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SURFACE AND GROUND WATER IN PERMAFROST REGION

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CONDITIONS AND PROCESSES OF FORMATION OF A BEADED CHANNEL OF A SMALL RIVER IN PERMAFROST, SHESTAKOVKA RIVER, CENTRAL YAKUTIA

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Observations over the thermal regime of soils, formation and destruction of river ice were carried out, the hydrological characteristics were obtained, and the geological structure of a small river in Central Yakutia was investigated in order to identify the processes forming the beaded shape of the river channel. This type of a channel is widespread in permafrost regions, characterized by alternation of the channel extensions, 'beads', and narrow runs, predetermining the specific thermal, water and ice regime of the river, which leads to alternation of the periods of mixing and stratification of the water, to the presence of pressured unfrozen water in winter, and the appearance of ice mounds and local underwater taliks. Despite the presence of thawed sediments under the channel, thermokarst does not play a significant role in the modern formation of the beads due to the low ice content in the underlying sediments. The maximum water discharges flow above the ice cover, so the expansion and deepening of the pools by the water flow is possible only when anomalously high flow events occur after thawing of ice in the channel. Significant mechanisms of modern deepening and widening of the beads can consist in repeated extrusion and subsequent removal of suspended matter and bottom sediments under cryostatic pressure during freezing of the channel, as well as stresses that occur on the ice-ground contact during freezing, leading to destruction of the banks.

River ice processes, channel processes, thermal regime of a river channel, river taliks, cryostatic pressure, cryogenic processes, Lena-Vilyuy interfluve

INTRODUCTION

Frozen ground affects the condition of the rivers located in the permafrost zone, changing their hydrological regime and the river channel morphology and deformation [*Korzhuyev, 1964; Scott, 1978; Are, 1985; Zaitsev and Tananayev, 2008; McNamara and Kane, 2009; Woo, 2012*]. The mechanisms of this impact have not been sufficiently investigated. The beaded shape of small streams (*beaded streams*), consisting of alternating deep lake-like extensions, pools (or *beads*), and connecting their narrow and shallow minor channels (runs), result from this impact. They occur in cold zones everywhere, constituting up to a half of the total length of the river network of the basins [*Arp et al., 2015*] and forming a specific type of the small river channels [*Tarbeeva, 2018*]. The beaded shape of a stream regulates the runoff, serve as overwintering habitats and migration routes of the aquatic fauna, and water in them has specific chemical composition [*Oswood et al., 1989; Gubar'kov and Leibman, 2010; Merck et al., 2011; Arp et al., 2015; Tarbeeva et al., 2016a*]. The issue of the origin of beaded streams in the permafrost zone is now being discussed. Many researchers [*Hopkins et al., 1955; Washburn, 1979; Ershov, 1982; Gubar'kov and Leibman, 2010; Woo, 2012; Tarbeeva and Surkov, 2013; Arp et al., 2015*] attribute such a shape of the river channel to thermokarst (thermal erosion), i.e., thawing of ice in the intersections of the ice wedge polygons. Thermokarst and thermal erosion, are not, according to numerous evidences, the only cause of their formation. Such rivers flow in the regions where the ice content of sediments is low, and wedge ice is missing. The size of the beads correlates with the order of the stream, not with the dimensions of the ice wedge polygons [*Tarbeeva, 2018*]. Small beaded streams exist in warm climates, too [*Tarbeeva et al., 2016b*]. A.A. Grigoryev [*1927*] explains such a shape of the river channel by uneven erosion of frozen and thawed grounds, S.S. Voskresensky [*1962*] – by pools preserved from the warm periods.

To ascertain the processes occurring in a beaded river channel and contributing to preservation or destruction of its shape, investigations were conducted on the Shestakovka River, the left tributary of the Lena River 20 km west of Yakutsk (Fig. 1). The basin of the river is well-studied [*Boytsov, 1985; Varlamov et*

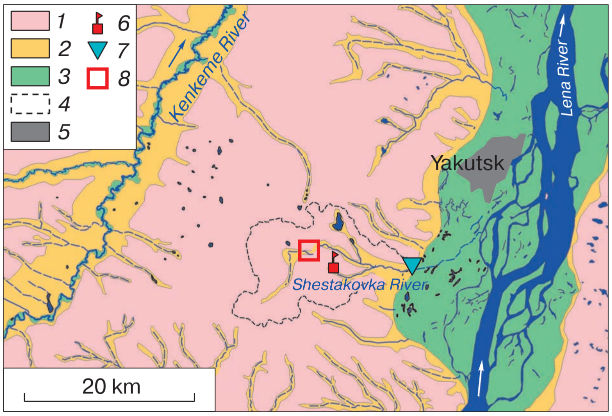

Fig. 1. Location of the basin of the Shestakovka River on the geomorphological map:

1 – interfluves represented by tall terraces of the Lena River [*Soloviev, 1959*]; *2* – valley slopes; *3* – valley bottoms; *4* – the watershed divide of the Shestakovka River; *5* – developed territories; *6* – automatic meteorological station; *7* – Kamyrdagystakh gauging station; *8* – the key site under study.

al., 2017], the Chabyda research station of the Melnikov Permafrost Institute, SB RAS, for permafrost and hydrogeological monitoring and the Kamyrdagystakh hydrological gauging station (observations have been conducted since 1951, and the catchment area is 170 km^2) are located there. The Levaya Shestakovka River, the main component of the stream, with the catchment area being 90 km^2, the least affected by the human economic activity, was studied in detail.

