UNIVERSITY OF POTSDAM

Faculty of Science

Institute for Earth and Environmental Science

Summer surface water chemistry dynamics in different landscape units from Yedoma Ice Complex to the Lena River

Master thesis

to attain the academic degree

Master of Science (M.Sc.) in Geoecology

Submitted by

Lydia Polakowski

Berlin, November 2015

Themenstellerin:	**Dr. Anne Morgenstern** Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI)	Zweitgutachter:	**Prof. Dr. Axel Bronstert** Universität Potsdam, Institut für Erd- und Umweltwissenschaften
Adresse:	Telegrafenberg A 43 14473 Potsdam	Adresse:	Karl-Liebknecht-Str. 24-25, Haus 1 14476 Potsdam-Golm

Contents

List of figures

List of tables

Abstract

About 25 % of the land mass of northern hemisphere is underlain by permafrost, which is one of the largest carbon pools. Yedoma Ice Complex is a particularly ice-rich type of permafrost. As a consequence of rapid climate warming of the Arctic, permafrost is affected by degradation processes like thermokarst. Thereby organic carbon is partially dissolved (DOC) in thermokarst lakes, and transported via rivers into the Arctic Ocean. On this way, large parts of DOC are mineralized by microbial processes and emitted as CO_2 and CH_4 to the atmosphere. The influence of different landforms in thermokarst affected permafrost regions on DOC concentration has not been thoroughly investigated. Addressing this research gap, this thesis examined the relationship between landscape units, water chemistry and hydrology for a small study site in the Lena River Delta, Siberia. On the basis of GeoEye satellite imagery eight landscape units were determined. These include thermokarst lakes and streams on the first terrace and on Yedoma Ice Complex, Yedoma Ice Complex streams, which are fed by the Ice Complex, Yedoma Ice Complex uplands, first terrace relict lake, and the Olenyokskaya Channel. Concerning pH value, electrical conductivity, isotopic composition and DOC concentration summer surface water samples and soil water samples of 2013 and 2014 were analyzed. These analyzes revealed that the system of the thermokarst lake Lucky Lake, its drainage flow path and source waters on Yedoma Ice Complex, is divided by landscape units. Source waters show significantly higher DOC concentrations and lower electrical conductivity than Lucky Lake and the drainage flow path. This suggests that labile organic carbon of Yedoma Ice Complex reaches the lake by degradation. Yedoma Ice Complex lake processes, despite evaporation, further reduce DOC concentration rapidly, probably by mineralization of labile DOC. Along the drainage flow path no further decrease of DOC concentration was observed, despite of changing discharge. Using discharge data of 2013 a DOC flux of about 220 kg in 29 days for the study site was calculated. A temporal variability of DOC concentration during the sampling periods was not determined using the utilized data.

Kurzfassung

Etwa 25 % der Landmasse der nördlichen Hemisphäre wird von Permafrost unterlagert, welcher einer der größten Kohlenstoffspeicher ist. Yedoma Eiskomplex ist ein besonders eisreicher Permafrosttyp. Als Folge der raschen Klimaerwärmung in der Arktis ist Permafrost von Degradationsprozessen, wie Thermokarst, betroffen. Dadurch wird organischer Kohlenstoff teilweise in Thermokarstseen gelöst (DOC), und gelangt über Flüsse in den Arktischen Ozean. Auf diesem Weg wird ein großer Teil von DOC durch mikrobielle Prozesse mineralisiert und als CO_2 und CH_4 in die Atmosphäre emittiert. Der Einfluss verschiedener Landschaftsformen in von Thermokarst betroffenen Permafrostregionen auf die DOC Konzentration wurde bisher nicht umfassend untersucht. Diese Masterarbeit widmet sich dieser Forschungslücke und Untersucht die Beziehung zwischen Landschaftseinheiten, Wasserchemie und Hydrologie in einem kleinen Untersuchungsgebiet im Lena Delta in Sibirien. Auf der Grundlage von GeoEye Satellitenbildern wurden acht Landschaftseinheiten bestimmt. Dazu zählen Thermokarstseen und Bäche auf der ersten Terrasse und auf dem Yedoma Eiskomplex, Yedoma Eiskomplexbäche, die vom Eiskomplex gespeist werden, das Hochland des Yedoma Eiskomplex, ein Restsee auf der ersten Terrasse, und der Olenyokskaya Kanal. Bezüglich pH Wert, elektrischen Leitfähigkeit, Isotopenzusammensetzung und DOC Konzentration wurden Oberflächenwasserproben und Bodenwasserproben aus dem Sommer 2013 und 2014 analysiert. Diese Analysen zeigten, dass das System vom Thermokarstsee „Lucky Lake“, seine Abflusskette und Quellenwässer auf dem Yedoma Eiskomplex von den Landschaftseinheiten unterteilt werden. Die Quellenwässer weisen eine deutlich höhere DOC Konzentration und niedrigere elektrische Leitfähigkeit als „Lucky Lake“ und Abflusskette auf. Dies deutet darauf hin, dass labiler organischer Kohlenstoff vom Yedoma Eiskomplex durch Degradation in den See gelangt. See-Prozesse auf dem Yedoma Eiskomplex führen trotz Evaporation zu einer raschen Reduzierung der DOC Konzentration, wahrscheinlich durch Mineralisation des labilen DOC. Entlang der Abflusskette wurde kein weiteres Absinken der DOC Konzentration beobachtet, trotz sich verändernder Abflusswerte. Unter Verwendung der Abflussdaten aus 2013 wurde ein DOC Austrag von 220 kg in 29 Tagen für das Untersuchungsgebiet berechnet. Eine zeitliche Variabilität der DOC Konzentration in der Beprobungsperiode konnte mit den genutzten Daten nicht bestimmt werden.

1 Introduction

Polar regions are particularly affected by the increase of global temperature. In the last decades the annual mean temperature in the Arctic rose almost twice as fast as in other regions in the world (AMAP, 2011). Arctic permafrost regions, about 25 % of the land mass of the northern hemisphere, are one of the world's largest carbon pools. Permafrost developed during the last ice age as a result of severe cold-climate conditions in non-glaciated areas and is therefore sensitive to climate change. In Siberia large areas are underlain by a particularly ice-rich type of permafrost. This Yedoma Ice Complex contains large quantities of fossil organic carbon (SCHIRRMEISTER et al., 2011a). TARNOCAI et al. (2009) estimated about 1700 Gt soil organic carbon stored in permafrost regions in high latitudes. About 400 Gt of this are locked in Yedoma deposits. As a result of permafrost degradation organic carbon is partially dissolved in thermokarst lakes and is transported to rivers and the Arctic Ocean. Large parts are emitted as CO_2 and CH_4 to the atmosphere by mineralization (FREY & SMITH, 2005). The export of organic carbon via rivers to the ocean is a major component of the global carbon cycle and a sensitive component of high-latitude carbon cycles (FINLAY et al., 2006; SPITZY & LEENHEER, 1991). Rapid permafrost degradation due to thermokarst and thermo-erosional processes can release DOC and nutrients from several meters below the active layer (BOWDEN et al., 2008; VONK et al., 2013). These changes in permafrost, caused by increasing temperatures, have significant impacts on the hydrology and biogeochemical cycling in periglacial ecosystems, as the surface area of water bodies is likely to increase due to permafrost degradation (FREY & MCCLELLAND, 2009; PROKOVSKY et al., 2011). These arctic matter fluxes are proposed to increase in the future (FINLAY et al., 2006). HOLMES et al. (2012) found that Arctic rivers deliver 34-38 Tg yr^{-1} of DOC to the Arctic Ocean. As a result, arctic ecosystems shift from carbon sink to a carbon source (OECHEL et al., 1993).

Carbon in arctic soils has a high climate and scientific relevance and is frequently the object of investigation (CHRIST & DAVID, 1996; HOBBIE et al., 2000; SHENG et al., 2004; STRAUSS, 2014). Many studies of DOC in soils and its release have been published (NEFF & HOOPER, 2002; PASTOR et al., 2003; FREEMAN et al., 2004; PROKUSHKIN et al., 2009; WICKLAND et al., 2007). BENNER et al. (2004), HOLMES et al. (2008) and RAYMOND et al. (2007) analyzed the DOC transport in rivers to the Arctic Ocean. Several studies published estimations for annual DOC discharge from the Lena River of 4.1 to 4.9 Tg C yr^{-1} (DITTMAR & KATTNER, 2003) and 5.6 to 5.8 Tg C yr^{-1} (RAYMOND et al., 2007; HOLMES et al., 2012). In recent years thermokarst lakes have been studied. BOIKE et al. (2015) analyzed thermal processes of lakes in the Lena River Delta, MANASYPOV et al. (2014) focused on thermokarst lake waters in different permafrost zones, and SHIROKOVA et al. (2013) found a negative correlation between DOC concentration and the size and age of thermokarst lakes. But different landscape units and their influence on the amount of DOC and other water chemistry parameters in permafrost landscapes have not been thoroughly investigated. This knowledge gap will be addressed by this thesis, which aims at quantifying the contribution of different landscape units, hydrological processes, thawing permafrost and their interrelation to the surface water chemistry and their transport to the headwaters. Therefore, the relationships between landscape units, water chemistry and hydrology will be examined for a small catchment in the Lena River Delta, Siberia.

This will be done by analyzing the contribution of different periglacial landscape units to the DOC concentration, pH value, electrical conductivity and isotope composition in surface waters. In addition to this spatial analysis the temporal variability during the summer period will also be examined as well as the relationship of the DOC concentration with other hydro chemical parameters and hydrological conditions within the catchment.

In summary, this thesis will answer the following research questions:

- Which landscape units can be determined in the study site?
- How do hydrochemical parameters vary spatially between the different landscape units?
- Which sources of DOC can be distinguished?
- How does DOC vary during the sampling periods?
- How much DOC is transported into the Lucky Lake and further into the Olenyokskaya Channel?

2 Scientific background

2.1 Permafrost

Permafrost is defined as "ground (i.e. soil and/or rock) that remains at or below 0 °C for at least two consecutive years" (FRENCH, 2007). It captures more than 20 % of the worlds land area (FRENCH, 2007) and is primarily located in the polar regions. There are four major zones in permafrost distribution: the continuous, the discontinuous, the sporadic and the isolated permafrost zone (*Figure 1*). In the continuous zone 90 to 100 % of the area is underlain by permafrost. In the discontinuous zone 50 to 90 %, in the sporadic zone 10 to 50 % and in the isolated zone less than 10 % of the area is underlain by permafrost. Permafrost also occurs in mountain regions, like the European Alps. Permafrost is driven by several factors which controls its distribution. Climate is one of the most important drivers, followed by snow cover, topography, vegetation, material and water bodies (FRENCH, 2007).

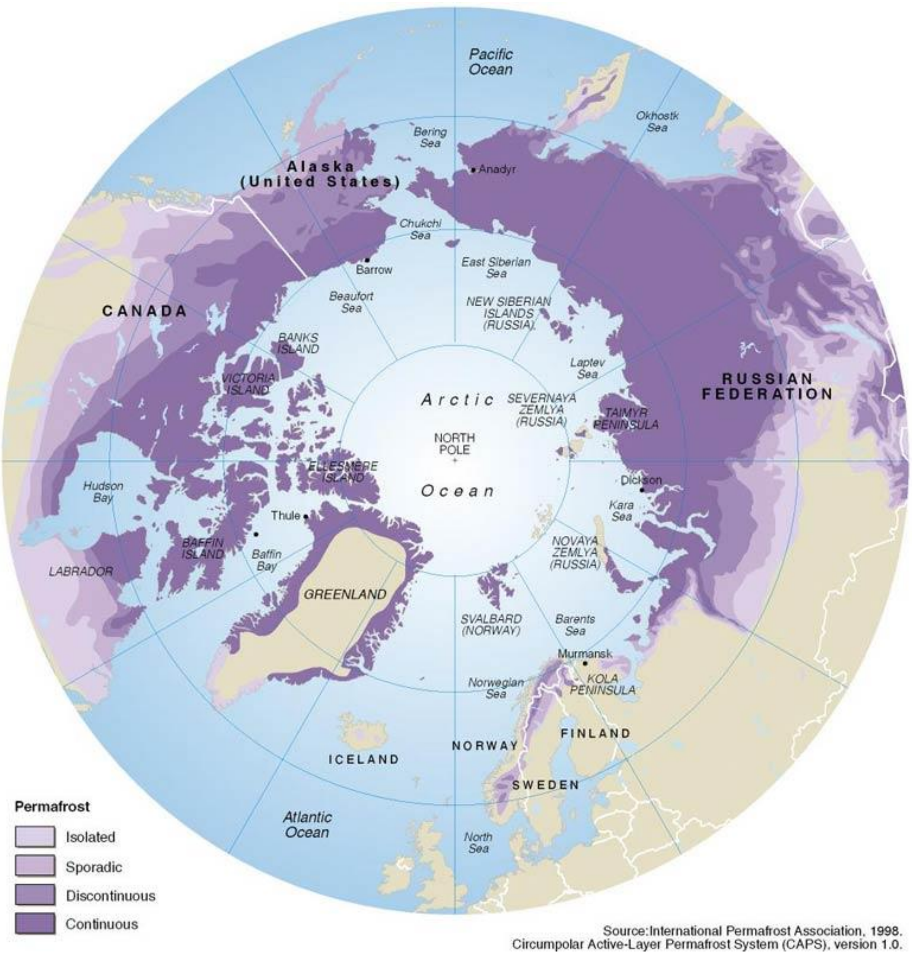

Figure 1: *Permafrost extent*

Permafrost is overlain by a layer which freezes in autumn and thaws in summer. This active layer varies in depth which also depends on the location and the enumerated driving factors. During the Weichsel glaciation Siberia was not glaciated to a greater extend and the ground was not protected from continuously cold air by an isolating snow cover. This climatic history leads to a permafrost depth of up to 1,500 m in Siberia compared to a permafrost depth of 20 m in Scandinavia. *Figure 2* schematically shows a profile between the Arctic Ocean and the Sea of Japan with permafrost characteristics that vary by latitude. It clarifies the increasing depth of permafrost and decreasing active layer thickness with higher latitudes and higher mean annual air temperature. The non-frozen area in permafrost is called talik (FRENCH, 2007).

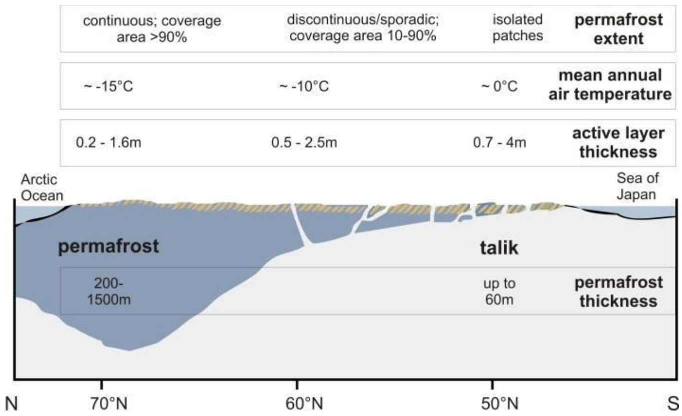

Figure 2: *Permafrost transect (after FRENCH 2007, modified by STRAUSS 2010)*

2.1.1 Ground ice

The term ground ice contains all types of ice in freezing and frozen ground and is characteristic for permafrost (VAN EVERDINGEN, 2005). Ground ice consists of loose sediments which is conjunct with ice. Thereby ground ice content in permafrost and landscape stability are closely linked. This means that degradation processes of permafrost leads to loss of stability in the landscape system (ROMANOVSKY et al., 2007).

2.1.2 Yedoma Ice Complex

Several definitions exist for the term ‘Yedoma’. In this thesis Yedoma is defined as a type of Ice Complex with ice-rich syngenetic permafrost deposits. The term ‘Ice Complex’ describes frozen deposits of different ages, compositions, genesis and thickness (SOLOV’EV, 1959). Driven by specific climatic and environmental conditions in the late

Pleistocene, Yedoma is originated from sedimentation and syngenetic freezing (SCHIRRMEISTER et al., 2013). Due to the high ground ice content Ice Complex is sensitive to climate warming and prone to degradation. So the ongoing global warming could transform the organic-rich Ice Complex from a long-term carbon sink to a carbon source that releases greenhouse gases (ZIMOV et al., 2006; SCHUUR et al., 2008). At thaw slumps, lake shores, and river banks Yedoma deposits are disclosed (SCHIRRMEISTER et al., 2013). Typical for landscapes with Yedoma are especially large ice wedges and large amounts of fossil organic carbon (SCHIRRMEISTER et al., 2011a). Interactions of climatic, landscape and geological preconditions are drivers of the Yedoma formation (SCHIRRMEISTER et al., 2013). In the first step of Yedoma formation accumulation of windblown snow, plants and fine-grained mineral detritus occurs in areas of e.g. low mountain ranges, areas among hills, steep slopes, valleys and cryoplanation terraces (*Figure 3a*). A mat of detritus gets formed and transported by meltwater. Downslope mineral debris and plants accumulate. Then fine-grained sediments are formed due to cycles of freeze and thaw in combination with wet conditions (*Figure 3b*). Fine-grained detritus gets transported by slope wash, solifluction, permafrost creep, alluvial, proluvial, colluvial and/or eolian processes (*Figure 3c*). This leads to the accumulation of different Yedoma deposits and to a development of polygonal ice-wedges by aggraded sediments (*Figure 3d*) (SCHIRRMEISTER et al., 2011b).

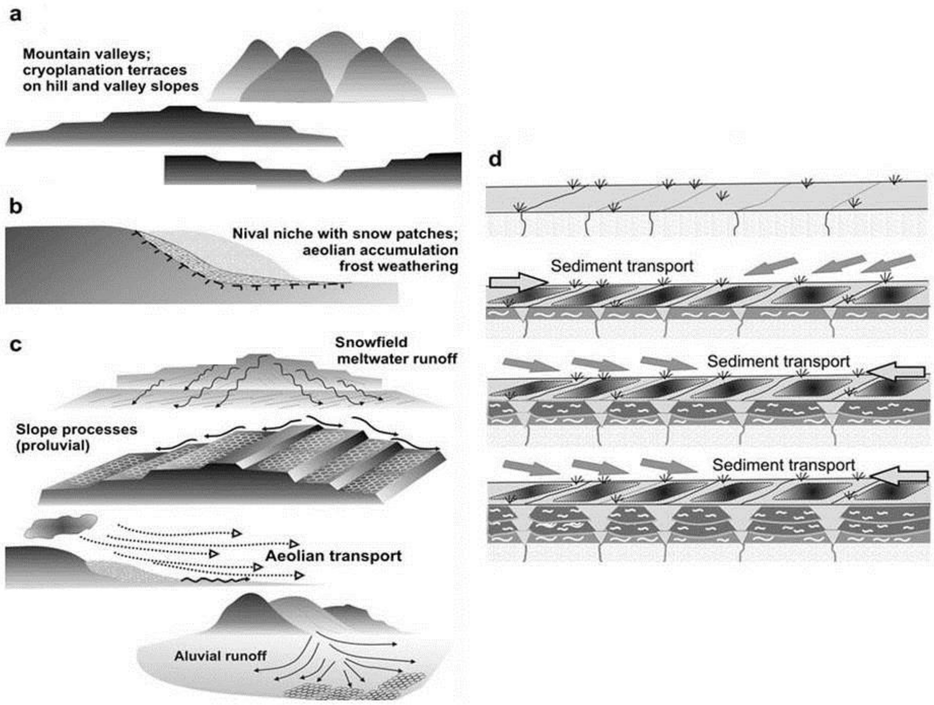

Figure 3: *Ice Complex formation (modified after SCHIRRMEISTER et al., 2011b)*

2.2 Permafrost degradation

Permafrost undergoes degradation processes due to its climate sensitivity and the ongoing global warming. These include permafrost warming, active layer deepening and decrease in permafrost thickness and extent. Those processes started after the Last Glacial Maximum 21,000 years BP (GROSSE et al., 2013). Two major types of permafrost degradation interacting with each other are thermokarst and thermal erosion.

2.2.1 Thermokarst

Thermokarst is a process which forms characteristic landscapes. It is defined as surface thaw of ice-rich ground or melting of massive ground ice. This process results in surface subsidence and leads to the formation of thermokarst lakes and basins (VAN EVERDINGEN, 2005). Changes in geomorphology, vegetation and climate are the main causes of thermokarst. Thermokarst processes are linked with globally significant emissions of methane from associated thaw lakes (FREY & MCCLELLAND, 2009).

