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Changes in Unfrozen Water Contents in Warming Permafrost Soils

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Abstract: Climate warming in the Arctic, accompanied by changes in permafrost soil properties (mechanical, thermal, filtration, geophysical), is due to increasing unfrozen pore water content. The liquid component in frozen soils is an issue of key importance for permafrost engineering that has been extensively studied since the beginning of the 20th century. We suggest a synthesis and new classification of various experimental and calculation methods for the determination of unfrozen water content. Special focus is placed on the method of applying measurements to the water potential, which reveals the impact of permafrost warming on unfrozen water content. This method was applied to natural soil samples collected from shallow permafrost from northern West Siberia affected by climate change, and confirms the revealed trends. The obtained results confirm that unfrozen water content is sensitive not only temperature but also particle size distribution, salinity, and the organic matter content of permafrost soils.

Keywords: permafrost; frozen soil; phase composition of pore water; unfrozen water content; water potential method; warming; permafrost degradation

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1. Introduction

The rapid development of permafrost territories worldwide has caused problems associated with climate-induced permafrost warming, especially in recent decades. The warming and degrading of permafrost substantially weakens its bearing capacity and poses risks to the stability and safe operation of engineering constructions [1–5]. Although the temperature of the permafrost in the northern hemisphere reaches −12 to −10 °C, some parts of the pore moisture remain unfrozen [6]. The pore moisture of frozen ground consists of ice, unfrozen water, and a small amount of gas (including water vapor) that has only a minor influence on permafrost properties. The phase equilibrium in the pore moisture changes under climatic temperature effects: ice content increases upon cooling, and the amount of unfrozen water increases upon warming. The changing percentages of solid (ice) and liquid (water) components of pore moisture affect physical and chemical processes in the permafrost and its related thermal and mechanical properties [7]. Ongoing climate warming in the Arctic leads to disturbed ecosystems, and induces a slow warming of ground that has been frozen for hundreds of years or longer [8].

Permafrost retains an enormous resource of coldness, and is unlikely to thaw to a catastrophic extent in the coming decades. Nevertheless, the continuous warming of shallow permafrost may change the phase composition of pore moisture by increasing the amount of unfrozen water, causing the solid permafrost to adopt a more plastic behavior. The unfrozen water content may further increase following thermal impact from buildings and facility constructions, drilling operations, pipelines and others [9]. Therefore, it is critical to develop advanced methods and instruments for the prediction of possible permafrost responses to increasing unfrozen water content as a result of global warming, to ensure the stability of buildings and structures in the Arctic [10–13].

2. Materials for Estimating Unfrozen Water Content in Permafrost

Experiments in the early 20th century showed that some amount of pore water in the ground exposed to negative temperatures remained unfrozen [14,15]. The idea that some pore moisture in artificially frozen soil and in natural permafrost may remain liquid appeared in the handbook "General Geocryology" [16]. Later experiments by Tsitovich laid the foundation for the phase equilibrium principle of pore water in frozen ground [17,18]: frozen ground at any low negative temperature always contains some residual liquid water, the amount of which varies as a function of temperature and pressure.

Further instrumental advances in the 1950–1970s provided a wealth of experimental constraints on the sensitivity of pore moisture phase composition and grain size, mineralogy, and salinity of permafrost. Later, it was found that unfrozen water in the pores of frozen ground could exist in capillary, film, adsorbed, or other forms [19–21]. Its content was studied in terms of its effect on the thermal, mechanical and electrical properties of permafrost soils [22–32], as well as on various physical and chemical processes [18,33–38]. Research along these lines by many teams from Russia, China, Canada, Japan, Germany and the USA continues.

Experimental research in the 1960s, 1970s and later was complemented by modeling based on empirical equations that related the amount of unfrozen pore water in permafrost to other variables. Correspondingly, unfrozen water content was estimated from such parameters as plastic limit, temperature [39] and salinity [40], according to the Design Standards currently used in Russia (equivalent to the standards of the American Society for Testing and Materials or ASTM); pore pressure in freezing soils [41]; specific particle surface area [42–44]; liquid limit [45]; specific volume of water, partial specific heat capacity, apparent specific heat capacity, and total moisture content [46]; total moisture and temperature of soil and freezing point of pore water [47]; liquid limit moisture for saline soil [48]; freezing point and unfreezable water content [49]; moisture and grain size of soil [50], and potential (activity) of pore water [51].

