

*SURFACE AND GROUND WATERS
IN TERRESTRIAL PERMAFROST REGION*

**THE ROLE OF SUPRAPERMAFROST SUBAERIAL TALIK AQUIFERS
IN SUPPLYING WATER TO SMALL TRIBUTARIES OF THE LENA RIVER ACCORDING
TO FIELD OBSERVATIONS**

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The article provides an assessment of the distribution of suprapermafrost subaerial aquifer taliks and their influence on the processes of runoff formation of two small rivers, Shestakovka and Markhinka, whose catchments are similar in area and are located near the city of Yakutsk in the continuous permafrost zone. The talik area fraction under pine forests in the Shestakovka River basin reaches 23%; in the entire basin, 9.5%. Under pine forests of the Markhinka River basin, taliks are not developed. The decisive role of suprapermafrost subaerial aquiferous taliks in the formation of low-flow river flow in summer and autumn, as well as in the dynamics of autumn freezing of watercourses, is shown. During the summer low-flow period, the Shestakovka River flow is maintained due to the discharge of groundwater from taliks and the deep active layer in pine forests. During the period of autumn–winter freezing, channel and slope aufeis are formed due to the cryogenic expulsion of groundwater from taliks and the deep active layer upon its freezing from the surface. These aufeis serve as an additional source of river water during spring floods. In the absence of taliks in the Markhinka River basin, the flow usually stops at the end of the spring flood; in summer, the river is a chain of hydraulically unconnected expansions; in autumn, it freezes and has no discharge.

Keywords: *permafrost, river flow, groundwater, ground penetrating radar, low-flow period, water chemistry, talik coverage, Central Yakutia.*

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INTRODUCTION

Permafrost has a significant influence on the processes of river runoff formation, which makes these processes in the permafrost zone fundamentally different from those in the regions with seasonally frozen ground [Piguzova, 1973; Sokolov, 1989; Arzhakova, 2001; Woo, 2012; Bring et al., 2016; Bröder et al., 2020]. In the areas of continuous permafrost, where the cryogenic aquiclude lies everywhere and close to the surface, a set of specific hydrological and hydrogeological processes and phenomena are observed: (1) limited interaction of surface and groundwater [Woo, 2012], (2) seasonal and interannual dynamics of the cryogenic aquiclude (permafrost table) [Shepelev, 2011], (3) seasonal and multiyear cryogenic redistribution of river runoff [Alekseev et al., 2011; Lebedeva et al., 2017], (4) aufeis formation and aufeis-derived runoff [Sokolov, 1975; Makarieva et al., 2022], (5) cryogenic floods, (6) in situ condensation of soil water [Bantsekina, Mikhailov, 2009], (7) winter freezing of the rivers to the bottom [Arzhakova,

2001], and (8) recharge of surface waters and groundwater by ground ice melt in its seasonal and multi-year dynamics [Woo, 2012].

Under continuous permafrost, groundwater contribution to small and medium-size rivers is negligible [Arzhakova, 2001]. With the permafrost aquiclude close to the surface and complete freezing of the seasonally thawed layer (**STL**) in winter, small rivers only function during the warm season, i.e., on average, from the end of April to the end of October. Complete freezing of the STL is not characteristic of all river basins in Central Yakutia. In some river basins, there are supra- and interpermafrost lenses of thawed water-saturated sediments – taliks – have been discovered. They do not freeze in winter and, together with the groundwater of the STL, act as sources of river water. The hydrological regime of such rivers differs from that of the rivers without taliks in their catchments. The depth of the permafrost table is not uniform even within a single small catch-

ment area and strongly depends on landscape conditions [Lebedeva *et al.*, 2023a]. For example, on the left bank of the Lena River, in the sandy sediments of the accumulative-denudation plain, in areas mostly covered by monodominant pine forest, suprapermafrost subaerial aquiferous taliks of up to 20 m in thickness are widespread and contain significant reserves of fresh groundwater [Boitsov, 2002; Lebedeva *et al.*, 2019, 2023b]. Taliks are confined to medium- or coarse-grained sands [Lebedeva *et al.*, 2023a]. They are absent under larch forests and peat bogs, where the STL thickness reaches only 0.5–1.0 m.

The aim of this study is to assess the distribution of suprapermafrost subaerial (open) taliks in the catchments of two small tributaries of the Lena River and to identify their role in the formation of the water level and hydrochemical and temperature regimes of the river runoff under conditions of continuous permafrost. This work is based on the results of geophysical surveys and parallel hydrological and hydrochemical observations in the two catchments in 2023.

STUDY OBJECTS

Field studies were conducted in catchments of the Shestakovka (170 km²) and Markhinka (227 km²) rivers – left tributaries of the Lena River located 25–30 km apart from one another in the northeastern part of the Prilensky Plateau (Central Yakutia) (Fig. 1, Table 1).

The climate of the study area is sharply continental, with severe long winters and short hot summers. The mean annual air temperature for the period 1951–2020 at the nearest Yakutsk weather station is –9.2°C, the mean monthly temperature in January is –39.6°C; in July, +19.2°C. The mean annual precipitation is 240 mm, of which 68% falls as rain and 32% as snow.

Geomorphologically, both catchments are located on an accumulative-denudation plain dissected by drainage valleys [Ivanov, 1984]. In both catchments, mixed larch–birch forests grow in ravines, hollows, and on level surfaces, while pine forests occupy better drained slopes and elevated watersheds. Swampy areas occur along streams and around lakes (Table 1). Google Earth satellite images and field descriptions were used to construct landscape maps of the two catchments (Fig. 1).

In the 1970s–1980s and in 2015–2023 researchers from the Melnikov Permafrost Institute conducted observations of the elements of the near-surface water cycle and discovered suprapermafrost subaerial aquiferous taliks in some areas under pine forests [Boitsov, 1985, 2002; Lebedeva *et al.*, 2019, 2023a,b; Shamov *et al.*, 2023]. However, their spatial distribution remained unclear. The coverage of pine forests in the Markhinka River catchment is smaller than that in the Shestakovka River catchment (Table 1), which suggests a smaller proportion of the area occupied by taliks.

The channels of both rivers have a distinct structure consisting of alternating lake-like widenings (beaded-channel pools) and narrows [Tarbeeva *et al.*, 2019]. In the Shestakovka River channel, widenings are developed in the upper and middle reaches; in the Markhinka River channel, they occur throughout the entire channel.

The upper part of the geological section of the Shestakovka River catchment to a depth of 30 m consists of loose sandy sediments with rare interlayers of clay [Boitsov, 2002]. In the bottoms of the valleys and ravines, wet sands (water content 15–25%) are covered by an organic layer; sphagnum peat bogs are often formed on the river terrace at the foot of watershed slopes.

The thickness of continuous permafrost in the area under consideration reaches 400–500 m. The temperature of permafrost at a depth of 100 m varies in the range of –0.6 to –1.0°C [Boitsov, 1985]; and at the depth of zero annual amplitudes, depending on the landscape, it varies from positive (close to 0°C) values to –2...–3°C and lower. The thickness of the STL varies from 4 m on gentle slopes and watersheds under with pine forest to about 0.5 m in swamps and peat sphagnum peat bogs [Varlamov *et al.*, 2023].

