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Abstract

Recent evidence has shown that Arctic regions have warmed about twice as much as elsewhere on the planet over the last decades, and that high-latitude permafrost-periglacial processes and hydrological systems are notably responsive to rising temperatures. The aim of this paper is to report on thermal regime of islands located along the Lena River floodplain, upstream of the city of Yakutsk (eastern Siberia). Four islands were monitored using waterproof dataloggers and continuous monitoring of frozen soil in contact with ice breakup of the Lena River. For each of these islands, we measured: i) ground surface temperature, air and frozen soil temperatures at different depths; ii) submersion duration during the flood. Our results show that within a zone of thick and continuous permafrost, the Lena floodplain is notably heterogeneous, with a combination of permanently and seasonally frozen islands. The ice breakups seem to have a negligible impact on the ground thermal regime. Our study confirms that relatively young (less than 30 years old) islands, composed of fine sand material, appear less prone to permafrost formation compared to older islands with ice-rich silty material.

1. Introduction

Permafrost has been warming at the global scale over the last decade, following the Arctic amplification of air temperature increase in the Northern Hemisphere (Biskaborn et al., 2019). Recent work has shown a significant increase in air and ground temperatures in central Yakutia (Eastern Siberia) since the late 1980s (Fedorov et al., 2014; Iijima et al., 2016, Zhang et al., 2012). In the Lena River valley (Figure 1), according to Iijima et al. (2010), the mean annual ground temperature at a depth of 3.2 m has increased by about 1.3°C since 1930. The mean annual air temperature at Yakutsk was -9.9° 9 and it ranged between -8°C and -12°C for the period 1936-199. The mean annual air temperature has increased to -8.4°C between 2000 and 2007 and to -7.4°C after 2008 (the last period ranging between -6.7°C and -7.8°C). A wetter period is registered between 2002 and 2008 (mean annual value for the period: 276 mm), however the precipitation has decreased after (about 220 – 230 mm). Very

wet conditions occurred in 1999, 2003, 2005, 2006, 2007 and 2013, with storms affecting Siberia resulting in more abundant late summer precipitation and early winter snow (Fedorov et al., 2014b; Iijima et al., 2016).

Furthermore, active layer deepening results in an increase in river discharge (Peterson et al., 2002). More recently, Gautier et al. (2018) reported a strong water discharge increase since the beginning of the 21st century for the Lena River at Tabaga (just upstream of Yakutsk city, at 61° 4'N and 129° 3'E, Figure 1): the 2000-2017 discharge was 15% higher than the discharge for 1936-1999. Furthermore, floods are also changing, with more frequent flood peaks and longer recorded flooding durations (Gautier et al., 2018). Recent exceptional flood events are reported (Shiklomanov and Lammers, 2009; Costard et al., 2014; Gautier et al., 2018; Tei et al., 2020). There has also been a decrease in winter river ice cover, used as road. Winter thawing/melting events, as well as spring ice jam floods during the ice breakups represent major risks for riverside residents, road and river infrastructures. All these factors lead to permafrost instability and consequent changes in forest, wetland, lake and river ecosystems.

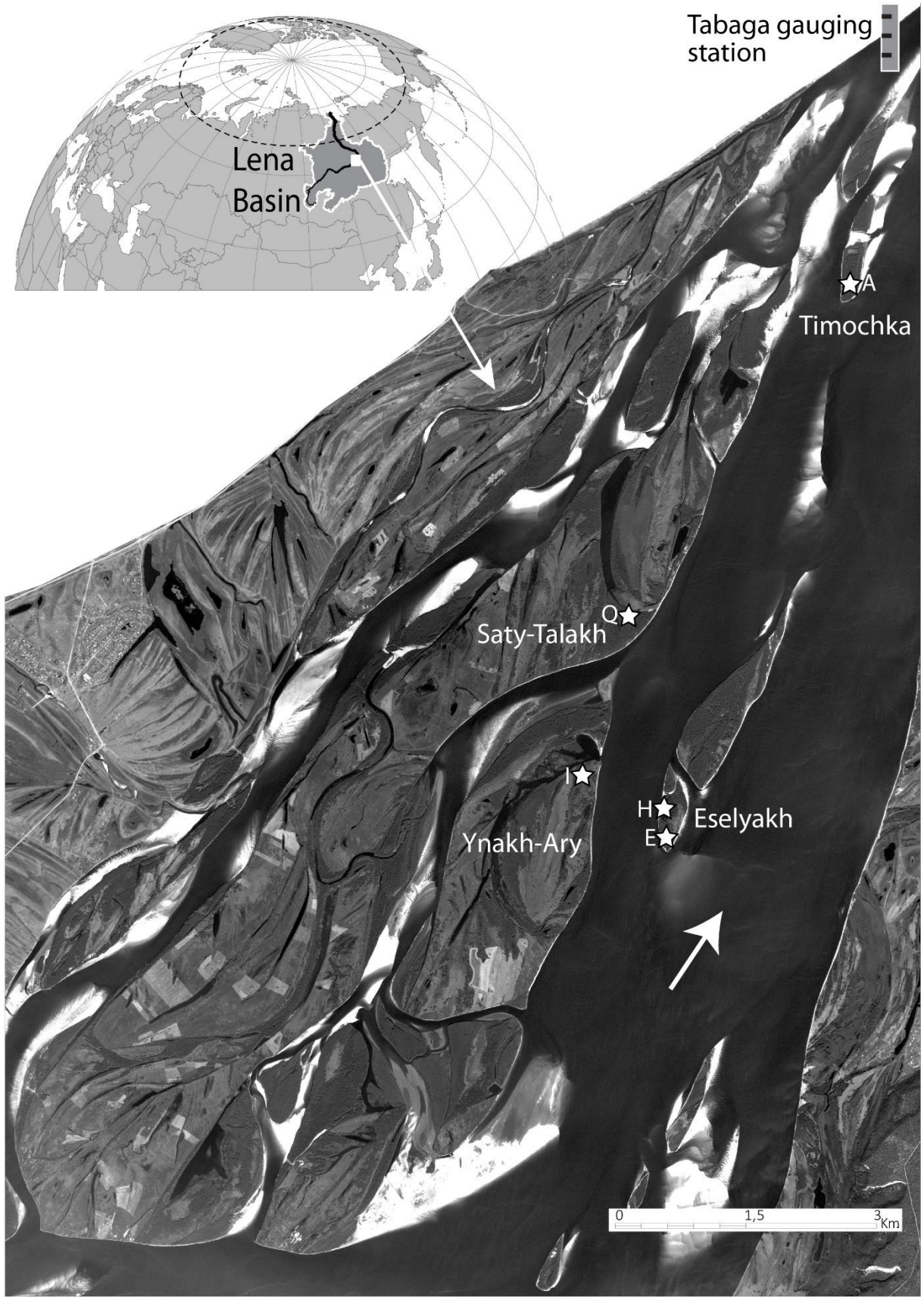


Figure 1: A: Location of the Lena basin and the study sites (upstream of Yakutsk). B: Observation points. Star with letters: Data loggers; Background image: Spot 2008 (CNES, France).

Very few studies have focused on permafrost in floodplains and little is known on geomorphological impacts of ice breakups and floods on major Arctic rivers. Most of the geomorphological studies report on river dynamics of breakup for Canadian Arctic rivers (Beltaos and Burrell, 2002). Specifically, studies have shown the role of the ice cover and its thickness on the intensity of ice jams produced by ice packs along the Yukon River (Shen, 2003; Walker and Hudson, 2003). With increasing discharge, the ice cover under pressure locally cracks and starts to move (Shen, 2003). This is the beginning of the "breakup" phase where ice rafts accumulate at the head of islands (Figure 2); ice breakup usually occurs in spring, between May 20th and early June on the middle Lena River, and in Mid-June or late June downstream, in the low valley (Gautier and Costard, 2000). The flow often carries these ice blocks along with tree trunks (Walker and Hudson, 2003). Ice jams produce local dams, resulting in a sudden rise of water levels (Billfalk, 1982; Beltaos and Burell, 2002; Costard et al., 2014). During the flood season from May to July, the stream water warms the frozen soils, leading to accelerated erosion of the banks (Are, 1983; Jahn, 1975; Walker, 1983). Melting of the ice contained in the porous sediment of the riverbank reduces its strength, and produces removable unconsolidated material (Costard et al., 2003). Furthermore, when the water level is above the bankfull level, the overbank water submerges the island soil that is still frozen. The effects of the submersion have never been studied.

Breakups and floods are strongly heterogeneous, as numerous factors control their starting date, duration and intensity (Costard et al., 2014; Gautier et al., 2018). The flood wave coming from the upper basin can occur on a floodplain that is still frozen or not (depending on the local temperature). Moreover, analysis of climatic and hydrological data near Yakutsk showed a very clear thinning trend in winter ice thickness and a significant increase in water temperature of the Lena River near Tabaga (gauging station upstream section of Yakutsk, Figure 1). We have also demonstrated the impact of recent warming on increasing erosion rates of the islands by thermal erosion (Costard et al., 2007; Gautier et al., 2021).

