Waste in Greenland and its impact on human wellbeing under warming climatic conditions

Jutta Lauf, Kim Vetting, Cristian Ciulean, Reiner Zimmermann

Dr. Jutta Lauf, Research Fellow at the NATO Climate Change and Security Centre of Excellence, Montreal, Canada

LTC Kim Vetting, Subject Matter Expert at the Research, Analysis and Lessons Learned Branch, NATO Climate Change and Security Centre of Excellence, Montreal, Canada

LTC Cristian Ciulean Subject Matter Expert at the Research, Analysis and Lessons Learned Branch, NATO Climate Change and Security Centre of Excellence, Montreal, Canada

Dr. Reiner Zimmermann, Head of Research and Lessons Learned Division at the NATO Energy Security Centre of Excellence in Vilnius, Lithuania

Corresponding address: kim.vetting@ccascoe.org

Summary

This article examines how historic and ongoing waste in Greenland—generated by settlements, military installations, and extractive industries—becomes an increasing threat as Arctic warming thaws permafrost and ice, destabilising infrastructure and remobilising contaminants. It outlines Greenland's physical and socio-political context, explains how pollutants can be transported in a warming Arctic (especially via meltwater and changing hydrology), reviews major contaminant classes and health pathways, and highlights the high costs and practical difficulties of remediation in remote Arctic conditions.

- **Core risk mechanism:** Permafrost and ice were long treated as stable "containment" for dumps, fuel stores, and contaminated sites. Warming (Arctic amplification) is weakening this assumption by increasing thaw, erosion, and water connectivity, which can release and spread toxic substances.
- **Greenland-specific exposure routes:** Ingestion is emphasised as the main human intake pathway (drinking water and food). Limited sanitation and uneven drinking-water treatment in smaller communities increase vulnerability to microbiological contamination.
- **Legacy military pollution:** The paper highlights major Cold War/WWII legacies, including the 1968 Thule (Pituffik) B-52 crash dispersing radioactive materials and the abandoned Camp Century ice-sheet base containing diesel, PCBs, sewage, and radioactive waste that may be remobilised as melt and englacial flow patterns evolve.
- **Mining and industrial legacies:** Historic mines have left persistent heavy-metal pollution in some coastal systems; future mining expansion raises the risk of new contaminated sites that may outlast company liability periods.
- **Key contaminant groups:** Heavy metals (non-degradable, bioaccumulative), petroleum hydrocarbons (toxic; partly biodegradable), PCBs (persistent; mobile in fuels; hard to remediate), pathogens (indicator: coliform bacteria), asbestos

(inhalation hazard if fibres become airborne), and radionuclides (long-lived risk requiring containment).

- **Transport under warming:** Thaw-driven changes can increase leaching, surface runoff, wind transport of particles, and especially glacier/ice-sheet meltwater pathways (including englacial aquifers), potentially moving pollutants before surface exposure occurs.
- **Economic and security implications:** Contamination can damage human wellbeing and local livelihoods and may also affect operational security for military activities. The fisheries export sector is flagged as economically sensitive if contamination is detected by importing countries.
- **Remediation realities:** Cleanup is costly and logistically difficult in the Arctic; delayed remediation can shift costs to the public if responsible organisations cease to exist. The paper points to Canadian Arctic remediation protocols as a potential blueprint for standards, monitoring, and cleanup approaches.
- **Preferred strategy:** Prevent future pollution through robust legislation, monitoring, and financial assurance mechanisms (e.g., long-term cleanup funds), and remediate known sites early—before thaw-driven dispersal expands impacts and raises costs.

Introduction

For decades most municipal, military, industrial and mining facilities in the Arctic were built and maintained on permafrost soils. Many military bases in the High North and the Arctic regions of the North Atlantic and Arctic Oceans were established because of the Second World War or the subsequent Cold War period. The discovery of large oil and gas reserves along the Arctic coasts resulted in a boom of exploration activities from the 1960ties on. Also, many mining operations sprung up. All these activities led to an influx of people from abroad. Consequently, the indigenous people of the High North were increasingly influenced in their way of living and most changed their nomadic and self-sustaining lifestyle with a sedentary or semi-nomadic lifestyle, often employed part- or full time in settlements or military bases.[1] Recent geopolitical developments have revived the interest in the panarctic region. This led also to environmental concerns over reactivation of frozen remnants and recently produced waste and its influence on human livelihood and wellbeing in civilian settlements and military installations under warming climatic conditions.

This concentration of industrial and military activities and the modern lifestyle which is based on imports of machinery, fossil fuels and consumer goods caused and still causes the accumulation of substantial amounts of waste. During the decades before the environmental and climatic risk awareness was rising, it was assumed that the permafrost would serve as a permanent and stable platform and could function as long-term containment for solid and liquid wastes due to its properties as a hydrological barrier (**Figure 1**a). This widespread belief led to the accumulation of a large quantity and variety of hazardous or outright toxic substances. Nowadays, abandoned buildings and infrastructures, earth covered frozen waste dumps and mud sumps with drilling residues on permafrost soils can be found all over the Arctic. Even hydrologically closed lakes and basins were used as natural dumps and spreading substance across a large area for dilution was also a common practice.[2]

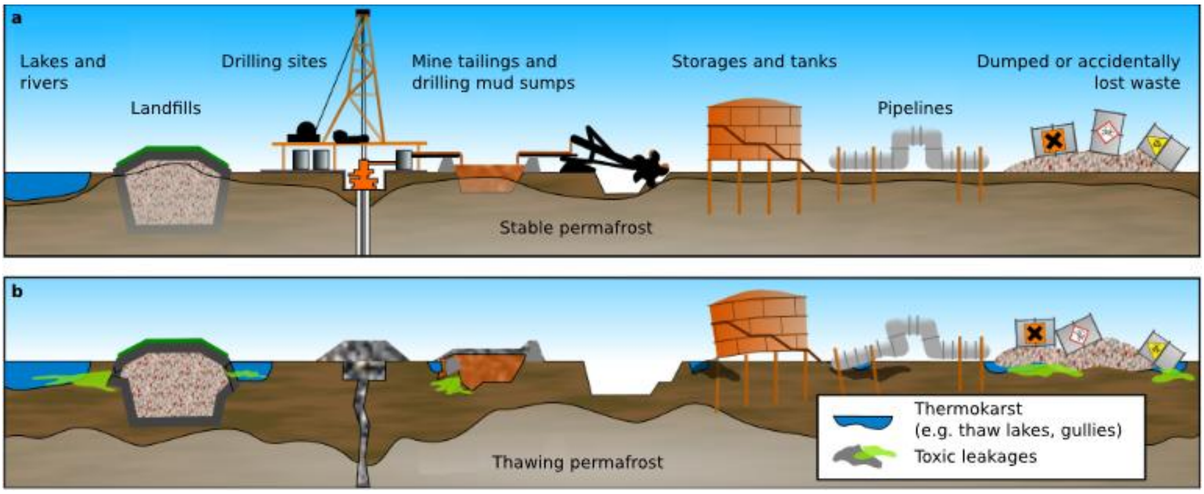

Figure 1. Impacts of thawing permafrost on above- and below-ground industrial infrastructure containing toxic substances or waste in the Arctic.
Past and present activities in the Arctic result in infrastructure construction and accumulation, storage or deposition of hazardous substances on permafrost soils (a). The warming and thawing of near surface permafrost unlocks frozen disposals sites and destabilizes infrastructure and containment structures (b). Furthermore, permafrost thaw intensifies thermo-hydrological erosion and increases the lateral flow of water fostering the dispersion of contaminants.[2]

In the Arctic, near-surface air temperatures are rising at rates at least two times faster than the rest of the globe, with latest data suggesting an up to four-fold faster warming [2,3]. By 2100 up to 65% of the Arctic's near-surface permafrost layers may have been thawed. It is assumed, that permafrost already loses substantial bearing capacity at temperatures close to zero degrees centigrade.[2,3]

The consequences of permafrost thaw are manyfold e.g. the destruction of road surfaces and airfields, collapse of load-bearing structures such as houses and storage tanks, destruction of gas, oil and water pipelines, disruption of the construction of new structures, destruction of natural barriers of landfills and toxic waste, reduction of accessibility and the changing of hydrological conditions (**Figure 1**b).[2,4] Permafrost thaw usually affects larger regions so that there is a risk of multiple contaminated sites leaking at the same time while the accessibility for mitigation and clean-up operations will become more difficult. By this time, the operating and liability period of most industrial and mining instalments has expired.[2,3]

In Greenland, most settlements and military bases were established on permafrost soils in coastal regions covered by sparse tundra vegetation. In exceptional cases, military bases were even built on glaciers or on ice sheets. Only a few structures were built on either unfrozen soils, founded below dug out permafrost soil or built on bedrock. After the end of the Cold War, numerous mining operations and military bases were either decommissioned or simply abandoned. This had negative economic and environmental consequences for the remaining local population. The Danish government made some efforts to clean up the waste deposits on abandoned military bases from their allies. However, climatic warming is now causing the thawing of permafrost and the ice shield, and this poses new challenges to the remaining "frozen waste deposits". The recent increase in naval and defence activities in the pan-Arctic region, the development of a tourist industry in Greenland and an expected increase of naval trade in the coming decades create new challenges for how historic waste deposits and new wastes should be dealt with based on how a clean and safe environment can be ensured in Greenland.

In this article the authors explore the natural setting of Greenland, the development of human activities which led to waste and contamination and the challenges that the current and future climatic changes pose for the environment, the people, and NATO military operational security in a rapidly changing environment and geopolitical situation.

Description of Greenland

Greenland is the world's largest island situated in the high North between the North Atlantic and the Arctic Oceans, mostly surrounded by deep seas reaching a depth of up to 5550 m. A notable exception is the submarine mountain ridge to the north-east no deeper than 180m which connects Greenland geographically with the North American continent. Greenland is separated from Canada's Ellesmere Island only by a distance of 26 km. The nearest European country is Iceland (320 km).[5]

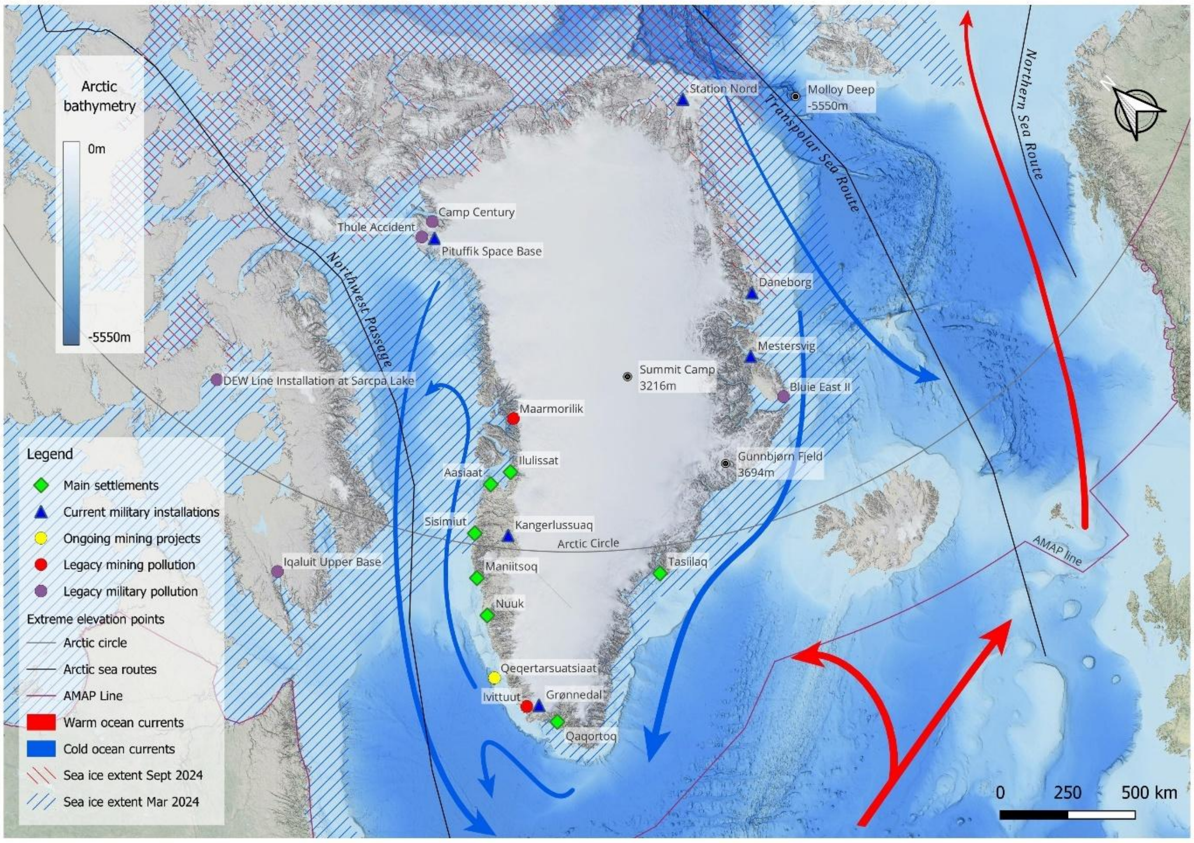

Figure 2. Map of Greenland with main civil settlements (green) in Greenland, legacy military pollution in Greenland and Canada (purple), legacy mining with pollution in Greenland (red) and ongoing mining projects in Greenland (yellow). The Arctic region as defined by the Arctic Monitoring & Assessment Program (see Box "Definition of the Arctic") is indicated by a yellow line and the Arctic Circle by a grey line. The Northwest-, Northeast- and Transpolar passages are shown in black. Red shaded stripes indicate the minimum and blue shaded stripes the maximum sea ice extend for 2024. Summit Camp (3216 m) marks the highest point on the ice sheet and Gunnbjorn Fjeld (3694 m) is the highest mountain peak. The deepest point in the surrounding ocean is Molloy Deep (5550 m).[6-8]

Greenland with the capital of Nuuk is formally associated with the Kingdom of Denmark. Since the self-rule agreement of 1979, enforced by the home-rule agreement of 2009[9], the population of Greenland can at any time take own responsibility of policy areas currently decided by the Danish Parliament in Copenhagen, ultimately also decide on its independence or political affiliation. Natural resources and waste management are competencies belonging to the

Greenlandic government in Nuuk, whereas security and foreign policy are determined in Copenhagen by the Danish Parliament. In 2019, and again in 2025, the political association with Denmark has been challenged by the United States President Donald Trump due to strategic interests of the USA. The possibility of a declaration of independence of Greenland and potential new affiliations continues to be a matter of internal political and international debates.