STUDY METHODS

At the end of August 2017, in order to detect and map talik zones, geophysical surveys using ground-penetrating radar (**GPR**) were carried out on 15 survey profiles under pine forests in various geomorphic positions within the Shestakovka River catchment; each profile was about 300 m or more in length [Lebedeva, 2018]. As a rule, the profiles were oriented across the slope. Four profiles were laid on the south-facing slopes; five, on the north-facing slopes; four, on the northwest-facing slopes; one profile was laid on the west-facing slope; and one, on the southeast-facing slope. Slope gradients ranged from 1° to 10°. The height of the pine stands varied from 8 to 20 m, and the canopy density ranged from 25 to 95%. The ground cover was represented by lichens and bearberry alternating with areas covered by needle litter. Traces of forest fires were observed on six profiles, and traces of former logging activities were noted on three profiles.

In August 2023, analogous geophysical surveys were carried out on twelve 300-m-long profiles within the Markhinka River catchment. Slope gradients ranged from 1° to 19°. Three profiles were laid on the west-facing slopes; three, on the east-facing slopes; five, on the south-facing slopes; one profile was laid on the north-facing slope. All twelve profiles were under pine forests with the canopy density of 25–65%. The ground cover consisted of bearberry, lingonberry, and lichens alternating with patches covered by needle litter. In general, landscape conditions were simi-

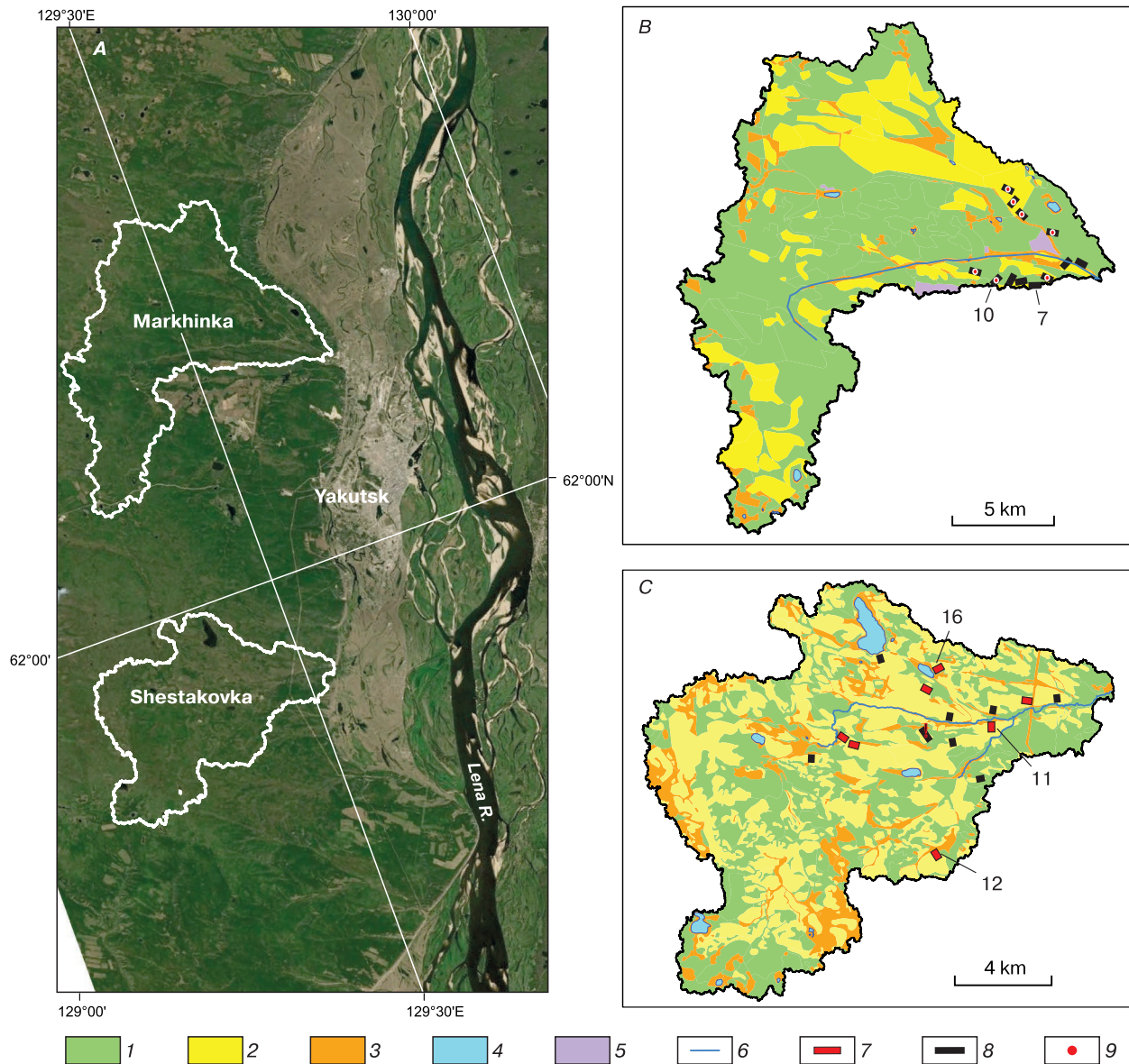


Fig. 1. Location of catchments on the satellite image (A) and schematic landscape maps of the Markhinka River (B) and Shestakovka River (C) catchments.

1 – dwarf shrub and dwarf shrub–moss larch forests; 2 – dwarf shrub and dwarf shrub–moss pine forests; 3 – bogs and swampy areas; 4 – lakes; 5 – anthropogenically altered areas; 6 – rivers; 7 – GPR profiles (11, 12, 16), where taliks were detected; 8 – GPR profiles (7, 10), where taliks were not detected; 9 – control boreholes on the profiles in the Markhinka River catchment.

Table 1. Characteristics of catchments of the Shestakovka and Markhinka rivers

River	Area, km ²	Height, m a.s.l.			Slope, degrees			Dwarf shrub and dwarf shrub–moss larch stands, %	Dwarf shrub and dwarf shrub–moss pine stands, %	Swamps, %
		average	min	max	average	min	max			
Shestakovka, Kamyrdagystakh gauging station	170	233	99	304	7.2	0	66	42	41	15
Markhinka, temporary gauging station	227	203	82	280	7.5	0	50	66	26	7

lar to those in the Shestakovka River catchment, where taliks were found.

In the GPR surveys, an AB-150 antenna unit with the center frequency of 150 MHz was used (OKO-3 GPR series produced by Logis LLC). Garmin GPSmap 64S navigator was used for georeferencing. To measure the distance traveled, a DPI odometer attached to the antenna unit and calibrated in the field before each survey was used. Recording was conducted in continuous profiling mode; trace time (sweep) was 400 ns, and signal accumulation was 16. Each radargram has two scales: the left scale is used to determine the time of arrival of reflected signals to the receiver, and the right scale denotes depth in meters calculated for a dielectric permittivity equal to 6. During data processing and interpretation, this value was corrected according to the drilling data, and the presence of local heterogeneities on the radargram. Almost all radargrams contain interference signals from double reflection from the STL boundary. The bottom of taliks on radargrams is detected in the form of high-amplitude reflected GPR signals – axes of in-phase pulses of the reflected wave. The maximum values of the amplitudes of reflected signals are determined in the lower part of taliks, near the permafrost table, where thawed rocks are fully water-saturated. Despite the attenuation of signals on the radargrams obtained in the Markhinka River catchment, the probing depth was at least 25 m when exponential amplification of signals was applied. For processing and interpretation of GPR data the GeoScan32 software was used.