The available methods for estimating the phase composition of pore moisture in frozen ground have been classified in different ways according to approaches to its determination [19,27,34,52]. We suggest an updated classification (Table 1), which combines all previous ones and divides the methods into experiments (direct measurements), modeling, and experiments + modeling (calculations based on measurements).

Table 1. Summary of methods for studying the phase composition of pore moisture in frozen soil.

Experiment	Combined (Experiments + Modeling)	Modeling Using Empirical Relationships with Other Soil Variables
Cryoscopy [15]	Calorimetry [53–57]	Plasticity, temperature, and salinity [39,40,53]
	Nuclear Magnetic Resonance (NMR) [58–63]	Total moisture and grain size [50]
Hygroscopic absorption [64]	Time domain reflectometry (TDR) [65–70]	Pore pressure [41]
	Thermometry [35,71]	Specific surface area [42–44]
Sublimation [72]	Desorption [27,73]	Total moisture and heat capacity [46]
	Water potential [74–78]	Total moisture, ground temperature, and freezing point [47,48]
Contact [19]		Freezing point and unfreezable water content [49]

The references are to papers where the respective methods were first described.

The methods of the first group include cryoscopy, hygroscopy, sublimation, and contact measurements of unfrozen water content. In the calorimetry, NMR, TDR, thermometry, desorption, and water potential methods (second group), water content is calculated from experimentally measured parameters. Modeling means the estimation of unfrozen water content using a correlation with other soil properties (e.g., grain size, specific surface area, salinity, plastic and liquid limits, freezing point, etc.).

The applicability of different methods depends on the lithology and temperature range of the soil, as well as on the required instrumental facilities and time, but most of these are labor- and time-consuming. Meanwhile, active construction on permafrost in Russia, China, Canada, and the US requires high-quality and high-performance engineering surveys and new or updated techniques for estimating the amount of unfrozen pore water.

3. Water Potential Method and Its Advantages

The water potential method is advantageous for estimating the amount of unfrozen pore water in permafrost [74–78]. It consists of measurements of pore water potential (or water activity) in samples with stepwise decreasing water content and subsequent thermodynamic calculations using measured data. The instruments used in this method provide automatic monitoring of measured water potential, which saves time and allows express measurements [78]. The method was applied to laboratory soil samples across a large range of negative temperatures reaching −15 °C and to natural samples collected during geological engineering surveys in northern West Siberia. The results agree well with data from other methods, including NMR and contact measurements, which are especially widespread in Russia [78].

The activity of pore water can be measured on a WP4 water potential meter (Pullman, WA, USA) [79] designed by the METER Group (formerly Decagon Devices). The details of this method are described in detail by Campbell et al. [79], and the thermodynamic background is provided by Istomin et al. [80]. The system (Figure 1) is based on sampling the pressure of water vapor over wet soil using the dew-point method.

(**a**) (**b**)

Figure 1. WP4-T (**a**) and WP4C (**b**) water potential meters.

The temperature dependence of unfrozen water content in frozen soil is obtained in several runs at different total moisture values measured by weighing the soil samples on analytical scales, to a precision of ±0.003 g, before and after water potential measurements are taken. First, the pore water potential (ψ) is measured in samples with known moisture content, and the results are converted to activity (α) which is further converted to the temperature of ice—pore water equilibrium or the equilibrium temperature (t_{eq}, °C)—which actually corresponds to the freezing point at the given total moisture.

The pore water activity in the range from 0.6–0.7 to 1.0 is related to the equilibrium temperature (t_{eq}, °C) as [75].

$$t_{eq} = 103.25 \ln \alpha + 5.57(1 - \alpha)^2, \quad (1)$$

Water activity (α) can be estimated by direct measurement at +25 °C or by thermodynamic calculations, as per [78].

$$\ln \alpha = \frac{\psi M}{RT} = 0.0073\psi, \quad (2)$$

The measurements of pore water potential begin in a soil sample with initial natural moisture or with pore moisture versus the total moisture (for laboratory-made samples). While the sample is being dried, the potential is measured over six or seven runs at each step of progressively decreasing content of unfrozen water. The acquisition commonly takes 20 to 30 min (60 min, the longest, for dry mud), which is the time required for soil moisture and vapor-bearing air in the sample chamber to reach full equilibrium.

