Risk of Anthropogenic Cryopeg Formation in Urban Areas in Central Yakutia

N A Pavlova¹, M V Danzanova¹

¹Laboratory of Permafrost Groundwater and Geochemistry, Melnikov Permafrost Institute SB RAS, Merzlotnaya Str. 36, Yakutsk 677010, Russia

E-mail: napavlova@mpi.ysn.ru

Abstract. Yakutsk, the largest city in the continuous permafrost zone, is used as a case study for examining natural and modified environmental conditions that control the character and intensity of water-logging in the active layer in relation to topography and drainage. Interpretation of aerial photography and satellite imagery was carried out, along with analysis of drilling and long-term hydrogeochemical monitoring data, in order to determine the response of natural landscapes to human impacts and to assess the probability of suprapermafrost cryopeg development with city expansion. The role of vegetation cover in controlling the temperature and moisture regime of the active layer was examined. Results suggest that the neighborhoods with chaotic development patterns and impeded drainage have high risk of cryopeg formation. Puddle water in these areas is characterized by high dissolved-solids levels (2–4 g/dm³). As puddles evaporate, salts settle on the underlying soil surface and then migrate into the active layer, increasing its salinity (up to 1.3%). Suprapermafrost water that forms in these soils has dissolved-solids concentrations as high as 8–10 g/dm³. Continuous supply of dissolved solids and their cryogenic concentration promote the formation of hydrochemical taliks and cryopegs. Remote sensing and mathematical modeling demonstrate that changes to the soil moisture and hydrogeochemical regimes cause forest degradation, which, in turn, promotes deeper seasonal thaw. This provides favorable conditions for the formation of subaerial water-bearing taliks and later anthropogenic cryopegs.

1. Introduction

Many years of experience have shown that in permafrost regions, the construction and operation of buildings and structures cause substantial modification of the geological environment associated with ground temperature changes, increased salinity and water contents of the active layer and underlying permafrost, and formation of highly mineralized groundwater lenses (cryopegs). Ground warming mainly results from placement of heat-generating underground utilities, snow redistribution, poor maintenance of water lines and resulting leaks, or modification of surface and suprapermafrost drainage [1-4]. In Barrow, Alaska, for example, a 17- to 41-cm difference in the depth of thaw between locations in the city and the surrounding undeveloped tundra was documented as a consequence of urban disturbances [5]. In Norilsk, 30% of the area is occupied by large warming zones, up to the formation of technological taliks with saline aggressive water [1]. Up to 40–60% of the buildings and structures are experiencing deformations in Igarka, Dixon, Dudinka, Vorkuta, Pevek and Anderma due to the changes in the ground temperature regime and the deterioration of permafrost-geological conditions [6, 7].
A similar situation is observed in Yakutsk, the largest population center on permafrost in the region of continental-type soil salinity. The first instances of building distress induced by cryopegs in the foundation soils were reported in the 1950s [8]. More extensive geotechnical investigations in the following decades showed that cryopegs developed more frequently in saline, oversaturated soils with high organic content. Cryopegs were found to generally occur within the depth of 6–10 m, occasionally 17–20 m, from the surface. Dissolved-solids concentrations of cryopegs vary widely, from 2–4 to 200 g/dm$^3$, and temperatures of host soils vary from –0.2 to –8°C [9]. Often, cryopegs have a multi-layer structure. The formation of multi-layer cryopegs and their upward or downward migration in subzero-temperature sands are related to the dynamics of meteorological parameters in annual and long-term cycles, as well as to the thermal effects of buildings and earthworks [10]. The irregular distribution and mobility of cryopegs present serious difficulties in investigating and controlling these features [11, 12].

The purpose of this study is to examine the cause and effect relationships among the processes that contribute to water-logging and ponding in Yakutsk and vicinities at different urbanization stages, as well as to estimate the probability of cryopeg formation with further urban expansion.

2. Methods
For spatial characterization of the chemistry of suprapermafrost water occurring in the active layer, samples were collected in July–early August from 43 pits, wells located in different parts of Yakutsk. The hydrochemical regime of active-layer groundwater was monitored at 10 monitoring sites during 5 years. Information on the occurrence of cryopegs in foundation soils was taken from existing geotechnical exploration reports, as well as obtained by drilling at monitoring sites.