In September 2023, verification drilling down to the permafrost table was performed at seven out of twelve geophysical profiles in the Markhinka River catchment, using a hand-held rig. At each drilling point, a brief landscape description was made, and a thawed soil sample was taken from the base of the STL to determine the gravimetric water content and particle-size distribution of the sediments.

To compare the hydrological regime of the studied rivers during the warm season of 2023, detailed parallel observations were carried out at the Kamyrdagystakh stream gauging station on the Shestakovka River and a temporary stream gauging station on the Markhinka River. These observations included daily measurements of water levels and discharges during the high-water period and less frequent measurements during the summer–autumn low-flow period; of river, atmospheric, and groundwater to determine the chemical composition; and visual observations of the river conditions. A total of 62 water samples were collected. Water discharges were measured using the area-velocity method with a Potok-1 flow velocity meter. Water levels and temperatures in the rivers were recorded using Hobo U20-L04 digital loggers with a 3-h time resolution. In addition, during discharge measurements, the water level was determined

using stakes preinstalled in the channel. Water conductivity and temperature during discharge measurements were recorded using a HydroMaster-200 thermal conductivity meter manufactured by HM Digital, Republic of Korea.

Camera traps KeepGuard KG762 installed before the snowmelt season near both gauging stations recorded the situation on both rivers every 3 h during the spring flood period and every 6 h during the low-flow period.

In the geochemical laboratory of the Melnikov Permafrost Institute, the content of macrocomponents in the water samples was determined using titrimetry and capillary electrophoresis methods.

Boundaries of the catchments were determined automatically using QGIS software and the Arctic-DEM surface model with a resolution of 10 m.

Daily weather records for 2023 at the Yakutsk weather station located 10–15 km from the stream gauging stations were obtained from [<http://meteo.ru/>]. As the Yakutsk weather station is located in the river valley, and interfluvial positions of the catchments are 100 m higher, observation data from the Yakutsk weather station are only conditionally representative of the catchments.

RESEARCH RESULTS

Structure of the upper section of permafrost in the Shestakovka River catchment. On 7 out of 15 geophysical survey profiles, areas identified as water-bearing taliks can be traced at distances of tens to hundreds of meters and have a thickness varying from 1 to 15 m. The radargrams of corresponding parts of the profiles have a length of 120 m (profiles 12 and 16) and 260 m (profile 11) and are shown in Fig. 2 at a scale of (length : depth) = 1 : 3. The location of the profiles is shown in Fig. 1.

The taliks identified at the seven profiles are generally located on slopes facing watercourse valleys, lake basins, and swamps. Profile 16 is located to the east of Malaya Chabyda Lake. Three shallow (2.0 to 3.5 m) taliks of about 10 m in length can be identified on its radargram (Fig. 2a). Profile 12 is oriented from southeast to northwest and is directed towards the swamp. At the end of the profile, a talik of 40–45 m in length and 10.5 m in thickness is found. Profile 11 is located on the right slope of the Shestakovka River valley and is oriented from north to south. Four taliks with a thickness from 3 to 13 m have been identified on it. The configuration of one of the taliks is rather complex because of the uneven depth of the permafrost table.

At the end of August, the thaw depth was similar across all the presented profiles ranging from 2.4 to 3.7 m (average 2.9 m) on profile 12, from 2.8 to 3.6 m (average 3.1 m) on profile 16, and from 2.3 to 3.1 m (average 2.9 m) on profile 11.

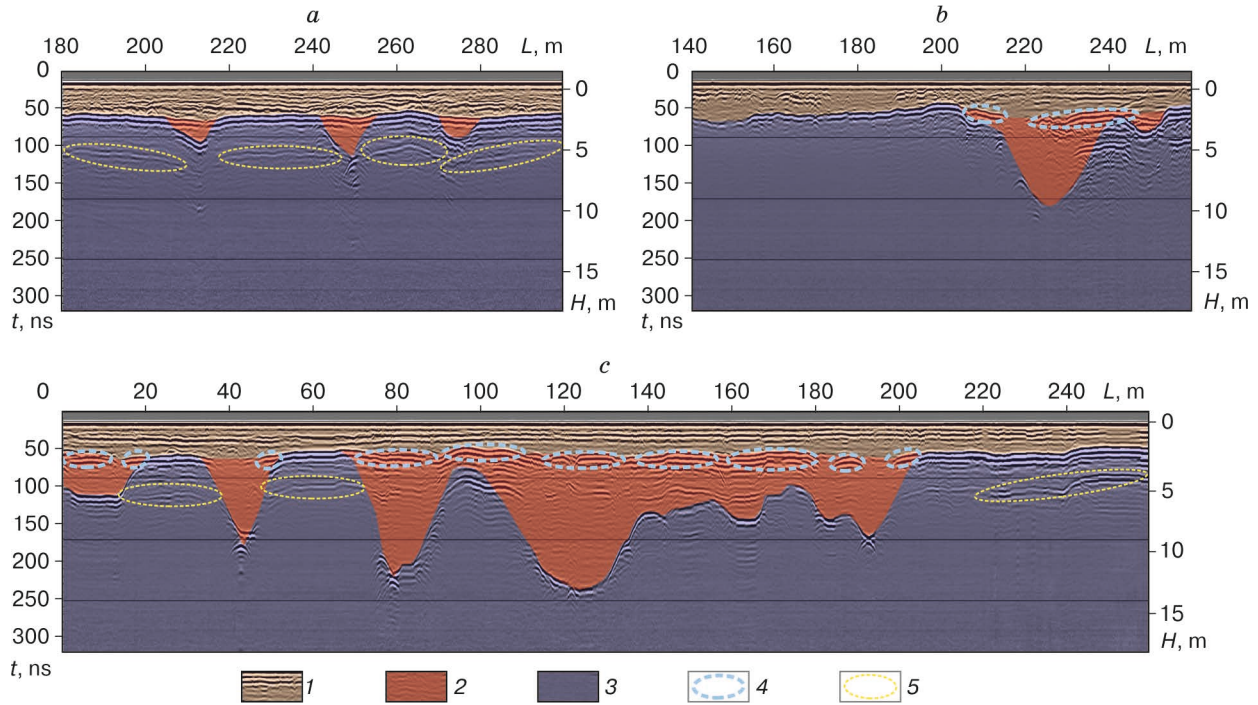


Fig. 2. Sections of interpreted GPR profiles 16 (a), 12 (b) and 11 (c) with the presence of taliks on radar-grams.

1 – seasonally thawed layer on August 29, 2017; 2 – taliks; 3 – perennially frozen sediment; 4 – lenses of seasonally frozen layer; 5 – double reflection from the boundary of seasonally thawed layer; t – time sweep of the radargram, ns; L – profile length, m; H – radargram depth, m at $\epsilon = 6$ (ϵ is dielectric permittivity).

