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METHODS OF CRYOSPHERIC RESEARCH

METHODOLOGY FOR ZONING OF THE TERRITORY OF LONG-DISTANCE LINEAR OBJECTS ACCORDING TO THERMOKARST FORMATION CONDITIONS

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The probabilistic-statistical method has been applied to study the causes of the thermokarst distribution heterogeneity along the long linear constructions. A list of natural conditions affecting the development of thermokarst along an oil pipeline is discussed. The methodology for zoning buffer area of long-distance linear constructions (e.g., oil pipeline) according to the conditions of thermokarst development is substantiated. We have delineated and mapped thermokarst-susceptible and thermokarst-tolerant areas along the oil pipeline buffer zone according to the environmental conditions.

Keywords: *thermokarst, trunk pipeline, zoning, big data, probability, statistics.*

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INTRODUCTION

In this paper, we define thermokarst phenomena as landforms appearing in a particular time slice of thermokarst process or after its end due to melting of massive or segregated ground ice, compaction of thawed ground, and its deformation regardless of the scale of the process [*Shur, 1988*]. In this paper, we consider both relic and ancient thermokarst phenomena along with modern ones.

Big data on the object and environmental conditions are being accumulated during the operation of trunk oil pipelines. In conditions of long-distance linear objects' specificity, it is impossible to provide equal spatiotemporal detail of information; one faces the problems of interpolation and extrapolation of data.

Numerical models describing the state of the "pipeline–environment" system have a range of limitations [*Radionova et al., 2016*]:

– a large set of required initial data,

– the need for the hypotheses about changes in the initial data with time;

– inconsistency between the grid size of the available environmental parameters and their actual variability,

– impossibility of comparing data of different scales.

Accumulation of big time-series data and the impossibility of providing equal spatiotemporal detail on linear objects' environment encourage the search for new means of processing and analyzing information, as well as the need to form a basis for rational planning of geological survey, considering the necessity and sufficiency requirements.

METHODOLOGY

This paper is aimed to develop and justify the methodology for zoning the territory of long-distance linear objects according to the conditions of thermokarst formation. East Siberia–Pacific Ocean-1 (ESPO-1) trunk oil pipeline buffer area has been chosen as the study area. This is the longest pipeline in the permafrost area (Fig. 1). Buffer area of trunk oil pipeline ESPO-1 is a 3-km-wide strip of land (1.5 km from the pipeline axis), 2085 km long (in the permafrost zone).

The width of the ESPO-1 buffer area allows one to conduct the analysis of thermokarst phenomena both in the zone of influence of the oil pipeline and in the undisturbed conditions. The underground laying of the oil pipeline along the entire route suggests an approximately similar technogenic impact on the environment during the construction and operation of the pipeline.

During the study, we identified thermokarst phenomena within the pipeline buffer area, searched for cause-and-effect relationships of uneven thermokarst distribution across the study area, and zoned the buffer area according to thermokarst forming conditions [*Makarycheva, 2018*].

Fig. 1. Scheme of trunk oil pipelines located in the areas with complicated environmental conditions.

(*1*) trunk oil pipelines of Transneft PJSC, (*2*) oil pipelines of Transneft PJSC under construction and design, (*3*) other trunk oil pipelines, (*4*) trunk pipelines for oil products of Transneft PJSC, (*5*) projected trunk pipelines for oil products of Transneft PJSC, and (*6*) geotechnical monitoring sites of Transneft PJSC.

Topographic maps of different scales, satellite images and aerial photographs of ultrahigh spatial resolution (0.19 m/pixel), three-year-long aerial and ground survey data obtained by the Sergeev Institute of Environmental Geoscience, Russian Academy of Sciences (IEG RAS) and the ESRC (Research Center for Emergency Situations) LLC in 2010–2012, as well as the results of engineering geological surveys and archieve data.

Thermokarst genesis of the identified landforms is confirmed by engineering-geological survey data, as well as by the additional image interpretation features, such as the subsidence of coastal slopes (cracks parallel to the slope and alternation of deep and shallow areas of the shore underwater part). An additional identification feature of thermokarst was the stable or positive dynamics of the waterlogging of the area throughout the entire survey period despite climatic oscillations. Overall, 2146 thermokarst landforms were identified and mapped.