Changes to the geobotanical conditions induced by urbanization were assessed using a time series of aerial photographs and satellite images (1946, 1952, 1973, 2008–2016) of a relatively new district of Yakutsk. To assess the temporal variations in puddle chemistry, water samples were collected during two years: in May immediately after snowmelt, in June–July, and in late September. Chemical analysis of water samples and water extracts from soil was carried out at the Melnikov Permafrost Institute using titration and capillary electrophoresis methods.

3. Results and discussion
Tuymaada Valley of the Lena River in its middle course is the most developed area in Central Yakutia. It is a location of the city of Yakutsk founded here in the 17th century. The rapid population growth in recent decades, as well as the aging and degradation of the housing stock demand more residential construction and expansion of the city. In order to prevent adverse effects of new development, it is important to predict potential changes to the environment based on the knowledge of permafrost and groundwater dynamics under natural conditions and in response to disturbances.

3.1. The setting
Monthly means of air temperature in Yakutsk vary from –43.2°C in January (the coldest month) to +20.1°C in July (the warmest month). Annual precipitation in Central Yakutia is 233–247 mm, about the same as in steppe climates. Because of the high summer temperatures and dry conditions, evaporation is high, exceeding precipitation by a factor of 2–4.

The city of Yakutsk is located on the low terrace of the Lena River. In its suburbs, the generally flat topography of the terrace is interrupted by 2–5 m high relic natural levees. The area is mainly drained by the Lena River and its minor tributaries, as well as by shallow oxbow lakes. The river terrace is composed of Quaternary alluvium, up to 20–25 m in thickness. The alluvium consists of fine to coarse sands with a gravel layer in the lower part of the profile and is overlain by silty sands and silts. Salinity of the near-surface soils varies from 0.1–0.5% in higher ground to 1.3% in topographic lows [9].

A discontinuous layer of anthropogenic ground, 1.5 to 4.0 m thick and up to 10 m in places, is present within the city. In the older part of Yakutsk, it consists of ice-rich silts containing household
garbage and construction rubble. The upper 1.0 meter of this cultural layer has salinities as high as 1–5%. Geochemical anomalies with elevated concentrations of chlorides, sulfates, sodium, and nitrogen compounds extend down to 8-10 m depth [13]. Starting from the 1960s, sand, gravel, broken bricks, etc. have been used as fill for construction projects. As a result of leveling, the terrace topography in the residential zone of Yakutsk has been strongly modified and the lakes and small streams can no longer provide drainage.

The active layer thickness ranges between 1.0 and 4.5 m [14]. Mean annual ground temperatures in the vicinity of Yakutsk vary from –1.2 to –3.7°C at the base of the active layer and from –2.0 to –3.7°C at the depth of zero annual amplitude (12-15 m) [15] The flat areas supporting birch stands with a forb and grass surface cover have warmer ground temperatures (–0.5°C) (Table 1). Within the urban area, ground temperatures at the depth of 10 m have increased, on average, by 3.5°C during the last 40–50 years.

Table 1. Parameters of soils thermal regime in the low terrace of the Tuymaada valley (S.P. Varlamov, P.N. Skryabin, Yu. B. Skachkov, 2010).

| Type of natural landscape | Lithology | Active layer soil moisture (%) | Active layer thickness (m) | Temperature at the base of the active layer (°C) | Thickness of the layer of annual temperature fluctuations (m) | Temperature at the depth of zero amplitude (°C) |
|---------------------------|-----------|-------------------------------|--------------------------|-----------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| Hilly landscape with rasp-grass steppe | Sandy loam, sand with peat interlayer | 12 | 1.9 | -1.2 | 13 | -2.0 |
| Hilly landscape with rasp-grass steppe | Sand, sandy loam with peat interlayer | 9 | 2.1 | -3.4 | 13 | -2.9 |
| Topographically low areas with a forb, pine and larch | Sandy loam, loam, sand with peat interlayer | 19 | 2.0 | -3.8 | 12 | -2.4 |
| With alkaligrass meadow | Loam | 18 | 2.0 | -3.2 | 12 | -2.0 |
| With alkaligrass meadow | Sandy loam, sand | 15 | 1.9 | -3.7 | 13 | -2.4 |
| The flat areas supporting birch stands with a forb and grass | Sandy loam, sand with peat interlayer | 23 | 1.8 | -0.4 | 4 | -0.5 |

Poor drainage conditions and low permeability of near-surface materials together with the shallow permafrost table are the main natural factors responsible for potential paludification and inundation of foundation soils.