Taking into account the fact that the thawing depth does not reach its maximum at the end of August, frozen interlayers remain in the upper part of the talik and disappear in September.

Previously, it was shown on the example of one key site that the talik is extended downslope towards the Shestakovka River valley [Lebedeva et al., 2019, 2023b]. The revealed configuration of taliks on profiles across the slope indicates that taliks are often oriented downslope and have the shape of nonfreezing ‘channels’ in the thickness of frozen rocks; they act as groundwater filtration pathways to rivers, lakes, and other depressions in the relief.

The total length of the 15 profiles surveyed in the Shestakovka River catchment reached 5953 m, of which the presence of suprapermfrost taliks was recorded in sections with a total length of 1361 m. It was impossible to identify the association of taliks with slopes of a particular steepness or aspect, forests with a particular canopy density, or the dominance of a particular type of the ground cover. As all the 15 profiles in the Shestakovka River catchment were established in relatively homogeneous landscape conditions (dwarf shrub and dwarf shrub–moss pine forests), the talik coverage in these landscape units is estimated at about 23%. For other landscape units,

taliks are not typical because of thin STL, which freezes completely in winter [Varlamov et al., 2023; Lebedeva et al., 2023a]. Taking into account the total area of the above landscapes (Table 1), the talik coverage in the entire Shestakovka River catchment is 9.5%.

Structure of the upper section of permafrost in the Markhinka River catchment. The distribution of pine forests indicates the possible development of suprapermfrost subaerial taliks similar to those in the Shestakovka River catchment. However, geophysical surveys in the Markhinka River catchment did not reveal taliks on any of the 12 profiles down to a depth of 25 m. Radargrams of two profiles – 7 (284 m) and 10 (290 m) – are shown in Fig. 3; their location is shown in Fig. 1. According to the geophysical data, the STL thickness varies between 2.3–3.1 m (average 2.9 m) along the entire length of profile 7 and between 2.2–3.2 m (average 3.0 m) along profile 10.

Verification drilling along the geophysical sections revealed that the permafrost table under pine forests in the Markhinka River catchment lies at depths from 1.6 to 2.6 m, which is close to GPR profiling data (from 1.5 to 3.2 m). This confirms the efficiency of the GPR method to determine the boundary between thawed and frozen layers in the near-surface horizons composed of sands and loamy sands.

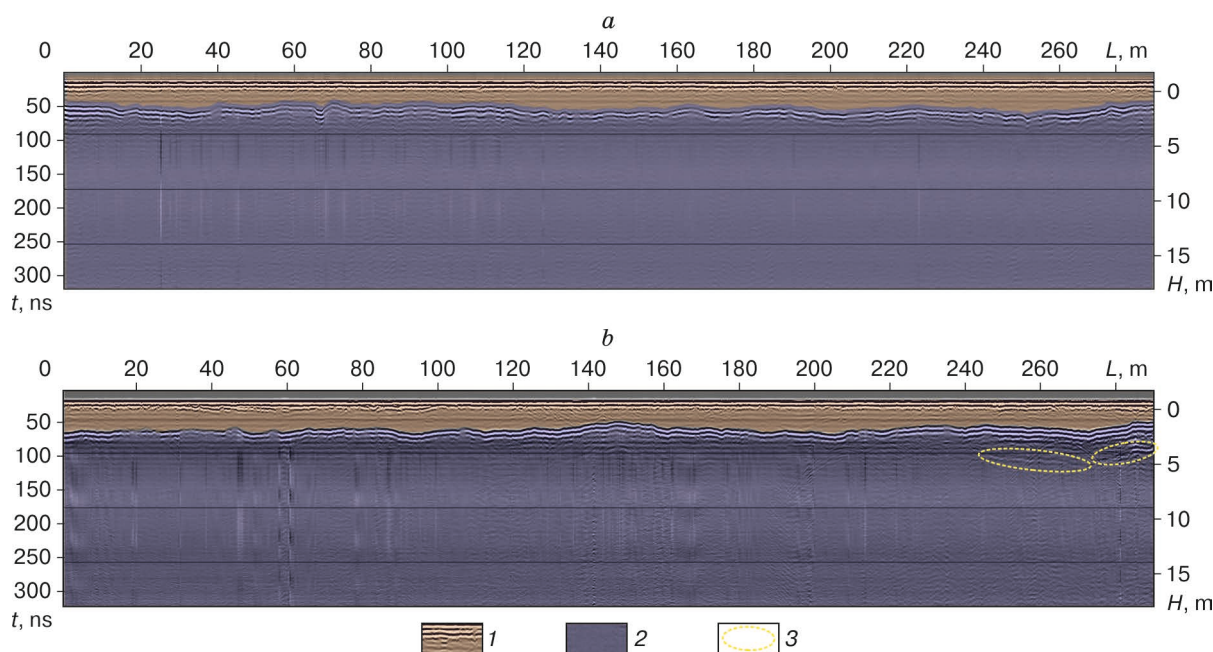


Fig. 3. Sections of interpreted GPR profiles 7 (a) and 10 (b).

1 – seasonally thawed layer on August 25, 2023; 2 – permafrost; 3 – double reflection from the boundary of the seasonally thawed layer.

The drilled sections are mainly composed of fine sand with interlayers of sandy loam, loam, and medium-grained sand. In two boreholes, at depths of 1.8 and 0.9 m, a water-saturated sand layer of up to 0.1 m in thickness has been found. This layer overlies interlayers of thawed loam above the frozen aquiclude. The weight moisture content in the soils at the foot of the STL varies from 9 to 24%. Six out of seven soil samples taken at the bottom of the STL during drilling represent fine-grained sands with a predominance of particles 0.10–0.25 mm (46–71%).

According to the results of geophysical surveys, the depths of seasonal thawing in catchments of the Shestakovka and Markhinka rivers are close under similar landscape conditions, but taliks were only identified in the Shestakovka River catchment. The geophysical and drilling works in the catchments allow us to conclude that there are virtually no suprapermafrost subaerial taliks under pine forests in the Markhinka River catchment. The attenuation of GPR signals with depth in this catchment is more pronounced than that in the Shestakovka River catchment, which may be related to the presence of sandy loamy and loamy interlayers in sandy sediments.

Water and temperature regime of the Markhinka and Shestakovka rivers in 2023. On the Shestakovka River, the runoff started on May 2, two days earlier, and the spring flood level reached its peak on May 8, a day earlier than that on the Markhinka River (Fig. 4, Figs. 5a and 5b).

After the beginning of runoff, the water level in the Shestakovka River fluctuated insignificantly (within 30 cm) until May 5. On May 5, against the background of significant and rapid warming from 12:00 to 20:00, it rose by 60 cm. On the Markhinka River, the corresponding rise was only 14 cm.

In accordance with the dynamics of water levels, the discharge of the Shestakovka River increased from 0.875 m³/s (May 5) to 5.17 m³/s (May 6), and that of the Markhinka River – from 0.056 m³/s to 0.33 m³/s.