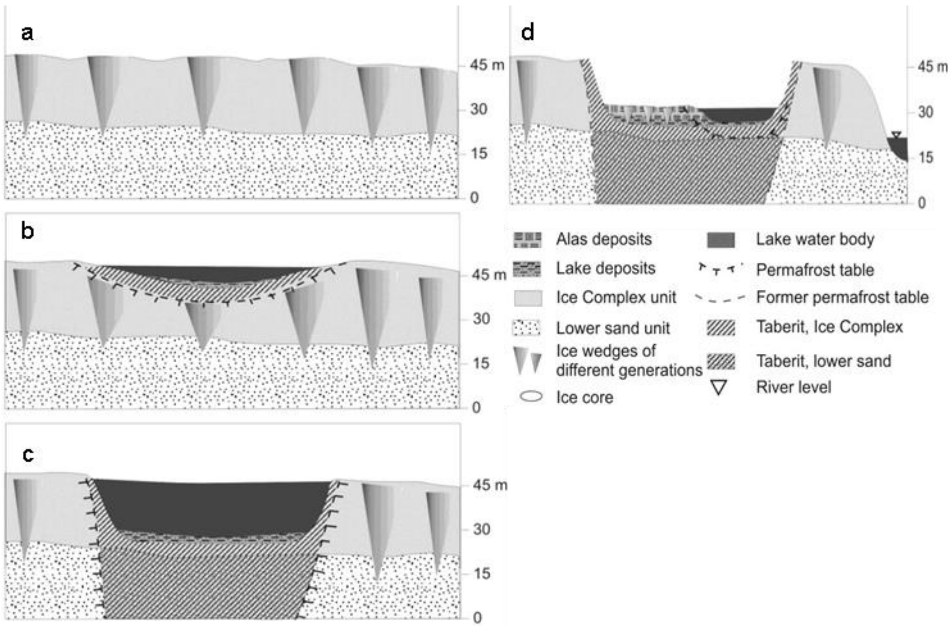

Figure 4: *Scheme of thermokarst development in cross section (modified after MORGENSTERN et al., 2011)*

As a consequence of increasing soil temperature massive ground ice starts to thaw and the ground surface collapse. *Figure 4a* schematically shows the undisturbed Yedoma uplands with polygonal tundra in the Lena River Delta. Due to thawing of ice-rich permafrost surface subsidence starts and meltwater of massive ground ice as well as meteoric water collects in the thermokarst basin (*Figure 4b*). In this initial stage of thermokarst development lake sedimentation occurs and the talik is in a non-steady state. *Figure 4c* shows a thermokarst lake, which has thawed deposits of the Ice Complex in its basin and developed a talik. Subsequent to this stage the thermokarst basin with the thermokarst lake gets partially drained, and refreezing of former taliks, lake sediments with ice aggradation and peat accumulation occur (*Figure 4d*) (MORGENSTERN et al., 2011). This development is accompanied by changes in surface hydrology, disturbance of vegetation, and mobilization of organic carbon pools (ZIMOV et al., 1997; OSTERKAMP et al., 2000; GROSSE et al., 2011). Thermokarst lakes range in size from 100 m to several kilometers in diameter and the depth depends on the amount and distribution of ground-ice (GROSSE et al., 2013). Lakes formed by thermokarst in the Lena River Delta are usually not more than 5 m deep (BOIKE et al., 2015).

2.2.2 Thermal erosion

Thermal erosion is defined as erosion of ice-bearing permafrost. This process is characterized by the combination of thermal and mechanical action of moving water (VAN EVERDINGEN, 2005). Typical locations for thermal erosion are river banks and coastlines, lake shores, and partially ice-rich lowlands. Thermo-erosional gullies and thermo-erosional valleys or valley streams are the resulting landforms in lowlands (MORGENSTERN et al., 2012).

2.3 Permafrost hydrology

Because permafrost acts as an impermeable layer, in continuous permafrost landscapes hydrologic fluxes from groundwater are negligible to non-existent (FRENCH, 2007). In discontinuous permafrost landscapes the lake water balance is influenced by groundwater flux. Sub permafrost groundwater movement is limited to taliks (*Figure 2*) and lateral water movement is limited to the active layer (supra permafrost groundwater). Three types of taliks exist. The supra-permafrost talik occurs below water bodies whereas intra-permafrost taliks are enclosed lenses within permafrost. Sub-permafrost taliks occur in unfrozen zones beneath permafrost (FRENCH, 2007). Regarding to thermokarst lakes, snowmelt in spring, rainfall in summer, and contribution of ground-ice regulates the storage of water (GROSSE et al., 2013). In winter, water balance of thermokarst lakes is locked.

2.4 Permafrost carbon

Soils are the second largest reservoirs of carbon, following the oceans with a carbon reservoir of 40,000 Gt (ZIMOV et al., 2009). ZIMOV et al. (2009) estimated the permafrost reservoir to be about 900 Gt with about 500 Gt in Yedoma ice type whereas TARNOCAI et al. (2009) published that terrestrial permafrost stores 1,672 Gt of carbon. Organic carbon is a result of metabolic activities of living organism (e.g. decomposition of plants, bacterial growth) and can be distinguished in particulate (POC), dissolved (DOC), purgeable (VOC) and non-purgeable (NPOC) organic carbon (*Figure 5)*. Organic carbon remaining in an acidified solution after purging it with gas is called non-purgeable organic carbon (NPOC) and organic carbon removed from a sample after purging with an inert gas is called purgeable or volatile organic carbon (VOC). The term 'Organic Matter' (OM) includes DOC and POC (SEMILETOV et al., 2011). Particulate and dissolved organic carbon differ in size, dissolved organic carbon is organic matter that passes a 0.7 µm filter whereas particulate organic carbon is too large. DOC is an important component of the global carbon cycle (BATTIN et al., 2009) and acts as a transport vector for metals and organic pollutants (LAUDON et al., 2012). With water as transport medium, soils with a high content of organic matter causes DOC in rivers and lakes. Autochthonous (produced in lake) and allochthonous (produced in catchment) DOC are subdivisions for DOC in lakes (TRANVIK et al., 2007).

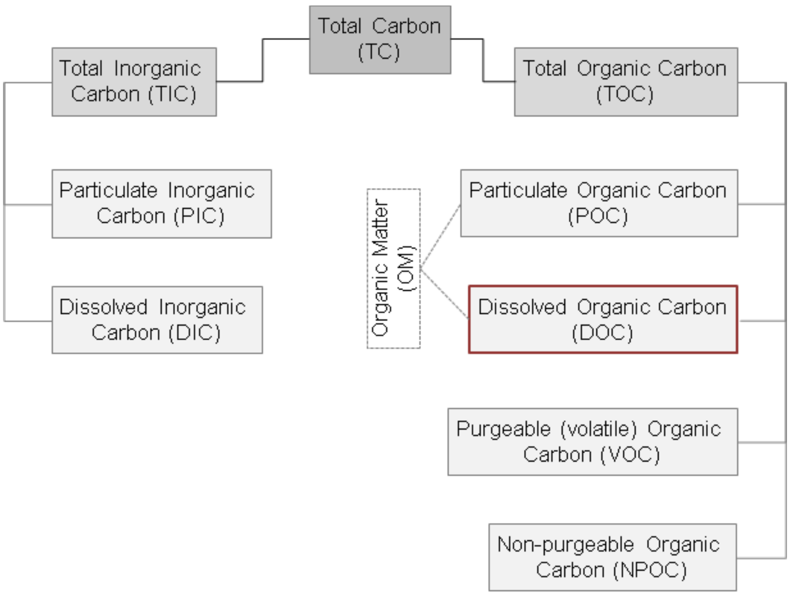

Figure 5: *Subdivision of carbon*

Terrestrial plant detritus, mineral soils and resuspended river sediments are the most dominant riverine allochthonous inputs of DOC (BAUER & BIANCHI, 2011). Via river discharge DOC is transported from arctic land to the Arctic Ocean entering the Arctic carbon cycle. During these processes microbial communities and photochemical reactions lead to DOC mineralization and it returns to the atmosphere as CH_4 and CO_2 (SCHUUR et al., 2009; BAUER & BIANCHI, 2011; FRITZ et al., 2015).

As in *Figure 6* shown the Artic carbon cycle includes two stocks of carbon: the terrestrial and the oceanic. Between those two carbon stocks a transfer of DOC, DIC, POC, PIC and CH_4 from the Arctic land stock to the Arctic Ocean stock occurs. Between the atmosphere and both arctic carbon stocks an exchange of CO_2 and CH_4 exists. Additionally between Arctic Ocean carbon stock and Pacific and Atlantic Ocean there is an exchange of DOC, DIC, and CH_4 (MCGUIRE et al., 2009). Several studies (e.g. HOLMES et al., 2008; FREY & MCCLELLAND, 2009) found substantial seasonal variability in lability of DOC. In spring, by short residence time and cold temperatures limiting microbial processes, DOC is relatively labile. DOC in summer is relatively refractory because an increased thaw depth causes limited interactions with shallow organic soils and slow water movements (HOBBIE et al., 2000; STRIEGL et al., 2005; WICKLAND et al., 2007; HOLMES et al., 2008; FREY & MCCLELLAND, 2009). Permafrost degradation is an important reason for the transport of DOC from highly organic soils to rivers and lakes and further due to river discharge or lake drainage to the Arctic Ocean.

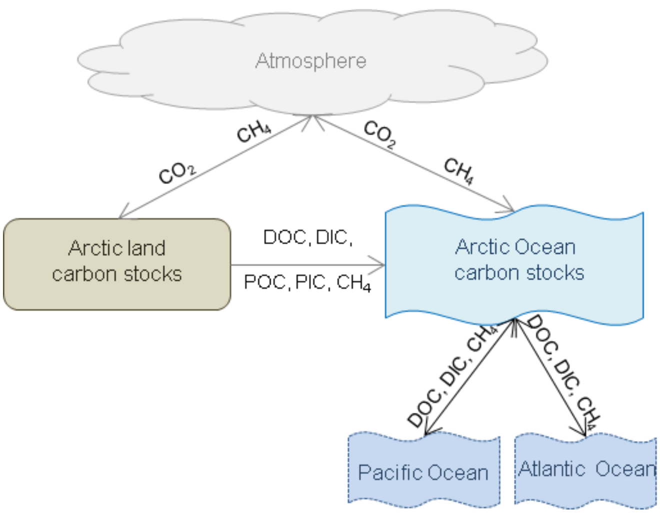

Figure 6: *Arctic carbon cycle (after MCGUIRE et al., 2009)*

3 Study area

3.1 Regional setting

With a length of 4,400 km the Lena River is one of the biggest rivers in Russia and one of the six largest Arctic watersheds (FREY & MCCLELLAND, 2009). The Lena River Delta covers an area of 29,000 km^2 with thousands of islands (SCHNEIDER et al., 2009). The Lena River Delta region is underlain by continuous permafrost with a mean annual temperature of -10 °C at 10 m depth but observations since 2006 noticed that it has warmed by more than 1.5 °C at 10.7 m depth (BOIKE et al., 2013; 2015). The study area in the southern part of Kurungnakh Island (72° 23'N; 126° 03'E) in the Lena River Delta is located in the continuous permafrost and subarctic tundra zone. It is characterized by continental arctic climate with short cold summers with mean temperatures between 4 and 8 °C in July and long winters with mean temperatures between -36 and -32 °C in January (MORGENSTERN, 2012). The mean annual precipitation is about 260 mm (BOIKE et al., 2008).

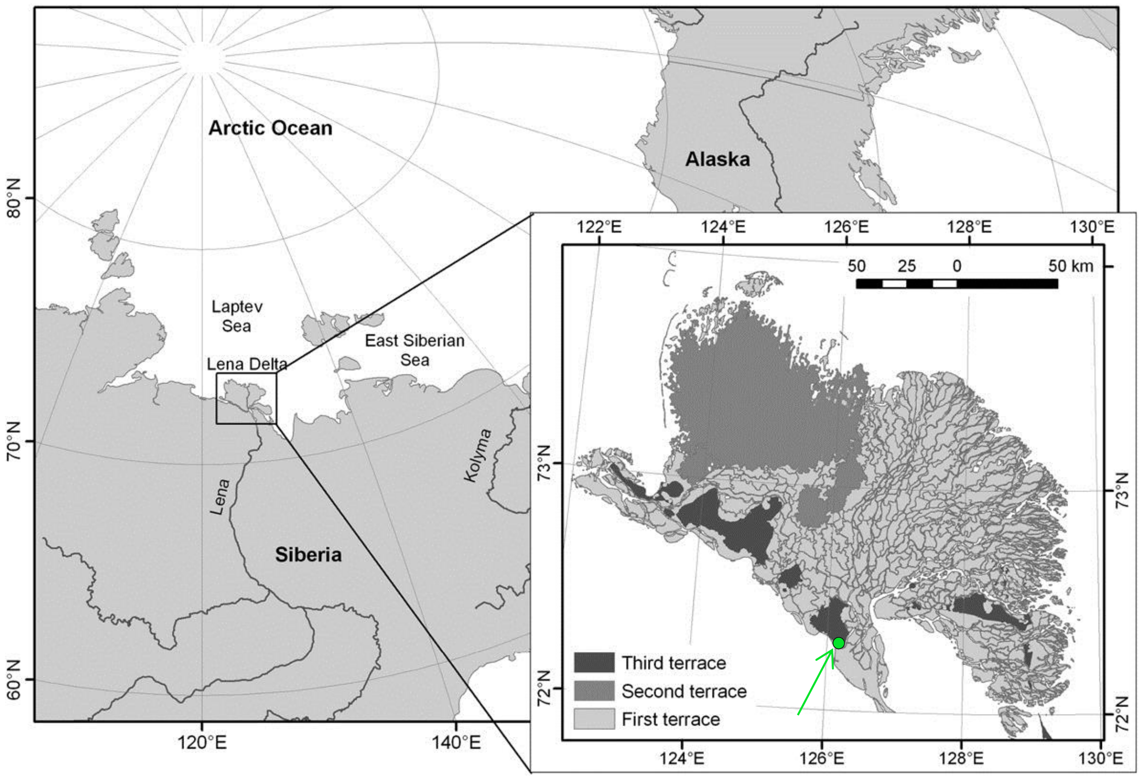

Figure 7: *Regional setting and distribution of the three geomorphological terraces in the Lena River Delta (modified after* SCHNEIDER *et al., 2009). The green dot marks the study site.*

Studies of SCHWAMBORN et al. (2002) showed that the Lena River Delta can be divided in three main geomorphological terraces *(Figure 7)*. This subdivision is due to different ages of sediments and deposits, as a consequence of their genesis. The first terrace is the youngest terrace and formed during the Mid Holocene. Patterned ground of ice-wedge polygons, thermokarst lakes, active flood plains and ice-rich sediments characterizes the terrace with a surface elevation of 1-12 m above sea level (a.s.l.) (SCHWAMBORN et al., 2002).

The second terrace is characterized by a lack of silt, clay or organic matter and low ice content (SCHWAMBORN et al., 2002; BOIKE et al., 2013). It was formed during the transition from Late Pleistocene to the Holocene and has a surface elevation of 11-33 m (a.s.l.) (SCHNEIDER et al., 2009).

The third terrace was formed in the foreland of Chekanovsky and Kharaulakh ridges, which contains remnants of Ice Complex accumulated during the late Pleistocene (SCHWAMBORN et al., 2002; SCHIRRMEISTER et al., 2003). The surface of the third and oldest terrace is characterized by thermokarst depressions with circular lakes and thermo-erosional valleys. This terrace reaches mean elevations of 30-40 m above sea level. The occurring fluvial sands, with plant remains and alluvial peaty layers with high gravimetric ice content, originate from the early and middle Weichselian period (SCHWAMBORN et al., 2002; SCHIRRMEISTER et al., 2011b).

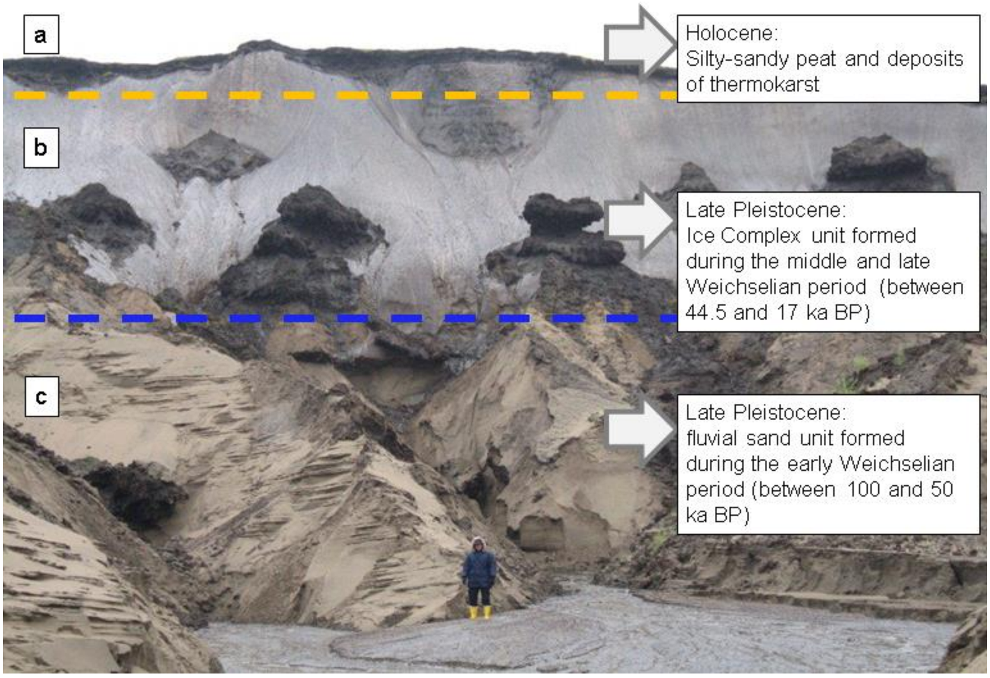

Figure 8: *Stratigraphical composition of the third terrace (Photo by M. Ulrich 2008)*

Divided in two late-Pleistocene units and one Holocene unit (*Figure 8*), each unit of the third terrace is characterized by different properties (SCHWAMBORN et al., 2002; SCHIRRMEISTER et al., 2003, WETTERICH et al., 2008). The oldest unit (*Figure 8c*) contains fluvial, interbedded medium-to-fine-grained and silty sand deposits with inclusions of plant remains and peaty layers, and a gravimetric ground ice content of 20-40 wt% (MORGENSTERN et al., 2011). The Ice Complex unit of the late Pleistocene (*Figure 8b*) is characterized by peat, silty sand, and peaty paleosoil layers with 38-133 wt% gravimetric ground ice content (MORGENSTERN et al., 2011). Ice bands, lens-like reticulated ice veins in mineral-rich layers, and especially tall ice wedges with gas bubbles characterizes the Ice Complex cryostructure (SCHIRRMEISTER et al., 2011b). The youngest unit from the Holocene (*Figure 8a*) contains silty-sandy peat and deposits of thermokarst (SCHIRRMEISTER et al., 2003).

3.2 Study site

The study site is located in the south of Kurungnakh Island in the Lena River Delta and includes the Lucky Lake, its inflows and outflows, and surrounding lakes. The first and the third terrace (Yedoma Ice Complex) are the main geomorphological units in this area. Partially Kurungnakh Island and thus also the study site is overlain by Yedoma Ice Complex deposits (SCHWAMBORN et al., 2002), which have been affected by terrain subsidence and surface changes due to thermokarst and thermal erosion since the transition from Pleistocene to Holocene. The study site is characterized by different periglacial landscape units (e.g. Yedoma uplands, thermokarst lakes and basins, thermo-erosional gullies, streams, polygonal tundra and ponds of the first terrace), which were formed since 13 to 12 ka BP (MORGENSTERN et al., 2011; 2012). The development of thermokarst in the study area was driven by changes in climate conditions to a warmer and more moisture climate during the transition from late Pleistocene to Holocene.

The Lucky Lake is a thermokarst lake, which has deeply subsided into the Yedoma upland and is therefore bordered by steep slopes. In the northeast of the lake the Ice Complex landscape drains into the lake by two gulleys (*Figure 9*). In the southeast a second thermokarst lake (Oval Lake) drains into the Lucky Lake and the main outflow, connecting Lucky Lake and Olenyokskaya Channel, is located at the southwestern shore of Lucky Lake.

