Assessment of sediment and organic carbon exports into the Arctic ocean: The case of the Yenisei River basin

C. Fabre [a, *], S. Sauvage [a], N. Tananaev [b, c], G. Espitalier Noël [a], R. Teisserenc [a], J.L. Probst [a], J.M. Sánchez Pérez [a, **]

[a] EcoLab, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France
[b] P.I. Melnikov Permafrost Institute, SB RAS, 677010, Merzlotnaya Str. 36, Yakutsk, Russia
[c] Ugra Research Institute of Information Technologies, 628011, Khanty-Mansiysk Mira Str. 151, Russia

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A B S T R A C T

The export of organic carbon export by the rivers to the oceans either as particulate organic carbon (POC) or dissolved organic carbon (DOC) is very sensitive to climate change especially in permafrost affected catchments where soils are very rich in organic carbon. With global warming, organic carbon export in both forms is expected to increase in Arctic regions. It should affect contemporary biogeochemical cycles in rivers and oceans and therefore modify the whole food web. This study tries to understand complex processes involved in sediment, POC and DOC riverine transport in the Yenisei River basin and to quantify their respective fluxes at the river outlet. The SWAT (Soil and Water Assessment Tool) hydrological model is used in this study to simulate water and suspended sediment transfers in the largest Arctic river. POC and DOC export have been quantified with empirical models, adapted from literature for the study case. First, the hydrological model has been calibrated and validated at a daily time step for the 2003 2008 and the 2009 2016 periods respectively, and its output has been compared with field data for water and sediment fluxes. Based on conceptualization of transfer processes, calibration on climate and soil properties has been performed in order to correctly represent hydrology and sediment transfer in permafrost basins. Second, calibration of empirical models for DOC/POC transport have been performed by comparing their output with field data, available from 2003 to 2016. Our study reveals that SWAT is capable of correctly representing hydrology, sediment transfer, POC and DOC fluxes and their spatial distribution at a daily timescale, and outlines the links between these fluxes and permafrost features. Our simulation effort results in specific sediment, POC and DOC fluxes of 2.97 t km ^{2} yr ^{1}, 0.13 t km ^{2} yr ^{1} and 1.14 t km ^{2} yr ^{1} for the period 2003 2016 which are in the range of previous estimates. About 60% of the total fluxes of sediment, DOC and POC to the Arctic Ocean are exported during the two months of the freshet. Spatial analysis show that permafrost free areas have returned higher daily organic carbon export than permafrost affected zones, highlighting the thawing permafrost effect on carbon cycle in climate change feedback.

1. Introduction

The Arctic is already affected by climate change which is advancing faster than in mid latitudes (Serreze and Barry, 2011; Ciais et al., 2013) and this tendency is expected to continue in the future. Arctic surface temperatures have never been higher than during the 3 past centuries (Moritz et al., 2002; Johannessen et al., 2004; Chapin et al., 2005; Kaufman et al., 2009; Cohen et al., 2012). After a relative stability in the temperature anomalies from 1900 to 1980, an increase of ca. 2 °C of annual surface air temperature in the Arctic region from 1980 to 2010 has been observed (Overland et al., 2017). Mean annual ground temperatures have been rising for several decades (Romanovsky et al., 2010), resulting in the deepening of the active layer (e.g. Anisimov et al., 1997) and intensification of geomorphological processes (Knight and Harrison, 2012). Air temperature rise may drive increased sediment input to the Arctic Ocean through higher rates of fluvial thermal erosion,

* Corresponding author.
** Corresponding author.
E-mail addresses: clement.fabre@ensat.fr (C. Fabre), jose.sanchez@univ-tlse3.fr (J.M.S. Pérez).

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increased sediment supplies from thaw slumps and other mass movement processes (Syvitski, 2002; Goudie, 2006; Costard et al., 2007).

Suspended sediment fluxes to the Arctic Ocean are estimated from 0.23 Gt at the lower end (Ludwig and Probst, 1998; Gordeev, 2006) to 0.35 Gt (Overeem and Syvitski, 2008) and 0.33–0.89 Gt at the upper end, of which no more than 63% can be considered as observed (Hasholt et al., 2006). The largest Arctic rivers have relatively low sediment load, but its overall increase of 32% is expected for each 2 °C of basin warming, runoff and sediment transport effects combined (Syvitski, 2002). The latter may involve into fluvial turnover and geochemical cycling a significant quantity of eroded material, including carbon stored in permafrost soils (Koven et al., 2011).

Permafrost stores an enormous pool of approx. 1030 Gt of ancient soil organic carbon in the first 3 m (Kuhry et al., 2013; Hugelius et al., 2014), preferentially consumed by bacteria to produce climate relevant gases when released to streams (Mann et al., 2015). Permafrost degradation has the potential to significantly influence terrestrial carbon exports to global rivers (Olefeld and Roulet, 2014), therefore potential release of ancient carbon from frozen soils constitutes a major concern.

Riverine organic carbon is commonly subdivided into three categories based on its origin (Hope et al., 1994): an allochthonous pool derived from terrestrial organic matter (soil leaching and physical erosion); an autochthonous pool derived from in situ biological production (phytoplankton); and an anthropogenic pool derived from agricultural, domestic and industrial activities (diffuse pollution and waste effluents). Organic carbon (OC) in stream waters is present in both dissolved (DOC) and particulate (POC) forms. POC and DOC originate from either catchment surface, bank and channel erosion. From 10 to 50% of POC and from 3 to 35% of DOC is labile which means it is subjected to various processes in the fluvial, estuarine and coastal marine environment like assimilation, mineralization or sedimentation (Ittekkot and Laane, 1991; Søndergaard and Middelboe, 1995; Cole et al., 2007; Holmes et al., 2008). On the one hand, POC concentrations vary with total suspended solids (TSS). The POC percent in the TSS is decreasing when the concentration of TSS is rising in the river as it has already been shown at a global scale in Ludwig et al. (1996). When the TSS concentration is low in the river, the riverine POC is linked to the autochthonous pool detailed before. The rise of TSS is generally due to erosion which implies a substitution of the main source of POC from the autochthonous to the allochthonous part. On the other hand, DOC concentrations increase with discharge (Ludwig et al., 1996) due to its transport by surface and subsurface water flows.

Global organic carbon flux to the ocean is estimated to be 300 TgC yr^{-1}, with a contribution of 140 TgC yr^{-1} and 160 TgC yr^{-1} for POC and DOC respectively (Seitzinger et al., 2010). Previous estimates range between 370 and 380 TgC yr^{-1} (Meybeck, 1988; Ludwig et al., 1996). In the Arctic ocean basin, DOC fluxes exceed those of POC, with 18–28 TgC yr^{-1} against 4–7 TgC yr^{-1} (Ludwig et al., 1996; Dittmar and Kattner, 2003; McClelland et al., 2016). The difference in the POC/DOC ratio is related to soil properties, with the presence of permafrost, restricting surface erosion. Better understanding of organic carbon origin and pathways in permafrost affected catchments will allow more accurate evaluations of potential impact of deeper active layers on sediment and organic carbon exports (Prokushkin et al., 2011).

Organic carbon concentrations in Arctic rivers follow the discharge with maximum values in spring during the high flows period (Dittmar and Kattner, 2003). Indeed, melting water percolates to join the river and is strongly enriched in organic compounds. Annual average DOC concentrations in Arctic rivers range between 2.8 and 12 mgC L^{-1} (Lobbes et al., 2000; Kohler et al., 2010; Amon et al., 2012). They are 1.3–28 times higher than POC concentrations (Lobbes et al., 2000) except for the Mackenzie River where POC and DOC concentrations are comparable. The Yenisei River presents the biggest flux of DOC to the Arctic Ocean. This flux represents 4.64–4.69 TgC yr^{-1} (Raymond et al., 2007; Holmes et al., 2012) while the POC export reaches only 0.17 TgC yr^{-1} (Lobbes et al., 2000). The POC fraction is found to be consistently older than DOC in major Arctic rivers (Guo et al., 2007; Gustafsson et al., 2011).

Carbon transfer in periglacial fluvial systems is complex because of freeze thaw processes. Only the seasonally thawed part of permafrost soil, or active layer, i.e. from first tens to several meters, is exposed to biogeochemical activity (Zhang et al., 2005; Schuur et al., 2008). The DOC transfer in soils is mainly possible through the thawed layer, while POC may originate from older stocks of glacial or floodplain sediment. In permafrost regions, 20%–60% of the organic carbon is stored in peatlands while 1%–20% is stored in mineral soils and its stock totals 472 ± 27 PgC (Hugelius et al., 2014) in the first meter of soil.

Numerous models have been used in past researches to simulate permafrost hydrology. (Fabre et al., 2017). The TOPMODEL, a surface runoff model, has shown its limits for small to the largest Arctic watersheds by omitting lateral and groundwater flow (Stieglitz et al., 2003; Finney et al., 2012). The Topoflow model is especially developed for Arctic catchments and has shown correct modeling for Arctic systems but it seems hard to use for the largest Arctic catchments as it requires a lot of data for calibration and does not take into account soil properties at different depths (Schramm et al., 2007). The Hydrograph model has been used at small and very large scale in numerous studies (Vinogradov et al., 2011). This model estimates the heat fluxes and permafrost hydrology with good accuracy at a stand scale (Gusev et al., 2010), but its applicability is limited by a randomization of the spatial distribution of model parameters which complicate large scale studies. The RiTHM model which is an adaptation of the MODCOU model, has returned a modeled permafrost hydrology estimated with low accuracy (Ducharne et al., 2003). Nohara et al. (2006) have performed a simulation on different catchments in the world including some Arctic watersheds with the TRIP tool, a model which uses the velocity of water for major calculations. This model does not integrate human impacts on the water cycle (e.g., dams) and does not include essential parameters for Arctic systems studies such as evaporation and sublimation module. The LMDZ model has been applied to some of the northernmost basins in the world including the Yenisei River (Alkama et al., 2006). This model handles snowmelt but does not consider percolation processes, which inhibit the conceptualization of permafrost soils. In a same way, the SDGVM tool has been used in a multi model analysis on various watersheds (Yang et al., 2015). This model has been developed for plant growth optimization but is able to calculate runoff. It has returned same difficulties to model permafrost hydrology. In this way, most of these models have returned bad detections of the freshets after ice melting and does not include TSS export simulations which are essential for our study. For those which include TSS export, they generally need a lot of inputs uneasy to measure or to calculate and they often do not integrate a spatial and a temporal variability in the outputs which is imperative for this study and more widely in large scale studies (de Vente and Poesen, 2005).