Box: Military relation between Denmark and the USA as a result of WW II

Greenland is a member of NATO through the Danish Kingdom. From 1973 until 1982 Greenland was member of the European Community (EC), the precursor of the European Union (EU). It left the EC in 1982 after successful departing negotiations. The EU remains the biggest foreign investor.

During the Second World War, when Denmark was occupied by German Forces, the exiled Danish Ambassador to the USA, Henrik Kauffman, signed on his own initiative and in the name of the Danish King a Defence agreement of Greenland with the USA.[10] This agreement authorising the United States to defend Greenland, was renewed in 1951, ensuring that the USA, within the NATO framework, is assisting Denmark in the defence of Greenland and has access everywhere in Greenland. This agreement is still in place, with modifications made in 2006 (Igaliku agreement), where Greenland for the first time was a co-signatory.

Following the 1941 Defence agreement, the USA immediately started creating several bases in Greenland, both for the purpose of defending critical mining infrastructure and to ensure the logistic lines and communication between North America and the warfighting troops in Europe. The first base and airport, called Bluie West 1, was built in Narsarsuag, and through the war and post war period a total of 14 military installations were build.

A notable network of military bases was a secret and nuclear-powered base built under the ice sheet in Greenland during the Cold War: Camp Century was supposed to have a nuclear strike capability against the Soviet Union. This camp was established in 1958 and abandoned again in 1965, because the constant movement of the surrounding ice sheet made such efforts too dangerous.

Indeed, most of the US bases are today abandoned, either because the critical mines which they were protecting are no longer operational, or because military airplanes no longer require a stop-over between Europe and the USA. Today, the US. Armed Forces are operating only one base in northwest Greenland, the Pittufik Space Station (formerly known as the Thule Airbase) ensuring early warning capability for missiles potentially fired over the north pole into mainland of the USA.

The Danish Armed Forces are operating throughout Greenland, either patrolling with dogs sled patrols (Sirius Patrol - in the Natural park to the north west), maintaining runways for supplies and emergency landing (Station Nord in the north), or are using former bases for operational and educational purposes, such as the former Bluie West 8 in Kangerlussuag, which serves as a base for the Danish Air surveillance and SAR activities in Greenland, as well as hosting the Arctic Basic Military education for the people of Greenland.

Greenland's population in 2023 was 56 000 people, of which 90% have indigenous and 10% Danish roots. Almost half of the population is concentrated in the capital Nuuk, following a political decision to move the population from smaller hamlets to cities and the capital, for health, education and economic development reasons. The population almost doubled between 1950 and 1980 by approx. 23 000 people[5,11] and stabilised at around the 56 000 ever since. Current predictions indicate a diminishing population of more than 15% towards 2025, primarily due to migration and lower fertility rates.[12] Life expectancy at birth in Greenland was 70.1 years in 2023 compared to 81.2 years in Denmark.[5]

The Gross Domestic Product (GDP) in Greenland in 2021 was \$2.750 x 10^9. It has risen from \$0.713 x 10^9 in 1970, in line with the population growth.[5,11] Greenland's economy is primarily based on fishing. Seafood is used for local consumption and exported either canned or frozen.

The export share of food products from 2010 onwards was always above 80%.[5] Since the enlargement of the air strip in Nuuk in 2024 and the planned establishment of more routine flights between Greenland, the USA and Denmark, export of fresh fish and sea food is expected to increase. Since the 1990s revenues from tourism have grown significantly. This sector is expected to grow with the enlargement of the Nuuk airport. The government, which receives substantial financial aid from Denmark employs nearly half of Greenland's labour force.[5,13]
Electricity production in Greenland ranged from 500 to 650 GWh between 2017 and 2022 with a share of hydropower varying between 75 and 86%. The remaining power is generated from fossil fuel.[14] Access of the population to electric power is 100% in Greenland.[15]
Depending on the definition used, Greenland belongs partly or completely to the Arctic (Figure 4).[16,17] The Arctic Monitoring & Assessment Program (AMAP) definition encompasses the geographical Arctic circle as well as regions, where similar weather conditions as above the Arctic circle are prevalent. Following the AMAP definition the whole of Greenland belongs to the Arctic This definition is used for practical reasons in this article.
The Greenland Ice Sheet covers more than 1.8 x 10^6 km^2 - over 80% of Greenland total land area. It has an average thickness of 1500 m, reaches a maximum of about 3000 m, and has some of the world's fastest moving glaciers which can move 30 m per day. It's coastal south western regions are mostly ice-free, while the east coast is dominated by highlands with mountain chains rising to 3700 m. Along large stretches of the northern and eastern coastline (total length 39 330 km) the Greenland ice sheet reaches the sea.[5] In the coastal waters of Greenland only the southwestern areas are ice-free all year around.
Average January temperatures range from −7 °C in the south to −34 °C in the north. Summer temperatures along the southwestern coast average about 7 °C during July, while the average in the far north is close to 4 °C. Greenland experiences about two months of arctic summer. Average annual precipitation decreases from more than 1900 mm in the south to about 50 mm in the north. Rapid weather changes from sunshine to blizzards are common. In general, the weather on the very sparsely populated east coast is harsher than on the west coast.[5]
The vegetation along the relatively mild and humid climate of the southwest coast consists of heathlands with dwarf shrubs and forest-like areas with birch and willow. Further east and north the vegetation cover becomes scarcer with herbs and grasses forming the arctic tundra and polar deserts dominated by lichens. The macrofauna comprises polar bears, reindeer, arctic foxes, musk ox, and snow hares on the coast while seals and whales are found in the adjacent waters. Cod, salmon, flounder, and halibut are important saltwater fish, and the island's rivers contain salmon and Arctic char.[5]
The GDP per capita in Greenland was approx. $49 100 in 2023 and in Denmark (including Greenland) it was $59 300 in 2022, which qualifies both as rich countries on a global scale.[11,18,19] In stark contrast to this high GDP, the environmental standards in Greenland are low. Safely managed sanitation services (defined as improved sanitation facilities that are not shared with other households and where excrements are safely disposed in situ or transported and treated off-site) are not available to any households in Greenland in 2022 (i.e. 0% availability).[20,21] This situation is mainly a result of the fact that excrements and wastewater of any kind are often disposed of into the environment without any treatment and may be washed back by the tides and the currents to the coasts.[21] Also, access to safe drinking water is not secured in many communities (**Figure 3**). In small communities (< 200 inhabitants) water is often sourced from rivers without advanced water treatment systems.[22] In comparison, in Denmark 98.8% of households have access to safely managed sanitation services.[20]

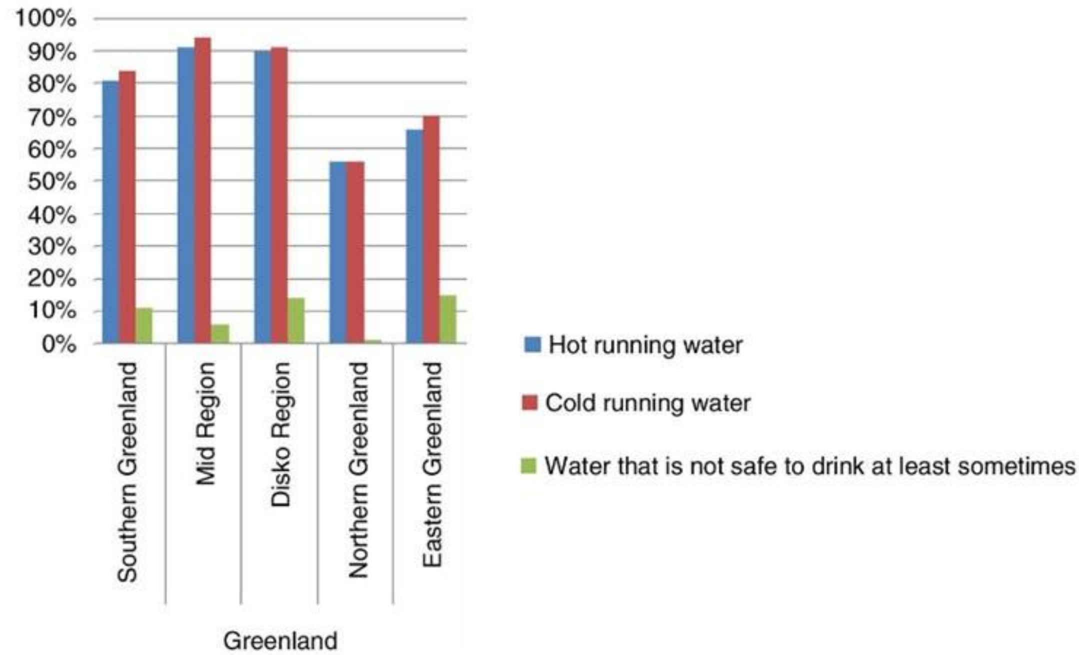

Figure 3. Residential water service in Greenland by regions (2001-2006). Modified after Bressler and Hennessy (2018).[22]

The safe disposal of any waste has long been neglected in Greenland, as the population was small, the land vast and the environmental conditions for maintaining infrastructure challenging.[21] However, the emerging threat of (re-)mobilization of hazardous waste as a consequence of climatic warming demand a sustainable approach to mitigate these risks.

Definitions of the Arctic

The Arctic can be defined geographically, climatically, botanically and politically, depending on the emphasis of the topics to be discussed.

The **Arctic Circle** (black line in Figure 4) as a geographic definition is the oldest. At and above the latitude of 66° 33'N the sun does not set for at least one full day during the summer solstice (21st of June) while in winter for the same amount of time the sun does not rise above the horizon. For simplification, the Arctic Circle is rounded to 66°N.[16,17]

Often the Arctic Circle definition is enlarged to 60°N as this allows the inclusion of regions which roughly marks the line of Arctic tundra. Policymakers, researchers, and politicians sometimes use 60° as a commonly accepted definition.[16,17]

The **10°C Isotherm Line indicates** where the mean temperature in July does not rise above 10°C further north (dotted black line in Figure 4). This line will shift northwards as the Arctic warms, being an indicator of climate changes. The 10°C isotherm is often used as a threshold for tree growth but does not entirely match with the actual treeline, especially in Siberia.[16,17]

The arctic **Tree Line** (dotted green line in Figure 4) is defined as the most northward location where individual trees exist. North of that line, the climatic conditions are too harsh for trees growth. Low shrubs do survive in the tundra north of the tree line and may form a plant cover of up to a foot in height. As in the case of the 10°C Isotherm line, the treeline will shift northwards as the climate continues to warm.[16,17]

The **High Arctic** and the **Subarctic are** regional definitions based on the prevalent vegetation on land (solid and thin green line in Figure 4).[16,17]

Based on oceanographic characteristics, the **Marine Boundary of the Arct**ic is situated along the convergence of cool, less saline surface waters from the Arctic Ocean and warmer, saltier waters from oceans to the south (blue line in Figure 4). This line is expected to shift northwards as the climate continues to warm. The effect is called “antlantification” of the polar ocean.[16,17]

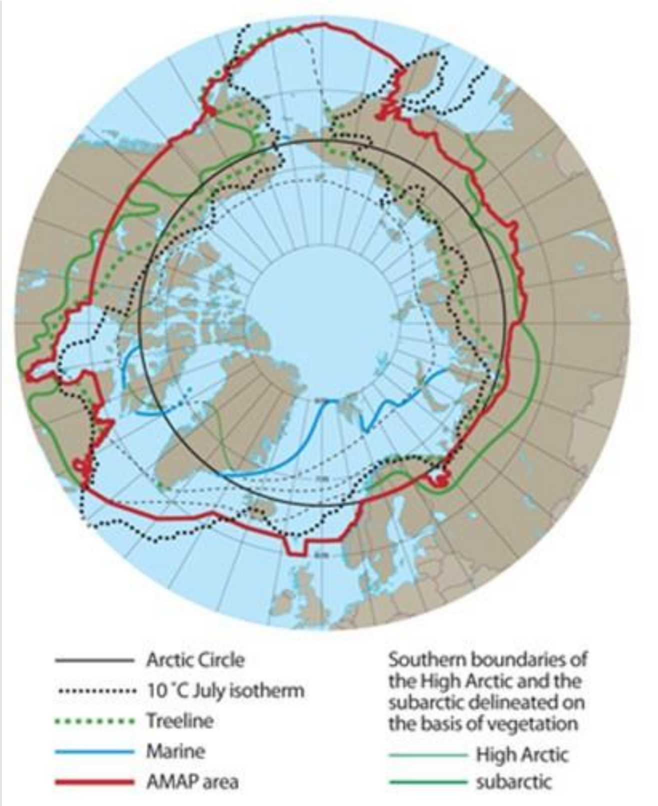

Figure 4. Delineation of the Arctic according to various definitions of the Arctic region. (Modified after Arctic Council 2024)[16].

The geographical coverage of the Arctic Monitoring & Assessment Program (AMAP, red line in **Figure 4**). extends on land from the High Arctic to the subarctic areas of Canada, the Kingdom of Denmark (Greenland and the Faroe Islands), Finland, Iceland, Norway, the Russian Federation, Sweden and the United States, including associated marine areas. The marine environment definition of the 'AMAP area' includes northern seas and coastlines, extending as far south as 51.1ºN to the James Bay in Canada as these regions are intimately connected to the Arctic by e.g. ocean currents.[16,17] The AMAP definition of the arctic is used in this article.

Greenlandic soils, permafrost thaw and transport mechanisms of substances

Soils and their formation in Greenland

Greenland's geology is characterized by ancient Precambrian rocks, including some of the oldest known rocks on Earth dating back to approx. 3.8 x 10^9 years. These ancient rocks provide the parent material from which Greenland's soils are derived.