Only a few studies report on permafrost thermal regime in Arctic floodplains, and in spite of a relatively good understanding of the initial stage of the breakup period of these periglacial rivers [Beltaos and Burrell, 2002; Shen, 2003; Billfalk, 1982], little is known regarding the influence of ice breakup and flooding on ground thermal regime during the flood season (Are, 1983; Walker, 1983). The major influence of water stream temperature on the thermal regime of frozen ground has already been demonstrated using cold room experiments (Costard et al., 2003), but only for river bank erosion.

Moreover, breakup and large flooding events represent an important risk in Arctic regions and can threaten infrastructures. In May 2001 and 2010, catastrophic breakup events linked to an early spring season following a severe winter strongly impacted the cities of Yakutsk and Lensk (Gautier et al., 2018). Recently, a project of a 6 km-long bridge across the Lena floodplain at Tabaga site is projected

and it implies accurate knowledge of the formation, and especially of the causes of the variable intensity of these ice breakups.

Figure 2: Beginning of the ice breakup on the Lena River, May 15th, 2010. Flow from right to left. During the first days, drifting ice blocks on the river formed thick ice accumulations at the head of Timochka Island, which led to a frontal erosion of up to 40 m within a few days.

The main objective of this paper is to analyze the near-surface thermal regime of four islands in the Lena River floodplain, eastern Siberia, and to determine to what extent it is affected by island dynamics and ice breakup/flooding events. We investigate the thermal influence of the water stream temperature by a vertical variation of the ground thermal regime during a typical submersion of the islands affected by ice breakups and flooding events.

2. Study area

Central Yakutia (eastern Siberia) is characterized by a continental periglacial climate with extreme variations in air temperatures, ranging from +30°C in summer to -50°C in winter (Fedorov et al., 2014) (see Figure 3 for the period 2009-2018). The region is characterized by a thick continuous ice-rich permafrost of late Pleistocene age, called “Yedoma” (Antonov, 1960; Schirrmeister et al., 2013). The mean air temperature at Yakutsk is -8.5 °C since the beginning of the 21st century. The winter temperature (October to April) ranged between -10°C and -40°C (Figure 3). The temperature becomes positive at the beginning of May and the mean monthly temperature can exceed +20°C from mid-June to mid-August. The low annual precipitation (230 mm near Yakutsk), together with a high evaporation rate, induces a dry climate (Antonov, 1960). Most of the precipitation occurs in summer, with 140 mm distributed between June and September. Snow cover thickness remains low (30 to 40 cm), which favors efficient frost penetration and the existence of a deep permafrost, especially underneath the taiga. The mean annual temperature of the permafrost at depths of 10 m to 20 m ranges from −2°C to

−4°C (Fedorov and Konstantinov, 2003). Since the end of the 1980s, it has undergone a warming of almost 1.5°C (at a depth of 3.2 m), together with a deepening of the active layer, with values ranging from 0.8 to 1.2 m at the latitude of Yakutsk (Fedorov and Konstantinov, 2003; Fedorov et al., 2014).

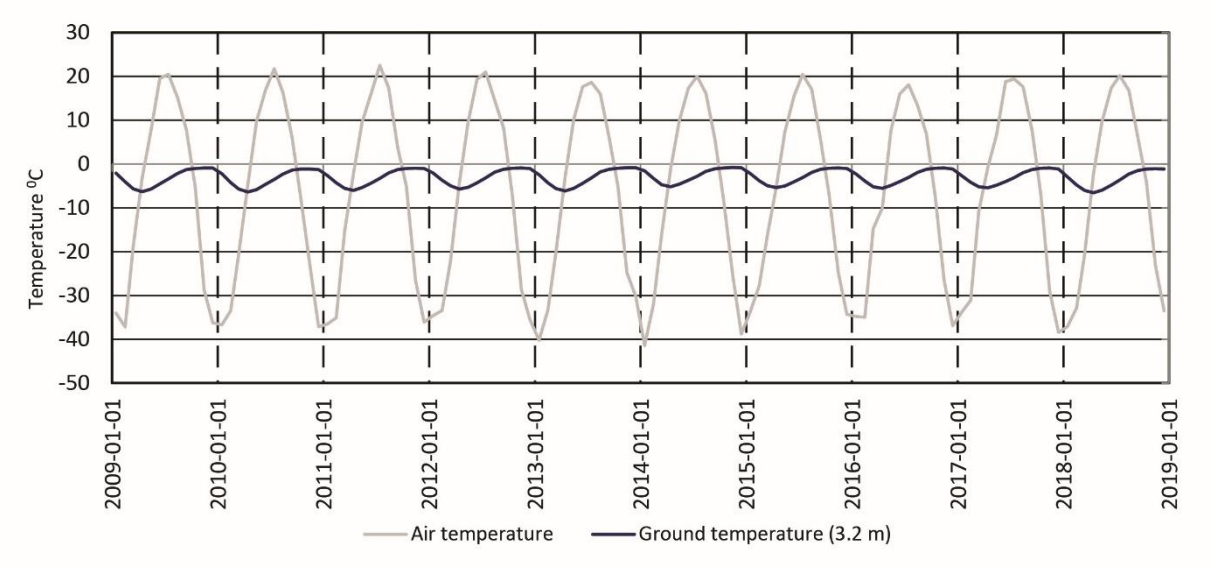


Figure 3: Mean monthly air and ground (3.2-m depth) temperature at Yakutsk (NOAA data) – July 2009 – July 2018.

The Lena River is one of the largest fluvial hydrosystems within the periglacial zone (Figure 1), with thick and continuous permafrost that covers 77% of the basin (Soloviev, 1973). During the winter season (October to April), the river flows under an ice cover with an average thickness of 1.4 m (min: 0.3 m; max. 2 m). The river discharge is then extremely low (less than 1500 $m^3 s^{-1}$ at the Tabaga station,) and reaches its lowest discharge of 870 $m^3 s^{-1}$ in April, at the end of the winter (Gautier and Costard, 2000; Gautier et al., 2018). The breakup and the flood occur between May 20th and June 10th. However, the recent years showed earlier or later events (Gautier et al., 2018). The overbank discharge (about 30 000 $m^3.s^{-1}$ at Tabaga) inundates the forested islands and the floodplain with a great irregularity: the inundation can last from a few days to one month. After the flood, the water level rapidly drops in July. On the Lena River, ice breakups are controlled by the meridian course of the river, with a 30- to 50-day lag between basin upstream and downstream (Gautier et al., 2003). As a result, when snow and ice covers melt, a flood wave propagates from the southern regions further to the still-frozen regions in the north. Therefore, the water discharge increases abruptly and massive ice and log jams can be formed on the island heads (figure 2). Within a few days, the volume of water flow increases 20 to 45 times (Gautier et al., 2018). The peak flood can reach up to 50,000 $m^3 s^{-1}$ (Antonov, 1960, Liu et al., 2005; Gautier et al., 2018). At the latitude of Yakutsk, the water level during the flood season can be

up to 8 to 10 m higher than during the winter low water level (Costard et al., 2007; Gautier et al., 2018). During high floods, the Lena flood spreads over a width of 15 km. The water stream temperature, about 0°C in the winter and up to 8°C at the beginning of the flooding season, increases rapidly to reach 17-18°C in July and August (Costard et al., 2014).

For the purpose of our study, a site upstream of Yakutsk (Figure 1) have been chosen, in order to avoid the urban heat flow. In addition, the upstream Lena River is not impacted by dams. Ten islands were preselected in the riverbed upstream of Tabaga gauging station, and four of them were instrumented and are discussed further in this paper (Figure 1). Eselyakh and Timochka islands (0.2 and 0.7 km² are located in the central part of the active channel, whereas Ynakh-Ary and Saty-Talakh are two much larger lateral islands, sizing 5 km² and 20 km², respectively (Table 1). The island elevation ranges between 92 masl for the highest parts (levees and center of old islands) and 88 masl for the depressions that generally correspond to abandoned channels. The islands are colonized by a homogeneous alluvial forest mainly composed of willows. On the Lena River, islands are formed by stabilization of sand bars by pioneer sequences. Because of their abundance, young trees trap the sediment load, causing rapid vertical accretion of the island (Gautier et al., 2021). Hence, the base of the island stratigraphy is mainly composed of homometric (D_{50} = 200 - 250 µm) sandy material organized in horizontal beds several tens of centimeters thick. The sandy deposits are often covered with layers of fine sand and silt (D_{50} = 50 - 100 µm) deposited by overbank flows. On the oldest islands, overbank deposits can be 2 m thick. Fine-grained deposits mixed with organic matter are found in abandoned channels. For a detailed description of the sedimentary sequences of these islands, see Gautier and Costard (2000), Costard et al. (2014), and Gautier et al. (2021).

Bank erosion of the Lena river ranges on average between 11 and 18 m yr^{-1} on island head (upper part) and 5 to 10 m on island side. In localized areas, erosion rates of 25 to 40 m yr^{-1} could be observed (Gautier et al., 2003; Costard et al., 2007, 2014; Tananaev, 2016; Dupeyrat et al., 2018; Gautier et al., 2021). The thermo-mechanical process explains the relative efficiency of bank retreat (Walker and Arnborg, 1963; Jahn, 1975; Walker, 1983; Costard et al., 2014).