Concerning modeling efforts on sediment and organic carbon transfers, only few models have been performed in Arctic watersheds since the processes involved are relatively poorly documented (Parmentier et al., 2017). Several models have been previously used in suspended sediment transfer modeling in Arctic regions, either simple rating curve models (Chikita et al., 2007) or climate based empirical equations (Syvitski, 2002). A recent simulation effort has been employed a coupled SWAT/USLE model to show a significant sediment load increase across the Northeast China region (Zhou et al., 2017). The relation between suspended load and POC has been modeled on a global scale by Ludwig et al. (1996) for large rivers at global scale, by McClleland et al. (2016) for big Arctic rivers, by Martins and Probst (1991) for major African rivers and by Boithias et al. (2014) for specific agricultural watersheds. The data on sediment loads and its POC fraction in Arctic streams are scarce, and almost no data are available for the ice free period, when the organic carbon fluxes are the greatest (Dittmar and Kattner, 2003). Similarly, the DOC modeling efforts are mostly based on previous observations and imply regression analysis, e.g. LOADEST estimator (Stubbins et al., 2015; Tank et al., 2016), or physiography driven models (Ludwig et al., 1996) in place of complex integrated models. Hence, there is an enormous knowledge gap in the modeling of sediment and POC/DOC fluxes in high latitude catchments using physically based dynamic models at daily timestep. The Soil and Water Assessment Tool (SWAT) has allowed us to cross all the obstacles revealed by the previous modeling efforts. Its capability to simulate water and sediment fluxes at a daily time step (Douglas Mankin et al., 2010; Krysanova and White, 2015) is an important advantage to detect the freshets in Arctic systems (Fabre et al., 2017) and it has already shown its potential to study daily organic carbon exports (Oeurng et al., 2011).

This work aims to understand, quantify and model the contemporary fluxes of suspended sediment and organic carbon, in both dissolved and particulate forms, at the scale of the largest Siberian watershed using a hydrological model. The major objectives set for this study include: (a) analyzing spatial variability of sediment and carbon pathways across different water regime phases, i.e. ice free vs ice covered channel periods, (b) quantifying daily suspended sediment, POC and DOC fluxes at the Yenisei River outlet; and, finally, (c) assessing SWAT capabilities to capture permafrost variability across subcatchments.

2. Materials and methods

2.1. Study area

The Yenisei River basin is the seventh largest watershed on Earth and the largest in the basins drained by the Arctic Ocean with a catchment area of 2,540,000 km^2 (Amon et al., 2012). It is the fifth longest river in the world (4803 km; Amon et al., 2012) with the sixth biggest discharge at the outlet (Ludwig et al., 1996; Raymond et al., 2007; Holmes et al., 2012; Amon et al., 2012). The main stream comes from Western Sayan Mountains (Southern Siberia) and passes through all Central Siberia going to the North and flows into the Kara Sea (Fig. 1; Amon et al., 2012). Its largest tributary, the Angara River, comes from Mongolia and is fed by the Lake Baikal, the biggest fresh water reserve on Earth (Lake Baikal, UNESCO). It plays the role of an enormous reservoir sustaining water flows during the frozen period with an average discharge of 3000 m^3 s^{-1} by the Irkutsk hydropower station downstream. The average discharge at the outlet approaches 20,000 m^3 s^{-1} with peaks higher than 100,000 m^3 s^{-1} and with low flows around 6000 m^3 s^{-1} mainly sustained by releases of dams (Fig. 1; Holmes et al., 2012).

The Yenisei River watershed is typically divided in three geographically distinct regions: mountainous headwater area at the southern limit of the watershed, a relatively plain area of boreal forest in its central and northern parts, and the Central Siberian Plateau in its northernmost large tributary basin, the Nizhnyaya Tunguska River (Fig. 1). The mean elevation is 670 m and the average slope is 0.2% (Amon et al., 2012).

Regarding the soil distribution, the southern and central parts of the Yenisei watershed are dominated by Podzoluvisols, Cambisols

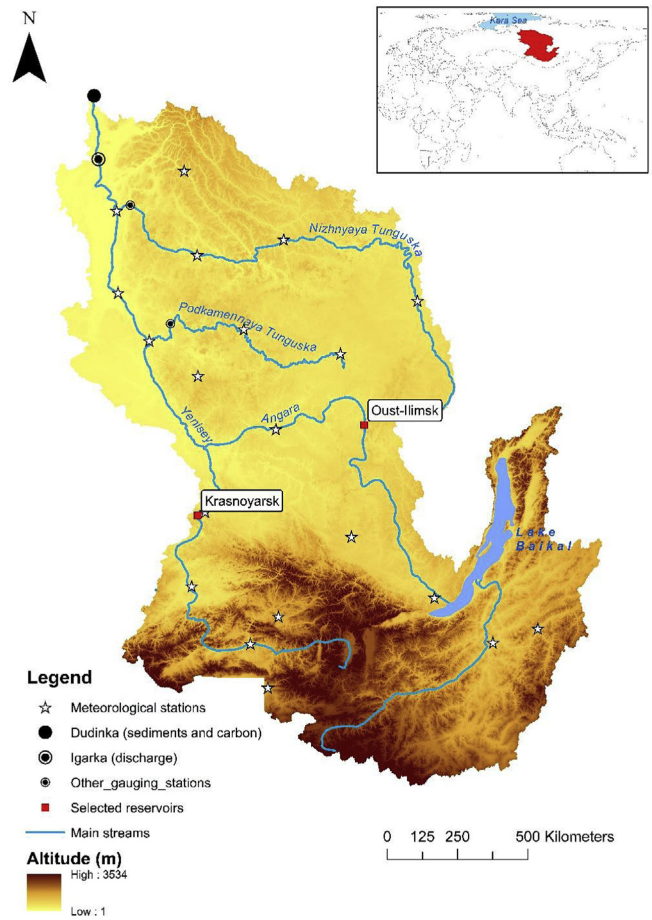

Fig. 1. Topography, main streams of the Yenisei River watershed from its sources to the Dudinka sampling station using a digital elevation model from de Ferranti and Hormann (2012). Meteorological stations from VNIIGMI-MCD (see Table 1), and sampling site for sediment and organic carbon from Arctic-GRO (https://arcticgreatrivers.org/).

and Podzols while Cryosols and Gleysols cover the largest area in the northern parts (Fig. 2a; Amon et al., 2012). Concerning land use, the boreal forest mostly represented by coniferous called taiga is dominant along the watershed (Fig. 2b). A lag time for snowmelt due to the forest dominance should be taken into account in the conceptual model as in these hydrosystems, the melting processes are slowed by the snowpack density. Around 90% of the Yenisei River watershed is covered by permafrost (Fig. 2c; Zhang et al., 1999) distributed as follows: 34% of continuous permafrost, 11% of discontinuous permafrost and 45% of sporadic and isolated permafrost (Fig. 2c; McClelland et al., 2004).

The watershed outlet in the modeling has been established near Dudinka (69°26′17″N 86°04′47″E; Fig. 1). It is the place where the TSS, POC and DOC concentrations have been sampled by the PARTNERS project and the Arctic Great Rivers Observatory (Arctic GRO; https://arcticgreatrivers.org/). This city has been chosen since the very beginning of the PARTNERS project because it was easier to communicate and make arrangements with Dudinka hydrologists, independent from Krasnoyarsk authorities, than with Igarka hydrologists. Daily discharges as well as samples of sediment and organic carbon from the TOMCAR Permafrost project have been measured upstream at Igarka (67°27′55″ N, 86°36′09″ E; Fig. 1).

Several physiographical and hydraulic characteristics of this watershed have made our modeling more difficult. Firstly, uneven permafrost distribution across the watershed forces to implement

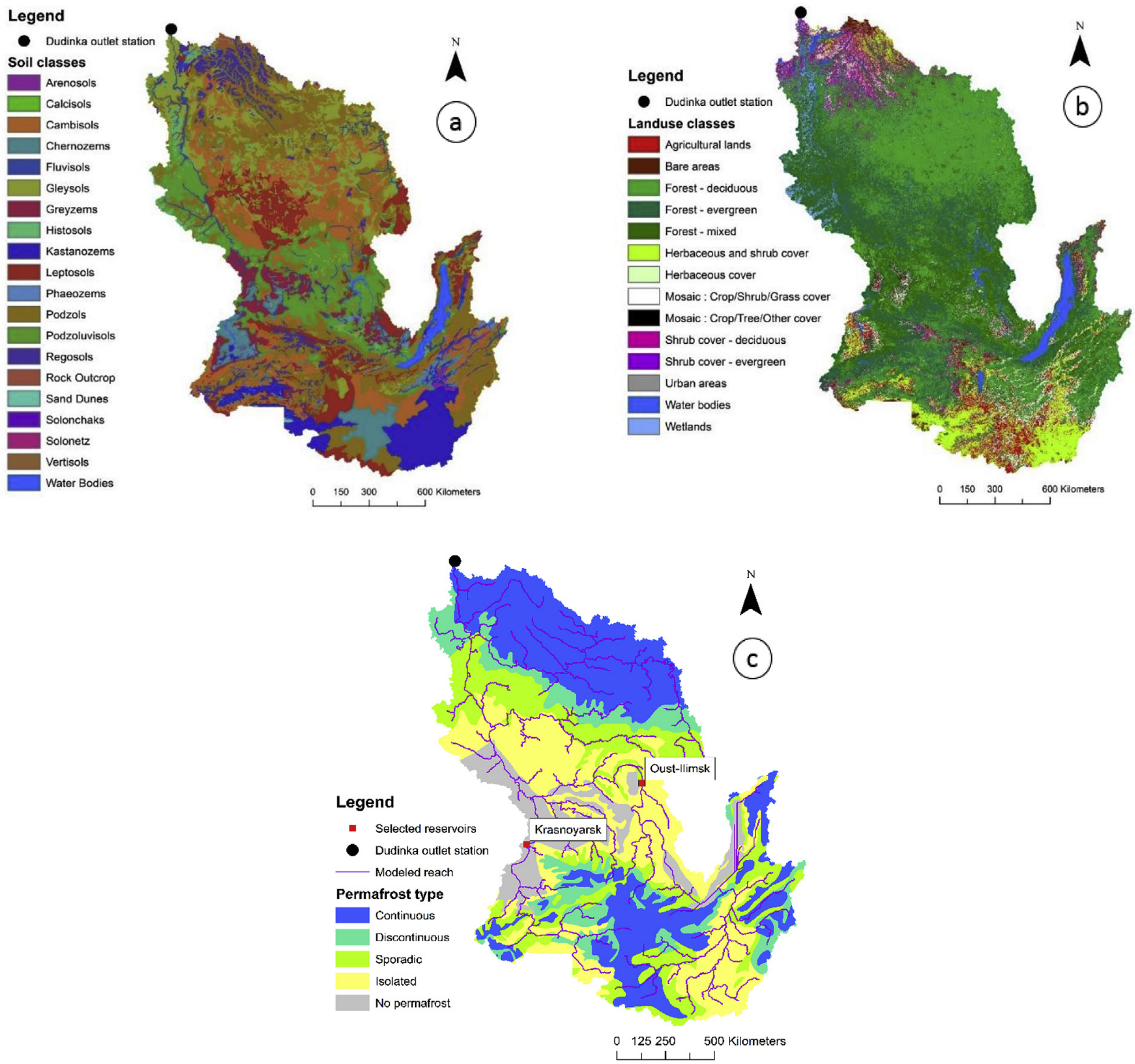

Fig. 2. Soils, land use and permafrost distribution along the Yenisei River watershed. (a) Soils distribution based on the Harmonized World Soil Database at a 1 km resolution (FAO et al., 2009). (b) Land use distribution from the Global Land Cover 2000 Database at a 1 km resolution (European Commission, 2003). The forest classes correspond to the tundra distribution. The shrub cover classes correspond to the taiga; (c) Model adaptation of the Yenisei River watershed and permafrost extent. The GIS map extracted from the National Snow and Ice Data Center (NSIDC) classifies permafrost types as the percentage of extent: continuous (90 100%), discontinuous (50 90%), sporadic (10 50%) and isolated (0 10%) (classification based on Brown et al., 2002). . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

different modeling strategies for the sub basins depending on permafrost types. Secondly, hydropower generation is an important activity in the Yenisei River, related to metallurgy which is highly energy consumptive. Seven large dams have been constructed on the Yenisei and the Angara rivers in the 1960s and 1970s.