THE NATURAL CONDITIONS OF THE TERRITORY

The basin of the upper flow of the Shestakovka River is situated in an elevated (200–300 m asl) hilly sandy plain, which is represented by high-level left-bank terraces of the Lena River, having an aeolian relief [*Filippov and Vasilyev, 2006*]. The alas relief characteristic of Central Yakutia has not been found in this area [*Soloviev, 1959*]. The climate in the area is sharply continental, with short hot summers (the mean July temperature is 18.7 °C) and severe seven-months-long (October–late April) winters (the mean January temperature is –42.6 °C). The annual precipitation is 245 mm (the data are on Jakutsk for 1950–2015, Yakutsk weather station). The thickness of permafrost in the river basin reaches 500 m, and the active layer depth varies from 0.5 m in bogged depressions and swampy sparse larch forests interrupted by hummocky bogs to 4 m on pine-covered interfluves [*Varlamov et al., 2017*]. Supra-permafrost subaerial taliks are characteristic of slopes covered by pine forests [*Shepelev, 2011; Lebedeva et al., 2019*].

The mean annual depth layer of the Shestakovka River near the Kamyrdagyzstakh gauging station is 24 mm. The spring floods last from early May to late June; the level rise is sharp, by1.4–2.2 m, and the decrease of the level is smooth. The mean maximum flood discharge is 2.8 m^3/s. The water regime is changeable: the maximum discharges observed during rain storm events reached 18 m^3/s (June 1984), and those observed in the breakup flood reached 13 m^3/s (May 2007), in the low-flow years, the maximum discharge values corresponded to the low-flow period values 0.05 m^3/s (1987). In 2016–2018, the high-flow discharge was lower than average. In the most high-flow year of 2017, the maximum discharge in the high-flow season was 1.8 m^3/s, which is 50 % lower than average. The river freezes from November to April.

THE CONTENT AND THE METHODS OF THE STUDY

In 2015–2018, the morphology and the conditions of formation of the channel of the Levaya Shestakovka River were investigated. In the winter period, ice was drilled in the beads and in the narrow runs, in which the condition of the bottom ground, the structure and the thickness of ice interlayers, and the presence of water under ice were investigated. In the subglacial water, the water temperature, the total dissolved solids (TDS), pH and the content of dissolved oxygen were measured using the *YSI Professional Plus* water quality control system.

In the valley of the Levaya Shestakovka River, a series of hydrogeological boreholes were drilled (10–20 m). In three of them, located in the flood plain, in the bead and in the run of the channel (3/17, 4/17 and 1/18, Fig. 2), the ground temperature was mea-

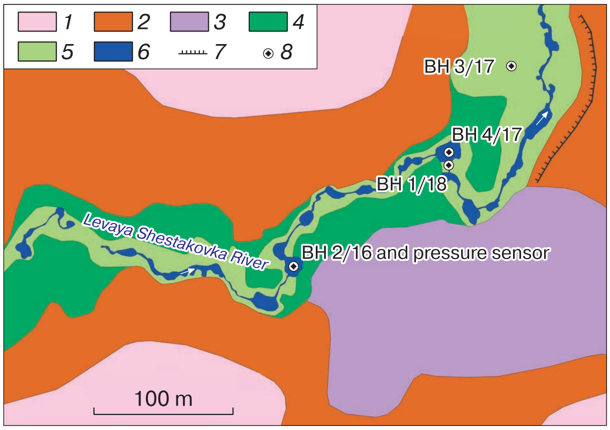

Fig. 2. The geomorphological map of the key site of the Levaya Shestakovka River and the location of the boreholes:

1 – interfluves represented by the Magan terrace of the Lena River [*Soloviev, 1959*; *Varlamov et al., 2017*], transformed by aeolian processes; *2* – slopes; *3* – slope marshes; *4* – high floodplain; *5* – low floodplain; *6* – river channel; *7* – slope icing; *8* – boreholes and their numbers.

sured, calibrated DL18B20 sensors were mounted, with 0.5–1.0 m pacing, the accuracy of which was ±0.5 °C.

In 2016, on the bottom of one of the beads (14 m long, 12 m wide and 2.5 m deep), a pressure (level) and water temperature gauge was established (*Keller DCX-18 ECO*), which remained in the channel for a whole year (Fig. 2). A correction was made for atmospheric pressure (measured with the automated weather station *HOBO Microstation*, established in the forest-covered interfluve 6 km away from the river valley, Fig. 1). To monitor glacial events, automated *Falcon Eye FE AC100* photo cameras were mounted. Parameters were recorded by them every three hours. Water discharge was measured with the GR-55 flowmeter GR-55 (Russia) at the gauging station established downstream of the key site.

Radiocarbon dating of the peat samples from the boreholes was carried out using as radiometric method in the Radiocarbon Dating and Electron Microscopy Laboratory of the Institute of Geography, RAS. In this study, uncalibrated radiocarbon data are provided.

DISCUSSION AND RESULTS

The morphology of the river valley and channel. The valley of the Levaya Shestakovka River is incised 8–10 m into the wavy surface of the ancient sandy terrace; the valley slopes are steep and convex-shaped. The flat bottom is narrowed to 30 m in some short sections and extended to 150–600 m in other sections, where it is covered by hummocky bogs and shrubs in the riparian zones. The river channel is not well-expressed in the headwaters, it appears downstream of the next boggy extension of the valley, somewhat upstream of the key site (Fig. 2). The catchment area here is 80 km^2.

The floodplain is stepped at the key site. The low near-the-channel level (0.2–0.6 m) is occupied by shrubs (mostly willows), and the high level (1.0–1.4 m) is covered by birch and pine-and larch forests. The valley extensions are occupied by sedge or shrubs, with underlying peat up to 0.5 m thick. The floodplain alluvium is represented by fine and medium-grain sand and sandy loam with interlayers of peat.

