matter. High HIX values denote the presence of highly humiﬁed or more complex organic matter (Ohno, 2002); 2) the fluorescence (FI) defined as the ratio of fluorescence emission intensities at 470 and 520 nm for excitation at 370 nm. The recommended FI for plant-derived organic matter is 1.3-1.4 and that for materials of microbial origin is 1.7-2.0 (McKnight et al., 2001); 3) the biological index (BIX), defined as the ratio of intensities at λem 380 nm and 430 nm for excitation at 310 nm and ranging from 0.6 to 1.0 or greater generally, is a complementary index for evaluating the relative contributions of microbial-derived organic matter (Huguet et al., 2009).

**2.4 Estimation of DOC load and yield**A web-based program LOADEST was used to estimate the DOC load for the three years (https://engineering.purdue.edu/~ldc/LOADEST). LOADEST uses linear regression models to identify relationships between discharge and DOC concentrations, and in turn to estimate daily DOC load by applying the statistical method of Adjusted Maximum Likelihood Estimation (AMLE), Maximum Likelihood Estimation (MLE), and least absolute deviation (LAD). Totally eleven models were used in the program, and the best one was automatically selected to fit the data on the base of Akaike Information Criterion (Park et al., 2015). In the study, there were 36, 35, and 31 measurements were used to calculate DOC loads for the year of 2012, 2013, and 2014 respectively. Estimated loads with MLE method were finally selected according to the presented standard error (SE) and the distribution of the residuals. The DOC yield equaled to the load divided by catchment area.

**2.5. Statistical analyses**

The mean and the standard deviation of the DOC concentration in the stream and soil pore water, and the three fluorescence indexes were statistically analyzed with the Statistical Program for Social Sciences (SPSS) version 13.0 software. The relationship between the hydrological factors and the DOC concentration and the fluorescence indexes was examined by a two-tailed Pearson correlation and regression analysis, where the p-values were calculated to test for significance. Analysis of covariance (ANCOVA) was also conducted to distinguish if the relationships between discharge and the DOC characteristics (concentration and fluorescence indexes) were statistically different for different years, and if there were other factors controlling the DOC characteristics besides of discharge.

**3. Results**

**3.1. Environmental conditions**

Substantial inter-annual and seasonal variations in precipitation were observed for the three years (Fig. 2). Total precipitation levels reached 202.5, 520.8 and 164 mm in 2012, 2013 and 2014, respectively. Based on our statistics on the regional climate dataset for 1970 to 2005, 2013 was an extremely wet year due to excessive rainfall occurring in the spring and summer. Precipitation levels in the growing season of 2012 remained within a normal range while those for 2014 denote the presence of very dry conditions in the study area. Influenced by unusual precipitation patterns, the mean air temperature of the growing season of 2013, 12.9℃, was somewhat lower than those of 2012 and 2014 (13.65 and 13.67℃). However, all mean values fell within the average range for the long-term climate dataset. We also found no significant differences in maximum thaw depths for the three years, finding values of approximately 70 cm. Standing water levels close to the stream channel declined overall across the growing seasons. No water level higher than peat surface were detected for the three years.

**Fig. 2** Dynamics of air temperature, precipitation, standing water levels, and thaw depth observed during the growing seasons of 2012 to 2014.

**3.2. DOC concentrations and loads**

DOC concentrations in the Fukuqi River fluctuated considerably with stream discharge during the three growing seasons (Fig. 3). A maximum concentration of 44.71 mg L-1 was found in the early spring of 2013 accompanied by the maximum flood for the three years. It is noteworthy that DOC concentration consistently exhibited high levels during successive big floods in the autumn of 2012 and the spring of 2013. Significantly positive correlations were found between DOC concentrations and discharge for all three growing seasons (Fig. 4). Results of covariance analysis indicated that the adjusted mean DOC concentrations after eliminating the influence of discharge were statistically different for the three years, with the highest value occurring in 2013 (Table 1). Meanwhile, DOC concentrations were positively related to turbidity and negatively related to conductivity (n=68, p < 0.01) while no significant relationship was found between the concentrations and air temperature or soil temperatures of active layer.

**Fig. 3** Dynamics of dissolved organic carbon (DOC) concentrations and discharge observed during the growing seasons of 2012 to 2014. The discharge (Q) unit used is 106 m3 d-1.

**Fig. 4** Relationships between discharge and the DOC concentrations for the three in years.

**Table 1.** Results of covariance analysis (ANCOVA) between discharge and the DOC concentrations for the three years.

There were great variations in the estimated DOC loads and yields for the three years (Table 2). The total load, as well as DOC yield, in the wet year 2013 was about six times of that in 2014. The annual load and yield also presented large discrepancy between 2012 and 2014, while the estimated mean concentrations were very close. Great variations in the monthly estimations were also found, with the maximum values appearing in either August or May. The mean DOC load reached 4.7 g m-2 yr-1 for the three years, while several large floods contributed to the major part of the load. Statistically, the nine flood events (maximum discharge > 1.0 × 106 m3 d-1) were responsible for 81% of the load while the five floods with a discharge level of > 2.0 × 106 m3 d-1 accounted for 65% of the total load.