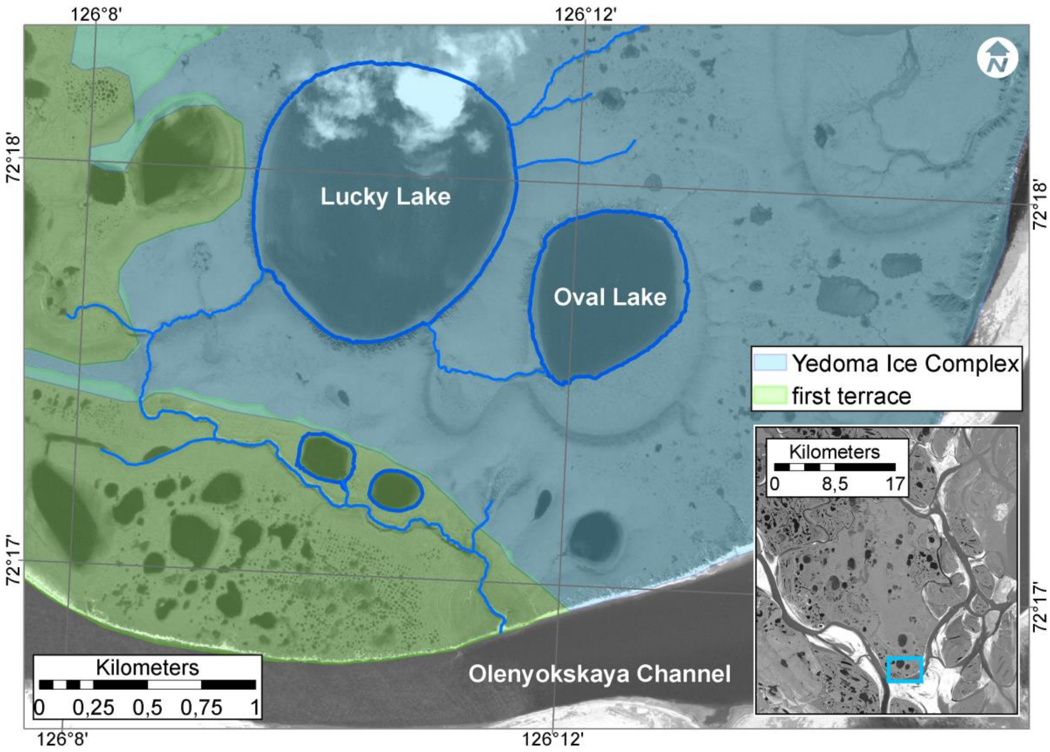

Figure 9: *Study site in the south of Kurungnakh Island. Background image: GeoEye, band combination 3,3,3(r, g, b) projection UTM Zone 52N within WGS 84 datum. Overview image: RapidEye, band combination 3,3,3(r, g, b) projection UTM Zone 52N within WGS 84 datum.*

3.2.1 Vegetation

Due to extreme climate conditions in the Arctic, the vegetation period in the Lena River Delta is limited to three months in summer. Thereby the vegetation is poor in species (SCHULTZ, 2000). According to the land cover classification of SCHNEIDER et al. (2009) vegetation vary between the different terraces of the Lena River Delta. The first terrace, represented at the southern tip of the study site, is allocated to the wet, sedge- and moss-dominated tundra as well as to the moist grass- and moss-dominated tundra. At the major channels mainly non-vegetated and shallow water areas are characteristic. The third terrace, the northern part of the study site, is characterized by moist grass- and moss-dominated tundra as well as dry tussock tundra.

4 Methods

The methodological approach combines laboratory work for hydrochemical measurements and analysis of satellite imagery with a geographical information system (GIS) (*Figure 10*). For analyses and interpretation isotopic composition of the collected samples, discharge data of 2013, meteorological date and literature was used.

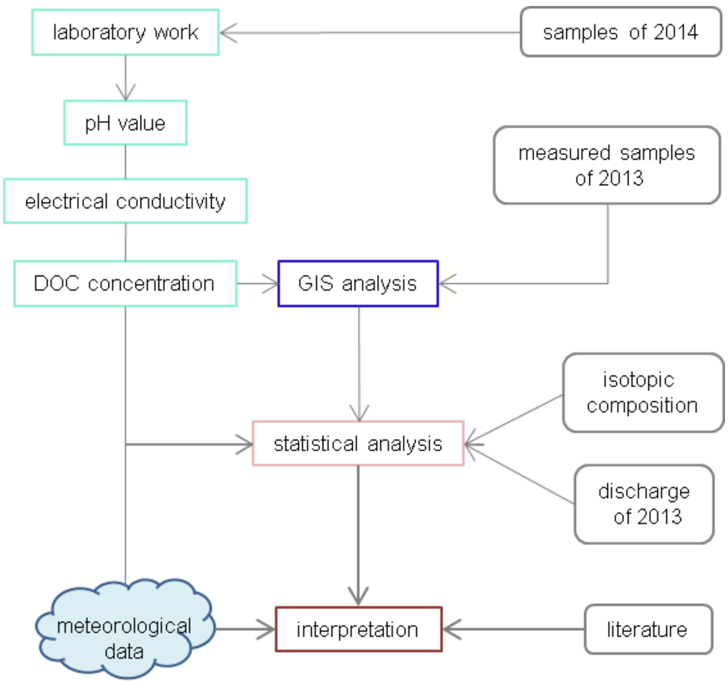

Figure 10: *Methodology of this thesis*

4.1 GIS analyses and landscape units

Using ArcGIS (10.3, ESRI) satellite imagery was analyzed to identify different landscape units in the study area (*Figure 11*). At first the study area was divided into major geomorphological units. Shapefiles of thermokarst lakes and basins in the study area were available from MORGENSTERN et al. (2011). These boundaries were used to determine thermokarst lakes in the study area. Additionally streams of the thermokarst lake Lucky Lake and its inflows were digitized in GIS on the basis of GeoEye satellite imagery (UTM Zone 52N within WGS 84).

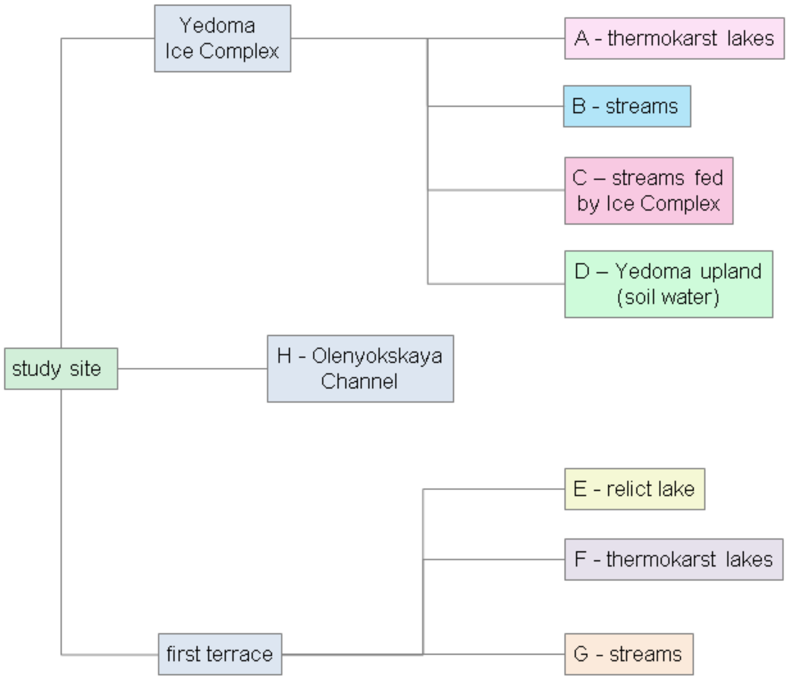

Figure 11: *Decision tree to divide the study area in landscape units.*

4.2 Meteorological data

Meteorological data for the study site were available from Samoylov Island weather station. This station was installed in 1998 (BOIKE et al., 2008) and recorded data including air temperature (2 m height), radiation, humidity, wind speed and direction, and snow depth (BOIKE et al., 2013). Measurements of air temperature in °C in 30 minutes intervals were averaged for each day. The half-hourly measurements of precipitation in mm were summed for each day.

4.3 Discharge

During field work in 2013 two weirs were installed Lena Delta expedition members at the outflow of Lucky Lake on Yedoma Ice Complex and downstream on the first terrace (*Figure 12*). Both weirs are combined with a radar height sensor. In 10 minute intervals a sill referenced water level was measured. This water level (mm) was subtracted from sensor height and discharge (l s^{-1}) was calculated by using the following formula:

$$Q = 0.0000004 * (WL)^3 + 0.0011 * (WL)^2 + 0.1358 * (WL) - \sqrt{(WL)} + 3.488.$$

Q is discharge and WL is the sill referenced water level subtracted from sensor height (RBC FLUME, 2000). Measurements of weir 1 were already analyzed and discharge was calculated by NIEMANN (2014).

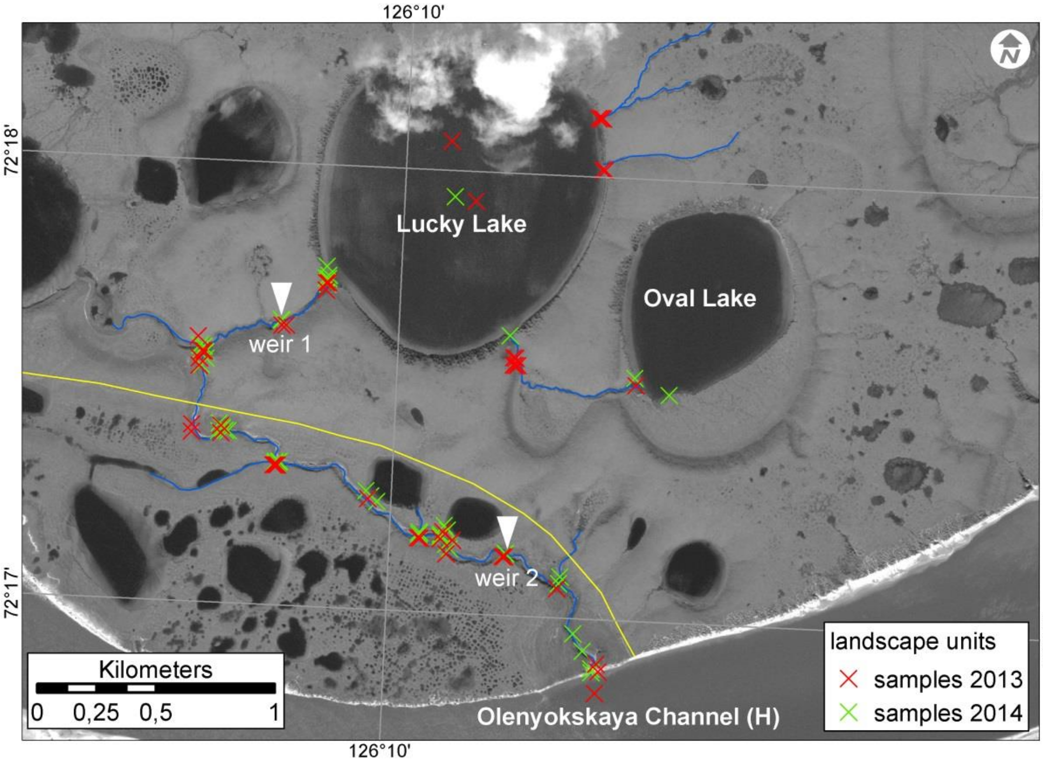

Figure 12: *Location of weirs (white arrow) and sample collection. The yellow line divides the study area in Yedoma Ice Complex (above) and first terrace (bellow). Background image: GeoEye-1, band combination 3,3,3(r, g, b) projection UTM Zone 52N within WGS 84 datum.*

Additionally, this data were available in m^3 d^{-1} for the time period from 27.07.2013 to 26.08.2013 (NIEMANN, 2014). Discharge measurements of weir 2 were analyzed after NIEMANN (2014), by using the data records (l s^{-1}), and were converted into m^3 d^{-1}. The discharge data of 2013 was used to calculate the flux of DOC at both weirs. The DOC flux is the product of summed discharge and DOC concentration.

4.4 Hydrochemical analyses

In this thesis 198 water samples of 2013 and 2014 were analyzed (*Figure 12*). Lena Delta expedition members collected 96 water samples in summer 2013, which were already measured by laboratory staff. Hence, results of lab analysis for hydrochemical parameters of 2013 were available for this thesis. In summer 2014 overall 102 surface water samples were collected from Lena Delta expedition members (*Table 1*) but hydrochemical measurements to determine pH value, electrical conductivity and DOC concentration for those samples had to be carried out. Fresh samples were collected with a 250 ml bottle. As backup sample and for isotope analyze 30 ml of the original sample were filled in two smaller bottles.

Table 1: *Number of collected water samples in each landscape unit*

Landscape unit		**2013**	**2014**
Yedoma Ice Complex	A - thermokarst lakes	12	4
	B - streams	18	17
	C – streams fed by Ice Complex	5	0
	D – Yedoma uplands (soil water)	23	0
First terrace	E – relict lake	1	3
	F - thermokarst lakes	3	9
	G - streams	20	24
Olenyokskaya Channel	H	14	45
Total		96	102

For analyzes of DOC 20 ml of the sample was filtered by a 0.7 µm pore size filter, preserved with 20-50 µl of 30 % hydrochloric acid (HCl) and send to Alfred Wegener Institute in Potsdam. The laboratory results of 198 water samples, which have been mapped after fieldwork, were allocated to the determined landscape units by using the decision tree (*Figure 11*).

4.4.1 pH value

The pH value indicates whether a solution is acidic or alkaline and ranges between 0 (acidic) and 14 (alkaline). With a pH value of 7 a solution is neutral. To determine the pH value a pH meter (WTW MultiLab 540) were used. A small amount of each sample was filled into a measurement glass and the electrode of MultiLab was inserted. The voltage between glass and reference electrode is used for the calculation of the pH value (Handbook WTW, 1989).

4.4.2 Electrical conductivity

The electrical conductivity indicates the concentration of ions (anions and cations) in a sample. A high electrical conductivity means a high concentration of ions and vice versa. Measured with MultiLab 540 the electrical conductivity is recorded in µS cm^{-1} and applied to a reference temperature of 25 °C (Handbook WTW 1993).

4.4.3 Stable hydrogen and oxygen isotopes

Isotope analyses of hydrogen (δD) and oxygen ($\delta^{18}O$) were already measured with a Finnigan MAT Delta-S mass spectrometer at the isotopic lab of Alfred Wegener Institute in Potsdam by using the equilibration technique (MEYER et al., 2000). This samples were collected from Tiksi (71°38’N, 128°52’E), which is close to the Lena River Delta. The results are given as permil difference to V-SMOW (‰ vs. VSMOV) and plotted in a $\delta^{18}O$-δD diagram. The lowest $\delta^{18}O$ and δD values reflect the coldest temperature. Vice versa, higher $\delta^{18}O$ and δD values reflect warmer temperatures (MEYER et al., 2002). DANSGAARD (1964) defined that precipitation deriving from evaporation of ocean water and secondary evaporation processes can be identified by the slope in a $\delta^{18}O$-δD diagram. The Global Meteoric Water Line (GMWL) was defined by CRAIG (1961) as reference and is a linear correlation of worldwide freshwaters. It is expressed as:

$$\delta D = 8 * \delta^{18}O + 10.$$

The isotopic composition of water varies due to the process of fractionation. CLARK & FRITZ (1997) described this process as temperature-dependent, which take place during phase changes. Two types of fractionation occur under kinetic or equilibrium conditions. Hence, this process is linked to evaporation/condensation and freezing/melting. The slope of the GMWL is about 8. A lower slope of about 4 to 5 and a larger deviation from the GMWL indicates that evaporation occurred. Disequilibrium processes result in deviation from the GMWL and δ values above the GMWL. With a trend to lower δ values (first meltwater) and afterwards to higher δ values (final meltwater) melting is a fractionation process in disequilibrium (CLARK & FRITZ, 1997). Additionally mean δ values of rain were available from KLOSS (2008).

4.4.4 DOC concentration

High-temperature catalytic combustion, low-temperature chemical oxidation and photochemical oxidation are the main methods for the measurement of DOC concentration (BAUER & BIANCHI, 2011). In this study 'Shimadzu TOC-V_{CPH}' for high-temperature catalytic combustion was used. For the monitoring during the measurement and validation of the results, standard samples and blank samples (ultrapure water) with known concentrations of organic carbon were added to the sample extent.

The direct method or so called NPOC-method (Non-purgeable-organic-carbon) was used to determine the DOC concentration. 9 ml of the sample was filled into a special 9 ml glass vial. Each vial was sealed with an aluminum foil and placed in the vial rack of 'Shimadzu TOC-V_{CPH}'. The vial rack has 93 places for vials. In one measurement cycle about 70 places can be stocked by samples. The remaining rack places were stocked by vials with blank samples and standard samples. During measurement the sample was acidified with hydrochloric acid to a pH value of 2-3 and afterwards treated with oxygen gas, which eliminates the component of inorganic carbon. Total inorganic carbon is converted to CO_2. In the next step NPOC passes the catalyst, where it heats up to 680 °C and the CO_2 passes the NDIR detector (Non Dispersed InfraRed). The NDIR detector measures the concentration and related software calculates the average of up to five measurement procedures of each sample (Manual Shimadzu/TOC-V, 2008). The DOC concentration is recorded in mg L^{-1}.

5 Results

5.1 GIS analyses and landscape units

The major landscape units in the study area in the south of Kurungnakh Island are the Yedoma Ice Complex, the Olenyokskaya channel and the first terrace. Demonstrated in *Figure 13* the area of Yedoma Ice Complex is characterized by flat inclined uplands (D) with thermokarst lakes (A) and basins, and streams (B, C). The streams of the Yedoma Ice Complex in the study site are divided into the stream that drains the Lucky Lake (B), inflows of this stream, and streams, which are fed by the Ice Complex and flow into the Lucky Lake (C). With an area of 1,228,688.9 m^2 and a maximum depth of about 8 m (NIEMANN, 2014) the Lucky Lake is the largest thermokarst lake in the study site. The neighbored Oval Lake has an area of 450,134.6 m^2, a depth of about 9 m (MORGENSTERN et al., 2011) and drains via a stream into the Lucky Lake.

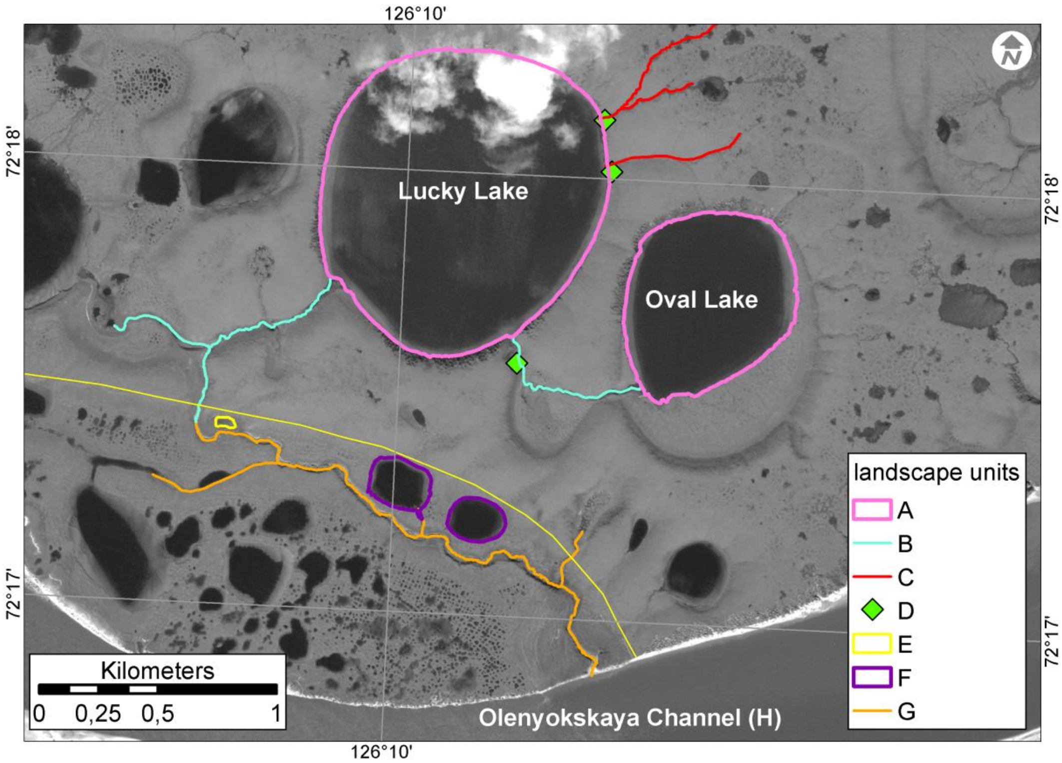

Figure 13: *Landscape units in the study site. A – Yedoma Ice Complex thermokarst lakes, B – Yedoma Ice Complex streams, C – Yedoma Ice Complex streams fed by Ice Complex, D – Yedoma Ice Complex uplands (soil water), E – first terrace relict lake, F – first terrace thermokarst lakes, G – first terrace streams. The yellow line divides the study area in Yedoma Ice Complex (above) and first terrace (bellow). Background image: GeoEye-1, band combination 3,3,3 (r, g, b) projection UTM Zone 52N within WGS 84 datum.*

The three streams in the northeast of the Lucky Lake, which are fed by the Ice Complex, have lengths of 454.9 m, 607.7 m and 1,010.6 m (*Table 2*). These streams, more specifically, are flumes which develop when snow melt begins. The outflow of Lucky Lake, here defined as main stream, has a length of 1,053.7 m on the Yedoma Ice Complex and a bigger inflow from western of the study site with a length of 778.2 m.

The first terrace in the study area is characterized by low elevation, polygonal tundra with numerous ponds, relict lakes (E) and thermokarst lakes (F). The streams of this terrace (G) include the main stream, inflows and the outlet. The main stream on both terraces can be described as valley with a stream course. On the Yedoma Ice Complex the main stream valley has a width of about 200 m, whereas the main stream valley on the first terrace has a width of about 80 m (STETTNER, 2014). Two thermokarst lakes of the first terrace in the study site have been considered in this thesis. With areas of 45,895.2 m^2 and 35,142.3 m^2 they are much smaller than thermokarst lakes on the Yedoma Ice Complex. Additionally one relict lake with an area of 2,883.9 m^2 has been identified, which is a remnant of an almost completely drained lake. The main stream on the first terrace has a length of 2,876.3 m.

