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Valery I Grebenets^{1,*}, Vasily A Tolmanov¹, Fedor D Iurov¹ and Pavel Y Groisman^{2,3} ¹ Moscow State University, Geographical Faculty, Department of Cryolithology and Glaciology, Moscow, Russia² Hydrology Science and Services Corp., Asheville, NC, United States of America³ North Carolina State University at NOAA National Centers for Environment Information, Asheville, NC, United States of America

* Author to whom any correspondence should be addressed.

E-mail: vgreb@inbox.ru**Keywords:** waste storage, climate change, arctic, permafrost, degradation, deformation of objects, disturbance of ecosystems**Abstract**

The specifics of solid waste storage in permafrost were analyzed. The main types of impact of the waste on the natural environment and frozen soils were determined as mechanical, physicochemical, load, and thermal. The research allowed us to define eight main types of waste storage in the permafrost zone, which were different both in terms of waste accumulation and in terms of their impact on the environment in general and the permafrost in particular. These were: industrial waste storage facilities (slag, sludge and tailing dumps, ash dumps); dumps of rock in sites of mining; household waste accumulators; dumps of wood processing waste in the centers of the timber industry; abandoned territories resulting from a decrease in the population of Northern settlements; storage areas for tanks with residues of fuels and lubricants; tank farms for storing petroleum products in settlements and cities of the North; storage areas for contaminated snow exported from built-up areas. Pollution of waste territories and destruction of many ecosystems as a result of waste storage were caused by use of imperfect technologies for the extraction and processing of raw materials, the 'legacy' of past years with disregard to the environmental conditions, the lack of special standards for the storage of garbage and by-product industrial materials, undeveloped methods of waste disposal in harsh climatic conditions.

1. Introduction

The problem of storing solid waste in cryolithozone is especially acute. It is associated with the harsh climatic conditions and the presence of permafrost. Currently, millions of cubic meters of industrial waste and waste rock are stored on the earth surface or fenced off with dams only in mining areas (Russia, China, Canada, etc), and there are no exact estimates of their volume. Serious problems are associated with deposits of wood processing waste, garbage dumps, areas for placing barrels with fuels and lubricants. The issue of waste disposal is especially relevant in the context of climate warming trends that have been recorded in the Arctic region in recent decades. The negative impact of pollutants on permafrost and Northern ecosystems is aggravated by climatic changes and the growth of technogenic pressure. This problem is significantly complicated by two factors: The first is weak development of processing technologies, and the second is remoteness of the settlements and the

production sites of the Far North from the regions where economically rational and technological waste disposal or recycling are possible. The objective of the study was to assess the effect of solid pollutants of different composition and the type of storage on permafrost. In this paper, we report on the first step of our research which resulted in the classification of waste that was based on the standpoint of its genesis with its impact on permafrost accounted for.

2. Overview of the problem

The current annual accumulation of waste in the world was estimated as 11 000 million tons per year (Song *et al* 2015). Work is underway to reduce the amount of waste and improve methods for its processing and reuse in various countries. Composting organic residues and incineration for thermal energy and heating are key ways to reduce the amount of landfilled waste that is not directly recyclable (Cheng and Hu 2010, Li *et al* 2020). The use of waste

as fuel is already widely implemented in a number of countries, including several states of the USA, despite the debate that it rises (Themelis and Millrath 2004). These methods are often not economically justified (due to small population of the territory and poorly developed infrastructure) or are complicated due to climatic features in areas where permafrost is spread. For example, household waste is delivered to landfills in a condition that is already partially frozen during transportation in the cold season. This makes it impossible to sort it afterwards. Composting waste or generating flammable gases from it is also difficult due to climatic and permafrost factors.

The rapid development of the resource potential of the Arctic region leads to the formation of huge amounts of pollutants in the permafrost zone. The amount of polluting industrial waste storages reached 340 in 2014 in Russia. Its elimination can cost at least 6000 million U.S. dollars (Khaustov and Redina 2018). 7266 million tons of waste was generated in Russia in 2018 according to official data, and only 3800 million tons were utilized. Methods for handling industrial waste in the Arctic zone are under development (Lipina *et al* 2017, Tsukerman and Ivanov 2020). However, there is still no coherent concept about how to reduce their negative impact on the Arctic environment and permafrost.