Soils within a few kilometres of the present inland ice sheet have developed during the Holocene in ice free areas for at least 4 to 14 x 10^3 years. During the Holocene climatic optimum (circa 8 to 6 x 10^3 years before present), the average temperatures in Greenland were probably 3 - 5ºC higher than today and the inland ice and local glaciers occupied smaller areas. Around

3000 years ago, the climate in Greenland turned colder and more humid and more intense cryoturbation, which is the mixing of soil layers due to freeze-thaw cycles, took place. The recent retreat of glaciers induced by a warming climate has revealed new surfaces in glacial forefields, and these exposed areas are now subject to soil formation processes and primary plant succession.[23]

The process of soil formation in Greenland is significantly influenced by permafrost, which underlies much of the ice-free land. Permafrost refers to ground that remains frozen for at least two consecutive years and can extend to depths of several hundred meters. The active layer above the permafrost thaws during the summer months, allowing limited biological activity and soil development. Most soils in Greenland are characterized by the presence of permafrost within two meters below the surface.[24]

Some soils in milder regions of southwestern Greenland show sporadic occurrences of permafrost and can be quite humid and rich in organic matter and may then carry a dense vegetation. These areas were once preferred by Vikings (during a relatively warm period around 980 AD which lasted for a few hundred years) for settlements, agriculture and pasture. However, these soils may not thaw completely until July and do not allow grain production. Nowadays these areas are often used as pasture for sheep [25], with some areas open for other crops like potatoes. The island's degree of self-sufficiency is approx. 17%.[26]

The northern and inland ice-free areas are dominated by shallow and humus-poor polar desert-like soils with slightly more humus-rich, deeper soils inland and along the coasts. Most soils are strongly affected by permafrost processes and cryoturbation. These so called Cryosols often contain ice wedges which are prone to melting and soil destabilization when the soil surface is disturbed e.g. by road construction or the removal of vegetation cover.

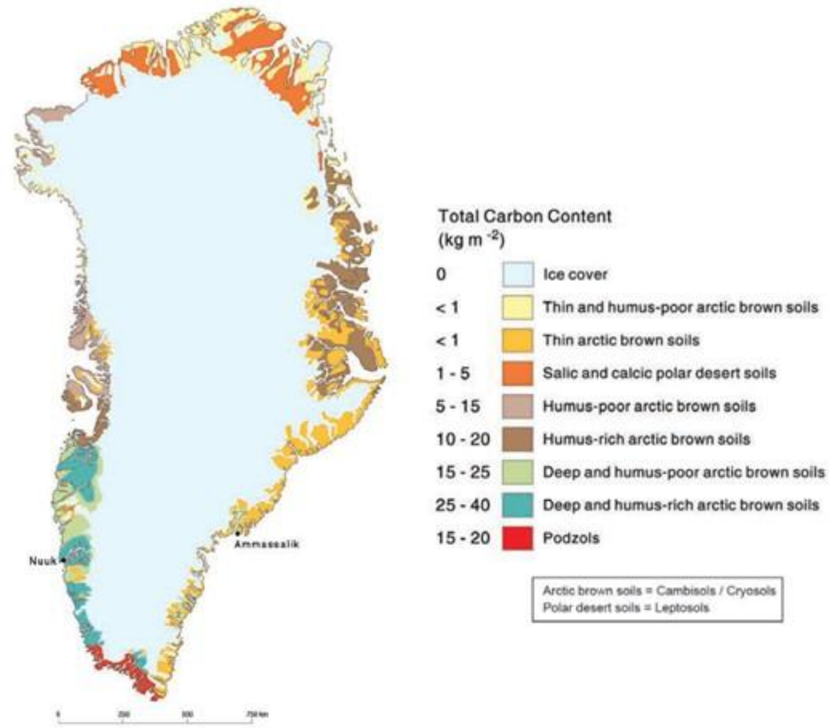

Figure 5. Type, distribution and soil carbon content of soils in Greenland.
Arctic brown soils of different stage of development and depths dominate the ice-free regions of Greenland and are limited to the coastal areas. These soils are often influenced by permafrost and cryoturbation. Relatively fertile deeper arctic brown soils (green and turquois colour) and less fertile podzols (red colour) occur only along the southwest coast of Greenland. This region is also the most populated area of Greenland.[27]

Physical effects of climatic warming on infrastructures

Increasing atmospheric and soil surface temperatures initially cause the thawing of the upper permafrost layer. This can result in uneven deepening or expansion of the soil, destabilizing existing infrastructure above. The complete thawing of the permafrost layer and thus the destabilization of the ground may take several decades to centuries because of the high amount of latent heat energy required (i.e. the additional energy input needed to melt solid ice to liquid water) before the soil warms up above the frozen state.[27] The projected changes in permafrost soils given a likely further climatic warming scenario will be particularly detrimental to infrastructure such as roads, airstrips, pipelines and buildings (**Figure 1**). This effect is aggravated by the fact that due to uneven thawing of the landscape infrastructures are often crossing thawed areas and remaining "islands" of permafrost. Uneven ground settlement due to subsidence caused by melting permafrost and soil erosion of unfrozen soils may lead to dramatic distortions of the landscape and badly affect constructions resulting in high costs for maintenance and repairs.

Transport of chemicals in the Greenlandic environment

Destroyed infrastructure and landfill containments lead to the release of hazardous or even toxic compounds into the environment. In ice sheets, frozen and unfrozen soils melting as well as recurrent freezing and unfreezing of water occur. Ice, snow and soil can be moved by wind drift and transport within glaciers via englacial flow is possible. These effects are even more complicated by possibly abundant liquid fossil fuels leading to very diverse transport pathways of chemical substances. Details are discussed in the Box "Enhanced transport of substances due to a warming climate in the Arctic".

Box: Enhanced transport of substances due to a warming climate in the Arctic

Chemical substances can move in the environment by several pathways. As biological pathways e.g. bioaccumulation in the food web, does not change due to climate change, they are not discussed here.

Substances can travel through the environment as solids, liquids and as gases. In the Arctic the gaseous transport is negligible, as the temperatures are too low for most of the substances to evaporate even in a warming climate they most commonly might be transported in water.

Chemical substances are solved in water. The extent of it is a basic property of the respective substance, which is influenced by the pH, the salt content, the temperature, organic contamination and many other properties of the dissolving water.

The main physiochemical pathways of substances originating in or on soils and surfaces through the environment are by leaching (a in (Figure 6) and through run off (b in Figure 6)[28,29].

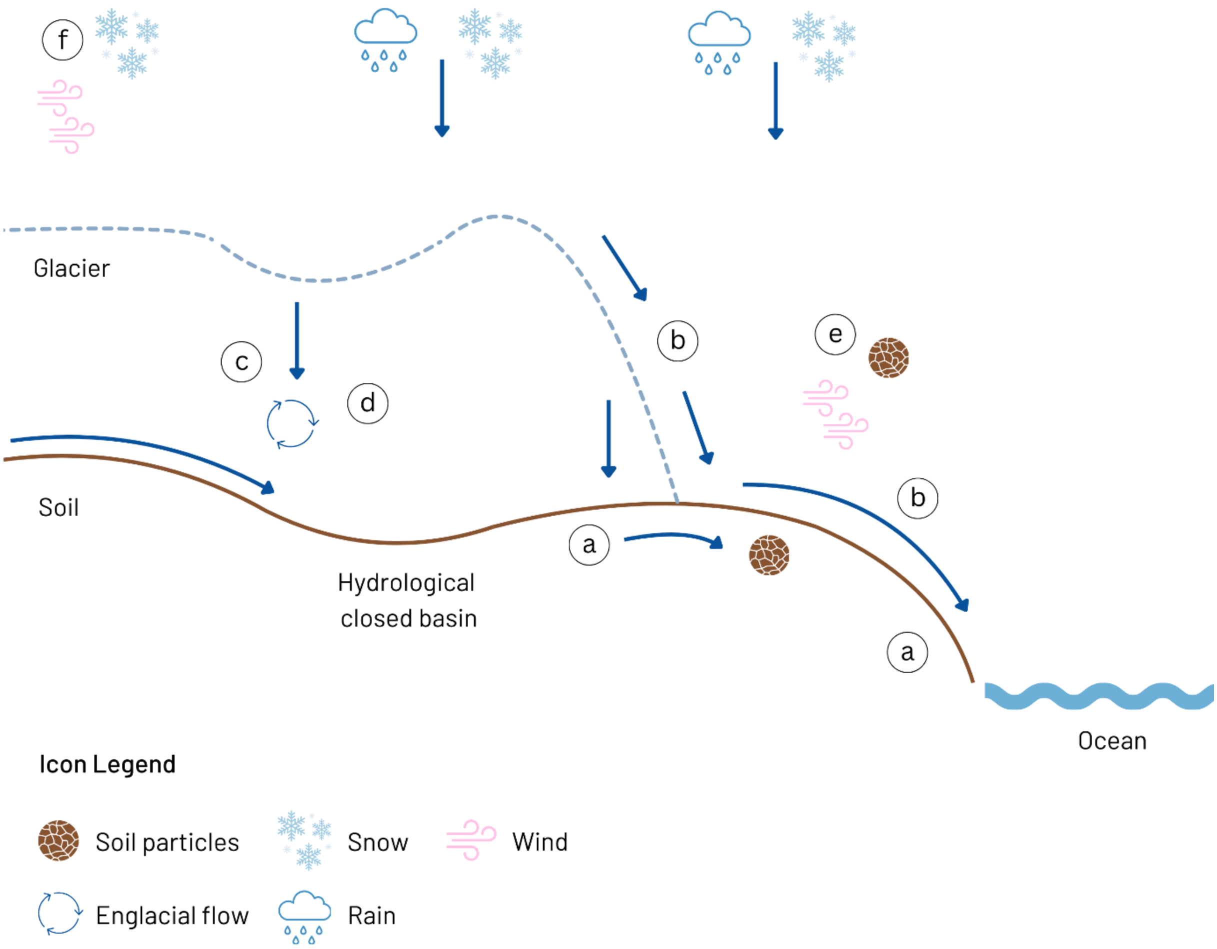

Figure 6. Selection of the most important physiochemical pathways of substances in the Arctic. Transport processes include: particle leaching (a), surface run off (b), melt water transport in glaciers (c), englacial flow i.e. internal circulation in glaciers (d), transport of soil particles by wind (e) and transport of ice particles by wind (f).

In the process of leaching water penetrates the soil and the dissolved substances interact with soil particles and microbes, which might alter or even decompose them. Dependent on the substance and the soil they be retained or travel with the water on various amounts due to the hydrological gradient. They end up in the ocean or will be contained in areas hydrologically locked by permafrost soil.

In the case of surface run off (b in Figure 6) the water and the dissolved substances do not interact with the soil. It flows directly into rivers and finally the ocean.

The meltwater from glaciers (c in Figure 6) can interact with the firn (i.e. surface ice over snow) rapidly via vertical percolation. Observations indicate that surface meltwater can percolate downward 10 m through firn in a single summer melt season.

Liquid meltwater can persist year-round within the firn of the Greenland ice sheet, forming an active englacial aquifer (d in Figure 6) that saturates pore space below 20 m depth. This is possible due to high ion concentrations which prevent water from freezing and forming an unfrozen zone. Toxic substances can be remobilized from the ice sheet by englacial water flow decades before surface runoff is observed at the site. Such hydrologic remobilization by englacial flow would transport these toxins down hydraulic gradient, deeper into the ice, before eventually reaching proglacial regions.[2,29,30]

Organic liquids such as diesel, kerosine and heating oil will not freeze at all. Lipophilic toxins will get concentrated in them e.g. polychlorinated biphenyls (PCB). They will travel as a “oil droplet” on liquid water year-round with respect to the hydrological gradient.

The thaw-induced changes in water flow pathways and hydrologic connectivity will open up new, so far unknown flow patterns in permafrost regions.[2,29]
Two main processes of atmospheric transport are possible. The toxin is absorbed on soil (e in Figure 6) or ice particles (f in Figure 6) and is transported by the wind. This process is merely physical without any chemical changes of the substance.

Hazardous and toxic substances, their health effects and decomposition

Many classes of hazardous substances have been accumulated over the past decades in the environments of Greenland. They are found in waste from settlements and military bases as well as from mining activities. The cold climatic conditions of in glacier ice and permafrost soils have so far preserved most deposits from leakage and spilling. However, these conditions are rapidly changing due to climatic warming. Arctic ecosystems are very vulnerable because most biological processes are very slow due to low temperatures and the decomposition of organic pollutants takes long periods of time, if possible, at all.
In the following the most important pollutants with respect to the Greenlandic situation are discussed, beginning with inorganic heavy metals, followed by organic substances such as fossil fuels and polychlorinated substances, bacteria, asbestos and radionuclides.