4. Main Controls of Unfrozen Water Content in Permafrost

The amount of unfrozen pore water depends on the temperature and composition of permafrost soil, including grain size, mineralogy, salinity, organic matter content, etc. Temperature-dependent variations of unfrozen water content can be plotted as in Figure 2. The geometry of the curve is approximately the same (Figure 2) at any lithology, mineralogy, salinity, peat content, and other properties of permafrost, and will vary only in the slope and specific values along the axes. At some subzero temperature ($t_{f1} \sim 0$ °C), the amount of unfrozen pore water may reach a point ($W_0 - W_1$) at which the phase composition of pore moisture no longer changes, because almost all the pore ice has already melted. In this case, permafrost will behave like unfrozen soil. However, it is at a negative temperature, and will lose the mechanical strength that was provided by the ice cement at lower temperatures (t_{f2}, t_{f3}, t_{f4}). Furthermore, the amount of residual pore water in frozen soil is proportional to its salinity and to the content of organic matter and clay particles, which has been confirmed in several studies [19,78,81,82].

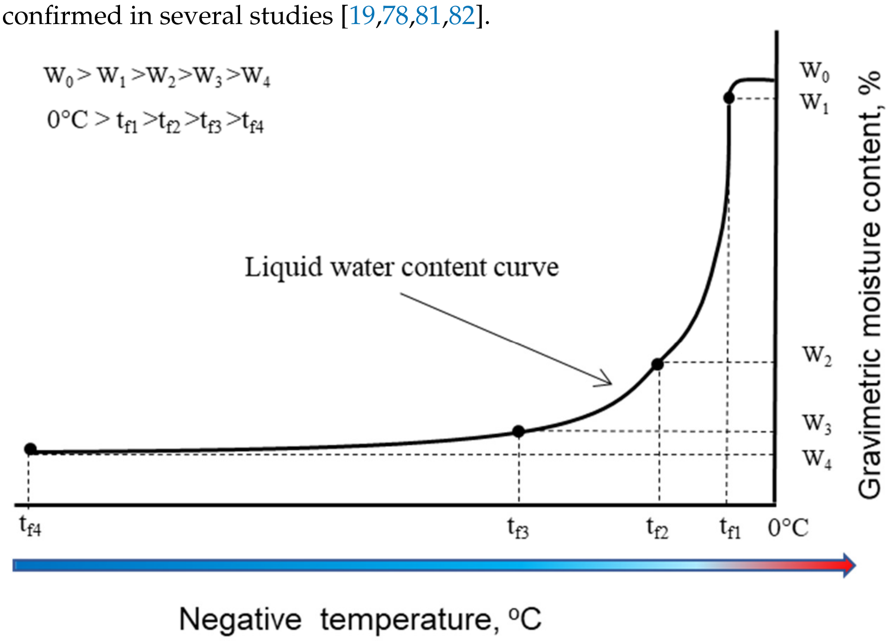


Figure 2. Temperature-dependent content of unfrozen pore water in permafrost. t_{f1}, t_{f2}, t_{f3} and t_{f4} are soil freezing points with moisture contents W_1, W_2, W_3, W_4, respectively. W_0 is the soil natural moisture content.

The sensitivity of unfrozen water content to organic matter (peat) content can be illustrated with silt–clay soil samples from northern West Siberia. The samples (Table 2) share similarity in grain size and mineralogy, consisting of 40% quartz and clay minerals (montmorillonite, kaolinite, hydromica, chlorite and mixed-layer groups). They are non-saline but contain different percentages of organic matter (peat). More details of these soils have been reported previously [78].

Table 2. Salinity and organic content in soil samples from northern West Siberia.

Sample	Soil Type *	Salinity, %	Organic Matter Content **, %
1	Lean clay (CL)	0.05	0.4
2	Sandy silty clay (CL-ML)	0.04	2.7
3	Lean clay (CL)	0.06	3.1
4	Silt (ML)	0.06	6.2

* Description according to ASTM D2487-06 [83]. ** OM content calculated as organic matter-to-dry sediment weight ratio from loss on ignition at 525 °C for 4 h.