**Table 2.** Mean DOC loads, concentrations and yields estimated by LOADEST program.

**3.3. Fluorescence indexes**

The three spectral indexes varied considerably with discharge during the growing seasons (Fig. 5). There was a significantly positive correlation between the HIX and logarithmic discharge while a negative correlation for both FI and BIX (Fig. 6). HIX ranged from 5.52 to 16.41 with an average value of 10.38, revealing a high volume of humification components in the stream discharge DOC (Ohno, 2002). FI and BIX values ranged from 1.43 to 1.62 and from 0.46 to 0.63 with average values of 1.52 and 0.54, respectively. The FI values indicate that DOC was from both plant-derived organic matter and microbe-originated matter (McKnight et al., 2001) while the BIX value denotes the presence of a low volume of fresh organic matter from biological sources in the discharge (Huguet et al., 2009). All of the three indexes were closely related to DOC concentrations and hydrological variables during the whole study periods, while only HIX also showed significant relationships with soil temperature (Table 3). In spite of the great variations during the growing seasons, the three indexes presented no statistical difference in the mean annual values for the three years according to the result of covariance analysis which eliminated the disturbance of discharge (Table 4).

**Fig. 5** Dynamics of the three spectral indexes following discharge during the growing seasons.

**Fig. 6** Relationships between discharge and the three indexes during the study period.

**Table 3.** Correlation analysis of the three fluorescence indexes with hydrological and climatic factors.

**Table 4.** Results of covariance analysis (ANCOVA) between discharge and the fluorescence indexes for the three years.

**3.4. Stable oxygen isotopes for river discharge, rainfall and soil pore water**

There were no great seasonal variations in δ18O‰ values for the rainfall samples as shown in Fig. 7. It seems that air temperatures and rainfall quantities had no effect on the depletion of oxygen isotopes in rainfall during the growing seasons. The mean value of rainfall was measured at -7.62 ± 0.53‰, which is significantly higher than that for river discharge and soil pore water (*P*<0.01). The δ18O‰ values for the river discharge fluctuated slightly around a mean value of -14.64 ± 1.75‰, which was not statistical different from that for the soil pore water (-14.67 ± 0.72‰) (*P* >0.01). The δ18O‰ values of soil pore water at the three sample sites did not vary largely by location or season.

**Fig. 7** Dynamics of stable oxygen isotope values for rainfall, discharge and soil pore water in the catchment. The discharge (Q) unit used is 106 m3 d-1.

**3.5. Concentrations and fluorescence indexes of soil water**

During the growing seasons, DOC concentrations in the soil pore water changed considerably with depth. Maximum DOC concentrations were typically found in the plant root layer while the minimum values were found at the mineral soil layer (Fig. 8). The difference along the profile could be clearly observed while active layer thawed below the organic layer. However, no significant relationship between DOC concentration and soil temperature at different depth was detected. The DOC concentrations in the upper organic soil layer increased remarkably from early to late June, while no meaningful changes were observed from July to late August. Across the whole growing seasons, no significant relationship was found between the mean DOC concentration and the mean soil temperature for the four group samples.

The HIX, FI, and BIX of the soil pore water varied greatly with soil depth (Fig. 9). Pronounced changes in the three indexes generally happened at the depth on which organic soil transformed into the mineral. The HIX values gradually decreased downwards while FI and BIX presented the opposite trend. The indexes for the upper organic soil layer changed remarkably along the growing seasons. However, no regular trend could be found from spring to autumn. The mean values for the three indexes were 16.62, 1.41, and 0.46 respectively during the seasons of 2013. The data indicated a much higher HIX level, while a lower FI and BIX level, in the soil pore water than that in the baseflow discharge. For all of the collected samples, HIX values were found to be significantly and positively related to DOC concentrations of the soil pore water while FI and BIX were inversely and significantly correlated with the parameter (n = 18, p < 0.01).

**Fig. 8** DOC concentrations in soil pore water along the soil profile for 2013.

**Fig. 9** Vertical distribution of the three spectral indexes for soil pore water along the soil profile for 2013.

**4. Discussion**

**4.1. DOC concentrations and yield**

DOC concentrations in boreal rivers have been reported to vary considerably owing to variable hydrology, soil type and topography (Andersson and Nyberg, 2008; Tunaley et al., 2016; Broder et al., 2017). Theoretically, the presence of organic soils in the catchment would contribute to high DOC concentrations in connected rivers. However, no direct relation between organic soil extent and mean DOC concentration was extensively found across the boreal regions. In our study, the annual mean concentration, 15.44 mg L-1, was in the middle range of reported limits from 1.52 to 35.3 mg L-1 in the boreal regions (Yates et al., 2016; Avagyan et al., 2016). It was noteworthy that the mean DOC concentrations in discharge varied greatly from wet to dry year. Although the predominant control of the discharge has been proved, analysis of covariance indicates that there ought to be other factors leading to the inter-annual variations. Temperature seemed to be the most possible factor for the concurrence of the highest mean temperature and the highest adjusted mean concentration in 2013 (Table 2). However, no convincing proof could be provided from field dataset by far, more detailed study is needed in the approaching research.