3.2. **Hydrochemical conditions**
Surface waters on the low Lena River terrace occur mainly in lakes, minor rivers and temporary micro-pools. The amount of total dissolved solids (TDS) in lake water varies from 0.3 to 1.3 g/dm³ in the suburbs and reaches 5 g/dm³ or more in the central part of Yakutsk [16, 17].

Temporary water bodies include puddles which exist from 1–3 days to 4 months. Puddle hydrochemistry was studied in the south-western part of the city where mass housing construction
began in the 1970s. Puddles generally occur along roads and in local topographic depressions. TDS values are highly variable, gradually increasing during the summer. Dissolved solids concentrations are lowest (0.05–0.20 g/dm$^3$) in puddles located in the higher-lying, forested area. Near road crossings, puddle TDS concentrations are as high as 0.5–0.7 g/dm$^3$ even during snowmelt, increasing to 2–4 g/dm$^3$ by October due to the accumulation of easily soluble chlorides and sulfates. The chemistry of puddle water is influenced by surface water–substrate interaction, low groundwater circulation, and high evaporation rates. As puddles dry up, part of the salts is transported by wind in the form of aerosols and dust, while some part remain in the active layer.

Suprapermafrost water is virtually ubiquitous in the active layer throughout the Tuymaada Valley [18]. In higher ground, the soils are less saturated because precipitation water infiltrating from the surface flows rapidly down to the depressions. In low-lying, gentle foostslope areas, the ice-rich soils thaw to a lesser depth. Here, the active layer is often saturated through its entire depth (1–1.5 m). In early summer, the low temperature of active-layer groundwater, on the one hand, reduces the solubility of some salts, and on the other hand, favors the enrichment of water with carbon dioxide which triggers chemical weathering [9]. For this reason, active-layer groundwater has elevated TDS levels (0.7–2.0 g/dm$^3$) as early as May and June. In better drained areas, groundwater TDS generally decreases over the summer. On poorly drained sites, TDS concentrations in the active-layer water range from 1 to 4 g/dm$^3$ in July–August, sometimes reaching 8–10 g/dm$^3$. The anion composition is dominated by bicarbonate ions with elevated concentration of chloride (Fig. 1). The cations are dominated by sodium, with magnesium being second, while calcium rarely exceeds 20%.

![Figure 1. Chemical composition of active-layer groundwater and cryopegs in Yakutsk (Piper diagram).](image)

Dissolved-solids concentration:
1) <1 g/dm$^3$; 2) 1–2 g/dm$^3$; 3) 2–3 g/dm$^3$; 4) 3-10 g/dm$^3$; 5) 10-35 g/dm$^3$.

Thin layers or lenses of saline suprapermafrost water may persist in the saline soils to the end of winter. Their chemistry is largely influenced by the processes of cryogenic metamorphization. In January–February, as the freezing front reaches the aquifers, calcium and magnesium bicarbonates partially precipitate. This results in the accumulation of magnesium and sodium chlorides and sulfates – salts with low freezing point – in the remaining pore solution. If the soils of the drainage area have significant salinities, suprapermafrost water TDS may exceed 10 g/dm$^3$.

The changes in the moisture and hydrogeochemical regimes of the active layer have resulted in disruption of the successional system, with tree vegetation replaced by salt-tolerant graminoids on drainageway slopes. Studies in Central Yakutia have shown that loss of vegetation or disturbance of its continuity lead to increases in seasonal thaw depth by up to 0.5 m, in active-layer moisture content by 50% or more, and in active layer temperatures by 0.5 to 1.0°C [19, 20]. Similar increases in active-
layer thickness and moisture content are predicted in the areas of forest degradation in the Tuymaada Valley. Mathematical modeling of ground thermal dynamics at the site of an extensive die-off of birch and drilling data demonstrated the possibility that subaerial taliks may develop in such areas [9, 21]. Continuous transport of dissolved solids from adjacent terrain via suprapermafrost flow, as well as longer water–soil interaction and cryogenic metamorphization of pore solutions are favorable factors for the formation of anthropogenic cryopegs.

4. Conclusions
In Yakutsk, dissolved-solids concentrations in surface and suprapermafrost waters are highly variable owing to the localized effects of anthropogenic factors. Where natural drainage has been disrupted, the ensuing changes in water chemistry lead to destruction of the mature vegetation communities, increased depths of the active layer, and relatively rapid formation of hydrochemical taliks (Fig. 2).