The natural soils of northern West Siberia with greater peat percentages (I_r, %) contain more liquid pore water, other things being equal (Figure 3). Specifically, unfrozen water content at −5 °C is ~3.5% in peat-free lean clay (I_r = 0.4%), 5% at I_r = 2.7%, and up to 6% and 8% at the peat content of I_r = 3.1% and 6.2%, respectively.

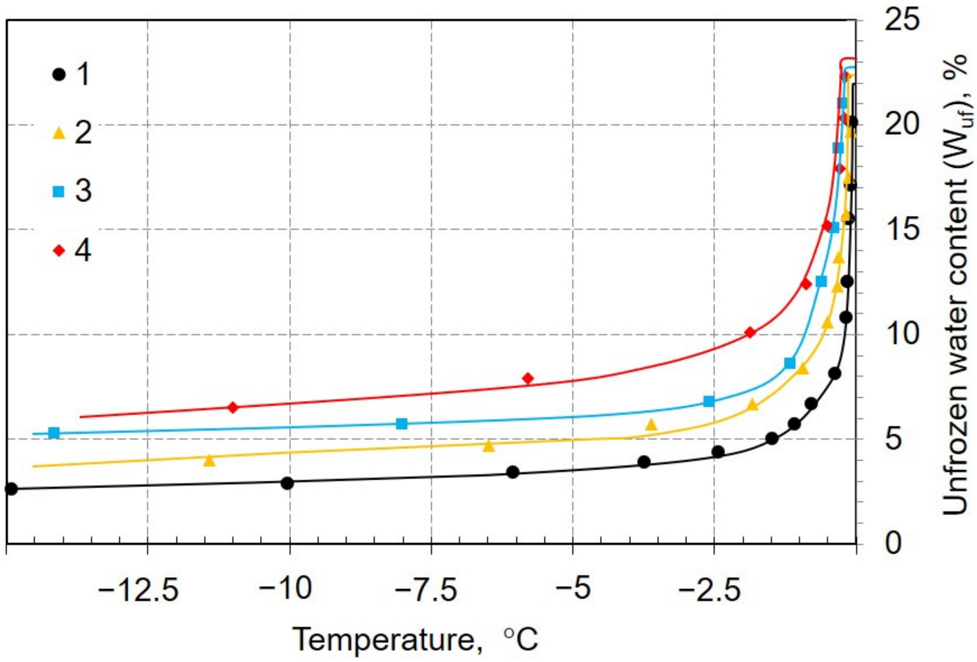


Figure 3. Temperature-dependent unfrozen pore water content in clay samples with peat contents (I_r) of 0.4% (1); 2.7% (2); 3.1% (3); 6.2% (4).

The samples were collected from −5 to −6 °C permafrost. Its unfrozen pore water content increases only slightly if the permafrost becomes 1–2 °C warmer (Figure 3) but may reach notably greater percentages upon further warming toward 0 °C, especially at greater peat content. The permafrost with the highest percentages of peat (6.2%) will contain 13–15% of unfrozen pore water at −0.5 to −1 °C (Figure 3).

The content of unfrozen pore water is also sensitive to the salinity of permafrost (Figure 4), expressed as dry-weight salt percentage (D_{sal}). The salinity dependence was studied for saline lean clay and sand soils interacting with seawater, from marine terrace I in northern West Siberia [82].

The unfrozen water content increases proportionally with salinity in both sand and lean clay samples. Upon warming from −10 °C to −2 °C, the increase is moderate in non-saline soils but increases by several times at maximum salinity (0.8% in sand and 1% in lean clay), from 2.5% to 12.5% in sand and from 10% to 25% in lean clay.