3. Methods

Field studies of the problems of waste accumulation and their negative impact on the environment were carried out by the authors at a number of points in the permafrost zone of Russia (Norilsk industrial area, Vorkuta industrial cluster, city of Igarka, settlements in the lower reaches of the Ob' river, national villages of Taimyr, etc). Field observations included an assessment of the area of litter and the type of waste, in many cases—sampling for chemical analyzes, thermometry, and mapping of hazardous processes. Analysis of literature, available data from ecological funds and remote sensing data made it possible to expand the geography of study. Drilling probes were taken to study the geochemical composition of the waters of the active layer in two case-study regions of Taimyr: the Ust'-Port settlement, where the anthropogenic influence is minimal, and the Norilsk industrial region (NPR), with the maximal technological impact of mining and metallurgical facilities. The probes were taken from the soils of the active layer and from the underlying permafrost strata. Laboratory studies were carried out in Norilsk and, partly at the University of Wageningen (Netherlands) and included the determination of the granulometric and geochemical composition of the sediments. Special emphasis was placed on the study of the readily soluble salts, as well as the heavy metals content. Modeling methods were used to assess the change in

the strength characteristics of permafrost foundations under the thermal and mechanical impact of waste deposited on the land surface.

4. Results and discussion

The active reclamation of the cryolithozone leads to an excessive accumulation of pollutants in fairly large areas. Water streams, wind activity and mechanical movement of excavated rocks contribute to ingress of pollutants, many of which contain heavy metals or radioactive materials. The problem of storage of solid waste is exacerbated by the fragility of ecosystems, the impermeable properties of frozen rocks and the development of destructive cryogenic processes in the permafrost zone. Large differences have been recognized for the settlements in the permafrost regions, both in natural (climate, state of permafrost, hydrological and hydrogeological features, etc) and in anthropogenic factors: population size, construction methods, methods of operating facilities, type of economic development, etc (Yoshikawa 2013). There are a number of very large (several hundred thousand people) settlements in the territory of the Russian Arctic region, that are the centers of the local industry. The amount of waste generated in such cities is incomparably greater than in small settlements in Greenland, northern Canada, Alaska, etc. The situation is aggravated by the climate warming trends (Pavlov 2008), which are especially important for the regions where several thousand million cubic meters of waste from mining and processing of ores and coal are stored in preserved (frozen) state, and where the trends towards an increase in air temperature over the past 30 years are 0.8 °C–1.4 °C (IPCC 2014). It should be noted that the rate of the air temperature increase in Siberia is higher than the average value for the northern hemisphere (+0.77 °C) and for the Arctic as a whole (+1.28 °C). The trend of surface air temperature change in Western Siberia is +1.39 °C (Groisman *et al* 2013).

The penetration of pollutants into the soil strata is largely correlated with the nature of the permafrost spread over the area. In this respect, the permafrost zone is divided into four main types: continuous, discontinuous, sporadic and isolated patches (Brown *et al* 1997).

In general, the impact of solid waste on the environment in the permafrost zone can be divided into the following types: (a) mechanical—the accumulation of material and changes in the relief and drainage conditions; (b) physicochemical—leading to the pollution of soils, surface and ground waters by the waste itself and by the products of its decay; (c) load—an increase in pressure on soil foundations; (d) thermal—causing warming and destruction of permafrost soils, activation of dangerous cryogenic processes.



Figure 1. Lebyazhye tailing dump, north-western outskirts of Norilsk. Photograph by A N Topoleva. Reproduced with permission.

The studies made it possible to identify eight main types of waste storage in the permafrost zone, associated with a certain nature of their accumulation:

4.1. Industrial waste storage

A special block of problems with this waste is related to the organization on the land surface of the slag-sludge-tailing dumps, ash dumps, where production waste is dumped in the form of a warm watered suspension, hot ash or in a molten state. In the permafrost zone, large systems of such type are located in the Norilsk region, Valkumey, Kular, Mirny, Longyearbyen (Spitsbergen) and other mining areas. The problem of creating tailing dumps affects not only the lowland regions of the permafrost, but also the more southern mountainous areas with glaciers and permafrost. For example, on the territory of the Central Tien Shan, there is a large tailing dump of the Kumtor mine. Its volumes, as of 2017, are estimated at 84 million m³ (Torgoev 2018). The sedimentation tanks for drilling fluids, which are widespread in the oil and gas producing regions of the Arctic: Western Siberia, Alaska and the North of Canada, can also be attributed to this type of waste storage. The material from tailings and other similar facilities is chemically highly aggressive (Danilov *et al* 2008) and has a colossal physicochemical impact on the environment. After storage, slag and sludge are subject to wind dispersal, which significantly increases the area of contamination. For permafrost soils, the danger is, first of all, in the thermal effect of production wastes supplied to storage sites at high temperatures, which leads to the degradation of frozen rocks (Grebenets 2012). This type of solid waste storage is widely represented in the NPR, where, at a distance of 15–20 km from the city of Norilsk, about 31 km² are occupied by tailing dumps, 2.2 km²—by slag dumps, and 5.1 km²—by sedimentation tanks for metal-containing raw materials. Tailings dump