Aerial survey data from 2011–2012 were also used to identify with compensatory measures and repair works and analyze the influence of thermokarst on the operation of the trunk oil pipeline.

We applied a probabilistic-statistical method to search for cause-and-effect relationships for the uneven distribution of thermokarst phenomena across the study area. As the source data, we used small-scale maps [*Fedorov et al., 1989; Fedorov, 1991; Mel'nikov, 1991; Ershov, 1996*], thematic large-scale maps of the territory along the oil pipeline created by the IGE RAS in 2010, the map of environmental complexes (scale 1:50,000), and the map of morphostructural zoning (scale 1:100,000), as well as archieve data [*Gerasimov, 1965; Kudryavtsev, 1975; Tyrtikov, 1976; Ospennikov et al., 1980*].

Thematic maps contain several characteristics of the study area. For example, the map of environmental complexes contains information about the landscape units, vegetation, topography, and swampiness of sections of the oil pipeline route. Landscape units are understood here as taxonomic units of the landscape distinguished by the homogeneity of the topography and zonal types of vegetation.

According to the map of morphostructural zoning, pre-neotectonic (ancient) regional structures and second-order neotectonic structures (arch, trough, and uplift) are identified within the study area.

Second-order neotectonic structures are distinguished by their direction (vertical and horizontal), intensity of movements, and features of their expression in the topography. Arches are mainly formed by vertical movements (stresses) and, to a lesser extent, by subhorizontal movements. These are relatively stable oval-shaped or isometric rises. Within the platforms, arches can be expressed in the form of slightly convex plateaus (arch-like plateaus) with a well-developed "ladder" of geomorphic surfaces.

Uplifts and troughs are formed due to predominantly subhorizontal movements (stresses) and are more intensively developing forms compared to arches. They have an extended or linear type of development. As a rule, uplifts and troughs are conjugated forms and are characterized by zonal development associated with highly active tectonic areas.

Independence of criteria while creating environmental (landscape) maps of the area allows to use them for searching the connections between thermokarst development and different geographical and geological conditions within the oil pipeline route, as well as to increase the reliability of the obtained data.

The influence of areal environmental conditions on the thermokarst distribution was carried out in a series of independent experiments. Thermokarst landforms and the particular environmental and technogenic conditions along the pipeline route were considered together.

A series of independent tests were carried out with following settings. We selected a characteristic of the study area, whose influence on the distribution of thermokarst interested us, for example, the separation of the territory by landscape units. A set of landscape units within the study area was determined. In our case, there were four landscape units: (1) intrazonal (terrace complexes of river valleys, floodplains, valleys of small rivers and waterlogged hollows, raised and transitional bogs, areas burned by a surface fire); (2) forest; (3) forest-tundra, mostly flat (plateaus); and (4) forest-tundra, mountainous. Then, we analyzed each kilometer of the pipeline route and identified the types of landscape units within it; the thermokarst phenomena within the identified landscape units were recorded. We summarized these data as in a table with the rows corresponding to kilometer areas of the pipeline route and the columns indicating landscape units. This information was encoded as follows: 0 – there is no such landscape unit within the study area, 1 – area is characterized by this landscape unit without thermokarst , and 2 – area is characterized by this landscape unit with thermokarst.

Next, we calculated the occurrence frequency of thermokarst landforms for each landscape unit. For this, we determined the number of kilometer areas of the pipeline route containing the given landscape unit and the number of them characterized by thermokarst phenomena. These operations were performed using GIS query builder, which allows to select all rows with a value of 1 and 2 from the table while calculating the occurrence of landscape units or 2 while calculating the occurrence of thermokarst phenomena.

Statistical processing was done in MapInfo software by applying a special algorithm to optimize processing time and increase reliability of the results [*Makarycheva et al., 2018*].

Thus, we obtained the data for statistical processing: the occurrence frequency of given landscape units N_k (the number of kilometer-long sections of the route containing a given landscape unit), the total occurrence of all landscape units $N \quad \sum N$ the frequency of thermokarst occurrence in a landscape unit n_k (the number of kilometer-long sections containing a given landscape unit with thermokarst), and the total number of all outcomes of the experiment $n \quad \sum n$ where k = 1, 2, 3, 4 is the number of the landscape unit.

