Environmental Science Advances

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Environ. Sci.: Adv.*, 2025, **4**, 1373

The status of domestic wastewater treatment in the Arctic†

Pernille Erland Jensen,[*ab] Débora Boratto,[c] Pekka M. Rossi,[d] Maria Velmitskaya,[d] Ida Beathe Øverjordet,[e] Hrund Ólöf Andradóttir,[f] Lisbeth Truelstrup Hansen,[bg] Inga Herrmann,[h] Rakul Mortensen,[i] Katrin Hoydal,[i] Aaron Dotson,[j] Hanne Kvitsand,[k] Elisangela Heiderscheidt,[d] Sarah Gewurtz,[l] Ken Johnson,[m] Petter D. Jenssen,[n] Anatoly Sinitsyn,[k] Bing Chen[o] and Rob Jamieson[c]

This paper provides a Panarctic review of the regulations, loads, and treatment of wastewater (WW) discharged in the Arctic region. WW regulation principles and practices vary across the Arctic nations, being based either on effluent quality criteria (Canada, Sweden and Cruise ships), recipient-based criteria (Greenland, Norway), or a combination of the two (Alaska, Faroe Islands, Finland, Iceland, Russia). Conventional centralized treatment, ranging from preliminary screening to advanced/tertiary treatment, is applied to 59% of Arctic WW. Natural centralized systems, including ponds, lagoons, wetlands, and infiltration systems, are used for the treatment of 5% of the WW in the region, while 16% is treated on-site, mostly using septic tanks, sometimes affiliated with drain fields, but small package plants and infiltration systems are also in use. Between 14–20% of Arctic WW is discharged without any treatment in line with the global regions with the highest WWT service levels. However, Arctic treatment systems frequently fail to meet regulations or have reduced requirements, and secondary treatment level or higher is accomplished for only 19% of the total WW in the Arctic region, compared to 86% in Europe and North America overall. Where treatment is absent or deficient, discharge of WW may contribute to the environmental degradation of receiving waters and pose the risk of exposure of local fauna and humans to chemical contaminants and pathogens. Ecosystem impacts have been described for communities with above 2000 inhabitants; however, more studies are needed. Most sludge in the Arctic region is landfilled or used as landfill coverage, also leaving risk of exposure. It is recommended to establish cross-regional collaboration to exchange knowledge and experience on solutions and practice, and to introduce an aligned legislation and monitoring framework to reduce the environmental footprint and the risk of exposure of WW in the region.

Received 28th March 2025
Accepted 10th July 2025

DOI: 10.1039/d5va00082c

rsc.li/esadvances

[a]Technical University of Denmark, Department of Environmental and Resource Engineering, Bygningstorvet, Bygning 115, Kgs. Lyngby, 2800, Denmark. E-mail: peej@dtu.dk

[b]Arctic DTU Sisimiut – Ilinniarfeqarfik Sisimiut, Siimuup Aqqutaa 32, B-1280, P. O. Box 3019, Sisimiut, 3911, Greenland

[c]Dalhousie University, Department of Civil and Resources Engineering, 1360 Barrington St., Halifax, Nova Scotia, Canada

[d]University of Oulu, Water, Energy and Environmental Engineering Research Unit, University of Oulu, P. O. Box 4300, 90014, Finland

[e]SINTEF Ocean AS, Department of Climate and Environment, Trondheim, Norway

[f]University of Iceland, Faculty of Civil and Environmental Engineering, Hjarðargata 2–6, Reykjavík, 107, Iceland

[g]Technical University of Denmark, National Food Institute, Henrik Dams Allé, Building 204, Kgs. Lyngby, 2800, Denmark

[h]Luleå University of Technology, Department of Civil, Environmental and Natural Resources Engineering, Laboratorievägen 18, Luleå, 97187, Sweden

[i]Faroese Environment Agency, Traðagøta 38, Argir, FO-165, Faroe Island, Denmark

[j]University of Alaska, Anchorage, Civil Engineering Department, 3211 Providence Dr, Anchorage, Alaska, 99508, USA

[k]SINTEF, AS, Department of Infrastructure, Trondheim, Norway

[l]Environment and Climate Change Canada, Science and Technology Branch, Burlington, Ontario, L7S 1A1, Canada

[m]National Research Council of Canada, Canada

[n]Norwegian University of Life Sciences (NMBU), Canada

[o]Memorial University of Newfoundland, Department of Civil Engineering, NRPOP Lab, St. John's, NL, A1B 3X5, Canada

† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d5va00082c

Environmental significance

The status and challenges of wastewater the Arctic region have received little attention in global inventories. This comprehensive Panarctic review of the status of wastewater treatment reveals how legislation, treatment technologies, and treatment levels are highly variable across the region and show significant deficits. Regulation, technologies, and inspection schemes developed for warmer and more densely populated regions have consistently shown to fail to deliver the necessary treatment quality, thus the average treatment level is lacking significantly behind. Insufficiently treated wastewater constitutes a local source of a range of contaminants, that may impact the natural environment in the Arctic region and expose the local population. Recipient ecosystems have only been sporadically investigated, and further studies and the exchange of knowledge, experience, and solutions across the Panarctic region are important to understand and reduce the ecosystem impacts of wastewater in the region.

1 Introduction

The status of wastewater treatment (WWT) among Arctic jurisdictions is not well documented. While reports point to the utilization of different wastewater (WW) management solutions across the Arctic region,[1–3] WWT system performance has been reported to be low.[3–5] For instance, operational challenges involving malfunctioning conventional systems were reported in the Canadian Arctic,[2] and failures of Arctic on-site and small-scale treatment systems were described in Finland, Sweden and Norway.[3] Globally, approximately 48% of WW was recently estimated to be discharged untreated.[6] In accordance, for some parts of the Arctic, WWT is known to be either absent or rudimentary,[7,8] but detailed information on the Arctic region cannot be retrieved from public international databases such as Global Water Intelligence or United Nations Statistics Division due to Arctic data getting lost in the data of large nations with relatively small Arctic populations, in parallel to observations for water supply services.[9] As a result, Arctic jurisdictions are either stated to have unknown wastewater treatment (WWT) or treatment levels identical to their overall national states in existing inventories.[6,10] The fraction of WW being safely (secondarily) treated in European and North American states was reported to be as much as 86% in 2022,[10] and since these states include the majority of the Arctic population, it might be anticipated that the situation in the Arctic region is equally good, but in reality this is unknown, and even questionable considering the repeated reporting about malfunctioning Arctic systems. Furthermore, the consistent reports on deficient and failing Arctic WWT systems across the region suggest that common denominators of the Arctic region apply to WWT.

Conventional WWT plants (WWTPs) are designed to remove readily biodegradable organic compounds, macro-nutrients like nitrogen (N) and phosphorus (P), and microorganisms, with the primary objectives of preventing eutrophication of receiving waters and human exposure to pathogens. In conventional plants, preliminary treatment typically involves the removal of larger particles *via* screening and filtering, while primary treatment adds the removal of suspended solids (up to 70%, including a significant fraction of the organic matter) by screening and/or sedimentation with or without chemical addition.[11] Secondary treatment removes biodegradable organics (up to about 95%) and is typically characterized by the production of a treated WW effluent with a biological oxygen demand over five to seven days ($BOD_{5/7}$) of $\leq$25 mg L^{-1} and total suspended solids (TSS) of $\leq$30 mg L^{-1}, as well as adding a disinfection effect. Tertiary treatment is used to enhance the removal of nutrients (N and P), most often *via* biological means, and to enhance disinfection. Conventional WWTPs produce sludge that contains inorganic solids, partially metabolized organic matter, sediment-bound contaminants, and chemically or biologically bound nutrients.[11] In addition to conventional WWTPs, WWT is also achieved through the utilization of natural treatment, commonly referred to as nature-based solutions or passive treatment systems, examples of which are treatment wetlands and stabilization lagoons.[1,4,12] The treatment efficiency in natural systems varies greatly and is affected by several factors, including the type of system and climate conditions.[4,12,13] In sparsely populated areas, where the establishment of sewage collection networks is not feasible due to excessive distances, small-scale on-site WWT facilities are normally used. These commonly serve from one household to a small community, or separate dwellings such as holiday resorts or schools.[3] Such small-scale systems may apply physical, chemical or biological processes similarly to larger conventional plants or natural systems, and the treatment efficiency spans preliminary to secondary levels.[3,14]

Where treatment is absent or deficient, the discharge of WW may contribute to the environmental degradation of recipient waters and pose risks of exposure of local fauna and humans to chemical contaminants and pathogens.[15] Significant discharges of insufficiently treated WW might potentially impact the environment on a regional scale. For example, microplastics potentially originating from untreated WW have been observed in the open Arctic Sea.[16] In addition to the discharge of the above-mentioned abundant WW constituents (organic matter, N, P and pathogenic microorganisms), heavy metals, persistent organic pollutants (POPs) and chemicals of emerging Arctic concern (CEACs) may be present in WW.[17] The load may be expected to increase, as communities in the Arctic grow and develop towards more modern lifestyles, including more abundant use of pharmaceuticals and personal care products (PPCPs), synthetic textiles and other industrial products. Because POPs and CEACs are of particular concern in the Arctic,[18] they are further discussed in the review by Jensen *et al.*[19] Alongside collaboration among Arctic nations on the protection of the region's environment *via* the Arctic council, each member state adheres to individual practices when it comes to treatment, monitoring and regulation of WW. Therefore, the exchange of experience and knowledge most frequently happens south-north bound internally in the states, with infrequent exchanges horizontally across the national boundaries. This may lead to a lack of awareness of experiences, progress and solutions generated in other parts of the Arctic and cause the repetition of failures and the implementation of inappropriate procedures and solutions by designers, builders and operators unfamiliar with the Arctic region.

The thematic network on Arctic water, sanitation and health (WASH) was formed under the University of the Arctic (UARCTIC) in 2016,[20] and aims to develop a Panarctic perspective on WASH-related matters. Here, we provide a first stepping-stone towards a framework of common understanding, knowledge exchange and capacity building through a Panarctic overview of current WW regulations and practices, WWT methods used, and WW loads discharged into the Arctic environment. To accomplish this, we surveyed and compiled national and international WW regulations, reports and statistics, and reviewed literature to identify challenges and best practices regarding WWT in the Arctic and its environmental impacts.

2 Methods

The WW loads by subregions of the Arctic, as defined geographically by the Arctic Monitoring and Assessment Program (AMAP),[21] were assessed as Population Equivalent (PE) loads by calculating all inhabitants and tourists in the subregions, regardless of the type of recipient. WW loads contributed by populations living outside the Arctic region were disregarded, even if their receiving water (*e.g.*, the sea or a river) transport a part of their load to the Arctic region, since this type of contribution is included in the definition of long-range environmental transport (LRET).[21] Exempt to this principle, however, were WW loads from two non-Arctic jurisdictions in Norway (Møre and Romsdal, and Trøndelag), which were included due to them discharging directly to the Arctic Ocean, and Sweden, where all Norrbotten County was included (see Section 2.10 for details). Loads from cruise ships have been included, while, for other than the major Arctic tourist destinations Iceland and Svalbard, loads from land-based tourism and incoming business travelers have been omitted, assuming that these are balanced by the local population travelling away for business and vacations. Data regarding population size and thus WW load in PE, WW collection, and treatment including sludge treatment and receiving environments was obtained *via* public/official sources and targeted inquiries to authorities in each region. Details on data acquisition and sources are given below by country. As for the evaluation of fraction and level of treatment per country, exact data were available for many of the countries while for others, assumptions based on our literature review combined with the information about legislative requirements and the Author's general familiarity with the region were made.

The graphical visualization was produced using ArcGIS Pro version 3.4. Map projection used for Fig. 1 and 2 was the North Pole Lambert Azimuthal Equal Area. For Fig. 3a (Norway) and 3b (Canada), map projections are WGS 1984 UTM Zone 36N and Canada Lambert Conformal Conic, respectively.

Scientific literature and regional grey literature were studied for information about environmental impacts and WW innovations.

2.1 Alaska

According to AMAP definitions, all of Alaska, with its almost 740 000 inhabitants, is considered Arctic. The number of inhabitants in each community including CDP's (census-designated places) estimated for 2023 by the Alaska Department of Labor and Workforce Development was used.[22] Information about community-level treatment systems was retrieved from The Alaska Certified Water/WW Operator Database for larger communities, and for smaller communities through a direct request to the state of Alaska, which provided information from a 2016 inventory.[23] Information about individual communities was combined to reflect the overall status for each of the five regions of Alaska (Far North, Interior, Southeast, Southcentral, and Southwest). The yearly number of cruise ship passengers (1.65 million to Southeast Alaska and 476 000 to Southcentral and Interior Alaska) was taken from by the Cruise Line Industry Association,[24] and recalculated to PE (36 000) following the method described in Section 2.3. Information about greywater treatment in Alaskan cruise ships was taken from the inventory made by White.[25]

2.2 Canada

In Canada, the number of inhabitants in each of the five Arctic regions (Yukon, Northwest Territories, Nunavut, Nunavik, and Nunatsiaviut) in 2021 was obtained from Statistics Canada.[26] The technology type and level of WWT and receiving water type were identified *via* a variety of sources, including reviewing water license documentation published on the websites of territorial water boards and personal communication with provincial/territorial personnel. For the Canadian Arctic, the number of yearly cruise-ship passengers (5400 passengers) was estimated based on the total cruise passengers disembarking on Canadian shores in 2023 (1.8 million) and the percentage of those associated with Arctic ports (0.3%), provided by Statistics Canada.[27] Including crew, this was recalculated to 91 PE permanent residents following the method described in Section 2.3.

2.3 Cruise ships and land-based tourism

For Cruise ships, the yearly PE load of WW discharged in the Arctic region was estimated based on numbers of passengers and crew for the individual countries (details on sources by country). For Alaska, Canada, the Faroe Islands, Greenland, Iceland and Norway, the number of crew members was calculated by multiplying the number of passengers by 0.4, which was the general average crew/passenger rate on cruise ships calculated by Vicente-Cera *et al.*,[28] and the number of "passenger and crew days" spent in the Arctic was calculated by multiplying by 4.4 for Alaska, Canada, Greenland, Iceland and Norway, which was the average number of days spent in Greenland;[29] the average stay in the Faroe Islands was one day.[30] For Iceland and Greenland, the achieved number was then divided by two due to most passengers visiting more than one harbor during a cruise. The sum of "passenger and crew days" was then divided by 365 days per year to obtain the PE load.

2.4 Faroe islands

The Faroe islands are entirely included in the Arctic region, and information on the number of inhabitants was taken from Statistics Faroe Islands.[31] Details about WWT methods, recipient types, and their current conditions were obtained through information collected from each of the 29 municipalities. The yearly load contribution from cruise ships was calculated as described in Section 2.3 using the 2003–2022 information from Statistics Faroe Islands as well as from the Port of Tórshavn.[30,31] This was determined to be 130 PE (avg. 47 437 passengers and crew per year).