Table 2: *Properties of landscape units on Yedoma Ice Complex and first terrace.*

Landscape unit			**area [m^2]**	**length [m]**
Yedoma Ice Complex	A - thermokarst lakes	Lucky Lake	1,228,688.9	
		Oval Lake	450,134.6	
	B - streams	main stream		1,053.7
		inflows		484.4
				778.2
	C – streams fed by Ice Complex			454.9
				1,010.6
				607.7
First terrace	E – relict lake		2,883.9	
	F – thermokarst lakes	Lake 1	45,895.2	
		Lake 2	35,142.3	
	G - streams	main stream		2,876.3
		inflows		571
				119.4
				269.7

Thermokarst lakes on Yedoma Ice Complex (A) drain into the stream on Yedoma Ice Complex (B), further in the stream on the first terrace (G), which is drained by thermokarst lakes on the first terrace (F), and flow into the Olenyokskaya Channel. Hence, landscape unit A, B, F, and G are the drainage flow path, whereas streams, which are fed by the Ice Complex (C), and soil water of Yedoma upland (D) are source water.

5.2 Meteorological data

Meteorological data of 2013 show fluctuating temperature with temperature differences of 11°C in a few days (*Figure 14*). Two bigger precipitation events at the beginning of July (> 200 mm) and in the middle of August (> 160 mm), and a rain event in the beginning of September (> 60) can be noticed. During field period of 2014 a decrease in air temperature from 7 °C to -3.8 °C at the end of May was measured. Afterward the temperature increased to 13 °C within two weeks. Till the end of measurements the temperature fluctuates between about 6.5 °C and about 16.5 °C. Two bigger precipitation events for this time were recorded in the middle of July (> 130 mm) and in the middle of August (> 80 mm).

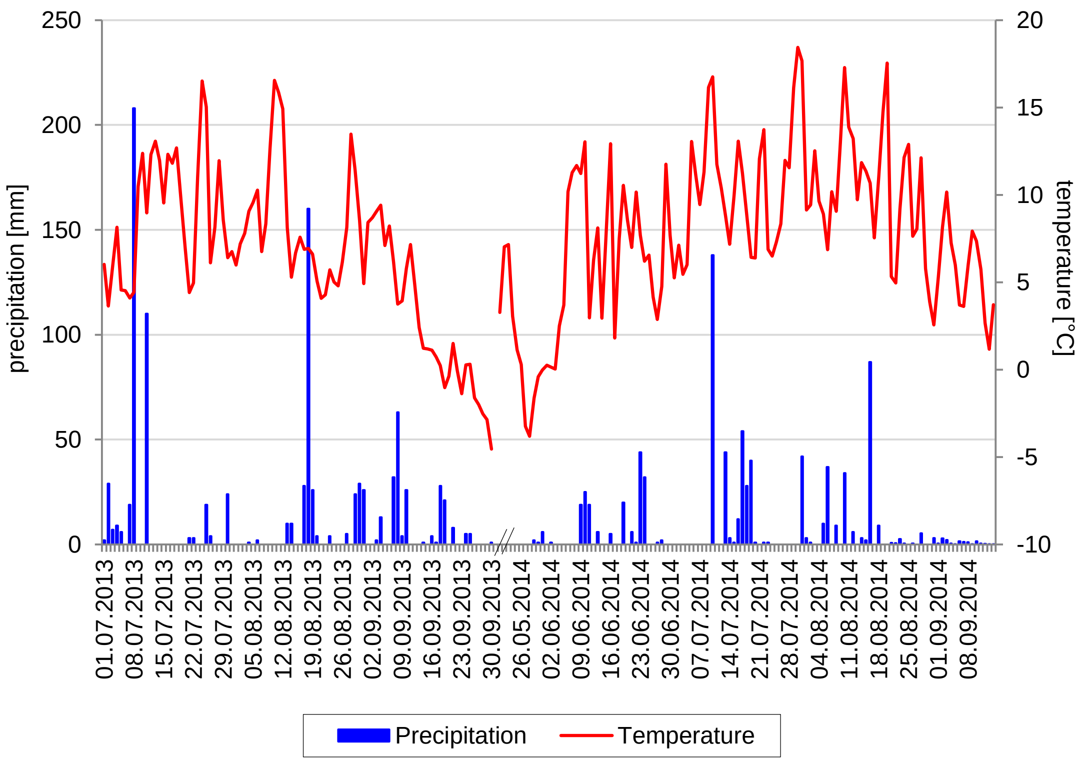

Figure 14: *Meteorological situation during field work in 2013 and 2014.*

5.3 Discharge

The discharge of weir 1 and weir 2 in the main stream were plotted in *Figure 15*. Additionally DOC concentrations of water samples, collected at these weirs during discharge record, were added. Discharge generally decreased during the measuring period. At weir 1 discharge decreased from about 1,700 $m^3\ d^{-1}$ to about 200 $m^3\ d^{-1}$. And at weir 2 discharge decreased from about 3,000 $m^3\ d^{-1}$ to about 500 $m^3\ d^{-1}$. Only due to the precipitation event in August (> 10 mm) the discharge increased at weir 1 from 270 $m^3\ d^{-1}$ to 518 $m^3\ d^{-1}$ and at weir 2 from 1116 $m^3\ d^{-1}$ to 1625 $m^3\ d^{-1}$. DOC concentrations of samples, collected at the two weirs during the period of discharge measurement, were added to the figure. Although discharge differs at both weirs, DOC concentration is similar.

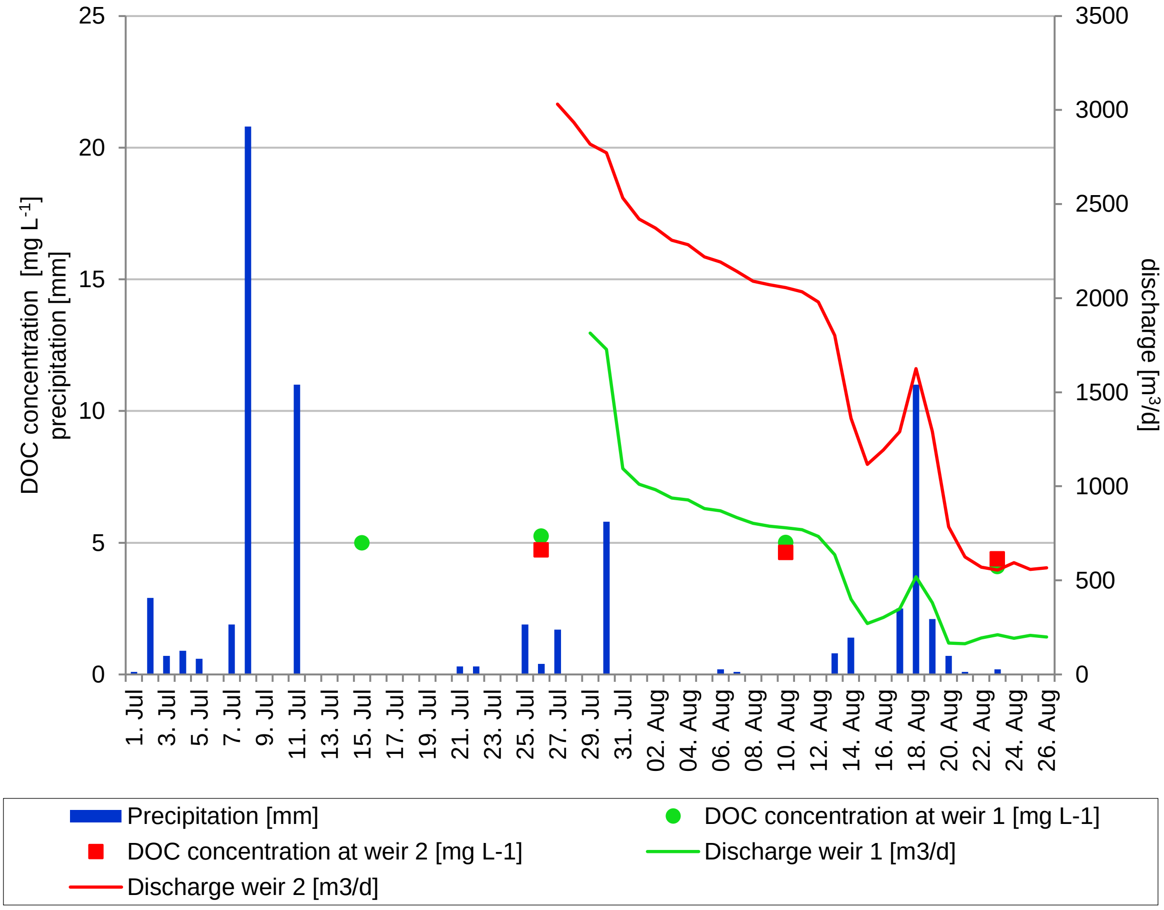

Figure 15: *Discharge of weir 1 and weir 2, daily precipitation and DOC concentration in 2013.*

5.4 Hydrochemical parameters

The hydrochemical parameters were summarized for 2013 and 2014 in *Table 3* and *Figure 16*. Because the values are not normally distributed, the median was used for further considerations.

Table 3: *Summarized DOC concentration [mg L^{-1}], electrical conductivity (EC) [µS cm^{-1}] and pH value of different landscape units for 2013 and 2014.*

Landscape unit			**no. of samples**	**DOC median**	**DOC range**	**EC median**	**EC range**	**pH value median**	**pH value range**
Yedoma Ice Complex	A	thermo-karst lakes	16	5.3	4.9-11.3	131	68-133	7.5	5.8-7.9
	B	streams	35	5	3.5-5.9	126	41-151	7.1	6.6-8
	C	streams fed by Ice Complex	5	10.9	8.9-12.7	47	39-59	6.5	6.2-6.7
	D	Yedoma uplands (soil water)	23	11.9	8.9-52.5	61	35-138	5.9	5.3-6.5
		total	79	5.5	3.5-52.5	110.5	35-151	6.9	5.3-8
First terrace	E	relict lake	4	13.1	11.1-15.6	65	54-91	6.4	5.7-6.6
	F	thermo-karst lakes	12	3.3	2.9-10.1	80.5	64-92	7.2	6.2-7.5
	G	streams	44	4.8	2.8-9.8	95	54-140	7.2	6.7-7.9
		total	60	4.7	2.8-15.6	89	54-140	7.14	5.7-7.9
Olenyokskaya Channel	H	total	59	10.5	4.5-15.7	140	98-542	7.5	6.9-7.8

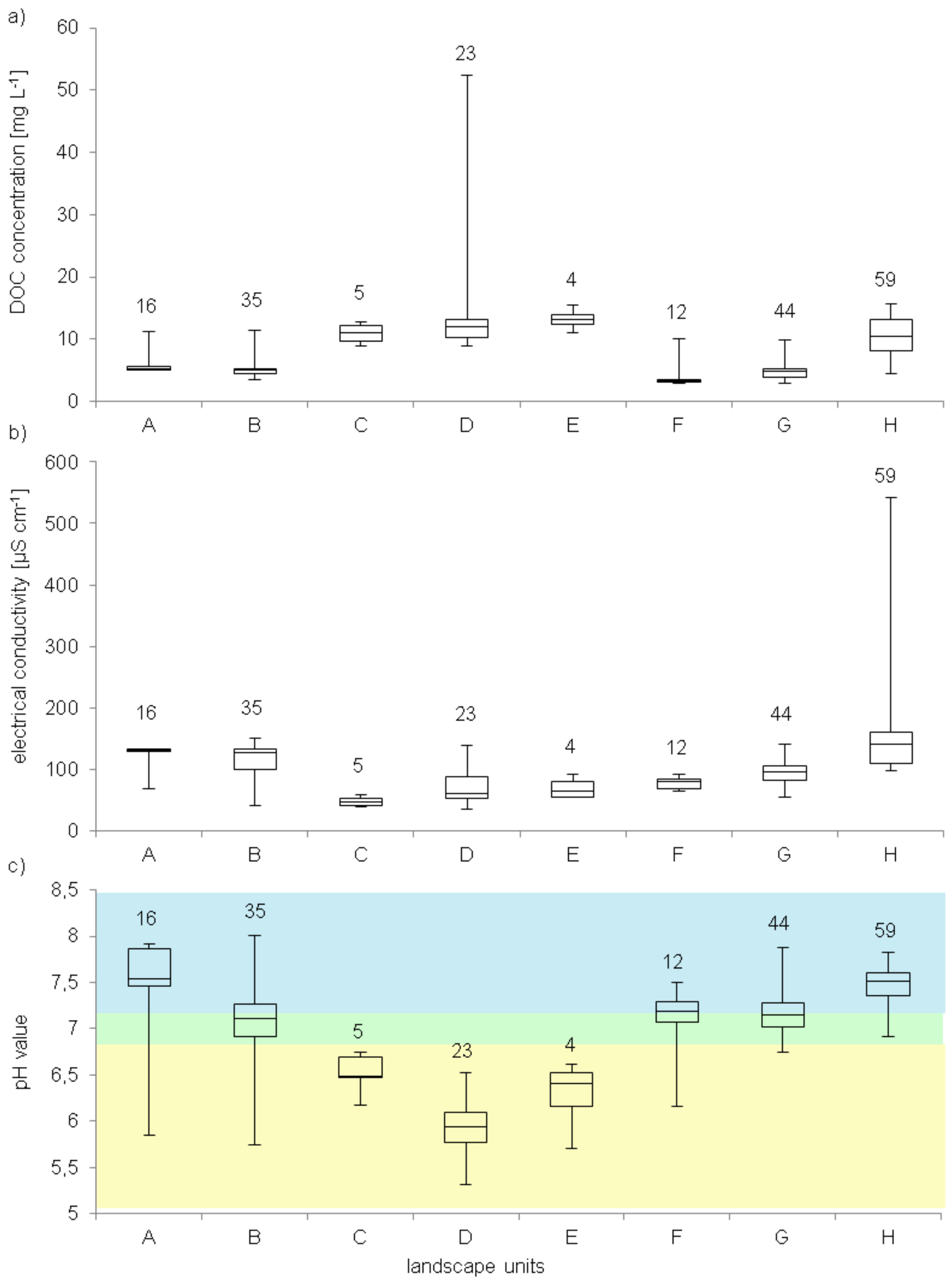

Figure 16: *Boxplots of DOC concentration, electrical conductivity and pH value in different landscape units of the study site for 2013 and 2014. A – Yedoma Ice Complex thermokarst lakes, B – Yedoma Ice Complex streams, C – Yedoma Ice Complex streams fed by Ice Complex, D – Yedoma Ice Complex uplands (soil water), E – first terrace relict lake, F – first terrace thermokarst lakes, G – first terrace streams, H – Olenyokskaya Channel. Plots show minimum, maximum, median, 25th and 75th percentile. Numbers above boxplots indicates amount of samples for each landscape unit.*

5.4.1 pH

Samples of thermokarst lakes of the Yedoma Ice Complex and the Olenyokskaya Channel have a median pH value of 7.5 (*Table 3*), which is the highest value of the different landscape units. It has to be noticed that there is a high range in the 25th percentile for thermokarst lakes on both terraces (*Figure 16c, "A", "F"*). With a median pH value of 5.9, soil water samples of the Yedoma uplands have the lowest value (*Table 3*). *Figure 16c ("C", "D", "E")* shows that these samples are slightly acidic, as well as samples of the relict lake of the first terrace and of streams which are fed by the Ice Complex. Samples of streams on both terraces are almost neutral but their values range widely in the 75th percentile (*Figure 16c, "B", "G"*).

5.4.2 Electrical conductivity

Samples of the Olenyokskaya Channel have the highest median electrical conductivity (140 µS cm^{-1}) and range widely in the 75th percentile (*Figure 16b, "H"*). Comparing thermokarst lakes on both terraces, on the Yedoma Ice Complex they have a higher median electrical conductivity (131 µS cm^{-1}) than thermokarst lakes on the first terrace (80.5 µS cm^{-1}). Streams of the Yedoma Ice Complex have a higher median electrical conductivity (126 µS cm^{-1}) than streams of the first terrace (95 µS cm^{-1}). Streams, which are fed by the Ice Complex, have the lowest median electrical conductivity (47 µS cm^{-1}). Samples of the relict lake of the first terrace and soil water samples of the Yedoma upland have almost similar values (*Table 3*).

5.4.3 Stable hydrogen and oxygen isotopes

δ^{18}O, as expression of the ratio of the stable oxygen ^{18}O and ^{16}O isotopes, and electrical conductivity were plotted (*Figure 17)*. It shows a large range in δ^{18}O values from about -15 ‰ to about -22.5 ‰. The electrical conductivity of the plotted samples ranges from 35 µS cm^{-1} to 151 µS cm^{-1}. A relation between δ^{18}O values and electrical conductivity is shown for thermokarst lakes (A and F) and streams (B and G) on both terraces, which is the drainage flow path (*Chapter 5.1*). Mainly, for these landscape units lower δ^{18}O values accompanied by higher electrical conductivity. Vice versa, higher δ^{18}O values accompanied by lower electrical conductivity (*Figure 17, "A", "B", "F", "G"*). In samples of the remaining landscape units no connection can be determined.

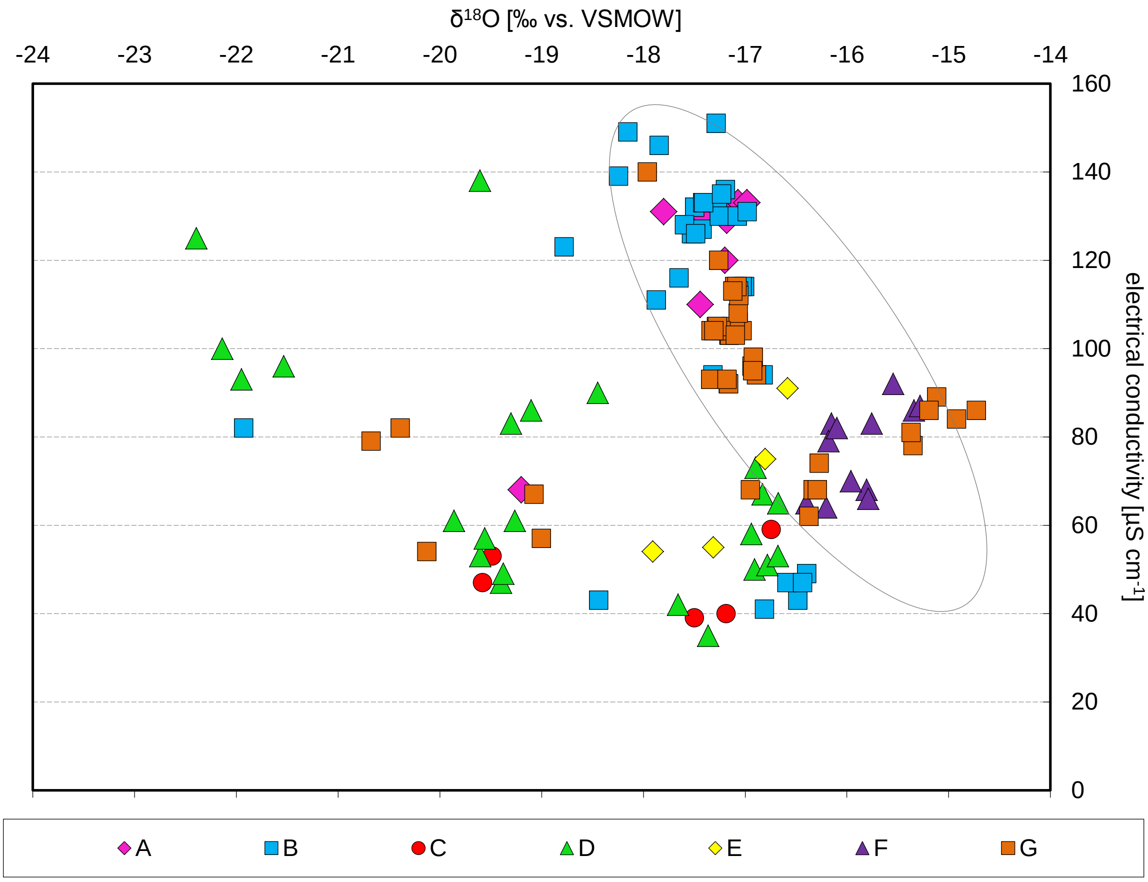

Figure 17: *Conductivity and δ ^{18}O for both years. The grey border marks the drainage flow path with landscape unit A, B, F and G. A – Yedoma Ice Complex thermokarst lakes, B – Yedoma Ice Complex streams, C – Yedoma Ice Complex streams fed by Ice Complex, D – Yedoma Ice Complex uplands (soil water), E –first terrace relict lake, F – first terrace thermokarst lakes, G – first terrace streams.*

δ^{18}O and δD for stable isotopes of hydrogen (D and H) were plotted and the Global Meteoric Water Line (GMWL) was inserted as reference (*Figure 18*). The isotopic composition of thermokarst lake samples on the Yedoma Ice Complex range between -17 and -19.2 ‰ for δ^{18}O and between -135.4 and -138.3 ‰ for δD (*Figure 18, "A"*). In contrast, thermokarst lakes on the first terrace have higher δ^{18}O and δD values (-15.3 to -16.4 ‰ for δ^{18}O and -123.2 to -131 ‰ for δD) (*Figure 18, "F"*). Streams on the Yedoma Ice Complex have δ values ranging between -16.4 and -21.9 ‰ (in ^{18}O) and between -130.1 and -160.8 ‰ (in D) (*Figure 18, "B"*). Mainly δ values of streams on the first terrace are higher than δ values of Yedoma Ice Complex streams but with a larger range between -14.7 and -20.7 ‰ (in ^{18}O) and between -119.4 and -160.8 ‰ (in D) (*Figure 18, "G"*). In contrast, *Figure 18 ("C")* shows that δ values of streams, fed by the Ice Complex, lie closely to the GMWL, partially above the GMWL, and range between -16.7 and -19.6 ‰ (in ^{18}O) and between -125.5 and -141.8 ‰ (in D).