No. 1 of the NPR (now mothballed) has accumulated 432 million tons of ‘tailings’ during its operation. The operating Lebyazhye tailing dump (No. 2) is designed for 168 million m³ of the material (Savchenko 1998). These objects are characterized by extremely high content of various chemicals. The content of precious and rare earth metals in tailings waste is 0.7–1.6 mg t⁻¹ for platinum and palladium, 0.15 g t⁻¹ for rhodium, 0.027 g t⁻¹ for iridium, and for copper and nickel up to 0.5% of dry matter weight (Tarasenko and Kirienko 1999). Thus, sampling from the dam of the Lebyazhye tailing dump (figure 1) showed a significant excess of the concentrations of metal ions. The content of sulfate ions here was 15 682 mg l⁻¹, while in tundra, 60 km from the city, the concentration of sulfate ions in the seasonally thawed layer was only 220 mg l⁻¹ (Grebenets 1998). It is characteristic that repeated attempts to form a soil and vegetation cover (due to the harsh climate and aggressive environment) at experimental sites in the Norilsk region did not lead to success. Experiments on silicatization or cementation of the surface at the test sites were also unsuccessful: frost cracking destroyed the artificially created protective crust. A serious problem is also the fact that such sedimentation tanks are fenced with dams with impermeable cores from the frozen soil. With the intensification of technogenesis and trends towards climate warming, anti-filtration curtains are being destroyed, soluble salts of sulfates, chlorides, carbonates, as well as inactive compounds of heavy metals enter tundra ecosystems, river basins, and ultimately into the ocean (Grebenets 2007). Field observations have shown that after 3–5 years of permafrost thaw under these dumps the polluted runoffs penetrate into subpermafrost groundwater. In the adjacent territories, vegetation was suppressed or killed completely, the protective role of the soil and vegetation cover for permafrost was minimized. At the same time, the depth of seasonal thawing increased, which

affected underground ice in areas close to the surface. This leads to the development of thermokarst and thermal corrosion.

4.2. Overburden in mining areas

The storage of gob as dumps in the permafrost zone occurs quite often. They are accompanying development of coal deposits (Neryungri, Vorkuta, Longyearbyen, etc), extraction of copper, nickel, gold, tin and other minerals (NPR, city Apatity, enterprises of the Magadan region, Chita region, north-east of Mongolia, etc).

In the conditions of permafrost existence, the formation of solid dumps has its own specifics. Storage of material on slopes leads to activation of solifluction, landslides, etc. Large masses of classic material in a cold climate begin to actively freeze through, which is due to the penetration of cold air into the 'porous' body of the dump in winter. For example, studies at the dumps of the Diavik mine (Canada) showed that over nine years the temperature of the strata of the dump at the study site dropped by 5 °C (Pham *et al* 2008). In addition, large masses of clastic material in combination with low temperatures can lead to the formation of technogenic rock glaciers (TCG), which was the case of the Rudnaya NPR. The clastic material that formed the basis for the emergence of the TCG was material from the Bear Creek open pit mine. The storage of solid material on the slopes of the mountain was carried out for 25 years and was completed in 1984, the volume of the material was about 65 million m³ with a total weight of about 110 million tons. The landfilling took place on a slope 12°–15°, the height of the dump was 100–120 m, and the final slope angle was 30°–36° (Grebenets and Kerimov 1998).

The beginning of the TCG movement down the slope in 1993 was caused by the change in permafrost conditions. In 1945, the temperatures of the slope soils at the level of zero annual fluctuations (at a depth of 8–10 m) were from –5 °C to –7 °C, and by 1996 (according to measurements in three thermometric wells) the temperatures in the body of a stone glacier at the depth of 20–50 m ranged from –2 °C to –0.5 °C (Grebenets and Kerimov 1998).

For the dump at Rudnaya, the change in permafrost conditions towards an increase in temperatures is catastrophic, since the dump body is highly saturated with ice, both that fell into the deposits of the clastic material during its layer-by-layer storage, and that formed during the inflow of water after burial. Changes in permafrost conditions lead to a decrease in the adhesion forces of ice-soil particles due to freezing and makes the TCG body more plastic and mobile. In addition, an increase in temperatures leads to a deterioration in the strength properties of the ice-loamy base of the dump (Grebenets 1998, Grebenets *et al* 2019).