According to our data, the DOC yield from the studied catchment was estimated at 4.7 g m-2 yr-1, which was in the lower range of reported permafrost estimates ranging from 1 to 35 g m-1 yr-1 (Fraser et al., 2001; Dinsmore et al., 2010; Moody et al., 2016). Typically, the DOC yield in our catchment was less than the net DOC loss from UK land (2.1-11.5 g m-2 yr-1)(Moody et al., 2013), while higher than that in Finnish rivers (3.5 g m-2 yr-1) (Räike et al., 2012), and that in Yukon River in Alaska (1.4-3.7 g m-2 yr-1) (Striegl et al., 2007), and that in central Siberian rivers (2.8-4.7 g m-2 yr-1) (Prokushkin et al., 2011). According to the estimation from Kichlighter et al. (2013), pan Arctic rivers exported 32 Tg C yr-1 of DOC to the Arctic Ocean, which indicated a mean yield of 5.1 g m-2 yr-1 from the pan Arctic land. In total, there seemed to be no clear trend in DOC yield from the north parts of the Eurasian permafrost to the south boundary. To estimate DOC load from boreal lands more accurately, detailed field studies in the regions out of research were still needed.

Based on the data of Miao (2014), the net ecosystem exchange (NEE) of peatland in the study catchment determined from carbon dioxide and methane fluxes between peatland surfaces and the atmosphere was 30.59 ± 1.98 g m-2 yr-1. The estimated DOC yield in our study accounted roughly for 18.3% of the net ecosystem carbon balance in the catchment. As the upland mountains, covered by mineral soils extensively, would likely export much less DOC to the stream than the peatland, the DOC yield from the sole peatland should be much higher than 4.7 g m-2 yr-1, and hence the proportion was a very conservative estimate. However, our data still highlighted the importance of stream carbon export for peatland net ecosystem carbon balance. Any disturbance altering DOC export magnitudes should disrupt the balance between of carbon sequestration and release in the peatland. In contrast to other studies, the proportion was much higher than that in a northwest Russia river through which the exported DOC accounted for 5.6-8.5% of the total carbon sequestration in the peatlands (Avagyan et al., 2016), while was close to the peat catchment in Scotland where DOC represented a loss of 24% of NEE (Dinsmore et al., 2010).

**4.2. Flow pathway and DOC export**

The increase in DOC concentration with stream discharge in the study was consistent with the patterns observed in other permafrost regions (Hinton et al., 1998; Petrone et al., 2007; Balcarczyk et al., 2009; Koch et al., 2013). This relationship was constant in both the wet and the dry year, which indicated the DOC export from the studied catchment was a transport-limited process. On the contrary, it could be confirmed not a carbon-limited process on the base of two facts: 1) the maintained high DOC concentrations in the two successive floods in 2013, and 2) the uncorrelated DOC concentrations in peat pore water with temperature, which hints that DOC production rate is not controlled by temperature only.

Given the transport-limited process, changes in flow pathway were considered to be the most important control on DOC export in the catchemt. Peatland in permafrost generally experienced subsurface flows but not over surface flows due to the occurrence of high rainfall infiltration into the thawed organic layer (Carey and Woo, 1997). In our study, the porosity of peat in the upper 40 cm layer could reach levels of 20-60% generally, which would necessarily lead to high infiltration rates for rainfall. Blocking by frost table of the active layer, the lateral subsurface flow parallel to the frost table took shape as a result. Lateral subsurface flow led the soil pore water in riparian zone to be pushed preferentially into the channel and form a major proportion of flood peaks owing to the high hydraulic conductivity of macroporous peat soil (Boyer et al., 1997; Carey and Woo, 2001). It was noteworthy that δ18O‰ values in the discharge were generally similar to those in soil pore water close to the stream channel while being more negative than those in rainfall, which was a direct proof that the stream discharge was mainly composed of soil pore water reserved in the peatland before new rainfall events occur. Similar studies have confirmed the fact that the riparian zone of peat-drained river stores and releases aged and DOC-rich pre-event water (Boyer et al., 1997; Tetzlaff et al., 2014; Guo et al., 2015). As shown in Fig. 2, the water level in the riparian peat fluctuated in good consistent with the stream discharge, which was an indirect proof of the riparian contribution. Given the concurrence of high DOC concentrations and the flood peaks, our results highlighted the importance of the riparian zone as both the main source of DOC and the generation of discharge, which was also recognized by Tunaley et al. (2016).