![Figure 2](image_url)

The detection of vegetation changes due to thermokarst subsidence, surface ponding, and soil salinization can be used to assess the magnitude of urbanization-induced transformation of the permafrost and groundwater conditions. In the Tuymaada Valley, the probability of cryopeg development is high in shallow inter-ridge depressions underlain by warm permafrost and identified by birch stands. Considering the vulnerability of such landscapes to urban development, it is very important to avoid disruption of natural surface and suprapermafrost drainage in order to prevent water stagnation and further soil salinization.
References

[1] Grebenets V I, Streletskiy D and Shiklomanov N 2012 Geography, Environment, Sustainability 3 (5) pp 104-119

[2] Syromyatnikov I I and Dorofeev I V 2014 Nauka i Obrazovanie 4 pp 42-45

[3] Nyland K E, Klene A E, Brown J, Shiklomanov N I, Nelson F E, Streletskiy D A and Yoshikawa K 2017 Characteristics, Temperature Monitoring, and Distribution. Geographical Review 107 (1) pp 143–158

[4] Shiklomanov N I, Streletskiy D A, Grebenets V I and Suter L 2017 Polar Geography 40 (4) pp 273-290

[5] Klene A E and Nelson F E 2019 Annals of the Association of American Geographers DOI: 10.1080/24694452.2018.1549972

[6] Kronik Ya A 2001 Accident risk and safety of natural and man-made systems in the cryolithozone Second Conf. of Geocryologists of Russia vol 4 (Moscow: Moscow State University Press) pp 138–147

[7] Grebenets V I 2008 Technocryogenesis Controls on the Permafrost and Geotechnical Factors in Towns of the Permafrost Zone Proc. 9th Int. Conf. on Permafrost (Fairbanks) pp 541–543

[8] Melnikov P I 1951 Permafrost-Geological Conditions and Case Studies of Civil and Industrial Construction in Central Yakutia (Moscow: USSR Acad. Sci. Press) p 136

[9] Anisimova N P and Pavlova N A 2014 Hydrogeochemical Studies of Permafrost in Central Yakutia (Novosibirsk: Academic Publishing House Geo Limited) p 189

[10] Pavlova N A and Danzanov M V 2018 Earth’s Cryosphere XXIII (6) pp 26-34

[11] Andreev S V 1985 On Control of Anthropogenic Cryopegs Regional and Engineering Geocryological Studies (Yakutsk: Permafrost Institute SB AS USSR) pp 127–132

[12] Danzanova M V and Pavlova N A 2016 Geokatsiya. Inzhenernaya Geologiya, Gidrogeologiya, Geokriologiya 6 pp 567–576

[13] Makarov V N and Torgovkin N V 2018 Earth’s Cryosphere XXII (3) pp 24-35

[14] Are A L and Demchenko R Y 1972 Selected Results of Long-Term Soil Thaw Observations in the Vicinity of Yakutsk Experimental Investigations of Heat Transfer in Frozen Ground (Moscow: Nauka) pp 91–97

[15] Varlamov S P, Skryabin P N and Skachkov Yu B 2010 Geothermal Monitoring of Soils in the Tuymaada Valley Scientific Support to Solving the Key Problems of Yakutsk Development. (Yakutsk: OOO Sfera) pp 97–102

[16] Sedelnikova A L and Makarov 2016 Nauka i Obrazovanie 1 pp 47-51

[17] Pavlova N A, Danzanova M V and Efremov V S 2015 Water: Chemistry and Ecology 3 pp 11-16

[18] Shepelev V V 2011 Suppermafrost Waters in the Cryolithozone (Novosibirsk: Academic Publishing House Geo Limited) p 169

[19] Skryabin P N and Varlamov S P 2013 Uspekhi Sovremennogo Estestvoznania 2 pp 73–76

[20] Fedorov A N, Konstantinov P Y, Argunov R N, Efremov P V, Iwahana G, Machimura T, Lopez L M and Takakai F 2017 Permafrost and Periglacial Processes 28 (1) pp 331-338

[21] Anisimova N P, Pavlova N A and Tetelbaum A S 2001 Temperature Dynamics of Anthropogenically Salinized Ground under Action of Short-Term Climatic Changes Proc. 7th Int. Symp. on Thermal Engineering and Science for Cold Regions (Korea, Seoul) pp 205–208

Acknowledgments

This study was supported by the Russian Foundation for Basic Research (Project 17-05-00926).