2.5 Finland

The Arctic region of Finland, as defined by AMAP, includes the part of Finnish Lapland (Lappi) which is above the Arctic circle. Information on the number of inhabitants was retrieved from the 2021 population census, and the treatment methods used in conventional WWTP were obtained from the local regional authority in Lapland, Lapin ELY-keskus.[32] Information on the population connected to centralized WWTP was based on the exact number retrieved from the ELY-keskus by the municipality (when available), or if the exact number of connected inhabitants was missing, the national VEETI database, which is updated by WW utilities themselves and contains the number of connected dwellings.[33] The number of inhabitants connected to the centralized systems was then estimated using the average household size of the specific municipality multiplied by the number of house connections. If the number of dwellings connected to the sewage network was missing in the data from ELY-keskus, the number of connections to the water distribution network was used (which usually overestimates sewer connections). Considerable seasonal variations in WW discharge occur between high seasons (*e.g.*, Christmas and Easter) and low seasons (*e.g.*, May) due to the presence of several downhill skiing centers in Lapland. These centers are connected to a conventional WWTP. There are also several cottages in the region serviced by decentralized solutions with seasonal inhabitants, creating a seasonal effect on loads.

2.6 Greenland

All of Greenland is defined as being Arctic according to AMAP. The number of inhabitants in each region of Greenland, as well as cruise ship passengers docking at any harbor (187 710 in 2023) was retrieved from Statistics Greenland.[34] Information about WWT, recipient type and status was based on the most recent WW (draft) plans from each of the four municipalities which had such a plan,[35–38] while for the last municipality (Kommune Qeqertalik), information was based on personal communication with municipal employees.

2.7 Iceland

All of Iceland is defined as being part of the AMAP Arctic region. The status of WWT in municipalities releasing more than 2000 PE in 2022 was retrieved from Environment Agency Iceland,[39] 2023, and adjusted for the population of January 1st, 2022.[40] Urban and rural communities under 2000 PE were assumed to have a septic tank if discharging to an inland river or groundwater, and no treatment if discharging to the ocean. Information about adherence to legislation was obtained *via* direct communication with the Icelandic EPA. WW from cruise ships in Iceland was estimated based on projected ship arrivals and the number of passengers in the six largest harbors for the year 2023 (812 000 passenger nights).[41]

2.8 Norway

The Arctic region of Norway, as defined by the AMAP boundary,[21] includes mainland Norway above the Arctic circle (66°33′ to 71°11′N), the Archipelago of Svalbard, (76°28 to 80° 49′N), Bjørnøya (74°31′N to 19°01′E) and Jan Mayen (70°59′N to 8°32′W). However, since the more southern regions of Møre and Romsdal as well as Trøndelag discharge their WW directly to seawater included in the AMAP region, these have been included in our load estimates. The numbers of inhabitants was retrieved from Statistics Norway.[42] Levels of WWT and receiving water type were identified *via* a combination of information from the local governments, discharge allowances from the local authorities, and personal communication with provincial/territorial personnel. More detailed information regarding geographical placement and technology type of WWT in Northern Norway and sludge handling was retrieved from the Norwegian Environment Agency and Statistics Norway.[43,44] The number of cruise ship passengers in 2023 was retrieved from Cruise Northern Norway Svalbard.[45]

2.9 Russia

For Russia, information on the territories officially included in the Russian Arctic and its population (2021) was derived from Roshydromet.[46] This report uses the definition of the boundaries of the Russian Arctic used by official governmental decree as well as datasets published on the Federal State Statistics Service website, such as the All-Russian Population Census 2020 and estimations of population. Although this official “Russian Arctic Zone” (AZRF) formation, created in 2014, continued to evolve, with the addition of regions and districts added through the years, utilizing the separate statistical reports created for the AZRF economic zone made it possible to identify WW contribution from the Arctic zone itself while excluding long-range transported contributions. This was particularly relevant for Russia because the Arctic Ocean serves as a drainage basin for river catchments that occupy more than 50% of the territory of Russia and parts of Mongolia and Kazakhstan. WW-related information was retrieved from the Federal State Statistics Service,[47–49] for which the Federal Agency of Water Resources produced the datasets. In general, very limited information about the sources of information on WW was available through open access. For example, according to Rosstat,[48] polluted WW is industrial and domestic (municipal) WW discharged into surface water bodies without treatment or after insufficient treatment, but it is uncertain whether the discharge from industries with WWT systems that are separate from centralized sewage was included in the assessment.

2.10 Sweden

Within the AMAP boundaries, only the Swedish territory north of the Arctic Circle is defined as Arctic. This area comprises the Swedish municipalities of Kiruna, Gällivare, Jokkmokk and Pajala, and included 50 362 inhabitants at the end of 2023. The Arctic Council also defines the territory of Norrbotten and Västerbotten counties as the Arctic territory of Sweden. As inventories on WW in Sweden are available on a regional basis, we included all of Norbotten county, with 249 649 PE, in our inventory. Information about the fraction of WW treated by conventional plants, on-site treatment or no treatment was retrieved from the national Swedish statistics database.[50]

3 Wastewater regulation in the Arctic

The legislative aspects of WWT in the Arctic region are summarized in Table 1. WW regulation is generally in place in the Arctic region, but the regulatory criteria vary significantly, being based on either effluent quality (Canada, Sweden and Cruise ships in the 3–12 nautical miles (NM) zone), recipient ecological quality/sensitivity (Greenland, Norway) or a combination of the two (Alaska, Faroe Islands, Finland, Iceland, Russia). The most common effluent criteria are set to limit particulate matter (TSS) and organic content, measured as biological oxygen demand (BOD_5, BOD_7) or chemical oxygen demand (COD). The macronutrients P and N have limits in Finland, Iceland, Russia and Sweden depending on PE load, while site specific (SS) limits apply in Canada, Norway and Russia. Fecal coliforms are regulated in Alaska and in some Canadian communities. Finland, Iceland, Russia and Sweden appear to have the strictest overall legislative limits on organic matter and nutrients among the Arctic countries, but the site-specific requirements that apply in Canada and Norway may in reality be equally strict. No criteria are stipulated for the coastal populations of the Faroe Islands and Greenland, apart from for mining sites in Greenland. None of the Arctic countries regulate or monitor any WW constituents beyond the ones mentioned in this section. However, with the recently commenced EU Urban WWT Directive (UWWTD),[51] EU member states must establish monitoring and treatment (quaternary) for micropollutants at urban WWTPs on a continuous basis to encompass all plants serving more than 10 000 PE by 2045. This will impact a significant fraction of the WW in the Arctic regions of Sweden and Finland, as well as Norway, which adhere to EU-regulations on the matter. Because the new legislation is expected to greatly impact practices in these countries, many municipalities are currently awaiting its implementation before they make any further investments.

Most countries agree that a higher level of treatment is necessary for larger communities than for smaller ones with outfalls to the ocean. For the urban communities, secondary treatment is most often required (Alaska, Canada, Finland, Iceland, Norway, Russia and Sweden), but the PE load triggering the requirement of secondary treatment varies significantly, from >150 000 PE when discharging into the ocean in Iceland (which is more than the number of inhabitants in the capital of Reykjavik, thus promoting no secondary treatment in the country at present), to >100 PE in Finland, to as little as four households in Alaska, and secondary treatment is required for all irrespective of PE load and recipient in Russia and Sweden. In the Faroe Islands and Greenland, WWT is currently not required. In Finland and Norway, regulations define discharge limits *via* environmental permits, which may be stricter than regulation, especially for N, thus in practice requiring tertiary treatment for many WWTPs discharging to freshwater recipients or the Baltic Sea. Also, Russian legislation requires tertiary treatment for urban WWTPs discharging to sensitive recipients.

Decentralized infiltration systems are permitted and common in rural Alaska, some regions of Canada (*e.g.*, Yukon), rural Russia and the three Scandinavian countries. In Finland, small-scale systems with a proximity to any water body of <100 m have strict discharge limits. In rural parts of Alaska, Finland, Iceland, Norway, Russia, and Sweden, the usage of septic tanks is accepted for treatment followed by some type of post-treatment, such as sand/soil infiltration or a package plant. In many Faroese communities, despite there being no requirement for treatment, the usage of septic tanks connected to a clustered communal sewer system that transports the WW to ocean outfalls without any further treatment is common practice. Other permitted and common on-site systems are outhouses (pit-privies), used in Rural Alaska, Finland and Russia; these also exist in Sweden and Norway, though mainly in cottages for leisure use. In rural Greenland and northern Alaska, bucket toilets (honey buckets) are common. In outhouses, the waste is deposited in a hole in the ground and undergoes natural degradation over time. The content of bucket toilets is either discharged into the sea (Greenland), lagoons (Alaska), or plastic bags, with the content of these are deposited on a solid waste dump site (both countries). Waste from outhouses and bucket toilets does not contain any water other than from urine and feces; the greywater from sinks, showers and laundry activities is in these communities discharged separately, either to the sea or land surface (Greenland) or in lagoons (Alaska).

At sea, greywater may be discharged untreated irrespective of distance to the shoreline, while blackwater may only be discharged untreated beyond the 12 NM zone, and in the 3–12 NM zone grinding and disinfection are required as a minimum. Within the 3 NM zone, national regulation applies. Iceland and Norway permit discharge of untreated WW as close as 300 meters from the shoreline.

3.1 Alaska

The Alaskan population is distributed over 346 communities and census-designated places (CDPs) (rural regions where a population concentration is defined by the United States Census Bureau for statistical purposes only), with populations ranging widely from one person in the smallest CDP to almost 300 000 in the Anchorage Municipality. The average community size is 2100 people, but the median is 250 only, showing that small communities and WW systems are predominant. WW effluents in Alaska are regulated based on treatment level and recipient type in accordance with the Federal Clean Water Act (CWA) of 1972,[52] similarly to the rest of the US. Regulation is managed by the Alaska Department of Environmental Conservation Division of Water according to Chapter 72 of the Alaskan Law of Environmental Conservation.[53] According to the CWA, when discharged to land or surface water, secondary treatment and disinfection are required, but when emitted to the subsurface, primary treatment is permitted. More advanced treatment may be required if deemed necessary to protect public health, water systems, or the environment. Upon implementation of the CWA, it was, however, recognized that requiring small Arctic villages with only hundreds of inhabitants to apply the same standards and documentation of treatment as large cities with millions of inhabitants was impractical. Thus, steps were taken to facilitate the possibility of waivers and reduced requirements for documentation for such communities.[54] This has resulted in state authorities granting waivers for the minimum treatment. Such waivers have been issued to small villages in Alaska with domestic WW only and outfalls to the ocean, due to the ocean currents and tides rapidly dispersing and assimilating the waste.[54] But wavers have also been given to larger facilities, including the largest WWT facility in Alaska, the John M. Asplund WWT Facility in Anchorage, which treats 94% of the city's WW. This plant has an exemption to perform primary treatment and disinfection only.[55] As for industrial WW, appropriate treatment is assigned by the Department of Environmental Conservation to protect public health, public and private water systems, and the environment. The requirement for pre-approval of WW facilities does not apply to pit privies, single households, multi family dwelling systems with no more than four single-family units, or small commercial facilities with a flow of no more than 1500 gallons per day.[53] Many Alaskan systems fall into these categories, and because permits are not required, no public recordings of these systems exist. In Alaska, septage, sewage, or sludge from a collection system, septic tank, holding tank, pit privies, vault privies, honey buckets, or WWTPs may only be disposed of at a facility holding an applicable department permit or approval for disposal of that material.[53]

3.2 Canada

Canada's Arctic territory is divided into five different administrative regions (Yukon, Nunavut, Northwest Territories, Nunavik, and Nunatsiavut) with distinct territorial, or provincial governments. The Canadian Arctic has a total population of approximately 129 000 people distributed across 93 communities, with populations ranging from <150 to 28 000 people.[27] In Canada, overarching federal legislation (the Fisheries Act) prohibits the release of deleterious substances (pollutants) into fish-frequented water unless authorized by federal regulation.[56] Federal wastewater regulations established national effluent quality standards that are generally achievable through secondary-level WWT.[57] Federal regulations apply to systems that treat an average of 100 m^3 of WW per day or more, which corresponds to communities of approximately 250 people and more. These federal regulations do not apply to WW systems located in four of the five arctic regions of Canada (Nunavut, Northwest Territories, Nunavik and Nunatsiavut), as it was deemed necessary to conduct further research to be able to set appropriate standards for the extreme climatic conditions found in these areas.[58] However, the Northwest Territories and the Nunavut Territory have territorial regulations applied through Territorial Water Boards that state discharge criteria for WW on a community basis. The territorial criteria are generally limited to Biochemical Oxygen Demand, and Total Suspended Solids. The Yukon has established an equivalency agreement with the federal government, meaning municipal WW systems in this region are expected to achieve, or surpass, the level of treatment specified in federal regulations.[59] Nunavut and the Northwest Territories have individual public boards that are responsible for establishing treatment standards for municipal WW systems in their region through a Water License for each community, and as such, there is considerable variability in effluent quality standards. Nunavik and Nunatsiavut are under the regulatory jurisdiction of the province where they are located. Provincial/territorial site-specific effluent quality limits apply to these Canadian WW systems, some of which may be equally to or less stringent than federal standards. In Canada, there are no national regulations pertaining to the management of sludge and biosolids from municipal WWT facilities,[60] and individual provinces and territories have established their own regulations for the use of WW biosolids for various end-uses.

3.3 Cruise ships and other vessels

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international agreement covering the prevention of pollution of the marine environment by ships from operational or accidental causes (International Maritime Organization, 2024). MARPOL includes cruise ships and other large vessels (400 gross tonnage and above) maneuvering in the international waters of the Arctic region. Annex IV, which went into force in 2003, is intended to prevent pollution by WW from vessels. Untreated WW may be discharged beyond 12 NMs from the nearest land as it is generally considered that on the high seas, the oceans are capable of assimilating and dealing with raw WW through natural bacterial action.[61] When the ship operates an approved WWTP or is discharging comminuted (ground) and disinfected WW using an approved system, it can discharge sewage beyond three NMs from the nearest land. To facilitate dilution, recommendations on maximum discharge rates as a function of the draft are given.[62] Regulatory criteria are given for fecal coliforms, TSS and BOD_5 in the effluent in Annex A of the International Effluent Standards for WWTPs.[63] Greater requirements for treatment apply to Special Areas and Particularly Sensitive Sea Areas, but no such area has been appointed in the Arctic. The OSPAR convention (1992), valid for Arctic waters among others, states that dumping of waste in international waters is prohibited, but disposal in accordance with MARPOL is not considered dumping.