Heavy metals

Heavy metals like arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), cobalt (Co), nickel (Ni), thallium (Tl), mercury (Hg), zinc (Zn) are inorganic environmental pollutants that are not bio-degradable and therefore accumulate in ecosystem food-webs and ultimately also in humans. They pose significant health risks to wildlife and humans and cause e.g. growth depression or failure of organs. Cognitive and cardiovascular illnesses can be induced by oxidative stress which is a primary cause of heavy metal poisoning.[31]
Heavy metals in the air or water originate from various mostly non-natural sources. The most common sources are fossil fuel combustion of leaded gasoline, chemical industrial production processes and urban runoff.[31]

Petroleum hydrocarbons (PHC)

Fossil crude oil and its refined products are the energy backbone of today's mechanized society. Petroleum hydrocarbons have become a threat to the environment due to extraction, transportation and usage. Contamination of soil and water resources with petroleum oil and its derive products has become a serious problem due to its negative health effects such as carcinogenicity, genotoxicity, skin irritation, childhood leukaemia, miscarriages in women, and respiratory system disorders.[32]
Bioremediation for PHC, such as diesel, gasoline, kerosine, lubricant and heating oil in soils, sediments and water, is possible, although difficult to achieve completely. The success of the remediation depends on the microorganisms present at the contaminated site. To boost biotic activity, the soils can be fertilized, irrigated or supplemented with commercially available, but expensive microorganisms.[33] The longer the site-specific growing season lasts, the more of the contaminants will be bio-degraded by microbial action. In any case, the biodegradation requires several years and some contaminating substances may not be broken down and remain in the environment.[32,34,35]

Polychlorinated biphenyls (PCB)

PCBs are a class of persistent organic pollutants. Mixtures of the chemically possible 209 PCBs congeners were widely manufactured from 1930 into the 1970s. They were used for thermal and electrical insulation, mostly as coolants, in transformer oil, dielectric fluids and lubricants. The production of PCBs was forbidden in 2001 by the Stockholm Protocol. However,, extensive environmental contamination still persists as a consequence of accidental spills and leaks from older equipment due to improper transport, storage and disposal.[36-38]
Because of their high molecular stability, low solubility in water and a strong tendency to adsorb on particulate phase, PCBs are extremely difficult to remove from soils. Their lipophilic character makes them mobile in organic solvents such as petroleum hydrocarbons. PCBs bio-accumulate in animals, mainly in fatty tissues and breast milk. They cause neurological, reproductive, endocrine, and cutaneous diseases. Many different infections are also ascribable to the reduction of immunity response. Most of traditional remediation techniques, such as burning, for PCB polluted soil cannot be performed on-site. The soil must be extracted and shipped to a treatment site. Bio- and phytoremediation options are currently studied and show promising results.[36]

Coliform bacteria

Contamination of drinking water with pathogenic microorganisms such as coliform bacteria are worldwide responsible for most of the waterborne diseases - mostly diarrhoea. The United Nations General Assembly declared in 2010, that access to clean drinking water and sanitation facilities is a basic human right (UN Sustainable Development Goal number six).
Not all disease-producing microorganisms present in water are known or easily identifiable. The best approach for identifying microbiological contamination is the use of the group of coliform bacteria as an indicator organism, which are found in the general environment and are present in large numbers in the faeces of warm-blooded animals.
The European Union (EU) directive number 2020/2184 requires at least one annual test for coliform bacteria for public drinking water sources. To qualify for drinking water with respect to microbiological criteria, zero coliform bacteria are allowed in 100 ml in a singular sampling.[39]
Whether EU legislation is used in Greenland is not known to the authors. It seems plausible to use it as an example of best practice and to treat Greenlandic and Danish citizens equally.

Asbestos

Asbestos was widely used for thermal and electrical insulation, especially in building materials. Asbestos is a group of naturally occurring, carcinogenic silicate minerals which consist of long, thin fibres. Inhalation of airborne fibres can lead to various dangerous lung conditions and lung cancer. The hazardous effects of asbestos were recognized as early as at the turn to the 20th century. The use of asbestos has been phased out in most industrial countries, but it is still produced in many developing countries. As asbestos fibres and asbestos containing building materials are extremely long lived, future contaminations are very likely.[40]
Asbestos containing materials are generally broken down with extreme caution, to avoid toxic dust. Generally, the material is wettened and works must wear protective face masks. Afterward the material is quickly transferred to the landfill, where it is immediately covered up with non-asbestos material, generally soil.

Radiation

All radioactive elements decay over time into non-radioactive elements. The decay process is element-specific and the time constat of the decay cannot be changed. The effect of emitted radiation during the decay process on living organisms depends on the radiation type, its energy and the proximity of living organisms to the radiation source. High energy radiation (e.g. gamma radiation) damages the DNA of cells. Low levels of radiation can cause cancer, often

years or decades after the exposure while high levels of radiation cause immediate symptoms ranging from nausea and burns to fatal multi-organ failure.[41-43]
The main problem with radioactive pollution is the length of time before radioactive substances have decayed to a point where they emit only low levels of radiation which is considered as non-damaging to living systems. During this time, radioactive material must be safely contained and protected against leaking into the environment. Common measures for safely storing low and medium radioactive materials are the reduction of the waste volume by physical and chemical methods and the subterraneous storage of the residues e.g. in former salt mines. So called bioremediation is used in the environment to fix radiating material and prevent dispersion in the environment until the radiation level is acceptably low. Even after that, these elements – mostly heavy metals – are still hazardous substances because of their toxic chemical properties.[43]

Table 1. List of the most important chemical, biological, radioactive and mineral pollutions in Greenland, their sources and guidelines and regulations for drinking water as well as values for fish toxicity. The list of chemical elements, substances and substance classes reflect the mandatory monitoring scope for contaminated soils according to the *Abandoned Military Site Remediation Protocol* of the Canadian government.
Column 1 contains a list of elements, substances, group of substances, group of bacteria, radiation and fibres important for human and ecosystem health. Column 2 contains the most important origins and usages of the named hazardous substance in Greenland and their legal status. Column 3 contains the guideline value of the World Health Organization (WHO) and the minimum requirement of the European Union (EU) for drinking water (directive 2020/2184 - quality of water). Column 4 contains ranges for Fish toxicity. LC_{50} fish = toxicity of each substance is indicated using the median lethal concentration after 96 hours of exposure and occurrence of 50% fatalities.

Substance	**Origin (source) in Greenland**	**Drinking water guidelines of the WHO [44] and minimum requirements by the EU [39]**		**Fish toxicity (LC_{50})[2]**
Chemical pollutants				
Arsenic (As)	Burning of fossil fuels, mining[45]	WHO: 10 µg/l	EU: 10 µg/l	1-10 mg/l
Lead (Pb)	Mobility (fuel, tyres, breaks), mining[45]	WHO: 10 µg/l	EU: 5 µg/l	1-10 mg/l
Cadmium (Cd)	Metal working industry, mining[45]	WHO: 3 µg/l	EU: 5 µg/l	
Chromium (Cr)	Mobility (tyres, breaks), mining[45]	WHO: 50 µg/l	EU: 25 µg/l	10-100 mg/l
Copper (Cu)	Mobility (tyres, breaks), mining[45]	WHO: 2000 µg/l	EU: 2000 µg/l	
Cobalt (Co)		WHO: not mentioned	EU: not mentioned	
Lead (Pb)	Mobility (fuel, tyres, breaks), mining[45]	WHO: 10 µg/l	EU: 5 µg/l	1-10 mg/l
Mercury (Hg)	Burning of fossil fuels, mining[45]	WHO: 6 µg/l	EU: 1 µg/l	<1 mg/l
Nickel (Ni)	Burning of fossil fuels, mining[45]	WHO: 70 µg/l	EU: 20 µg/l	
Zinc (Zn)	Mobility (tyres, breaks), mining[45]	WHO: Not of health concern at levels found in drinking-water.		
PHC	Fossil fuel	WHO: Taste and odour much below critical values.		10-100 mg/l
PCB	Electrical components, paint, coolants, fire protection Production globally forbidden since 2001[37]			10-100 mg/l
Biological pollutants				
Total coliform bacteria	Waste water	WHO: 0 in 100 ml	EU: 0 in 100 ml	
Mineral pollution				

Asbestos	Building materials Production forbidden in the EU since 2005 as well as in many industrial countries[40]	WHO: No consistent evidence that ingested asbestos is hazardous to health		
Radioactive Pollutants				
Gross alpha activity	Atomic bombs, nuclear reactor		EU: 0.04 Bq/l	
Gross beta activity	Atomic bombs, nuclear reactor		EU: 0.4 Bq/l	
$^{239}Pu/^{240}Pu$	Atomic bombs		EU: 0.04 Bq/l	

Sources of pollution

Past and recent pollution

Military

Greenland is remote and thinly populated. During WWII and later in the cold war it gained importance, as it provided the shortest missile line of flight between Moscow (Russia) and Washington (USA) and provided a strategic stopover point for airplane transfer to Europe. After WWII it was integrated into NATO's policy of deterrence and a multitude of military bases, radar stations, air strips and harbours were built. The operation of these instalments led to pollution as well as accumulation of waste which contains radioactive, chemical and biological waste. All of the US military bases but one, were decommissioned and had been abandoned by the end of the Cold War. In the following three examples of pollution in Greenland resulting from military activities are provided, first a nuclear incident at the coast following a military airplane crash, second legacy radioactive contamination at an abandoned military camp and third an oil spill at a former active military base. These examples are a selection of contaminated sites, as many abandoned bases are still not fully explored and existing waste deposits fully recorded, analysed and cleaned up.

Strategic Air Command plane crash near the Pituffik Space Base (Thule Accident)

On the 21st of January 1968, a US Air Force B-52 bomber of the Strategic Air Command involved in the operation "Chrome Dome" and carrying four nuclear hydrogen bombs crashed approx. 13 km south of the US Thule air base (now called Pituffik Space Base) near the coast over the ocean ice sheet. The on board non-nuclear high explosives and all air fuel detonated and burned upon impact blowing the four hydrogen bombs apart and spreading a total of 10 Terra Becquerel (10^{12}) of radioactive plutonium, uranium, americium and tritium over an area of at least 7.7 km². Due to the burning plane parts and air fuel the pack ice melted on the impact side and an estimated 5 Giga Becquerel (10^{9}) of radioactive plutonium sank into the ocean. A cloud carrying radioactive isotopes drifted south to populated areas. The accident can be compared with the detonation of a "dirty bomb".[30,46,47]
Directly after the accident, fishing and hunting were forbidden in the area. Clean up operations were undertaken immediately; even as the arctic winter severely complicated them. Up to 90% of the plutonium was recovered from the ice, leaving about 1 Terra Becquerel (10^{12}) around Thule.[30,46,47]
Plutonium (Pu) is a highly toxic heavy metal with no civil usages. Ingestion can cause severe damage to the kidney and liver which is typical for any heavy metal. Much more dangerous than the chemical effects are the radioactive properties of plutonium, which varies a lot, depending on the isotope. Weapon grade plutonium consists of at least 92% ^{239}Pu which has an extremely long half-life time of 24 110 years. It emits alpha radiation with a low range. The decay products of Plutonium are also radioactive.[47,48]
Alpha radiation has a short range and is therefore not very dangerous for the skin and protection by shielding the skin is easy. When orally ingested ^{239}Pu does not cross from the intestines into the blood and is quickly excreted. For example, the additional dose for indigenous people around Thule who are hunting and eating 15kg musk ox meat per year is extremely low. The same holds true for inhaled ^{239}Pu if people stay in the contaminated area for 14 days per year. However, when Plutonium is inhaled ^{239}Pu crosses into the blood and is sequestered in the human body. Small quantities of Plutonium may remain in the lungs or move into the bones, liver, or other body organs. The Plutonium that is not readily excreted stays in the body for decades and continues to expose the surrounding tissue to alpha radiation. Plutonium inhaled or ingested will increase a person's chance of developing cancer, but such cancer effects may not become apparent for several years.[49] A low additional radiation dose of ^{239}Pt is possible by contamination of open wounds with soil or vegetation.[48]

Epidemiological studies on the health status of the local population around Thule and workers involved in the clean-up operations in 1968 are patchy, but indicate increased cancer rates compared to people from non-contaminated areas.[46,48] The contamination of fish and hunting game e.g. musk ox was until now only estimated but never really measured. Studies about the possible effects of mobilised ^{239}Pu from the ocean sediments and their transport with ocean currents and within the food web are rare.

Abandoned Camp Century

Camp Century was a system of five connected US military bases built into the Greenland ice sheet in the vicinity of Pituffik Space base. The camp was powered by a nuclear reactor and operated from 1959 until 1967 when important mobile equipment was dismantled and the base abandoned[30]. The ice mass movements within the ice sheet had caused problems to the infrastructure integrity and resulted in the decision to abandon the base. The tunnel network covered an area of 55 ha. When it was decommissioned, physical, chemical, biological and radioactive waste was left behind. The physical waste including buildings amounts to approx. 9.2×10^3 t.[30,50]
The main components of the left behind chemical waste are diesel fuel and polychlorinated biphenyls (PCBs). An estimated amount of 2.0×10^5 l of diesel fuel in tanks were left in Camp Century. The tanks most probably are destroyed by now and the diesel forms a liquid bubble inside the ice. PCBs are valued because of their high heat capacity, low flammability, and physical flexibility and are used as coolants and in paints (up to 5% by weight). PCBs are most likely the most consequential waste at Camp Century.[28,30] The biological waste consists of at least 2.4×10^7 litres of grey water, including sewage, disposed in unlined sumps drilled into the ice beneath the camp.[30] Radiological waste - coolant from the portable nuclear reactor - had a bulk radioactivity of 1.2×10^9 Bq at the time of disposal (1960-1963) in an unlined sump. The remaining bulk radioactivity as of 2025 is unknown.[30]
The Camp Century tunnels are constantly buried deeper into the ice sheet. Therefore, most of the solid waste was assumed to be residing in 2016 at a depth of approx. 36m, today most likely even deeper (**Figure 7**). As liquids do move very efficiently through the ice, the burial depth of the frozen sumps is less certain and was assumed to be located at 65m of depth in 2016. The location of the diesel fuels is even less certain as it might have stayed liquid until today.[30]

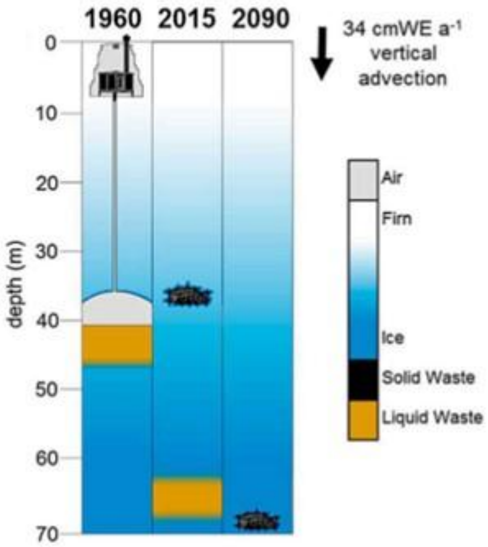

Figure 7. Estimated depth of Camp Century solid and (partly re-frozen) liquid waste in 1960, 2015 and 2090, based on estimated vertical advection rates. WE = Water equivalent. (Modified after Colgan et.al. 2016).[30]

In a business-as-usual climate scenario (RCP 8.5) model calculations suggest that until the year 2100 the ablation (melting) zone of the ice sheet will move towards to Camp Century's position. This would make the coastward remobilization of abandoned wastes inevitable by either surface exposure of abandoned wastes via persistent ablation of overlying firn and ice or subsurface hydrology via meltwater percolation and englacial flow though overlying firn.[30]

Fuel spill on the East coast at the Bluie East Two air base

Between 1942 and 1945, the Bluie East Two air base on the eastern coast of Greenland was used as a stopover to refuel airplanes on their way to the European front in WW II. Bluie East Two had a 2000-meter-long landing strip, and in 1943 about eight hundred American soldiers were stationed there.[50,51] Bluie East Two was built deliberately remote from the next indigenous settlement, which was more than 20 km away. Though, the area of the air base included customary hunting and fishing grounds and a campsite of the nearby Inuit villages.[51]
In 1947 the soldiers left the area, and all materials and waste were left behind. The estimated amount of barrels varies between 33 000 to 60 000[50] and 20 0000 to 300 000[51] (**Figure 8**). According to Herzberg et. al. 2019[51] their content was deliberately emptied into the environment shortly after the troops left. This led to surface water contamination, wilted plants and wiped-out seal and fish populations. In 2019 local hunting and fishing has resumed, but the immediate surroundings of the former air base vegetation has not yet fully recovered.[51] Research on the scale of the environmental pollution is scarce.