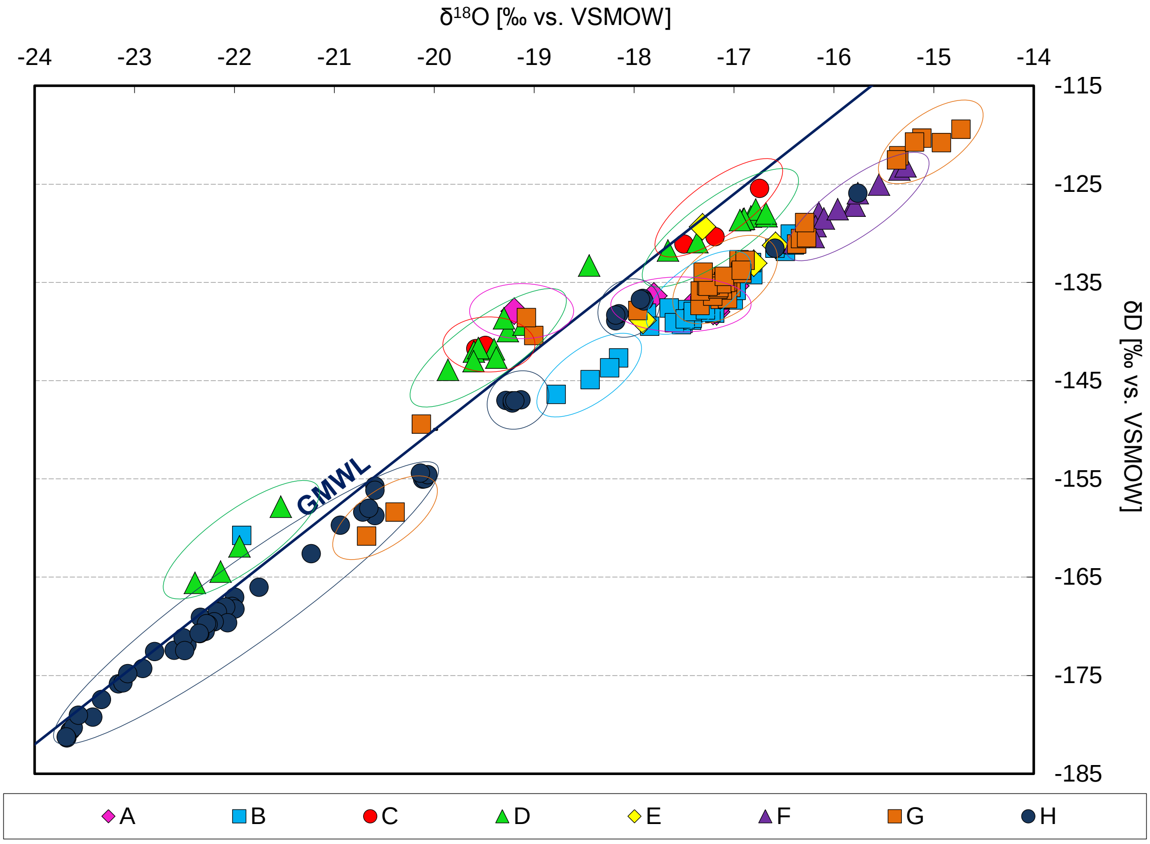

Figure 18: *δD and δ ^{18}O for all samples and both years and with clusters. A – Yedoma Ice Complex thermokarst lakes, B – Yedoma Ice Complex streams, C – Yedoma Ice Complex streams fed by Ice Complex, D – Yedoma Ice Complex uplands (soil water), E –first terrace relict lake, F – first terrace thermokarst lakes, G – first terrace streams, H – Olenyokskaya Channel.*

Also a large part of soil water samples of Yedoma uplands lie above the GMWL and δ values range between -16.7 and -22.4 ‰ (in ^{18}O) and -127.6 and -165.6 ‰ (in D) (*Figure 18, "D"*). Relict lake samples plot closely together and have lower δ values than thermokarst lakes on the first terrace, ranging between -16.6 and -17.9 ‰ (in ^{18}O) and between -129.35 and -138.9 ‰ (in D) (*Figure 18, "E"*). In contrast, δ values of the Olenyokskaya Channel samples are widely scattered (-15.8 to -23.7 ‰ for δ^{18}O and -126 to -181.4 ‰ for δD) (*Figure 18, "H"*). In summary, the drainage flow path is characterized by increasing δ^{18}O and δD values downstream. In contrast, samples of source water mostly lie above the GMWL.

Almost each landscape unit range widely in its isotopic composition and several clusters in each unit can be noticed (*Figure 18, "clusters"*). For further analysis the existing landscape units were subdivided, wherever possible. Thereby thermokarst lakes on Yedoma Ice Complex are subdivided into Lucky Lake and Oval Lake, streams on Yedoma Ice Complex were subdivided into main stream and inflows and soil water samples of Yedoma uplands were subdivided by their distribution in the field (sampling point A, B and C). Also thermokarst lakes on the first terrace were subdivided into Lake 1 and Lake 2, and streams on the first terrace were subdivided into main stream, inflows and outlet. For each subdivided landscape unit minimum, maximum and mean values of $\delta^{18}O$ and δD were calculated and summarized in *Table 4*. Mean values of $\delta^{18}O$ and δD were plotted in the co-isotope plot (*Figure 19*). This figure shows that the isotopic composition of thermokarst lakes differs between the terraces. Thermokarst lakes on the first terrace have higher mean $\delta^{18}O$ and δD values than thermokarst lakes on Yedoma Ice Complex. Additionally thermokarst lakes differ on each terrace (*Table 4*). The mean $\delta^{18}O$ value of Lucky Lake samples is higher than the mean $\delta^{18}O$ value of Oval Lake samples and samples of Lake 1 on the first terrace has a higher mean $\delta^{18}O$ and δD value than Lake 2 on the first terrace (*Figure 19, "A – Lucky Lake", "A – Oval Lake", "F – Lake 1", "F – Lake 2"*).

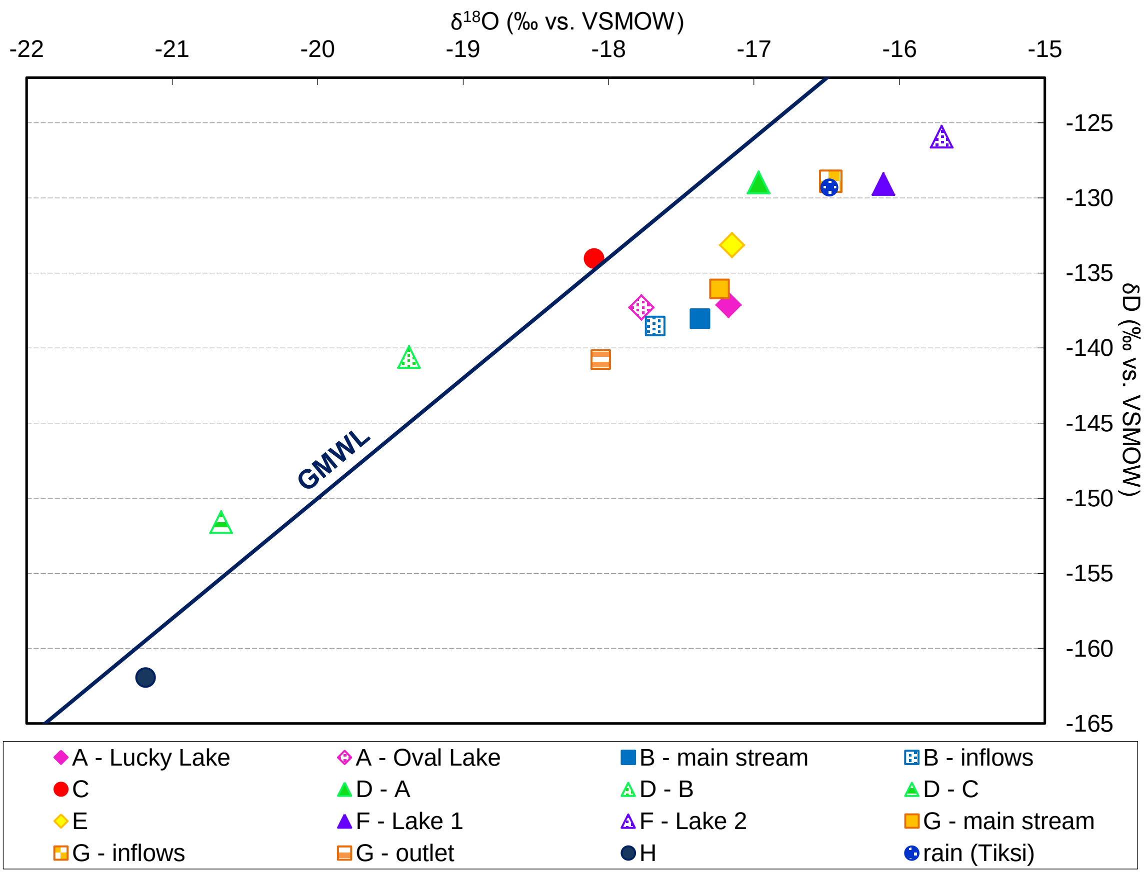

Figure 19: *Mean $\delta^{18}O$ and δD for subdivided landscape units and both years. A – Yedoma Ice Complex thermokarst lakes, B – Yedoma Ice Complex streams, C – Yedoma Ice Complex streams fed by Ice Complex, D – Yedoma Ice Complex uplands (soil water), E – first terrace relict lake, F – first terrace thermokarst lakes, G – first terrace streams, H – Olenyokskaya Channel. Mean δ values of rain were available for Tiksi from Kloss (2008)*

Mean $\delta^{18}O$ and δD values of main stream and inflows on Yedoma Ice Complex plot closely and closely to samples of Yedoma Ice Complex thermokarst lakes (*Figure 19, "B – main stream", "B - inflows"*). In contrast, samples of main stream, inflows and outlet on the first terrace differ in their isotope composition (*Figure 19, "G – main stream", "G - inflows", "G - outlet"*). Whereas the outlet has mean δ values of -18 ‰ (in ^{18}O) and -140.8 ‰ (in D), mean δ values of inflow samples are higher (*Table 4*). Samples of the main stream on the first terrace have mean δ values of -17.2 ‰ (in ^{18}O) and -136.1 ‰ (in D) and plot closely to samples of the Lucky Lake (*Figure 19, "G – main stream"*). Mean δ values of rain water samples from Tiksi (-16.5 ‰ in ^{18}O and -129.3 ‰ in D) are similar to mean δ values of first terrace inflows. Mean δ values of soil water samples of Yedoma uplands range widely (*Table 4*). Whereas samples of soil water sampling point B and C have low mean $\delta^{18}O$ and δD values and plot above the GMWL, samples of sampling point A have high mean $\delta^{18}O$ and δD values and plot below the GMWL (*Figure 19, "D - A", "D - B", "D - C"*). Also samples of streams, which are fed by the Ice Complex, with mean δ values of -18.1 ‰ (in ^{18}O) and -134 ‰ (in D) are plot above and closely to the GMWL. Of all mean δ values, the mean δ value of samples of Olenyokskaya Channel are the lowest (-21.2 ‰ for $\delta^{18}O$ and -162 for δD) (*Table 4*).

Table 4: *Minimum, maximum and mean of stable isotopes ($\delta^{18}O$ and δD).*

Landscape unit			**no.**	**$\delta^{18}O$ [‰]**			**δD [‰]**		
				min.	max.	mean	min.	max.	mean
Yedoma Ice Complex	A	Lucky Lake	11	-17.4	-17	-17.2	-138	-135.4	-137.1
		Oval Lake	5	-19.2	-17.2	-17.8	-138.3	-136.2	-137.3
	B	main stream	22	-18.2	-16.8	-17.4	-143.7	-133	-138.1
		inflows	12	-21.9	-16.4	-17.7	-160.8	-130.1	-138.5
	C		5	-19.6	-16.7	-18.1	-141.8	-125.5	-134
	D	A	9	-17.7	-16.7	-17	-131.8	-127.6	-129
		B	6	-19.6	-19.1	-19.4	-142	-138.7	-140.6
		C	8	-22.4	-18.5	-20.7	-165.6	-133.3	-151.6
First terrace	E		4	-17.9	-16.6	-17.2	-138.9	-129.4	-133.1
	F	Lake 1	5	-16.4	-15.8	-16.1	-131	-127.2	-129.1
		Lake 2	7	-16.2	-15.3	-15.7	-128.5	-123.2	-125.9
	G	main stream	25	-20.4	-16.9	-17.2	-158.4	-132.7	-136.4
		inflows	13	-20.1	-14.7	-16.5	-149.5	-119.4	-128.9
		outlet	5	-20.7	-17.1	-18.1	-160.8	-134.4	-140.8
Olenyokskaya Channel	H		58	-23.7	-15.8	-21.2	-181.4	-126	-162

5.4.4 DOC concentration

Samples of the first terrace relict lake have the highest median DOC concentration (13.1 mg L^{-1}). Comparing thermokarst lakes on both terraces, on the Yedoma Ice Complex they have a higher median DOC concentration (5.2 mg L^{-1}) than thermokarst lakes on the first terrace (3.3 mg L^{-1}). Streams on both terraces show similar median DOC concentrations (*Table 3*). Streams, which are fed by the Ice Complex, have a median DOC concentration of 10.9 mg L^{-1}. This value is almost similar to the median DOC concentration of Olenyokskaya Channel (10.5 mg L^{-1}). Soil water samples of the Yedoma uplands have a median DOC concentration of 11.9 mg L^{-1} and values range widely in the 75th percentile (*Figure 16, "D"*). Comparing the two major geomorphological units, Yedoma Ice Complex and first terrace, the summarized median DOC concentration of landscape units in each geomorphological unit is a little higher for the Yedoma Ice Complex (5.5 mg L^{-1}) than for the first terrace (4.8 mg L^{-1}). Notice that samples of streams which are fed by the Ice Complex and soil water samples of Yedoma uplands only exists for 2013 (*Table 1*).

5.4.4.1 Spatial variability

Figure 20 shows the connections between DOC concentration and electrical conductivity of the landscape units. Generally, two major groups can be determined in the plot. The drainage flow path, which is highlighted by a border, is characterized by DOC concentrations < 6.5 mg L^{-1} and shows a low range in DOC concentration and a high range in electrical conductivity. Samples of lower DOC concentrations exhibit lower electrical conductivity. This figure shows a decrease of DOC concentration and electrical conductivity from Yedoma Ice Complex thermokarst lakes downstream to first terrace thermokarst lakes. In contrast, samples with DOC concentrations > 6.5 mg L^{-1} show no connection of the two parameters and demonstrate the source signal.

The spatial variability of median DOC concentration in the study site was summarized for both years, 2013 and 2014, and visualized in *Figure 21*. The transport of DOC starts at streams, which are fed by the Ice Complex, in the northeast of Lucky Lake. They develop during snowmelt in spring, drain into the Lucky Lake and enrich the thermokarst lake with meltwater. These streams have a high median DOC concentration between 10 mg L^{-1} and 10.9 mg L^{-1}. Additionally soil water of Yedoma uplands with high median DOC concentrations between 10 mg L^{-1} and 12.9 mg L^{-1} enters the system. Streams, fed by the Ice Complex, and Yedoma uplands act as source signal of DOC.

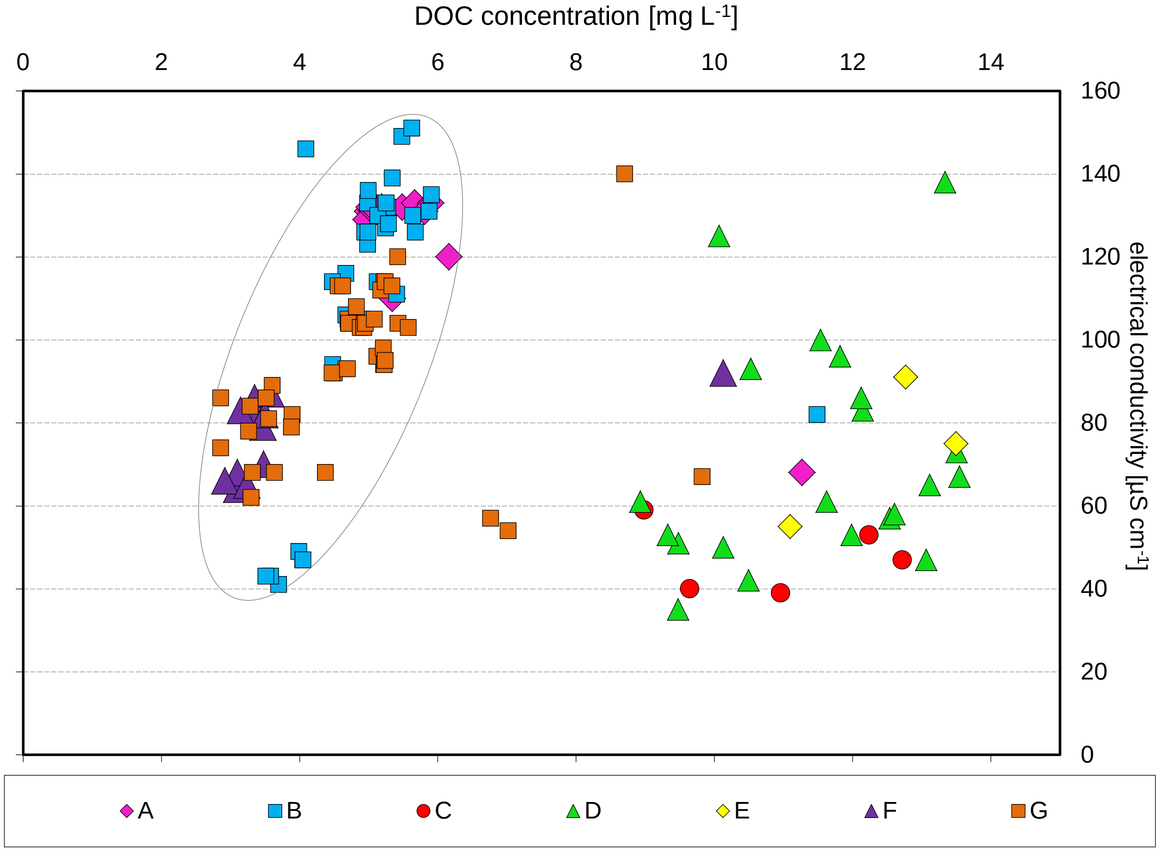

Figure 20: DOC concentration and electrical conductivity for 2013 and 2014. The grey border marks the drainage flow path with landscape unit A, B, F and G. A - Yedoma Ice Complex thermokarst lakes, B - Yedoma Ice Complex streams, C - Yedoma Ice Complex streams fed by the Ice Complex, D - Yedoma Ice Complex uplands (soil water), E - first terrace relict lake, F – first terrace thermokarst lakes, G – first terrace streams.

Connected with the Lucky Lake the adjacent Oval Lake has an almost similar median DOC concentration, comparing with DOC concentration of Lucky Lake. The figure nicely shows that median DOC concentration of Lucky Lake and main stream on the Yedoma Ice Complex are almost similar and that median DOC concentration of main stream inflows are lower. Median DOC concentration of the main stream on the first terrace is little lower, comparing with the main stream on the Yedoma Ice Complex. Inflows and thermokarst lakes on the first terrace have a lower median DOC concentration than main stream. The outlet of the main stream, where it drains into the Olenyokskaya Channel, has a median DOC concentration which is a little higher than the concentration of the first terrace main stream. *Figure 22-24* show a higher DOC concentration of inflows on Yedoma Ice Complex comparing with inflows on the first terrace, except of the last inflow before the outlet.