**4.3. DOC sources and chemical characteristics**

Considerable fluctuations in the three fluorescence indexes, HIX, FI, and BIX during the rainfall-runoff events were observed in the study, which implied the alterations in DOC sources and chemical characteristics during the runoff processes. The three indexes varied largely from organic soil to mineral soil, and held the vertical variation throughout the whole growing seasons (Fig. 8), which made themselves good indicators of resource alteration of the DOC. Given the significant correlation between the indexes and the discharge, it could be concluded that the DOC released in flood period derives mostly from the upper organic layer, while the DOC in the recession and baseflow periods was mainly from the lower mineral soil layer. Carey and Woo (2001) described permafrost soil as a two-layer flow system based on the difference in hydraulic conductivity between the upper organic soil and lower mineral soil: Quickflow took place through highly porous peat in the upper layer defined as matrix flow or preferentical flow interconnecting soil pipes and rills, while slowflow was defined as laminar flow in the lower saturated mineral soils with flow velocities that were orders of magnitude lower than quickflow. As the porosity declined exponentially in the transition from organic to mineral soil in the studied peatland, the pre-event water in the upper organic soil with high concentration of DOC ought to be delivered by quickflow in the flood periods, while the baseflow was the result of slowflow with much lower DOC content from mineral soil.

Previous studies of permafrost catchments have recorded alterations in DOC source and compositions across seasons (Spencer et al., 2008; O’Donnell et al., 2010). However, our results highlighted the alterations in the temporal scale of rainfall-runoff event. In our study, the deepening of active layer led to the presence of vertical discrepancy in hydraulic conductivity in the discharge-yield profile, and in turn the shifts in DOC sources and chemical characteristics during flooding processes. As few rainfall occurred in 2014, we were able to identify effects of the gradual deepening of the active layer throughout growing seasons. Remarkable elevations in BIX and FI values in the baseflow from the spring to the autumn were found (Fig. 4), which implied the increase in the contents of microbial-derived DOC with deepening of active layer. As deepening of active layer, the hydraulic residence time of water and the DOC mineralization rate, as well as physical adsorption, in the mineral soil would increased concurrently (Cronan and Aiken, 1985; Sebestyen et al., 2008), which would alter DOC chemical characteristics in baseflow. In our study, the DOC in the soil pore water exhibited higher HIX values and lower FI and BIX values compared to that in the baseflow, which was also a proof of the adsorption-mineralization actions. The actions deceased the DOC humification and increased microbial-derived components when the DOC was transported by the slowflow across the mineral soil. The result was in good consistence with the conclusions of Prokushkin et al. (2007) who also found higher levels of microbially transformed and/or derived material export due to the presence of a deeper active layer in the summer and autumn in Siberia. Changes in biochemical compositions (decreases in the lignocellulose complex; increases in the hydrophilic fraction) were confirmed further in Kawahigashi et al. (2004). Based on the similar observations, about 9%-11% reduction in DOC load in the Yukon River by 2050 due to permafrost degradation was predicted (Walvoord and Striegl, 2007), and an increase in dissolved inorganic carbon (DIC) was also hypothesized by Striegl et al. (2005). In summary, it could be conjectured that the deepening of active layer due to warmer climate would reduce DOC export by baseflow, as well as alter the chemical characteristics to more structure-simple microbial-derived components in the study region.

The humification degree of DOC as determined by HIX showed no clear trend during the seasons of 2014. A minor flood could even introduce a great elevation in humification degree of exported DOC, suggesting the sensitivity of DOC chemical characteristics to the flowpath-shift process. All of the analysis above highlighted the importance of the seasonal thawing of active layer on the flowpath and DOC chemical characteristics. However, the result of covariance analysis indicated that the discharge was the sole factor leading to the inter-annual variations in the DOC chemical characteristics. There was no remarkable difference in the maximum thaw depths of active layer for the three years (Fig. 2), which was likely the reason why cannot distinguish the inter-annual effect of permafrost thawing. In total, it could be concluded that there was different controlling factors on DOC chemical characteristics in different temporal scales. Long term field investigation is especially needed to evaluate the influence of the deepening of active layer.

**5. Conclusions**

Eurasian permafrost serves as an important potential carbon pool for the atmosphere and for linked aquatic and ocean ecosystems. Investigations of DOC responses to permafrost peatland can be used to predict the ecological consequences of climatic change in these regions. Our study thoroughly investigated the loads and determinants of DOC export from a peatland catchment along the southern margins of Eurasian permafrost. The catchment exhibits a lower magnitude of DOC loads compared to other studies in permafrost regions, and the yield data estimated is a supplement for the estimation of global fluvial carbon export. The peat catchment shows a transport-limited process in DOC export, and the stable relationship between DOC concentrations and discharge makes the total discharge a strong indicator of the annual DOC loads. Field investigation shows that the DOC source and chemical characteristics are greatly affected by the flowpath-shift process, which is closely related to the vertical soil structure and seasonally thawing of active layer. Deepening of active layer following permafrost degradation would increase the content of microbial-originated DOC in baseflow discharge by elevating the contribution from the lower mineral soil layer. The study has so far provided limit field data on the DOC dynamics in the southern region of Eurasian permafrost, and more extensive works are needed to predict the possible effect of DOC export on the carbon pools in the region.

**Acknowledgements**

The work was supported by National Key Research and Development Program of China (2016YFA0602303), National Natural Science Foundation of China (41571097), Key of Frontier Sciences, Chinese Academy of Sciences (QYZDJ-SSW-DQC013), Research Program of Northeast Institute of Geography and Agroecology, Chinese Academy of Science (IGA-135-05).