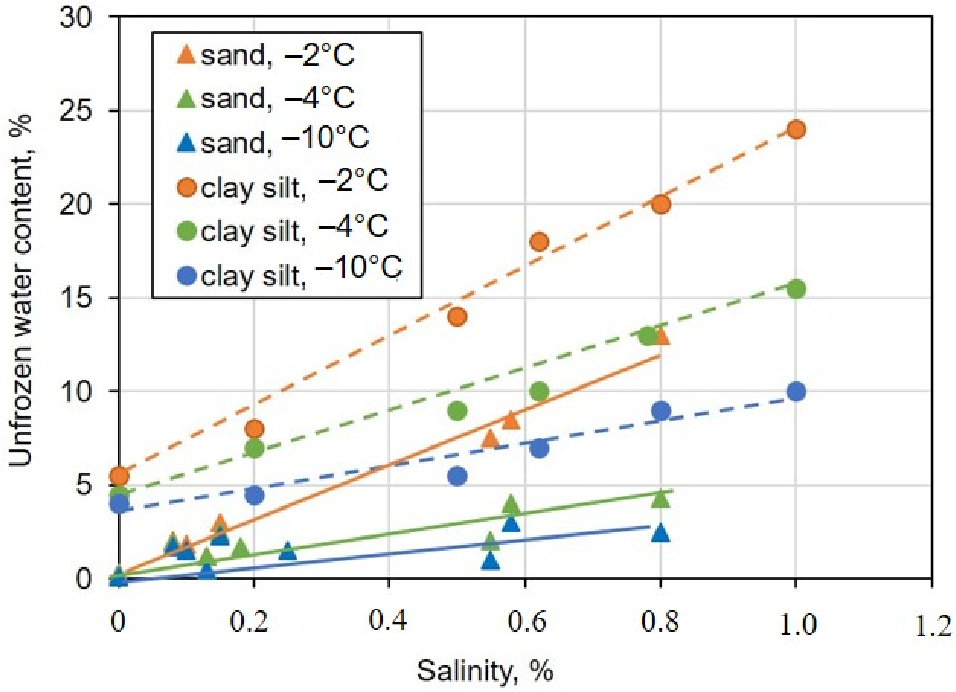


Figure 4. Salinity-dependent unfrozen pore water content in sand and lean clay soils at temperatures of: −2 °C; −4 °C; −10 °C, after Aleksyutina and Motenko [82].

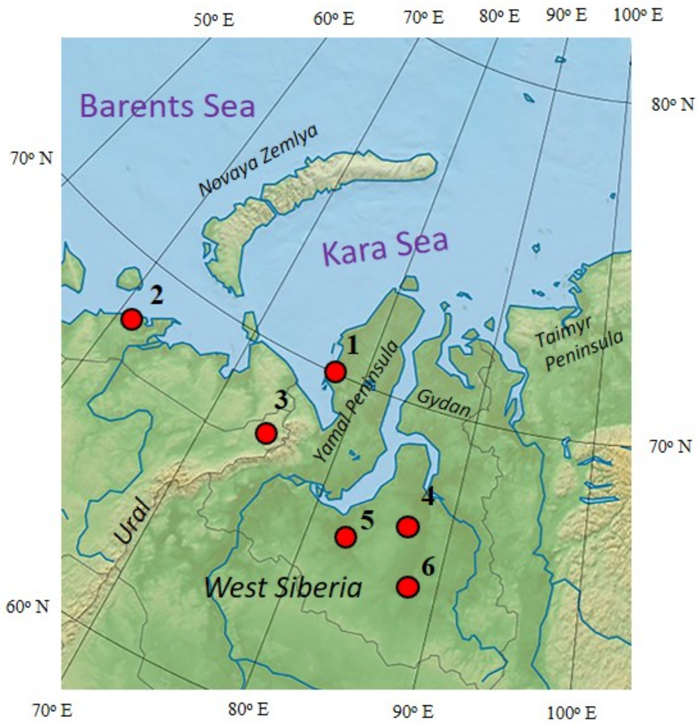
5. Discussion

Unfrozen water is a ubiquitous component of interstitial moisture in permafrost. It may occur as lenses or layers of brines called cryopegs, or as thin film around ice crystals and mineral particles. Locally, saline unfrozen water may fill pores and voids in the soil skeleton, making miniature cryopegs. The amount of unfrozen water is proportional to the organic matter (peat) content and to salinity, because saline water has a lower freezing point than fresh water. The permafrost soil gains mechanical strength and stability as its liquid pore moisture decreases upon cooling to lower negative temperatures and, vice versa, loses strength and acquires plastic properties at greater percentages of residual unfrozen water. Pore ice can melt under external effects, i.e., mechanical loading [25,84], where films of unfrozen water on mineral particles and ice crystals become thicker. In this case, frozen sediments behave like ductile material, with their mechanical properties approaching those of unfrozen rocks. Frozen ground can resist brief (even strong) impact but undergoes strain and creep under prolonged, increasing loads. Creep shows up as increasing plasticity and large strain following relatively small but long-lasting loading.