There are at least three other large TCGs in Eurasia (Gorbunov and Gorbunova 2010). The Kola technogenic glacier, located in the Khibiny Mountains on the slope of Rasvumchorr, the material for which was the waste rock dumps from a quarry. The Kumtor TCG on the Ak-Schyrak ridge, formed from the dumps of the Kumtor gold mining, which is at the stage of active movement. The TCG at the Kubaka field in the Kolyma Highlands, which is at the stage of formation and has not yet undergone significant deformations. However, the predictive model shows that after 80–100 years, the dump body will begin to actively deform and the speed of the TCG along the slope will reach 0.5 m yr^{–1} (Galanin *et al* 2006).

Waste dumps in coal mining areas are characterized by oxidation of coal fragments, which leads to an increase in temperature. Thus, studies at one of the dumps of a coal mine in the vicinity of Longyearbyen showed that at a depth below 5 m in the body of the dump there are stable positive temperatures (about 4.5 °C); only the upper 2–3 m are subject to freezing. Recorded trends towards an increase in average annual air temperatures can accelerate the oxidation process of coal by 10%–30% (Hollesen *et al* 2009).

4.3. Municipal solid waste dumps near settlements

Storage of municipal solid waste (MSW) at disposal dumps (figure 2)—household or construction waste, plastic, scrap metal, etc—are the most common and accompany all the settlements and sites. In addition to changing landscapes due to the filling of large areas with waste, solid waste landfills can have a negative physicochemical impact on the environment due to the discharge of toxic materials (mercury lamps, lead-acid batteries, aerosol containers, etc). When these materials, without waterproof coatings, come into contact with natural soils, their ingress into groundwater and water bodies occurs.

For the permafrost zone such wastes are also dangerous due to the thermal effect during the decomposition of household waste (degradation of permafrost soils under landfills, activation of cryogenic processes). In addition, the heat release from waste does not allow the creation of completely frozen landfills, where it would be possible to reliably conserve pollutants and prevent them from emitting into the environment. Currently, in Alaska, there is an experience of creating landfills for solid waste using frozen barriers around the perimeter and in the bottom, designed to 'encapsulate' non-freezing waste (Magee and Rice 2002). However, in most cases the storage of solid waste is carried out without the use of such measures, and the removal of garbage is economically inexpedient. A similar situation takes place, for example, on the Tibetan Plateau (Jianguo *et al* 2009). In Russia until 2010, landfills for storage of solid waste were created without proper planning and relevant regulatory documentation (Maslennikov 2017). The 'Comprehensive



Figure 2. Solid waste dump in the area of Norilsk. Photograph by A N Topoleva. Reproduced with permission.

Strategy for the Management of Solid Municipal (Household) Waste in the Russian Federation' has only been adopted since 2013. However, this document and the set of rules regulating the design and operation of solid waste landfills developed within the framework of the Concept (SP 320.1325800.2017) do not take into account the specifics of the permafrost zone.

A separate danger is posed by old solid waste landfills. Snow and ice contribute to their formation during the year-round dumping of waste. After the summer rains, the water transforms to ice in the landfills' body resulting in the waste dumps to be the ice-saturated heterogeneous stratum. After the completion of the operation of such landfills and end of burial of solid waste the construction of objects is often carried out on their surface with use of technogenic bedding from crushed stone or crushed metallurgical slag (in Norilsk, for example). Technogenic impacts and warming climate trends cause negative changes in artificial frozen grounds at such sites (e.g. Khantayskaya Street, Laureatov Street in Norilsk, etc). Most of the buildings here are deformed or destroyed.

4.4. Timber waste dumps

Large areas are occupied by heaps of sawdust, bark and other waste in centers of timber processing. For example, in the southeastern outskirts of the City of Igarka, the storage area of such waste (figure 3) stretches along the Yenisei in a strip of almost 5 km in length and up to 0.5 km in width. Rotting sawdust causes degradation of icy permafrost foundations. A particular danger is imposed by the emerging fires. Fires of wood processing waste in Igarka lasted for almost 2 months (July–August) in the dry summer of 2013. It should be noted that modern trends in climate change increase the risk of natural fires due to an increase in air temperatures, earlier melting of

snow cover and an increase in thunderstorm activity (Groisman *et al* 2007).