3. Methods

In order to determine the ground temperature and to evaluate the active layer thickness on the islands, various methods were integrated. First, a drilling campaign (2008) enabled the installation of several temperature sensors at different depths and a precise measurement of the active layer with a steel stick. Thus, topographic conditions do not change a lot in the proximity of the sensors. We used HOBO

4-channels dataloggers (model U12-008) to record variations in the thermal profile. Each datalogger, previously calibrated in the laboratory, includes 4 thermistor sensors (TMCx-HD) that produce a temperature-dependent voltage, which is then converted to temperature and stored in the datalogger, every hour, with an accuracy of ±0.25°C, in the soil, at 0 m (soil surface), 1 m, 2 m and 3.2 m depth (Figure 4). On Saty-Talakh island, the sensors have been installed at 2 m, 3 m and 4 m depth (plus the surface). The annual periods are delimited from July to July. Once a year, after the ice breakup, we went to the instrumented sites to collect data from the dataloggers and to ensure the equipment maintenance on site. During the first year (2008) on Timochka and Eselyakh islands, only two among the four sensors worked well and the others were broken by the strong ice breakup. They were modified to ensure waterproof conditions and to improve the robustness of the equipment in order to control the mechanical effect of ice breakups (e.g., internal pressure). Thus, we had to develop a new system (Figure 4) that is much more efficient and could resist the repeated impacts of ice rafts and water pressure (Konstantinov et al., 2011). Unfortunately, because of the extremely rough conditions, the duration of measurements of the temperature sensors is very variable (Table 1): some of them have been working for more than 10 years, whereas others disappeared during a flood or were buried under meters of sediment and woody debris. Due to some severe breakups, some ground temperature sensors were broken during the first year. In the present study, we present the data of the devices that were installed several dozen meters away from the riverbank and that were preserved from erosion and/or thick sediment deposition during floods.

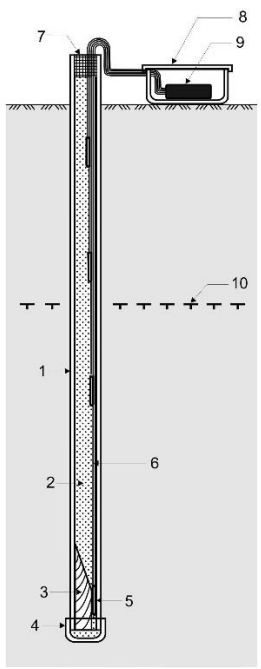


Figure 4: Sketch on the left: Drilling in the frozen soil for the installation of thermistor sensors placed at 0 m (soil surface), 1 m, 2 m and 3.2 m depth. 1- polypropylene tube; 2- dry sand; 3-wooden bloc; 4-tube plug; 5-sensor; 6-cable; 7- waterproofing compound; 8-protective box; 9-data logger; 10-bottom of active layer. Photo on the right: HOBO datalogger modified to resist flooding of the island during spring breakup. Note the two weights on the box and the wooden support holding the datalogger in the waterproof box. (Figure modified from Konstantinov et al., 2011). Every sensor position was precisely determined with a GPS and a total station.

The water levels and the daily discharge were recorded at Tabaga (gauging station, 8 km north from the sites, see Figure 1). The overbank discharge and the submersion duration of the islands have been determined during field observations during the flooding season. Island inundation begins when the river discharge reaches about 30 000 $m^3.s^{-1}$ (Costard et al., 2014 and Gautier et al., 2001; Tananaev, 2016). The lowest parts of the islands can be inundated for a discharge a bit lower and the highest parts need about 32 000 m^3-s^{-1} to be flooded.

Table 1: Main features of the four study islands. Letters: temperature sensors.

	Area (m^2)				Dataloggers			
Island Name	1967	2008	2017	Age	Mean temp. at -3.2 m (°C)	Duration of measurement	Sediment	Geomorphic Unit
Eselyakh – Upstream part Downstream part	 486,726 416,877	 198,256 790,189	 105,520 675,931	> 60 yr	E: -2.2 H: -0.4	 2008 – 2011 2008 – 2011	 Mixed sed. Sand	 Abandoned channel Bar/island
Timochka - Upstream part Downstream part	 216,239 0	 135,560 70,300	 107,161 79,164	< 30 yr	A: 1.2	2008 – 2014	Sand	Bar/island
Ynakh-Ary	5047,718	5338,126	50294,298	> 70 yr	I:-3.9	2009 – 2016	Mixed sed.	Abandoned channel
Saty-Talakh	18 247,279	20 125,713	19 685,946	> 70 yr	Q: -0.6	2009 – 2018	Sand	Bar/island

We estimated the age of the islands based on the year of their appearance from a previous pluri-decadal analysis of aerial pictures and satellite images (Figure 1 and Table 2) used by Gautier et al. (2021). We also used the dendrochronology method to precisely measure the age of the oldest trees. Our objectives were to determine whether the thermal regime is related to the age (and/or size) of the islands.

For each of these sites, we also did an analysis of the sediments and stratigraphy using a soil moisture sensor and grain-size was determined with a laser granulometer (see Suplementary material S1). The

depth of the permafrost table and its ice content were obtained by sampling with a drilling machine down to 3.2 m; the permafrost table was also measured every year with a stick. The analysis of the sediments was done at the Melnikov Permafrost Institute in Yakutsk.

4. **Results**

The analysis reveals an important inter-annual variability, which underscores the heterogeneity of the thermal regime of islands within the Lena floodplain. On the basis of field surveys and soil temperature data, we are able to distinguish two main types: islands with a perennially frozen soil (*i.e*. with a permafrost), and islands with a seasonally frozen ground only.

4.1. Islands with permanently frozen soil

Eselyakh Island

The Eselyakh Island (Figure 5) has a permanently frozen soil. According to Hobo E (Figure 6), the annual average temperature at 3.2 m depth was -2.2°C for 2009-2010 and -3°C for 2010-2011. At 1 m and 2 m depths, the Hobo recorded a slightly lower mean temperature and a higher intra-annual variability (1m: -2.5°C in 2009-2010 and -4.3°C in 2010-2011; 2m: -2.4°C in 2009-2010 and -3.5°C in 2010-2011). Hobo measurements coupled with successive field campaigns have shown that the active layer is thinner on the upstream section (1.2 m depth) of the island than on the downstream section (1.5 m depth) (Figure 5). The active layer is composed of peaty sandy loam with a volumetric moisture content of 25% to 53%. Based on drilling operations, the permafrost table at Hobo E site is located at 1.5 m and contains ice-rich sandy loam materials with 19% to 50% ice content by volume.

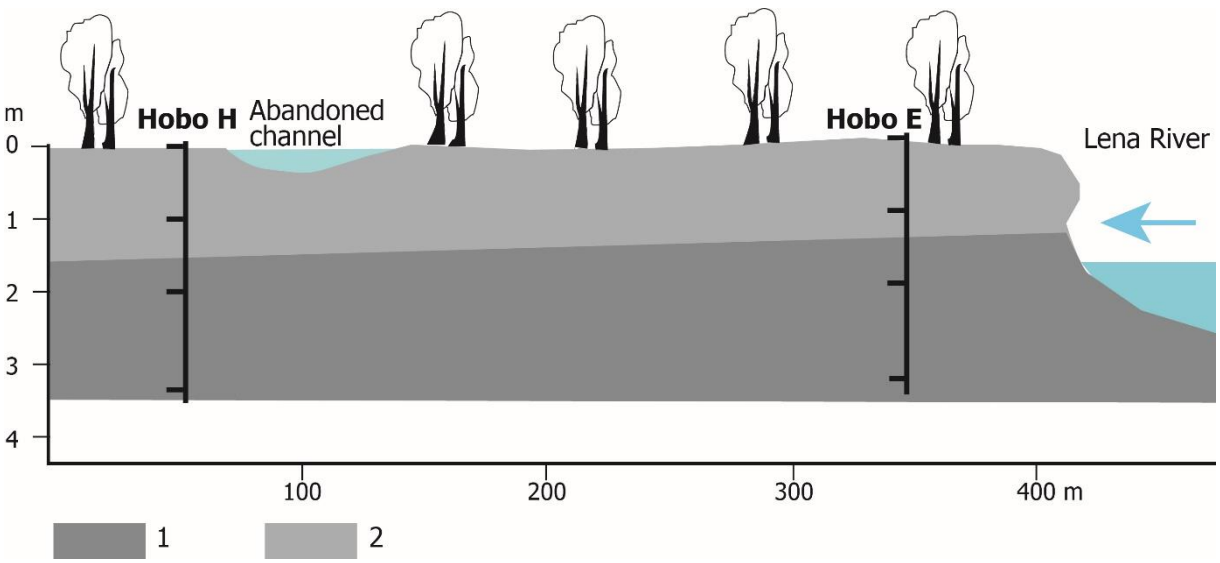
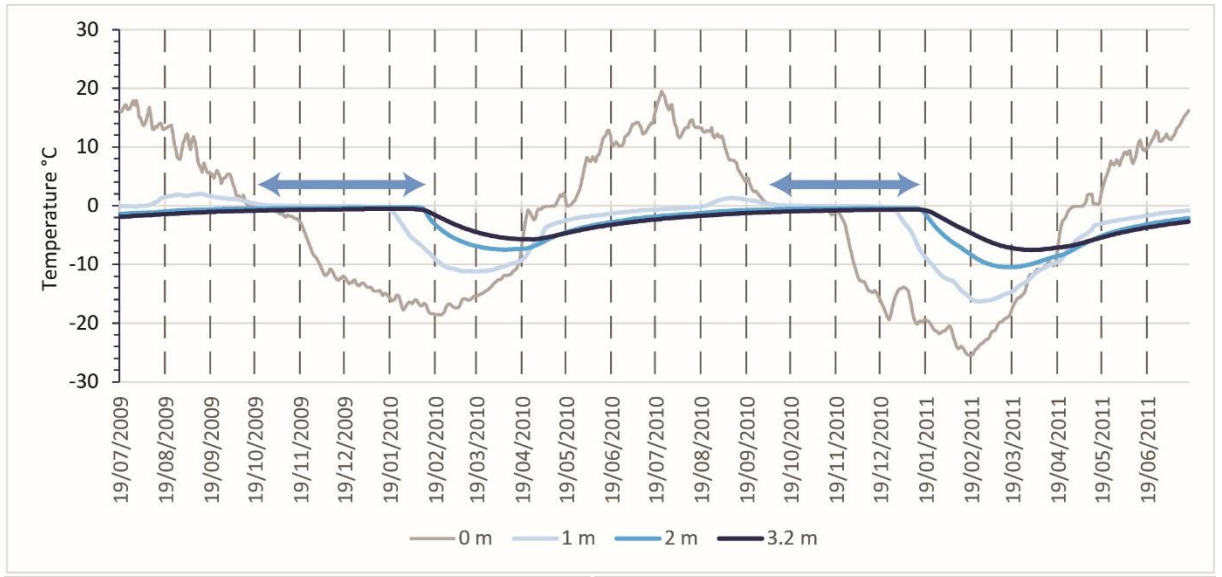