The beads, round or, more often, oval in shape, are 7–12 m wide, up to 12–18 m long and 1.5–3.5 m deep. The connecting channels, 5–40 m long, are slot-like, 0.5–1.5 m wide and 0.5 m deep, and are often wide in the lower part. The average grade of slope is 3–7 ‰, in the beads, it is practically zero. The river channel has geniculate bends, most likely caused by frost cracking.

Downstream the key site, the height of the floodplain gradually rises to 2.0–2.5 m, and the low willow floodplain becomes narrowed. The beads become shallow and elongated, their width decreases to 5–7 m and their depth goes down to 1.5 m; they are more often found on tops of the river bends; they resemble common river pools of a meandering river channel. The narrow runs, on the contrary, become wider. As the flow enters a bead from a narrow section, sandy depositional forms are formed. This seems to be caused by greater channel gradients and water discharges, which increase the intensity of the water flow downstream. Shallowing of the beads may be related to both deposition of sediments in them and their drainage by the incising stream and, possibly, to attenuation of the processes causing their formation. 8 km from the key site, the beaded river channel is replaced with an incised, relatively straight or meandering channel. Thus, the Levaya Shestakovka River has a beaded channel only in the upper flow, with a combination of relatively small stream gradients and low water and sediment runoff.

The characteristics of the winter condition of the river channel. In winter, the Levaya Shestakovka River freezes. The height of the snow above ice is 25–30 cm, which is less than on the slopes and in the interfluve (30–50 cm). In the runs, the river ice is bedfast, and the underlying ground is frozen. Ice domes (mounds) grow in the beads, up to 0.5 m high and 10–15 m in diameter (Fig. 3); ice thickness varies in them from 80 to 160 cm. Lenses of pressured water are preserved under the ice of the larger domes, 2–3 m deep (Fig. 3, *c*). The tops of the ice mounds are divided by radial cracks 5–15 cm wide, caused by cryostatic pressure.

Ice in the river channel has two layers. On top, it is layered ice, turbid, yellowish, with interlayers of larch needles on the lower border, suggesting numerous outflows of water onto the ice surface under snow. Layered ice in the narrow sections of the river channel is a little thinner (5–15 cm) than in the beads (15–50 cm). Under the turbid layered ice, there is transparent river ice, which is essentially thicker in the beads (60–120 cm) than in the narrow sections of the river channel (20–50 cm). Frozen gas bubbles can be seen in it, resulting from decomposition of organic remnants and functioning of aquatic organisms. The cracks are partly filled with turbid ice.

When boreholes were drilled in early April, reddish-brown pressured water flew from the ice mounds, its temperature being –0.6...+0.6 °C, the oxygen content being 0.27–0.30 mg/L, and pH 5.5–6.5. The TDS of the subglacial water varied in a wide range 74–919 mg/L. The water outflow was accompanied by emissions of biogenic gas, sometimes during an hour. The water bursts from the holes sometimes contained minnows, common water beetles, frogs, leeches, all of them alive and actively moving.

The bottom of the beads was covered with fine- or medium-grain well-washed bluish-gray quartz sands, sometimes overlapped by a thin (not more