**References**

Ågren, A., Haei, M., Köhler, S. J., Bishop, K., Laudon, H.: Regulation of stream water dissolved organic carbon (DOC) concentrations during snowmelt; the role of discharge, winter climate and memory effects, Biogeosciences, 7, 2901–2913, 2010.

Avagyan, A., Runkle, B. R. K., Hennings, N., Haupt, H., Virtanen, T., Kutzbach, L.: Dissolved organic matter dynamics during the spring snowmelt at a boreal river valley mire complex in Northwest Russia, Hydrol. Process., 30, 1727–1741, 2016.

Andersson, J-O., Nyberg, L.: Spatial variation of wetlands and flux of dissolved organic carbon in boreal headwater streams, Hydrol. Process., 22,1965–1975, 2008. DOI:10.1002/hyp.6779.

Balcarczyk, K.L., Jones Jr, J.B., Jaffé, R., Maie, N.: Stream dissolved organic matter bioavailability and composition in watersheds underlain with discontinuous permafrost, Biogeochemistry, 94, 255–270, 2009.

Boyer, E.W., Hornberger, G.M., Bencala, K.E., Mcknight, D.M.: Response characteristics of DOC flushing in an alpine catchment. Hydrol Process 11:1635–1647, 1997.

Broder, T., Knorr, K. H., Biester, H.: Changes in dissolved organic matter quality in a peatland and forested headwater stream as a seasonality and hydrologic conditions, Hydrol. Earth Syst. Sci., 21, 2035–2051, 2017.

Carey, S., Woo, M.K.: Snowmelt hydrology of two subarctic slopes, Southern Yukon, Canada. In Proceedings of the Eleventh Northern Research Basins Symposium and Workshop (Vol 2), Prudhoe Bay/Fairbanks Alaska. The Water and Environmental Research Centre, University of Alaska, Fairbanks, pp. 15–35, 1997.

Carey, S.K., Woo, M.K.: Slope runoff processes and flow generation in a subartic, subalpine catchment, J. Hydrol., 253, 110–129, 2001.

Cory, R.M., Ward, C.P., Crump, B.C., Kling, G.W.: Sunlight controls water column processing of carbon in arctic fresh waters, Science, 345, 925–928, 2014.

Cronan, C.S., Aiken, G.R.: Chemistry and transport of soluble humic substances in forested watersheds of the Adirondack Park, New York, Geochim. Cosmochim. Acta, 49, 1697–1705,1985.

Dinsmore, K.J., Billett, M.F., Skiba, U.M., Rees, R.M., Drewer, J., Helfter, C.: Role of the aquatic pathway in the carbon and greenhouse gas budgets of a peatland catchment, Global Change Biol., 16, 2750–2762, 2010.

Frey, K. E., McClelland, J. W.: Impacts of permafrost degradation on arctic river biogeochemistry, Hydrol. Process., 23, 169–182, 2009.

Fraser, C.J.D., Roulet, N.T., Moore, T.R.: Hydrology and dissolved organic carbon biogeochemistry in an ombrotrophic bog, Hydrol. Process., 15, 3151–3166, 2001.

Guo, Y.D., Song, C.C., Wan, Z.M., Tan, W.W., Lu, Y.Z., Qiao, T.H.: Effects of long-term land use change on dissolved carbon characteristics in the permafrost streams of northeast China, Environ. Sci.: Processes Impacts, 16, 2496-2506, 16, 2014.

Guo, Y.D., Song, C.C., Wan, Z.M., Lu, Y.Z., Qiao, T.H., Tan, W.W., Wang, L.L.: Dynamics of dissolved organic carbon release from a permafrost wetland catchment in northeast China. J. Hydrol., 531, 919–928, 2015.

Hinton, M.J., Schiff, S.L., English, M.C.: Sources and flowpaths of dissolved organic carbon during storms in two forested watersheds of the Precambrian Shield. Biogeochemistry, 41,175–197,1998. doi:10.1023/A:1005903428956

Huguet, A., Vacher, L., Relexans, S., Saubusse, S., Froidefond, J.M., Parlanti, E.: Properties of fluorescent dissolved organic matter in the Gironde Estuary, Org. Geochem., 40, 706–719, 2009.

Jin, H.J., Li, S.X., Cheng, G.D., Wang, S.L., Li, X.: Permafrost and climatic change in China, Global Planet., Change 26, 387–404, 2000.

Kalbitz, K., Schwesig, D., Rethemeyer, J., Matzner, E.: Stabilization of dissolved organic matter by sorption to the mineral soil, Soil Biol Biochem., 37, 1319–1331, 2005.

Kawahigashi, M., Kaiser, K., Kalbitz, K., Rodionov, A., Guggenberger, G.: Dissolved organic matter in small streams along a gradient from discontinuous to continuous permafrost, Global Change Biol., 10, 1576–1586, 2004.