2.2. Model choice

SWAT is a hydro agro climatological model developed by USDA Agricultural Research Service (USDA ARS; Temple, TX, USA) and Texas A&M AgriLife Research (College Station, TX, USA; Arnold et al., 1998). SWAT is firstly designed to predict impacts of human activities management on water, sediment and agricultural chem ical yields in ungauged catchments and can provide continuous simulations for dissolved and particulate elements (Arnold et al., 1998). Its performance has already been tested at multiple catch ment scales in various climatic and soil conditions on hydrology but also on water chemistry especially TSS and nitrogen exports (Schuol et al., 2008; Douglas Mankin et al., 2010; Kuzin et al., 2010; Faramarzi et al., 2013; Krysanova and White, 2015 and references therein). Importantly, both the SWAT model and the ArcSWAT interface are open–source and free, allowing reproducibility of the results once the input data are well–documented (Olivera et al., 2006). The SWAT model has already been tested in Arctic systems (Krysanova and White, 2015; Hülsmann et al., 2015) and revealed its capability to accurately represent permafrost hydrology (Fabre et al., 2017). Theory and details of hydrological processes inte grated in SWAT model are available online in the SWAT docu mentation (http://swatmodel.tamu.edu/).

This study uses the SWAT model to simulate hydrology, sedi ment and organic carbon export of a permafrost watershed including hydropower stations. SWAT uses small calculating units, called Hydrological Response Units (HRUs), homogeneous in terms of land use and soil properties (Flügel, 1995). The SWAT system coupled with a geographical information system (GIS) engine integrates various spatial environmental data, including soil, land cover, climate and topographical features. The SWAT model allows the management soils types and properties. It decomposes the water cycle and returns the water pathways and other information on the water cycle in the studied watershed.

2.3. SWAT data inputs

An overview of the inputs data is given in Table 1. The ArcSWAT software has been used in the ArcGIS 10.2.2 interface (http://www.esri.com/) to compile the SWAT input files. Coarse DEM resolution has been judged sufficient because of the large watershed size. The global soil map containing initially 6000 categories has been simplified into 36 categories by averaging their initial soil properties. The soils have been aggregated on their common structural properties. 20 soils categories have been covering the watershed. The meteorological inputs for SWAT (precipitation, temperature, average wind speed, solar radiation and relative humidity), essential for evapotranspiration calculation, have been extracted from 20 stations, unevenly distributed in the watershed (see Fig. 1 for station locations), and compared to a reanalyzed dataset (Climate Forecast System Reanalysis, http://rda.ucar.edu/pub/cfsr.html). The two datasets have been found in good agreement with each other, except for precipitations, hence this study used reanalyzed data for all meteorological parameters apart from precipitations where observation records have been kept.

2.4. Observed data

Daily discharge data at the Igarka gauging station from Arctic GRO (Shiklomanov et al., 2017) and at the exits of two reservoirs have been used (Roshydromet): one on the Yenisei River at Krasnoyarsk and one on the Angara River at Ust' Illimsk (Fig. 1). Concerning sediment and organic carbon, samples have been collected at Dudinka in the scope of PARTNERS and Arctic GRO I/II projects from 2003 to 2013 (Holmes et al., 2017) and have been completed by other samples at Igarka from 2014 to 2016 with the collaboration of the TOMCAR Permafrost project (Herrault et al., 2016; Le Dantec, 2018). All of the databases and publications of the Arctic GRO projects as well as the details on the sampling protocols are freely available online (Table 1; https://arcticgreatrivers.org/). The TOMCAR Permafrost project has followed the same protocols as the Arctic GRO projects. A low number of data is available during the break up as the sampling is dangerous and difficult in these regions. Most of the sampling have been done during the ice free and the freezing periods from June to December but the TOMCAR Permafrost project has filled the gap on the exports of sediment and organic carbon during the freshet of the Yenisei River.

2.5. Conceptualization

The conceptual model used in this study is based on snow and freeze/thaw soil behavior depending on the season as shown in Fabre et al. (2017). During winter, the stability of the snowpack and the soil freezing sustain low fluxes of organic carbon. An increase in temperature induces a rapid snowmelt leading to a strong surface runoff and a freshet during few days. A subsurface flow comes with the surface flow due to a first unfreezing of the superficial soil layers. Sediment and organic carbon fluxes follow the freshet dynamic. In a third time, during the recession, the thawed layer reaches its maximal depth called active layer resulting in a balance between surface and subsurface flows. The last period shows the thawed layer freezing from both the top and the bottom while the snow starts to accumulate. Only lateral flow is possible by a piston effect which could engender DOC fluxes but TSS and POC fluxes should be reduced accordingly.

The catchment has been discretized into 257 sub basins. These sub basins have been further divided into 3158 HRUs from a combination of 14 land uses, 20 soils and three slopes classes (0–1, 1–2, and >2%).

The discharge peak occurring in May is mostly due to the snowpack melt. Snowfall must be aggregated and should stay in the subbasin until the snowmelt period so the snowpack can be modeled big enough to sustain the spring freshet. It is assumed that the annual average ratio rainfall/snowfall is 60/40 (Su et al., 2006). The low number of available meteorological stations for precipitations data should be taken into account to respect this ratio. Indeed, the highest station is at 1100 m above sea level whereas the highest point in the Yenisei watershed is near 3500 m (Fig. 1). An elevation gradient should be integrated in the modeling to compensate the lack of data. Evapotranspiration based on Hargreaves and Samani (1985) equation and sublimation have also been calibrated based on past studies (Su et al., 2006; Gusev et al., 2010; Fukutomi et al., 2003) because of their influence in the water balance of Arctic catchments, ranging respectively between 36 and 50% of precipitations and between 4 and 20% of snowfall (Suzuki et al., 2015).

A very low groundwater contribution to streamflow should be considered in watersheds presenting permafrost soils. Groundwater flows are assumed to be low due to frozen soil conditions but have not been well studied in Arctic watersheds yet (Woo, 2012). The surface/subsurface flows ratio is depending on the variation of the thawed depth.

Permafrost behavior in the watershed has been conceptualized following an approach from Hülsmann et al. (2015). An impermeable boundary has been considered in the soil profile which should represent the active layer limiting by this way percolation in permafrost environments (Woo, 2012). More details about the

Table 1
SWAT data inputs and observations datasets.

Data Type	Observations		Source
Digital Elevation (DEM)		500 m	Digital Elevation Data (http://www.viewfinderpanoramas.org/dem3.html)
Soil		1 km	Harmonized World Soil Database v 1.1 (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/index.html?sb 1)
Land use		1 km	Global Land Cover 2000 database (http://forobs.jrc.ec.europa.eu/products/glc2000/products.php)
River network dataset		500 km	Natural Earth (http://www.naturalearthdata.com)
River discharge, TSS, POC and DOC samples	2003 2016	2 stations	Arctic Great Rivers Observatory (http://arcticgreatrivers.org/) TOMCAR-Permafrost (https://www.tomcar.fr/)
Reservoirs deliveries	2008 2016	2 stations	Roshydromet (https://gmvo.skniivh.ru/)
Meteorological data	1999 2016		Observed: Global center for meteorological data, VNIIGMI-MCD, Region of Moscou (http://aisori.meteo.ru/ClimateR) Simulated: Climate Forecast System Reanalysis (CFSR) Model (http://rda.ucar.edu/pub/cfsr.html & http://globalweather.tamu.edu/)

conceptualization of the Yenisei River basin water balance can be found in Fabre et al. (2017).

2.6. Equations used to model organic carbon release

To better understand the POC exports, the method used by the SWAT model to model sediment yield is detailed hereafter. The riverine sediment produced by physical soil erosion for each HRU is calculated in SWAT using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The MUSLE equation is calculating a sediment yield as followed:

$$TSS \quad 11.8 \, . \left(Q_{surf} \, . \, q_{peak} \, . \, area_{hru}\right)^{0.56} \, . \, K_{USLE} \, . C_{USLE} \, . \, P_{USLE} \, . \, LS_{USLE} \, . \, CFRG$$

where TSS represents the sediment yield per day in tons. ha^{-1}, Q_{surf} is the surface runoff volume (mm. ha^{-1}), q_{peak} is the peak runoff rate (m^3. s^{-1}), $area_{hru}$ is the HRU area in ha, K_{USLE} is the USLE soil erodibility factor, C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topo graphic factor and CFRG is the coarse fragment factor. The equation is based on the runoff in a HRU and on specific factors dependent on the soil and land use properties. Details of the USLE equation factors can be found in Neitsch et al. (2005). The TSS concentration is ob tained from the river sediment yield. The fluvial transport of sedi ment in the channel is controlled by two simultaneous processes: deposition/sedimentation and re suspension/erosion. The MUSLE equation has already shown its capability to predict sediment yield in various watersheds (Douglas Mankin et al., 2010; Krysanova and White, 2015). The advantages of using this equation integrated in SWAT are that it allows spatial and temporal variability in the resulting sediment yields by using few inputs data and without any measures on the field (Merritt et al., 2003; de Vente and Poesen, 2005). Here, we assume that the MUSLE equation is working in permafrost affected areas as it has never been tested in this type of watershed. However, the K_{USLE} parameter should allow the user to integrate the freezing effect in the erodibility.

To model the POC, the following relation with TSS is used as proposed by Boithias et al. (2014):

$$\%POC \quad \frac{9.40}{[TSS] \quad a} + b$$

where %POC is the part of POC in the TSS, [TSS] is in mg L^{-1}, a and b two parameters which have to be defined depending on the watershed (see details in Fig. 3). In the end, a specific POC flux (F_{POC}) is calculated. Thus, sediment exports have to be predicted correctly to model POC with accuracy. The reliability of this equa tion in another type of watershed has been statistically checked as shown in Fig. 3.