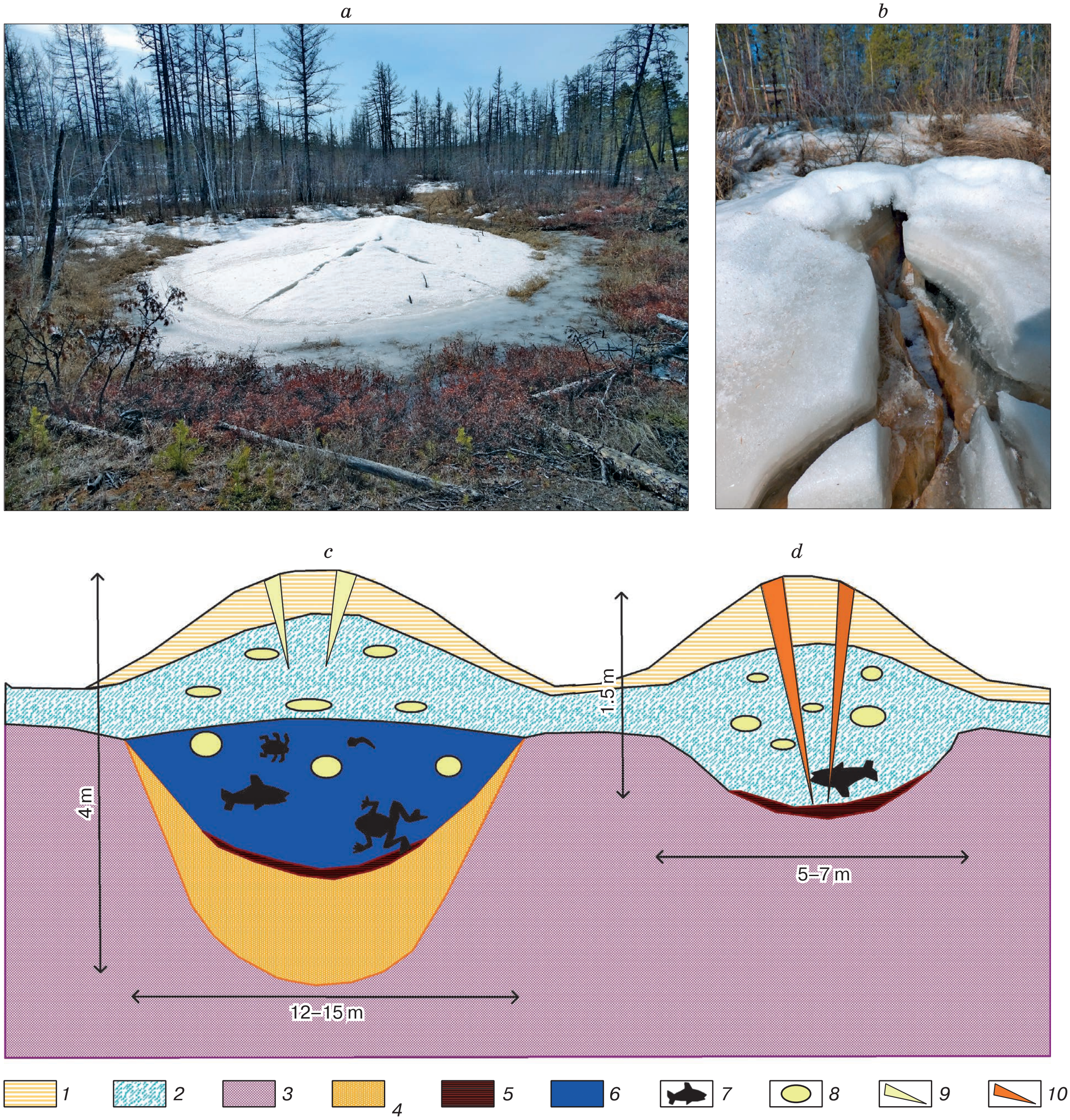

Fig. 3. Frozen and unfrozen beads.

a – an ice mound at the site of an unfrozen bead (a photo by A.M. Tarbeeva); *b* – reddish-brown ice filling the ice crack in the frozen bead (a photo by T.N. Lutsenko). A schematic longitudinal section of a beaded channel in the winter period with a large unfrozen bead (*c*) and a small frozen bead (*d*): *1* – yellow layered ice; *2* – transparent ice; *3* – permafrost ground; *4* – thawed ground; *5* – plant remains; *6* – water; *7* – aquatic organisms (beetles, frogs, leeches, fishes); *8* – gas bubbles; *9* – cracks in the ice filled with turbid ice; *10* – cracks in the ice filled with reddish-brown ice with a large amount of suspended matter.

than 5–10 cm) layer of poorly-decomposed plant remains. Taliks 1.3 and 3 m deep were discovered under the largest beads (boreholes 2/16 and 4/17).

Small beads freeze completely, and ice mounds are also formed under them, with lesser diameter and height, but often with greater (up to 160 cm) ice thickness, underlain by frozen ground (Fig. 3, *d*). The cracks in such domes are sometimes filled with ice of the bright brown-red color (Fig. 3, *b*), which is related to pressing out of the most mineralized water with a large amount (to 480 mg/L) of suspended matter from the channel bed during freezing. Small beads frozen to the bottom prevail downstream of the key site, where the gradient of the valley bottom rises and the depth of the river channel's incision increases.

Thus, the specific characteristics of beads in the winter season are the presence of unfrozen mineralized pressured water, thawed sediments on the bottom and essential pressure arising under ice in the bead in freezing of the adjacent parts of the river channel and of the active layer in the flood plain. It periodically goes down when the ice mounds crack, with subglacial water flowing out together with suspended matter. The bottom of the beads is not silted, which may indicate the continuing process of their deepening.

The geological structure of the valley bottom. The geological structure of the valley bottom was studied in the 20-m borehole 3/17 located in the central part of the valley broadening at the height of approximately 0.5 m over the low water line. The granulometric composition and the ice content of the rocks were investigated in the borehole, as well as the probability of thermokarst development.

According to the drilling results, the valley bottom is composed of frozen sands and sandy loams to the depth reaching 20 m (Fig. 4). The half-a-meter's active layer consists of peat with interlayers and lenses of ice up to 3 cm thick. From the depth of 0.33–0.40 m of peat, radiocarbon (^{14}C) dating of 130 ± 50 years BP was obtained (IGAN-5930), i.e., the peat was of modern age. Lower, at the depth to 5 m, bluish-gray medium-grained stratified sands, sometimes ferruginized. Vertical, inclined and horizontal schliers of ice up to 2 cm thick occur in the sands, as well as interlayers of peat, which are the thickest and most common in the upper 3 meters. At the depths of 5–7 m, silty sands prevail. In the range of 2.5–6.5 m, the layers' folding into small folds, their vertical shifts and other deformations and changes in the structure are noted. The following radiocarbon dates were obtained from the peat interlayers: from the depth of 2.59–2.63 m – 1630 ± 60 years BP (IGAN-5931), from the depth of 2.65–2.75 m – 1510 ± 60 years BP (IGAN-5932), from the depth of 2.80–2.83 m – 1510 ± 70 years BP (IGAN-5933). Close values and inversions of the obtained dates in the range of 2.59–2.83 m confirm active cryoturbations in this part of the ground in the past.

In the lower part of the borehole (from 8 to 15 m), there are fine-grained, horizontally stratified homogeneous sands, well-sorted with massive cryotexture, becoming silty sandy loams below 15 m. The bedrocks (horizontally stratified gray fine-grained sandstones) were supposed to have been reached in borehole 3/17 and were opened in borehole 4/17 at the depth of 12 m. The upper 5-m patch of medium-grained ferruginized sands with peat interlayers is tentatively interpreted as Holocene alluvial deposits of the Levaya Shestakovka River, with its upper part, composing the surface of the low floodplain, interpreted as belonging to Late Holocene. The lower border of the alluvial deposits of the Levaya Shestakovka River is marked in borehole 1/18 at the depth of 4.5 m by an interlayer of large-grained sand and gravel. The bottom consisting of silty sandy loams and well-sorted mine-grained sands is likely to be of aeolian origin and of the pre-Holocene age. According to the data stored in the Melnikov Permafrost Institute, SB RAS, the sandstones opened in the boreholes in the area of the Chabyda station are of the Jurassic age.