Figure 5: Schematic longitudinal section of Eselyakh Island. 1: permanent frozen soil; 2: active layer. Blue arrow indicates flow direction (to the North). Hobo H is located near a 30 m wide abandoned channel.

According to the thermal profile of HOBO E (Figure 6), underneath the active layer, there is permanently frozen soil with temperatures ranging from -0.3°C to -10.4°C at a depth of 2 m during the two consecutive years (2009 – 2010 and 2010 – 2011). At 3.2m depth, the variability of frozen soil temperature was even less pronounced, ranging between -0.5°C and -7.5°C. We note a downward propagation of the winter freezing wave and a time lag with depth for reaching minimum temperature due to the thermal inertia of frozen ground (Figure 6). For example, the minimum annual temperature was reached in mid-February at the soil surface, in early March at a depth of 1 m, in late March at 2 m, and in mid-April at 3.2 m, during the first winter. The second winter was harsher and a colder weather occurred earlier with -20°C in December and -25°C in February, at the soil surface. Consequently, this ~ 20-day time lag between different depths was also observed during the second winter, although nearly three weeks earlier than the previous year (in mid-February, early March and late March, respectively). For the October – December period, temperatures were stabilized (70 to 80 days) just below 0°C at a depth of 1 m due to the effect of latent heat (zero curtain effect on Figure 6). At 2m and 3.2m-depth, temperature began to decrease at the end of January.



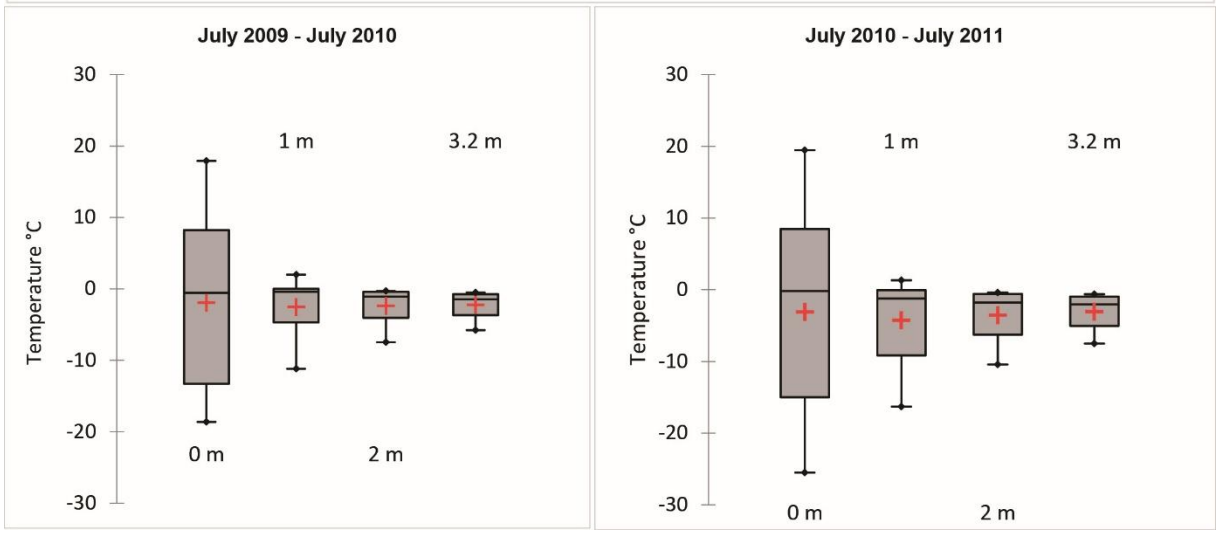


Figure 6: Ground thermal profiles on Eselyakh Island at 1 m, 2 m and 3.2 m depth for HOBO E datalogger; 0 m: soil surface temperature (July 2009 – July 2011). Blue arrows correspond to the zero-curtain effect during phase change of the water-ice in winter season.

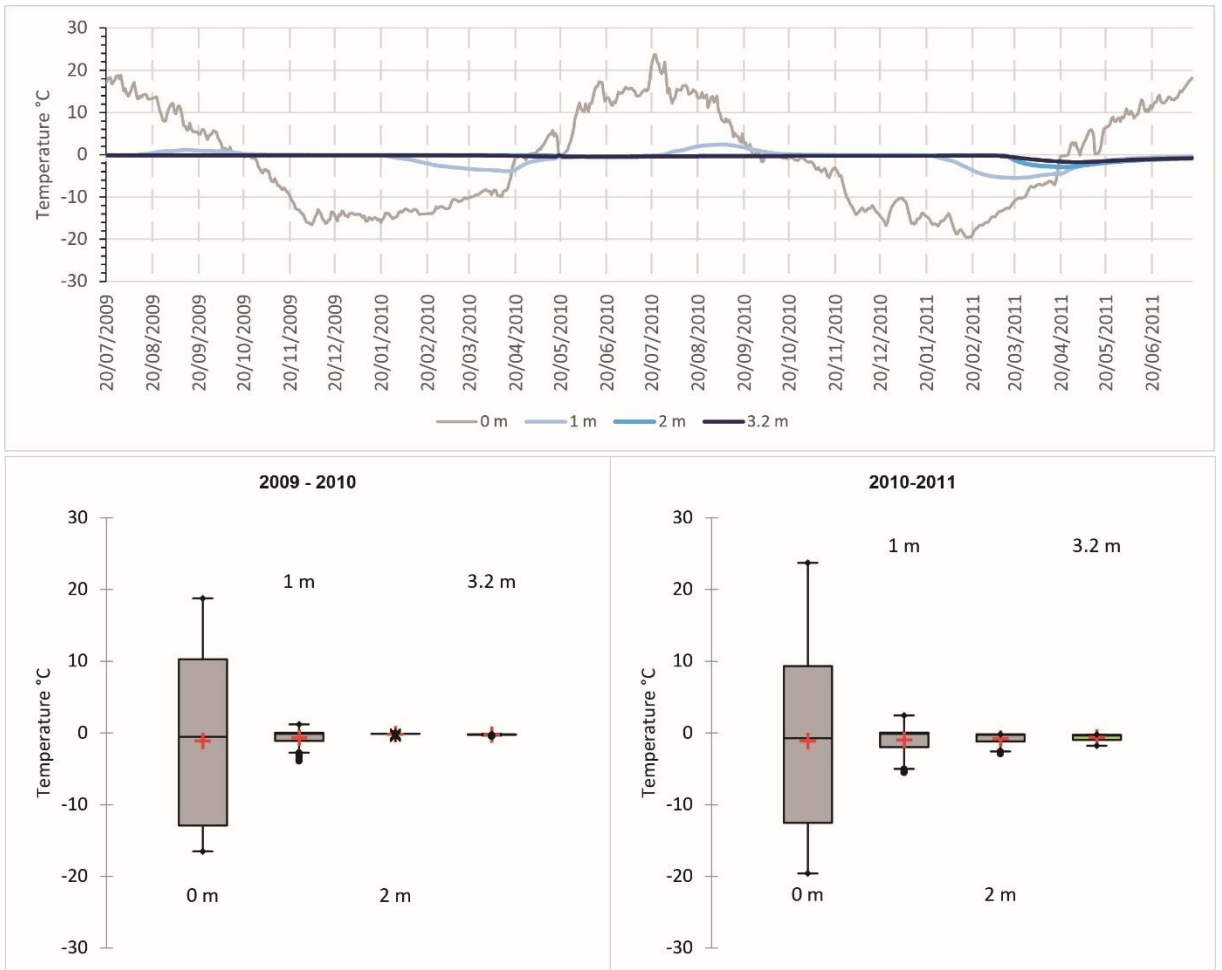


Figure 7: Ground thermal profiles on Eselyakh Island at 1 m, 2 m and 3.2 m depth for HOBO H datalogger; 0 m: soil surface temperature (July 2009 – July 2011).