Kicklighter, D. W., Hayes, D. J., McClelland, J. W., Peterson, B. J., McGuire, A. D., Melillo, J. M.: Insights and issues with simulating terrestrial DOC loading of Arctic river networks, Ecol. Appl., 23, 1817–1836, 2013.

Koch, J.C., Runkel, R.L., Striegl, R., McKnight, D.M.: Hydrologic controls on the transport and cycling of carbon and nitrogen in a boreal catchment underlain by continuous permafrost, J. GEOPHYS. RES-BIOGEO., 118, 698–712, 2013. doi:10.1002/jgrg.20058,

Laudon, H., Berggren, M., Ågren, A., Buffam, I., Bishop,K., Grabs, T., Jansson, M., Köhler, S.: Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: the role of processes, connectivity, and scaling, Ecosystems, 14, 880–893, 2011.

Lessels, J.S., Tetzlaff, D., Carey, S.K., Smith, P., Soulsby, C.: A coupled hydrology-biogeochemistry model to simulate dissolved carbon exports from a permafrost-influenced catchment. Hydro. Process., 29, 5383–5396, 2015.

Lyon, S. W., Destouni, G., Giesler, R., Humborg, C., Mörth, M., Seibert, J., Karlsson, J., and Troch, P. A.: Estimation of permafrost thawing rates in a sub-arctic catchment using recession flow analysis, Hydrol. Earth Syst. Sci., 13, 595–604, 2009.

Lyon, S.W., Morth, M., Humborg, C., Giesler, R., Destouni, G.: The relationship between subsurface hydrology and dissolved carbon fluxes for a sub-arctic catchment, Hydrol. Earth Syst. SC., 14, 941–950, 2010.

Mann, P.J., Davydova, A., Zimov. N,, Spence,r R.G.M., Davydov, S., Bulygina, E., Zimov, S., Holmes, R.M.: Controls on the composition and liability of dissolved organic matter in Siberia’s Kolyma river basin, J. Geophys. Res-Biogeo., 117, G01028. DOI: 10.1029/2011JG001798, 2012.

McKnight, D. M., Boyer, E. W., Westerhoff, P. K., Doran, P. T., Kulbe, T., and Andersen, D. T.: Spectrofluorometric characterization of dissolved organic matter for indication of precursor organic material and aromaticity, Limnol. Oceanogr., 46, 38–48, 2001. doi:10.4319/lo.2001.46.1.0038.

Miao, Y.Q.: Net ecosystem carbon fluxes of peatland in the continuous permafrost zone, Great Hinggan Mountains. Dissertation. University of Chinese Academy of Sciences. pp, 120, 2014. (in Chinese)

Moody, C.S., Worrall, F., Burt, T.P.: Identifying DOC gains and losses during a 20-year record in the Trout Beck catchment, Moor House, UK, Ecol. Indic., 68, 102–114, 2016.

Moody, C.S., Worrall, F., Evas, C.D., Jones, T.G.: The rate of loss of dissolved organic carbon (DOC) through a catchment, J. Hydrol., 492, 139–150, 2013.

Ohno, T.: Fluorescence inner-filtering correction for determining the humification index of dissolved organic matter, Environ. Sci. Technol., 36, 742–746, 2002.

O’Donnell, J. A., Aiken, G. R., Kane, E. S., Jones, J. B.: Source water controls on the character and origin of dissolved organic matter in streams of the Yukon River basin, Alaska, J. Geophys. Res., 115, G03025, doi:10.1029/2009JG001153, 2010.

Olefeldt, D., Roulet, N.T.: Effects of permafrost and hydrology on the composition and transport of dissolved organic carbon in a subarctic peatland complex, J. Geophys. Res., 117, G01005, doi:10.1029/2011JG001819, 2012.

Opsahl, S., Benner R., Amon R. M. W.: Major flux of terrigenous dissolved organic matter through the Arctic Ocean, Limnol. Oceanogr., 44, 2017–2023, 1999.

Park, Y.S., Engel, B.A., Frankenberger, J., Hwang, H.: A-web-based tool to estimate pollutant loading uing LOADEST, Water, 7, 4858-4868, 2015. doi:10.3390/w7094858.

Petrone, K.C., Jones, J.B., Hinzman, L.D., Boone, R.D.: Seasonal export of carbon, nitrogen, and major solutes from Alaskan catchments with discontinuous permafrost, J. Geophys. Res., 111, G02020, doi:10.1029/2005JG000055, 2006.

Petrone, K.C., Hinzman, L.D., Shibata, H., Jones, J.B., Boone, R.: The influence of fire and permafrost on sub-arctic stream chemistry during storms, Hydrol. Process., 21, 423–434, 2007. doi:10.1002/hyp.6247.

Prokushkin, A.S., Pokrovsky, O. S., Shirokova, L.S., Korets, M.A., Viers, J., Prokushkin, S.G., Amon, R. M. W., Guggenberger, G., McDowell, W.H.: Sources and the flux pattern of dissolved carbon in rivers of the Yenisey basin draining the Central Siberian Plateau, Environ. Res. Lett., 6, 045212, 2011. doi:10.1088/1748-9326/6/4/045212.