In national waters (*i.e.*, within the 3 NM limit), vessels must meet national regulations. For example, in Canadian national waters, cruise ships certified to carry more than 100 people and equipped with overnight accommodations must not discharge WW within 3 NMs from shore where safely, technically, and geographically possible, and if WW is discharged, treatment for fecal coliforms (disinfection) to the same standard as required for the 3–12 NM zone is required and discharge must not contain any visible solids or cause a sheen on the water, discoloration of the water or its shorelines or entail WW sludge or an emulsion to be deposited beneath the surface of the water or on its shorelines.[64] In Alaskan national waters, large vessels (>250 overnight accommodations for passengers) must treat their WW, and the discharge must be at, or below, permit limits before it can be discharged. Discharging ships can have end-of-pipe limits (effluent criteria) or an authorized mixing zone requirement, which allows for a small area of dilution beside the vessel.[65] The requirements are <150 mg L^{-1} TSS, <60 mg L^{-1} BOD_5, and <40 MPN per mL fecal coliforms. Cruise ships are required to sample, report, and address monitoring issues as they occur.[66] Small vessels (50–249 accommodations for passengers) have less stringent discharge limitations than their larger counterparts, but still closely mirror the discharge limitations placed on many shore-based dischargers like municipal WWT facilities (*i.e.*, <150 mg L^{-1} TSS and <200 MPN per mL fecal coliforms).[67] According to the Cruise Lines International Association Alaska,[68] cruise ships in Alaska treat their WW beyond requirements to some of the world's most stringent standards. However, according to the Cruise Ship Report Card published by Friends of the Earth, major cruise companies score poorly with regards to WWT, with all 18 companies reviewed scoring 'C' or lower (on a scale of A to F).[69] It should be noted that ships with advanced WW treatment systems were downgraded from A to C in 2020 because no companies had publicly reported their performance since 2019.[69] Greenlandic legislation prohibits discharge of WW from vessels larger than 400 GRT (gross register ton) or more than 50 people within the 3 NM zone unless treated by an approved treatment facility and not leaving visible traces.[70] Exemptions can, however, be granted for vessels not regularly leaving the 3 NM zone, indicating that common practice may be to dispose of in international waters rather than implementing advanced treatment. No inspection of vessel WW discharge is in place in Greenland territories. In Iceland, the eight article within the law on protection against pollution of seas and beaches nr. 33/2004 states that discharge of WW from ships is not permitted in harbor areas or within 300 meters from the shoreline (as determined at the lowest monthly ebb tide), which is less strict than the regulations set out in MARPOL. Vessels larger or equal to 400 GRT or registered to carry >15 people are, however, not permitted to discharge WW within the 12 NM zone of the territorial sea line. WW that has been treated using technology approved by the Icelandic Transport Authority (or similar governmental authority of another state) may be discharged outside of the 3 NM zone. Port authorities are responsible for the availability of adequate reception facilities in ports to receive waste from ships, including WW. For example, if a ship wants to discharge WW ashore, it is usually handled by having a pump truck come to the side of the ship to receive the waste. In general, however, environmental agencies do not have information on where vessels discharge WW. Cruise ships in Faroese territorial waters need to follow similar rules, with restricted discharge of treated WW only permitted if at least 3 NMs from land, and discharge of untreated WW only allowed if at least 12 NMs from the coast. The regulation "Environmental safety for ships and mobile offshore units" sets out the rules for the dumping of WW from ships in Norwegian territorial waters.[71] It is prohibited to release WW, gray water, wash water and similar in any freshwater body. In Norwegian coastal waters, it is permitted to release untreated WW as close as 300 meters. Ships that have treatment facilities that fulfill the requirements of MARPOL IV/9.1.1 are exempted from the 300 meter rule and may discharge even closer. The background for the less strict rules for WW dumping in Icelandic and Norwegian (Arctic) coastal waters compared to the MARPOL regulations is that it is believed that the dilution effect is sufficient to prevent environmental impacts from WW pollution. Stricter regulations have recently been adopted for five World Heritage fjords on the west coast of Norway and for the Oslo fjord (not Arctic) in the south due to observed effects of nutrient pollution.

3.4 The Faroe islands

Faroe islands are a self-governing territory within the Kingdom of Denmark, and have authority over the majority of policy domains, including environmental policy. Administratively, the Faroe islands are split into 29 municipalities, with populations varying from 42 to 23 315 residents, making a total population of just under 55 000 people.[31] Faroese regulation does not explicitly require WW treatment. Instead, the regulation mandates that WW must be discharged in locations where ocean currents ensure sufficient dilution and dispersion, ideally dispersing the WW in the ocean at a suitable depth and distance from shore to minimize environmental impact. The regulation also allows for alternative solutions if approved in a WW management plan.[72] The executive order mandates the regular removal of sludge from septic tanks. Another executive order specifies that the removed sludge must be treated (dewatered) and disposed of in an approved facility for incineration or landfilling. In practice, the commonly used septic tanks are typically emptied approximately once per year.[73]

3.5 Finland

The Finnish region above the Arctic Circle includes 13 municipalities, four of which overlap the Arctic Circle. These municipalities have a total population of 111 000 inhabitants. The largest city in the region is Rovaniemi with 64 000 inhabitants of which 54 000 live in the main urban area, just south of the Arctic Circle. All municipalities have centralized WWTPs serving the urban regions, and each WWTP has operational requirements defined by the municipality and regional environmental authorities *via* environmental permits. All inhabitants within the sewage network coverage are required to connect. WWTP regulations are defined by the Finnish national decree,[74] based on EU directives but with additional restrictions based on local environmental sensitivity. Based on the information given by the regional authorities,[32] 81% of the inhabitants in the region are connected to a sewage network, and thus centralized treatment. Each WWTP needs an environmental permit, which might require stricter limits than the ones stated in Table 1, depending on local conditions, according to the "no environmental harm principle" of the EU. All Finnish WWTPs discharge to freshwater lakes and rivers, which in turn discharge to the Baltic Sea, except the River Ivalojoki and Tenojoki situated in Inari and Utsjoki municipalities, which flow to the Arctic Sea. In rural areas, which are not serviced by centralized WWTPs, decentralized WWT (on-site and small-scale systems) is utilized. Decentralized and onsite treatment have separate regulation, with limits for basic and sensitive areas defined by decree.[75] This legislation has been a controversial topic in Finland in previous years and the debate has resulted in the implementation of variable requirements depending on, for example, the age of inhabitants, distance to surface water or aquifer area, the age of the dwelling, and whether there has been recent renovation on the property. Each municipality is responsible for registering the onsite treatment systems alongside construction permits for the individual dwellings. This information is, however, generally scattered and not easily available in all municipalities. Therefore, exact information on the decentralized WWT methods is lacking. In general, the methods engaged are holding or storage tanks (to be emptied and sewage transported to local WWTP), septic tanks (sometimes followed by infiltration systems), package plants or outhouses. Disposal of sludge in landfills is forbidden in Finland. Sludge management options depend on local services and transport distances. Common options include: (i) composting onsite or by local contractors with compost used in landscaping and landfill coverage, (ii) transport to a mixed feed anaerobic digestion plant, or (iii) transport to a waste incineration plant. Sludge from septic and holding tanks is collected by contracted services and transported to nearby conventional WWTP for treatment.

3.6 Greenland

Like the Faroe islands, Greenland is a self-governing region of the Kingdom of Denmark, and exercises control over most of its policy areas, including environmental policy. Greenland is administratively divided into five municipalities with 17 towns (historical administrative centers typically with >500 inhabitants) and 52 affiliated smaller communities with 10–500 inhabitants. The total population reached 56 000 in 2022 with almost 20 000 living in the capital of Nuuk.[34] Based on the recommendations of a report made in 2005,[76] when Greenlandic environmental policy was still under Danish jurisdiction, WWT has not been introduced in Greenland. It was concluded that the receiving environments (almost exclusively the sea) were mostly unimpacted by domestic and other types of WWs and that treatment for the removal of organic matter and nutrients was thus not necessary (*i.e.*, dilution is the solution). The relevance of treatment was, however, mentioned as a future possibility for WW discharge to receiving environments with low water exchange or where local visual impacts or eutrophication could be observed. Only nutrients and organics have been mentioned in relation to WW legislation in Greenland, even though it has been illegal to release harmful chemicals to the sea or freshwater in Greenland since the introduction of the Environmental Act of 1988.[77] According to current WW law, the municipality is the local pollution control authority for up to 50 PEs, although the ministry may require WWT be implemented if deemed necessary to protect specific receiving environments,[78] but this has not been done thus far. A noteworthy exception in Greenland is the introduction of specific WW standards for the raw material sector in Greenland.[79] Here, specific outlet criteria for nutrients and organics are stated not only for the process WW but also for domestic WW from the mine staff. In addition, criteria are given for toxic elements, nutrients and organics in the receiving environment.[79] Thus far, however, the mines operating in Greenland are small scale and have been exempted from treatment of domestic WW. With no WWT, no sludge is produced, thus no regulation of sludge disposal is in place.

3.7 Iceland

Iceland is a small island nation with 89% of its 377 053 inhabitants living in urban areas along the coastline.[40] 63.5% of the population resides in the capital region of Reykjavík, in the southwest of the country. To this must be added the significant land-based tourism because, according to the Icelandic Tourist Board,[80] as many as 2.2 million tourists spent a total of 7.8 million nights in Iceland in 2023, adding up to 21 370 PE. Federal regulation stipulates WWT requirements based on two factors: (i) BOD_5 loading (measured in people equivalent, assuming each person is responsible for 60 g BOD_5 per day), and (ii) the sensitivity of the receiving waters to nutrients.[81] The guiding principle is that communities with >2000 PE must perform secondary treatment, with additional nutrient removal if the load is >10 000 PE and the receiving water is sensitive, such as freshwater rivers. If the eutrophication and oxygen depletion risk in receiving waters is low, as for example in estuaries and the ocean with high water renewal, municipalities with 10 000–150 000 PE may conduct less stringent, primary treatment. Smaller municipalities must perform "appropriate" treatment. All WWTPs serving >50 PE must operate under conditions stipulated in a work permit that is overseen by the local Health Inspection Authorities. The work permit details the handling of sludge, which should not pose harm to the environment. Overall, there is limited central reporting of sludge handling. Similarly, the local Health Inspection Authorities and Environmental Agency of Iceland can set requirements to pre-treat industrial WW if it includes, for example, toxicants or high levels of fats, oils and/or proteins. To date, most industries pre-treat their wastes before discharging either into the centralized WW collection system or directly to receiving waters.

3.8 Norway

The Arctic region of mainland Norway includes a total of 439 320 inhabitants in 66 municipalities within three different counties north of the Polar circle: 27 municipalities in the county of Nordland (four of which are situated on both sides of the Arctic circle – the municipalities of Rana, Rødøy, Lurøy, Træna), 21 municipalities in the county of Troms, and 18 municipalities in the county of Finnmark. These municipalities have a population of 194 657 inhabitants (Nordland, north of the Polar circle), 169 610 inhabitants (Troms), and 75 053 inhabitants (Finnmark).[42] The largest city in mainland Arctic Norway is Tromsø, with 78 745 inhabitants, followed by Bodø (53 712 inhabitants), Alta (21 708 inhabitants) and Narvik (21 580 inhabitants). Additionally, we also considered PE load from the non-Arctic jurisdictions in Norway that discharge directly to the Arctic Ocean, Møre and Romsdal, and Tøndelag, with 270 624 and 482 956 inhabitants, respectively.[42] This adds up to 1 192 900 inhabitants considered to contribute WW directly to an Arctic recipient from northern Norway. In addition, there are 2552 inhabitants in the two Norwegian settlements at Svalbard. To the Svalbard load was added land-based tourism (139 371 tourist days or 382 PE)[82] and 390 PE from Russian communities. There are no permanent settlements at Bjørnøya or Jan Mayen. WW purification regulations in Norway are defined by the regulation on the imitation of pollution, part 4 on WW,[83] which sets national minimum requirements for the treatment of WW and the control of discharge. All municipalities in Artic Norway have centralized WWT systems, with the region of operation defined by the municipality. Residents inside this region are required to join the sewage network. Residents outside of this region have decentralized solutions such as septic tanks and disposal fields or, less often, small scale treatment systems. The WW systems of the region discharge to the open sea or fjords connected to the Norwegian Sea, or to freshwater lakes and rivers with catchments discharging to the Norwegian Sea. The requirement for treatment varies and depends on the vulnerability of the local receiving water towards eutrophication and other types of contamination, as well as on user interests. Discharge regulations of decentralized sanitation are defined by the regulation on the limitation of pollution.[84] The municipality is the local pollution control authority for up to 50 PE and can set stricter treatment requirements for decentralized WWT than the standard requirements by preparing local regulation.[83] The purpose of local regulation is to better protect recreation areas, drinking water or vulnerable areas in general. Municipalities are required by law to collect WW sludge from private septic tanks and to arrange facilities for the collection of WW from camper vans and leisure boats, *etc.*[84] The collected sludge and WW is mostly transferred to the centralized WWTPs. Sludge from the WWTPs is preferably used as fertilizer and soil improvement in parks and agricultural lands. Incineration requires a permit from the national pollution control authority (Miljødirektoratet), and landfilling is prohibited.[44] The revised regulations promote recycling but sharpens the quality criteria, which are performance based, and suggest that the sludge treatment method is unimportant as long as the set quality criteria are met.[84]

3.9 Russia

The main regulations concerning WW discharge and treatment in Russia are the Water Code of the Russian Federation, Federal law No. 7-FZ "On Environmental Protection", the Resolution of the Government of the Russian Federation 15.09.2020 No. 1430 "On approval of technological indicators of the best available technologies in the field of WWT using centralized WW disposal systems of settlements or urban districts", Code of Practice 32.13330.2018 "SNiP 2.04.03-85 Sewerage, pipelines and wastewater treatment plants" with Amendments No. 1 (2019), No. 2 (2021), No. 3 (2023), and two resolutions from the Chief State Sanitary Doctor of the Russian Federation – SanPiN 1.2.3685-21 and SanPiN 2.1.3684-21 (this type of resolutions is usually frequently updated). WW effluent criteria are set in accordance with the Government Resolution No.1430 of 15.09.20 in Russia. The legislation (Government Resolution No. 1379 of 26.10.2019 used in GR No. 1430 of 15.09.20) specifies effluent quality criteria based on the receiving water sensitivity, where waterbodies are divided into categories: A (A) most protected (*e.g.*, nature parks, lake Baikal, *etc.*); B (Б) the Caspian, Black, Baltic Seas, the Sea of Japan, the Sea of Azov, swamps, streams, canals, *etc.*; C (В) the Pacific Ocean, ponds, some rivers, flooded quarries, *etc.*; and D (Г) some rivers and less valued waterbodies. Likewise, WWTPs are divided into categories based on their capacity in terms of volume of WW discharged (here recalculated from m^3 per day to PE assuming 100 m^3 per day per 250 PE as in Canada): super-large and largest (>0.5 mio. PE – no such cities are found in the Arctic region), large (100 000–500 000 PE), big (25 000–100 000 PE), medium (10 000–25 000 PE), small (2500–10 000 PE), tiny (250–2500 PE), and ultra-tiny (25–250 PE). Effluent quality criteria are defined based on combined categorization. According to the Code of Practice 32.13330.2018 (with amendments), the mandatory stages of treatment of municipal and industrial WW, regardless of the capacity of the facilities and discharge conditions, are the removal of coarse mechanical impurities, biological purification, disinfection, and dewatering of the resulting sediment. Sludge must be dewatered and stabilized for odor reduction, disinfection, and the improvement of physical and mechanical properties to ensure the possibility of environmentally safe disposal or storage. The temperature of WW entering biological treatment must be no lower than 10 °C and no higher than 39 °C. If necessary, temperature adjustment (heating, cooling) should be provided. The possibility of using biological or biochemical phosphorus removal must be confirmed through calculations based on the quality indicators of WW and the requirements for the quality of purified water. Septic tanks can be used if PE is less than 100 (1 cell septic tank < 5 PE, 2 cells < 50 PE, 3 cells < 100 PE) followed by soil-based treatment. In addition, an amendment introduced in 2022 to the Water code of the Russian Federation prohibits any discharge of sewage on glaciers.[85] In Russia, WW accumulated in septic tanks is pumped out by sewer trucks and transported to a WWTP.[8]