The gravity water (ice) content of the deposits in the upper 8 meters varies much and is on average 20–40 %, below it reduced to 15–20 % (Fig. 4). Because of ice on the ground surface and of large (up to 3 cm) interlayers of ice in the peat, the ice content in the active layer is rather high. Thus, the active layer is ice-rich, at the depth of less than 8 m, the ground is primarily icy, and below this depth, the ice content is low. No large ice bodies were found in any of the boreholes drilled in the valley.

The ground temperature. The ground under the beads is much warmer than in the adjacent areas. The mean annual temperature of the ground at the depth of 10 m in the floodplain (borehole 3/17) is –5.2 °C, that in the bead (borehole 4/17) is equal to –0.85 °C, and in the river channel narrowing (borehole 1/18) is about –2 °C. In mid-April, at the moment of the most intense freezing of the ground the benthic deposits directly under the bead bed are thawed and warmer than the surrounding grounds by 12.5 °C (Fig. 5), and at the depth of 10 m, the difference between the ground temperatures under the bead and under the floodplain is 6 °C. The ground temperatures in the narrow parts of the river channel are negative, although higher than in floodplain (borehole 1/18). In summer, the ground under the narrow parts of the river channel thaws to the depth of up to 1 m. Under a bead (borehole 4/17), the lower border of the talik is located at the depth of 8 m from the low water line and does not significantly change during a year.

The aquatic and thermal regime of the river, the behavior of the highwater season. The values of the pressure obtained from a barometric data logger put on the bottom of one of the beads reflect the behavior of the water level in the period from mid-August to October 26 (Fig. 6). (The pressure of 10^4 Pa approximately corresponds to the water depth above the logger in meters in the period of the ice-free channel.) In this period, gradual reduction of the water levels is recorded, simultaneously with decrease of the temperature of the benthic water (Fig. 6, 7, *a*). In late September, as the air temperature dropped below 0 °C, the surface flow of water from the watershed stopped, part of the water turned into ice cover, due to which the level of water (and, correspondingly, the pressure) went down more dramatically. On October 27, the time lapse cameras recorded water out-

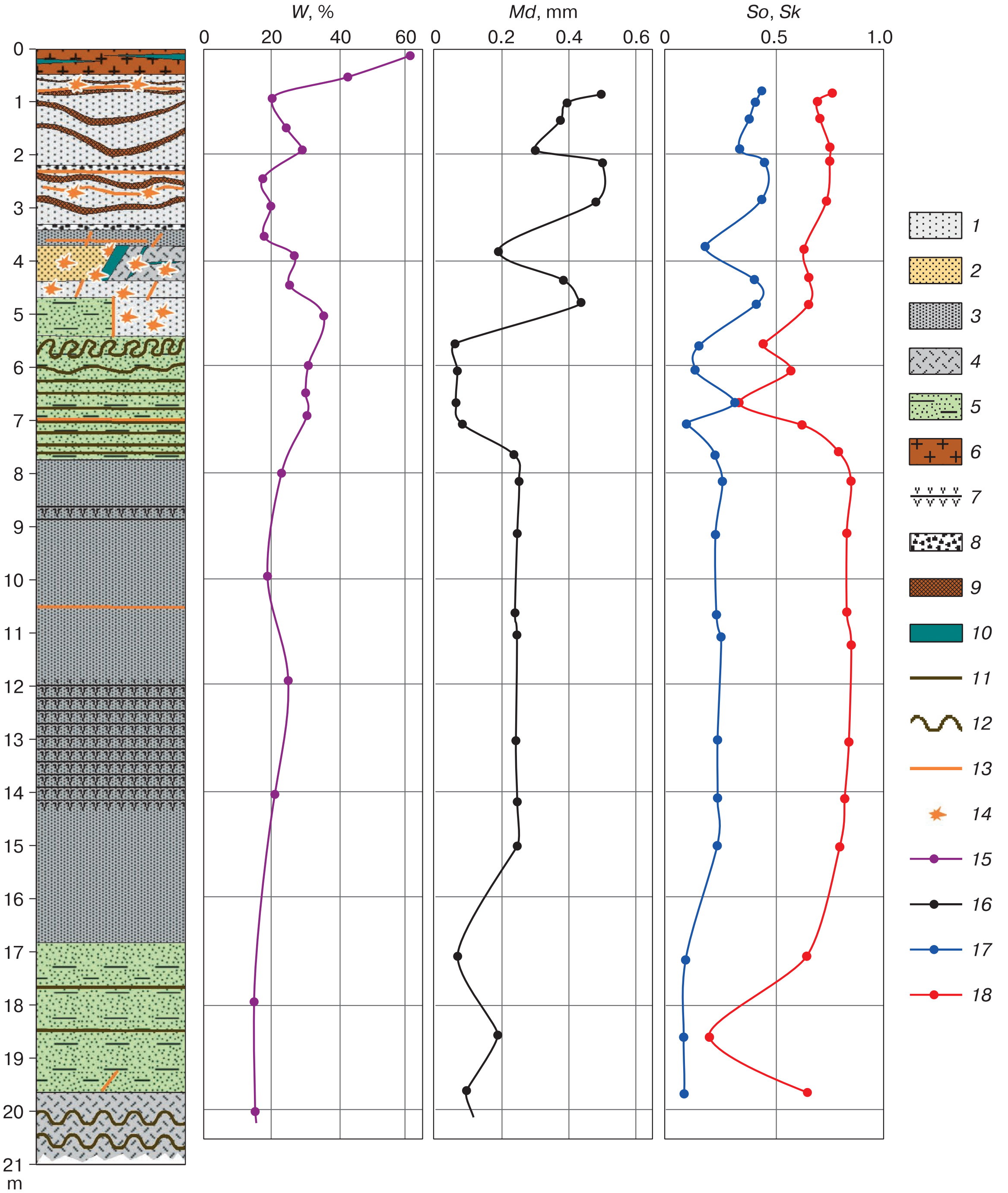

Fig. 4. The geological cross section of permafrost ground in borehole 3/17 on the low left-bank floodplain in the widening of the valley bottom of the Levaya Shestakovka River.