Contrastingly, the thermal profile of HOBO H, located further downstream on the island (Figure 7), shows a notably warmer frozen soil. For 2009-2010, the mean temperature was -0.67°C, -0.18°C and -0.24°C at 1 m, 2 m and 3.2 m, respectively. In 2010-2011, the mean temperature was lower (-1°C, -0.8°C, -0.6°C at 1 m, 2 m and 3.2 m). Furthermore, the temperature ranged between ~ 0°C and -5.5°C (1 m), between -0.1°C and -2.9°C (2 m) and between -0.2°C and -1.7°C (3.2 m) during the second (colder) winter. The temperature did not vary substantially during the first winter and decreased a bit more during the second winter. The lowest temperature was registered in April before the breakup (-1.8°C at 3.2m). The lowest temperatures are not as cold as the one registered by Hobo E (-7.5°C in April 2011 at 3.2 m). The sediment is identical, with the same composition and grain size characteristics as on the previous site.

Large lateral islands (Ynakh-Ary and Saty-Talakh)

On Ynakh-Ary, Hobo I has been working from 2009 to 2016 (Figure 8). The temperature varied between -0.1 and -14°C (1 m) -1.2°C and -11.1°C (2 m) and between -1.2°C and -8.9°C (3.2 m depth). When comparing the same years (2009 to 2011), Ynakkh – Ary has a colder soil than Eselyakh: -2.98°C for 2009-2010 (at 3.2 m) and -3.97°C for 2010-2011 mean value. We also observed a two month-time-lag separating the beginning of continuous negative temperature on the soil surface (October) and the start of the cooling within the frozen soil: beginning of January at 1 m and 2 m depths, end of January or early February at 3.2m depth.

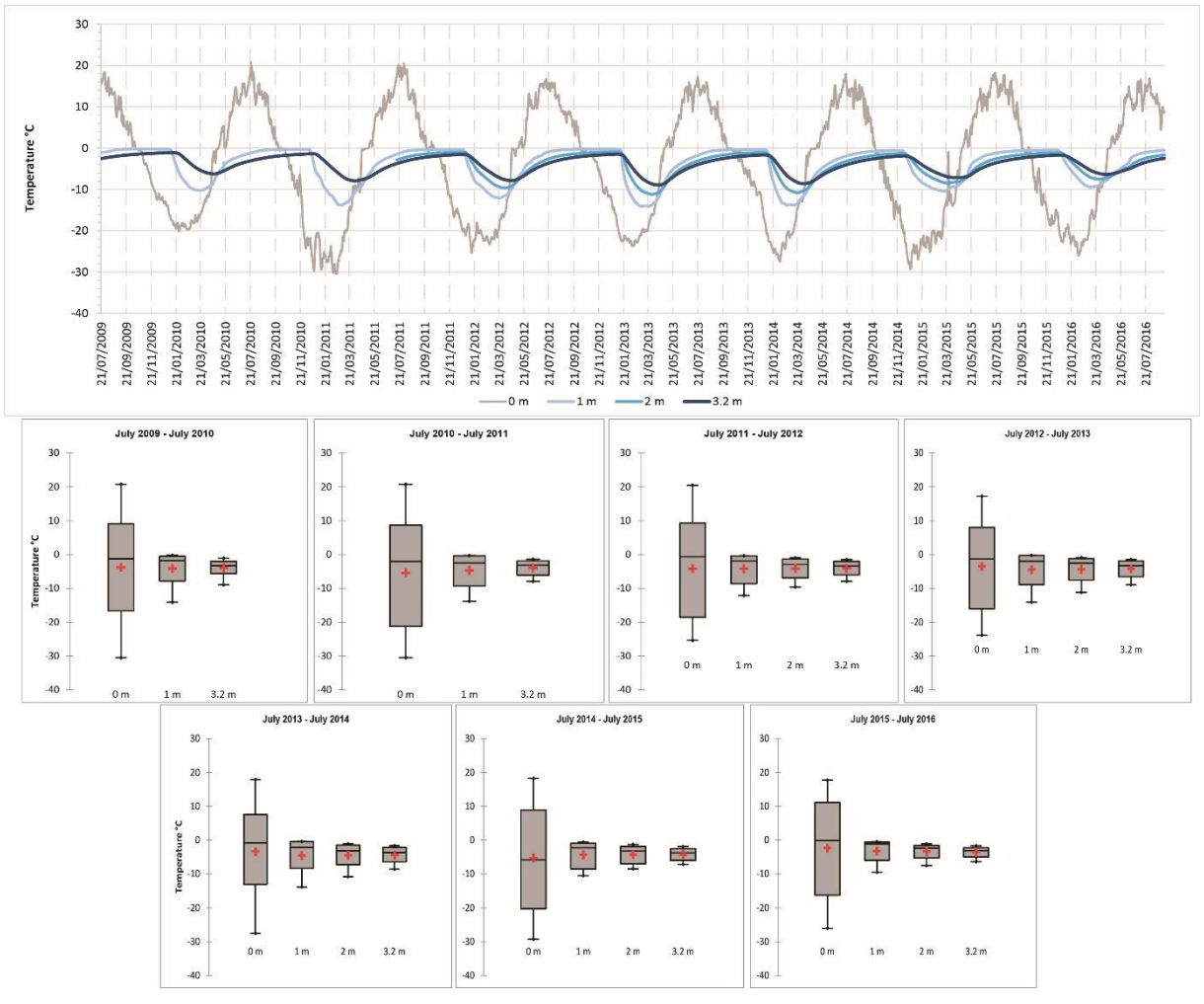


Figure 8: Ground thermal profiles on Ynakh-Ary island, at 1 m, 2 m and 3.2 m depth for Hobo I datalogger; 0 m: soil surface temperature (July 2009 – July 2016).

On Saty-Talakh, which is also a large lateral island, Hobo Q has been working from 2010 to 2018 (Figure 9). The thermal profile differs from the data registered on Ynakh-Ary. The temperature regime is similar

to Hobo H on Eselyakh island, because of a relatively warm permafrost at 3.2 m depth. For 2010-2011, the mean temperature (3.2 m) was -0.79°C and dropped to -1.81°C at the end of the winter. The cold winter 2017 – 2018 induced a stronger cooling; the 3 m Hobo recorded -3°C in mid-April.

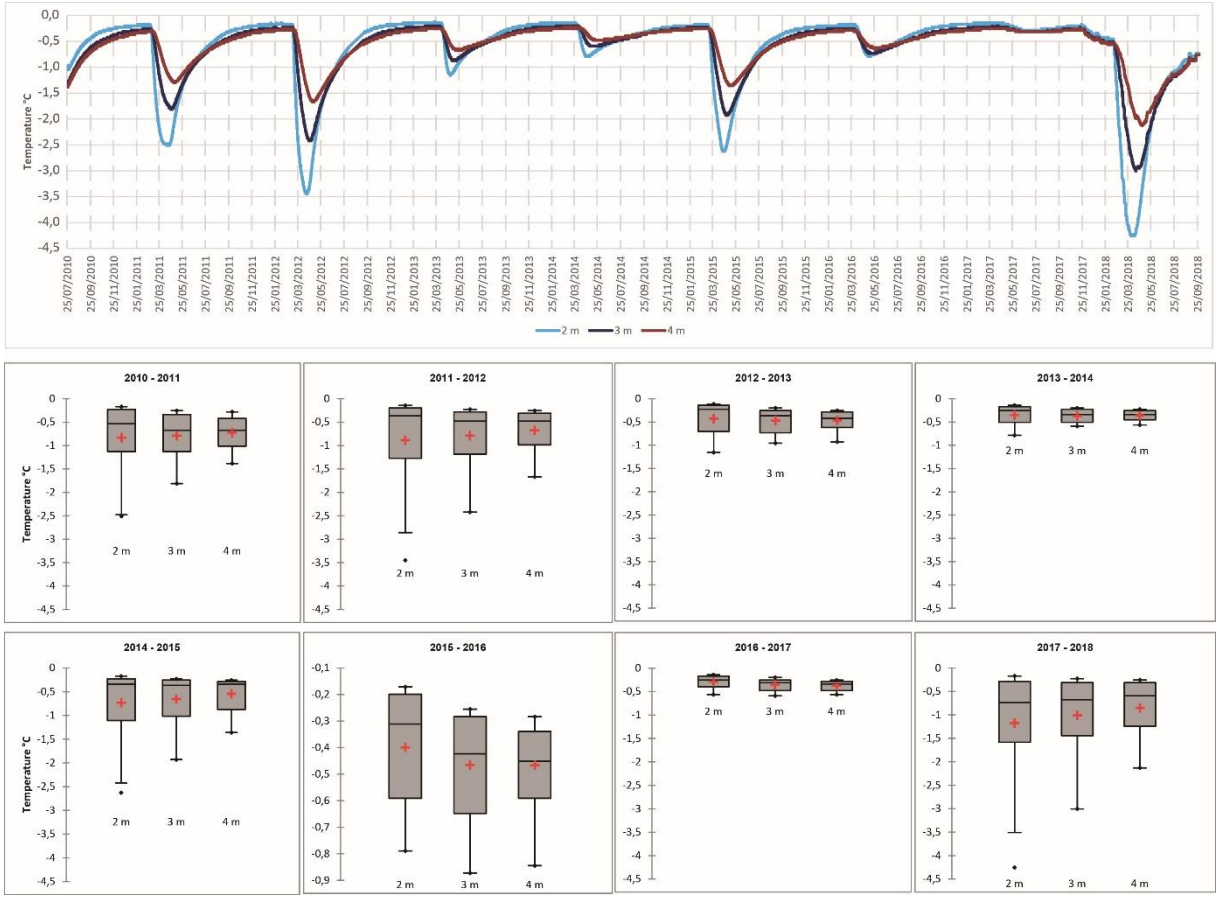


Figure 9: Ground thermal profiles on Saty-Talakh island, at 2 m, 3 m and 4 m depth for Hobo Q datalogger (July 2010 – September 2018). No data logger at the soil surface for Hobo Q.