Prokushkin, A.S., Gleixner, G., McDowell, W.H., Ruehlow, S., Schulze, E.D.: Source and substrate-specific export of dissolved organic matter from permafrost-dominated forested watershed in central Siberia, Global Biogeochem. Cy., 103, 109–124, 2007.

Räike, A., Kortelainen, P., Mattsson, T., David N. Thomas, D. N.: 36 year trends in dissolved organic carbon export from Finnish rivers to the Baltic Sea, Sci. Total Environ., 435–436, 188–201, 2012.

Sebestyen, S.D., Boyer, E.W., Shanley, J.B., Kendall, C., Doctor, D.H., Aiken, G.R., Ohte, N.: Sources, transformations and hydrological processes that control stream nitrate and dissolved organic matter concentrations during snowmelt in an upland forest, Water Resour. Res., 44, W12410, 2008. doi:10.1029/2008WR006983.

Spencer, R. G. M., Aiken, G. R., Wickland, K. P., Striegl, R. G., Hernes, P. J.: Seasonal and spatial variability in dissolved organic matter quantity and composition from the Yukon River basin, Alaska, Global Biogeochem. Cycles, 22, GB4002, doi:10.1029/2008GB003231, 2008.

Spencer, R.G., Mann, P.J., Dittmar, T., Eglinton, T.I., McIntyre, C., Holmes, R.M., Zimov, N., Stubbins, A.: Detecting the signature of permafrost thaw in Arctic rivers, Geophys. Res. Lett., 2015, 42(8), 2830–2835.

Striegl, R. G., Aiken, G. R., Dornblaser, M. M., Raymond, P. A., Wickland, K. P.: A decrease in discharge-normalized DOC export by the Yukon River during summer through autumn, Geophys. Res. Lett., 32, L21413. DOI:10.1029/2005GL024413, 2005.

Striegl, R. G., Dornblaser, M. M., Aiken, G. R., Wickland, K. P., Raymond, P. A.: Carbon export and cycling by the Yukon, Tanana, and Porcupine rivers, Alaska 2001–2005, Water Resour. Res., 43, W02411, doi:10.1029/2006WR00, 2007.

Tetzlaff, D., Birkel, C., Dick, J., Geris, J., Soulsby, C.: Storage dynamics in hydropedological units control hillslope connectivity, runoff generation, and the evolution of catchment transit time distributions, Water Resour. Res., 50, 969–985, 2014. doi:10.1002/2013WR014147.

Townsend-Small, A., McClelland, J. W., Max Holmes, R., Peterson, B. J.: Seasonal and hydrologic drivers of dissolved organic matter and nutrients in the upper Kuparuk River, Alaskan Arctic, Biogeochemistry, 103,109–124, 2011.

Tunaley, C., Tetzlaff, D., Lessels, J., Soulsby, C.: Linking highfrequency DOC dynamics to the age of connected water sources, Water Resour. Res., 52, 5232–5247, 2016.

Vonk, J.E., Mann, P.J., Davydov, S., Davydova, A., Spencer, R.G.M., Schade, J., Sobczak, W.V., Zimov, N., Zimov, S., Bulygina, E., Eglinton, T.I.: High biolability of ancient permafrost carbon upon thaw, Geophys. Res. Lett., 40, 2689–2693, 2013.

Walvoord, M. A., Striegl, R. G.: Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen, Geophys. Res. Lett., 34, L12402, 2007. doi:10.1029/2007GL030216.

Yates, C.A., Johnes, P.J., Spencer, R. G. M.: Assessing the drivers of dissolved organic matter export from two contrasting lowland catchments, U.K, Sci. Total Environ., 569–570, 1330–1340, 2016.

**Table 1.** Results of covariance analysis (ANCOVA) between discharge and the DOC concentrations for the three years.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Source** | **Sum of squares** | **df** | **Mean squares** | **F.** | **Sig.** |
| Corrected model | 2895.334 | 3 | 965.111 | 41.213 | 0.000 |
| Log10Q | 2026.994 | 1 | 2026.994 | 86.559 | 0.000 |
| Year | 303.294 | 2 | 151.647 | 6.476 | 0.002 |
| Error | 2294.932 | 98 | 23.418 |  |  |

DOC concentrations and log10Q are dependent variable and covariate respectively; Year denotes fixed factor; Adjusted mean annual concentrations for the three years are 15.25±0.88, 18.32±0.84, and 14.22±0.81 mg L-1 in turn.