Concerning DOC modeling, we have adapted the Michaelis–Menten equation in this study (Johnson and Goody, 2011) to predict the DOC concentration ([DOC]) in milligrams per liter (mg L^{-1}) by correlating it with discharge (Q) as followed and as shown in Fig. 4:

$$[DOC] \quad \frac{\alpha * Q}{\beta + Q}$$

with Q in millimeters per day (mm d^{-1}). This equation underlines the need to well model discharge in order to obtain good results for DOC concentrations. α In mg L^{-1} represent the potential of the maximum DOC concentration we could find at the outlet of the watershed and β in mm d^{-1} the specific discharge at which the DOC concentration is half of α. They have been estimated based on observed data from the Arctic GRO sampling projects. The equation is calculating a daily average concentration and has for now been tested only at the basin outlet. We have made the hypothesis that the relation is valuable at the subbasin scale to see the spatializa tion of DOC concentrations in the watershed. The whole area the subbasin is draining is included in the calculation in order to obtain a hydrological unit similar to a watershed.

2.7. From concepts to modeling

The impervious boundary depth has been assigned as a function of permafrost type in each sub basin, based on active layer depth estimates (Zhang et al., 2005). By using remote sensing, the different average active layers' depths have been estimated with the annual thawing index. The conceptualized maximal depth of the active layer has been set to 800 mm, 1500 mm, 1750 mm and 2000 mm respectively for continuous, discontinuous, sporadic and isolated permafrost. The maximal depth to impervious layer parameter (DEPIMP) has been used to represent this concept. The approach used neglects the temporal variations of the thawed depth.

Parameters controlling the snow behavior (SMTMP, SFTMP, SMFMN, SMFMX, TIMP, SNO50COV, SNOCOVMX; see details of parameters role in Table 2) and depending on temperature have been calibrated, with literature for SNOCOVMX (Yang et al., 2007) and by expertise and auto calibration for the others, to separate rainfall and snowfall and to contain the snowpack on the lands before the massive snowmelt. As there is no meteorological station in high altitude, the precipitation lapse rate (PLAPS) parameter has been used to adapt precipitation to mountainous zones.

Evapotranspiration has been calibrated using measures from past studies with parameters that influence soil evaporation (ESCO) and water extracted from soils by the vegetation (CANMX). The parameters SLSOIL, LAT_TTIME and SURLAG have been used in or der to model the water volume flowing via surface and subsurface flows and the time lag they need to join the HRU outlet. For sedi ment exports, the parameter PRF_BSN has been used to reduce the impact of discharge peaks on erosion and hence on sediment ex ports while the USLE_K parameter (K_{USLE} in the equation above) has been calibrated gradually depending on the permafrost type to slow down erosion in the most frozen zones.

2.8. Model calibration and validation

The calibration and validation of the hydrology and the different components of the water balance have already been discussed in Fabre et al. (2017). The simulation has been performed from January 2003 to December 2016 (excluding a 4 yr warm up from January 1999 to December 2002). In this study, the calibration has been done manually based on Fabre et al. (2017) and expertise by com parison to observed data. Sediment and organic carbon exports have been calibrated at a daily time step compared to sparse data from January 2003 to December 2008 and validated from January

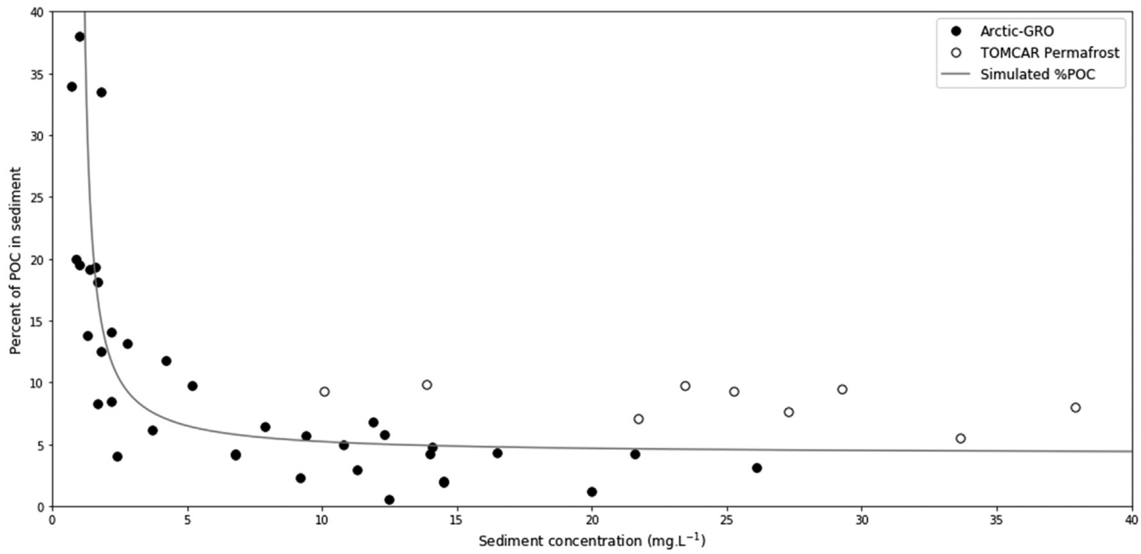

Fig. 3. Percent of particulate organic carbon present in the total suspended solids: observed and simulated values. The equation of Boithias et al. (2014) is applied to observed and simulated data on the Yenisei River catchment from datasets of the Arctic Great Rivers Observatory and the TOMCAR Permafrost project. The parameter *a* is the vertical asymptote corresponding to the organic matter the richest in organic carbon (OC; phytoplankton and residuals) and the parameter *b* corresponds to the horizontal asymptote representing the suspended matters with low OC concentration (near soils OC content). The root mean square error (RMSE) has been calculated to validate the fitting (RMSE = 0.0025).

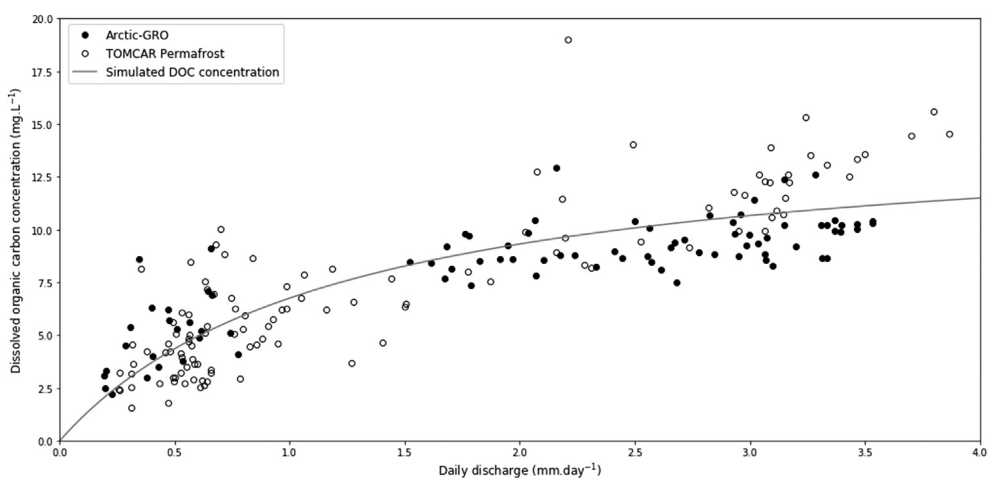

Fig. 4. Dissolved organic carbon concentration correlated with daily discharge: observed and simulated values. The correlation is based on the sampling performed on the Yenisei River by the Arctic Great Rivers Observatory and the TOMCAR Permafrost project during the period of study. The parameter α representing the horizontal asymptote correspond to the maximum dissolved organic carbon concentration organic matter which could be reached at the outlet of the basin and the parameter β corresponds to the discharge at which the dissolved organic carbon concentration is half of the value of α. The root mean square error (RMSE) has been calculated to validate the fitting (RMSE = 8.31).

2009 to December 2016. Table 2 gives calibrated and validated parameters values.

2.9. Model evaluation

The performance of the models has been evaluated using the Nash Sutcliffe efficiency (NSE) index, the coefficient of determination (R^2), the percent of bias (P BIAS) and the root mean square error (RMSE).

The NSE is a normalized statistic, usually used in hydrological modeling, which determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970; Moriasi et al., 2007).

$$NSE = 1 - \frac{\sum_{i=1}^{n}(obs_i - sim_i)^2}{\sum_{i=1}^{n}\left(obs_i - \overline{obs}\right)^2}$$

where *obs* and *sim* represents observed and simulated data while $\overline{obs}$ is the observed data mean.

NSE ranges from $-\infty$ to 1. If NSE = 1, there is a perfect match between simulated and observed data. If NSE = 0, it indicates that model predictions are as accurate as the mean of the observed data. If NSE <0, the mean of the observations is a better predictor than the model. The NSE is usually used because it is easy to interpret. Indeed, the more the NSE is close to 1, the more accurate the model is. Modeling at a daily step are generally considered satisfactory if NSE >0.5 (Moriasi et al., 2007).

Table 2
Calibrated values of SWAT parameters.

Parameter	Name	Input File	Literature range	Calibrated value
Hydrology:				
CANMX	Maximum canopy storage (mm H_2O)	.hru	0 100	1.90
CN2	Curve number	.mgt	35 98	Relative change: x0.85
DEP_IMP	Depth to impervious layer in soil profile (mm)	.hru	0 6000	800 2000
ESCO	Soil evaporation compensation factor	.bsn	0 1	0.86
LAT_TTIME	Lateral flow travel time (days)	.hru	0 180	9.06
PLAPS	Precipitation lapse rate	.sub	0 500	0.015 0.08
SFTMP	Snowfall temperature (°C)	.bsn	−5 5	1.52
SLSOIL	Slope length for lateral subsurface flow (m)	.hru	0 150	0.50
SMFMN	Melt factor for snow on December 21 (mm H_2O/°C-day)	.bsn	0 10	0.25
SMFMX	Melt factor for snow on June 21 (mm H_2O/°C-day)	.bsn	0 10	5.88
SMTMP	Snow melt base temperature (°C)	.bsn	−5 5	4.95
SNO50COV	Fraction of SNOCOVMX that corresponds to 50% snow cover	.bsn	0 1	0.57
SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover (mm H_2O)	.bsn	0 500	67.73
SURLAG	Surface runoff lag coefficient	.bsn	0.05 24	24
TIMP	Snow pack temperature lag factor	.bsn	0 1	0.42
Sediment:				
PRF_BSN	Peak rate adjustement factor for sediment routing	.bsn	0 1	0.25
USLE_K	USLE equation soil erodibility factor	.sol	0 0.49	Relative change: from x0.05 to x1

R^2 describes the degree of collinearity between simulated and measured data (Moriasi et al., 2007). R^2 represents the proportion of the variance in measured data explained by the model and ranges from 0 to 1, with higher values indicating less error variance. Values greater than 0.5 are typically considered acceptable.

$$R^2 = \frac{\sum_{i=1}^{n}\left(obs_i - \overline{obs}\right)\left(sim_i - \overline{sim}\right)}{\left(\sum_{i=1}^{n}\left(obs_i - \overline{obs}\right)^2\right)^{0.5}\left(\sum_{i=1}^{n}\left(sim_i - \overline{sim}\right)^2\right)^{0.5}}$$

The PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Moriasi et al., 2007). It expresses the percentage of deviation between simulations and observations and the optimal value is 0. PBIAS can be positive or negative which reveals respectively a model underestimation or overestimation bias (Moriasi et al., 2007).

$$PBIAS = \frac{\sum_{i=1}^{n}(obs_i - sim_i)\ x\ 100}{\sum_{i=1}^{n}(obs_i)}$$

The RSR is the ratio between the RMSE and standard deviation of measured data (Moriasi et al., 2007). The RSR ranges from the optimal value of 0 to $+\infty$.