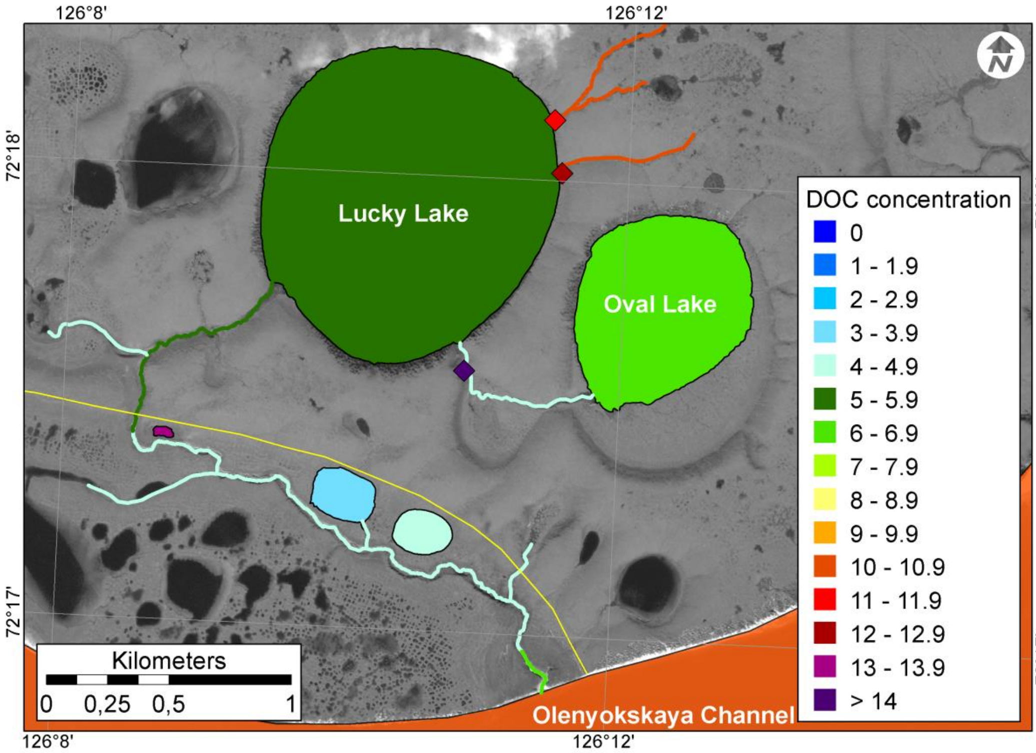

Figure 21: *Median DOC concentration [mg L^{-1}] in landscape units for 2013 and 2014. The yellow line divides the study area in Yedoma Ice Complex (above) and first terrace (bellow). Background image: GeoEye-1, band combination 3,3,3 (r, g, b) projection UTM Zone 52N within WGS 84 datum.*

Using the discharge data with a record period of 29 days a DOC flux of 92.5 kg was estimated for weir 1 and a DOC flux of 220.5 kg was estimated for weir 2. The higher DOC flux at weir 2 is due to the higher discharge at this weir.

5.4.4.2 Temporal variability

Figure 22-24 show pathways of DOC in the study site. *Figure 22* demonstrates the pathway of median DOC concentration of each samples site for a whole field period in 2013 and 2014, whereas *Figure 23* and *24* demonstrate DOC concentration of each sampling site for several sampling days in a year. *Figure 22* starts at source water sample sites draining into the Lucky Lake up to the main stream outlet. It shows higher median DOC concentrations in thermokarst lakes on Yedoma Ice Complex, in the main stream on both terraces and in all inflows. Additionally higher median DOC concentrations at each sample site in 2014 comparing with 2013 can be determined. *Figure 23* and *24* demonstrate the pathways of DOC for several sampling dates in 2013 and 2014. In 2013 the Lucky Lake main stream and its inflows was sampled at three days during summer (15.07.2013, 26.07.2013 and 10.08.2013).

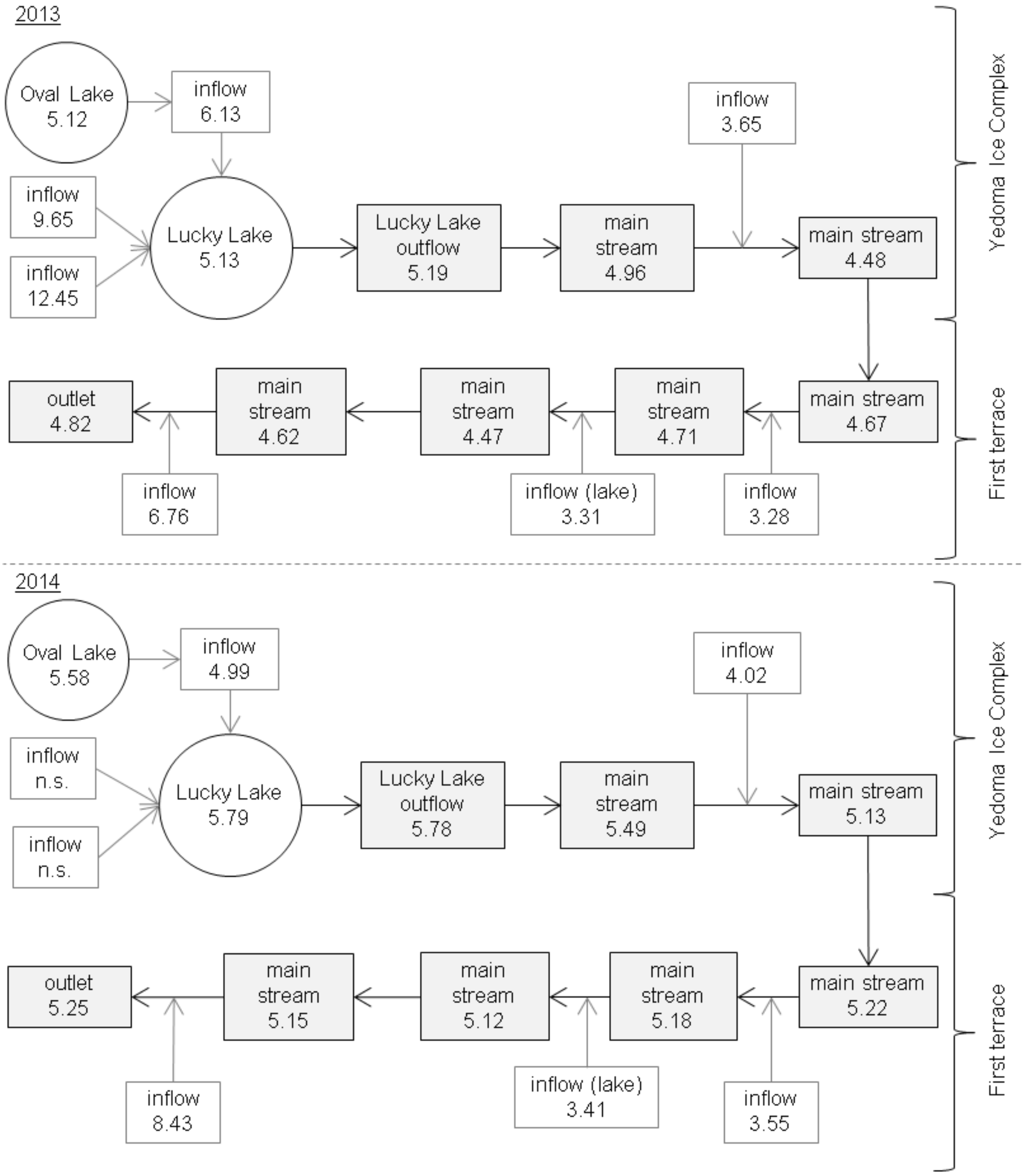

Figure 22: *Flow path of median DOC concentration [mg L^{-1}] for 2013 and 2014 (n.s. indicates location was not sampled).*

Samples of 26.07.2013 have the highest DOC concentrations in the main stream and the outlet has the highest DOC concentration at 10.08.2013. A slight increase in DOC concentration from 15.07.2013 to 26.07.2013 and a decrease to 10.08 2013 can be observed. In 2014 Lucky Lake main stream and its inflows was sampled at four days (16.06.2014, 17.07.2014, 30.07.2014 and 10.09.2014).

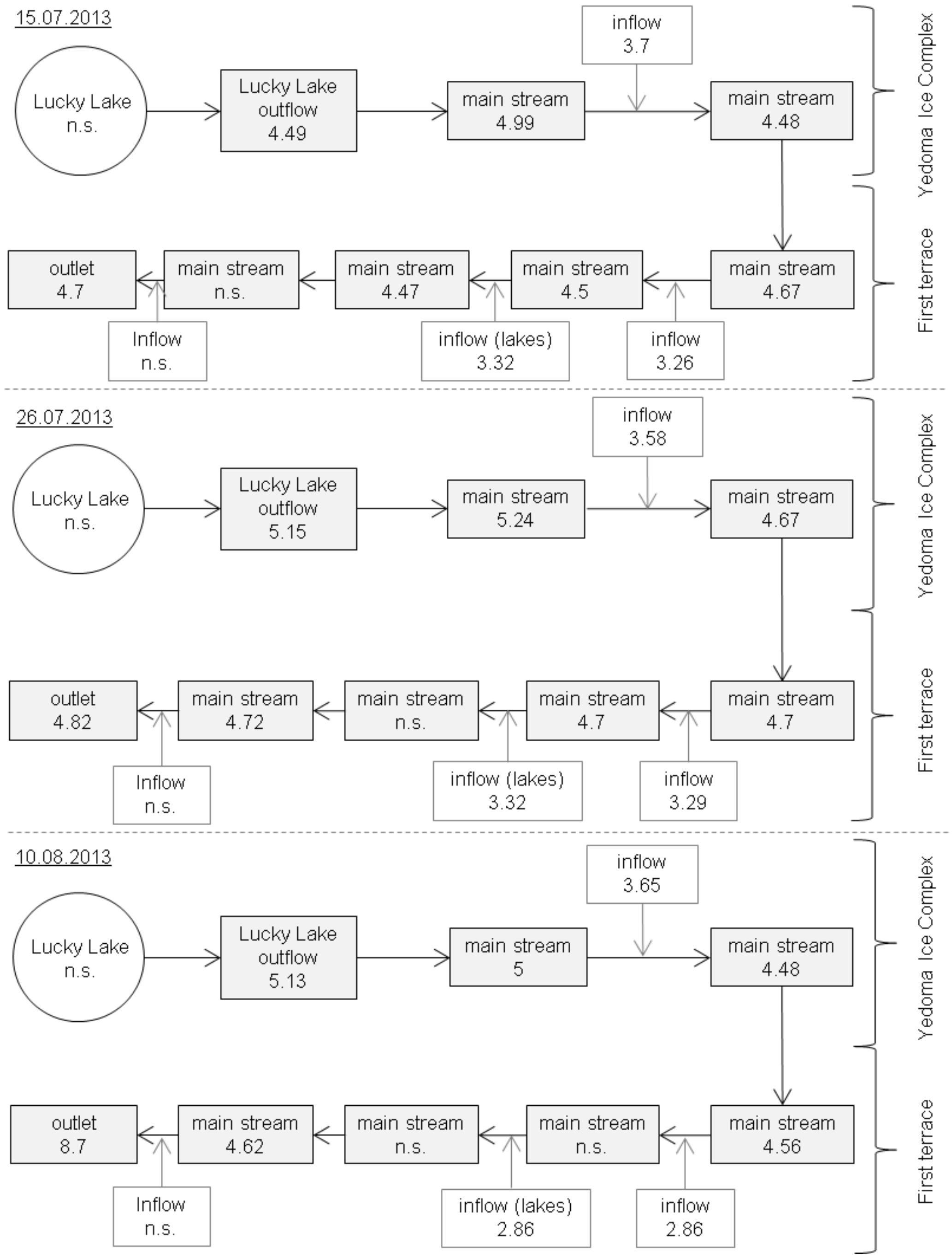

Figure 23: *Flow path of DOC [mg L^{-1}] for three sampling dates in 2013 starting at Lucky Lake outflow (n.s. indicates location was not sampled at this day)*

At 16.06.2014 several sampling points were not sampled, including inflows on the first terrace. These were still frozen and sample collection of fresh water was impossible. There is an increase in DOC concentration from 16.06.2014 to 30.07.2014, like in 2013. To 10.09.2014 a tendency of DOC concentration decrease can be observed.

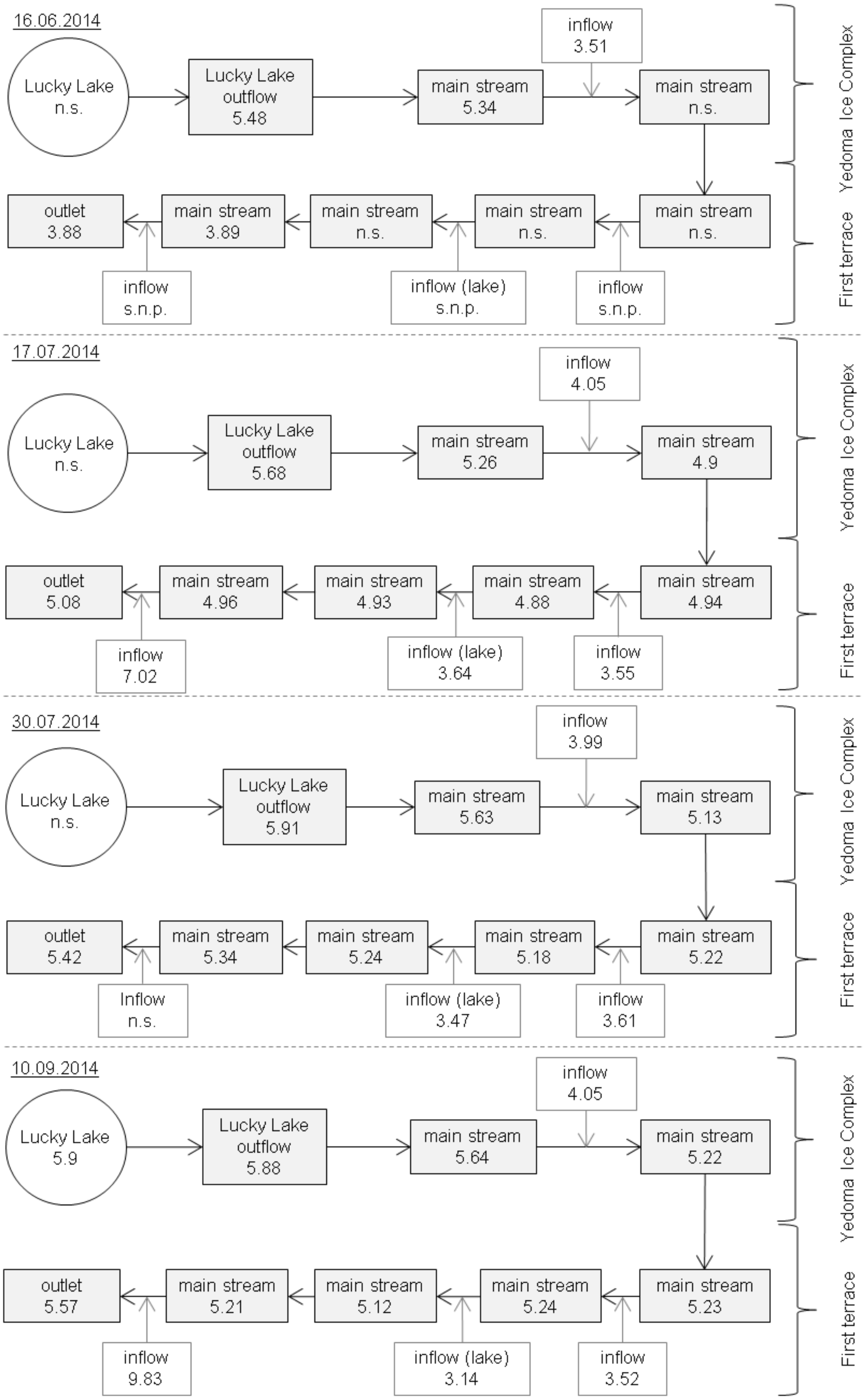

Figure 24: *Flow path of DOC [mg L^{-1}] for three sampling dates in 2014 starting at Lucky Lake outflow (n.s. indicates location was not sampled at this day, s.n.p. indicates that sampling was not possible because inflows were still frozen)*

Figure 25 and *Figure 26* show DOC concentration of each landscape unit and the meteorological situations for measuring periods in 2013 and 2014. Generally, for 2013 no major changes in DOC concentration during the measuring period can be noticed. DOC concentrations of Yedoma Ice Complex streams range between 3.6 mg L^{-1} and 5.4 mg L^{-1} but show no tendency of an increase or decrease during the period of sampling (*Figure 25, "B"*). DOC concentration of streams, which are fed by the Ice Complex, ranges from 9.3 mg L^{-1} to 13.5 mg L^{-1} after a precipitation event (*Figure 25, "C"*). Soil water samples of Yedoma uplands show two higher values > 14 mg L^{-1} but no changes in the remaining samples (*Figure 25, "D"*). First terrace relict lake and thermokarst lakes were sampled once during measuring period in 2013, so no temporal variability for these landscape units for 2013 can be determined.

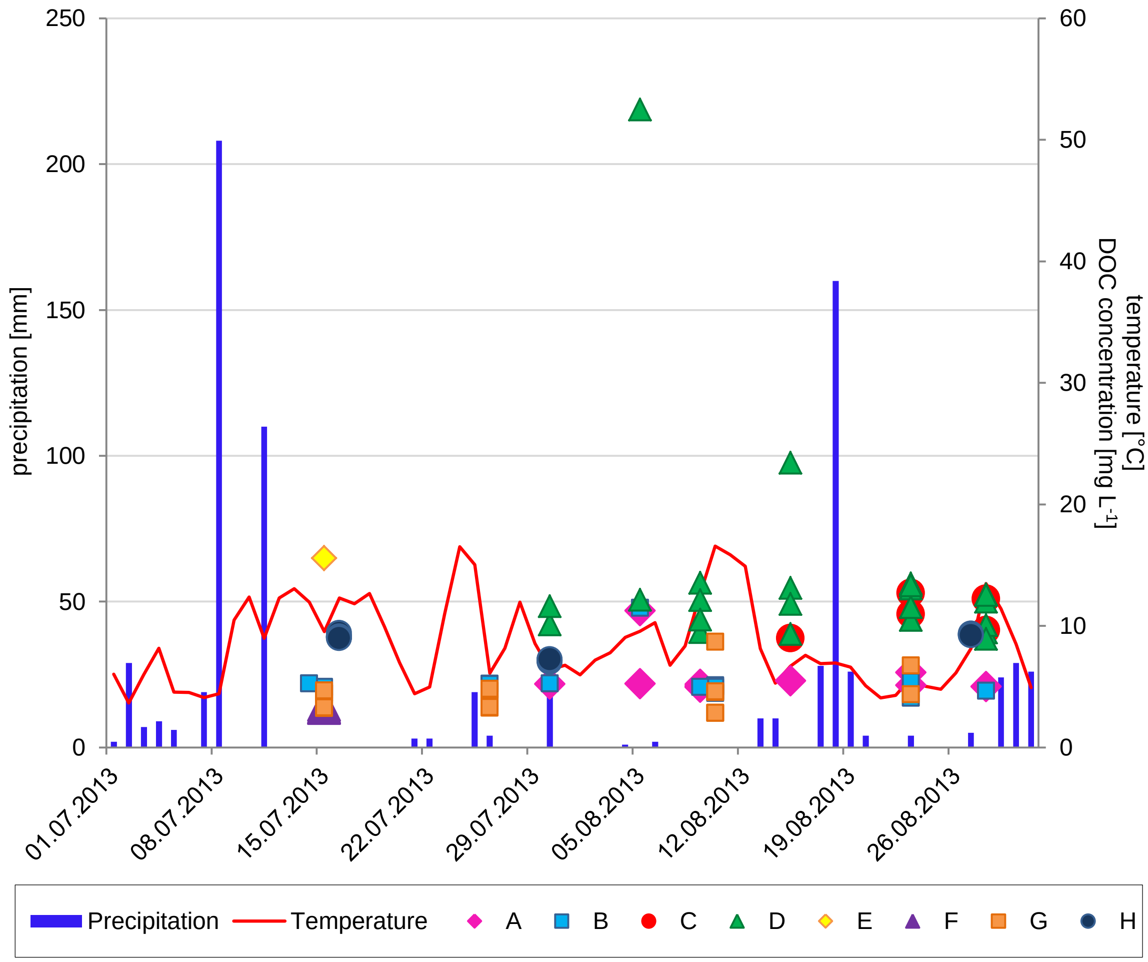

Figure 25: *DOC concentration, air temperature and precipitation for the field work period in 2013 (01.07.2013 – 31.08.2013). A – Yedoma Ice Complex thermokarst lakes, B – Yedoma Ice Complex streams, C – Yedoma Ice Complex streams fed by Ice Complex, D – Yedoma Ice Complex uplands (soil water), E – first terrace relict lake, F – first terrace thermokarst lakes, G – first terrace streams, H – Olenyokskaya Channel.*

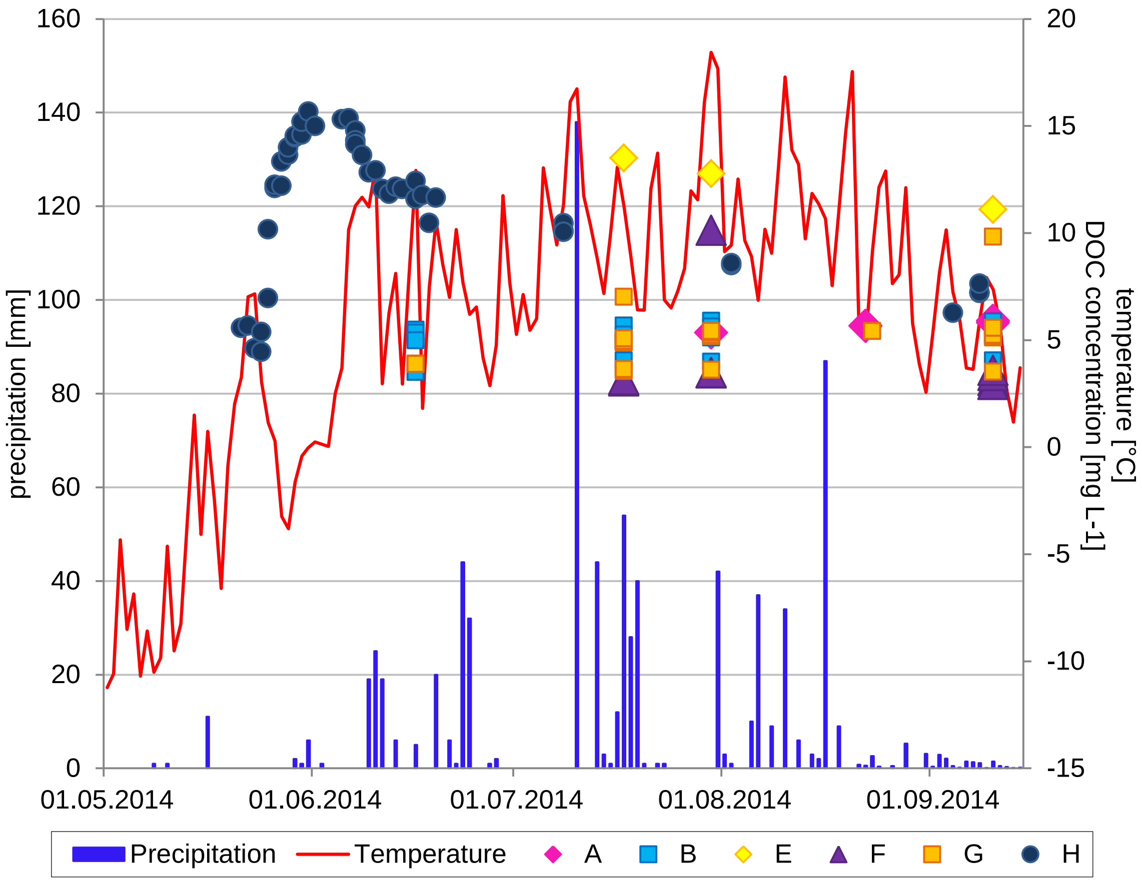

Figure 26: *DOC concentration, air temperature and precipitation for the field work period in 2014 (01.05.2014 to 10.09.2014). A – Yedoma Ice Complex thermokarst lakes, B – Yedoma Ice Complex streams, C – Yedoma Ice Complex streams fed by Ice Complex, D – Yedoma Ice Complex uplands (soil water), E – first terrace relict lake, F – first terrace thermokarst lakes, G – first terrace streams, H – Olenyokskaya Channel.*

Samples of Olenyokskaya Channel increased in DOC concentration from 4.5 mg L^{-1} at 24.05.2014 to 15.7 mg L^{-1} at 31.05.2015. Afterwards DOC concentration decreased to 6.3 mg L^{-1} at 04.09.2014 and finally increased (*Figure 26, "H"*). Thermokarst lakes and streams on both terraces show no changes in DOC concentration during the measuring period (*Figure 26, "A", "B", "F", "G"*). The DOC concentration of first terrace relict lake samples decreased from 17.07.2014 (13.5 mg L^{-1}) to 10.09.2014 (11.1 mg L^{-1}) (*Figure 26, "E"*).