4.5. Abandoned and littered territories resulting from population decline in northern settlements

A rapid decline of the population in most cities of the Far North of Russia began in 1990s. It led to the decommissioning and gradual destruction of residential and industrial buildings and of entire villages. As a result of the gradual destruction of abandoned buildings, new waste storage sites are formed, including household waste. It is rather problematic to assess the impact of such landfills on permafrost foundations. It largely depends on the composition and specifics of waste deposition at each particular site, including the possibility of cooling rocks under the dumps due to the penetration of cold winter air into the body. Examples of such littered areas are the abandoned microdistricts and villages of Vorkuta (Oktyabrsky settlement (figure 4(C)), Rudnik microdistrict, Promyshlenniy settlement, etc), the territory of a timber processing plant in Igarka (figure 4(D)), on the outskirts in Norilsk (figures 4(A) and (B)), etc.

It should be noted that the area of such abandoned and littered territories can be comparable to the territories of functioning residential zones of cities and towns. For example, the residential area of Vorkuta (excluding settlements) occupies about 12.9 km², while, according to the field survey in August 2018, the area of abandoned built-up territories (Yur-Shor, Promyshlenniy, Mulda, Oktyabrsky, Ayach-Yaga, etc) is about 7.7 km² (that is, almost 60% of the 'acting' residential area).

Among the waste stored at the territories of the abandoned settlements and industrial areas, there is a fairly large proportion of scrap metal of various origins. The largest share of metal amongst the waste



Figure 3. Dump of MSW with timber waste from timber processing factory in Igarka.



Figure 4. Examples of littered territories with abandoned and crumbling buildings: (A) and (B)—Norilsk. Photograph by A N Topoleva. Reproduced with permission. (C)—Vorkuta. Photograph by E I Bashkova. Reproduced with permission. (D)—Igarka. Photograph by A N Topoleva. Reproduced with permission.

is observed at the territory of former industrial sites: ports (there are even entire ‘ship graveyards’), mining enterprises (for example, closed coal mines in the Vorkuta region, the ‘Kularzoloto’ plant in Yakutia, a number of mining and processing plants on the Chukotka Peninsula), geological exploration bases, and military bases. There is a large amount of equipment, such as old cars that are not taken out for recycling due to the lack of recycling facilities in these regions, as well as extremely high transportation costs to industrial centers.

4.6. Dumps of fuel drums with residues of fuels and lubricants

There is a specific form of waste accumulation in the regions of the Far North—barrels with residues of fuels and lubricants (figure 5) at the sites of acting and abandoned airfields, transshipment points of the Northern Sea Route, military facilities and polar stations (Grebenets *et al* 2018). There are more than 70 large areas with such drums in the Russian Arctic alone (Golubchikov and Maslennikov 2017). The number of abandoned drums containing fuel, oils



Figure 5. Empty barrels on the shore in the Marre-Sale region, Western Yamal. Photograph by M Golubchikov. Reproduced with permission.



Figure 6. Cracking of the concrete blind area of the tank. Photograph by F D Yurov. Reproduced with permission.

and other technical fluids is estimated as 12 million. Drums are also dumped in the Canadian Arctic and Alaska (AMAP 2009). Typically, the environment is polluted directly by the barrels, as well as by fuel, oils, paint or varnish liquids flowing out of corrode and collapsing barrels. For example, 60 pollution sites were identified on the Franz Josef Land Archipelago, where 2800 m³ of aviation fuel, 1671 m³ of diesel fuel, 3169 m³ of oils and more than 20 000 tons of ferrous scrap were stored (Shchegolev 2015). Spills of fuel and lubricants have a negative impact on the state of permafrost due to changes in their thermophysical properties and the destruction of vegetation that performs a protective function.

4.7. Oil tank farms in settlements and cities of the North

There are storage sites for oil products that are necessary for the operation of boiler-houses, power plants and equipment in many settlements of the permafrost zone. Investigations of the current state of large oil tank farms were carried out in the North of Western Siberia. Numerous deformations are revealed that are very typical for such systems: cracks in the concrete foundations (figure 6), numerous tilts of tanks with fuels and lubricants, failures of coatings in adjoining areas, individual thermokarst subsidence, uneven frost heave of soils and buckling of foundations. Areas were identified where the most negative consequences

for the state of the tanks are confined: (a) in the wind shadow of the reservoirs—there is annual accumulation of snow, leading to warming of frozen soils; (b) in areas where there were streams and runoff troughs before the development; and (c) in areas where thermokarst, thermal erosion and slope cryogenic processes develop near the storage sites for oil products.