For statistical processing, it was assumed that: (1) the presence or absence of thermokarst phenomena in a given landscape unit (under given natural or technogenic conditions) is a *random event* (the outcome of the experiment); and (2) thermokarst phenomena have a *uniform* distribution of probabilities across all landscape units; the more often a given landscape unit occurs, the greater the likelihood of finding thermokarst phenomena in it.

These assumptions, as well as the above-mentioned method of determining the occurrence of a very short section length in comparison with the total length of the pipeline route, allow to accept the formula $p_k = N_k/N$ for calculating the probability p_k of thermokarst occurrence in the k-unit. If the specified assumptions are true, then the frequencies of occurrence of thermokarst phenomena should have a polynomial probability distribution [*Prokhorov et al., 1988*].

Below we test the hypothesis that the experimentally obtained frequencies of thermokarst occurrence found within landscape units n_1, n_2, n_3, n_r have a polynomial distribution.

Pearson's chi-squared test is recommended to test this hypothesis [*Prokhorov et al., 1988*]. This criterion, however, rejects the hypothesis, for all indices k in case of disagreement, if the occurrence of outcomes in at least one landscape unit is *nonrandom*. The authors are interested, however, in discrimination between *random* and *nonrandom* (subjected to systematic influences of conditions, the presence of connections). It is impossible to answer this question using the Pearson's criterion.

The polynomial distribution has an important property: each of the r random variables n_k has a binomial probability distribution. This allows us to consider a system of k different binomial distributions with the expected values $M_k = np_k$ (theoretical frequencies), dispersions $D_k = np_k\left(1 - p_k\right)$, and standard deviations $\sigma_k = \sqrt{np_k\left(1 - p_k\right)}$ instead of one polyno-

Table 1. **Analysis output: influence of landscape units on the distribution of thermokarst in the buffer area of the oil pipeline**

Numerical characteristics	Landscape unit			
	Intrazonal	Forest	Forest-tundra, mainly flat (plateaus)	Forest-tundra mainly mountainous
Number of landscape unit (k)	1	2	3	4
Total occurrence of thermokarst within all landscape units (n)	388	388	388	388
Detected occurrence of thermokarst within one landscape unit (n_k)	216	158	4	10
Lower threshold of "reliability" ($M_k - 3\sigma_k$)	105.28	174.86	–2.14	29.28
Upper threshold of "reliability" ($M_k + 3\sigma_k$)	161.41	233.87	4.95	68.50
Connection characteristic of the direct type $\delta_k\uparrow$	54.6	–	–	–
Connection characteristic of the inverse type $\delta_k\downarrow$	–	16.86	–	19.28
Type of relationship	Direct	Inverse	Absent	Inverse

mial distribution, where $n \quad \sum n$ is the total occurrence of thermokarst within all landscape units.

Using the above equations, one can obtain numerical characteristics allowing to extract nonrandom experimental results [*Makarycheva et al., 2018*]. For this, for each landscape unit, the 3σ-rule was used; this rule is widely applied in mathematical statistics [*Ivashov-Musatov, 2003*]. By calculating M_k, σ_k, and making a comparison, we can state that our hypothesis is true, if n_k falls within the interval:

$$\left[M_k - 3\sigma_k; M_k + 3\sigma_k\right]. \qquad (1)$$

In this case, the value n_k is the value of a random variable that obeys the specified distribution law. Otherwise, the hypothesis is rejected, from which it follows that this landscape unit systematically affects the value of n_k.

If $n_k > M_k + 3\sigma_k$ (experimental frequency is higher than the upper threshold), then k-landscape unit promotes the thermokarst formation:

$$\delta\uparrow = n_k - \left(M_k + 3\sigma_k\right). \qquad (2)$$

If $n_k < M_k + 3\sigma_k$ (experimental frequency is lower than the lower threshold), the landscape conditions hinder the thermokarst formation:

$$\delta\downarrow = \left(M_k - 3\sigma_k\right) - n_k. \qquad (3)$$

Values (2) and (3) can be called quantitative characteristics of direct and inverse relationships. They are expressed by numbers showing the excess of the upper threshold (1) by the experimental frequency and the amendment to the experimental frequency to the lower threshold, respectively.