Deposits: *1* – bluish-gray medium-grained sand; *2* – reddish-brown fine-grained sand; *3* – bluish-gray fine-grained sand; *4* – bluish-gray silty sand; *5* – bluish-greenish-gray silty sandy loam; *6* – peat. Textures (off-scale): *7* – thin (1–5 mm) subhorizontal interbeds of plant remains; *8* – interbeds of well-washed large-grained sand with gravel; *9* – interbeds of peat from 1 to 10 cm thick; *10* – vertical, inclined and horizontal interbeds and lenses of ice 0.5–3 cm thick; *11* – subhorizontal loam interbeds 0.5–2 cm thick, enriched with organic matter; *12* – folded loam interbeds 0.5–2 cm thick, enriched with organic matter; *13* – ferruginized interbeds; *14* – iron stains. Diagrams of dependences: *15* – gravimetric ice content in % (*W*); *16* – median size of particles (*Md*); *17* – sorting coefficient (*So*); *18* – quartile coefficient of asymmetry (*Sk*) [*Shvanov, 1969*]. Ice content was determined by V.S. Efremov. Granulometric analysis was performed by areometric and sieve methods in the laboratory of the Permafrost Institute, SB RAS, by Yu.G. Sleptsova and A.L. Lobanov.

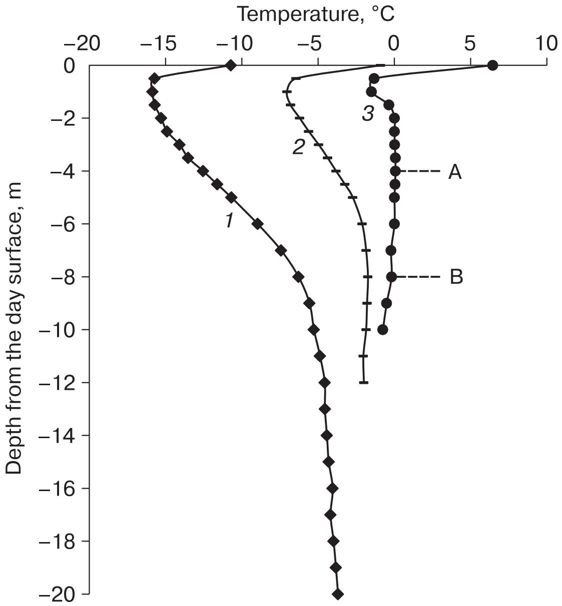

Fig. 5. Distribution of temperatures by depth in the boreholes on the floodplain, in the narrow run and in the bead of the Levaya Shestakovka River, 12.04.2018:

1 – borehole 3/17 in the low floodplain; *2* – borehole 1/18 in the narrow run; *3* – borehole 4/17 in the bead; A – the bottom level in the bead; B – the lower boundary of the talik in the bead.

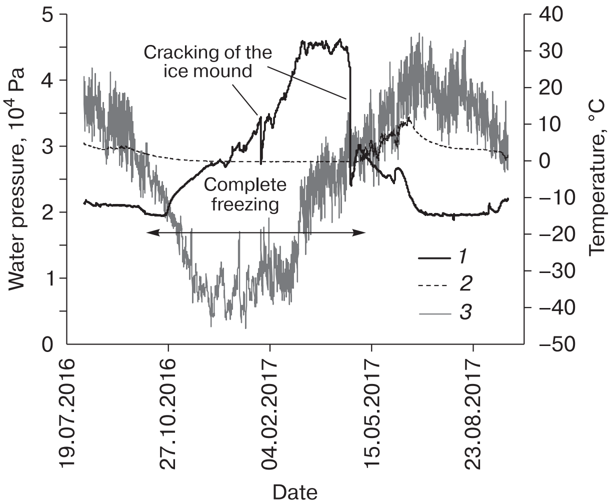

Fig. 6. Combined curves of variations in air temperature, the temperature and pressure of water in the benthic layer of a bead in the Levaya Shestakovka River in 2016–2017 (see the location of the sensor in Fig. 2).

1 – pressure of water in the benthic layer; *2* – water temperature in the benthic layer; *3* – air temperature at the automated meteorological station.

flows along the river banks, water flowing across the surface of the river ice and forming icing (Fig. 7, *b*). That was related to sinking of the ice cover and to appearance of cracks along the contact of ice and ground, through which part of the water flew onto the ice surface and froze again. However, after October 27, when the air temperature reached −14... −17 °C, sharp increase of the pressure was recorded in the frozen bead. This is explained by formation of the ice cover on the river and by freezing of the water to the bed in the narrow parts of the river: water in the bead becomes compressed from both sides by the intensely freezing water-saturated ground of the active layer in the floodplain, and in the periphery of the river channel, as well as by the ice cover growing downwards and enlarging in its volume when freezing. A significant change in the position of the freezing front is not observed only below, as a talik 1.3 m deep is located under the bottom, underlain by frozen ground with relatively high (−0.85 °C) temperatures. The air temperature in the benthic layer decreases to 0 °C and remains at this value throughout the winter.