6 Discussion

6.1 Spatial variability of hydrochemical parameters

Figure 17-20 show that drainage flow path and source water differ in values of the analyzed hydrochemical parameters. Additionally *Figure 27* demonstrates a division of the study site in Yedoma Ice Complex and first terrace. This figure shows general lateral transport down the drainage flow path from Yedoma Ice Complex to the first terrace and lateral transport from adjacent areas.

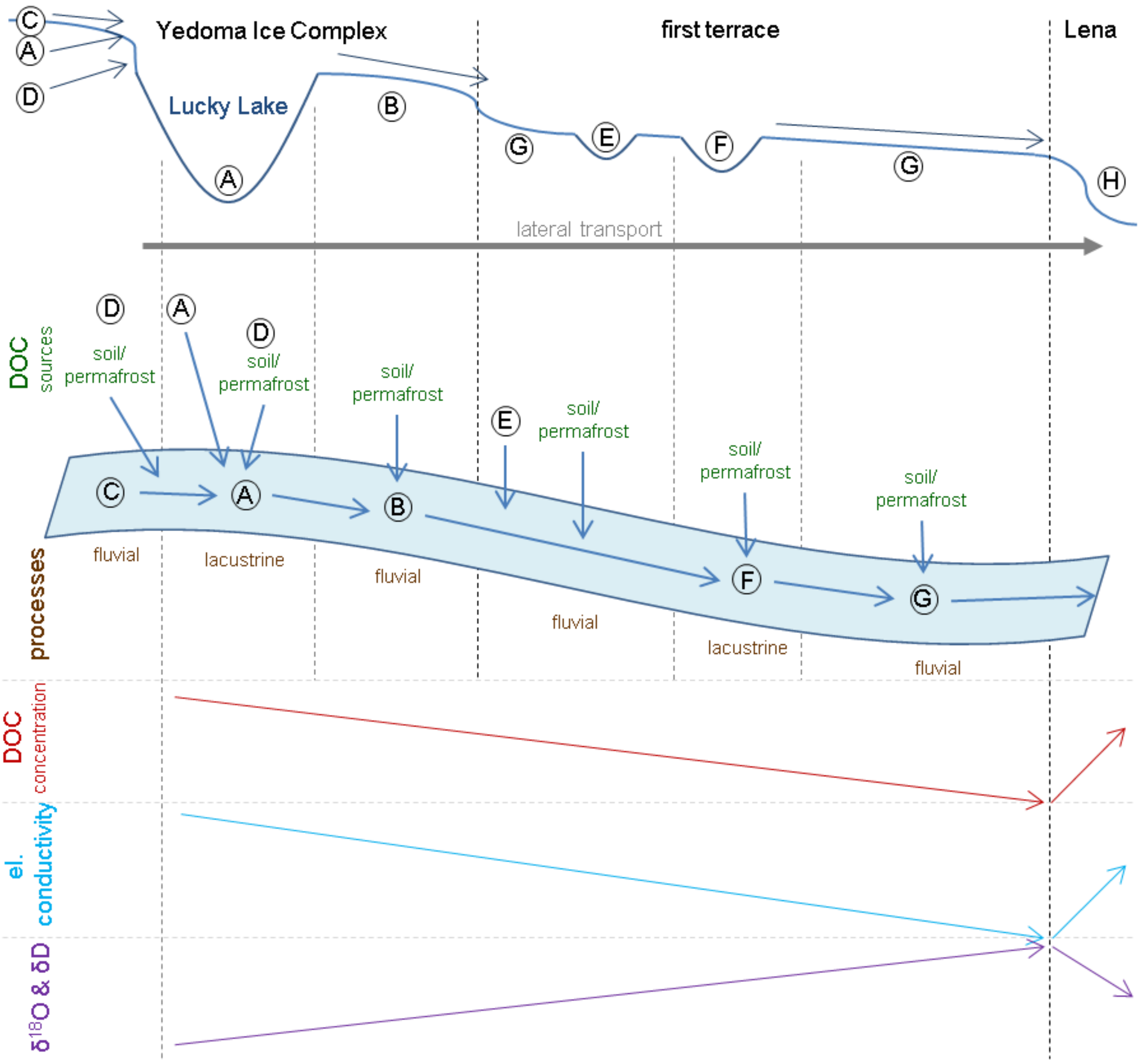

Figure 27: *Scheme of landscape units, influencing processes and changes of hydrochemical parameters. A – Yedoma Ice Complex thermokarst lakes, B – Yedoma Ice Complex streams, C – Yedoma Ice Complex streams fed by Ice Complex, D – Yedoma Ice Complex uplands (soil water), E – first terrace relict lake, F – first terrace thermokarst lakes, G – first terrace streams, H – Olenyokskaya Channel.*

The ultimate sources for drained water are rain and spring snow melt, and water deriving from soil thawing, either in the active layer, or from the underlying ice-rich Yedoma Ice Complex. The drainage flow path is dominated by relatively rapid fluvial processes, leading to transport of sediments and dissolved material. Thermokarst lakes on both terraces are characterized by lacustrine processes, such as water exchange with the atmosphere, potential exchange with deeper sediment in the unfrozen talik beneath the lake, and microbial and chemical reactions in the lake water column.

Chapter 5.4.3 describes decreasing **electrical conductivity** of the drainage flow path with highest electrical conductivity in thermokarst lakes on the Yedoma Ice Complex (*Figure 27*). The Lucky Lake is influenced by soil water of Yedoma uplands, streams, which are fed by the Ice Complex, and by the Oval Lake (*Figure 27*). These source waters contribute dissolved material to Lucky Lake, which becomes even more concentrated. The observed higher median electrical conductivity of landscape units on Yedoma Ice Complex than on first terrace (*Table 3*) are the result of ion-rich load from the third terrace. From Lucky Lake on Yedoma Ice Complex to the outlet on the first terrace, several inflows contribute to the stream. This causes an increase of discharge from weir 1 to weir 2 (*Figure 15*). These inflows are less concentrated then the stream itself and therefore do not lead to a concentration of stream water, but rather dilute the stream. Since contributing to the drainage flow path on the Yedoma Ice Complex is higher in DOC concentration and electrical conductivity in summer, this suggest that precipitation there infiltrates and reacts with soil substances more effectively than on the first terrace, where contributing waters have a dilution effect. This may be the result of deeper and/or longer flow pathways on the Yedoma Ice Complex. The electrical conductivity of the Olenyokskaya Channel is much higher than any of the waters along the drainage flow path. Backflow occurs and affect only the lower reaches of the drainage flow path. But compared with the small stream in the study site, the Lena River has a huge watershed with different discharge and temperatures, draining very diverse landscapes much further southward, including landscapes less affected by permafrost. Thereby a direct comparison of those two systems here is not useful.

The observed increase in **isotopic composition** moving downstream along the drainage flow path (*Figure 18, 19* and *27*) could be a result of fractionation or of dilution by inflowing water with different isotopic composition than in the drainage flow path. Because fractionation (e.g. evaporation) would cause an increase in the electrical conductivity and probably also in DOC concentration, neither of which were observed, this reason for increasing $\delta^{18}O$ and δD values might be excluded. Therefore increasing inflows, consisting of a mix of soil water, rain, surface runoff, lake water (thermokarst lakes and relict lake) and stream inflows, change the isotopic composition of the main stream. Due to disequilibrium processes (e.g. thawing/freezing) source waters (soil water samples of Yedoma uplands and streams, which are fed by the Ice Complex) result in δ values, which lie above the GMWL. This is caused by thawing in spring and freezing in fall of the active layer, where the soil water samples were collected. Higher $\delta^{18}O$ and δD of thermokarst lakes on the first terrace compared with thermokarst lakes on Yedoma Ice Complex might be a result of warmer temperatures during the Holocene, when the first terrace was formed. Similar δ values of rain and first terrace inflows suggest that rain has a stronger effect on the first terrace. Due to more water surface adventitious rain leads to run off, whereas rain on Yedoma Ice Complex can infiltrate and react with soil substances.

Table 3 shows median **DOC concentration** of 5.3 mg L^{-1} for thermokarst lakes on Yedoma Ice Complex ranging between with DOC values ranging between 4.9 – 11.3 mg L^{-1}. A median DOC concentration of 3.3 mg L^{-1} was determined for thermokarst lakes on the first terrace with DOC values ranging between 2.8 – 9.8 mg L^{-1}. The DOC concentration of the relict lake on the first terrace ranges between 11.1 – 15.6 mg L^{-1}. For tundra lakes and ponds in northeastern Canada, Breton et al. (2011) found a higher DOC range of 1.3 mg L^{-1} to 26 mg L^{-1} compared with the analyzed thermokarst lakes in this thesis, as well as Laurion et al. (2010), who found a DOC range of 1.5 mg L^{-1} to 20.8 mg L^{-1} and Abnizova et al. (2014) with a DOC range from 1.5 mg L^{-1} to 41.6 mg L^{-1} and a median DOC concentration of 10 mg L^{-1}. Abnizova et al. (2014) collected samples from spring to fall, whereas Breton et al. (2011) and Laurion et al. (2010) collected samples several times over a period of two months, which is more comparable with this thesis.

In *Chapter 5.4.4* a decreasing DOC concentration along the drainage flow path is described. Whereas samples of the drainage flow path have DOC concentrations < 6.5 mg L^{-1} source water samples have higher and more scattered DOC concentrations (*Figure 20*). Inflows of lower DOC concentration, especially on the first terrace, dilute the main stream and cause a decrease in main stream DOC concentration. *Figure 27* shows sources of DOC for each landscape unit along the drainage flow path. Sources of Lucky Lake DOC on Yedoma Ice Complex are Yedoma uplands (*Figure 27, "D"*), streams, which are fed by the Ice Complex (*Figure 27, "C"*), and the Oval Lake, which drains into the Lucky Lake (*Figure 27, "A"*). The DOC concentration of the stream, which drains the Lucky Lake, is influenced by Lucky Lake DOC concentration. The stream on the first terrace is influenced by DOC concentration of the relict lake and of a thermokarst lake, draining into the stream. Additionally, the soil and permafrost can be described as DOC source for the whole drainage flow path.

Yedoma Ice Complex is rich in fossil organic carbon, but also Holocene deposits, which are characteristic for the first terrace, are rich in organic carbon (SCHIRRMEISTER et al., 2011a). This Holocene surface layer also overlies Yedoma Ice Complex (*Figure 8*). However, carbon in Yedoma Ice Complex is more labile (VONK et al., 2013; STRAUSS, 2014) and more decomposable than in other thawed mineral soils (WALTER ANTHONY et al., 2014). Comparisons of DOC concentrations in different landscape units show that DOC concentrations of source waters on Yedoma Ice Complex (soil water of Yedoma uplands and streams, which are fed by the Ice Complex) are higher than Lucky Lake DOC concentration. This might be a result of thorough mixing of the lake, the quality of carbon, snowmelt dilution or DOC mineralization. The observation that DOC concentrations of Lucky Lake do not increase due to the inflow of DOC rich water suggest that these inflows are rich in old and labile organic carbon from Yedoma Ice Complex. Further, this suggests that Yedoma Ice Complex is degraded at the sampling sites.

The heavier isotopic signatures and higher electrical conductivity suggest that some evaporation occurs, but the DOC concentration in Lucky Lake is nevertheless about half as much as the input of the lake. This suggests that DOC in the lake gets mineralized. Mineralization of DOC is due to microbial activities and photochemical reactions and was also observed by SCHUUR et al. (2009) and BAUER & BIANCHI (2011). After the outflow of Lucky Lake DOC concentration slightly decrease due to short residence time from Lucky Lake downstream to the Olenyokskaya Channel. *Figure 15* shows no changes in DOC concentration despite of changes in discharge. This suggests that any process of changing DOC concentration occurs in the Lucky Lake. Nevertheless DOC fluxes for weir 1 and weir 2 were calculated for the measurement period of 29 days in 2013. A DOC flux of 92.5 kg for weir 1 and a DOC flux of 220.5 kg for weir 2 is presented in *Chapter 5.4.4.1*. Because no high-resolution digital elevation model for the study site was available an exactly calculation of watershed areas was not possible, but was estimated for the entire study site above weir 2, covering an area of 6.45 km^2. This suggests that the DOC flux of the watershed is about 34.2 kg km^{-2} for 29 days and about 1.18 kg per day. FINLAY et al. (2006) published a Lena River DOC flux of 1811 kg km^{-2} y^{-1}. Scaled down to one day this results in a DOC flux of 4.96 kg. LEWIS et al. (2012) studied DOC fluxes of a watershed with almost similar size (8 km^2) in the Canadian Arctic. From 2006 to 2009 they calculated a mean DOC flux of about 350 kg km^{-2} y^{-1}. Scaled down to one day this results in a mean DOC flux of 0.96 kg, which is a little lower than for the watershed in this thesis. These estimations are benchmarks, which do not include spring floods, snow melt, rain events or the frozen period.

Figure 21 shows a higher DOC concentration in the outlet of the main stream on the first terrace. This outlet is influenced by Olenyokskaya Channel water, which has a median DOC concentration of 10.9 mg L^{-1}. Backwater of the Olenyokskaya Channel enriches the stream outlet with DOC and causes an increase of DOC concentration in the outlet.

6.2 Temporal variability of DOC

In *Figure 22* a higher median DOC concentration in 2014 is observed for the entire system, except for Olenyokskaya Channel. *Figure 23* and *24* show slightly increasing DOC concentrations in the main stream till the end of July and slightly decreasing DOC concentrations afterwards. BAUER & BIANCHI (2011) described that temporal variability of carbon in estuaries is attributable to the variability in insolation, precipitation, temperature and snowmelt up to extreme events like floods. But such a relation between the enumerated factors and DOC concentration was not determined and could not be analyzed due to insufficient data density in this thesis. *Figure 25* and *26* show no significant changes in DOC concentration due to temperature or precipitation. *Figure 26* shows that there is a significant increase in DOC concentration of the Olenyokskaya Channel when temperature rose above 0 °C and ice break-up and snow melt started, which also means an increased discharge. But this is not comparable with the Lucky Lake stream system. In summary, no significant temporal variability of DOC concentration during summer could be determined by using the analyzed data. This might be a result of too large sampling intervals, but may also reflect the influence of lakes in the drainage flow path on DOC concentration.

6.3 Outlook

For further studies an end member analysis of stable isotopes would be advantageous to determine the waters’ origin in the studied landscape units. A longer sampling period with shorter sampling intervals could be used to determine a temporal variability of DOC concentration. Additionally extra sampling after big rain events or extreme changes in air temperature would be interesting as well as a high resolution digital elevation model for exact analyzes of the watershed in the study site. This approach to characterize differences in DOC concentration in several landscape forms could be used to compare watersheds in arctic regions, e.g. where Yedoma Ice Complex is located. Future studies should compare drainage from Yedoma Ice Complex with and without lakes in order to assess the importance of lacustrine processes in changing land-to-ocean transport processes. During this thesis, it became clear that the spatial variability of DOC concentration in a permafrost affected landscape is very complex and that the utilized data set still contains a high potential for further studies.

7 Conclusion

The aim of this thesis was to identify different landscape units of a permafrost influenced catchment in the Lena River Delta and to analyze their influence on the amount of DOC and other water chemistry parameters. Overall 175 summer surface water samples of 2013 and 2014 plus 23 soil water samples of 2013 were allocated to the determined landscape units: Yedoma Ice Complex thermokarst lakes (A), Yedoma Ice Complex streams (B), Yedoma Ice Complex streams, which are fed by the Ice Complex (C), Yedoma Ice Complex uplands (D), first terrace relict lake (E), first terrace thermokarst lakes (F), first terrace streams (G) and Olenyokskaya Channel (H). Analyzes of electrical conductivity, isotopic composition and DOC concentration revealed that the drainage flow path is divided by landscape units, from the Yedoma Ice Complex thermokarst lake Lucky Lake downstream to the first terrace stream outlet, and source waters, located on Yedoma Ice Complex. The results of this work show that source waters have significantly higher DOC concentrations, lower electrical conductivity and δ values, which lie above the GMWL. It can be observed that high DOC concentrations of source waters do not result in increasing DOC concentration in the Lucky Lake. This suggests that the inflowing organic carbon is labile and that mineralization occurs rapidly. Accordingly the labile organic carbon is of degrading Yedoma Ice Complex origin. Downstream the drainage flow path DOC concentration does not change significantly. In short, in summer waters from the Yedoma Ice Complex provide more DOC than those from the first terrace, as a result of differences in either organic carbon quality and/or in flow pathways. Yedoma Ice Complex lake processes, despite evaporation, further reduce DOC concentration, probably through mineralization. Streams draining Yedoma Ice Complex directly, without intermediary lakes, thus probably have higher DOC concentrations. A temporal variability of DOC concentration was not observed in this thesis. Discharge data of a 29 days measuring period enabled the calculation of a DOC flux of about 220 kg for 29 days for the entire system.

8 References

ABBOTT, B.B., J.R. Larouche, J.B. Jones Jr., W.B. Bowden, A.W. Balser (2014): Elevated dissolved organic carbon biodegradability from thawing and collapsing permafrost. Journal of Geophysical Research: Biogeosciences. 119, 2049-2063.

ABNIZOVA, A., J. Siemens, M. Langer, J. Boike (2012): Small ponds with major impact: The relevance of ponds and lakes in permafrost landscapes to carbon dioxide emissions. Global Biogeochemical Cycles. 26, GB2041.

ABNIZOVA, A., K.L. Young, M.J. Lafrenièr (2014): Pond hydrology and dissolved carbon dynamics at Polar Bear Pass wetland, Bathurst Island, Nunavut, Canada. Ecohydrology. 7, 73-90.

AMAP (2011): Snow, water, ice and permafrost in the Arctic (SWIPA). Oslo, Monitoring and Assessment Programme (AMAP).

BATTIN, T.J., L.A. Kaplan, S. Findlay, C.S. Hopkinson, E. Marti, A.I. Packman, J.D. Newbold, F. Sabater (2009): Biophysical controls on organic carbon fluxes in fluvial networks. Nature Geoscience. 1, 95-100.

BAUER, J., T. BIANCHI (2011): Dissolved organic carbon cycling and transformations. Treatise on Estuarine and Coastal Science. E. Wolanski & D.S. McLusky (eds.), Waltham Academic Press. 5, 7-67.