Table 1 summarizes the results of probabilistic-statistical analysis of the relationship between the thermokarst phenomena and the landscape units in the buffer area of the oil pipeline.

The occurrences of landscape units had the following values $N_1 = 1331$, $N_2 = 2040$, $N_3 = 14$, $N_4 = 488$, $N = 3873$.

We have performed the zoning of the buffer area of the trunk oil pipeline according to conditions that promote or hinder the formation of thermokarst phenomena based of dependencies obtained from the probabilistic-statistical analysis. All conditions and factors were divided into two groups: those promoting the formation of thermokarst and those hindering the formation of thermokarst. Promoting conditions were those, for which direct relationship with the thermokarst occurrence frequency was found. Hindering conditions were characterized by the inverse relationship with the thermokarst occurrence frequency. Then, we generated two separate zoning maps by overlaying the distribution areas according to conditions that promote and hinder thermokarst formation.

THERMOKARST DISTRIBUTION HETEROGENEITY ANALYSIS

The considered analysis has been applied to the entire oil pipeline route and for each of the three ancient tectonic structures separately.

Thermokarst phenomena are distributed unevenly relative to ancient tectonic structures, but neither direct nor inverse relationships with particular tectonic structures have been identified. At the same time, regional ancient structures determine the material and structural heterogeneity of the territory, which in turn indirectly affects the patterns of thermokarst distribution.

The oil pipeline route crosses three ancient tectonic structures: sedimentary layer of the Siberian Platform (including the Central Siberian Plateau), the Aldan-Stanovoy shield of the Siberian Platform, and the Mongol-Okhotsk fold system. We have identified changes in the relationships between thermokarst distribution landscape conditions (landscape unit, vegetation, topography), and second-order morphostructures of the relief (arch, uplift, trough) during the transition from one tectonic structure to another. We have also determined quantitative characteristics of these relationships and their direction (direct, inverse, or no connection) and identified conditions affecting the thermokarst formation.

Table 2 summarizes the sample of environmental conditions directly affecting thermokarst development as obtained from the statistical analysis of data on the three ancient tectonic structures. It should be noted that a change in both the type of relationships and their quantitative characteristics takes place upon the transition from one tectonic structure to another.

We have statistically proven the relationship between the distribution of thermokarst and uplift zones within the sedimentary layer of the Siberian Platform. This relationship is debatable; it is important that second-order morphostructures of the relief that reflect the direction and intensity of neotectonic movements can often manifest themselves not directly, but through other factors, including the entire set of landscape conditions.

It can also be assumed that denudation processes in the areas of uplifts lead to the displacement of the base of the active layer deep into the rock, so that it reaches layers with the high ice content, which are susceptible to thermokarst. The oil pipeline route in the southern part of the Central Siberian Plateau is characterized by the distribution of permafrost (including high-ice permafrost and permafrost with ice wedges) buried under the layer of surface sediments.

Table 2. **Quantitative environmental assessment of relationships between thermokarst distribution wand environmental conditions within ancient tectonic structures**