Oil products leak out as a result of the operation and deformation of the tanks. When the products percolate the frozen rocks, negative changes in frozen soils are observed in the base of reservoirs: the temperature of the onset of freezing decreases and the strength properties of soils deteriorate. This leads to a decrease in the reliability of the base of the tanks and the further development of deformations up to their destruction. An example of such an emergency is the spill of diesel fuel from a tank at the site of the Nadezhda Metallurgical Plant in the NDP on 29 May 2020. About 21 000 tons of diesel fuel were released into the environment as the result of this accident (BBC 2020). A number of reasons for failure of the tank, which was in operation for about 35 years, were revealed: The tank (42 m in diameter at the base) was supposed to bear on a solid rock foundation, but the ends of the piles did not reach the rock at the depth of 10–12 m but were frozen into the overlying strata. For many decades, the liquid in the reservoir (non-freezing diesel) was significantly cooling in winter, while in the warm season had cooling effect on the base soils, working as a ‘refrigerator’ and maintaining the permafrost state of the upper (above the rock) sedimentary rocks. However, the winter of 2019–2020 turned out to be abnormally warm for the entire period of the city’s existence (since 1933). For the first time the average monthly air temperatures were recorded were positive in May (+4 °C), it was the warmest January (−19.3 °C) and February (−15.6 °C). The average long-term temperature of the winter months (from October to April) in Norilsk was −20.5 °C according to the Norilsk Meteorological Laboratory. However, the average temperature of these months in 2019–2020 was only −14.2 °C. In fact, only 70% of the cold storage capacity was achieved and the storage device could not act as a usual ‘refrigerator’. The winter was extremely snowy. In the wind shadow of the container (relative to the southwest wind directions prevailing in the winter season), the snow drift of more than 3 m high was formed and prevented cold propagation to the ground. There was partial thawing of the ground and an increase in temperature in the frozen zone, which quickly and very significantly reduced the bearing capacity of the frozen-in piles. The tank filled with diesel fuel began to settle sharply in the northeast direction, and this reinforced by frost destruction for 35 years caused the concrete slab of the tank’s base to split, destroying the tank with diesel fuel itself.

Even without major accidents, the tank farms are a source of oil pollution. Traces of fuels and

lubricants were found in the drainage systems at the surveyed sites, through which rainwater and spring snowmelt are removed from the territories of the tank farms. Concrete structures are severely damaged as a result of frost destruction, uneven settlement and heaving of soils, which does not allow them to be considered sufficiently hermetic.