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}(obs_i - sim_i)}}{\sqrt{\sum_{i=1}^{n}\left(obs_i - \overline{obs}\right)}}$$

3. Results

3.1. Hydrology and water balance

The water balance has been calibrated based on results found in Fabre et al. (2017). The total simulated water yield has been checked at the Igarka gauging station upstream of the outlet (Fig. 5). As in this previous work, the model shows a good representation of the freshets during the period of study and it reaches an annual mean specific discharge of 188 mm yr^{-1} for a standard deviation of 21 mm yr^{-1} on the whole period of study. This result is close to the observations with an underestimation of only 45 mm yr^{-1}. It reveals that around 47% of the yearly water is exported during the freshet in May and June. Concerning meteorological simulations, the model returns 477 mm yr^{-1} of total annual precipitations with 299 mm yr^{-1} and 178 mm yr^{-1} respectively for rainfall and snowfall corresponding to a ratio of 63/37. Snowmelt amounts to 142 mm yr^{-1} which equals to 80% of total snowfall and sublimation is returned as 37 mm yr^{-1} or 21% of total snowfall. Evapotranspiration is high in these regions with the dominative presence of forest and is returned as 276 mm yr^{-1} with a potential evapotranspiration of 550 mm yr^{-1}.

The average subbasin flow components distribution is as follows: 36, 164 and 11 mm yr^{-1} respectively for surface, subsurface/lateral and groundwater flows corresponding to 17%, 78% and 5% of total river discharge. The ratio between surface and subsurface flows is different from what have been observed in another permafrost affected watershed in Canada (60/40; Carey and Woo, 1999) but this difference could be due to the distribution of permafrost soils in the Yenisei basin with more than half of the watershed with sporadic, isolated or no permafrost (Fig. 2c; McClelland et al., 2004). For more details on hydrology modeling and calibration/validation details see Fabre et al. (2017).

3.2. Simulations of daily TSS, POC and DOC fluxes

The model has predicted correctly the specific flow of sediment at the outlet during the calibration and validation periods (Fig. 6). The dynamic is following the freshets. The statistical performance is satisfactory for the calibration and validation periods compared to previous studies with NSE of 0.74 and 0.26 and R^2 of 0.98 and 0.55. For a daily time step modeling, our results can be considered as accurate regarding difficulties to calibrate TSS fluxes and to catch the freshets without offsets.

For POC, the measures and the simulations are following the equation from Boithias et al. (2014) with the coefficients *a* and *b* statistically determined and fixed respectively to 0.95 and 3.9 for the Yenisei River (Fig. 3). Daily POC specific fluxes have been correctly predicted (Fig. 7). The same problems are found with the low number of data during high flow periods. The statistical performance has returned low NSE of 0.27 and 0.16 and satisfactory R^2 of 0.91 and 0.54 for the calibration and the validation periods which could be judged as accurate regarding the number of observed data.

Regarding DOC simulated concentrations, the best fitting for the α and β parameters have been found as 15.0 and 1.29 as shown in Fig. 4. The model used is estimating with accuracy the DOC

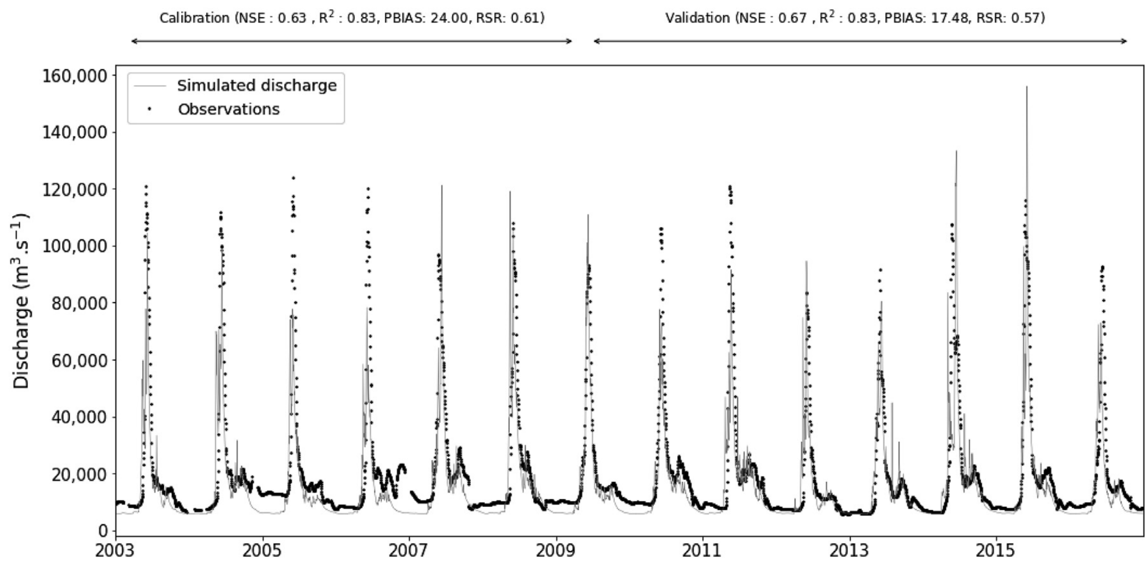

Fig. 5. Simulated discharge of the Yenisei River compared to observations at the Igarka gauging station.

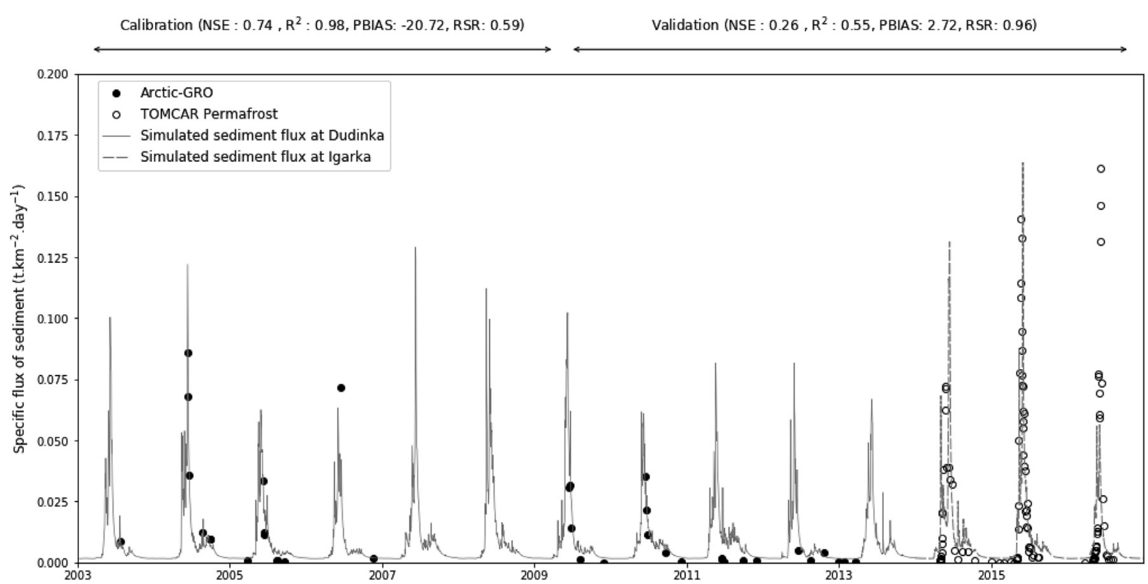

Fig. 6. Simulated specific flux of sediment compared to observations at Dudinka from 2003 to 2013 and at Igarka from 2014 to 2016. Calibration period: 2003 to 2008. Validation period: 2009 to 2016.

concentration in the stream at the outlet as shown in Fig. 8a. The NSE reveals some troubles with the validation period but is satisfactory during the calibration period while the R^2 is very satisfactory during both of the periods. In the same way, the predicted DOC fluxes exported at the outlet show a good tendency but return a low NSE in the validation period (Fig. 8b).

Our results have shown that the predictions are really good during low flows for any export studied on the calibration and the validation period but have revealed underestimations during high flows period for the three variables (Fig. 9). Nevertheless, the returned p values for each period are good and reveal strong evidence of correlations between observations and predictions.

3.3. Temporal and spatial distribution of TSS, POC and DOC fluxes

As expected, permafrost thaw triggers the POC and DOC transfers (Fig. 10a). POC and DOC exports rise drastically with the spring freshet due to snowmelt and follows the surface runoff dynamic. This study reveals that POC and DOC are mostly exported during the freshet as 57% and 65% of the yearly fluxes are transported in May and June 2013 (Fig. 10a) while these exports reach respectively 60% and 68% of the yearly fluxes over the whole simulation.

In order to outline processes involved in organic carbon transfer, we have focused on the year 2013 as this year returned the best statistical responses to study the spatial distribution of POC and DOC fluxes in each subbasin (Fig. 10b). First, a link with the main stream near the outlet is relevant for the POC flux. Another variable is influencing both POC and DOC transfer which is the permafrost type. The unfrozen zones present higher fluxes than the most frozen soils. During the increase in the exports, a disturbance in the subbasins close to the outlet due to the discharge rising is clear. Some other subbasins have returned significant fluxes due to precipitation events.

The flux of particles is partially dependent on the permafrost

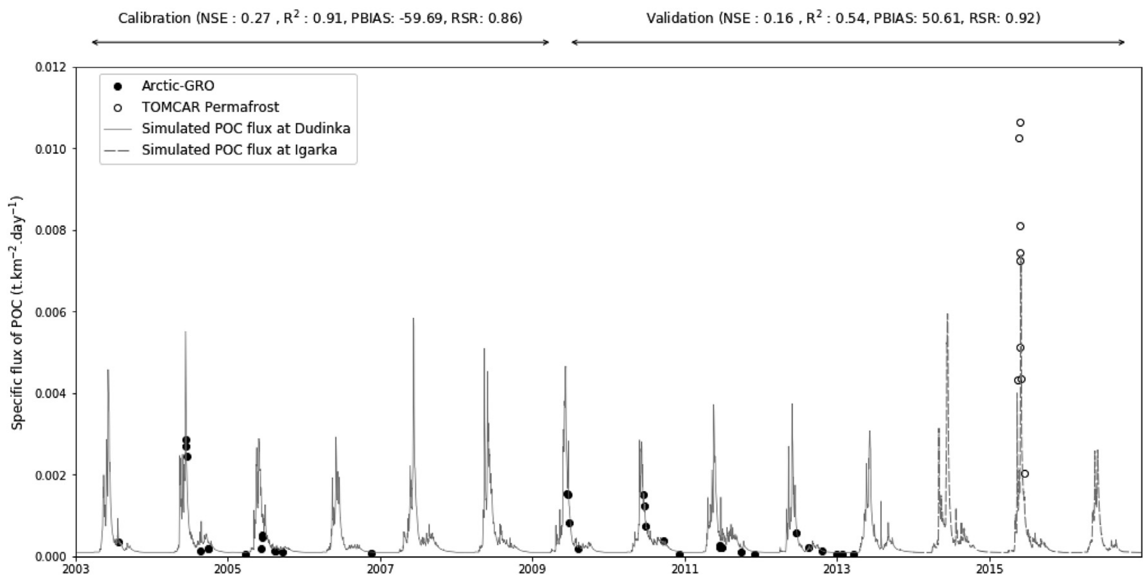

Fig. 7. Simulated specific flux of particulate organic carbon (POC) compared to observations at Dudinka from 2003 to 2013 and at Igarka from 2014 to 2016. Calibration period: 2003 to 2008. Validation period: 2009 to 2016.

type (Fig. 11). For POC, it is mainly driven by the subbasins presenting sporadic permafrost, isolated permafrost or without permafrost and it reveals a really low contribution of discontinuous permafrost to the total fluxes. Regarding DOC, the contributions are more distributed along the basin with still a dominant contribution from no permafrost zones.