4.2. Islands with seasonally frozen ground

Timochka Island

Timochka Island has a seasonally frozen ground; negative temperature is observed from November to the end of April at 1m depth. At 3.2 m depth, the average annual temperature ranges between +1°C and +1.5°C. Thus, temperatures remain constantly above 0°C even at a depth of 3.2 m (Figure 10). This island is mostly composed of fine sand, and the willows are relatively younger than those on Eselyakh Island (Gautier et al., 2021). The volumetric soil moisture content ranges from 4% at 0.1 m depth to 40% at 1 m depth. Similarly to other Hobo sites on the other islands, however, ground temperature

variability is notably larger near the surface (at 1 m deep) compared to several meters deep (Figure 10, lower graphs).

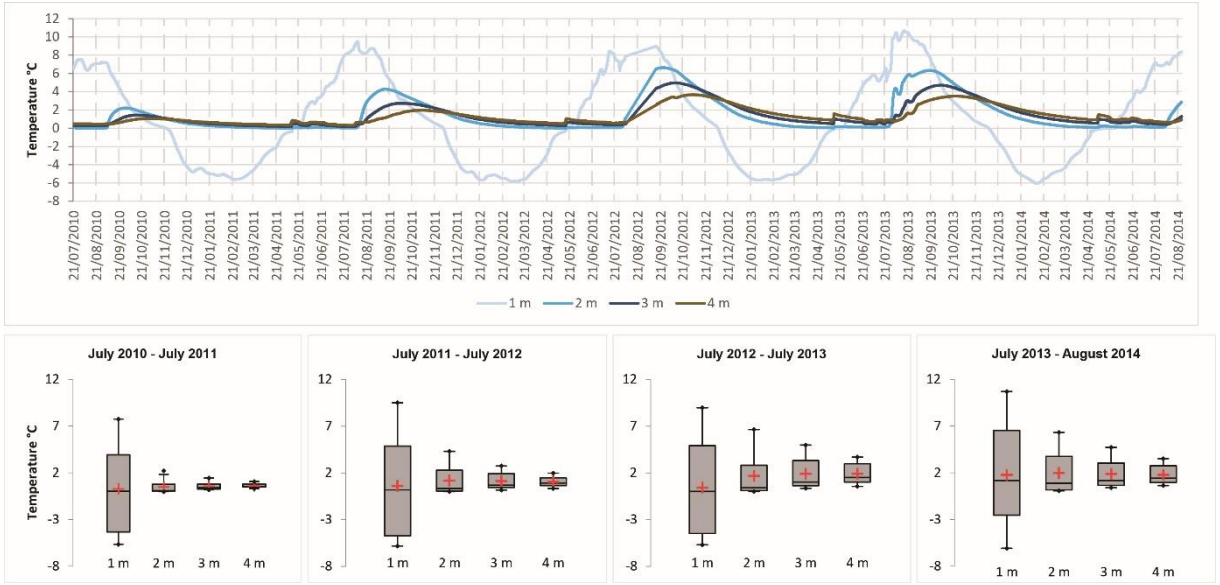


Figure 10: Ground thermal profiles on Timochka Island at 1 m, 2 m, 3 m and 4 m depths for HOBO-A (July 2010 – August 2014), without a permanently frozen soil. No data logger at the soil surface for Hobo A.

5. Discussion

Our results demonstrate that, even in an area of thick continuous permafrost, the ground is not permanently frozen everywhere within the Lena floodplain. This study also highlights not only a strong inter-annual variability in ground temperature, but also the spatial heterogeneity of the thermal regime of frozen soils. On the one hand, some sites along the islands show a colder permafrost conditions that vary little throughout the years, and on the other hand, other sites are underlain by a notably warmer seasonally frozen ground affected by strong thermal variability. Two main factors are inferred to influence permafrost dynamics in the Lena floodplain: the age of the islands and the thermal effect of spring breakups.

Age and thermal state of the islands

The middle Lena River develops a multiple-channel pattern with large forested islands (Costard et al., 2000; Gautier et al., 2008). The anabranching fluvial pattern implies relative stability of the channels and islands, although some islands quickly migrate downstream. This is the case for Eselyakh and Timochka islands that are located in the central part of the active channel (Figure 1). Thus, they rapidly

migrate downstream, as the head is progressively eroded, whereas the tail (downstream) progresses by deposition (Figure 11). Island sides are also exposed to erosion, explaining the reduction in form size (Table 1). The two other islands (Ynakh-Ary and Saty-Talakh) are much larger lateral islands, and are more stable. As they are located at the margins of the river active channel, they are subjected to a reduced reshaping (sediment drift) with a local erosion of their bank (Figure 11).

Eselyakh and Timochka are relatively small islands with surface area of 0.2 km² and 0.13 km², respectively (Table 1). They are bisected with a secondary channel between the two parts (Figure 1, Table 1). Eselyakh is older than Timochka, as its two parts were already formed in 1967 and a dendrochronological analysis of a willow puts its age at 56 years in 2010. It suggests the stabilization of a sand bar during the 1950's. The upper part of Eselyakh is progressively shrinking due to head and side erosion, whereas the lower part is growing by sedimentation. Timochka is an elongated island that is migrating very rapidly since its formation. Hence, the present-day island is young: the upper part corresponds to a deposition zone formed between 1980 and 1996.

Ynakh-Ary and Saty-Talakh are large islands with surface area of 5 km² and 20 km², respectively. They had the same general shape in 1967 (Figure 11). According to local inhabitants, they are very old islands. They were formed by merging of different islands, and lakes and swamps occupy the former inter-island channels.

It appears that the oldest islands are thus at least 70 years old in our selected study area (Gautier et al., 2021). The Ynakh-Ary, Saty-Talakh and Eselyakh islands are old islands with a permanent frozen soil developed in fine-grained material (silt-clay) deposited by overbank flows overlaying a sandy base. Timochka Island is much younger, with only seasonally frozen ground and mostly sand deposits, as the island has been formed by the colonization of a former sand bar by willows. This apparent relationship between the age of deposition/formation and the thermal regime of the ground can also be extended to the much older permafrost near Yakutsk (Figure 3), where ground temperatures at 3.2 m can remain below -1°C at the end of the summer and below -4°C at the end of the winter. Contrastingly, ground temperatures barely or never attain such low values at Eselyakh (Figures. 6 and 7), Ynakh-Ary (Figure 8) or Saty-Talakh (Figure 9), which are nevertheless underlain by frozen ground. Permafrost obviously had much less time to develop at these sites and is in equilibrium with current climate conditions, which is not the case 'onshore' near Yakutsk.

However, the age of the island is not the only parameter explaining the observed differences. Local parameters, and more precisely, abandoned channels, also seem to explain the observed thermal heterogeneity. Hobo H is located not far from a 30 m-large abandoned channel (Figure 5), which obviously induces a thermal effect by heating the upper part of the frozen soil. Widespread along the floodplain, such abandoned channels are watered more frequently and they are located on lower