The intense growth of the water pressure under the ice cover in the bead continued till January 26, with the air temperature decreasing to −30...−40 °C. Water pressure caused gradual plastic deformity of ice and the growth of the ice nound above the bead center. On January 26, the ice nound cracked, and part of the water flew out onto the ice surface, which was expressed in the sharp drop of the water pressure curve in Fig. 6. After this, the water pressure regained the previous values within 5 days and continued to grow till March 8. In early March, the air temperature rose to −10...−15 °C, with a trend for further growth, the water pressure in the bead became stabilized in the value of $4.5 \cdot 10^4$ Pa, i.e., freezing of the active layer and growth of the active layer thickness stopped. It is to be noted that such water pressure is approximately equivalent to the weight of a column of water 4.5 m high, with the height of the ice mound in the bead in question being only 30 cm in 2017. The water pressure in the river channel before the beginning of complete freezing was about $2 \cdot 10^4$ Pa, which corresponded to the depth of 2 m.

On April 24, the mean daily air temperature rose above 0 °C, but the river was still under snow; the ice mound cracked, possibly, considering the absence of other visible causes, due to thermal expansion of ice (Fig. 7, *c*). Destruction of the ice mound reduced the excessive water pressure, and stagnant reddish-brown water appeared along the riverbanks. The water began to flow down the channel later (April 28), and the subsequent rise of pressure was already related to the growth of the water depth under the sensor as the water discharges and levels increased in the high-flow period.

At the beginning of the spring flood, water flew above the river ice, on the periphery of the remaining ice mounds (Fig. 7, *d*). As the water levels further rise, the ice mound turn out to be completely under water. Ice remains in the river channel during two-three weeks after the beginning of the spring flood, protecting the bead bottom from underwater erosion. The maximum upstream water discharge measured in 2017 was observed on May 3 and was 0.944 m^3/s, the flow velocities in the narrow parts of the channel exceeded 1 m/s, but significant masses of the ice drowned and frozen to the banks remained in the river. The rise of the water level at the peak of the high-flow period in different sections of the river was 0.7–1.0 m. The beginning of the rise of benthic water temperature in the bead coincided with achievement of the water level peak on May 3–4, when mixing of the water flowing on the ice surface with the water conserved inside the ice mound started.

Of interest is the essential growth of the temperature of water in the benthic layer of the bead at the runoff recession. On June 21, 2017, it reached the maximum value in the year: +12.1 °C (Fig. 6). The daily profile of the temperature of benthic water reflected changes in the air temperature, indicating intense mixing of water in the beads at high (up to 1 m/s) flow velocities. In the low-flow period (from late June), as the water discharges reduce to 0.05–0.06 m^3/s, the temperature of benthic water to +3.0...+3.5 °C dramatically drops in the beads, even despite the continuing growth of the air temperature. Diurnal variation of the temperature of benthic water stops. Hence, as water discharges and the flow velocities decrease to the low-water values in the beads, mixing of water attenuates or stops, and stratification of the water mass intensifies, i.e., the lacustrine regime begins to function. The surface layers of water are well-warmed, reaching +15...+16 °C at the depth

Fig. 7. Successive photographs of the channel of the Levaya Shestakovka River taken with a time lapse camera (in the area of installation of the pressure and temperature sensor, borehole 2/16 in Fig. 2):

a – an ice-free channel, 18.08.2016; *b* – outflow of water onto ice, 27.10.2016; *c* – the river channel at the moment of relieving pressure from the ice mound (line *1* in Fig. 6), 24.04.2017; *d* – flow-around of the top of the ice mound by waters in the high-flow period, 30.04.2017.

of 0.2 m in July–August, and the temperatures of the benthic water do not exceed +3 °C. Discharges of water in the summer low-flow period are extremely low (0.005–0.02 m^3/s).

Thus, the thermal regime suggests active mixing of water in the beads after thawing of the ice cover at the end of the high-flow period and the stagnant water regime in the low-flow period. The mean annual water temperatures in the benthic layer of the beads are positive, and, according to the 2016–2017 observations, were +1.9 °C, whereas at the negative mean air temperature in the same period, the same values were equal to –7 °C. The maximum benthic water temperatures are observed at the end of the high-flow period and reach +12 °C, affecting the thermal regime of the underlying grounds and accounts for preservation of taliks. Although thawed sediments remain in the beads all the year round, maximum discharges of water in the high-flow period do not significantly affect erosion of the river bottom, as they flow over the ice surface.

THE POSSIBLE MECHANISMS OF FORMATION OF A BEADED RIVER CHANNEL

Beaded river channels are widespread in the permafrost zone, including Central Yakutia. They are characteristic of first-order rivers with relatively small flow gradients, water and sediment runoffs and become alluvial meandering channels downstream.

The peculiar structure of the beaded river channels – deep broadened parts (pools), divided by narrow and shallow runs, – accounts for the specific thermal regime of these rivers, resulting in the fact that the temperature of the ground under the channel is essentially warmer than that in the floodplains. Despite the severe climatic conditions of Central Yakutia and the small sizes of the rivers, because of the lacustrine type of the water regime in freezing and good mixing of water at the beginning of summer, positive benthic water temperatures are recorded in the beads, and unfrozen water remains in winter, which contributes to essential warming of the underlying grounds and to formation of underwater taliks.

The positive temperatures of the ground under beads are likely to result in their deepening due to thermokarst. It is possible that this process is one of the leading causes of formation of beads under conditions of highly icy permafrost. However, the absence of significant volumes of underground ice and rather non-deep bedrocks under the riverbed of the Levaya Shestakovka River exclude thermokarst from the main modern processes of bead formation, although its action in the past is possible.