3.10 Sweden

In Sweden, WW management is regulated in different ways depending on the size of the treatment facility. Two national authorities provide guidance regarding WWT to local supervising authorities. For WWT facilities designed for 200 PE or more and for industrial WW, guidance is provided by the Swedish EPA. The Swedish Agency for Marine and Water Management (SwAM) provides guidance for domestic WWT up to 200 PE. Sweden is divided into 21 counties/regions and 290 municipalities, each overseen by local governments with different responsibilities. For WWTPs designed for 2000 PE or more, the County Administrative Boards are the supervising authorities, with WWT below 2000 PE supervised by the municipalities. The management and governance of WW systems is regulated through a number of different national laws, *i.e.*, the Swedish Environmental Code (SFS 1998:808), the Public Water Services Act (SFS 2006:412) and the Ordinance Concerning Environmentally Hazardous Activities and Protection of Public Health (SFS 1998:899). The Public Water Services Act states that it is the responsibility of the municipalities to manage WW services, rather than responsibility being on the property owner, if there are any risks to the environment or human health and if the area in question is large (§ 6, SFS 2006:412). The treatment requirements for WWTPs designed for 200 PE or more are stipulated by the permitting authority (*i.e.*, the County Administrative Board), who regulates the discharge of BOD and P in the arctic region on a site-specific basis. The treatment requirements for on-site WWT (<200 PE) are stipulated in the Advice for Small Treatment Facilities for Domestic WW (Swam, 2016). The removal requirements are 90% for BOD and 70 to 90% for P, depending on the sensitivity of the receiving water.[86] The removal of N or treatment of N compounds is generally not required in the Arctic region of Sweden. The sludge produced in WWT can be used in agriculture if it meets requirements on the concentrations of heavy metals, as stipulated in ordinance 1998:944. There are also limits on the amount of phosphorus allowed to be spread on agricultural land through organic fertilizers.

4 The status of wastewater treatment in the Arctic

4.1 Exempts to requirements substantiated by arctic conditions

Possibilities for exemptions to the national WW regulations for systems in the Arctic region are common in all parts of the Arctic region, where WWT is required (Table 1), and often substantiated by the cold climate. Waivers for treatment given to small communities with outfalls to the ocean in Alaska are in line with the absence of requirements for treatment in Greenland and Faroe Islands, where all communities are relatively small and have outfalls to the ocean, as well as site-specific practice in Norway, where small coastal communities are also not required to treat WW. In contrast, in the Canadian Arctic, exemption from treatment is not explicitly stated as an option, but due the Arctic climate, national regulation is exempt, and less strict site-specific requirements apply in four of the five Arctic territories. The fact that only 24% of the population in Nunatsiavut is serviced by any form of WWT indicates a practice of issuing exemptions in this part of the region. In Iceland, the emission of untreated WW is not permitted, but reduced treatment performance is accepted in cold weather, which is common in Iceland, and preliminary treatment only (filtering) is accepted if the recipient is not sensitive, which in practice means if the outfall is to the sea. On this basis, the mechanical treatment technologies adopted in the largest urban areas, as well as a selection of smaller communities, do not satisfy the 50% TSS and 20% BOD_5 removal stipulated (primary treatment), and thus most of the WW in Iceland is preliminarily treated only. In Sweden, WWTPs (>200 PE) are exempt from N removal (tertiary treatment) in the northern part of the country, prompting no requirement for tertiary treatment in the Arctic region of Sweden. Before 2022, a similar exemption was given in Russian systems at temperatures below 12 °C, but this option ceased with new legislation. Finland, on the other hand, issues exemption from requirements in rural areas based on non-climatic parameters, such as age of dwellings and inhabitants.

4.2 Arctic system challenges and deficits

Despite the above-mentioned reduced requirements and exemptions from regulatory requirements, many Arctic communities suffer further issues with adherence to regulations. This is especially true for small and on-site treatment systems. In the Faroe Islands, a significant portion of the WW is discharged to recipients that do not align with the requirements of the executive order of the Faroese Environment Agency. In Finland, Norway and Sweden, usage of septic tanks without secondary treatment is still common for many single households and smaller settlements, despite being banned for decades,[3] however, in Norway, this is only when the effluent is discharged to the open sea. In Finland, it is estimated that >65% of properties outside sewage network areas are served by septic tanks or other types of system which do not meet regulatory requirements.[3] A survey in four Arctic municipalities of Sweden (Kiruna, Gällivare, Pajala and Jokkmokk), revealed that approximately 37% of the septic tanks did not meet the requirement of secondary treatment, and thus met primary treatment level only,[87] and in general the function of particularly privately owned and managed onsite/natural WW systems (*e.g.*, soil-based infiltration systems) pose many challenges in Sweden. In Iceland, only two of the 29 municipalities with >2000 PE satisfy the treatment requirements of the regulation.[39] Some of the issues regarding WWT in Iceland pertain to small treatment plants, which are required to have a work permit defining a monitoring program issued by local Health Inspection Authorities (if >50 PE), but as there is not enough capacity at the local level to issue these work permits, there is no monitoring program. Moreover, the locations of many small facilities are not registered. Package treatment systems have become increasingly popular as an onsite treatment system in Scandinavia over the last three decades.[88] Despite independent certification according to EU-standards, several do not meet the requirements for public use in Norway and Sweden.[89,90] Recent investigations (unpublished) show little improvement and almost 50% do not meet all the requirements. Lack of maintenance is a major problem, but equipment malfunction and failure to meet the varying load conditions posed by different families also influence results.

Larger Arctic WWT systems may also fail to meet regulatory criteria. In Canadian pond and lagoon systems, treatment performance was strongly influenced by interannual climate variability and only met the level they were designed for a fraction of the time.[91] Mechanical WW systems in the Canadian Arctic face a significant number of challenges with design, construction, operation and maintenance.[2] The process design of the systems must carefully consider operational fluctuations that may result from the seasonal dilution of the WW caused by additional flows associated with freeze protection, high strength WW associated with truck sewage flows, and the equalization of WW flows with the intermittent nature of truck sewage collection. Facility design must also take into consideration the extreme cold in the design and operation of the building envelope. The construction of these systems is very expensive, as is their operation and maintenance.[92] For example, the capital cost of the mechanical WW system serving Dawson City (*ca.* 1600 PE) was $30 million (CDN$, 2010). The operation and maintenance cost for the Dawson City facility has been estimated to be $1 million per year (CDN$, 2010). Operation and maintenance must also consider cold climate operation with bacterial cultures that must be maintained. The operation of the mechanical systems must consider the human resource requirements, as well as the training and certification of human resources.[93] Regulatory frameworks for all WW systems in the Canadian Arctic have come under increased scrutiny in the past decade, meaning the system design must consider this requirement.[94] In the Arctic region of Norway, only 47% of the population was serviced by WWT that met legislative requirements in 2016, while 31% did not and 21% was undocumented.[95] The National Norwegian numbers were slightly better at 55%, 22%, and 12%, respectively,[95] which underlines the fact that treatment is especially challenging in the Arctic region, even in places with plentiful economical and educational resources. For example, in the largest town in Svalbard, Longyearbyen, a mechanical filter installed in the spring of 2024 was inoperative for almost a full year. The frequent issuing of exemptions from requirements to WWTPs in Norway, however, should be halted with the implementation of a new EU directive.[51] Russia, despite having the strictest and most detailed regulatory criteria of all Arctic countries, discharged between 427 and 594 million cubic meters of untreated or insufficiently treated WW into the Arctic environment in 2021 according to Russian public statistics,[46–48] this accounts for 64–84% of Russian Arctic WW. However, due to the strict Russian treatment requirements, the phrasing of the public statistics leaves much room for interpretation as to whether it is mostly untreated or is treated to a level lower than required. One report states that 89.6 million cubic meters of completely untreated WW was discharged in the Russian Arctic Zone in 2021.[96] This is equivalent to 13% of Russian Arctic WW. On top of this number, decentralized and unmonitored sanitation serves more than 27% of the overall Russian population and 76% of the Russian rural population, with at least 4% not having any sanitation at all in Russia.[96] Where centralized sanitation is in place, 46% (93 438 km) of the sewer network was reported to be in need of complete replacement,[49] creating a risk of nonintentional leakage of untreated WW to sensitive recipients or exposure of humans or animals. As an example, in the Nenets autonomous okrug in the northwestern part of Russia, which is a rural Arctic region with 44 000 inhabitants, 2.5% of the population were reported to have centralized sewerage, 62.5% had decentralized sewerage, and 35% had no sewerage at all.[97] Vialkova and Glushchenko found that more than 60% of the communities in the Nenets autonomous okrug either don't have WWTPs or have very low-efficiency plants that do not treat WW to the required standards, partly due to WWTPs with biological treatment being challenging in the Arctic climate.[8]

Generally, in the Arctic region, monitoring and recipient status evaluation is absent or deficient. Due to a lack of (human) resources and transportation related issues, sampling and analysis is highly challenging. In Iceland, monitoring of treatment systems and receiving waters was found to be non-adequate; only three of 62 municipalities operating primary or secondary WWT carried out inspections and monitoring in full accordance with the requirements of the regulation to justify that primary treatment was sufficient. On-site systems like septic tanks can be resource intensive to monitor, meaning this is rarely done. Where passive treatment systems like post treatment fields after septic tanks, ponds and wetlands are used, it is notoriously challenging to collect representative samples *e.g.* due to uncontrolled discharges from some lagoons making it difficult to orchestrate the sampling with the lagoon discharge. In addition, WW is dispersed and mixed with precipitation in the wetlands.[98] Likewise, in Arctic Sweden, the supervision of particularly privately owned and managed onsite/natural WW systems (*e.g.*, soil-based infiltration systems) poses many challenges, since their functioning cannot be measured directly, making only visual inspection possible in many cases. Therefore, it is challenging for the local authorities to follow up on old or malfunctioning systems. In addition, Swedish authorities have trouble assessing on-site treatment units when issuing new permits due to suppliers bringing new units to the market with unclear performance. The assessment of recipient impacts is also challenging in the Arctic. For example, no standard ecotoxicological methods engage Arctic species,[99] and the evaluation of vast recipients, widely spread geographically in a region with challenging infrastructural connectivity, has high resource requirements. As an example, only one of five municipalities in Greenland evaluated the recipient status for all recipients (Kommune Kujalleq, 2020) to justify their exemption from treatment,[36] while three municipalities evaluated recipients in their largest communities.[35,37,38] The evaluations were, however, based on visual inspections only, apart from in the capital, where coliforms and benthic conditions were investigated on one occasion.[37]

The failures of both conventional and small-scale systems in the Arctic may be due to several factors, including extreme climate, a lack of experience of engineers, builders and operators working in the Arctic, and the remoteness of communities leading to a lack of service availability and information sharing.[2,3]

4.3 Load and treatment principles for Arctic domestic wastewater

Based on the provided information on current legislation, known deficits, and data on population and treatment retrieved from literature and environmental agencies, the PE load and treatment type of domestic WW in the AMAP region was estimated. The result is illustrated in Fig. 1 (data summarized in Table S1†). Due to limitations in the available information, particularly in the larger countries with significant rural populations, the following interpretations were made. For Alaska, it

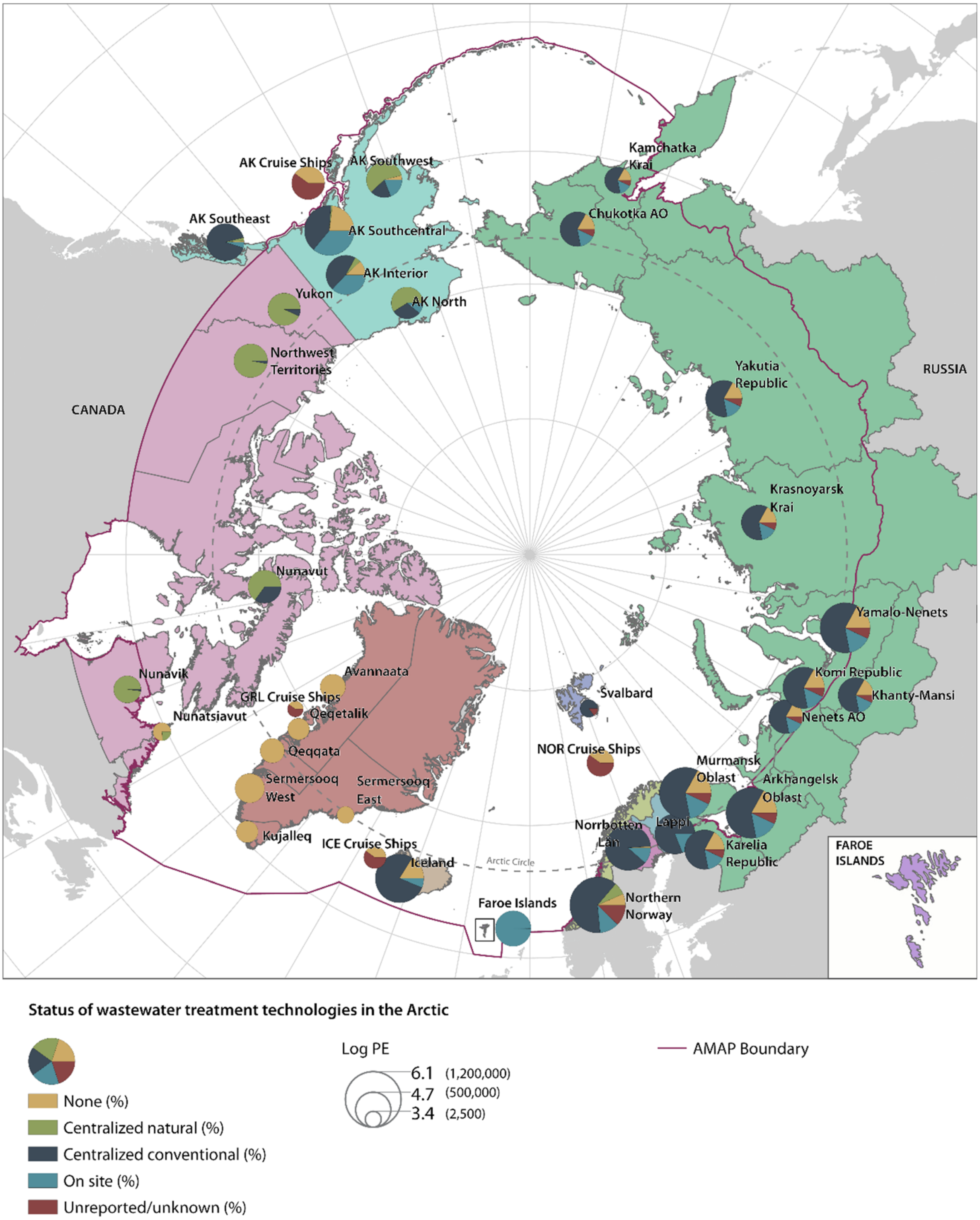

Fig. 1 Wastewater treatment technologies applied and PE load for domestic wastewater in the Arctic region. Centralized natural treatment includes ponds, lagoons, wetlands, and infiltration systems; conventional plants include systems ranging from preliminary screening to advanced/tertiary; on-site treatment includes septic tanks with/without drainfield, small infiltration systems and package plants as well as outhouses.