Figure 8. Barrels dumped after the closure of the East Bluie Two airbase near Tasiilaq, East Greenland (Photo K. Pavelka, 2019).[50]

After a long period of negotiations between the USA and the Kingdom of Denmark remediation work started in 2019, as part of a six-year, 180 million kroner ($30 million) Danish funded program to identify and clean up pollution at WW II-era installations.[52,53] An area of approx. 1.6 ha was at that time covered by barrels. By the end of August 2021, the area has been reduced to 0.7 ha. Whether the barrels have been remover or only moved is not known to the authors.[50] Furthermore, it is not clear whether the content of all barrels had been emptied (**Figure 8**) because the hulls of the barrels are deteriorating after seventy years of unprotected storage and may leak their hazardous content.

Extracting industries

The side effects of extracting industries like oil drilling and mining have a high potential for polluting the environment. Test drilling for fossil resources in the Arctic waters around

Greenland began in 2010. Licensing agreements were delayed because environmental concerns grew in response due to the oil spill of the Deepwater Horizon in the Gulf of Mexico in the same year. As of 2025, no commercial oil exploration has taken place in Greenland.[5,34] In contrast, mining in Greenland has started as early as 1854 and today there are still some mines operational. Legacy pollution from mines is a persistent environmental problem, mostly involving heavy metals, as described in the following.[54]

Heavy metal pollution at the cryolite mine at Ivittuut

The cryolite mine at Ivittuut in the Arsuk Fjord of southwest Greenland (Figure 9) started operating in 1854 and production lasted for more than 130 years until the mine was closed in 1987. Cryolite (Na_3AlF_6) is a rare mineral and the mine in Ivittuut was the major source globally. Its main use is for aluminium production by smelting-flux-electrolysis. It is added to the aluminium containing mineral bauxite to reduce the melting point. Today, cryolite is synthetically produced.[54]

Figure 9. Mine pit and buildings of the abandoned cryolite mine in Ivittuut in 2015. Photo: Morten Birch Larsen.[54]

The ore was blasted, crushed and sorted on site and shipped to Denmark for further processing. The mine was an open pit mine situated in immediate vicinity to the shoreline and waste rock was used as landfill between the pit and the fjord. The landfill was open to the tidal movements, saturating the rocks with seawater.[54] During WW II aluminium production was in high demand, and cryolite became crucial for the war effort. After the occupation of Denmark by Germany in 1940 the United States realized that an occupation of the mine must be avoided. The measures taken included that a small detachment for the protection of the mine and the negotiation of the 1941 defence treaty between the USA and Greenland.[1] The first environmental studies in the area were conducted in 1982 and revealed significant marine pollution with mainly lead and zinc in the Arsuk Fjord. Especially affected were brown seaweed *(Fucus vesiculosus*) and blue mussels (*Mytilus edulis*), while fish and prawns from the fjord were not impacted.[54] In 2013 the Arsuk Fjord and adjacent waters up to 4 km were still polluted with lead and zinc while the pollution is slowly decreasing.[54]

Heavy metal pollution from the lead-zinc-silver mine at Maarorilik

The underground lead-zinc-silver mine in Maarmorilik operated from 1973 to 1990. The ore consisted of lead (4%), zinc (12%) and silver (30 ppm). The current pollution originates from tailings, waste rock and residues of ore and concentrates from the refining process. It mainly contains lead and zinc and to a lesser content cadmium, silver, arsenic and mercury. Elevated concentrations of metals were documented in seawater, sediments and in several terrestrial and marine species. The most recent study in 2017 confirmed a lasting significant pollution.[54]

Municipal waste

Municipal waste is accumulated in all areas with human activity. It is critical to human health because it often contains biological contaminants.[22,55] The Sustainable Development Goal 6 of the United Nations is to “ensure availability and sustainable management of water and sanitation for all”. Inadequate water and sanitation services are often associated with poor health status and this burden in Greenland is prevalent among rural indigenous populations.[22,55] Access to safe water prevents waterborne infections which mainly cause gastrointestinal illness. So called water-washed infecting are prevented by an adequate quantity of water for personal hygiene and cleaning of household items.[22,55] In Greenland individual in-house water services are not common to all households.[22] It can be assumed, that the situation in Greenland is similar[22] to rural Alaska where the daily available amount of clean water per person is sometimes even below the recommended 15 litres for disaster response situations by the WHO.

Waste water treatment facilities in Greenland are not always available or do not exist.[20-22] This poses a risk for households and communities because such waste has to be removed in containers. This can lead to contamination of clean water, containers and surfaces inside the household with contaminated water, especially in water deprived environments.[22,55] If the wastewater is leaking into the drinking water supply, whole communities may be affected. This is a real risk, as the most Greenlandic populations are obtaining drinking water from unsafe sources at least for some time of the year (**Figure 3**).[21,22]

Future pollution

Oil extraction and mining

Because of its geology, Greenland has a high potential of containing critical raw material deposits and several deposits have already been identified. The government is favouring mining.[56-58] Potential fossil resources are currently not further explored in Greenland because in 2021 the Greenlandic government has decided to suspend such activities.[59]

Only one mine at White Mountain is currently operating in Greenland where Anorthosite, a raw material to produce rock wool, is mined since 2018. The latest mine to close in September 2024 was the Greenland Ruby mine in Aappaluttop where rubies had been extracted since 2017.[60] Standard environmental studies were performed for both mines before they went operational to document the previous environmental conditions. Although no pollution has been recorded for these sites[54,58], the bankruptcy of the ruby mine in Aappaluttop shows the risks of legacy pollution found after the closure of the mine with no financial means left to remediate them.

Box: Critical raw materials and their deposits in Greenland

Known critical raw minerals – termed that way as they are needed for many advanced technologies - deposits with resource potential in Greenland contain antimony, beryllium, bismuth, cobalt, fluorspar, gallium, germanium, graphite, hafnium, indium, lithium, niobium, platinum group metals, phosphorus, rare earth elements, scandium, silicon metal, tantalum, titanium, tungsten, vanadium.[56] Non-critical raw minerals like copper, manganese and nickel which are also found in Greenland are needed for the green revolution.[56]

Figure 10. Locations of deposits with known critical raw material resources and areas with known or assumed potential for critical raw material resources in the Greenland.[56]

Among planned mining projects is the mine in Kuannersuit (Kvanefjeld). The deposit contains rare earth elements, uranium, zinc and sodium fluoride. An undesired and useless mining byproduct will be the highly radioactive element thorium which would accumulate in the tailings. The freshwater demand of the mine was calculated as 115 m³ per hour. The most likely highly polluted wastewater will be discharged into one of the fjords surrounding the local town. The mine is located in Greenland's very small agricultural region, which increases the worries about pollution.[57,61] The political discussion around the opening of the mine led to an agreement that uranium should not be mined in Greenland. The project is therefore currently on hold. However, the Australian based mining company holds a valid mining concession and has invested huge amounts of money into the exploration of the site and legal proceedings are therefore currently underway. The ore was planned to be shipped to China and be processed by a Chinese company due to the general Chinese expertise with rare minerals refinement.[61] It is a strategic concern of NATO nations that the processing of rare earth metals in China may also mean a restricted access to the final products.[57] Neither Denmark, Greenland or Australia have signed a Memorandum of Understanding for the Belt and Road Initiative with China. Consequently, no contractual obligation is given for the export of the refined minerals on the basis of a good partnership.[62]

Tourism

Sea-ice retreat has already enabled the rapid growth of arctic marine cruises tourism and a niche market in "last chance" tourism is developing.[63] The arctic tourism is currently growing, but the boom may be influenced by the global economy.[13,63] Cruise ship tourism has a strong negative impact on the environment due to high emission of ship exhaust fumes and the discharge of sewage and ballast water.[4] A specific risk in the Arctic involves the expansion of routes in uncharted regions with the associated danger of accidents and the need for rescue operations.[63] Access to the large National Park in Northeast Greenland and to the inland ice is already regulated. The construction of supporting infrastructure is under development or completed, such as the deep-water harbour in Nuuk and the international airports in Nuuk, Ilulissat and Qaqortoq. Cruises to the North Pole are currently rare, but available.[64] Depending on their starting points in Europe or North America they will not stopover in Greenland. Therefore, Greenland may have to deal with the respective pollutions without having any direct benefits from these activities.

Polar shipping routes

The ongoing sea ice retreat in the Arctic is already extending the navigable season for shipping. On a local scale the accessibility of small communities will increase. If the current trend continues, summer conditions by mid-century will result in an almost ice-free Arctic Ocean. On a global scale the North-West Passage will connect the Pacific with the Atlantic Ocean via Canadian and possibly Greenland waters, while the North-East passage will connect the Oceans via Russian waters. The Transpolar route will lead directly over the North Pole (**Figure 2**). Of these three routes, the Transpolar route is currently rarely used, mostly by icebreaker cruise ships.[64] The North-East passage, often referred to as the Northeastern Sea route, is currently the only active Arctic circumventing sea route. It had a record of 97 transit voyages carrying 3.1 million tonnes of goods in 2024, double the average of the past decade. All the traffic has been between Russian and Chinese ports and the vessels are possibly part of Russia's shadow fleet.[65] The Northwest Passage in comparison had just 24 transits in 2023 and 18 in 2024 (almost half of these were cruise ships). It is estimated that in the future this route will see a huge increase in shipping[66] and commodity transportation ships serving the East Asia-North America trade will travel the full length of the West coast of Greenland. Mine ore ships from the Mary River Iron Mine in Baffin Bay (Canada) do already use this route in the summer months.[67] Besides the pollution from ship exhausts, noise, light, fuel, sewage and ballast waters, the probability of serious accidents which may include lost containers and oil spills will increase.[4,63]

Consequences of pollution for humans

Environmental pollution is harmful to ecosystem fauna and flora. Of special concern for the human wellbeing are direct as well as indirect pathways of pollution and their consequences for humans. In the following some effects of direct contact of pollutants on human health as well as indirect consequences via the accumulation of hazardous substances along the food chain and food production are discussed. Several pathways for the direct uptake of pollutants into the human body are possible. In Greenland, dangers from inhalation of pollutants may only be relevant for asbestos[44] and some radioactive nuclides[47] while the ingestion of pollutants is the main intake pathway for humans and animals.

Inhalation

Asbestos, mainly from construction material, is disposed of in earth covered dumps. There, it is not mobile in the soil. As long as no asbestos mineral dust is created during handling of the material, it poses no risks for human and animal health.[44]

Radioactive material in Greenland originates from atomic bombs from the Thule bomber crash[30,46,47] and from general waste from the non-nuclear sections of the Camp Century nuclear reactor.[28,30] In both cases the bulk of the radioactive particle contamination is currently covered by ice or enclosed in soils and water and thus the probability of an airborne distribution of radioactive substances and of inhalation is minimal.

Ingestion of contaminated drinking water

Humans consume one to two litres of water per day. The cleaning of cooking utensils and kitchen surfaces demands an additional few litres of drinking water. The percentage of people served monitored drinking water by the government owned Greenlandic water supply company Nukissiorfiit[68] is unknown to the authors but the consumption of unsafe water as well as water scarcity can lead to serious medical conditions.[21,22]

Potential chemical pollutants in drinking water in the Greenlandic context are heavy metals leaking from former military bases and mining operations into freshwater systems which are used as drinking water sources. The radioactive metals from the Thule bomber crash were distributed on the sea ice and are not connected with fresh water sources. In contrast, the radioactive metals from Camp Century waste will probably by the end of this century end up in freshwater systems either by percolating through the icesheet or by thawing of the covering ice. PHC and PCB's may travel in small amounts in drinking water, which has to be free from both compounds to be fit for human consumption. The detection of one of those compounds is always a sign of contamination, as they are not found in nature. In Greenland, wastewater, which is a source of microbiological contamination is often disposed of into the ocean without any treatment - especially in remote locations.[21,22] As saltwater cannot be used for human consumption, a cross contamination with drinking water seems impossible.

The population density in Greenland is low and freshwater is plentiful available. Therefore, contaminated water sources can be avoided, especially as the few polluted areas are documented. Well managed, e.g. by monitoring programmes, threats to human health by a centralised and even a decentralized drinking water supply can be avoided, now and in the future.

In the case of polluted drinking water sources, the duration of their closure depends on the kind of the pollution. Heavy metal, PCBs and PHC pollution will remain in the freshwater system – even after the remediation of the source - for decades or even centuries. PHC and PCBs are only very slowly bio-degraded while heavy metals are not bio-degradable at all. They will stay within the catchment area, being washed out and pollute other regions or, when effectively diluted, may cause no harm in the regions they are transferred to.