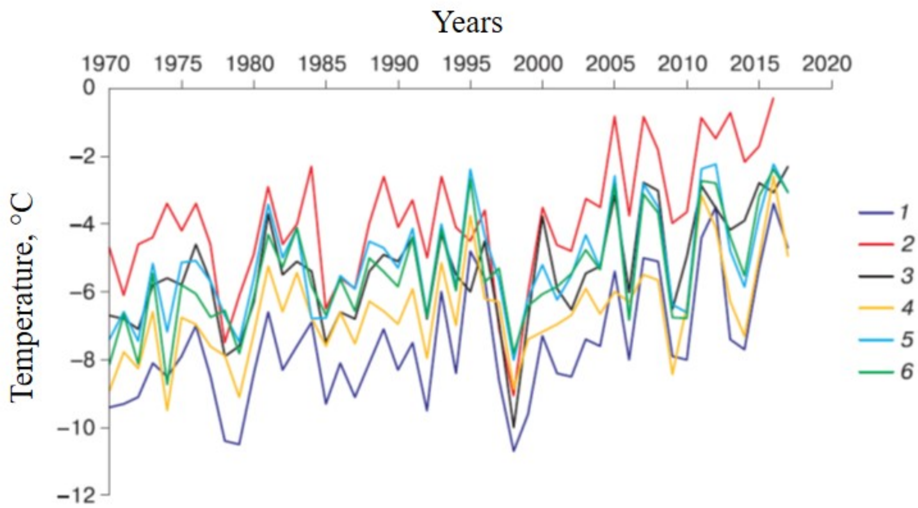
Additionally, in some cases, it is assumed that the existing highly mineralized intrapermafrost waters (cryopegs) are desalting via newly formed fresh waters that have arisen with an increase in the temperature of the ice-rich permafrost. This will possibly occur in the case of a hydraulic connection between different horizons of thawing permafrost.

The permafrost of the western part of the Russian Arctic has been experiencing such an effect from global warming since the 1970s (Figure 5).

The long-term warming of air temperatures in the Arctic correlates with the gradual warming of shallow permafrost (Figure 6) and the related increase of unfrozen water content at depths attainable by heat waves. The process cannot be classified as thawing because the frozen sediments do not become fully unfrozen, and remain at negative temperatures, despite containing greater amounts of unfrozen pore water. However, the permafrost is actually degrading.



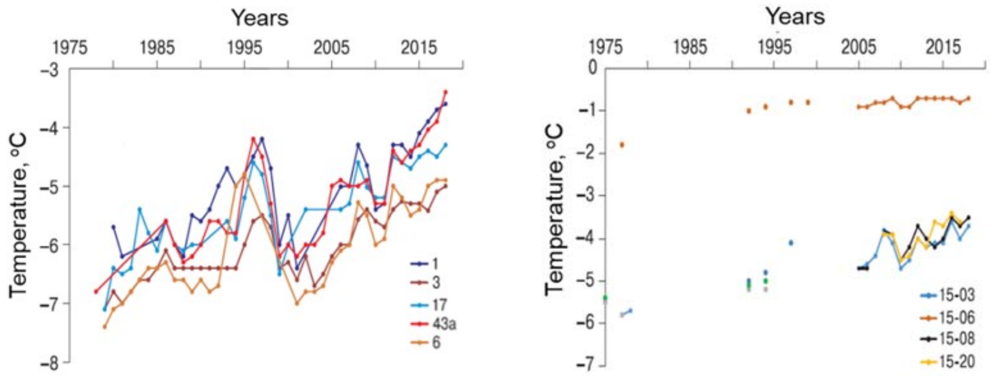
(**a**)



(**b**)

Figure 5. Geocryological station location in the western segment of the Russian Arctic (**a**) and time-dependent changes in air temperature at nearby meteorological stations (**b**): 1 = Marre–Sale; 2 = Cape Konstantinovsky; 3 = Vorkuta; 4 = Novy Urengoi; 5 = Nadym; 6 = Tarko–Sale, after Vasiliev et al. [82].