was roughly estimated that communities with no sewer system stated to be available (NA) and CDP districts, where no information was given, had 75% onsite treatment (such as septic systems) and 25% no treatment. This may overestimate the share of no treatment and/or on-site treatment in those specific communities. Conversely, for communities serviced by centralized lagoon/wetland treatment systems or conventional WWTPs, 100% of inhabitants were assumed to be connected to those treatment systems, most likely underestimating the households that have on site systems or no treatment. For Russia, due to the mentioned space for interpretation of the statistical information, we roughly estimated that the 80% of the Arctic population living in the nine largest cities (Arkhangelsk, Yakutsk, Murmansk, Severodvinsk, Norilsk, Petropavlovsk-Kamchatsky, Novy Urengoi. Noyabrsk, and Magadan) were connected to centralized conventional treatment plants and 10% have no treatment due to, among other issues, aging and, reportedly, leaky sewer systems. This can be seen in the numbers given by Russian public statistics,[47] and is supported by an experiment in the city of Saint Petersburg outside the Arctic region in 2014 described in a local newspaper, where volunteer ecologists flushed hundreds of GPS trackers down toilets in several apartment buildings. Approximately 10% of them reached the Gulf of Finland within three weeks, demonstrating the lack of even preliminary wastewater treatment in some districts of the city.[100] As for the rural population outside these cities, we roughly estimated that 35% had no treatment (7% of the total population) and 65% have on-site systems, identically to the situation in the rural Nenets autonomous okrug.[97]

The total Arctic region has a combined population of 5.2 million inhabitants. As nearly half of the population lives in Arctic Russia (43%), followed by Northern Norway (23%) and Alaska (14%), WW emissions are not uniformly spatially distributed throughout the Arctic. The majority of WW (56%) and 43% of the untreated WW load are discharged in the southeastern area of the AMAP geographical coverage, including the regions of northern Norway, Norrbotten Län – Sweden, Lappi – Finland, Murmansk Oblast, Arkhangelsk Oblast and Karelia Republic – Russia. Centralized natural systems, including ponds, lagoons, wetlands, and infiltration systems, are used for the treatment of approximately 5% of the WW in the region, while approximately 16% is treated on-site, mostly using septic tanks and septic drain fields, and approximately 59% of the WW is treated by conventional treatment plants. None of the WW in Greenland is treated, but the population represents only 1% of the total AMAP population. The majority of untreated WW (52%) originates in the Arctic Russian region, where it comprises 17–24% of the total Arctic Russian WW. Despite its large population, northern Norway only contributes 11% of the untreated WW, and around 63% of the population is serviced by conventional treatment systems. The majority of WW in Norrbotten Län (Sweden), Lappi (Finland) and Iceland is also treated using conventional systems, serving 87, 81 and 77% of the inhabitants in the regions, respectively. Conventional systems are also common in Alaska, particularly in urban areas, where they are used for the treatment of around 44% of the WW in the state. Centralized natural systems are primarily used to treat WW in Canada's Arctic regions (Yukon, Northwest Territories, Nunavut, Nunavik and Nunatsiavut), accounting for 85% of the total volume of WW generated. In rural Alaska, centralized natural systems treat 58% of the WW in both the north and the southwest, and account for 8% of the states total WWT. Centralized natural systems are also used in northern Norway (7%). Alaska, Lappi (Finland), Russia, Norrbotten Län (Sweden), Norway and Iceland use decentralized WW management approaches for 31, 19, 15, 12, 11 and 6% of their WW, respectively. Septic tanks (onsite) are the major technology used in the Faroe Islands (99.5% of total WW), while the onsite systems used in Sweden range from more advanced package plants or septic tanks with sand filters to septic tanks alone.[87] The WW load from cruise ships constitutes only slightly more than 1.1% of the total WW in the region and is mostly located around Alaska, Iceland and Norway. However, at these major cruise destinations, cruise ship activity constitutes a significant fraction of the PE load and is increasing.[24,41,45] Since greywater from cruise ships may be released untreated, this is likely done, and as greywater generally accounts for approximately 40% of the COD,[101] we estimated that 40% of cruise ship WW PE load is released untreated. Many cruise ships advertise that they are equipped with some kind of treatment for blackwater, but its use is only required within the 12 NM zone, and since cruise ships do not report how large a fraction of their WW they treat, this information is unknown, so we have marked blackwater treatment in cruise ships as unreported/unknown.

Altogether, the data reveals that a minimum of 14% of Arctic WW is not treated, and on top of this, treatment of 6% of the WW is unreported/unknown by authorities, making it likely untreated because treatment systems typically imply financing, registration, monitoring, and/or inspection. With 20% of the WW untreated/unknown, this leaves the Arctic region significantly ahead of the overall global situation, where 48% of WW is estimated to be released to the environment untreated, and in line with the regions with the highest WWT service levels (western Europe, Chile and Australia).[6] However, due to the general lack of adherence to regulatory requirements and the challenges regarding operation and monitoring in the Arctic discussed above, the level of treatment is likely to be significantly lower, as discussed below.

4.4 The quality of domestic wastewater emitted in the Arctic

The different treatment principles (conventional, centralized natural and on-site) applied in the Arctic region may produce any effluent quality (preliminary, primary, secondary, tertiary or even advanced quaternary). The above discussion suggests that in many cases, the treatment levels obtained by systems in the Arctic may not be the highest. For example, the most common on-site system, the septic tank system, delivers treatment at a primary level with a well-functioning tank (such as in Faroe Islands), while post-treatment in drainage fields may increase treatment levels to at least a secondary stage, depending on construction, climate, *etc.*[102] The natural systems in use are mostly passive systems that take advantage of natural processes

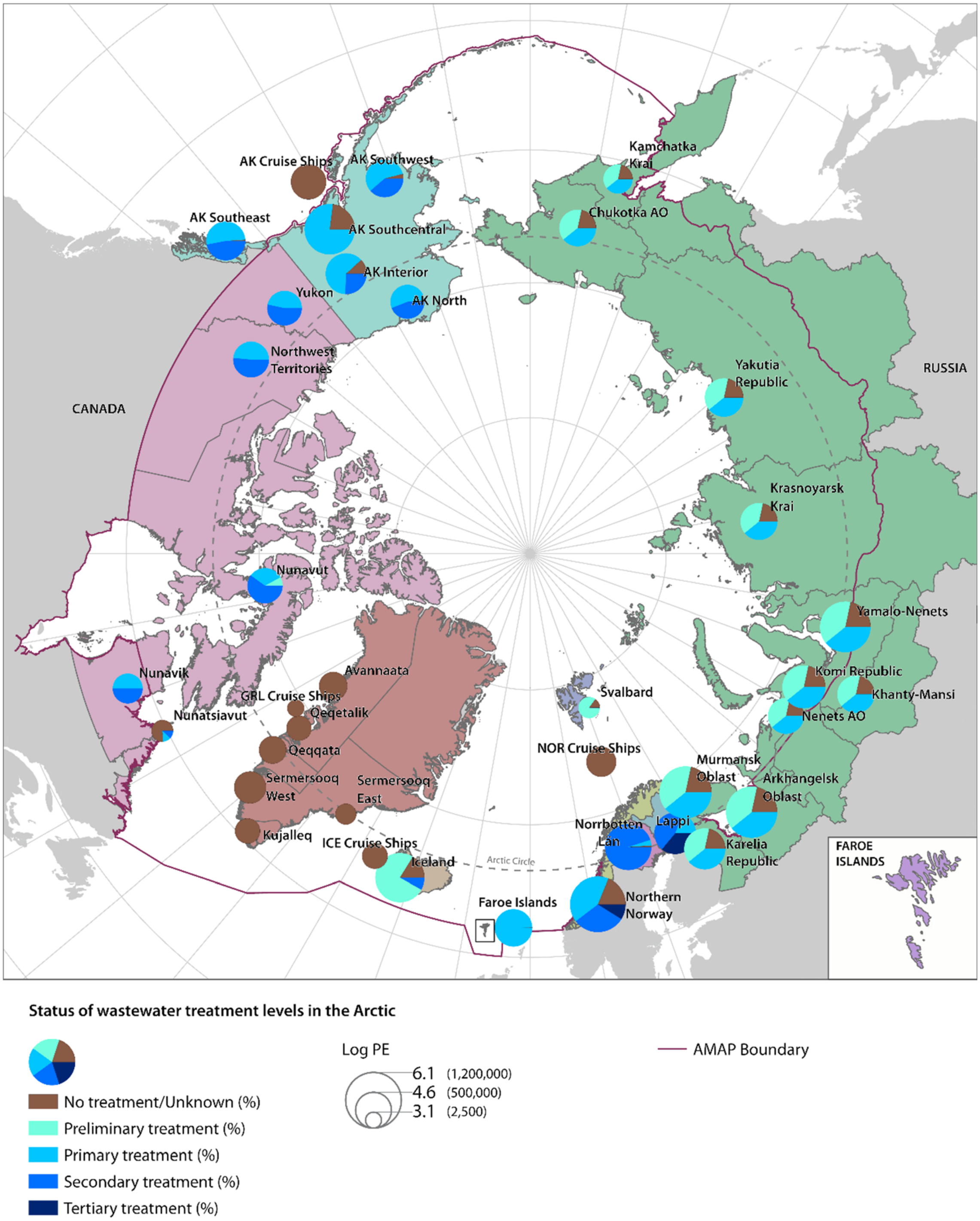

Fig. 2 Wastewater treatment levels and PE load for domestic wastewater in the arctic region.

like sedimentation, microbial decomposition, and filtration, requiring minimal operation and energy compared to conventional treatment systems.[103,104] Pond systems are typically also designed to reach secondary treatment. The efficiency of pond systems in Canada's Arctic was, however, shown to vary, some delivering primary treatment only, others secondary treatment, and some fluctuating between the two over time.[91,105] The same could be speculated to be the case for similar systems in other Arctic locations. However, when following treatment in tundra wetlands was applied, secondary treatment level could be achieved during an entire treatment season,[98] though rate constants for arctic tundra wetland were shown to be comparable to low rate constants derived from wetlands operating in non-arctic climates.[106]

To elucidate the potential environmental implications of Arctic WW discharge in a more generic manner and irrespective

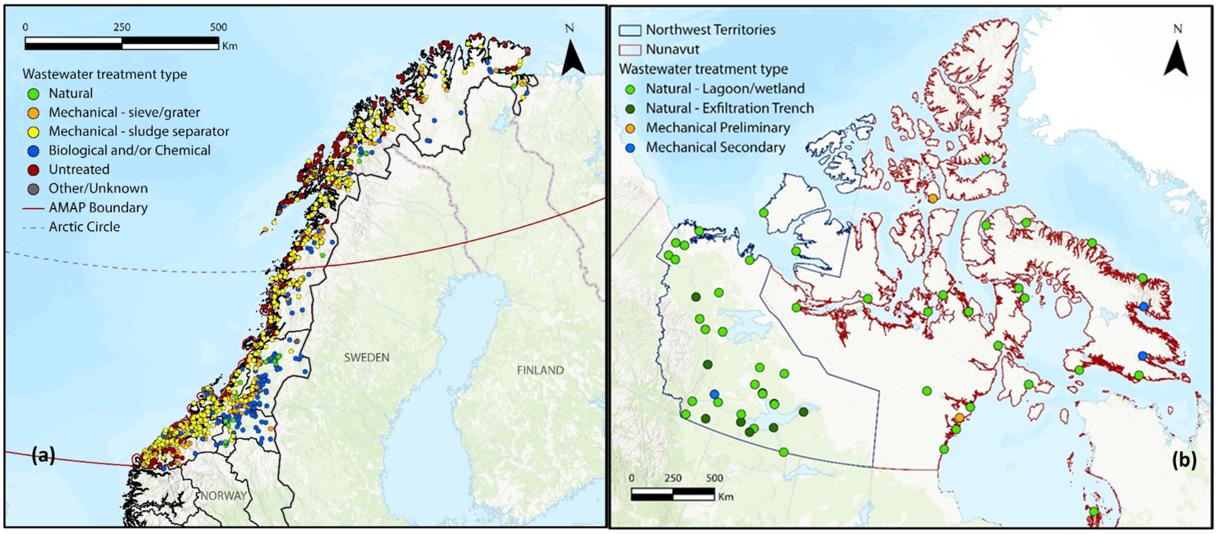

Fig. 3 (a) Geographical placement and types of WWTPS in Northern Norway (Norwegian Environment Agency, 2025); (b) geographical placement and types of WWTPS in the Northwest Territories and Nunavut, both regions located in the Canadian Arctic.

of individual national and regional regulations, we compiled the available information and supplemented it with estimates to evaluate the treatment levels obtained in the various parts of the region. In Fig. 2, the estimated levels of treatment obtained in the region are illustrated. The data used to generate the figures can be found in ESI S2.† The following major assumptions were made:

(i) None/insufficient treatment and unreported/unknown treatment were merged into one category named no treatment/unknown.