4. Discussion

4.1. Conceptualization of the water, sediment and organic carbon river transport in the Yenisei River watershed

This paper mentions new strengths in modeling permafrost, sediment and organic carbon behavior in river. This is the first study modeling fluvial sediment and riverine organic carbon behavior in an Arctic watershed presenting all the types of permafrost at a daily time step. By providing equations to predict organic carbon exports and used it coupled to a daily time step hydrological modeling, this paper reveals the possibilities of precise modeling of organic carbon in a permafrost dominated Arctic catchment.

Concerning hydrology, this paper brings new opportunities as the whole basin of the Yenisei River is modeled unlike in Fabre et al. (2017) where the modeling has been dependent on 2 reservoirs. This modeling could represent the flow distribution upstream of the reservoirs and also show the impact of the elevation gradient on the water balance in the higher zones of the basin that have been excluded from the previous work. The discharge has been checked at the exits of the reservoirs and at the outlet of the different main tributaries with observed data available for the period 2008–2016 (Fig. 1 for stations location). These five gauging stations are not representative of a permafrost type as they integrate more than one. This constraint has disturbed the calibration of soil properties for each permafrost type. But the two tributary stations are mostly integrating continuous permafrost on one hand and sporadic and isolated permafrost on the other hand which has allowed us to approach soil properties based on these stations. The other soils properties have been deduced accordingly. Concerning precipitations data, the lack of data is a problem in this study. With 20 stations for the fifth biggest watershed in the world, some peaks modeled in summer and not present in reality could be linked to an accumulation of rainfall in the various subbasins linked to a station predicting a strong rainfall event. SWAT transfers the climate data to a subbasin from the closest meteorological station input. At this scale, with 20 stations and 257 subbasins, an accumulation of meteorological events is possible especially in the middle of the basin where we find a low number of stations (Fig. 1).

To simulate river sediment yields at a daily step is really rough (Oeurng et al., 2011). Using the SWAT model is an adapted choice to the results expected as this model allows spatial and temporal predictions of river discharge and sediment fluxes in a very large Arctic watershed. Some other models could return more precise results but they need a larger number of measured variables which, unlike the variables used in SWAT, are quite difficult to collect. Moreover, SWAT is one of the model validated for river sediment transport studies (Moriasi et al., 2012) and has already been used to study organic carbon transport (Oeurng et al., 2011).

This study includes 20 soil types. The good results obtained at the outlets of the reservoirs, of the tributaries and of the whole Yenisei watershed lead to the conclusion that this resolution is sufficient at this scale to represent the processes in the basin. But, as the exports of TSS, POC and DOC are mainly driven by soil characteristics, the spatial distribution of TSS, POC and DOC fluxes would be more precise by integrating another soil dataset with better distribution and resolution of soil types. Still, the quantification of organic carbon content in permafrost soils remain uncertain as shown in Kuhry et al. (2013), Hugelius et al. (2014) or Schuur et al. (2015). Considerations on the databases available should be done to better model organic carbon yields because organic carbon content is much more linked to the permafrost type than to the soil type. Taking into account a freezing degree in the soil characteristics and adding this parameter to the soil data could be a first good improve to fill this data gap and better predict the transfers in that kind of watersheds without too important calibrations.

In the same way, the parametrization of soil properties has allowed a discretization of permafrost types. The soils parameters have been calibrated to limit the erosion and sediment supply in the most frozen zones. This paper is the first study trying to explain the permafrost impact on physical erosion of soils and the

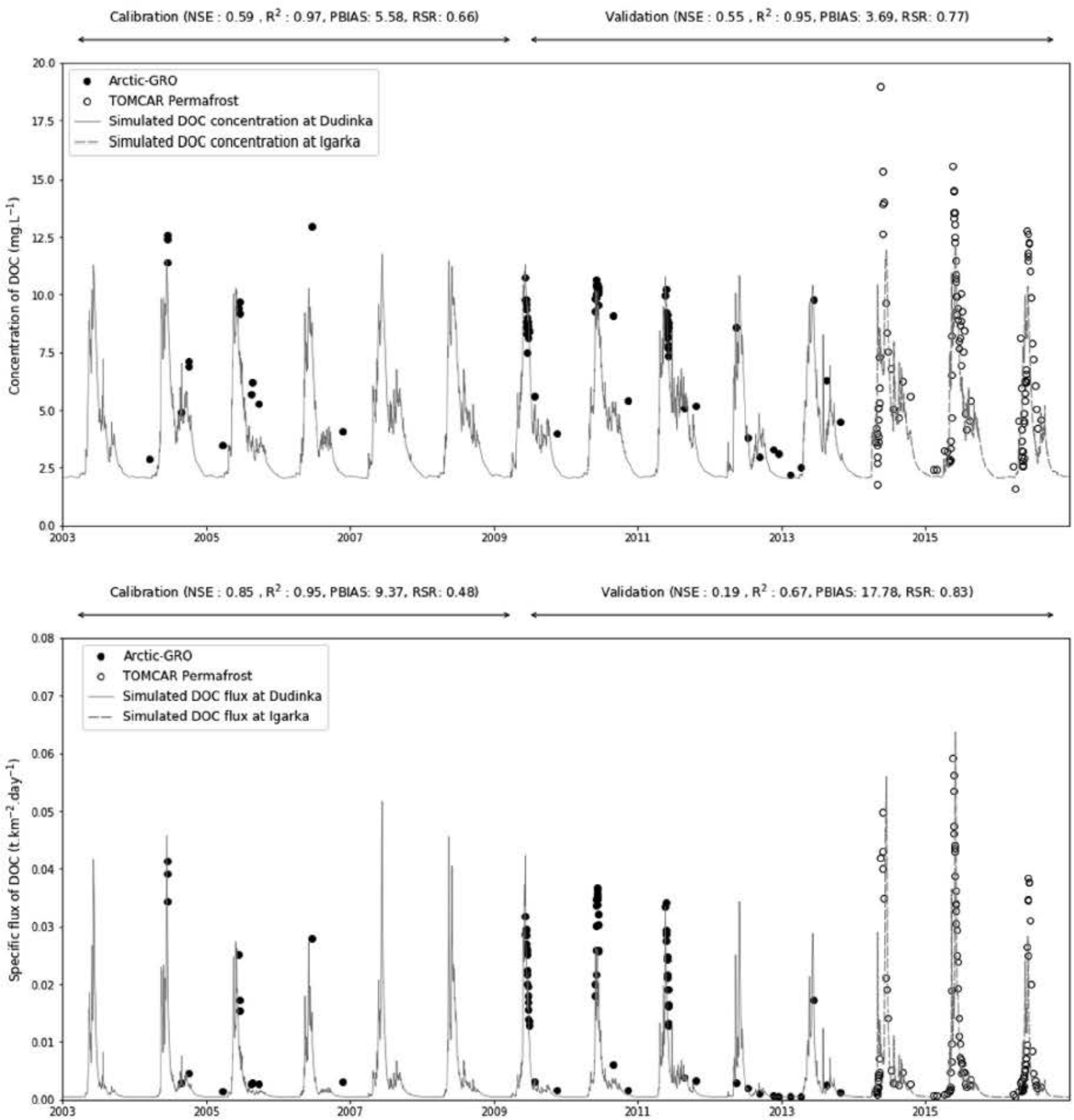

Fig. 8. a) Simulated concentration of dissolved organic carbon (DOC) and b) Simulated flux of DOC compared to observations at Dudinka from 2003 to 2013 and at Igarka from 2014 to 2016. Calibration period: 2003 to 2008. Validation period: 2009 to 2016.

subsequent river sediment transports. By doing other investigations in various watersheds impacted by permafrost with the same size such as the Ob, the Lena or the Mackenzie which are the other main contributors of organic carbon to the Arctic Ocean (Dittmar and Kattner, 2003), we could check and refine the calibration suggested here.

Our conceptualization of the processes in permafrost affected watersheds seems quite accurate regarding the results obtained. The returned statistical performances have showed the difficulties for the modeling to fit the observations in the validation period. This problem is due to offsets of few days between the observed and the predicted freshets. This is revealed by Fig. 9 where the model has returned equally higher or lower fluxes than observed ones. More researches are still needed in snowmelt processes to better model the discharge peaks in this type of watersheds. These offsets could be due to the lack of meteorological stations with observed precipitations mentioned previously. A better spatialization of these data coupled with a spatial study on the order of the subbasins contributions to the snowmelt should provide interesting information to improve the hydrological modeling by better representing the peaks of discharge and removing the offsets. Then, the modeling should be able to reproduce the observed exports of sediment, POC and DOC. However, a focus on modeled specific fluxes of sediment on the year 2016 has revealed some troubles to represent the observed peak. This year is presenting a low amount of precipitations and a lower discharge peak than the two previous years. Still, the maximal observed sediment concentrations are in the range of the ones observed in 2014 and 2015. With this in mind, we could assume that an unknown process is explaining these concentrations or that there have been problems in the sampling