Subsequently, the water level and discharge of the Shestakovka River demonstrated a distinct diurnal variation driven by fluctuations in air temperature, which determined the intensity of snowmelt in the catchment. The most intense increase in the discharge occurred in the afternoon; during nighttime cold spells, especially frosts, the inflow of meltwater from the catchment decreased, the river water level stabilized and then slightly dropped until the beginning of air warming in the morning. On the Markhinka River, diurnal fluctuations in the runoff were less pronounced and smoothed.

Already in the first days of the runoff, ice near the stream gauging station at the Markhinka River completely melted, and river water began to warm up in the daytime, while the water temperature of the Shestakovka River fluctuated around zero degrees Celsius until May 13, and ice remained in the channel. The inflection points of both hydrographs during the spring flood period (Fig. 4) correspond to the re-

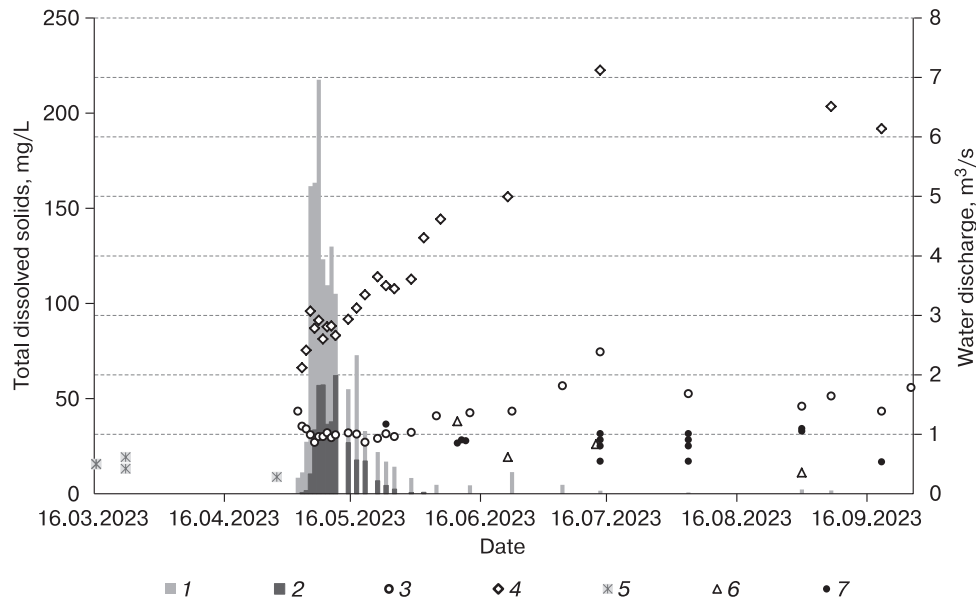


Fig. 4. Dynamics of water discharge measured on the (1) Shestakovka and (2) Markhinka rivers and total dissolved solids in water of the (3) Shestakovka and (4) Markhinka rivers, (5) snow, (6) rainwater, and (7) groundwater sampled in the catchments of these rivers during the warm season of 2023.

turn of cold weather and the decrease in snowmelt runoff intensity in the river valleys.

The discharge of the Shestakovka River exceeded that of the Markhinka River by several times (by an order of magnitude or even more during the spring flood decline) (Fig. 4).

The Shestakovka River is characterized by a wider range of fluctuations in the water level and discharge, as well as by a more diffuse relationship between them during the rising and falling floods (hysteresis): at equal water levels, the discharge during the falling flood is up to three times higher than that during the rising flood (Fig. 6). The ambiguity in the relationship between water discharge and water level in the Markhinka River is less pronounced, allowing the curve to be approximated by a single nonlinear function. Deviations of the empirical points from the approximating curves correspond to periods of sharp changes in air temperature and corresponding changes in the river's supply of meltwater.

The discharge of the Markhinka River ceased on June 6. In the area of the stream gauging station, the river represented a series of water-filled pools, with no flow between them. The water level in the pools gradually dropped, and the tracks of dry land between them became overgrown. Several rain-induced rises in the water level failed to restore the flow. The Shestakovka River's flow continued throughout the warm season of 2023.

During the period of the main spring flood from May 7 to May 26, the daily runoff depth from the Shestakovka River catchment was 2.3–7.6 times

greater than that from the Markhinka River catchment. During the spring flood's peak, this ratio reached 21. The total runoff depth from the Shestakovka River catchment from May 2 to June 5 was 27.7 mm, while that from the Markhinka River catchment was 6.6 mm (4.2 times less).

Water temperature of the Markhinka River was higher than that of the Shestakovka River throughout the low-flow period by 4–12°C. The difference in water temperatures between the two rivers also had a diurnal variation with maximum values at 16–17 hours.

Ice regime of the Markhinka and Shestakovka Rivers in 2023. The onset of ice formation on both rivers was observed on September 21 amid overnight subzero air temperatures (Figs. 5c and 5d). In the absence of runoff, ice growth on the Markhinka River was controlled only by air temperature fluctuations. Stable ice cover formed on October 14. The water level remained virtually unchanged during the ice formation period. No aufeis formation was recorded (Fig. 5e).

Ice formation on the Shestakovka River was complicated by the presence of runoff: the areas of flowing water froze later than stagnant areas, and ice drift and destruction of young shore ice were frequently observed during sharp rises in the water level associated with a narrowing of the flow cross-section. Therefore, this river froze later than the Markhinka River despite the same temperatures. Thus, a warming at the end of the first ten-day period of October caused a massive ice drift that completely destroyed