(ii) For Russia, 50% of the treated WW was estimated to reach the preliminary level and 50% the primary level, whether conventional or on-site systems, based on the information cited in Sections 3, 4.1 and 4.2 including taking into consideration that a major fraction does not meet regulatory levels. The treatment level reached in Russia constitutes the largest insecurity in our data, and should be perceived as a most likely average only.

(iii) WWT in the Canadian Arctic mostly uses centralized natural systems, except for Nunatsiavut. Half of the natural systems were estimated to function at primary level, while half functioned at the secondary level based on the information cited in sections 4.1 and 4.2. Although, this may vary over season and years. Conventional plants in the Northwest Territories (Fort Simpson) and Yukon were anticipated to meet the secondary level, while for Nunavut, conventional plants achieved secondary (Pangnirtung and Iqaluit) or preliminary treatment (Rankin Inlet and Resolute) based on the information cited in Sections 4.1 and 4.2.

(iv) For Alaska, half of the conventional and natural systems were estimated to function at primary level, while half at the secondary level, with the exception that in the Southcentral region of Alaska, all WW was anticipated to be treated to primary level only due to the largest facility in Anchorage treating to primary level. This results in 70% of Alaskan WW being treated to a primary level, 13% to secondary level, and 17% being unknown/untreated.

For the remaining countries, more precise information could be retrieved. In the Faroe Islands, the largest plant (Sersjantvíkín) in Tórshavn (~12 000 PE) treats WW to a primary level. While the old WWT plant at the Faroese National hospital used to treat the WW from 180 patients and staff (~600 PE) to achieve secondary level,[107] the new mechanical plant only treats WW to the primary level, leaving 99.7% of the WW treated to the primary level and 0.3% with unknown treatment. In Iceland, most WW (75%) is treated to preliminary level only. This is because most of the population lives by the ocean and the mechanical treatment technology adopted does not meet the treatment targets of 50% TSS and 20% BOD reduction of primary treatment plants. Neither do the biological treatment plants operating inland achieve the secondary treatment requirements of 90% TSS and BOD removal.[39] In the Finnish Arctic region, there are 2 tertiary treatment plants (36% of total WW), 2 minor primary plants (19%), with all remaining WW treated at a secondary level (45%), based on the information from the regional authorities. In Greenland, all WW is untreated. For Norway, relatively exact numbers could be retrieved from Statistics Norway.[95] Treatment involves preliminary treatment (in Svalbard), primary, secondary and some tertiary treatment systems. Less than 10% of the population in the Arctic region of Norway are connected to tertiary WWT, and between 7–19% have direct discharge without any treatment. Even large facilities treating WW from coastal urban centers like Tromsø treat to primary level only.[107] In Sweden, all conventional plants use biological treatment and coagulation because P reduction is required. For on-site treatment, we extrapolated the information from the survey by to the rest of the Swedish Arctic and found that 95% of the Swedish Arctic WW is treated to secondary level in accordance with legislation, 4% by primary treatment only, and 1% is unknown.[87] As for WW from cruise

Table 1 Overview on regulation for WW discharged to the Arctic region. NA: not available, SS: site specific, $k = 1000$

	Alaska	Canada	Cruise ships	Faroe islands	Finland	Greenland	Iceland	Norway	Russia	Sweden
Inhabitants PE	740 000	129 000	58 951	55 000	111 000	56 000	398 423	1 192 900	2 270 240	249 649
Regulating authority	US Federal government	Federal Government of Canada. Local authorities for Nunavut, Northwest Territories, Nunavik, Nunatsiavut	MARPOL in >3 NM zone (international waters) National authorities if <3 NM zone	Government of Faroe Islands	Government of Finland	Government of Greenland	Government of Iceland	Government of Norway, but municipalities decide operational requirements for WWTPs	Government of Russia and local authorities	Swedish EPA (>200 PE) Swedish Agency for marine and water management (<200 PE)
Supervising/inspecting authority	Alaska Department of Environ-Mental Conservation Division Of Water	Federal Government Territorial/provincial authorities	National authorities in <12 NM zone	Municipality	Municipality/regional authority	Municipality	Local health inspection authorities for plants PE > 50	Municipality	Local authorities	County administrative board (>2000 PE) Municipality (<2000 PE) Private actors (on-site/natural systems)
Regulation criteria	Treatment level and recipient quality	Effluent quality	Effluent quality	Treatment level and recipient type	Effluent criteria and recipient quality	Recipient quality	BOD_5 and recipient quality	Recipient sensitivity	Effluent quality, treatment facility size and recipient sensitivity	Effluent criteria
Treatment requirement	Secondary + disinfection	Secondary if >100 m^3 per day in Yukon	<3 NM zone: national regulation	None	Conventional centralized WWTPs: requirements follow EU UWWTD or stricter	None unless deemed necessary to protect specific receiving environment	Secondary (PE > 2000) with nutrient removal if sensitive recipient (PE > 10k)	Treatment is required; level varies depending on recipient	Mandatory stages of treatment: removal of coarse mechanical impurities, biological purification, disinfection, dehydration of the resulting sediment	Secondary treatment is required if >2000 PE
	Primary if emitted	Local requirements for the	3–12 NM zone: WW must be treated or		Decentralized including onsite treatment: own		Primary if the recipient is not affected (PE 10–		Septic tank if <100 PE, further soil-based	On site treatment is allowed if <200 PE

Table 1 (*Contd.*)

	Alaska	Canada	Cruise ships	Faroe islands	Finland	Greenland	Iceland	Norway	Russia	Sweden
	terrestrial subsurface	Nunavut, Northwest Territories, Nunavik, Nunatsiavut and Yukon. In addition, federal general prohibition on the release of pollutants to water	ground and disinfected. Stricter national requirements may apply. >12 NM no treatment required		regulation with limits for basic and sensitive areas		150k). "Appropriate" centralized treatment otherwise. Septic tanks for de-centralized		treatment required	
Sludge treatment	Must be disposed of in facility with permission. Incineration (large facilities) or landfill	Landfill	Dependent on the national practices in the country receiving the sludge at their port facilities	Sludge from septic tanks is dewatered and landfilled or incinerated	Sludge from on-site systems is transported to central WWTPs. Common solutions are composting and use in landscaping and landfill coverage, incineration or anaerobic digestion. Landfilling is forbidden	Not relevant (no sludge produced)	Re-used if possible. Otherwise landfilled. Must be disposed of without harming the environment. Discharge into surface water is banned	Mixing with wood chips and composting is most common, followed by disposal as cover material where needed. Landfilling is normally not allowed	Disposal, storage, re-use or incineration after dewatering and stabilization. Disinfection is required before reuse. If anaerobic digestion, the biogas must be utilized	Landfill cover/ spreading on agricultural land/ incineration
Possibility for exempts	Waivers for treatment to small communities with outfall to the ocean	Nunavut, Northwest Territories, Nunavik and Nunatsiavut are exempt from national regulation. Site-specific effluent quality requirement in licenses issued by territorial authorities	Only blackwater is regulated. Greywater may be discharged directly. In Greenland, territory vessels that rarely leave the 3 NM zone may be given an exemption to discharge untreated wastewater within this zone. In Norway, WW can be emitted in national waters if > 300 m from shoreline	NA – no treatment required	Old dwellings and elderly people in rural areas are exempt from requirements	NA – no treatment required	Preliminary treatment accepted if the recipient is not sensitive. Reduced treatment performance accepted if cold No monitoring required if PE < 50	Many WWT are exempt from the current (former) regulations. With the new EU directive, there will be no possibility of exemption	Under favorable conditions, the use of natural methods (*e.g.* wetlands) is permitted For tiny and ultra-tiny facilities or in unfavorable climatic conditions, use of bio-chemical package plants is permitted	N removal is not required in the arctic region

Table 1 (*Contd.*)

	Alaska	Canada	Cruise ships	Faroe islands	Finland	Greenland	Iceland	Norway	Russia	Sweden
Irregularities		Treatment performance of pond systems varies and does not meet the level designed for	General lack of monitoring and reporting	Regulations regarding point of discharge are not fully adhered to. Septic tanks are common despite no requirement		Evaluation of ecosystem impacts not completed for four of five munici-palities	Only two of the 29 largest municipalities met legislative requirement in 2022 General lack of monitoring			
Waste-water effluent criteria										
BOD_5 mg L^{-1} O_2	NA	SS	<50	NA	30 (BOD_7)	NA	25; >70% removal for secondary	SS	<3–12 depending on category	30 (PE < 200)
	<60 for vessels				Minimum 80% removal if >20 000 PE	<15 for mines	>20% for primary			SS (PE > 200) (BOD_7) for conventional systems, 90% if on-site
COD mg L^{-1} O_2	NA	NA	NA	NA	125	NA <75 for mines	125 >75% removal	SS	<40–80 depending on category	NA
TOC mg L^{-1}	NA	NA	NA	NA	37	NA	NA	SS	NA	NA
TSS mg L^{-1}	NA <150 for vessels	SS	<100	NA	<35	NA	(35 optional); >90% removal for secondary; >50% for primary	SS	<5–15 depending on category	NA
Total P mg L^{-1}	NA	NA	NA	NA	<3 (PE < 2k); <2 (PE 2k –100k); <1 (PE > 100k)	NA <1.5 for mines	If sensitive recipient: < 2 (PE 10k–100k); <1 (>100k)	SS	No TP, but phosphate ion <0.5–5 depending on category	<1 or <3 depending on recipient (PE < 200) SS but minimum 80% removal (PE > 2k)
Total N mg L^{-1}	NA	NA	NA	NA	15 (PE 10k–100k) 10 (PE > 100k)	NA <8 for mines	15 (PE 10k–100k), 10 (>100k)	SS	No TN, but for nitrite: 0.1–0.25; ammonium: 1–20; nitrate: 9–18 depending on category	40 (PE < 200); NA (PE 200–2k); SS (PE > 200) for mechanical systems, 70–90% if on-site
Fecal coliforms MPN/100 mL	NA <4k for vessels	SS <250 for vessels	<250	NA	NA	NA	NA	SS	NA	NA

ships, we have marked treatment as no treatment/unknown, due to the lack of requirements for greywater to be treated, the possibility of discharging blackwater untreated or preliminarily treated into international waters, and the general lack of data on how cruise ships treat and where they emit.

Overall, in the Arctic region, preliminary, primary, secondary, and tertiary treatment levels are accomplished for approximately 22, 39, 16 and 3% of total WW, respectively. This leaves 20% of the total WW untreated or unknown. These average Arctic treatment levels are thereby significantly lower than those reported in, for example, the EU, where as much as 81% of the WW was reported to be treated to at least a secondary level in 2022,[108] and also below the treatment level (86% secondary treatment) in Europe and North America overall.[109]

To exemplify the diverse suite of treatment principles engaged in the Arctic region, the distribution of systems in Norway and Canada, which have the highest variability in treatment methods engaged and treatment levels achieved, is illustrated in Fig. 3. In Norway, this is likely due to the legislation setting variable requirements based on both PE load and receiving water sensitivity, while in Canada the different administrative units for distinct territorial and provincial governments result in diverse solution preferences. Fig. 3a shows how larger inland WWT plants in Norway treat to a high level, while many coastal communities discharge WW untreated to the sea. For comparison, the types of WWT employed within the Northwest Territories and Nunavut, two of the Canadian Arctic regions, is illustrated in Fig. 3b. The majority of WWT systems in these territories would be considered natural systems, consisting of engineered lagoons, exfiltration trenches, or natural lake lagoons, and would achieve primary to secondary level treatment. Conventional plants are used in a small number of communities and are generally only employed if natural systems are not feasible due to the size of the community or physical constraints. Exfiltration trenches are also used in a few communities in the Northwest Territories if suitable soil and permafrost conditions allow for effluent to be distributed into the subsurface environment.[110]

4.5 Sludge management

When in place, WWT produces sludge that consists of inert particles and biosolids, including organic matter, nutrients, and microorganisms, of which some pathogenic, and may hold a suite of heavy metals and chemicals ad/ab-sorbed depending on the original content of the WW. According to the information in Table 1, the reuse of sludge for soil amendment/landfill coverage is widespread in Iceland, Norway, Russia and Sweden. The application of sludge on agricultural land is subject to legislative requirements on heavy metal and microbial content. Disposal in approved facilities is required in Alaska, Canada and the Faroe Islands, while incineration or pyrolysis is used for larger facilities in Alaska, Norway, Russia and Finland. Only in Finland is treatment by composting mentioned (Table 1). In Alaska, the sludge handling facilities vary greatly with respect to treatment among urban and rural areas. In rural areas, landfilling or other types of local disposal is common. In such facilities, the waste may be treated more like solid waste and disposed of, chemically treated, or buried, while sludge from larger facilities is incinerated or occasionally landfilled. In the Canadian Arctic, for the few communities (*e.g.*, Iqaluit, Pangnirtung) that operate conventional treatment plants, continuously produced sludge is dewatered and disposed of in municipal solid waste facilities. Most treatment systems, however, are lagoons and/or wetlands and therefore do not continuously produce sludge. Sludge will accumulate in lagoons, which require periodic removal in order to maintain treatment capacity and performance, but only a select few of the WWT ponds in Canada's Arctic have been desludged to date (pumping of sludge to a drying bed), thus most communities have yet to remove sludge from their municipal WWT systems. The general plan in principle for the desludging of lagoons uses sludge pumping to a dewatering basin. Moreover, best practices for treatment and disposal/use has yet to be developed, as lagoon desludging in remote, arctic communities faces significant logistical challenges.[111] In the Faroe Islands, sludge from domestic septic tanks is dewatered and deposited in a common facility designed to store sludge from the entire country, as opposed to the previously used method in which five facilities in different parts of the country were used. In Iceland, despite legislation urging the reuse of sludge, sludge is landfilled after dewatering in the capital region.[39] Two current projects, however, are focusing on re-using sludge for soil improvement to combat desertification on the Island. In Sweden, a certification system (REVAQ) for sludge to be recycled to agricultural land is in place with the aim of decreasing the flows of toxic substances to the treatment plant to generate cleaner sludge. REVAQ members must continually increase the quality of the produced sludge through upstream measures in the WW system. In on-site WWT facilities, such as septic tanks, sludge is collected by truck and transported to a central WWTP, where it is integrated into the sludge management of the plant. In the arctic region of Sweden, however, sludge is generally not spread on agricultural land but used for other purposes; for example, in Kiruna, according to the municipalities' environmental report for 2021, most of the sludge produced from the biggest WWTP in 2021 was used to cover landfills and only a minor part (*ca.* 1% in 2021) was incinerated in the local district heating plant. In Norway, the focus is similar to that of Sweden, and 85% of the sludge is disposed of in agriculture, as cover for green areas, or used in soil production.[112] But, while spreading sludge on agricultural fields/parks after disinfection and stabilization is common, the amount used in agriculture in the Arctic region is very small. Most Arctic sludge is sent to composting and mixed with wood chips, which creates an end product that is not very attractive for agriculture. It is disposed of as cover material where needed. New regulations view sludge as a resource and further encourage reuse.[113]

5 The ecosystem impacts of WW observed in the Arctic

5.1 Ecosystem disturbance

The organic matter and nutrients in WW can result in an enrichment of pelagic and benthic aquatic habitats. Common consequences of this enrichment include an increase in primary productivity, oxygen depletion, and changes in the composition of aquatic plant and animal communities.[116] Municipal WW also may contain a suite of contaminants, including heavy metals and persistent organic compounds, that can disrupt aquatic food webs.[117] Various components and characteristics of aquatic food webs can be targeted for the measurement of the biological effects of WW discharge, including fish, phytoplankton, periphyton, benthic invertebrates, and sediment microbial communities. The composition of benthic invertebrate communities has been the most widely used monitoring tool for assessing the ecological effects of WW inputs on aquatic environments because they play important roles in aquatic food webs, have relatively low mobility, and are easy to sample and identify.[118]

In most Arctic countries regular monitoring of the ecological status of surface water bodies is required. In example, Finland, Sweden, Norway and Iceland must assess and manage the quality of rivers, lakes, transitional, and coastal waters to achieve at least "good ecological status" by 2027 at the latest according to the EU Water Framework Directive.[114] According to the directive, the ecological status must be determined based on biological quality elements and supported by physico-chemical and hydromorphological quality elements. In other Arctic countries, however, no requirements are set. In example, though the Greenlandic wastewater regulation provides the governmental environmental authority the possibility to set environmental targets for specific recipients,[78] this has so far not been done.