Environmental conditions	Platform (sedimentary layer)	Aldan-Stanovoy shield	Mongol-Okhotsk fold system
Direction of neotectonic movements			
Arch	Inverse	1.00*	Absent
Uplift	36.50	Absent	Absent
Landscape unit			
Intrazonal landscapes	29.29	14.11	Absent
Forest-tundra, mainly flat (plateaus)	Absent	Absent	0.28
Topography			
Elevated moderately dissected plateaus and steplike plateaus	Absent	3.18	Absent
Low valleys and intermountain depressions	8.69	Absent	Absent
Low-elevation ridged relief	1.49	Absent	Absent
Mid-elevated moderately dissected plateaus and steplike plateaus	48.27	Absent	Absent
Vegetation			
Raised and transitional bogs	Absent	0.93	Absent
Bogs and transitional fens with meadow-bog communities	Absent	7.09	Absent
Meadow-shrub communities with individual small-leaved trees	9.35	Absent	Absent
Burnt areas with groups of larch, less often pine with burned ground cover	2.40	Absent	Absent
Birch and willow shrublands with single low larch, pine, and birch trees, deadwood on felling sites and burnt areas, partially swampy	Absent	Absent	1.24
Birch shrub-green moss communities with single larch, pine, and birch	23.85	Absent	Absent
Shrub hummock communities with single low larch and birch trees, often swampy	8.37	6.80	Absent
Larch woodlands with patches of rocky ground	7.68	Absent	Absent
Larch-birch and birch forests	8.45	Absent	Absent
Non-vegetated dredging areas	Absent	Absent	0.52
Pine-spruce-fir forests	12.82	Absent	Absent
Pine and birch forests with isolated wetlands	8.06	Absent	Absent

* All presented values represent quantitative characteristics of direct relationships: $\delta_k\uparrow = n_k - (M_k + 3\sigma_k)$.

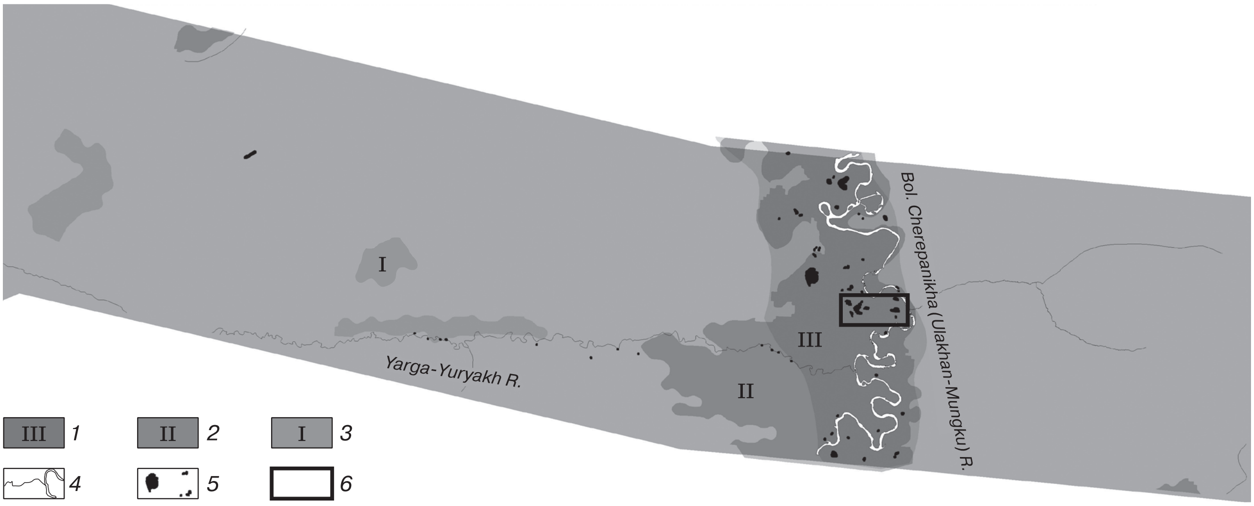

Fig. 2. Fragment of the zoning map of buffer area of the trunk oil pipeline at the intersection with the Bolshaya Cherepanikha River according to conditions of thermokarst development:

Superposition of (*1*) three (III) and (*2*) two (II) environmental conditions promoting the development of thermokarst, (*3*) one (I) environmental condition favoring the development of thermokarst; (*4*) streams, (*5*) thermokarst phenomena, and (*6*) site of ground geological survey.

In the discontinuous permafrost zone of the Central Siberian Plateau, thermokarst phenomena are confined to intrazonal landscapes, which is associated with the widespread distribution of sandy loamy and biogenic (peat) sediments with the high ice content in these landscapes (Fig. 2).

Additionally, we have identified the relationship between burnt areas (fires) and thermokarst for the Siberian Platform. Disturbances of vegetation cover resulting from fires create conditions for the uneven thawing of peat and formation of water-filled depressions. Surface subsidence begins under these depressions. Small lakes are formed, if peatlands are underlain by not subsiding permafrost with the low ice content.