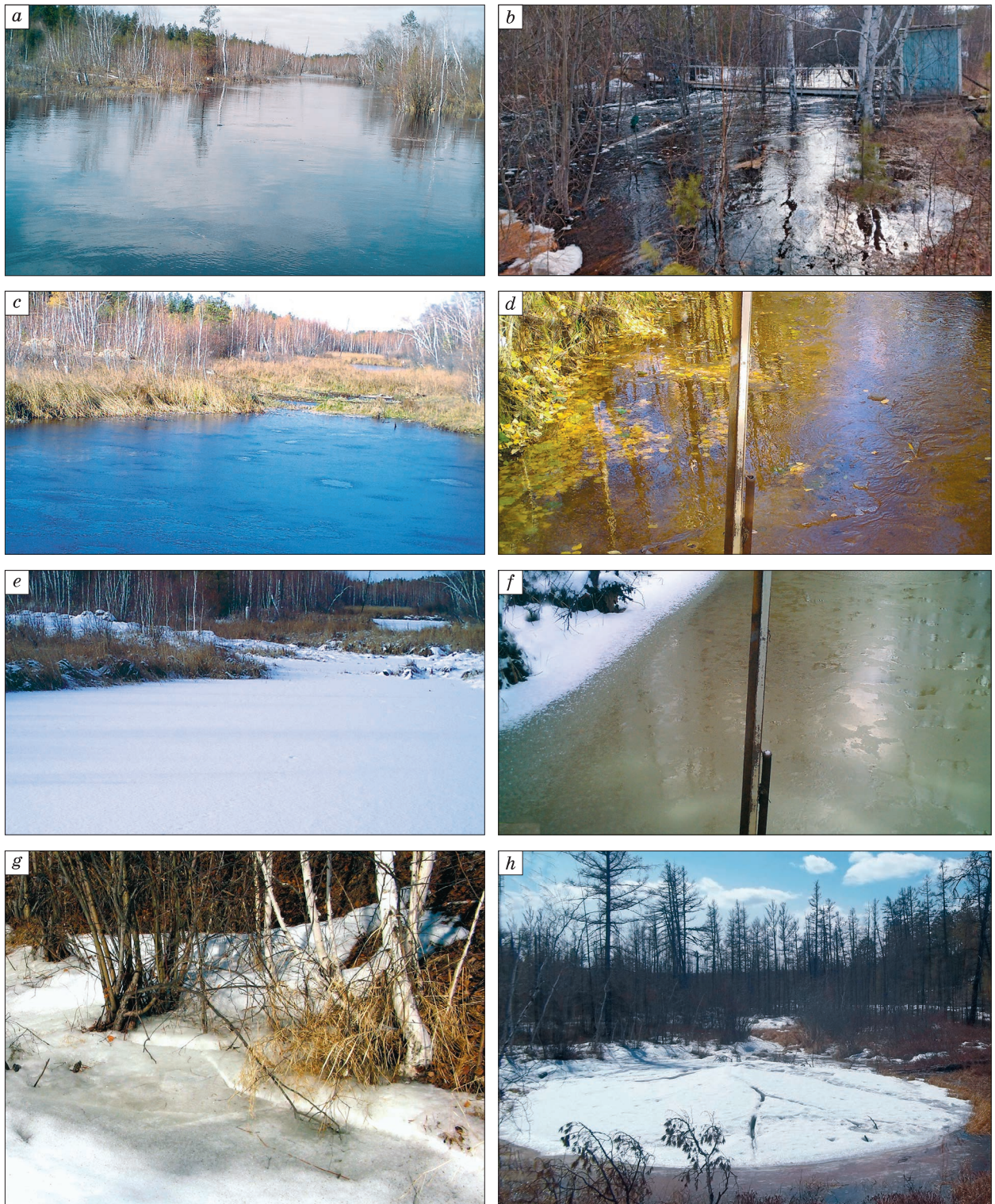


Fig. 5. Hydrological phenomena on the studied rivers in different seasons of 2023.

a – spring flood on the Markhinka River, May 8; *b* – spring flood on the Shestakovka River, May 8; *c* – first ice formation and the absence of runoff of the Markhinka River, September 21; *d* – first ice formation and runoff on the Shestakovka River, September 21; *e* – established ice cover on the Markhinka River, October 25; *f* – water outflow in the channel of the Shestakovka River, October 25; *g* – ice subsidence at the water edge of the Markhinka River, April; *h* – cryogenic ice heave on the Shestakovka River, April.

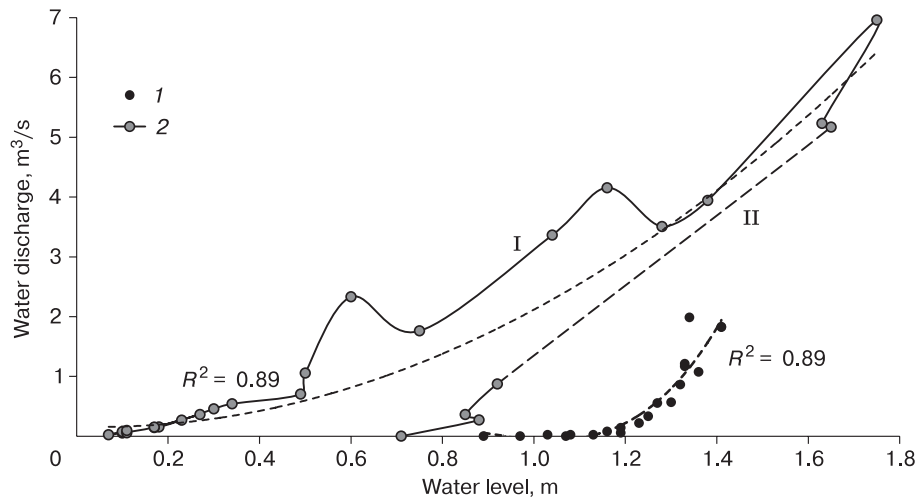


Fig. 6. Relationship between water level and discharge during the spring flood period on the Markhinka (1) and Shestakovka (2) rivers, May 2023.

For the Shestakovka River: I – spring flood decline phase, II – spring flood rise phase.

the previously established thin ice cover and caused an ice jam with a significant rise in water level. A few days later, with a steady decrease in air temperature, ice began to form again in the area of the gauging station. At the same time, the water level rose again due to a narrowing of the flow cross-section.

The thaw on October 22–25 led to the formation of a polynya (Fig. 5f). On October 30, as the air temperature dropped, channel aufeis began to form. November frosts caused regular water expulsion onto the ice surface and the aufeis growth.

Chemical composition and dynamics of total dissolved solids (TDS) in the Markhinka and Shestakovka rivers in 2023. In terms of chemical composition, the water in the Shestakovka and Markhinka rivers is ultra-fresh, of bicarbonate magnesium-calcium and calcium-magnesium compositions, less often mixed in cations with a predominance of calcium (35–43%-eq., Fig. 7). The water reaction is slightly acidic at the beginning of the spring flood (pH 5.4–6.3) and neutral at the end (pH 6.7–7.0). Five snow samples collected in March–April 2023 belong to ultra-fresh bicarbonate calcium waters with a TDS of 8–20 mg/L and neutral reaction (Fig. 4). The TDS of rainwater in June–July is slightly higher, up to 38 mg/L. Talik groundwater in the Shestakovka River basin in summer 2023 is also ultra-fresh, with a TDS of 17–32 mg/L (Fig. 4) and pH 6.5–6.9.

The seasonal dynamics of water TDS in the two rivers differs (Fig. 4). During the spring flood period, it changes in the opposite directions. In the Shestakovka River, water reached its maximum (43.4 mg/L) at the beginning of the runoff and then decreased to 27 mg/L on May 7, on the eve of the spring flood peak. Intensive melting of snow and aufeis formed on

the slopes of the river valley in the winter contributed to a decrease in TDS (27–32 mg/L) of the river water until the end of May. Desalination of the river water was mainly due to a decrease in the concentration of sulfate and chloride anions and calcium and sodium cations (Fig. 7). Only in June, against the background of an increase in evaporation, a significant decrease in water discharge and the transition of the river to a low-flow regime, water TDS gradually increased up to 75 mg/L in mid-July. This increase was associated with an increase in the concentration of all macrocomponents, except for potassium, the concentration of which remained almost constant throughout the summer (Fig. 7).