The temperature patterns of permafrost are mainly characterized by their mean annual values measured at the depth of zero annual amplitudes, which is commonly 10–15 m in northern West Siberia. The 2.8 °C warming from 1970 to 2018 led to a mean annual increase of 0.056 °C/yr for permafrost colder than −3 °C in this Arctic region, and 0.04 °C/yr in Russia's European north [85]. Thus, the low-temperature Arctic permafrost heats up faster and can persist longer than that further in the south, due to its larger cold resources, while the "southern" permafrost, with its subzero mean annual temperature, will degrade faster. Therefore, a smaller amount of heat is required to warm up the permafrost until it starts thawing. See some temperature logging data from West Siberia in Figure 6.



(**a**) (**b**)

Figure 6. Variations of mean annual permafrost temperatures at the depth of zero annual amplitudes, from temperature logs at Marre–Sale (**a**) and North Urengoi (**b**), zones of typical and southern tundra, respectively [85]. Numbers on legends indicate borehole numbers. Single temperature measurements (grey and green points) are made in unnumbered wells.

In general, permafrost warming is very slow, but its consequences will be felt even in areas that are free from anthropogenic effects, provided that the climate trends of recent decades persist for a long time into the future. Mean annual temperature trends of shallow permafrost can be predicted by modeling. For instance, a model for the Marre–Sale area (western Yamal Peninsula, northern West Siberia) predicts that changes in mean annual ground temperature may reach a depth of 50 m in the coming 50 years [86]. Specifically, the permafrost may become 1.3 °C and 23 °C warmer at depths of 20 m and 7–10 m, respectively, while its shallowest 5 m may warm up as much as above 0 °C.

However, temperature variations are controlled by the composition of permafrost, as well as the effect of deeply penetrating heat pulses. Our results, as well as published data [21,25,27,34,38,78,82], show that the amount of unfrozen pore water varies as a function of salinity and peat content: it is much greater in saline and peat-rich sediments (Figures 3 and 4) than in non-saline rocks poor in organic matter. This fact must be taken into account in the operation of existing engineering structures and in new projects.

Climate-induced heat waves are especially expected to influence shallow permafrost, the effect being controlled by grain size, total moisture/ice content, salinity, and peat percentage. These data can be used to predict the response of permafrost to warming at a certain depth. For instance, probable changes can be inferred from the depth profiles of permafrost properties (up to 100 m), as made for the area of the Bovanenkovo gas field on the Yamal Peninsula (Figure 7). The sampled 20 m of Yamal permafrost is composed mainly of clay lying over ground ice that encloses soil material and has a sand layer at the base. Below 20 m, there follows clay silt with massive lens-like cryostructures. The permafrost temperature below 5 m varies from −4.0 to −5.5 °C and reaches a minimum at 40–60 m. The total moisture of soil remains almost invariable (30–40%) below 40 m, but ranges from 30 to 130% at shallower depths due to the presence of ground ice lenses and layers (Figure 7).

Deposition and glaciation in the area have produced quite complex depth-dependent salinity and organic matter patterns. However, the history of permafrost is much less important for the predictions of water–ice phase changes than the actual depth profiles of its variables. The presence of saline and organic-rich layers in the upper 10–20 m of permafrost, where warming pulses will be able to penetrate within a few decades, may cause a considerable increase in the amount of unfrozen pore water. Meanwhile, as shown by experiments, this amount may increase even upon a minor warming of such permafrost, which may make it ductile. The situation may be worse in the presence of zones with high total moisture (ice content). In this case, special permafrost stabilization operations should be carried out during the design of engineering constructions (thermosiphons, thermal insulation covers, cryogels etc.).