BENNER, R., B. Benitez-Nelson, K. Kaiser, R.M.W. Amon (2004): Export of young terrigenous dissolved organic carbon from rivers to the Arctic Ocean. Geophysical Research Letters. 31, L05305.

BOIKE, J., C. Wille, A. Abnizova (2008): Climatology and summer energy and water balance of polygonal tundra in the Lena River Delta, Siberia. Journal of Geophysical Research. 113, 03025.

BOIKE, J., B. Kattenstroth, K. Abramova, N. Bornemann, A. Chetverova, I. Fedorova, K. Fröb, M. Grigoriev, M. Grüber, L. Kutzbach, M. Langer, M. Minke, S. Muster, K. Piel, E.-M. Pfeiffer, G. Stoof, S. Westermann, K. Wischnewski, C. Wille, H.-W. Hubberten (2013): Baseline characteristics of climate, permafrost and land cover from a new permafrost observatory in the Lena River Delta, Siberia (1998-2011). Biogeoscience. 10, 2105-2128.

BOIKE, J., C. Georgi, G. Kirilin, S. Muster, K. Abramova, I. Fedorova, A. Chetverova, M. Grigoriev, N. Bornemann, M. Langer (2015): Physical processes of thermokarst lakes in the continuous permafrost zone of northern Siberia – observations and modeling (Lena River Delta, Siberia). Biogeosciences. 12, 6637-6688.

BOWDEN, W.B., M.N. Gooseff, A. Balser, A. Green, B.J. Peterson, J. Bradford (2008): Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. Journal of Geophysical Research. 113, G02026.

CHAPIN, F., M. Sturm, M. Serreze, J. McFadden, J.R. Key, A.H. Lloyd, A.D. McGuire, R.S. Rupp, A.H. Lynch, J.P. Schimel, J. Beringer, W.L. Chapman, H.E. Epstein, E.S. Euskirchen, L.D. Hinzman, G. Jia, C.-L. Ping, K.D. Tape, C.D.C. Thompson, D.A. Walker, J.M. Welker (2005): Role of land-surface changes in Arctic summer warming. Science. 310, 657-660.

CHRIST, M.J., M.B. DAVID (1996): Temperature and moisture effects on the production of dissolved organic carbon in a spodsol. Soil, Biology & Biochemistry. 28/9, 1191-1199.

CLARK, I.D., P. FRITZ (1997): Environmental isotopes in Hydrogeology. Lewis Publishers, Boca Raton. New York, USA.

CRAIG, H. (1961): Isotopic variation in meteoric waters. Science. 133, 1702-1703.

DANSGAARD, W. (1996): Stable isotopes in precipitation. Tellus. 16, 436-468.

DITTMAR, T., G. KATTNER (2003): The biogeochemistry of the river and shelf ecosystem of the Arctic Ocean: a review. Marine Chemistry. 83, 103-120.

DUBINENKOV, I., R. Flerus, P. Schmitt-Kopplin., G. Kattner, B.P. Koch (2015): Origin-specific molecular signatures of dissolved organic matter in the Lena Delta. Biogeochemistry. 123, 1-14.

DUTTA, K., E.A.G. Schuur, J.C. Neff, S.A. Zimov (2006): Potential carbon release from permafrost soils of Northeastern Siberia. Global Change Biology. 12, 2336-2351.

FEDOROVA, I., A. Chetverova, D. Bolshiyanov, A. Makarov, J. Boike, B. Heim, A. Morgenstern, P.P. Overduin, C. Wegner, V. Kashina, A. Eulenburg, E. Dobrotina, I. Sidorina (2015): Lena Delta hydrology and geochemistry: long-term hydrological data and recent field observation. Biogeosciences. 12, 345-363.

FINLAY, J., J. Neff, S. Zimov, A. Davydov, S. Davydov (2006): Snowmelt dominance of dissolved organic carbon in high-latitude watersheds: Implications for characterization and flux of river DOC. Geophysical Research Letters. 33, L10401.

FREEMAN, C., N. Fenner, N.J. Ostle, H. Kang, D.J. Dowrick, B. Reynolds, M.A. Lock, D. Sleep, S. Hughes, J. Hudson (2004): Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. Nature. 430, 195-198.

FRENCH, H.M. (2007): The periglacial environment. Third Edition, John Wiley & Sons, Chichester.

FREY, K.E., L.C. SMITH (2005): Amplified carbon release from vast West Siberian peatlands by 2100. Geophysical Research Letters. 32, L09401.

FREY, K.E., J.W. MCCLELLAND (2009): Impacts of permafrost degradation on arctic river biogeochemistry. Hydrological Processes. 23, 169-182.

FRITZ, M., T. Opel, G. Tanski, U. Herzschuh, H. Meyer, A. Eulenburg, H. Lantuit (2015): Dissolved organic carbon (DOC) in arctic ground ice. The Cryosphere. 9, 737-752.

GROSSE, G., J. Harden, M. Turetsky, A.D. McGuire, P. Camill, C. Tarnocai, S. Frolking, E.A.G. Schuur, T. Jorgenson, S. Marchenko, V. Romanovsky, K. P. Wickland, N. French, M. Waldrop, L. Bourgeau-Chavez, R.G. Striegl (2011): Vulnerability of high latitude soil carbon in North America to disturbance. Journal of Geophysical Research. 116, G00K06.

GROSSE, G., B. Jones, C. Arp (2013): Thermokarst Lakes, Drainage, and Drained Basins. Treatise on Geomorphology. Glacial and Periglacial Geomorphology. Academic Press. 8, 325-353.

Handbook WTW (1989): pH-Fibel: Einführung in die pH- und Redox Meßtechnick. Wiss.-techn. Werkstätten GmbH, Weilheim.

Handbook WTW (1993): pH-Fibel: Einführung in die pH- und Redox Meßtechnick. Wiss.-techn. Werkstätten GmbH, Weilheim.

HOBBIE, S.E., J.P. Schimel, S.E. Trumbore, J.R. Randerson (2000): Controls over carbon storage and turnover in high-latitude soils. Global Change Biology. 6, 196-210.

HOLMES, R.M., J.W. McClelland, P.A. Raymond, B.B. Frazer, B.J. Peterson, M. Stieglitz (2008): Lability of DOC transported by Alaskan rivers to the Arctic Ocean. Geophysical Research Letters. 35, L03402.

HOLMES, R.M., J.W. McClelland, B.J. Peterson, S.E. Tank, E. Bulygina, T. I. Eglinton, V.V. Gordeev, T.Y. Gurtovaya, P.A. Raymond, D.J. Repeta, R. Staples, R.G. Striegl, A.V. Zhulidov, S.A. Zomov (2012): Seasonal and Annual Fluxes of Nutrients and Organic Matter from Large Rivers to the Arctic Ocean and Surrounding Seas. Estuaries and Coasts. 35, 369-382.

KLOSS, A.L. (2008): Water isotope geochemistry of recent precipitation in Central and North Siberia as a proxy for the local and regional climate system. Thesis. Lebniz Universität Hannover.

LAUDON, H., J. Buttle, S.K. Carey, J. McDonnell, K. McGuire, J. Seibert, J. Shanley, C. Soulsby, D. Tetzlaff (2012): Cross-regional prediction of long-term trajectory of stream water DOC response to climate change. Geophysical Research Letters. 39, L18404.

LAURION, I., W.F. Vincent, S. MacIntyre, L. Retamal, C. Dupont, P. Francus, R. Pienitz (2010): Variability in greenhouse gas emissions from permafrost thaw ponds. Limnology and Oceanography. 55, 115-133.

LEWIS, T., M.J. Lafrenièr, S.F. Lamoureux (2012): Hydrochemical and sedimentary response of paired High Arctic watersheds to unusual climate and permafrost disturbance, Cape Bounty, Melville Island, Canada. Hydrological Processes. 26, 2003-2013.

MANASYPOV, R.M., O.S. Pokrovsky, S.N. Kirpotin, L.S. Shirokova (2014): Thermokarst lake water across the permafrost zones of western Siberia. The Cryosphere. 8, 1177-1193.

MANN, P.J., A. Davydova, N. Zimov, R.G.M. Spencer, S. Davydov, E. Bulygina, S. Zimov, R.M. Holmes (2012): Controls on the composition and lability of dissolved organic matter in Siberia's Kolyma River basin. Journal of Geophysical Research. 117, G01028.

Manual Shimadzu/TOC-V (2008): Shimadzu TOC-V Series Total Organic carbon Analysator. TOC-V CPH/CPN, TOC-Control V, Version 2.00. Kyoto, Japan.

MCDOWELL, W.H., A. Zsolnay, J.A. Aitkenhead-Peterson, E.G. Gregorich, D.L. Jones, D. Jödermann, K. Kalbitz, B. Marschner, D. Schwesig (2006): A comparison of methods to determine the biodegradable dissolved organic carbon from different terrestrial sources. Soil Biology & Biochemistry. 38, 1933-1942.

MCGUIRE, A.D., L.G. Anderson, T.R. Christensen, S. Dallimore, L.D. Guo, D.J. Hayes, M. Heimann, T.D. Lorenson, R.W. MacDonald, N. Roulet (2009): Sensitivity of the carbon cycle in the Arctic to climate change. Ecological Monographs. 79, 523-555.

MEYER, H., L. Schönicke, U. Wand, H.-W. Hubberten, H. Friedrichsen (2000): Isotope studies of hydrogen and oxygen in ground ice – experiences with the equilibration technique. Isotopes in Environmental and Health Studies. 36, 133-149.

MEYER, H., A. Dereviagin, C. Siegert, L. Schirrmeister, H.-W. Hubberten (2002): Palaeoclimate Reconstruction on Big Lyakhovsky Island, North Siberia – Hydrogen and Oxygen Isotopes in Ice Wedges. Permafrost and Periglacial Processes. 13, 91-105.

MORGENSTERN, A., G. Grosse, F. Günther, I. Fedorova, L. Schirrmeister (2011): Spatial analysis of thermokarst lakes and basins in Yedoma landscapes oft he Lena Delta. The Cryosphere. 5, 849-867.

MORGENSTERN, A. (2012): Thermokarst and thermal erosion: Degradation of Siberian ice- rich permafrost. Dissertation thesis. University of Potsdam.

NEFF, J.C., D.U. HOOPER (2002): Vegetation and climate controls on potential CO2, DOC, and DON production in northern latitude soils. Global Change Biology. 8, 872-884.

NIEMANN, S. (2014): Seewasserbilanz eines Thermokarstsees im Lena Delta, Nord-Sibirien. Master thesis. University of Potsdam.

OECHEL, W.C., S.J. Hastings, G. Vourlrtis, M. Jenkins, G. Riechers, N. Grulke (1993): Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source. Nature. 361, 520-523.

OSTERKAMP, T.E., L. Viereck, Y. Shur, M.T. Jorgenson, C. Racine, A. Doyle, R.D. Boone (2000): Observations of thermokarst and ist impact on boreal forests in Alaska, U.S.A. Arctic. Antarctic and Alpine Research. 32, 303-315.

PASTOR, J., J. Solin, S.D. Bridgham, K. Updegraff, C. Harth, P. Weishampel, B. Dewey (2003): Global warming and the export of dissolved organic carbon from boreal peatlands. OIKOS. 100, 380-386.

RBC Flume (2000): Operating Instructions of 13.17.08 RBC flume.

PROKOVSKY, O.S., L.S. Shirokova, S.N. Kirpotin, S. Audry, J. Viers, B. Dupré (2011): Effect of permafrost thawing on organic carbon and trace element colloidal speciation in the thermokarst lakes of western Siberia. Biogeosciences. 8, 565-583.

PROKUSHKIN, A.S., M. Kawahigashi, I.V. Tokareva (2009): Global Warming and Dissolved Organic Carbon Release from Permafrost Soils. Permafrost Soils, Soil Biology 16, 237-250.

RAYMOND, P.A., J.W. McClelland, R.M. Holmes, A.V. Zhulidov, K. Mull, B.J. Peterson, R.G. Striegl, G.R. Aiken, T.Y. Gurtovaya (2007): Flux and age of dissolved organic carbon exported to the Arctic Ocean: A carbon isotopic study of the five largest arctic rivers. Global Biogeochemical Cycles. 21, GB4011.

ROMANOVSKY, V.E., S. Gruber, A. Instanes, H. Jin, S.S. Marchenko, S.L. Smith, D. Trombotto, K.M. Walter (2007): Frozen Ground (Chapter 7). Global Outlook for Ice and Snow, edited. UNEP, 183-200.

SCHIRRMEISTER, L., G. Grosse, G. Schwamborn, A.A. Andreev, H. Meyer, V.V. Kunitsky, T.V. Kuznetsova, M.V. Dorozhkina, E.Y. Pavlova, A.A. Bobrov, D. Oezen (2003): Later quaternary history oft he accumulation plain north of the Chekanovsky Ridge (Lena Delta, Russia): A multidisciplinary approach. Polar Geography. 27/4, 277-319.

SCHIRRMEISTER, L., G. Grosse, S. Wetterich, P.P. Overduin, J. Strauss, E.A.G. Schur, H.-W. Hubberten (2011a): Fossil organic matter characteristics in permafrost deposits of northeast Siberian Arctic. Journal of Geophysical Research. 116, G00M02.

SCHIRRMEISTER, L., V. Kunitsky, G. Grosse, S. Wetterich, H. Meyer, G. Schwamborn, O. Babiy, A. Derevyagin, C. Siegert (2011b): Sedimentary characteristics and origin oft he Late Pleistocene Ice Complex on north-east Siberian Arctic coastal lowlands and islands – A review. Quaternary International. 241, 3-25.

SCHIRRMEISTER, L., D. Froese, V. Tumskoy, G. Grosse, S. Wetterich (2013): Yedoma: Late Pleistocene ice-rich syngenetic permafrost of Beringioa. Enyclopedia of Quaternary Science. 2nd Edition, Elsevier, in press.

SCHNEIDER, J., G. Grosse, D. Wagner (2009): Land cover classification of tundra environments in the Arctic Lena Delta based on Landsat 7 ETM+ data and its application for upscaling of methane emissions. Remote Sensing of Environment. 113, 380-391.

SCHULTZ, J. (2000): Handbuch der Ökozonen. Verlag Eugen Ulmer GmbH & Co. Stuttgart, Germany.

SCHUUR, E.A.G., J. Bockheim, J.G. Canadell, E. Euskirchen, C.B. Field, S.V. Goryachkin, S. Hagemann, P. Kuhry, P.M. Lafleur, H. Lee, G. Mazhitova, F.E. Nelson, A. Rinke, V.E. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J.G. Vogel, S.A. Zimov (2008): Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. BioScience. 58/8, 701-714.

SCHWAMBORN, G., V. Rachold, M.N. Grigoriev (2002): Late Quaternary sedimentation history of the Lena Delta. Quaternary International. 89, 119-134.

SEMILETOV, I.P., I.I. Pipko, N.E. Shakhova, O.V. Dudarev, S.P. Pugach, A.N. Charkin, C.P. McRoy, D. Kosmach, Ö. Gustafsson (2011): Carbon, transport by the Lena River from its headwaters to the Arctic Ocean, with emphasis on fluvial input of terrestrial particulate organic carbon vs. carbon transport by coastal erosion. Biogeoscience. 8, 2407-2426.

SHENG, Y., L.C. Smith, G.M. MacDonald, K.V. Kremenetski, K.F. Frey, A.A. Velichko, M. Lee, D.W. Beilman, P. Dubinin (2004): A high-resolution GIS-based inventory of the west Siberian peat carbon pool. Global Biogeochemical Cycles. 18, GB3004.

SHIROKOVA, L., O. Pokrovsky, S. Kirpotin, C. Desmukh, B. Pokrovsky, S. Audry, J. Viers (2013): Biogeochemistry of organic carbon, CO2, CH4, and trace elements in thermokarst water bodies in discontinuous permafrost zones of Western Siberia. Biogeochemistry. 113, 559-573.

SOLOV'EV, P.A. (1959): Cryolithozone of the northern part of the Lena and Amga interfluve. USSR Academy of Sciene, Moscow. (in Russian).

SPITZY, A., J. LEENHEER (1991): Dissolved Organic Carbon in Rivers (Chapter 9). Biogeochemistry of Major World Rivers.

STETTNER, S. (2014): Characterizing thermos-erosional landforms in Siberian ice-rich permafrost: Morphometric investigations in the Lena Delta using high-resolution satellite imagery and digital elevation models. Master thesis, Freie Universität Berlin.

STRAUSS, J. (2010): Late Quaternary environmental dynamics at the Duvanny Yar key section, Lower Kolyma, East Siberia. Thesis. University of Potsdam.

STRAUSS, J. (2014): Organic carbon in ice-rich permafrost: Characteristics, quantity, and availability. Dissertation thesis, University of Potsdam.

STRIEGL, R.G., G.R. Aiken, M.M. Dornblaser, P.A. Raymond, K.P. Wickland (2005): A decrease in discharge-normalized DOC export by the Yukon River during summer through autumn. Geophysical Research Letters. 32, L21413.

TARNOCAI, C., J.G. Canadell, E.A.G. Schuur, P. Kuhry, G. Mazhitova, S. Zimov (2009): Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochemistry Cycles. 23, GB2023.

TRANVIK, L.J., S. Sobek, Y.T. Prairie, P. Kortelainen, J.J. Cole (2007): Patterns and regulation of dissolved organic carbon: An analysis of 7,500 widely distributed lakes. Limnology and Oceanography. 52/3, 1208-1219.

VAN EVERDINGEN, R.O. (Ed.) (2005): Multi-language glossary of permafrost and related ground-ice terms. National Snow and Ice Data Center/World Data Center for Glaciology. Boulder.

VONK, J.E., P.J. Mann, S. Davydov, A. Davydov, R.G.M. Spencer, J. Schade, W.V. Sobczak, N. Zimov, S. Zimov, E. Bulygina, T.I. Eglinton, R.M. Holmes (2013): High biolability of ancient permafrost carbon upon thaw. Geophysical Research Letters. 40, 2689-2693.

WALTER ANTHONY, K.M., S.A. Zimov, G. Grosse, M.C. Jones, P.M. Anthony, F.S. Chapin III, J.C. Finlay, M.C. Mack, S. Davydov, P. Frenzel, S. Frolking (2014): A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. Nature. 511, 452-456.

WETTERICH, S. S. Kuzmina, A.A. Anreev, F. Kienast, H. Meyer, L. Schirrmeister, T. Kuznetsova, M. Sierralta (2008): Palaeoenvironmental dynamics inferred from late Quaternary permafrost deposits on Kurungnakh Island, Lena Delta, Northeast Siberia, Russia. Quaternary Science Reviews. 27, 1523-1540.

WICKLAND, K.P., J.C. Neff, G.R. Aiken (2007): Dissolved Organic Carbon in Alaskan Boreal Forests: Sources, Chemical Characteristics, and Biodegradability. Ecosystems. 10, 1323-1340.

ZIMOV, S.A., Y.V. Voropaev, I.P. Semiletov, S.P. Davidov, S.F. Prosiannikov, F.S. Chapin III, M.C. Chapin, S. Trumbore, S. Tyler (1997): North Siberian lakes: A methane source fueled by Pleistocene carbon. Science. 277, 800-802.

ZIMOV, S.A., E.A.G. Schuur, F.S. Chapin III (2006): Permafrost and the global carbon budget. Science. 312, 1612-1613.

Danksagung

An dieser Stelle möchte ich mich bei Dr. Anne Morgenstern bedanken. Sie gab mir nicht nur die Möglichkeit zur Anfertigung dieser Arbeit, sondern unterstützte mich dabei in jeglicher Hinsicht. Ich danke ihr für ihre liebe und freundliche Art und für viele anregende Unterhaltungen. Auch danke ich Prof. Dr. Axel Bronstert dafür, dass er sich als Gutachter für diese Arbeit zur Verfügung stellte.

Ich möchte mich besonders bei Antje Eulenburg bedanken. Sie wies mich in die Laborarbeit ein, hatte immer ein offenes Ohr und sorgte mit ihrer guten Laune immer für eine schöne Arbeitsatmosphäre. Dr. Julia Boike, Dr. Paul P. Overduin und Dr. Hanno Meyer danke ich für ihre fachliche Hilfe und spannende Diskussionen.

Besonderer Dank gilt Thimo Stolpmann, der mich während der gesamten Studienzeit in allen Belangen unterstützte. Er gab mir immer den nötigen Halt und bewältigte jede noch so große Hürde mit mir.

Abschließend möchte ich meinen Eltern, Andrea und Wolfgang, von Herzen ewige Dankbarkeit zum Ausdruck bringen. Mit ihrer Geduld und Unterstützung machten sie dieses Studium überhaupt möglich und hielten mir in anstrengenden Phasen immer den Rücken frei.

Eigenständigkeitserklärung

Hiermit versichere ich, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe. Alle von Autoren wörtlich übernommenen Stellen, wie auch sich an die Gedanken anderer Autoren eng anlehnende Ausführungen meiner Arbeit, sind unter Angabe der Quelle kenntlich gemacht. Außerdem versichere ich, dass diese Arbeit in gleicher oder ähnlicher Fassung noch nicht Bestandteil einer Studien- oder Prüfungsleistung war.

Berlin, den 20. November 2015

Lydia Polakowski