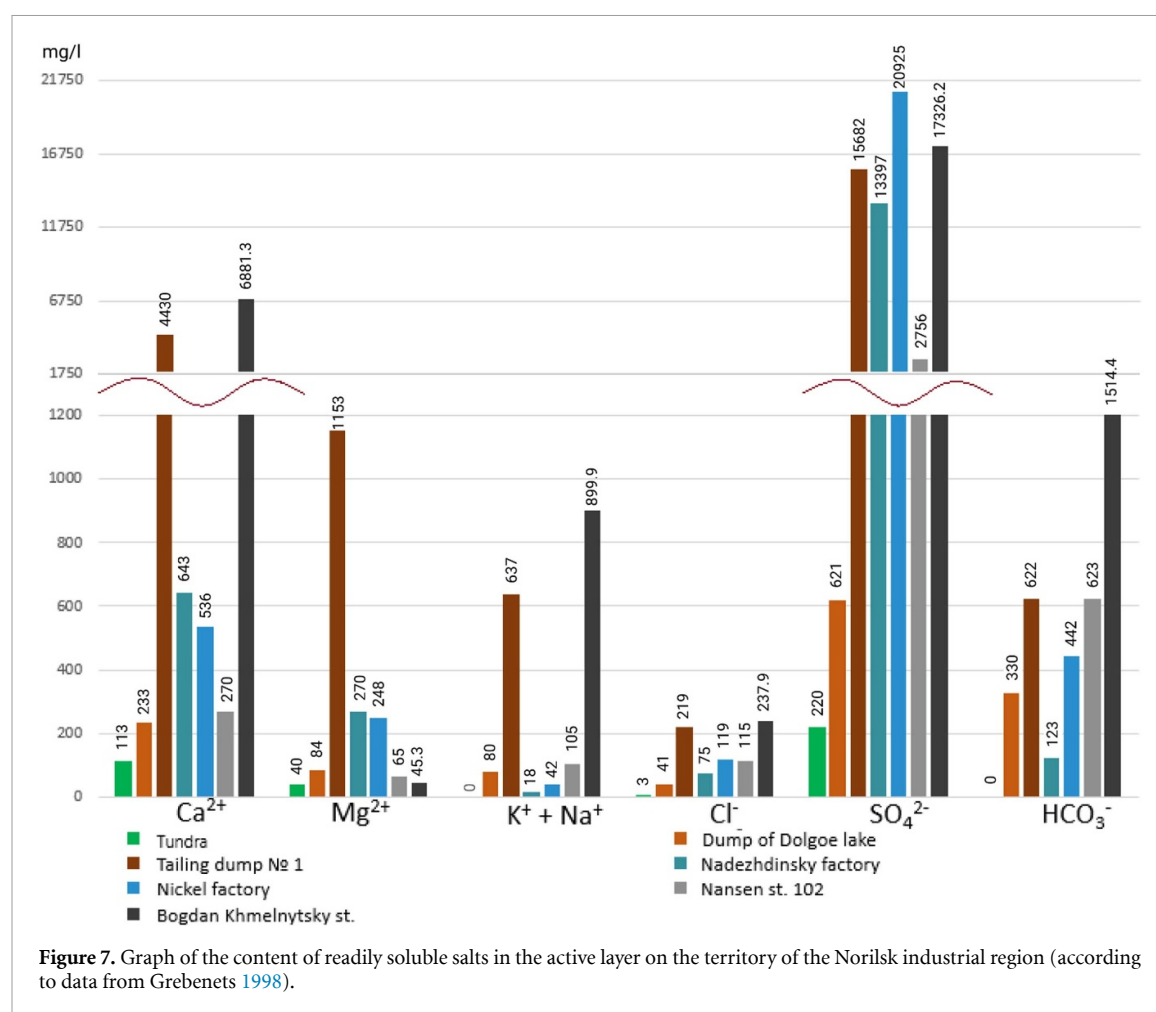
4.8. Snow disposal sites for snow and snow-dirt sludge

Mechanized snow removal from the urban areas is carried out annually in large settlements of the Arctic. The key difference between the settlements of the Arctic zone from the cities outside the permafrost zone is the absence of special installations for melting of the removed snow. Snow in these settlements is transported from the residential areas to landfills. Here, it is stored and melted in the spring-summer period naturally. Along with snow such landfills receive a significant amount of pollutants: household waste (including plastic); chemical reagents used for street de-icing; fuels and lubricants falling from cars on the roadway, etc. As a result, pollution centers are formed at the snow storage landfills, and some of the pollutants enter the rivers along with the spring snowmelt. It should be noted that in a number of cities, waste (slag) of metallurgical or mining enterprises is used as the anti-icing bedding on roads and sidewalks, which also gets into the storage area during snow removal. In these areas, the permafrost temperature rises (up to the formation of blind taliks), nivation, thermal erosion and solifluction on the slopes are noticeably activating.

5. Large-scale anthropogenic pollution of the environment in the Arctic

The geoecological and geotechnical situation in the industrial centers of the permafrost zone is complicated by the problem of the penetration of various pollutants into the seasonally thawed layer and their subsequent penetration into the frozen strata, into which the foundations are frozen. Our investigations show that the content of readily soluble salts within the tundra landscapes is many times less than in the industrially developed territories (figure 7). It should be added that these readily soluble salts are aggressive for the materials of underground structures.

It is typical that the content of hazardous low-mobile salts of heavy metals in the active layer is many times higher than their amount in the permafrost soils of the underlying rocks. For example, the copper content in the seasonally thawed layer on the territory of Norilsk reaches 2.6 mg l^{−1}, while the background values outside the city are less than 0.1 mg l^{−1}. The nickel content within the active layer is 0.4–0.5 mg l^{−1}, while in the frozen soils the concentration of nickel is from 0.017 to 0.019 mg l^{−1} (at depths of 21.3 and 6.5 m respectively). The content of cobalt in



the body of frozen soils is 0.009–0.014 mg l⁻¹, and in soils of the active layer it reaches 0.15–0.27 mg l⁻¹.

As a result of acid rains the discharge of industrial and household waste, as well as the filtration of the suprapermfrost waters of the seasonally thawed layer, surface waters are polluted in the zone of influence of the industrial centers of the cryolithozone with salts of heavy metals, sulfates, nitrates, etc.