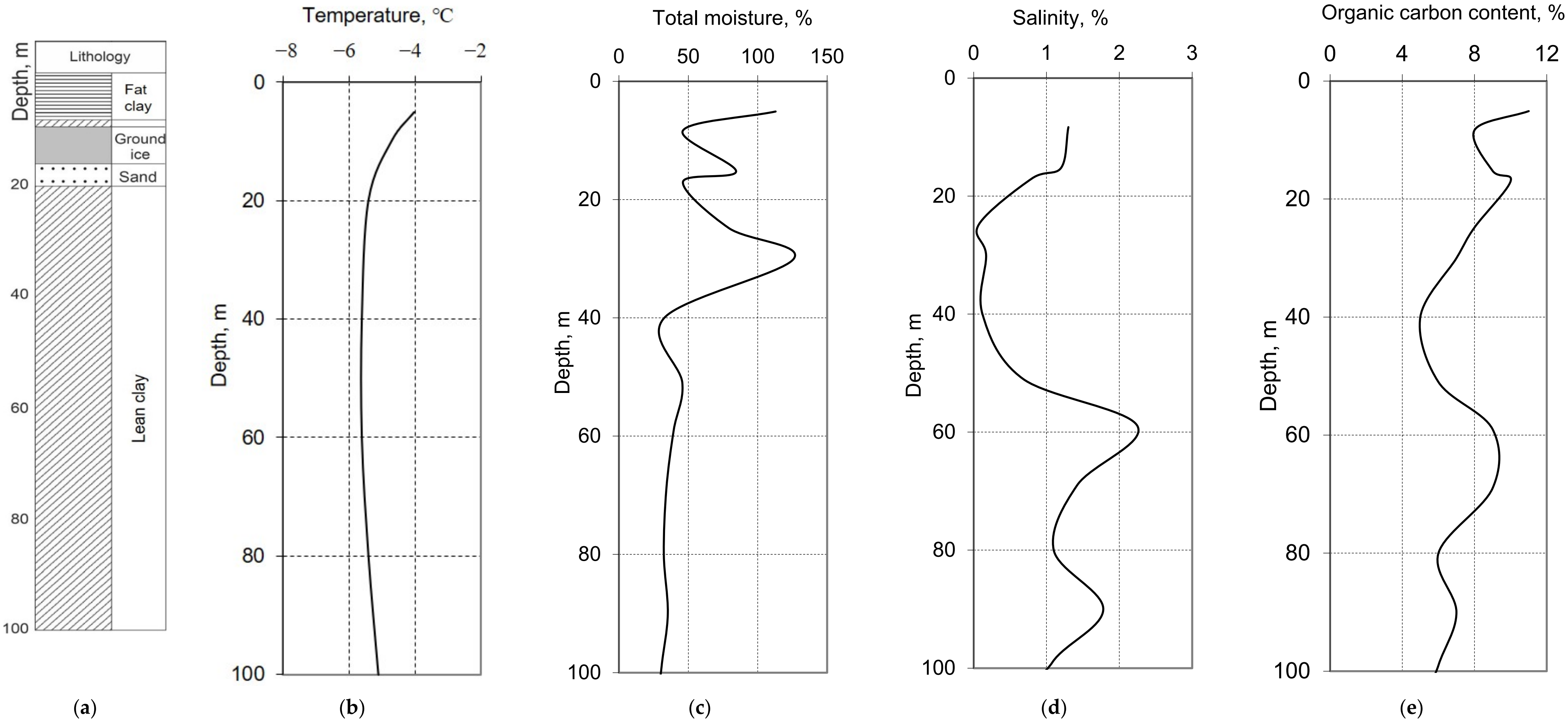


Figure 7. Depth profiles (to 100 m) of permafrost type (**a**), temperature (**b**), total moisture (**c**), salinity (**d**), and organic carbon content (**e**) estimated from log data for the area of the Bovanenkovo gas field in the Yamal Peninsula [87].

6. Conclusions

The design of engineering structures on permafrost and economic planning in Arctic areas require accounting for the trend of global warming in recent decades and the related slight warming of negative permafrost temperatures. The warming of permafrost may lead to changes in its properties due to its increasing content of unfrozen pore water, which may be unevenly distributed in the heterogeneous permafrost. Meanwhile, despite the heterogeneity, unfrozen water may exist across a large range of negative temperatures.

The liquid component of pore moisture has been a subject of research worldwide for about 100 years, but many aspects of the problem remain poorly understood, in particular the control of the permafrost phase composition. The suggested overview and classification of methods for estimating unfrozen water content in permafrost may be of interest to permafrost scientists. Such estimation can be performed successfully with thermodynamic calculations based on water potential measurements, which is a simple, fast, and high-performance tool.

The amount of unfrozen pore water is sensitive to the salinity and peat content of permafrost, as illustrated by data on the natural samples of saline and organic-rich soil from northern West Siberia. The revealed pore water and mean annual temperature variations in shallow permafrost from the Yamal Peninsula were used to predict possible phase changes in pore moisture in response to ongoing climate warming. These results can be used when designing engineering constructions and facility buildings for new gas fields in the north of Western Siberia (South Tambey, Salman, Kharasavey, etc.) to extend their service period and reduce geotechnical and environmental risk.

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