Ingestion of contaminated food

Heavy metals, PHC and PCBs are accumulating in plants and animals, especially in fat tissue. In cold climates, most animal have thick fat layers for insulating against the cold and as energy reserves. Most obvious are whales and seals, but livestock and fish also have fat layers. Aquatic and terrestrial plants do not have obvious fatty tissues, but the pollutants are fixed in their cell membranes.[69]

The effects of toxic compounds in water to fish is described with the proxy of the so-called fish toxicity. It is generally high for heavy metals, PHC and PCBs (**Table 1**). Acute and severe spills generally go with dying animals. In the case of oil spills typically sea birds and sea mammals are affected by the acute physical effects of oil contamination of feathers, skins or lungs. Fish and shellfish also die but are often not washed to the shore in greater numbers and therefore not recognized as casualties but are eaten by predators. After the acute phase of a spill chronic contamination can last for years and decades, leading to the bioaccumulation of the pollutants in the food webs and especially at the top predator, generally humans.

The situation on land is similar but generally spills of toxic materials are smaller in terms of the spilled volume. Animals which have died of natural or unknown causes are generally not consumed by humans. Therefore, the uptake of exceptionally high toxic concentrations is low.

But, as the top predator, humans will bioaccumulate toxins via wild and cultivated plant products, hunting game, fishing and via livestock.
Food stuff is far more difficult to monitor for pollutants than drinking water, especially when hunting and fishing is an integral and important part of the food supply. The situation is complicated by small communities, long distances and seasonal difficult weather situations. Only a few scientific studies about the concentration of pollutants in wild animals exist. Mostly mercury is studied - as it is the most toxic heavy metal of the monitoring list - in birds[70], reindeer[71] and top predators such as seals and polar bears.[72]
In small Greenlandic communities seasonal hunting is supplemented by dinghy fishing in summer and ice fishing in winter. In 2021 seals (93 752 animals), whales (5708 animals), land mammals (15 443 animals) and birds (97 145 animals) where hunted in greater numbers. They were eaten in Greenland or fed to sledge dogs. A huge part of the 217 600 tonnes of fish and shellfish caught in 2023 by Greenlandic vessels is probably consumed in Greenland. The livestock raised in Greenland is also consumed by Greenlanders. In 2023 sheep (17 268) and tame reindeer (3000) are the main livestock kept on Greenlandic farms.[12]

Fish and shellfish exports

The majority of Greenland´s exports (90%) consist of fish (64 000 tons in 2023) and shellfish (57 200 tons in 2023).[12] Importing countries generally monitor the incoming goods and may detect contaminations earlier than Greenlandic authorities. If contaminations were detected, the whole industry would certainly suffer for decades. This is a real danger as the example from Canada shows. Jermilova *et al.* (2025)[73] modelled the impact of climate warming related leaking waste dumps, operational and legacy mining, oil and industrial sites in the catchment of the Mackenzie River in the Canadian Arctic with respect to mercury pollution. The authors come to the conclusion that 17 to 30% of commercially viable fish will probably trespass the Canadian commercial sales guidelines for fish, depending on the region within the catchment area.[73] Another example is the major 1989 *Exxon Valdez* oil spill in the Prince William Sound (Alaska, USA) where the recovery of many aquatic species was incomplete in 2014.
Experiences with spills of hazardous and toxic substances and their remediation in Greenland are scare. The known contaminated legacy sites should be remediated before a leakage occurs. In some cases, this is not possible, e.g. Camp Century[30] or the Thule bomber crash.[46,47] Some of them may never recover and the consume ability of the recovered species has yet to be tested.[34]

Remediation of contaminated sites in the Arctic

Avoiding future pollution should be a priority, as remediation is expensive and difficult – especially in the Arctic with its cold climate, long periods of darkness and the permanent danger of deadly ice bear attacks.[34,35,74] With the advantage of hindsight, a complete removal of dangerous and hazardous material after the abandonment of military and civil installations would have been cheaper than the necessary clean-up decades later. Delayed remediation is possible when nation states are responsible for the polluted sites as they usually are long lived and generally do not fail financially. This is not true for private companies and civic society may not be able to hold them responsible for the damages they caused. They may have closed business[54] or have been bankrupt[54,60] by the time of the needed remediation. Some even file for bankruptcy after they have been informed about their obligations.
To avoid contamination a long-term mind set of the government is needed to create, implement and monitor environmental legislation as well as litigate possible trespassers. In this context, the government must take responsibility for the public domain such as a sustainable municipal waste and wastewater management while the corporate world must take care for its operations. The second-best measure would be to cleanup polluted sites as soon as they are

identified. With an effective monitoring system installed, this should be an easy task for ongoing operations as the pollution is not yet widely distributed in the environment. The most problematic cases are the polluted legacy sites without proper knowledge and documentation of the affected sites as well as the used materials and their quantities. These sites pose a serious risk to the environment, local populations and the cleanup personnel. Remediation costs can easily rise into billions of dollars.
The costs for avoiding monitoring and the cleaning up of pollution in the public domain has to be paid by the citizens through taxes and charges. Nations states theoretically can bear the costs. Whether the cleanup is politically feasible is decided by the citizens.
Corporations must pay for their environmental obligation with a share of their profit and generally try to avoid these costs. To avoid privatising profits and socialising costs, environmentally dangerous companies must be held responsible by legislation for setting aside a feasible amount of money – with respect to their trade – in a governmental trust dedicated to cleanup operations for at least 50 years after closure of the site. Long-term thinking trumps short term profits with respect to environmental issues and successful clean-up operations in the Arctic. The remediation of some sites has already been scientifically monitored and gives valuable insights into the process and future possible polluting avoidance strategies.

Remediation in the Arctic

Remediation studies of permafrost soil in the Arctic are rare. In Greenland the most important sources of soil pollution are from mining and military activities. The abandoned mines were located on the coastline, and the pollution is found mostly in the ocean. Monitoring of the mining sites is well documented.[54] Remediation studies of military installations in the arctic rarer.[28,35]
In the case of Greenland, there are – as to the knowledge of the authors – ongoing negotiations about the responsibility of remediation efforts between the USA and Denmark.
Canada remediated many former arctic military sites[75] and has performed remediation studies of military bases and also has developed the very detailed and sophisticated “Abandoned Military Sites Remediation Protocol” which defines methods of testing for pollutions and cleaning up contaminated military sites in the Arctic.[74] As some of the military installations in Canada and Greenland originates from the same time period or from the same line of defence, e.g. the Distant Early Waring (DEW) Line and are both located on permafrost soil, the conditions seem to be similar, and therefore these studies are discussed as a blueprint in the following.
In the Canadian “Abandoned Military Sites Protocol” the analysis of nine inorganic elements (arsenic, cadmium, chromium, cobalt, copper, lead, mercury, nickel and zinc), PHC and PCBs are defined (Annex 1). For the remediation of DEW Line sites installations a specific set of minimal requirements for testing and remediation measures has been developed, which specifies minimum requirements with respect to the location e.g. with respect to the closeness to a waterbody.[74]
The assessment of the DEW Line and related sites showed that the most common contaminations are copper, lead, zinc and PCBs. In the Arctic PCBs and lead have been shown to travel several km from point sources.[28]
Most of the remediation work is related to PCB contamination. In the Arctic PCBs do move in water or adsorbed to soil particles (Figure 6). Leachate tests with arctic soil have shown, that they are generally confined in the top 30 cm of the soil, which is also true for other contaminants. Therefore, soil sampling in monitoring studies as well as the cleanup – excavations - of contaminated soils can be limited to the top unfrozen soil layer.[28]
Environmental assessments were conducted at all 42 DEW Line stations in Canada from 1989 to 1993. Three examples with specific challenges will be discussed in the following.

Polluted soils were excavated and disposed of from the Iqualit Upper Base (Canada)

Iqualit, (population 3500) is located on the southern end of Baffin Island. Adjacent to the town is a former military base, known as the Upper Base, which was originally a Second World War airbase and afterwards performed several purposes. The site accommodated 130 servicemen at the height of operations. The military camp is completely cleaned up with an ongoing monitoring program established. The cleanup included the demolition of all buildings and the removing of the heavy-metal and PCB contaminated soils. Soil with PCBs content >5ppm was excavated and shipped south for disposal mostly by burning. Soils containing 1-5ppm of PCBs were buried on site along with non-hazardous debris. While most contamination was in the first few centimetres of the active layer, some migration of PCBs along the surface of the underlying bedrock at greater depth was found.[28,74]

Leaching PCBs at the Sarcpa Lake Distant Early Warning (DEW) Line instalment (Canada)

At the former DEW Line installation at Sarcpa Lake, a dump on permafrost soil was leaching PCBs and therefore was excavated and disposed. The PCBs in the dump were from electrical equipment and/or PCB-containing paint. Investigation of the painted material at the site showed PCB levels as high as 7.4% in the paint. Asbestos was containerized and removed. The research station in Sarcpa Lake is now completely cleaned up with an ongoing monitoring program established.[28,74,76]

Barriers to prevent PCB containing leachate to reach waterways at Resolution Island (Canada)

The DEW-Line installation on Resolution Island is located on Baffin Island. The main station site is situated on a summit 360 m above sea level on Cape Warwick at the northeastern end of the island. The site is situated on bedrock with steep slopes in many places. Soil is restricted to isolated pockets in gullies and valleys and virtually nonexciting outside of these locations, significantly reducing the possibility of any retention and degradation of pollutants in the soil.
The extent of contamination is much larger than at the already described sites. Interceptor barriers were installed to prevent PCB containing leachate to reach the ocean. The presence of petroleum products along the drainage pathway has led to increased transport of PCBs due to their higher solubility in these organic solvents as compared to water. The camp is now completely cleaned up with an ongoing monitoring program established.[28,74]

Bioremediation of diesel contaminated soil from Station Mestersvig in Greenland

Petroleum pollution due to diesel, gasoline, kerosine, lubrication and heating oil are a problem in themselves[35] but they are also a solvent for organic compounds. In this capacity, they mobilise otherwise stationary polluting point sources and distributing them into the wider environment, as described for the leaching of PCBs at the Resolution Island military site.[28] Severe oils spills are generally associated with former airfields.
Station Mestersvig, located 200 km north of Ittoqqortoormiit on the east cost of Greenland, is a remote military airfield. In 2007 an environmental survey showed high concentrations of oil products in the soil and in the groundwater, mainly caused by a leak of 43 000 l of Arctic grade C fuel in 2001 at the stations power station. Arctic grade C is a low-sulphur Arctic diesel with a boiling point range of 150-275 °C.
Previous research has shown that hydrocarbon-degrading microorganisms are common in oil-polluted Arctic soils and bioremediation may therefore be an appropriate technology. In the summers of 2011 and 2012 a waterproof basin was constructed, and the contaminated soil was transferred to it – in the following called “landfarm”. In 2012 the soil was ploughed,

enriched with an agricultural fertiliser and irrigated. This process was repeated six times until 2018.[35]
A complete remediation of the contaminated soil was not achieved until 2018, although the progress was impressive. 64% of the diesel was removed in the landfarm within the first year, but a recalcitrant fraction (18%) remained after five years (**Figure 11**). The removed components consist mainly of n-alkanes, alkylbenzenes and alkyl naphthalene. Cycloalkanes, hydroxy-PAH (polycyclic-aromatic hydrocarbons) and sulphur-heterocycles had very few or no specific degraders, these compound may consequently be degraded only by slow co-metabolic processes or not at all.[35]

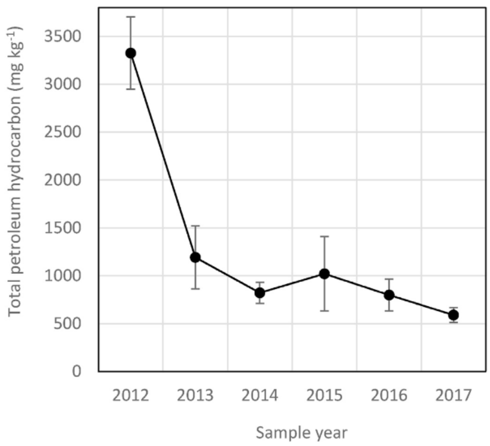

Figure 11. Changes over time in mean diesel concentration (Total Petroleum Hydrocarbon, TPH) in the landfarm. Error bars show one standard deviation.[35]

Outlook

For decades private, communal and military settlements in the Arctic operated under the assumption that the permafrost soil in the Arctic circle will contain any waste from spreading into the environment. This scenario is no longer valid under the already observed and the future forecasted warming.
In the Greenlandic context the most dangerous legacy pollutions are the dispersed radioactive isotopes from the plane crash of a Strategic Air Command plane with four nuclear warheads on board near the Thule air base. Hughe parts of the radioactive isotopes sank to the sea floor and are prone to be allocated by the currents which encircles Greenland (**Figure 2**). In this specific case, the pollution was never contained in the permafrost.
Only vaguely known in terms of position and composition are the remnants of the Camp Century complex in the Greenland Ice Sheet. The pollution contains construction waste and the typically used chemical building materials of the time, heating oil, radioactive material from a nuclear power plant and biological waste. Whether the hazardous and dangerous compounds will turn up on the surface of a quickly melting ice sheet or as polluted melt water at the mouth of a glacier is until know not foreseeable.
The location of abandoned mining and military installations from the WW II and the Cold War aera are well known. Especially in the case of the military bases the remediation status varies wildly and detailed information about the status of pollution and monitoring programs are wildly absent. Whether and when the probably existing pollution will break the permafrost barrier is unknown and currently unpredictable. The only fact known is that they will eventually penetrate the wider environment.
Municipal wastewater treatment may not be available for all Greenlandic citizens – especially in smaller communities[21,22]. With the current small population size and cold weather conditions, this fact is currently unsavoury, but not a great danger to human health. This may change in a warmer climate, as the organisms endangering human health will be able to survive in the

environment and the amount of disposed waste may be rising due to an increasing population and tourism sector.
In general, a warming climate in the Arctic will bring more commercial and recreational shipping to Greenland as new shipping routes will open. This may cause unintended consequences such as naval accidents, lost cargo, waste disposal on high sea and distribution of new species. The warming climate will bring serious challenges with respect to the mobilisation of currently frozen waste as well as new sources of pollution to the Greenlandic population. Whether the benefits of the warming climate due to higher agricultural yields, fishing and tourism can be reaped, may significantly depend on the ability of the Greenlandic society to deal with the legacy pollution.