The impact of stored and recently accumulated solid waste on permafrost is one of the most acute problem in assessing the permafrost-ecological and geotechnical stability in the permafrost zone.

6. Conclusions

The pollution of vast territories of the permafrost zone with the solid household and industrial waste is currently a serious and persistent problem. The use of imperfect technologies for the extraction and processing of raw materials, the 'legacy' of past years with disregard to the ecological situation, the lack of special standards for the storage of waste and by-product industrial materials, undeveloped methods of waste disposal in harsh climatic conditions require special study and a necessity to reach new levels of development of the northern territories.

The results presented above provide a pilot idea of the complex and urgent problem of waste disposal in the Arctic. They suggest the need to attract a wide range of specialists to deepening scientific research and development of effective methods to minimize damage from pollution in the Arctic, including improvement of modern technologies and creation of national standards for waste management in the permafrost zone. It is necessary to implement interdisciplinary projects on the nature of waste accumulation to study the types of settlement and methods of their economic development in certain regions of the permafrost zone that account for the waste problem. An in-depth study of the impact of different types of waste on soils of different composition, moisture content, ice content and temperature are still required. These studies should account for physicochemical transformations of waste in specific landscape-permafrost conditions of the Far North. In this work, the classification of wastes is carried out according to their genesis, type of storage and peculiarities of impact on permafrost. Eight main types of waste accumulation are identified and their main characteristics, distribution areas, and hazards associated with the lack of systematic work on their elimination/recycling. These types include:

- Industrial waste storage facilities in industrial centers and near mining sites (slag, sludge and tailing dumps, ash dumps, accumulators of drilling fluids), which have a powerful negative impact on permafrost due to heat generation and technogenic soil salinization. Under such objects, talik zones are formed and the permafrost thaws. In the adjacent territories, cryogenic processes (thermokarst and thermal erosion) are activated, being provoked by the degradation of the permafrost.
- Dumps of overburden in mining areas. The formation of dumps on the slopes provokes the development of slope technogenic stone glaciers. Dumps of coal-bearing rocks have a noticeable warming effect on the underlying frozen rocks due to the oxidation of coal in the body of the dump.
- Waste dumps located near settlements. Waste has a warming effect on the permafrost due to heat release from decomposing organic matter. Warming and technogenic salinization of soils leads to the formation of talik zones under landfills, activation of thermokarst and thermal erosion.
- Dumps of wood processing waste, which pose a danger to the permafrost due to the release of heat during their decomposition, as well as during fires in abnormally hot summer seasons. The abundant release of heat leads to the formation of talik zones and the activation of 'warm' cryogenic processes.
- Abandoned and littered territories that have arisen as a result of population decline in northern settlements. In such areas, the impact of waste on the permafrost varies greatly from the composition of the waste and the specifics of its storage.
- Dumps of barrels with remnants of fuels and lubricants, widespread in the areas of airfields, military facilities, polar stations and ports. Due to the leakage of the contents, technogenic salinization of frozen soils occurs, and their thermophysical properties change.
- Tank farms for the storage of petroleum products in the villages and cities of the North. The negative impact on the permafrost of such objects is determined, first of all, by the leakage of oil products and their penetration into the strata of frozen soils. In addition, the destruction of soil and vegetation leads to a change in the conditions of heat exchange and the activation of dangerous cryogenic processes: thermal erosion and thermokarst in the adjacent territories, frost heaving and frost cracking within the square of reservoirs.
- Areas for storing snow removed from built-up areas. Powerful snow plows have a warming effect on the underlying frozen soils, provoking the formation of talik zones. A large amount of pollutants contained in the stored snow leads to technogenic soil salinization and changes in their thermophysical characteristics.

The negative impacts of pollutants on permafrost are largely related to regional features, that is, with the zoning of permafrost, which requires additional research. The problems of environmental pollution in the permafrost zone were known from the beginning, but the cost of eliminating their consequences seemed unaffordable. Now, these consequences have reached crisis levels, pollutants that, in the past, were kept in reasonably stable frozen storage are more frequently released in the atmosphere and hydrosphere and create obstacles for the further sustainable development of the regions of the Russian North. But society as a whole has become richer and more technologically equipped with means of combating environmental pollution. Therefore, our work, documentation of the occurred and ongoing anthropogenic pollution of the permafrost zone, is the first step towards the systematic elimination of these pollution and the reclamation of territories and ecosystems exposed to the adverse effects of the initial period of industrial development of the northern territories of the country.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iD

Pavel Y Groisman  <https://orcid.org/0000-0001-6255-324X>

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