Pressured unfrozen water was found in winter in the pools of the beaded river channels of the Coastal Plain of Alaska [*Arp et al., 2015*]. It is likely to remain in the pools and in the other beaded rivers in permafrost. In the rivers of Central Yakutia, freezing of beads results in formation of ice mounds, which has not been revealed in Alaska, possibly, due to the deeper snow cover above the river channels formed by blizzards [*Arp et al., 2015; Tarbeeva and Arp, 2018*], under which it is simply difficult to detect their presence, or due to the lower thickness of the active layer and, accordingly, to the lower volume of the freezing ground. We observed similar ice mounds, not high but of a larger area, in the environs of Yakutsk, in the channel of a large meandering Kenkeme River (the catchment area is 3550 km^2). In the lower curvature sections of this river's bends, where the width of the river channel is 10–15 m, and its depth is about 1 m, it freezes completely, but in the top of the meander, where there are wide pools up to 3.5 m deep, the width of the river channel increases to 30–40 m, unfrozen water is preserved, and ice mounds are formed, 20–30 cm tall. Thus, uneven distribution of depths in the river channel, originally caused by the river channel processes, leads to its uneven freezing, occurrence of warm areas and increased pressure under the ice cover in the pools, and to formation of underwater taliks.

The growth of ice mounds in winter in the river channel which is not completely frozen to the bottom inevitably affects the river bottom and banks. The presence of excessive pressure in the under-ice water may exert influence on compacting of the surrounding ground; however, this process requires additional estimation. Expansion of water in freezing, uneven thermal expansion and compression of the river ice and of the ground contacting it, large temperature contrasts, arising in spring at the contact of the cold ice and of well-warmed banks, result in emergence of tensions on the periphery of an ice mound and may contribute to disintegration of sediments on the river terraces, contributing to their further erosion. Deviation of the water flow towards the banks, arising during the flow around the ice mound in the snowmelt period, also contributes to this.

For small beads that freeze to the bottom, the following process of their deepening is characteristics. At the last stage of their complete freezing, the suspended matter contained in the benthic water and, perhaps, thawed bed sediments from the bottom are pushed out through cracks in the ice due to cryostatic pressure. This is evidenced by the reddish-brown color of the ice veins filling the cracks of the ice mounds over the frozen beads (Fig. 3, *b*). When ice melts, this material does not subside to the bottom but is carried out by the stream in the high-flow period. Its volume is not large, but repetitions of the process gradually deepen and widen the bead at the early stage, when it fully freezes by the end of winter.

Considering the essential difference in the washout ability of frozen and thawed sands [*Dostovalov and Kudryavtsev, 1967*], taliks in the beads and frozen narrow runs in the high-flow period may contribute to its uneven washout and to preservation of the beaded shape. The greater area of the cross section of the channel on unfreezing sections of the rivers, compared to those freezing to the bottom, has been reported for the rivers of Alaska [*Best et al., 2005*]. However, maximum discharges of water normally occur on ice, which protects the thawed bottom of the beads from erosion. The flow of the high-flow period, with mean maximum water discharges of about 1 m^3/s, characteristic of rivers of the first and second orders, is not strong enough to wash out the bottom of the beads to the depth of 2–4 m. The rivers of the permafrost zone are known for essential annual variation of the runoff, and formation of deep beads may occur during rare anomalous flood events. Their deepening is possible in the final phase of the spring floods or during rainstorm events, the maximum volumes of which on small rivers exceed the maximum water discharges during snowmelt. Formation of beads could occur under other climatic conditions in the past, too, as S.S. Voskresensky noted [*1962*]. In addition, the comparatively narrow strip of a young low floodplain, compared to the more ancient wide rarely flooded plain, indirectly indicates attenuation of the channel-forming activity of the modern stream of the Levaya Shestakovka River. However, the presence of sand on the bottom of the beads and the absence of the silt deposit indicate the continuing process of their deepening.

Thus, the data obtained disclose complex relations among the numerous processes arising due to the beaded shape of a river channel. Yet, the issue of the mechanism of formation of beaded river channels, at least, in relation to the Levaya Shestakovka River, so far remains open.

CONCLUSIONS

1. The morphology of a beaded channel predetermines the special thermal, water and ice regime of a river, which results in the presence of pressured unfrozen water in the beads, emergence of ice mounds, and formation of local underwater taliks.

2. Formation of a beaded channel is a multi-factorial process with numerous positive feedbacks. The contribution of different processes to deepening and expansion of the beads seems to vary depending on the environmental conditions.

3. In the regions with the high ice content in the sediments, thermokarst may become the major mechanism of deepening and expansion of the beads. However, due to the low ice content of the underlying ground, thermokarst does not now play a significant role in deepening of the beads of the Levaya Shestakovka River, although its impact in the past is not excluded.

4. Deepening of beads with a water flow is possible only with passage of high discharges of water during rainstorm events or at the end of the spring floods after thawing of ice in the channel, as maximum discharges of small rivers in the spring occur on ice, which prevents erosion of the river bottom. To ascertain this issue, observations over the sediment runoff are required.

5. Extension of beads may be caused by tensions on the contact of ice and ground, arising from the growth of ice mounds and uneven widening and compression of ice and ground, resulting in disintegration of the ground on the banks and alleviating their erosion. The issue of the impact of the pressure arising in ice mounds on the substrate requires additional studies.

6. One of the essential modern mechanisms of deepening of small beads may consist in pushing up of suspended matter and bottom sediments in the final phase of the freezing of an ice mound under cryostatic pressure and their subsequent transport by the waters of the high-flow period.

7. The larger river pools, resulting from channel processes, are often unfrozen sections of the river channel, in which cryostatic pressure arises, therefore, the original location of the beads may be determined by the channel activity of the stream.

8. The process of formation of beads in the Levaya Shestakovka River seems to continue in the modern time, as the bottoms of the beads we have studied are not silted.

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