In scientific literature, we identified a relatively small number of studies that have specifically examined the ecological effects of municipal WW discharge in the Arctic. These included six studies from Canada, two from Norway, three from Greenland and one from each of Russia, and Alaska. In contrast, the ecological effects of municipal WW discharge on freshwater and marine environments have been extensively studied in non-Arctic regions.[115] Most of the Arctic studies focused on benthic invertebrates as the primary indicators of ecosystem disturbance, with plankton, indirect measurements of productivity (*e.g.*, sediment pigments), and chemical food web signatures (stable isotopes, sterols) also occasionally employed.

Krumhansl *et al.* investigated the ecological effects of WW discharge on coastal aquatic environments in five communities across the territory of Nunavut, Canada using benthic invertebrates.[15] The study sites varied in population size, level of treatment, and the hydrodynamics of the receiving environment. They found that the magnitude, and spatial scale, of detected effects was related to the community population, and therefore the volume of WW. In smaller communities (<2000 people) minimal effects were detectable at distances greater than 225 m from WW release locations. However, in the one larger community they sampled (Iqaluit: ∼7000 people), they found that the receiving environment (Frobisher Bay) was virtually devoid of benthic invertebrates up to 600 m from the WW discharge location.[15] Schaefer *et al.* also studied the ecological effects of WW discharges in Frobisher Bay, focusing on chemical contamination and gene expression in soft shell clams (*Mya truncata*). They observed that clams collected closer to the WW discharge location possessed higher levels of heavy metals and different gene expression profiles compared to those collected at reference sites.[119] Jewett *et al.* used benthic invertebrates as a tool to assess WW impacts in Kottzebue Sound, Alaska and observed that benthic invertebrate communities in WW affected areas had lower diversity and a greater abundance of pollution tolerant species.[120] Bach *et al.* used a specific benthic amphipod species, *Orchomenella pinguis*, as an indicator of WW impacts in Sisimiut, Greenland. They compared the species diversity and the tolerance of *O. pinguis* collected from locations adjacent to sewage outfalls and those from unimpacted reference locations and were able to detect differences in genetic diversity and tolerance between impacted and unimpacted locations.[99] Furthermore, they observed reduced tolerance towards environmental pressures such as changes in salinity among the population collected at the WW impacted sites.[121] Holte *et al.* studied benthic invertebrate diversity in the Isfjord system in Svalbard and also observed some evidence of increased abundance of sewage tolerant species in one location.[122] Kreissig *et al.* detected a higher content of fecal indicator bacteria, altered seaweed microbiomes, and human pathogens on bladder wrack specimens harvested near two main WW outlets in Sisimiut, Greenland (∼5500 PE) compared to bladder wrack from an unimpacted site, indicating the localized impact on the recipient.[123] The remaining marine study, conducted in a coastal environment in Canada, examined phytoplankton biomass and taxonomy in the waters adjacent to the WW discharge location in Cambridge Bay, Nunavut. They were able to detect significant increases in primary productivity that they attributed to WW nutrient inputs.[124]

Several studies also examined the current and/or historical effects of WW discharge on the biology of freshwater environments (lakes) in Arctic regions. Two of these studies used Paleolimnological techniques (sediment cores) to assess changes in either phytoplankton, zooplankton, or invertebrates in lakes that had received sewage inputs in previous decades. They found evidence of the alteration of both benthic and planktonic community structures and of anoxia that correlated with the timing of sewage inputs.[125,126] Gallant *et al.* also examined sediment cores from a lake in Resolute, Nunavut, that had received sewage inputs. They detected increased levels of heavy metals and fecal sterols at the time of sewage inputs.[127] Meyer *et al.* recently reported changes in filamentous algae (increased abundance) and benthic invertebrates (decreased abundance of sewage sensitive taxa) in locations that were proximal to WW sources in Lake Baikal, Russia.[128] Kalinowska *et al.* observed greater planktonic bacterial abundance and a shift in dominant taxa in a lake that had received sewage inputs in Svalbard.[129]

Although small in number, these studies demonstrate that municipal WW discharge in the Arctic has measurable local effects on several ecosystem components including nutrient enrichment, oxygen depletion, and disruption of aquatic communities. Overall, Arctic WW discharge was shown to have measurable, though localized, ecological effects across multiple ecosystem components. It is challenging, however, to identify the specific WW constituents that are responsible for these effects. Many of the detected differences in ecosystem components can be attributed to conventional WW impacts such as eutrophication, but recent studies which have employed novel biochemical assays suggest that chemical contaminants could be linked to biological impairments.[119]

5.2 Antibiotic resistance

Antibiotic resistance (AR) is recognized globally as one of the greatest threats to public health. Municipal WWT systems have been identified as a potential pathway for the spread of antibiotics, antibiotic resistant bacteria (ARB), and antibiotic resistance genes (ARGs) into the environment, which may contribute to the dissemination of AR.[130] A growing number of studies have also investigated the presence of antibiotic resistance determinants, such as ARB and ARGs, in WW systems and receiving environments. Several of these studies have been conducted in the Arctic and provide additional information on the potential effects of local sources of this class of POPs.

Most of the studies that we reviewed used the detection of ARGs to indicate resistance to a variety of classes of antibiotics. Environmental media that have been monitored include WW influent/effluent, inland and coastal waters, sediments, and biota (*e.g.*, clams). Khmelevtsoval *et al.* conducted a thorough review of work focused on antibiotic resistance in environmental media in Russia.[131] They identified several studies which observed antibiotic resistance in bacterial isolates collected in arctic waters receiving sewage discharge. Several studies have been conducted in Canada in recent years focusing on this topic. Neudorf *et al.* and Starks *et al.* both investigated ARGs in WW and the receiving environment in Iqaluit, Nunavut.[132,133] Both studies identified elevated levels of ARGs in WW effluents but found that the levels of ARGs in the receiving water environments were comparable to reference sites. Several studies examined ARGs in WWT lagoons in Nunavut,[132,134,135] and observed the enrichment of ARGs within lagoon systems, which may be related to the long storage times of WW in these systems.[132,135] Hayward *et al.* studied ARG presence in tundra wetlands receiving municipal WW effluent in two Nunavut communities and observed higher levels of ARGs in WW impacted wetlands compared to reference wetlands.[136]

Mortensen *et al.* found antibiotic resistant Gram-negative bacteria and antibiotic resistance genes in wastewater from the WWTP (Sersjantvíkin) and surrounding areas in Tórshavn, Faroe Islands in both summer and winter.[137] While the abundance of ARBs decreased in effluents compared to influents, the opposite trend was seen for ARGs, indicating that horizontal gene transfer occurs in the WWTP.[137] ARGs and multidrug-resistant bacteria were also found in the marine water and terrestrial tidepools surrounding and close to the outlet from the WWTP. Interestingly low levels of the three monitored ARGs (bla_{OXA}, *tet*A and *sul*2) were also detected at the reference site at Gomlurætt.[137]

Perez-bou *et al.* examined ARGs in the influent and activated sludge of five activated sludge plants in Arctic Finland.[138] They noted that ARGs were present in these WWTPs, but that environmental samples from sites not impacted by WW had similar levels of ARGs.[138] Makowska-Zawierucha *et al.* conducted a monitoring study of ARGs in Svalbard and observed that WW discharge contained ARGs but that melting glaciers were also an important source of ARGs to coastal environments.[139] In accordance antibiotic resistance of Enterococcus isolates was observed in isolates from both WW impacted and reference lakes.[129]

In summary, WWT systems in the Arctic are a potential source of antibiotic resistance determinants to the environment, possessing levels of ARGs that are comparable to non-Arctic WW systems. Evidence from Canada, the Faroe Islands, Finland, and Svalbard shows that ARGs can persist in treated effluent and spread to surrounding environments. Horizontal gene transfer within WWT systems may contribute to ARG proliferation. Interestingly, ARGs have also been found in remote Arctic sites suggesting natural background levels.[140] This complicates the use of ARGs as sole indicators of pollution. Overall, Arctic WWT systems contribute to environmental AR, but natural sources also play a role.

6 Arctic wastewater treatment design solutions and innovations

Efforts have been made to demonstrate solutions/designs that may overcome some of the above discussed challenges with conventional WWT systems in the Arctic region. In the Russian Code of Practice,[141] general and specific design considerations for WWTPs in permafrost regions are given. They include design principles for foundations, pipelines and sewerage lines in permafrost, methods to avoid freezing of the sewerage lines, and other relevant information.[142,143] Specific considerations concerning the selection of treatment methods and degree of purification according to the temperature of WW are given. Several models for septic tanks tailored to cold climate are present on the Russian market (*e.g.*, "Skarabey" and "Bionix P", 161, 162 as well as other producers and models). They have insulation and include heating elements and are normally installed above ground (*i.e.*, are not embedded into the permafrost). In Norway, infiltration systems are built according to current regulations and are regarded as the preferred solution for rural onsite systems by most municipalities. This is due to decades of experience and research showing that these systems are reliable, robust to load variations, and meet current requirements provided correct siting and construction.[102,144,145] Large scale infiltration facilities are shown to operate with excellent performance in the Arctic region of Norway. This is demonstrated by the treatment system serving Bardu municipality (5000 PE at 69° north), where the groundwater beneath the infiltration basins has been monitored for over 25 years, showing 85–95% removal of COD, 35–85% removal of total N, and 99% removal of total P.[146] A study conducted in Fort Good Hope, Northwest Territories, Canada (628 PE at 66° north) in 2023/2024 also demonstrated the satisfactory performance of a soil-based wastewater infiltration system that has been in operation for more than 20 years despite harsh climate and extreme operating conditions.[147,148] Likewise, in sub-arctic Alaska the performance of two peat leachfields suggested such treatment can be adopted to treat residential WW in rural sub-Arctic Alaska and other northern countries without compromising ground or surface water quality, as the quality of the effluent was similar to WW that had undergone tertiary treatment.[149] No infiltration systems have, however, been reported from the permafrost region, thus their functioning in high arctic remains unknown and even questionable. The use of a membrane bioreactor at a tourist resort in Alaska was reported, but only for summer operations.[150] The EU project SiEUGreen (www.sieugreen.eu) demonstrated a decentralized system where blackwater was converted to biogas, fertilizer and growth media in the southern part of Norway. In a nearby super insulated greenhouse, vegetables could be grown year-round down to a minimum temperature of −20 °C, to which the biogas provided heat and power. This circular system has the potential not only to treat WW in cold climates but also to provide vegetables to the Arctic population. As for the challenges of monitoring decentralized systems, Norway has developed a GIS based digital system that can ease necessary monitoring and follow up on all types of decentralized and small-scale treatment system.[151]

Few lab and bench-scale efforts to develop special WWT methods that are fit for the Arctic region have also been attempted. Tang *et al.* isolated a cyanobacteria strain from the Arctic, which exhibited better uptake of P than green algae at temperatures below 10 °C, in addition to its superior assimilation of nitrate at all temperatures. They suggested this strain could be used for tertiary WWT in cool climates.[152] Bridson-Pateman *et al.* investigated the geotextile biofiltration of primary treated municipal WW under simulated arctic summer conditions and showed that it is possible to accumulate biomass on geotextile material over a 3 month period at these temperatures, which corresponded with 1–2 log reductions in hydraulic conductivity.[153] The significant removal of total suspended solids, BOD_5, total N, and total P was observed. Though removal efficiencies for most parameters were reduced at the lower temperature, this study demonstrates how geotextiles could be used to enhance the performance of pond-systems operating in Arctic climates. Chhetri *et al.* investigated the disinfection efficiency of treating raw WW in Greenland in a simple system involving only chemical coagulation, sedimentation and UV-radiation/peracetic acid disinfection.[154] They concluded that such physicochemical treatment of raw WW followed by disinfection showed potential for the treatment of Arctic WW. Interestingly, in their setup, the effect of disinfection of untreated WW with UV was also significant, providing a potential low-tech solution in sites where human risk of exposure to pathogens is the main concern. Finally, Ragush *et al.*, who investigated the influence of temperature, irradiance, initial carbon concentrations, and organic loading rate on the performance of wastewater stabilization ponds, showed that temperature (5 °C *vs.* 15 °C) and initial carbon concentration were the most important factors, and concluded that WSPs are an appropriate municipal wastewater technology for the Arctic which can achieve effluent BOD_5 concentrations that meet secondary wastewater treatment standards, provided they are appropriately sized, designed, and operated for arctic conditions.[155]

While the potential for the reuse of WW for the production of biodiesel (based on the use of microalgae for nutrient treatment of WW) in Arctic conditions was advocated, but not proven by Kashulin *et al.*,[156] a study in Norway successfully used urine to fertilize microalgae for the production of biodiesel. They utilized the fact that microalgae grow down to +4 °C provided there is enough light.[157] The development of purely physico-chemical treatment systems, including coagulation, chemical oxidation and precipitation, to combat the challenges of biological treatment in cold climates was advocated and tested by Vialkova and Glushchenko.[8] Haritonov suggested extracting heat from WW by simultaneously freezing it into ice blocks. The blocks could subsequently be transported to a centralized treatment facility, which would eliminate the need to build sewer pipelines. However, such an approach seems to only be feasible when air temperatures are negative.[158]

For the situation in Greenlandic and Alaskan villages where bucket or honey bucket toilets are used (simple dry toilets equipped with a plastic bag to collect the waste), Gunnarsdóttir *et al.* suggested the installation of improved dry or low flush toilets. These would collect toilet waste at the household level and centralize treatment.[7] They investigated a suite of different posttreatment options for disinfection of the toilet waste and documented significantly greater reduction of pathogen indicator organisms during anaerobic treatment compared to aerobic storage,[159] long-term freezing, or multiple freeze–thaw cycles.[160] The freeze and freeze–thaw treatments did not succeed in reducing fecal streptococci/enterococcus group or bacteriophages (virus indicators). A significant effort was recently made in The Alaskan Water and Sewer Challenge to develop improvements for honey bucket users.[161] They recommended the use of a ventilated dry-toilet with the possibility to connect to a seepage-pit engineered to work with the natural freeze/thaw cycles of the ground in permafrost regions to ensure appropriate treatment.[162] However, evidence of its functioning still remains. Another innovation proposed was so-called Bio-Electrochemical Anaerobic Sewage Treatment, developed by the National Research Council of Canada, which can biodegrade organic waste through a simple, low energy bioelectrochemical process, which applies approximately 1.5 volts of electricity to stimulate bioactivity.[163]

The Cold Regions Utilities Monograph, which offers insights into engineering solutions engaged in the cold regions in North America listed several complicating factors for WWT in the region including the impacts of low temperatures affecting the water viscosity and thereby retention times and economical costs of most processes involved in conventional treatment.[164] They furthermore underlined that "repeated studies of treatment systems in cold regions have shown that performance does not achieve the design goals because of poor operation and maintenance. Initial operator training is essential to successful system performance. Another critical element in the design process for wastewater treatment is the preparation of an operation and maintenance (O&M) manual."[164] Our study shows that these points are most likely still relevant.