386 topographic levels. These depressions are humid and occupied by swampy vegetation. Eselyakh (Hobo
387 E) and Ynakh-Ary dataloggers are installed on higher topographic levels.
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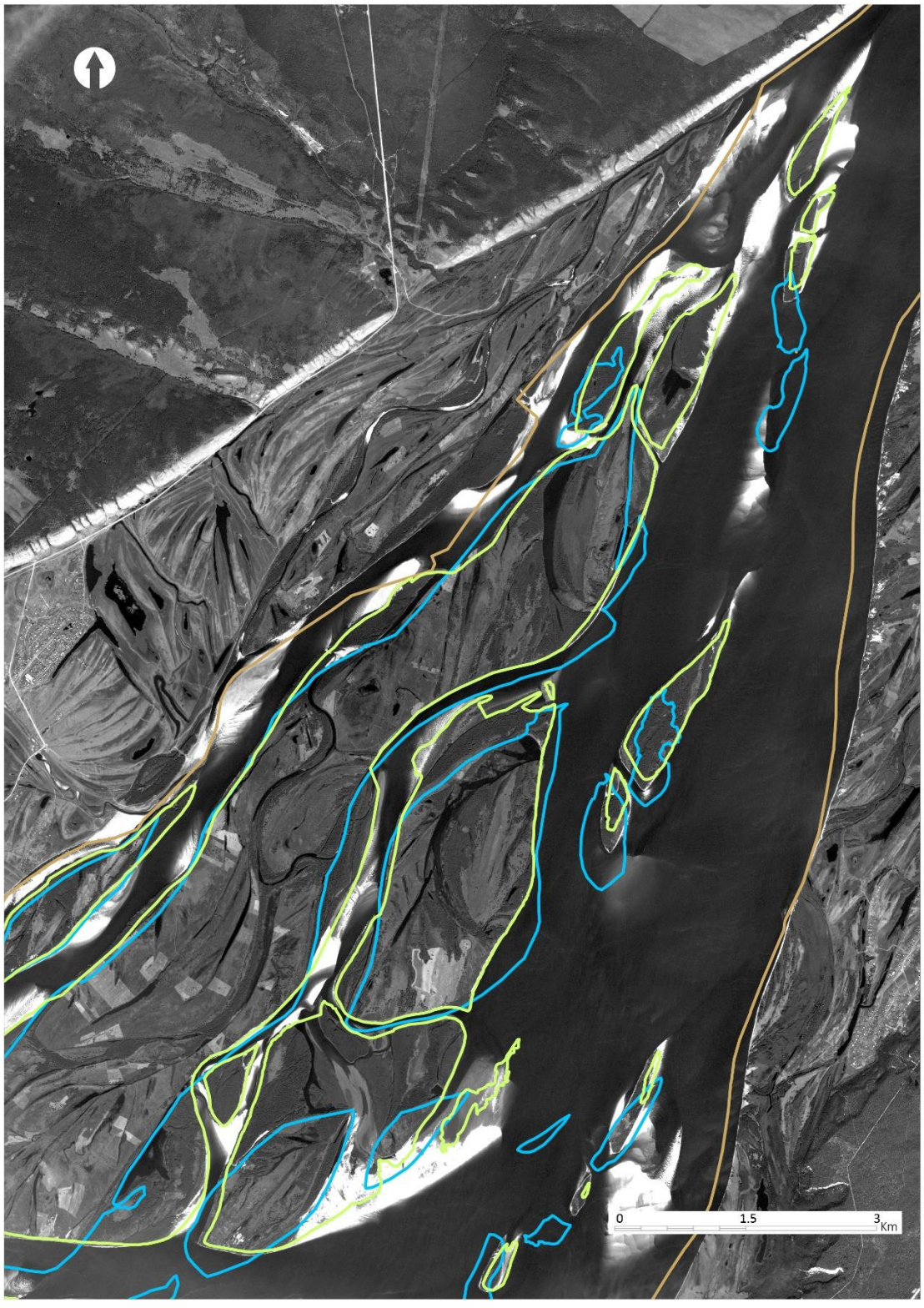

389

390 Figure 11: Island migration of the study reach upstream of Yakutsk city from GIS study. Blue line: island

391 shape in 1967 (Corona photographs); Brown line: channel bank in 1967; Green line: island shape 2017

(Pleiade images © CNES, 2017, Distribution Airbus DS, all rights reserved). Background image: Spot 2008 (© CNES, Freance)

Thermal effect of spring breakup: the example of 2010

During spring floods, the islands along the Lena River channel are submerged and this induces an additional thermal imprint. Our dataloggers were able to record this specific stage on Eselyakh and Ynakh-Ary islands (Figure 12). It can be seen that the temperature variations on the ground are suddenly interrupted on May 19, 2010 with a temperature dropping and remaining at 0°C until May 25 (Figure 12; Table 2). This is due to the inundation of the islands when the flooding begins (for a discharge exceeding about 30,000 $m^3.s^{-1}$). The submersion duration greatly varied during the study period (Table 3).

Furthermore, the sensor installed at the soil surface (0 m on Figure 12) registered the water stream temperature. At the beginning of the flooding, temperatures close to 0°C confirm the existence of a mixture of water and ice during the breakup. Then, after a few days, the water temperature slightly increases (1°C to 3°C) as the islands are inundated by water only.

Table 2. Flood duration, number of flood peaks and temperature range of the study sites along the Lena River

	Flooding duration (Days)	Flood peaks	Stream water temperature range (°C)
2009	26	June 3rd – June 28th	ND
2010	9	May 19th – May 27th	0°C – 0.9°C
2011	6	May 13th – May 18th	0.2°C – 1.4°C
2012	36	May 17th – May 26th June 5th – June 19th July 5th – July 9th July 28th – August 4th	0°C – 3°C 9.5°C – 12°C 15°C – 15.5°C 15°C – 16.5°C
2013	14	May 14th – May 21st July 23rd – July 29th	5°C – 5.5°C 18°C – 19°C
2014	0		
2015	7	May 13th – May 19th	0.3°C – 3°C
2016	10	June 10th – June 16th	11.6°C – 13.3°C

		July 31st – August 3rd	14.6° – 15°C
2017	5	July 20th – July 24th	19°C – 19.5°C
2018	17	May 5th – May 10th July 19th – July 25th	ND

411

412 However, the observed effect of island submersion at the time of breakup appears to have a relatively
413 moderate impact on thermal profile at depth (i.e. more than 1 m deep). This can likely be explained by
414 1) the duration of submersion, which in that case is too short to have a long-term thermal impact in
415 the ground, and 2) the water temperature, still near 0°C, again precluding major thermal disturbance
416 within the ground, at least below the surface. Figure 12 clearly shows that the ground temperature
417 regime for the two islands (Eselyakh and Ynakh-Ary) did not change, even during the 10-day
418 submersion of the island during the ice breakup in May.

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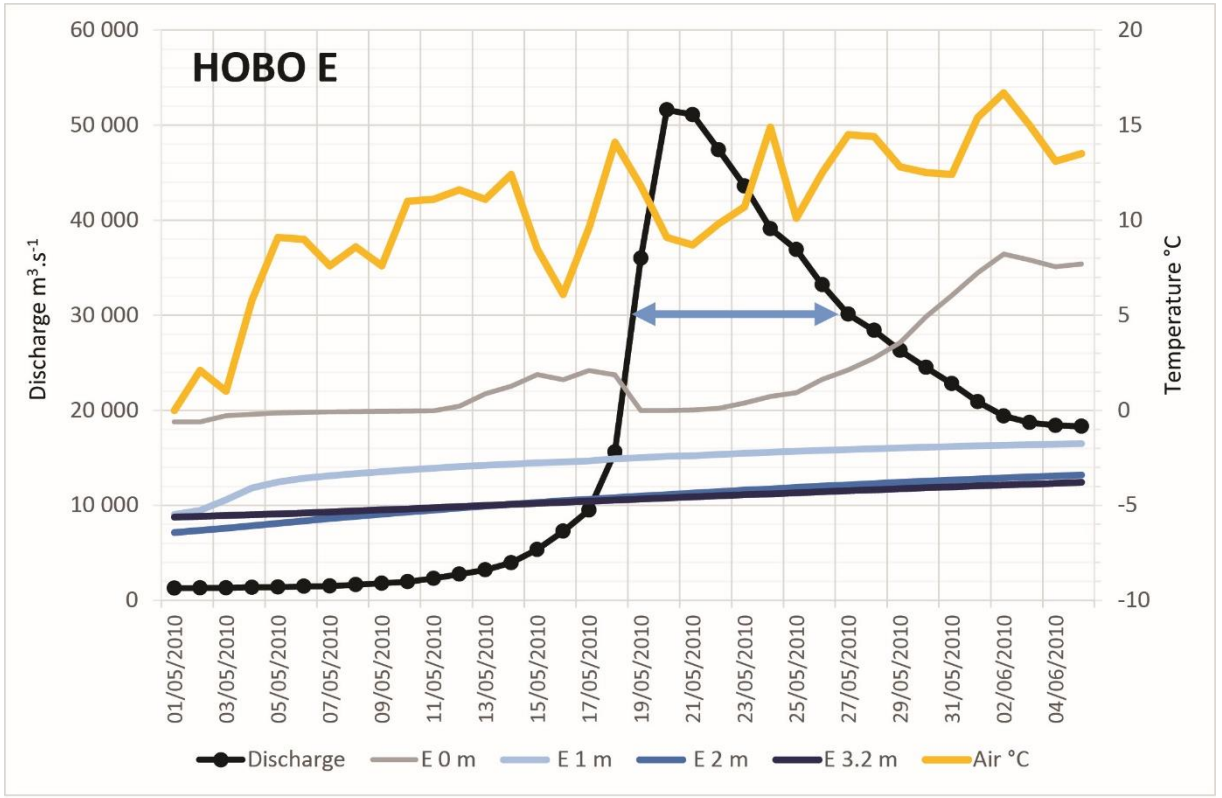