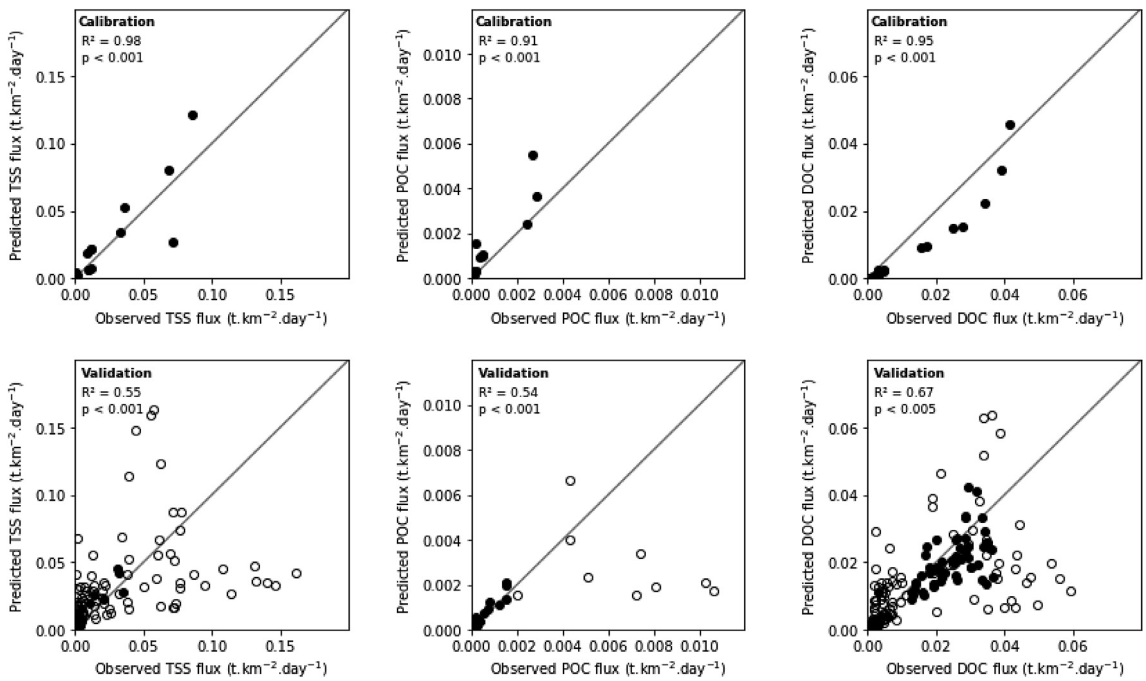

Fig. 9. Comparison between predicted and observed values for sediment, POC and DOC for the calibration and the validation period. It reveals that fluxes of sediment, POC and DOC are better modeled in low-flow periods than in high flow periods where the offset between predictions and observations is larger. The dots represent the observed data of the Arctic Great Rivers Observatory while the circles represent the observations of the TOMCAR Permafrost project.

for this specific year. Moreover, the influence of the reservoirs is strong. Field experiments must be performed in different parts of the watershed in order to check the contribution of each stream and each permafrost type on the organic carbon transfer. By sampling water chemistry at the reservoirs outlets and doing isotopic studies on river waters at the basin outlet, this work could be validated.

During the freezing period, as the soil is inaccessible for water and as the snow accumulates, the river sediment and organic carbon exports are really low and mainly dependent to the dams' releases. As in past researches (Table 3), the spring freshet is the main factor controlling sediment and organic carbon exports. This study provides new information of spatial hotspots of organic carbon exports. These spatial outputs are driven by precipitation intensity, snow thawing, and permafrost type. Permafrost free areas deliver higher fluxes of organic carbon which has already been demonstrated by comparing different Arctic watersheds (Frey and McClleland, 2009).

The spatial study leaves to interesting and solid conclusions on the behavior of river organic carbon in Arctic watersheds. Riverine organic carbon transfer processes are variable in time and space. Organic carbon exports are mostly linked to surface runoff (Fig. 10a) as most of the river organic carbon is exported during the annual freshet due to snow and ice melt. The organic carbon fluxes are also spatially dependent on the permafrost type distribution within the catchment (Fig. 11). The continuous and discontinuous permafrost area present low export of POC and DOC while the more unfrozen zones fed the stream flow in organic carbon. As our simulated results at the outlet are close to observations, we could assume that the time and space distribution shown by our modeling is close to the reality and that surface runoff is the main pathway contribution to POC and DOC river transports.

Concerning the data quality, the TSS, POC and DOC datasets for the Yenisei River present a lack as only few data are available on our period of study and only few years have been sampled at a high frequency. Regarding the difficulties to sample during the freshet period, the access to a high frequency dataset of sediment and organic carbon on specific years at the outlet of the Yenisei River is an important opportunity to better understand the fluxes exported during this ephemeral event.

The SWAT model is using the MUSLE relation to estimate sediment yield in each HRU. This equation has already returned good results in various watersheds (Douglas Mankin et al., 2010; Krysanova and White, 2015) but has never been tested in Arctic watersheds. Sadeghi et al (2014) have proven that this equation should be used with caution. Other experiments should be done in other permafrost affected watersheds to confirm the validity of the MUSLE equation in these areas.

The equation we used in this study to model POC, adapted from Boithias et al. (2014) has produced relatively accurate results (Fig. 7). In previous works, the POC export has been explained by empirical relations based on statistical fitting with suspended solids (Ludwig et al., 1996) or discharge (McClelland et al., 2016). Ludwig et al. (1996) equation has been designed for a global scale analysis and has not been able to represent precisely the POC exports at a daily time step for each catchment. The relation published by McClelland et al. (2016) for Arctic watersheds allow to calculate POC fluxes at a daily time step but has been unable to estimate the percentage of POC in suspended solids. The equation we used here is based on physical basis with asymptotes linked to parameters corresponding to the in stream organic matter with high organic carbon content in TSS (phytoplankton and residuals) and to TSS with the lowest organic carbon content corresponding to organic carbon concentration in the deepest soil layers. It allows the user to adapt the parameters depending on the study case.

The spatialized resulting exports in each subbasin for the POC fluxes calculated with the equation adapted from Boithias et al. (2014) reveals limits in the validity of the equation (Figs. 7 and 9). The equation is firstly designed to express a result at the outlet of the watershed as the asymptotes evoked before are defined on the

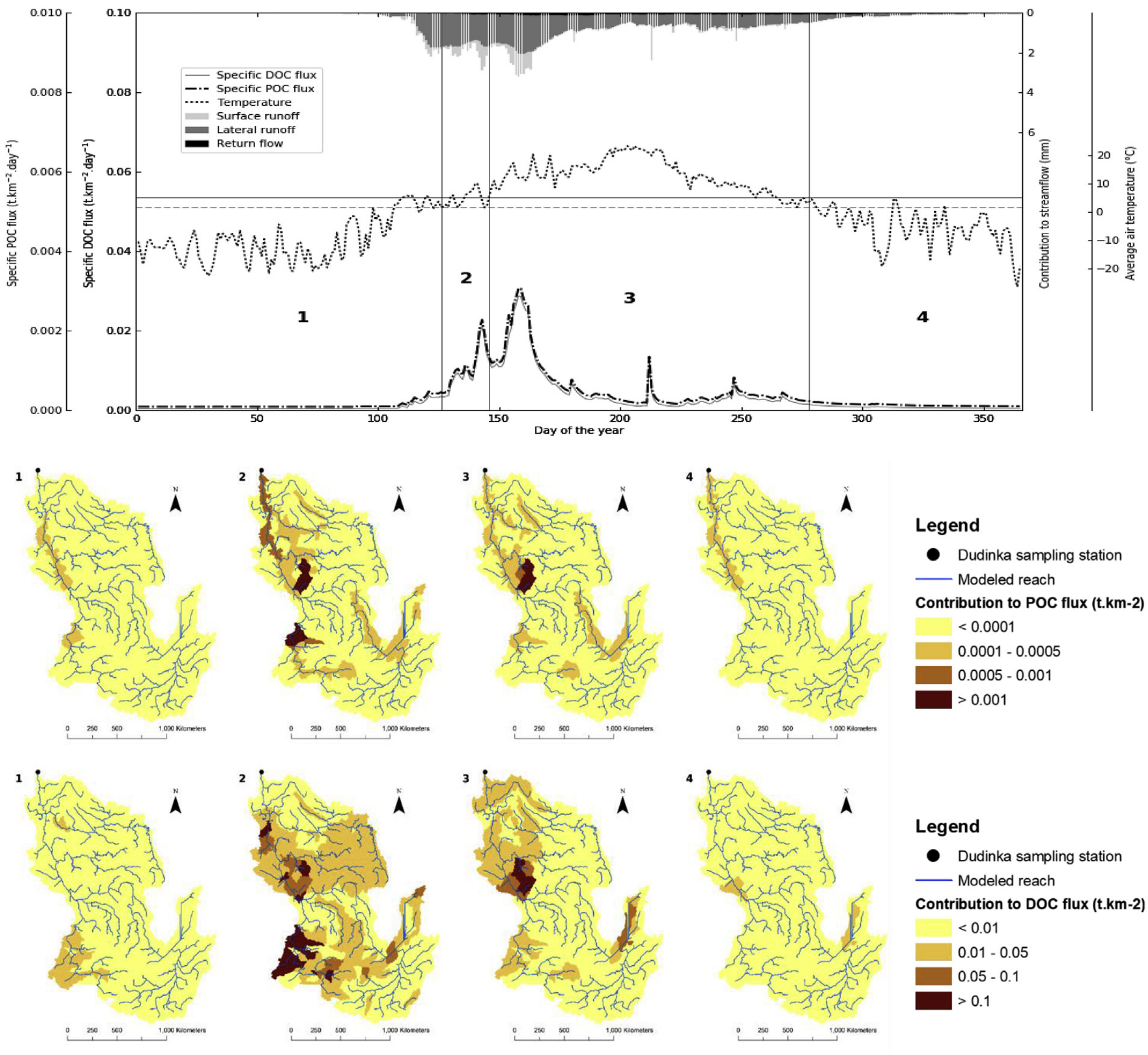

Fig. 10. a) daily POC and DOC fluxes at the outlet on year 2013. We highlight 4 periods with 4 different organic transfer trends corresponding to the conceptual model described in Fabre et al. (2017). The spatial average contributions of each hydrological component per day and the average air temperature in the whole basin are also represented. The horizontal lines correspond to the modeled limits of snowfall (dashed line, 1.52 °C) and snowmelt (solid line, 4.95 °C) temperature (see Table 2). The vertical lines which separate the periods represent the date when temperature reaches the limits defined. b) Spatial average subbasin contributions to POC and DOC fluxes. The maps represent the average yields of each subbasin during the 4 periods detailed in Fig. 10a.

basis of observed data at the outlet of the basin. Thus, the export distribution shown in this paper is based only on the amount of sediment exports in the subbasins as the asymptotes are fixed equal in all the subbasins. But the equation could be influenced by chemical parameters such as the organic carbon content in soils which is really variable in Arctic watersheds. Improvements could be performed with more spatialized observed data of POC to see if the asymptotes of the equation are dependent on environmental or climatic variables and have to be adapted in the different parts of the watershed. The equation used firstly in a French catchment is after all transposable in watersheds with other hydro pedo climatic conditions. Only the parameters a and b have to be adapted to the watershed. The other parameter (i.e. the constant 9.40) representing the shape of the curve seems to be stable independently to the watershed. More studies are needed in wa tersheds with different climatic or anthropogenic influences such as tropical and equatorial catchments or really urbanized water sheds to validate this hypothesis.

Concerning DOC modeling, the adapted model from Michaelis Menten equation based only on discharge could be limited. The equation underestimates low and high DOC fluxes but over estimates middle fluxes (Figs. 8 and 9). For now, the parameters α and β are determined statistically based on the dataset available. A focus on these parameters is needed to better understand their link with environmental variables such as organic carbon content in soils and slopes (Ludwig et al., 1996) or the percentage of peatlands and wetlands areas within the catchment (Hope et al., 1994; Gergel et al., 1999; Ågren et al., 2008). Again, this equation needs to be tested in different subbasins to assess the existence of different α and β values at a catchment scale and in other catchments with different hydro pedo climatic conditions to evaluate its replica bility at global scale.