The minimum value of water TDS in the Markhinka River (66 mg/L, Fig. 4) was observed at the beginning of the spring flood flow on May 4, which was due to the inflow of ultrafresh meltwater from the river catchment into the channel. As the spring flood level rose, stagnant water from pools enriched in dissolved substances was involved in the flow, and water TDS of the Markhinka River increased to 96 mg/L on May 6 and stabilized at values of the level of 81–91 mg/L during the passage of maximum spring flood discharge in May 7–15. During the spring flood decline after May 15 and up to the complete cessation of flow in early June, water TDS increased from 91 to 110 mg/L. In June and July, the concentration of dissolved solids in the water of pools increased to 222 mg/L (Fig. 4). The increase in water TDS was mainly due to bicarbonate, calcium, and magnesium ions (Fig. 7). The concentration of sulfate and chloride ions changed insignificantly. Changes in the concentration of sodium and potassium ions in the waters of both rivers are noteworthy. From the begin-

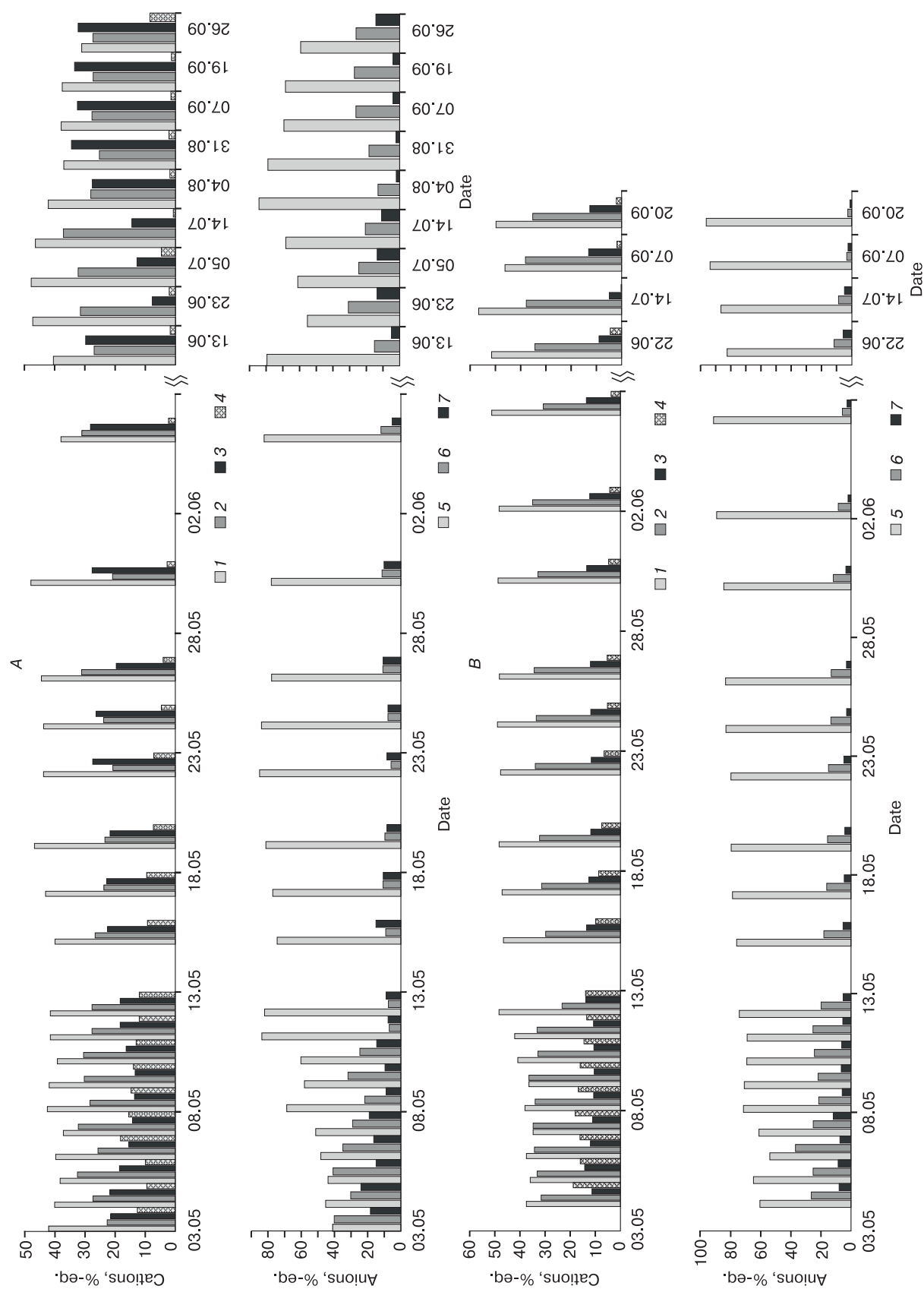


Fig. 7. Changes in cation and anion composition of water in the Shestakovka (A) and Markhinka (B) rivers.

1 – Ca^{2+} , 2 – Mg^{2+} , 3 – Na^+ , 4 – K^+ , 5 – HCO_3^- , 6 – SO_4^{2-} , 7 – Cl^- .

ning of the spring flood until May 12, the shares of these ions were comparable (12–20%-eq. each). Then, until mid-June, against the background of increased concentration of calcium and magnesium ions, the concentration of potassium ion in the water of the Shestakovka and Markhinka rivers decreased to 2 and 4%-eq., respectively (Fig. 7).

In winter, water was only preserved in distinct widenings of the river. By the beginning of the spring flood, the TDS of water under the ice cover in pools varied within 84–220 mg/L in the Shestakovka River and reached 426 mg/L in the Markhinka River.

DISCUSSION

Differences in the structure of the upper section of permafrost in the catchments of the Shestakovka and Markhinka rivers. The presence of sub-aerial aquiferous closed taliks in the areas of pine forests in the Shestakovka River catchment has been confirmed by drilling of 20-m-deep boreholes at two key sites in the 1980s and in the recent 8 years [Boitsov, 1985; Boitsov, Lebedeva, 1989; Lebedeva et al., 2019]. The taliks are confined to medium- to coarse-grained sandy sediment; less often, to fine-grained sands; interlayers of loam or clay were not detected in the boreholes drilled in the areas of talik development [Lebedeva et al., 2023a]. The widespread occurrence of closed taliks in the Shestakovka River basin is confirmed by the presence of numerous slope and channel aufeis. The two largest aufeis studied have a length of more than 80 m. Their occurrence and growth are associated with the discharge of groundwater from taliks and deep STL, which intensifies in winter due to the development of cryogenic pressure.

Despite similar landscape conditions, taliks have not been detected along the profiles studied in the Markhinka River catchment. We hypothesize that this is due to the somewhat heavier texture of the sediments, as indicated by borehole data from seven profiles. However, more data on grain-size distribution are needed to confirm this hypothesis.

According to the composition of dissolved ions, the Markhinka River water is bicarbonate water with magnesium-calcium or calcium-magnesium cations, whereas the Shestakovka River water has a more complex cationic composition containing up to 34%-eq. of sodium (Fig. 7). According to the specificity of the cationic composition and TDS of the river water, it can be assumed that its chemical composition in the Shestakovka catchment is formed due to water interaction with well-permeable aluminosilicate rocks, while sandy sediments in STL of the Markhinka River catchment also contain calcium carbonates precipitating from suprapermafrost groundwater during freezing and partly dissolving under the impact of infiltrating atmospheric precipitation.

Changes in the concentration of potassium ions in waters of the Shestakovka and Markhinka rivers in summer correlate with the observed differences in the texture of the sediments. Potassium is a highly biophilic element and belongs to the active water migrants. The decrease in the potassium concentration in the water of the Shestakovka River with sandy sediments in the aeration zone is more pronounced than that in the Markhinka River, where the upper layers of Quaternary sediments in the catchment contain more silt particles.