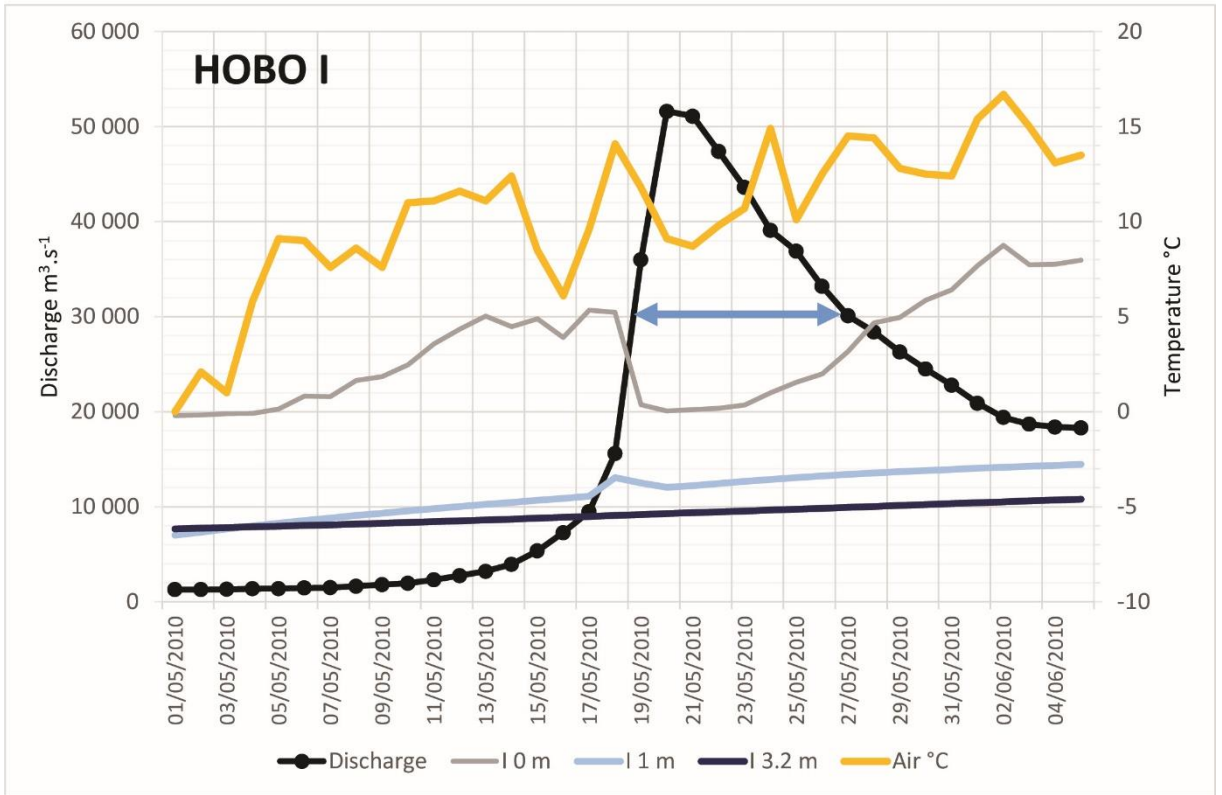

Figure 12: Mean daily discharge and temperature on islands with a permanent frozen soil (2010, May 1 – June 5). Eselyakh Island (HOBO E), Ynakh-Ary Island (Hobo I). Water Discharge at Tabaga gauging station (Roshydromet data); 0 m: soil surface temperature; ground temperature at different depths (1

m, 2 m and 3.2 m); air temperature at Yakustk (NOAA, NASA data). The blue arrow corresponds to the submersion duration of the islands in relation with a discharge > 30,000 $m^3.s^{-1}$.

Interestingly, multiple water level increases during the warm seasons have occurred in the Lena River. During some years, the islands can be inundated twice or more often. For example, in 2012, the Lena River underwent four flood peaks (Figure 13) with 36 days of total flood duration (Table 2). The repeated inundations and warm stream water did not significantly affect, however, the ground temperature regime of the islands.

Regarding the surface temperature recorded in 2010 and in 2012 for Eselyakh Island (HOBO E) and Ynakh-Ary Island (Hobo I), we can observe a systematic decrease of the surface temperature (0 m) during each of these breakups and flood seasons (Figures 12 and 13). The water stream temperature is systematically lower than the air temperature due to the water/ice mixture of the breakup that decreases the surface temperature of the islands during the submersion phase. We also observed that the initial phase of the breakup in May is accompanied by a net decrease in air temperature (yellow curve on figure 12 and figure 13). Finally, regardless of the water stream temperature or the thermal state and water/ice content of the subsoil, the thermal regime of the subsoil at 1 m depth (Figure 13) does not appear to be affected.

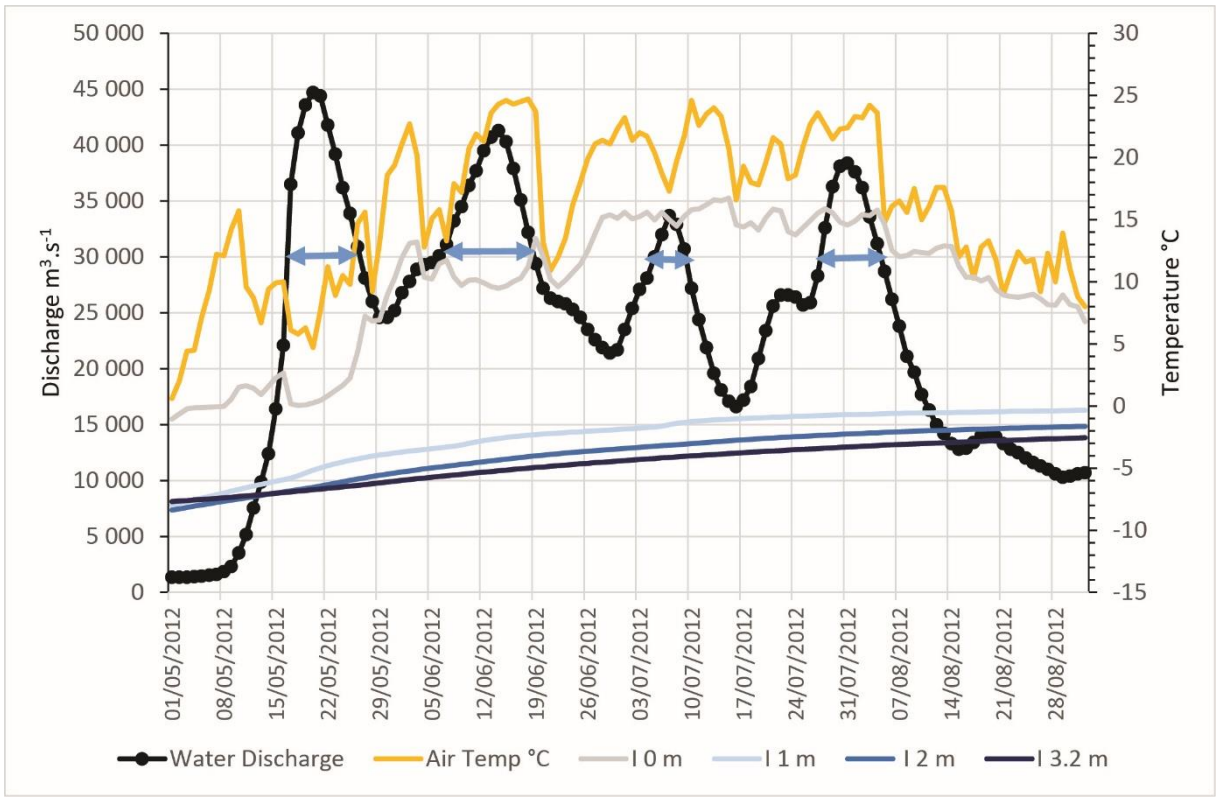

Figure 13: Mean daily discharge, air temperature and thermal regime of subsoil of Ynakh-Ary (HOBO I) between May and August 2012. Water Discharge at Tabaga gauging station (Roshydromet data); 0 m: soil surface temperature; ground temperature at different depths (1 m, 2 m and 3.2 m); air temperature at Yakutsk (NOAA, NASA data). Blue horizontal line corresponds to a water discharge > 30,000 $m^3.s^{-1}$ in relation with the submersion of the island.

6. Conclusion

For a first time, we were able to instrument a large Arctic fluvial system in order to acquire new data on frozen ground development within a large floodplain. Our measurement campaigns revealed that the floodplain of the Lena River, upstream of Yakutsk, does not everywhere contain permanently frozen soil, and that some highly mobile and young islands have (only) a seasonally frozen ground. Even in old islands, where frozen ground is present, a marked variability is noticeable. We also conclude that the ice breakups and floods seem to have a negligible impact on the ground thermal regime. Our study confirms that relatively young (less than 50 years old) islands, composed of fine sand material, appear less prone to permafrost formation compared to older islands with ice-rich silty material. Thus, the Lena floodplain is notably heterogeneous, with a combination of permanently and seasonally frozen islands. The observed disparity between these islands is significant and unexpected, because it confirms that the Lena River floodplain is far from being thermally and geomorphologically homogenous. It rather consists of a juxtaposition of seasonally frozen islands and permanently frozen islands in the regional context of a floodplain affected by thick and continuous permafrost. The heterogeneity could also induce differential responses of the frozen and unfrozen parts of the floodplain to global warming.

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