Acknowledgments

The authors gratefully acknowledge the NATO Climate Change and Security Centre of Excellence for providing a fellowship grant to the lead author to work on climate warming related topics in the Arctic. The authors also thanks Emilie Blanchard (CCASCOE) for clarifying legal issues and to Stephanie Ricci (CCASCOE) for editorial support.

List of compounds analysed to determine whether a) water has drinking water quality and b) a soil is uncontaminated

Jutta Lauf, Kim Vetting, Cristian Ciulean, Reiner Zimmermann

Dr. Jutta Lauf, Research Fellow at the NATO Climate Change and Security Centre of Excellence, Montreal, Canada

LTC Kim Vetting, Subject Matter Expert at the Research, Analysis and Lessons Learned Branch, NATO Climate Change and Security Centre of Excellence, Montreal, Canada

LTC Cristian Ciulean Subject Matter Expert at the Research, Analysis and Lessons Learned Branch, NATO Climate Change and Security Centre of Excellence, Montreal, Canada

Dr. Reiner Zimmermann, Research, Analysis and Lessons Learned Branch, NATO Climate Change and Security Centre of Excellence, Montreal, Canada

Corresponding address: kim.vetting@ccascoe.org

Column 1: Substance
List of elements, substances, group of substances, group of bacteria, radiation and fibres important for human and ecosystem health.

BTX = Total of benzene; toluene; xylene in this context. BTX and BTEX are sometime used synonyms. But correctly used, BTEX is the total of benzene, toluene, ethylbenzene and xylene.

PCB_6 = indicator PCB's, six most common and toxic PCB's (PCB 28, PCB 52, PCB 101, PCB 138, PCB 153, PCB 180) out of 209 congeners[38].

PAH = polycyclic aromatic hydrocarbons
PAH_{16} = 16 representatives of several thousand PAH[77]

Column 2: Origin/Usage
Most important origin and uses of the named hazardous substance and its legal status.

Column 3: Guideline value WHO[44] or EU directive 2020/2184 (quality of water)[39] for drinking water
Guidelines for drinking water from the World Health Organization (WHO) and minimum requirements of the European Union (EU).

Column 4: Fish toxicity (LC_{50})
LC_{50} fish = toxicity of each substance or substance groupe is indicated using the median lethal concentration after 96 h of exposure and 50% mortality[2].

Column 5: Canadian DEW Line Cleanup criteria for soil[28]
Cleanup criteria developed for the Distant Early Waring (DEW) Line as explained in the *Abandoned Military Site Remediation Protocol* of the Canadian government. Minimum requirements are given for contaminated soils and the protection of freshwater aquatic live within 30 m of a waterbody. Different protection areas and goals lead to different minimum requirements.

Values given on the amount of soil [ppm] generally reflect to maximum amount of the substance in the soil. Soils containing one or more substances in excess of the mentioned minimum requirements are to be treated/disposed of in a manner that precludes contact the Arctic ecosystem.

Column 6. Soil content for unrestricted usage of sandy soils[78]
Minimum requirements under German law for sandy soils for unrestricted use. Different soil types and usages lead to different minimum requirements.
Values given on the amount of soil [mg/kg] generally reflect to maximum amount of the substance in the soil.

Column 7: Eluate from sandy soils for unrestricted usage[78]
Minimum requirements under German law for sandy soils for unrestricted use. Different soil types and usages lead to different minimum requirements. Sandy soils and unrestricted usage have the lowest minimum requirements of all possible cases.

Values given on the amount of percolated water [µg/l] through an artificial column of soil is a proxy of the amount of substance which can be washed out by rain.

Substance	Origin/Usage	Guideline value WHO[44] or EU directive 2020/2184 (quality of water)[39] for drinking water	Fish toxicity (LC_{50})[2]	Canadian DEW Line Cleanup criteria for soil[28]	Soil content for unrestricted usage of sandy soils[78]	Eluate from sandy soils for unrestricted usage[78]
Chemical pollutants						
Arsenic (As)	Burning of fossil fuels, metal working industry, mining[45]	WHO: 10 µg/l EU: 10 µg/l	1-10 mg/l	30 ppm	10 $mg/kg_{dry\ matter}$	14 µg/l
Cadmium (Cd)	Metal working industry, mining[45]	WHO: 3 µg/l EU: 5 µg/l		5 ppm	0.4 $mg/kg_{dry\ matter}$	1.5 µg/l
Chromium (Cr)	Mobility (tyres, breaks), mining[45]	WHO: 50 µg/l EU: 25 µg/l	10-100 mg/l	250 ppm	30 $mg/kg_{dry\ matter}$	12.5 µg/l
Copper (Cu)	Mobility (tyres, breaks), mining[45]	WHO: 2000 µg/l EU: 2000 µg/l		100 ppm	20 $mg/kg_{dry\ matter}$	20 µg/l
Cobalt (Co)		WHO: not mentioned EU: not mentioned		50 ppm		
Lead (Pb)	Mobility (fuel, tyres, breaks), mining[45]	WHO: 10 µg/l EU: 5 µg/l	1-10 mg/l	500 ppm	40 $mg/kg_{dry\ matter}$	40 µg/l
Mercury (Hg)	Burning of fossil fuels, metal working industry, mining[45]	WHO: 6 µg/l EU: 1 µg/l	<1 mg/l	2 ppm	0.1 $mg/kg_{dry\ matter}$	< 0.5 µg/l
Nickel (Ni)	Burning of fossil fuels, metal working industry, mining[45]	WHO: 70 µg/l EU: 20 µg/l		100 ppm	15 $mg/kg_{dry\ matter}$	15 µg/l
Thallium (Tl)		WHO: nn			0.4 $mg/kg_{dry\ matter}$	
Zinc (Zn)	Mobility (tyres, breaks), mining[45]	WHO: Not of health concern at levers found in drinking-water.		500 ppm	60 $mg/kg_{dry\ matter}$	150 µg/l
Total organic compounds (TOC)		EU: No abnormal change			0.5 $\%_{weight}$	

Extractable organic halogenated hydrocarbons (EOX)	Industry				1 $mg/kg_{dry\ matter}$	
PHC	Fossil fuel	WHO: Taste and odour much below critical values	10-100 mg/l	Protection of freshwater Aquatic life Non-mobile types: 0 mg/kg Mobile types: 330 mg/kg	100 $mg/kg_{dry\ matter}$	
BTX (benzene, toluene, xylene)	Industry	WHO Benzene: 10 µg/l EU Benzene: 1 µg/l WHO Toluene: 700 µg/l WHO Xylene: 500 µg/l	Benzene: 10-100 mg/l		1 $mg/kg_{dry\ matter}$	
Volatile halogenated hydrocarbon	Cooling fluids’				1 $mg/kg_{dry\ matter}$	
PCB	Electrical components, paint, coolants, fire protection Production globally forbidden since 2001[37]		10-100 mg/l	5 ppm	PCB_6: 0.05 $mg/kg_{dry\ matter}$	
PAH_{16} (polycyclic aromatic hydrocarbons)	Incomplete burning of fossil fuels[77,79]	WHO: Indicator is Benzo[a]pyrene EU PAH_4: 0.1 µg/l			3 $mg/kg_{dry\ matter}$	
Benzo[a]pyrene (a PAH component, especially toxic)	Incomplete burning of fossil fuels[77,79]	WHO: 0.7 µg/l EU: 0.01 µg/l			0.3 $mg/kg_{dry\ matter}$	
pH						6.5 – 9.5
Conductivity		EU: 2500 µS/cm				250 µS/cm
Chloride (Cl^-)						30 mg/l
Sulphate (SO_4^{-2})		WHO: Not of health concern at levers found in drinking-water. EU: 250 mg/l				20 mg/l
Cyanide	Industry	EU: 50 µg/l				5 µg/l

Phenol index	Industry					20 µg/l
Biological pollutants						
Intestinal enterococci/Total coliform bacteria	Waste water	WHO: 0 in 100 ml EU: 0 in 100 ml				
Mineral pollution						
Asbestos	Building materials Production forbidden in the EU since 2005 as well as in many industrial countries, in developing countries still in production[40]	WHO: No consistent evidence that ingested asbestos is hazardous to health	Nn		Zero contamination	Zero contamination
Radioactive Pollutants						
Gross alpha activity	Atomic bombs, nuclear reactor	EU: 0.04 Bq/l				
Gross beta activity	Atomic bombs, nuclear reactor	EU: 0.4 Bq/l				
$^{239}Pu/^{240}Pu$	Atomic bombs	EU: 0.04 Bq/l				

1 References

1. Herzberg J, Kehrt C, Torma F, eds. *Ice and Snow in the Cold War: Histories of Extreme Climatic Environments: "Camp Century" and "Project Iceworm" - Greenland as a Stage for US Military Service Rivalries*. Berghahn; 2019.
2. Langer M, Deimling TS von, Westermann S, et al. Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. *Nat Commun*. 2023;14(1):1721. doi:10.1038/s41467-023-37276-4
3. Miner KR, D'Andrilli J, Mackelprang R, et al. Emergent biogeochemical risks from Arctic permafrost degradation. *Nat Clim Chang*. 2021;11(10):809-819. doi:10.1038/s41558-021-01162-y
4. Jaskólski MW. Challenges and perspectives for human activity in Arctic coastal environments – a review of selected interactions and problems. *Miscellanea Geographica*. 2021;25(2):127-143. doi:10.2478/mgrsd-2020-0036
5. Encyclopedia Britannica. Greenland - History, Population, Map, Flag and Weather. Published December 13, 2024. Accessed December 13, 2024. https://www.britannica.com/place/Greenland
6. NOAA. National Centers for Environmental Information (NCEI). Published February 1, 2025. Accessed February 2, 2025. https://www.ncei.noaa.gov/
7. Jakobsson M, Mayer L, Coakley B, et al. The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0. *Geophysical Research Letters*. 2012;39(12). doi:10.1029/2012GL052219
8. GEBCO. The General Bathymetric Chart of the Oceans. Published February 2, 2025. Accessed February 2, 2025. https://www.gebco.net/
9. Inatsisinik nalunaarutit. Lov nr 473 af 12_06_2009. Published April 3, 2023. Accessed January 17, 2025. https://nalunaarutit.gl/rigslovgivning/2009/lov-nr-473-af-12_06_2009?sc_lang=kl-GL
10. The Copenhagen Post. In the name of the king or traitor to the crown? *The Copenhagen Post.* Published March 5, 2018. Accessed January 17, 2025. https://cphpost.dk/2018-03-05/business-education/in-the-name-of-the-king-or-traitor-to-the-crown/
11. Ritchie H, Rodés-Guirao L, Mathieu E, et al. Population Growth: Data adapted from PBL Netherlands Environmental Assessment Agency. [Gapminder, United Nations. Retrieved from https://ourworldindata.org/grapher/population]. Published December 15, 2024. Accessed December 15, 2024. https://ourworldindata.org/grapher/population?time=1840.latest&country=~GRL
12. Kleemann N. *Greenland in Figures 2020.* 21st edition; 2024. ISBN: 978-87-998113-9-7, ISSN: 1604-7397; 21st Edition. Accessed January 22, 2025. https://stat.gl/publ/en/gf/2024/pdf/greenland%20in%20figures%202024.pdf
13. Murray Nielsen A. Greenland to get new international airport at capital Nuuk. Published October 21, 2024. Accessed December 15, 2024. https://www.bbc.com/news/articles/cy4dz7l181wo
14. Ember – with major processing by Our World in Data. Electricity production by source - Greenland: Data source :Ember Energy Institute - Statistical Review of World Energy (2024). Published December 15, 2024. Accessed December 15, 2024. https://ourworldindata.org/grapher/electricity-prod-source-stacked?tab=chart&country=~GRL
15. Hannah R. Share of electricity production by source. Published April 17, 2021. Accessed April 17, 2021. https://ourworldindata.org/grapher/share-elec-by-source?country=~MAR

16. Arctic Council. Definitions of the Arctic region: AMAP. Published November 4, 2024. Accessed November 4, 2024. https://www.amap.no/documents/doc/definitions-of-the-arctic-region/248
17. Wilson SJ, Murray JL, Huntington HP. *AMAP Assessment Report - Arctic Pollution Issues*. 1998.
18. Our World in Data. Data Page: Gross domestic product (GDP): Data adapted from World Bank and OECD. [Retrieved from https://ourworldindata.org/grapher/national-gdp-constant-usd-wb]. Published December 15, 2024. Accessed December 15, 2024. https://ourworldindata.org/grapher/national-gdp-constant-usd-wb?tab=chart&country=~GRL
19. Roser M, Arriagada P, Hasell J, Ritchie H, Ortiz-Ospina E. Data Page: GDP per capita: part of the following publication:"Economic Growth". [- Data adapted from World Bank. Retrieved from https://ourworldindata.org/grapher/gdp-per-capita-worldbank]. Published December 17, 2024. Accessed December 17, 2024. https://ourworldindata.org/grapher/gdp-per-capita-worldbank?tab=chart&country=USA~DNK~FIN~SWE~NOR~CAN~RUS~ISL
20. Ritchie H, Spooner F, Roser M. Clean Water and Sanitation: "Data adapted from WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP). [Retrieved from https://ourworldindata.org/grapher/share-using-safely-managed-sanitation]. Published December 13, 2024. Accessed December 13, 2024. https://ourworldindata.org/grapher/share-using-safely-managed-sanitation?tab=chart&country=GRL~DNK~NOR~SWE~RUS~FIN~CAN~USA
21. Hendriksen K, Hoffmann B. Greenlandic water and sanitation systems-identifying system constellation and challenges. *Environ Sci Pollut Res*. 2018;25(33):32964-32974. doi:10.1007/s11356-017-9556-6
22. Hennessy TW, Bressler JM. Improving health in the Arctic region through safe and affordable access to household running water and sewer services: an Arctic Council initiative. *International Journal of Circumpolar Health*. 2016;75:31149. doi:10.3402/ijch.v75.31149
23. Rutherford GK. Soils of Some Norse Settlements in Southwestern Greenland. *Arctic*. 1995;48(4). doi:10.14430/arctic1254
24. Jiao Y, Kramshøj M, Davie-Martin CL, Elberling B, Rinnan R. The active layer soils of Greenlandic permafrost areas can function as important sinks for volatile organic compounds. *Commun Earth Environ*. 2025;6(1):32. doi:10.1038/s43247-025-02007-8
25. Krogh KJ. Erik den Rødes Grønland. *Historisk Tidsskrift*. 1982;1985(Bind 14. raekke, 6):266 s. Ill. 183 kr. http://img.kb.dk/tidsskriftdk/pdf/hto/hto_14rk_0006-PDF/hto_14rk_0006_80978.pdf
26. Binggeli M. In Grönland beginnt die Selbstversorgung mit Kartoffeln | Polar Journal. Published March 12, 2025. Accessed March 12, 2025. https://polarjournal.net/de/in-groenland-beginnt-die-selbstversorgung-mit-kartoffeln/
27. Jones A, ed. *Soil Atlas of the Northern Circumpolar Region: An Initiative of the European Union to Support the International Polar Year, 2007 - 2008 ; Activity No. 1210 Under IPY Expression of Intent*. European Commission Publ. Off. of the European Union; 2010.
28. Poland JS, Mitchell S, Rutter A. Remediation of former military bases in the Canadian Arctic. *Cold Regions Science and Technology*. 2001;32(2-3), pp. 93-105. doi:10.1016/S0165-232X(00)00022-7
29. Wallroth T, Lokrantz H, Rimsa A. *The Greenland Analogue Project (GAP): Literature Review of Hydrogeology/hydrogeochemistry*; 2010; ISSN 1402-3091. https://www.osti.gov/etdeweb/biblio/992726
30. Colgan W, Machguth H, MacFerrin M, Colgan JD, van As D, MacGregor JA. The abandoned ice sheet base at Camp Century, Greenland, in a warming climate. *Geophysical Research Letters*. 2016;43(15):8091-8096. doi:10.1002/2016GL069688