The area of taliks in the Shestakovka River basin reaches 9.5%. This is a high value for Central Yakutia, and it exceeds previously reported value of 4% [Anisimova, 2003]. This suggests the existence of significant reserves of shallow talik groundwater in some areas of pine forests and their participation in the formation of the discharge of small rivers in the area of continuous permafrost, though the signs of landscape indication of aquiferous closed taliks within pine forests have not yet been identified.

The relationship between the features of spring flood development and the structure of the channel and the upper part of the permafrost. Channel widenings and beaded-channel pools are developed only in the upper and middle reaches of the Shestakovka River [Tarbeeva et al., 2019] and throughout the entire channel of the Markhinka River. On average, pools on the Markhinka River are larger (in the area of the gauging station, their width is 12–20 m, length 35–50 m, and depth 3.0–3.5 m) than on the Shestakovka River (7–12, 12–18, and 1.5–3.5 m, respectively) [Tarbeeva et al., 2019]. On the Markhinka River, traces of the ice surface subsidence during river freezing (Fig. 5g) were found; in contrast, the pools of the Shestakovka River often have convex ice surface (Fig. 5h). The concave shape of the ice in the Markhinka River pools indicates insignificant inflow of suprapermafrost groundwater into the channel or its absence after the onset of ice formation. At the same time, pools of the Shestakovka River continue to be fed by water from the freezing STL and taliks, and during further winter freezing, cryogenic pressure develops in taliks and in unfrozen lenses of water in pools of the channel, which leads to some heaving of the ice cover in pools of the Shestakovka River.

The earlier onset dates and higher runoff layer depth in the Shestakovka River may be related to lower water retention capacities of the channel and the entire catchment. The smaller size and number of pools in the Shestakovka River channel and the presence of ice mounds in them (Fig. 5h) reduce the overall capacity of the channel network, while the concave shape of the ice cover in the large and numerous pools of the Markhinka River (Fig. 5g) implies a larger storage of water in the channel until overflow and runoff onset, and also contributes to the reten-

tion of part of the runoff. In addition, groundwater from the taliks discharges onto the surface and forms streams in spring; together with melting channel and slope aufeis, which lasts 2–3 weeks longer than snowmelt, it contributes to a higher discharge of the Shestakovka River in comparison with the Markhinka River.

Hysteresis of the relationship between discharge and water level of the Shestakovka River during the spring flood (Fig. 6) is caused by a general decrease in the ice surface and water surface elevation due to melting of more than 0.5-m-thick ice layer on the river bottom. In the Markhinka River channel, the ice near the gauging station is less thick and melts much earlier, which explains a simpler relationship between river discharge and water level. Aufeis in the Shestakovka River channel is formed in November–December due to supraperafrost groundwater from taliks and deep STL, the discharge of which is intensified during seasonal freezing of the ground. In addition to direct contribution to the river runoff, channel aufeis maintains the temperature of the river water close to 0°C until their complete destruction, and also causes a complex relationship between the water level and discharge of the Shestakovka River. On the Markhinka River, channel aufeis does not form, water begins to warm up earlier, and the relationship between water level and discharge is closer.

The increase in TDS of water of the Markhinka River during the spring flood in 2023, on the third day of runoff, may be due to melting of pools, the water of which has the maximum concentration of dissolved substances before the spring flood. The accumulation of chemical elements in the water of pools is due to evaporation during the previous summer period; it continues in winter, when the water freezes under conditions of impeded water exchange. The cryogenic metamorphism of the water of pools is evidenced by an increase in the concentration of bicarbonates of magnesium and sodium. The opening and “inclusion” of pools with their mineralized and oxygen-deficient waters in the already developing process of spring runoff formation was also observed earlier on the Shestakovka River [Shamov *et al.*, 2023]. However, the volume and number of pools in the Shestakovka River are smaller in comparison with the Markhinka River, so they have no significant influence on TDS of river water.

The relationship between the features of the hydrological regime of rivers during the summer low-flow period and during the period of autumn freezing with the spread of taliks. The hypothesis about the predominant role of talik groundwater and deep STL is confirmed by the cessation of flow of the Markhinka River in the summer low-flow period; there are no taliks in the pine forests of the Markhinka River, while the area of taliks in the catchment of the Shestakovka River reaches 9.5%, and the

river discharge is continuous until complete freezing in November–December.

During the summer–autumn low-flow period, the Shestakovka River maintains its flow due to groundwater supply from taliks and from deep STL of sand massifs in pine forests, and partly due to the inflow of water from melting aufeis. Some of them are found in summer under the moss layer in the area of waterlogged footslopes. During the whole summer–autumn low-flow period, the water temperature of the Shestakovka River is significantly lower than that of the Markhinka River, which can also be explained by the inflow of cold water from taliks and STL into the channel of the Shestakovka River, as well as by the favorable warming conditions in the Markhinka channel pools.

The differences between the two rivers during the freezing period are also related to the presence of groundwater supply to the Shestakovka River from talik aquifers. The Markhinka River freezes in the absence of runoff and limited groundwater supply, while the Shestakovka River flow continues even at subzero temperatures and is accompanied by the inflow of significant volumes of water into the channel, water level difference due to cryogenic narrowing of the flow cross-section, the formation of channel aufeis, and, later, as the river freezes and a seasonally frozen layer is formed above the talik zones, cryogenic pressure develops, and numerous and extensive slope aufeis are formed.

CONCLUSIONS

The study examines the role of supraperafrost subaerial aquifers in the formation of the runoff of two small tributaries of the Lena River in its middle reaches – the Shestakovka River and the Markhinka River.

In the Shestakovka River catchment, in sandy sediments covered by pine forests, supraperafrost subaerial aquiferous taliks of up to 15 m in thickness and hundreds of meters in length are formed, which is confirmed by ground-penetrating radar profiling and drilling. The area of taliks is estimated at 23% under pine forests and 9.5% of the entire catchment. No taliks were found in the Markhinka River catchment under similar landscape conditions, which we hypothesize is due to a heavier texture of sediments in the upper part of the section.

The runoff of the Shestakovka River continued throughout the warm period, in contrast to the Markhinka River, where runoff stopped on June 6.

The prolonged freezing of the Shestakovka River until mid-November was complicated by the presence of runoff, which led to regular ice drifting and the formation of channel aufeis due to expulsion of groundwater from taliks. The Markhinka River froze in mid-October in the absence of runoff, and no aufeis formed in its valley.

The temperature and TDS of water in the Shestakovka River were lower than those in the Markhinka River due to the influx of cold and ultrafresh water from melting aufeis and from suprapermafrost groundwater from taliks. Water of the Markhinka River had higher TDS and temperature, especially in the summer low-flow season, due to intensive evaporation and lack of groundwater supply.

The hydrological differences between the two rivers are explained both by the talik area fraction and the associated aufeis and by the structure of the channel. A large number of channel pools along the entire course of the Markhinka River retain part of the runoff, while slope and channel aufeis in the Shestakovka valley provide an additional source of water for the river.

The study highlights the significant role of suprapermafrost aquiferous taliks in shaping the hydrological regime of small rivers under conditions of continuous permafrost.

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