In the Aldan Shield area of the Siberian Platform, thermokarst phenomena are mostly confined to the arch zones. Minor topographic differences represented by elevated plateaus and step-like plateaus with moderately dissected surfaces create limited conditions for drainage of surface water. Modern tectonic activity in the near-surface zone occurs under extensional conditions (the route crosses these structures across their strike), which is the reason for the presence of a large number of elevated river terraces. Fens and transitional bogs, as well as swampy areas, are widespread within the Aldan shield; their freezing and subsequent thawing contributes to the development of thermokarst.

Neotectonic movements are highly intense in area where the oil pipeline route crosses the Mongol-Okhotsk fold system. Zones of uplifts and troughs are characterized by large differences in elevation. In this area, no relationship between thermokarst development and neotectonic structures has been found. At the same time, we have found the relationship of thermokarst phenomena with partially swampy clearcut and burnt areas on plateaus occupied by birch and willow communities. The morphological characteristics of individual thermokarst phenomena (the shape of the coastline cut by straight segments with right angles, grid-like patterns or blocks on aerial photographs and satellite images) indicate the spread of ice wedges.

ZONING THE BUFFER AREA OF THE TRUNK OIL PIPELINE ACCORDING TO THERMOKARST FORMING CONDITIONS

The obtained dependencies formed the basis for the zoning of the territory. All conditions and factors were divided into two groups: those that hinder the thermokarst formation and those that promote it.

Based on the results of this work, we have compiled zoning maps of the three-kilometer buffer area of the trunk oil pipeline (scale 1:50,000) over 2085 km (Fig. 2). These maps provide rationale for selecting and optimizing the observation network of monitoring points.

Areas with the direct relationship between thermokarst development and environmental conditions are indicated by color and the number. The more conditions favor thermokarst, the more intense is the color.

The site of ground geological observations lies in the discontinuous permafrost zone, within which three environmental conditions favor thermokarst development: (1) mid-elevated moderately dissected plateaus and steplike plateaus, (2) intrazonal landscape unit, and (3) larch-birch and birch forests. In the oil pipeline land allotment boundaries (50-m-wide) of this area, we have identified the phenomena of technogenic thermokarst associated with the thermal impact of the operating underground oil pipeline.

Outside the land allotment boundaries, in a three-kilometer zone, we have identified elongated lakes and depressions with the shores dissected by rectilinear segments with right angles.

According to ground observation data (description of pits), the site is composed of low- and medium-ice loam with layered cryostructures. Moreover, a massive ice body of 4 m in thickness was found.

The ground temperature in the boreholes next to the pipeline (–1.5 to –2°C) is higher than in the borehole beyond the land allotment boundaries (–3°C). Data from instrumental measurements in the pit indicated the development of a thaw bulb around the oil pipeline (up to 1.2 m under the pipeline section) [*Novikov et al., 2015*].

CONCLUSIONS

1. We have proposed a methodology for zoning the territory of long-distance linear objects according to the conditions of thermokarst formation based on the probabilistic-statistical method.

2. This methodology allows one to quickly analyze large amounts of data, and also to implement algorithms for automated analysis of the environmental conditions of the area, and to create zoning maps of long-distance linear objects.

3. The probabilistic-statistical method can be used to search for the dependence of thermokarst distribution on the geological and geographical conditions at the stage of design and operation of linear objects, including poorly studied areas.

The differences between the proposed methodology and those previously applied are:

– the ability to determine the experimental outcomes, which are caused by the presence of certain dependencies in the distribution of the phenomena and studied conditions, and which are random,

– the presence of quantitative criteria for the relationships between the studied phenomena and the conditions influencing their distribution,

– the ability to identify conditions both promoting and hindering the spread of the phenomena,

– the ability to analyze both regional and local relationships,

– the possibility of obtaining spatial patterns in conditions of insufficient input data, their uneven spatial distribution, and scales difference.

The developed methodology is universal, it can be applied to analyze spatial relationships when processing large amounts of data accumulated over the lifetime of a long-distance linear object.

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