31. Abdelmonem BH, Kamal LT, Elbaz RM, Khalifa MR, Abdelnaser A. From contamination to detection: The growing threat of heavy metals. *Heliyon*. 2025;11(1):e41713. doi:10.1016/j.heliyon.2025.e41713
32. Ashar HN, Rafique HM, Zahir AZ, et al., eds. *Soil Science: Petroleum Hydrocarbons-Contaminated Soils: Remediation Approaches*. Springer International Publishing; 2016., ISBN: 978-3-319-34449-2
33. CoreBiologic. Oil Destroyer. Published February 20, 2025. Accessed February 20, 2025. https://corebiologic.com/oildestroyer
34. Barron MG, Vivian DN, Heintz RA, Yim UH. Long-Term Ecological Impacts from Oil Spills: Comparison of Exxon Valdez, Hebei Spirit, and Deepwater Horizon. *Environ Sci Technol*. 2020;54(11):6456-6467. doi:10.1021/acs.est.9b05020
35. Johnsen AR, Boe US, Henriksen P, Malmquist LMV, Christensen JH. Full-scale bioremediation of diesel-polluted soil in an Arctic landfarm. *Environ Pollut*. 2021;280:116946. doi:10.1016/j.envpol.2021.116946
36. Passatore L, Rossetti S, Juwarkar AA, Massacci A. Phytoremediation and bioremediation of polychlorinated biphenyls (PCBs): state of knowledge and research perspectives. *Journal of Hazardous Materials*. 2014;278:189-202. doi:10.1016/j.jhazmat.2014.05.051
37. United Nations Environment Programme. *Stockholm Convention on Persistent Organic Pollutants (POPS)*. [Revised in 2023]. UNEP-POPS-COP-CONVTEXT-2023.English.pdf - Suchen
38. Dreyer A. *Polychlorierte Dibenzodioxine Und -Furane (PCDD/F) Und Polychlorierte Biphenyle (PCB) in Der Außenluft Und Deposition Im Ländlichen Hintergrund Von Deutschland: Texte 75/2021*; 2021. Texte; 75. Accessed on: 29.12.2024. https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021-05-06_texte_75-2021_hintergrundmessung_teil_1.pdf
39. *Directive (EU) 2020/2184 of the European Parlament and of the Council of 16 December 2020 on the Quality of Water Intended for Human Consumption*.
40. Umweltbundesamt. Asbest. Published January 7, 2025. Accessed January 7, 2025. https://www.umweltbundesamt.de/themen/gesundheit/umwelteinfluesse-auf-den-menschen/chemische-stoffe/asbest#undefined
41. Skoog DA. *Principles of Instrumental Analysis: Chapter 32 Radiochemical Methods.* 5th ed. Saunders College Pub; 1998.
42. BASE. Radiologische Grundlagen für Entscheidungen über Maßnahmen zum Schutz der Bevölkerung bei unfallbedingten Freisetzungen von Radionukliden, Kapitel 3-15.2: Bundesamt für die Sicherheit der nuklearen Entsorgung, Wegelystraße 8, 10623 Berlin Deutschland. Published July 22, 2024. Accessed July 22, 2024., BASE - Gesetze und Regelungen - 3 Bekanntmachungen des BMUKN
43. Tochaikul G, Phattanasub A, Khemkham P, Saengthamthawee K, Danthanavat N, Moonkum N. Radioactive waste treatement technologiy: a review. *Kerntechnik*. 2022;(2):208-225. https://www.degruyter.com/document/doi/10.1515/kern-2021-1029/html
44. WHO. *Guidelines for Drinking-Water Quality.* Fourth edition incorporating the first addendum. World Health Organization; 2017.
45. Umweltbundesamt. Schwermetall-Emissionen. Published December 27, 2024. Accessed December 27, 2024. https://www.umweltbundesamt.de/daten/luft/luftschadstoff-emissionen-in-deutschland/schwermetall-emissionen#entwicklung-seit-1990
46. Rosen A. Thule, Greenland: Accident involving nuclear weapons. [Hibakusha worldwide An exhibiton by the International Physicians for the Prevention of Nuclear War]. Accessed December 25, 2024. https://www.nuclear-risks.org/fileadmin/user_upload/pdfs/HBWW/thule_web.pdf

47. Ulbak K. *The Thule Accident: Assessment of Radiation Doses from Terrestrial Radioactive Contamination*; 2011. National Board of Health; NEI-DK--5612. ISBN:978-87-7104-229-0
48. Juel K. High mortality in the Thule cohort: an unhealthy worker effect. *Int J Epidemiol*. 1994;23(6):1174-1178. doi:10.1093/ije/23.6.1174
49. US Environmental Protection Agency. EPA Facts about Plutonium. Published February 16, 2025. Accessed February 16, 2025. https://semspub.epa.gov/work/11/176324.pdf
50. Bouček T, Stará L, Pavelka K. Monitoring of the Rehabilitation of the Historic World War II US Air Force Base in Greenland. *Remote Sensing*. 2023;15(17):4323. doi:10.3390/rs15174323
51. Herzberg J, Kehrt C, Torma F, eds. *Ice and Snow in the Cold War: Histories of Extreme Climatic Environments: Inuit Responses to Arctic Militarization - Examples from East Greenland*. Berghahn; 2018.
52. Wenande C. Denmark reaches accord with Greenland over US base clean-up. Published March 12, 2025. Accessed March 12, 2025. https://cphpost.dk/2018-01-11/news/denmark-reaches-accord-with-greenland-over-us-base-clean-up/
53. McGwin K. Copenhagen to foot bill to clean up US pollution in Greenland. *ArcticToday.* Published January 11, 2018. Accessed March 12, 2025. https://www.arctictoday.com/copenhagen-to-foot-bill-to-clean-up-us-pollution-in-greenland/
54. Søndergaard J, Hansson SV, Bach L, et al. *Environmental Monitoring at Mine Sites in Greenland: A Review of Research and Monitoring Practices and Their Role in Minimising Environmental Impact*; 2020. Scientific Report from DCE – Danish Centre for Environment and Energy No. 364. ISBN: 978-87-7156-466-2
55. Cassivi A, Covey A, Rodriguez MJ, Guilherme S. Domestic water security in the Arctic: A scoping review. *International Journal of Hygiene and Environmental Health*. 2023;247:114060. doi:10.1016/j.ijheh.2022.114060
56. Eilu P, Bjerkgård T, Franzson H, et al. *The Nordic Supply Potential of Critical Metals and Minerals for a Green Energy Transition: Nordic Innovation Report*; 2021; ISBN 978-82-8277-115-3 (digital publication), ISBN 978-82-8277-114-6 (printed). Accessed January 7, 2025..
57. Andersson P, Zeuthen JW, Kalvig P. *Chinese Mining in Greenland: Arctic Access or Access to Minerals?*; 2018. Arctic Yearbook; 1-15 pp. Accessed on: 29.12.2024, Chinese Mining in Greenland: Arctic Access or Access to Minerals? - Arctic Yearbook
58. The Ministry of Mineral Resources. Grønlands mineralstrategi: Imaneq 4, B-2285, P.O. Box 930, 3900 Nuuk, Greenland. Accessed January 9, 2025. https://govmin.gl/wp-content/uploads/2020/03/Greenlands_Mineral_Strategy_2020-2024.pdf
59. CBC. Greenland bans all oil exploration. Published July 16, 2021. Accessed January 9, 2025. https://www.cbc.ca/news/business/greenland-oil-1.6105230
60. Bye H. Mining Company Greenland Ruby Declared Bankrupt. Published September 27, 2024. Accessed January 13, 2025. https://www.highnorthnews.com/en/mining-company-greenland-ruby-declared-bankrupt
61. Denton J. 'Red-carded' Australian miner signals intention to play on in Greenland. Accessed on: 09.01.2025, https://news.mongabay.com/2021/07/red-carded-australian-miner-signals-intention-to-play-on-in-greenland/
62. Lauf J, Zimmerman R. 2023: Ten years of China's Belt and Road Initiative - The fate and future of energy infrastructure projects in some NATO member states. *Energy Highlights*. 2024;(19). *ISSN 2335-7975*
63. Arctic Monitoring and Assessment Programme. *Baffin Bay / Davis Strai Region: Overview Report*; 2017; 24 pp. Accessed January 9, 2025. https://www.amap.no/documents/doc/adaptation-actions-for-a-changing-arctic-aaca-baffin-bay-davis-strait-region-overview-report/1530

64. North Pole Cruises. North Pole Cruises & Luxury Expeditions. Published October 4, 2024. Accessed February 2, 2025. https://www.northpolecruises.com/cruises/north-pole/
65. Balmasov S. Main Results of NSR Transit Navigation in 2024. *Centre for High North Logistics.* Published November 28, 2024. Accessed January 20, 2025. https://chnl.no/news/main-results-of-nsr-transit-navigation-in-2024/
66. Stewen C. Shipping through the Northwest Passage | Aker Arctic. Published November 12, 2024. Accessed January 20, 2025. https://akerarctic.fi/news/international-voyages-on-the-northwest-passage-in-2024/
67. Baffinland. Mary River Mine. Published March 12, 2025. Accessed March 12, 2025. https://www.baffinland.com/operation/mary-river-mine/
68. Nukissiorfiit. Nukissiorfiit: Water. Accessed January 21, 2025. https://nukissiorfiit.gl/da/Produkter/Vand
69. Halsband C, Thomsen N, Reinardy HC. Climate Change increases the risk of metal toxicity in Arctic zooplankton. *Front Mar Sci*. 2024;11. doi:10.3389/fmars.2024.1510718
70. Renedo M, Amouroux D, Albert C, et al. Contrasting spatial and seasonal trends of methylmercury exposure pathways of Arctic seabirds: combination of large-scale tracking and stable isotopic approaches: Accessed on: 28.01.2025, https://hal.science/hal-02969848v1 *Environmental Science and Technology*. 2020;2020(54 (21)):13619-13629.
71. AASTRUP P, RIGET F, Dietz R, ASMUND G. Lead, zinc, cadmium, mercury, selenium and copper in Greenland caribou and reindeer (Rangifer tarandus). *0048-9697*. 2000;245(1-3):149-159. doi:10.1016/s0048-9697(99)00440-4
72. Dietz R, Born EW, Rigét F, et al. Temporal trends and future predictions of mercury concentrations in Northwest Greenland polar bear (Ursus maritimus) hair. *Environ Sci Technol*. 2011;45(4):1458-1465. doi:10.1021/es1028734
73. Jermilova U, Kirk JL, Moe SJ, et al. Assessing mercury exposure to water and fish of the Mackenzie watershed using a Bayesian network analysis. *Integrated Environmental Assessment and Management*. 2025. https://doi.org/10.1093/inteam/vjae011
74. INAC. *Abandoned Military Sites Protocol: Volume I - Main Report*; 2008. Accessed November 20, 2024. https://nwb-oen.ca/sites/default/files/cms_uploads/techguides/090703-08DN082-Abandoned%20Military%20Site%20Remediation%20Protocol-IMAE.PDF
75. Contenta S. DEW Line: Canada is cleaning up pollution caused by Cold War radar stations in the Arctic. Accessed November 20, 2024. https://www.thestar.com/news/insight/dew-line-canada-is-cleaning-up-pollution-caused-by-cold-war-radar-stations-in-the/article_3b7cc76e-ddb9-5cfb-99fd-36928bd966bc.html
76. Analytical Services Unit. Sarcpa Lake Clean-Up. Published January 13, 2025. Accessed January 13, 2025. https://www.queensu.ca/asu/arctic-projects/sarcpa-lake-clean
77. Umweltbundesamt. *Was Sind Polyzyklische Aromatische Kohlenwasserstoffe (PAK), Wie Kann Ich Belastete Produkte Erkennen?*; 2010. Accessed December 29, 2024. https://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/faqs-pak.pdf
78. Länderarbeitsgemeinschaft Abfall. *Anforderungen an Die Stoffliche Verwertung Von Mineralischen Abfällen: Teil II: Technische Regeln Für Die Verwertung 1.2 Bodenmaterial (TR Boden)*; 2004.
79. Umweltbundesamt. Emissionen persistenter organischer Schadstoffe. Published December 27, 2024. Accessed December 27, 2024. https://www.umweltbundesamt.de/daten/luft/luftschadstoff-emissionen-in-deutschland/emissionen-persistenter-organischer-schadstoffe#umweltwirksamkeit-von-persistenten-organischen-schadstoffen