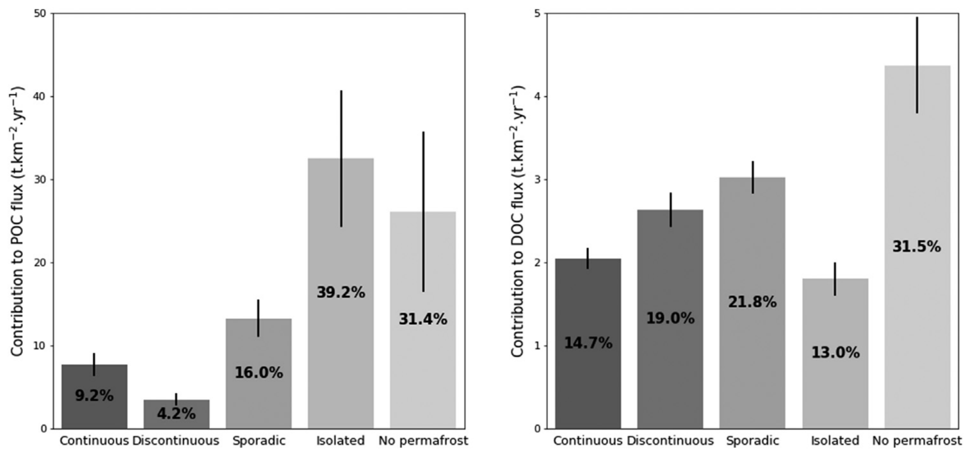

Fig. 11. Average contribution of subbasins to POC and DOC riverine fluxes depending on the type of permafrost. The TSS fluxes distribution is not represented as sediment flows are proportional to the POC fluxes (see the POC equation above).

Table 3
Interannual mean of water fluxes at the Yenisei River outlet compared to previous studies.

Source	Years	Method	Specific fluxes (t km ^{2} yr ^{1})			Fluxes (Tg yr ^{1})		
			Sediment	POC	DOC	Sediment	POC	DOC
This study	2003 2013	Modeling	2.97 ± 0.53	0.13 ± 0.02	1.14 ± 0.22	7.54 ± 1.35	0.33 ± 0.05	2.90 ± 0.56
Ludwig et al. (1996)	1989 1999	Modeling	5	0.07	1.33	12.7	0.18	3.38
Lobbes et al. (2000)		Estimation		0.07	1.99		0.18	5.05
Syvitski (2002)		Modeling	12.7 78.3			30.9 191.2		
Dittmar and Kattner (2003)		Estimation		0.07	1.68 2.01		0.18	4.27 5.11
Gebhart et al. (2004)	1970 1986	Estimation	2.06	0.23		5.23	0.58	
Holmes et al. (2002)	1970 1995	Estimation	1.9			4.7		
Hasholt et al. (2006)	1941 2000	Estimation	2.3			5.6		
Amon et al. (2012)		Estimation			2.08			5.28
McClelland et al. (2016)	2003 2011	Modeling		0.14 ± 0.001			0.25 ± 0.003	

4.2. Predicted exports of sediment and organic carbon

Concerning TSS, we found a specific flux at the outlet in the range of previous studies with an average of 2.97 t km^{-2} yr^{-1}. Regarding the specific POC and DOC fluxes, the annual fluxes are in the range of other studies on the Yenisei River with respectively 0.13 t km^{-2} yr^{-1} and 1.14 t km^{-2} yr^{-1}.

This study outputs 1.2 to 2 times lower fluxes of DOC, 1.6 times higher to 26 times lower exports of sediment compared to previous studies (see Table 3) while it returns POC fluxes in the same range. For sediment exports, previous exports which are closer to 12–14 Tg. yr^{-1} are estimated based on data from pre dam period. The dams' influences have reduced drastically the export and post dam researches have estimated the sediment export between 4 and 6 Tg. yr^{-1} while our estimate of 7.5 Tg. yr^{-1} is above average. These past studies have estimated the fluxes based on sporadic data often on a period inferior to the 10 years of this study. By integrating the high water discharges at a daily time step in this modeling, the fluxes given in this paper should be closer to real fluxes than past studies as previous works could have underestimated or over estimated the influence of the freshets on the exports. It has already been demonstrated that daily time step modeling is essential in the study of Arctic systems water flows (Fabre et al., 2017). As sediment and organic carbon are strongly correlated with water flows, a daily time step study is also primordial in this case. Besides, our modeling returns peaks of TSS, POC and DOC in the range of ob servations but Fig. 9 reveals that an offset in high flow periods re mains and a focus on the detection of the peaks could be done to improve the modeling.

A better consideration on sampling protocols is encouraged in Arctic systems as most of the hydrological and biogeochemical processes are happening on a short time period. During low flow periods, sampling each month could be possible especially between November and March where precipitations fall as snow and accu mulate which strongly limits the number of water pathways in the basin. A focus should be provided on high flow periods as proposed by the TOMCAR Permafrost Initiative. This study has revealed that POC and DOC are mostly exported during the freshet with respec tively 59% and 65% of the yearly exports on the months of May and June of the 2003–2016 period. Studying the organic carbon behavior during the freshet is a main concern for this type of wa tersheds. As the ice break up is hard and dangerous to prospect, new improvements are necessary to facilitate sampling in Arctic watersheds and assess the impact of the break up on the organic carbon exports. A daily to weekly sampling protocol would be necessary in the period of transition especially at the end of May and the beginning of June as the flux peaks do not persist more than 3 days (Fig. 10a).

We have explained that around 60% of the organic carbon ex ports happen during the high flow periods. As in this paper, most of the previous studies based their modeling or estimations on spo radic data without data during the peak of discharge which leave uncertainty on the behavior of organic carbon in the critical period of the freshet. They could have underestimated the peaks of TSS and DOC fluxes but could have overestimated the time of transition between low flows and high flows periods which have resulted in higher annual exports.

Compared to other large watersheds, Arctic watersheds have a special behavior which influences the way to study them. Wang et al. (2012) have compared two Asian rivers, the Yangtze River with a close draining area to the Yenisei River (1,940,000 km^2) and the Yellow River which is smaller (752,443 km^2). Even if the Yenisei basin presents similar draining area characteristics as the Yangtze River, its hydrological and biogeochemical functioning is closer to smaller watersheds because of the flood events dynamic: the snowmelt impact on the freshet gives high peaks on short time periods like on the Yellow River. The Yangtze River has longer high flow periods which allow a less frequent sampling protocol to represent well the whole hydrological cycle. The Yellow River and the Yenisei River, with shorter high flows period, need a high frequency sampling during the transition to take into account the strong influence of the freshet on the annual fluxes. This catchment behavior could be also related to really small catchments functioning with flash floods (Oeurng et al., 2011) where high flows could supply more than 60% of yearly sediment exports.

4.3. Future modeling opportunities

A first step to improve the modeling of sediment and organic carbon exports in permafrost catchments is to adjust the parameters of the MUSLE equation based on the permafrost type or to add a time dependent parameter in the equation to express the freezing percent of the soil.

As the Yenisei River is polluted by tritium (Bondareva, 2015) which is found in sediment, zoobenthos, fishes or plants and by mercury in frozen soils, river sediment fluxes simulated by SWAT could be helpful to trace of these pollutants exports. Predict the origin and the transport of the sediment allows some considerations on the management of these pollutants in the river. Indeed, they constitute a strong issue for humans living near the Arctic Ocean by potentially causing ecotoxicological disturbances in aquatic ecosystems while the sea is the main food resource for these populations.

Another perspective of this paper is to better understand and quantify the final state of all the organic matter exported to the ocean. The models for POC and DOC are not taking into account the consumption by organisms in the river or in alluvial plains which could be important and could impact the final flux to the ocean. By knowing the quantity interfering in the carbon and the nitrogen cycle, predictions on climate change could be performed. A first possible approach could be to use the biogeochemical oxygen demand (BOD) to calculate the potential organic matter decomposition by microorganisms.

By incorporating global warming scenario, this modeling could be used to explore reactions of permafrost affected watersheds to climate change. Permafrost extent should be affected by climate change and thus the final exports of sediment and organic carbon could increase (Ciais et al., 2013). As shown in Fig. 11, the main contributive areas to the POC and DOC exports are the unfrozen zones. Even if TSS and organic carbon transport are also dependent on other variables such as land use and soil types, higher exports of organic carbon could be possible as a reduction of the permafrost areas and a complete redistribution of different permafrost types is expected with global warming (McGuire et al., 2018). TSS and POC exports, transported by surface runoff should not be significantly affected by a deeper active layer but only by an increasing erodibility factor due to the unfreezing. DOC fluxes should be much more affected by permafrost thawing as the contribution to total flux is mostly driven by the unfrozen zones (Fig. 11). This rise in organic carbon fluxes to the ocean could accelerate the permafrost carbon feedback (Schuur et al., 2015). This hypothesis is putting forward the amplification of surface warming due to carbon dioxide (CO_2) emissions from thawing permafrost (Schuur et al., 2015). As labile POC and DOC are consumed by organisms resulting in the production of CO_2, the increase in the organic carbon fluxes could fit with this concept.

With global warming, an increase of 15.6% of water discharge in the Yenisei River is expected by 2100 with a stronger effect on the peaks of discharge (Peterson et al., 2002; Nohara et al., 2006). This modification could again strongly disturb global carbon cycles. By assuming that climate change will have the same impacts on sediment, POC and DOC exports, these fluxes will reach 3.13, 0.12 and 1.19 t km^2 yr^{-1}. These increases are only calculated based on the discharge effect but other changes mentioned above should be taken into consideration such as the permafrost degradability and its probable feedback on global climate change (Prokushkin et al., 2011; MacDougall et al., 2012; Schuur et al., 2015; Abbott et al., 2016) which could accelerate the permafrost unfreezing and could liberate more organic carbon in freshwater (Frey and McClleland, 2009). Testing the introduction of a feedback loop effect of permafrost degradation on global warming in modeling tools could lead to better estimates of future sediment and organic carbon exports to the Arctic Ocean.

5. Conclusion

This study has allowed us to understand, model and quantify sediment, POC and DOC fluxes at the outlet of the biggest DOC provider of the Arctic Ocean, the Yenisei River, and to outline carbon transfer processes with a spatialization of the study. This is the first study trying to model TSS and POC fluxes in an Arctic watershed with a spatial and temporal variability and the first study trying to model spatially DOC fluxes in a watershed. The fluxes estimated in this study could be considered with a better interest than those proposed in prior researches on sediment and organic carbon in Arctic rivers as our study integrates the contribution of high flow periods in the modeling while previous studies have generally extrapolated these periods using samples collected during low flow periods. Finally, the main conclusions of this paper are essential in a context of climate change. It underlines the contribution of each permafrost type to the total export of organic carbon by the Yenisei River. By integrating all the periods of the hydrological cycle, this paper could lead to a better quantification of future sediment and organic carbon exports in a thawing permafrost scenario.

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