**Table 2.** Mean DOC loads, concentrations and yields estimated by LOADEST program

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Period** | **Load (Kg)**  ***SE*** | | | **Concentration (mg L-1)**  ***CV (%)*** | | | **Yield (g m-2)**  ***SE*** | | |
| 2012 | 2013 | 2014 | 2012 | 2013 | 2014 | 2012 | 2013 | 2014 |
| May  June  July  August  September  Annual | 1388  *161*  5917  *619*  3372  *268*  9385  *982*  8788  *870*  6092  *423* | 66502  *7479*  3728  *235*  12228  *1261*  14475  *1394*  3875  *471*  19022  *1521* | 4238  *194*  3574  *164*  4056  *191*  2194  *95*  1977  *106*  3211  *89* | 9.00  *39.3*  16.53  *30.4*  14.08  *26.9*  13.35  *48.1*  11.12  *48.3*  13.26  *38.6* | 35.49  *25.2*  17.92  *26.0*  16.76  *19.6*  16.14  *49.8*  13.49  *26.7*  19.57  *29.4* | 15.04  *30.5*  15.88  *16.4*  15.02  24.0  11.32  *12.7*  10.09  *11.3*  13.48  *19.0* | 0.08  *0.009*  0.62  *0.02*  0.36  *0.09*  1.01  *0.03*  0.77  *0.03*  2.84  *0.18* | 6.02  *0.13*  0.39  *0.07*  1.32  *0.04*  1.56  *0.15*  0.38  *0.03*  9.68  *0.38* | 0.40  *0.06*  0.37  *0.07*  0.44  *0.07*  0.24  *0.03*  0.19  *0.03*  1.64  *0.26* |

**Table 3.** Correlation analysis of the three fluorescence indexes with hydrological and climatic factors.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | DOC | Q | Conductivity | Turbidity | Tair | Tsoil |
| HIX Pearson  Sig. (2-tailed)  n | 0.708\*\*  0.000  92 | 0.609\*  0.000  92 | 0.451\*\*  0.005  68 | −0.592\*\*  0.000  68 | 0.342  0.115  92 | 0.395\*  0.02  92 |
| FI Pearson  Sig. (2-tailed)  n | −0.594\*\*  0.000  92 | −0.606\*\*  0.000  92 | −0.477\*\*  0.004  68 | 0.469\*\*  0.001  68 | 0.353  0.203  92 | 0.389  0.128  92 |
| BIX Pearson  Sig. (2-tailed)  n | −0.64\*\*  0.001  92 | −0.707\*\*  0.000  92 | −0.488\*\*  0.001  68 | 0.322\*  0.012  68 | −0.027  0.823  92 | 0.384  0.129  92 |

DOC is dissolved organic carbon; Q is stream discharge; Tair is the average air temperature over the past three days; Tsoil is the average soil temperature of the active layer; “\*\*” denotes p< 0.01; “\*” denotes p< 0.05

**Table 4.** Results of covariance analysis (ANCOVA) between discharge and the fluorescence indexes for the three years.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Index** | **Source** | **Sum of squares** | **df** | **F.** | **Sig.** |
| HIX | Log10Q | 296.045 | 1 | 70.315 | 0.000 |
| Year | 9.318 | 2 | 1.107 | 0.335 |
| FI | Log10Q | 0.097 | 1 | 63.490 | 0.000 |
| Year | 0.007 | 2 | 2.128 | 0.125 |
| BIX | Log10Q | 0.084 | 1 | 86.098 | 0.000 |
| Year | 0.004 | 2 | 1.850 | 0.163 |

The indexes, HIX, FI, and BIX, are set as dependent variables; log10Q are covariate; Year denotes fixed factor.

tu2

**Russia**

Amur River

**Mongolia**

**China**



Continuous permafrost

Discontinuous permafrost

Island-patched permafrost

Peatland

Soil pore water sampling point

Meteorology/water level gauging point

River sampling profile

N 53.06

E123.03



**A**

**B**

north



10 km

N 52.94

E122.87



**Fig. 1** Geographic location of the study area



Thaw depth (cm) Water level (cm) Air temperature (℃)

Precipitation (mm)



****

**Fig. 2** Dynamics of air temperature, precipitation, standing water levels, and thaw depth observed during the growing seasons of 2012 to 2014.



DOC concentration (mg L-1)

Q (106 m3 d-1)

**Fig. 3** Dynamics of dissolved organic carbon (DOC) concentrations and discharge observed during the growing seasons of 2012 to 2014. The discharge (Q) unit used is 106 m3 d-1.



Log10Q (Q, m3)

DOC concentration (mg L-1)

**Fig. 4** Relationships between discharge and the DOC concentrations for the three in years.



HIX



FI

Q (106 m3 d-1)



BIX

**Fig. 5** Dynamics of the three spectral indexes following discharge during the growing seasons.



Log10Q (m3 d-1)

**Fig. 6** Relationships between discharge and the three indexes during the study period.



δ18O (‰)

Rainfall (mm)



Q (106m3d-1)

δ18O (‰)

**Fig. 7** Dynamics of stable isotope oxygen values for rainfalls, discharge and soil pore water in the catchment. The discharge (Q) unit used is 106 m3 d-1.



DOC concentration (mg L-1)

Soil depth (cm)

25th Aug

30th Jun

8th Jun

27th Jul

Organic soil

Mineral soil

**Fig. 8** DOC concentrations in soil pore water along the soil profile for 2013.

HIX FI BIX



Soil depth (cm)

Organic soil

Mineral soil

**Fig. 9** Vertical distribution of the three spectral indexes for soil pore water along the soil profile for 2013.