7 Conclusions and recommendations

Based on our review of public statistics, reports and direct information from authorities, as well as scientific literature on WW regulations, treatment and impacts in the Arctic region, we found that:

• WW regulation varies across the Arctic nations, with the use of effluent based criteria (Canada, Sweden and Cruise ships in the 3–12 NM zone), recipient-based criteria (Greenland, Norway) or a combination of the two (Alaska, Faroe Islands, Finland, Iceland, Russia).

• Across several states, it is agreed that a higher level of treatment is needed to protect fresh water, while less/no treatment may be acceptable in most jurisdictions for small communities with outfalls to the ocean.

• In many parts of the region, authorities have issued waivers and exemptions to national legislation due to special Arctic conditions.

• Nevertheless, an inability to meet regulatory criteria prevails across the region.

• Monitoring wastewater and recipient quality is a major challenge in most of the region.

• Altogether, the data reveals that a minimum of 14% of Arctic WW is not treated, and on top of this, treatment of at least 6% of WW is unreported/unknown by authorities, thus also likely to be untreated. This is in line with the global regions with the highest WWT service levels.

• Centralized natural treatment is used for approximately 5% of the WW in the region, while 16% is treated on-site, mostly using septic tanks and septic drain fields, and 59% of the WW is treated by conventional treatment plants.

• Conventional WWT plants are the most common system in the Scandinavian Arctic, Russia, Iceland and in urban Alaska, while natural systems are most common in the Canadian Arctic and rural Alaska. On-site systems are used across the Faroe Islands and in most rural areas of the Arctic region except for the Canadian Arctic (where only centralized treatment is used) and Greenland (which has no treatment).

• Cruise ships may discharge untreated greywater at any location and blackwater in international waters but must grind and disinfect blackwaters within the 3–12 NM zone. National legislation applies within the 3 NM zone. Inspection and documentation of cruise ship WW practice is lacking. Altogether, this renders treatment of WW from vessels unknown, but likely to be predominantly absent.

• Overall, in the region, preliminary, primary, secondary, and tertiary treatment levels are accomplished for approximately 22, 39, 16 and 3% of total WW, respectively, which is significantly lower than in the global regions with high service levels.

• In the Arctic region, most sludge is landfilled or used as landfill/surface coverage, creating a risk of environmental exposure of entrapped contaminants.

• The relatively few studies that deal with assessment of ecosystem impacts from WW in the Arctic region demonstrate that municipal WW discharge in the Arctic have measurable local effects on several ecosystem components. Recent studies suggest that chemical contaminants could be linked to biological impairments.

• WWT systems in the Arctic are a potential source of antibiotic resistance determinants to the environment, possessing levels of ARGs that are comparable to non-Arctic WW systems.

Based on our findings, we have several recommendations for the improvement of WWT and sludge handling methods suitable for the Arctic region:

• First, we recommend the establishment of a framework for collaboration on WWT across the Arctic nations to ensure a uniform and appropriate legislative framework to protect Arctic recipients from environmental degradation, including a forum for authorities in the region to exchange knowledge and experience on WWT system development and practice.

• Arctic nations should undertake a collaborative effort to monitor WW from vessels in all zones of the ocean.

• Simple but sufficient methods to monitor and evaluate the ecosystem impacts of WW in the Arctic region should be developed and implemented.

• An assessment of WW as a source of anthropogenic chemicals such as pharmaceuticals and personal care products, PFAS, and other compounds included in the listings of Persistent Organic Pollutants and Chemicals of Emerging Arctic Concern according to the Stockholm Convention and AMAP (Arctic Monitoring and Assessment Program) in Arctic WW should be made.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its ESI.†

Author contributions

Conceptualization and methodology: Pernille Erland Jensen, Rob Jamieson, Débora Boratto. Literature review and compiling original draft: Pernille Erland Jensen, Lisbet Truelstrup Hansen, Débora Boratto and Rob Jamieson. Data curation interpretation and writing of country specific information: Alaska: Aaron Dotson and Pernille Erland Jensen; Canada: Rob Jamieson, Sarah Gewurtz, Débora Boratto, Ken Johnson and Bing Chen; Cruise ships: Pernille Erland Jensen; Faroe Islands: Lisbeth Truelstrup Hansen, Rakul Mortensen and Katrin Hoydal; Iceland: Hrund Ólöf Andradóttir; Norway: Ida Beathe Øverjordet, Hanne Kvitsand and Petter D. Jenssen; Finland: Pekka M. Rossi and Elisangela Heiderscheidt; Russia: Maria Velmitskaya, Anatoly Sinitsyn and Pernille Erland Jensen; Sweden: Inga Herrmann. Visualization: Débora Boratto. Review & editing: All.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors would like to acknowledge the inputs from the following persons and organizations: Environment and Climate Change Canada (Alexandre Richard), Environment Protection Agency of Iceland (Hólmfríður þorsteinsdóttir); Orkuveita Reykjavíkur utility company in Iceland (Hlöðver Stefán þorgeirsson). The following funds contributed to this work: The European Union's Horizon Europe research and innovation programme under Grant Agreements No. 101093865, CLIMAREST and No. 101133587, ILLUQ; Interreg NPA programme co-funded by the European Union under grant agreement No. 0700172 ArcticSewlutions; Danish EPA Grant No. 2022 – 86245, Contribution to AMAP's work on Arctic pollution.

References

1 C. N. Yates, B. C. Wotton and S. D. Murphy, Performance assessment of arctic tundra municipal wastewater treatment wetlands through an arctic summer, *Ecol. Eng.*, 2012, **44**, 160–165.
2 K. Johnson, G. Prosko and D. Lycon, Mechanical wastewater facility challenges in the Canadian Arctic, *Environ. Ecol. Res.*, 2017, **5**, 100–106.
3 V. Laukka, J. Kallio, I. Herrmann, R. Malila, R. Nilivaara and E. Heiderscheidt, Governance of on-site sanitation in Finland, Sweden and Norway [report], Finnish Environment Institute, 2022, **https://helda.helsinki.fi/items/b1c850e3-49f7-47b1-8d79-e5f40e8d767d**, Accessed June 2025.
4 K. Johnson and A. Sarah, Kimmirut, Nunavut—wastewater planning study, in *Proceedings, Annual Conference - Canadian Society for Civil Engineering*, 2017, pp. 318–327.
5 Y. Huang, C. M. Ragush, L. H. Johnston, M. W. Hall, R. G. Beiko, R. C. Jamieson and L. T. Hansen, Changes in bacterial communities during treatment of municipal wastewater in Arctic wastewater stabilization ponds, *Front. Water*, 2021, **3**, 710853.
6 E. R. Jones, M. T. H. van Vliet, M. Qadir and M. F. P. Bierkens, Country-level and gridded estimates of wastewater production, collection, treatment and reuse, *Earth Syst. Sci. Data*, 2021, **13**, 237–254.
7 R. Gunnarsdóttir, P. D. Jenssen, P. E. Jensen, A. Villumsen and R. Kallenborn, A review of wastewater handling in the Arctic with special reference to pharmaceuticals and personal care products (PPCPs) and microbial pollution, *Ecol. Eng.*, 2013, **50**, 76–85.
8 E. Vialkova and E. Glushchenko, Wastewater Treatment in Remote Arctic Settlements, *Water*, 2021, **13**, 919.
9 T. W. Hennessy and J. M. Bressler, Improving health in the Arctic region through safe and affordable access to household running water and sewer services: an Arctic Council initiative, *Int. J. Circumpolar Health*, 2016, **75**, 31149.
10 UN Water, *Progress on the proportion of domestic and industrial wastewater flows safely treated*, United Nations, 2024, **https://www.unwater.org/publications/progress-wastewater-treatment-2024-update**, Accessed June 2025.
11 Metcalf & Eddy Inc., *Wastewater Engineering: Treatment and Resource Recovery*, McGraw-Hill, New York, 5th edn, 2014.
12 J. Vymazal, The Historical Development of Constructed Wetlands for Wastewater Treatment, *Land*, 2022, **11**, 174.
13 L. Büngener, H. Postila, M. G. J. Löder, C. Laforsch, A. K. Ronkanen and E. Heiderscheidt, The fate of microplastics from municipal wastewater in a surface flow treatment wetland, *Sci. Total Environ.*, 2023, **93**, 166334.
14 J. Kinnunen, P. M. Rossi, I. Herrmann, A.-K. Ronkanen and E. Heiderscheidt, Factors affecting effluent quality in on-site decentralized wastewater treatment systems in cold climate regions, *J. Cleaner Prod.*, 2023, **404**, 136756.
15 K. Krumhansl, W. Krkosek, M. Greenwood, C. Ragush, J. Schmidt, J. Grant, J. Barrall, L. Lu, B. Lam, G. A. Gagnon and R. C. Jamieson, Assessment of arctic community wastewater impacts on marine benthic invertebrates, *Environ. Sci. Technol.*, 2015, **49**, 760–766.
16 A. P. W. Barrows, S. E. Cathey and C. W. Petersen, Marine environment microfiber contamination: global patterns and the diversity of microparticle origins, *Environ. Pollut.*, 2018, **237**, 275–284.
17 L. G. Chaves-Barquero, K. H. Luong, C. J. Mundy, C. W. Knapp, M. L. Hanson and C. S. Wong, The release of wastewater contaminants in the Arctic: a case study from Cambridge Bay, Nunavut, Canada, *Environ. Pollut.*, 2016, **218**, 542–550.
18 C. A. de Wit, D. C. G. Muir, R. Kallenborn and K. Vorkamp, Local sources versus long range transport of contaminants to the Arctic - State of knowledge, conclusions and recommendations, *Environ. Sci.: Adv.*, 2025, in prep.
19 P. E. Jensen, S. Gewurtz, D. Borato, P. Rossi, E. Heiderscheidt, I. B. Overjordet, H. O. Andradottir, L. T. Hansen, I. Hermann, R. Mortensen, K. Hoydal, A. Dotson, H. Kvitsand and R. Jamieson, The importance of wastewater as source of POPs and CEACs in the Arctic environment, *Environ. Sci.: Adv.*, 2025, in prep.
20 P. E. Jensen, T. W. Hennessy and R. Kallenborn, Water, sanitation, pollution, and health in the Arctic, *Environ. Sci. Pollut. Res.*, 2018, **25**, 32827–32830.
21 Arctic Monitoring and Assessment Programme (AMAP), *AMAP Assessment Report: Arctic Pollution Issues*, AMAP, Oslo (Norway), 1998, ISBN 82-7655-061-4.
22 Alaska Department of Labor and Workforce Development, Population and census, **https://live.laborstats.alaska.gov/landing/pop-cen.html**, Accessed March 2024.
23 Alaska Department of Environmental Conservation, Alaska certified water/wastewater operator database, **https://dec.alaska.gov/Applications/Water/OpCert/Home.aspx?p=SystemSearchResults&search=**, Accessed April 2024.
24 Cruise Line Industry Association, Alaska cruise history, **https://akcruise.org/economy/alaska-cruise-history**, Accessed June 2024.
25 E. White, Grey Water from Passenger Vessels in Alaska 2000–2019: An overview of grey water management for passenger vessels in Alaska, as well as summaries of

requirements and sample data results, Report, Washington, DC: Ocean Conservancy, 2021, https://oceanconservancy-org.webpkgcache.com/doc/-/s/oceanconservancy.org/wp-content/uploads/2021/03/Grey-water-from-passenger-vessels-in-AK.pdf, Accessed June 2024.
26 Statistics Canada, Census Profile, 2021, https://www12.statcan.gc.ca/census-recensement/2021/dp-pd/prof/index.cfm?Lang=E, Accessed November 2023.
27 Statistics Canada, Cruise disembarkations sail past pre-pandemic levels in 2023, https://www.statcan.gc.ca/o1/en/plus/5620-cruise-disembarkations-sail-past-pre-pandemic-levels-2023, Accessed February 2024.
28 I. Vicente-Cera, A. Acevedo-Merino, J. A. López-Ramírez and E. Nebot, Use of AIS data for the environmental characterization of world cruise ship traffic, *Int. J. Sustain. Transp.*, 2019, **14**, 465–474.
29 Visit Greenland, Tourism Statistics report 2022, https://tourismstat.gl/wp-content/uploads/2023/07/Tourism-Statistics-Report-Greenland-2022.pptx_compressed.pdf, Accessed February 2024.
30 Port of Tórshavn, https://www.portoftorshavn.com, Accessed February 2024.
31 Statistics Faroe Islands, Fólkatal [Population count], https://hagstova.fo/fo/folk/folkatal/folkata, Accessed February 2024, in Faroese.
32 Lapin ELY-keskus, *Data of Centralized Wastewater Treatment Plants in Lapland in 2021*, 2023.
33 Finnish Environment Institute, National VEETI Database, https://vesi.fi/aineistopankki/vesihuoltolaitosten-raportteja/, Accessed February 2024.
34 StatBank Greenland, https://bank.stat.gl, Accessed February 2024, in Danish/Greenlandic.
35 Avannaata Kommunia, *Spildevandsplan 2018–2024 3. Udkast [Wastewater Plan 2018–2024 3rd Draft]*, 2020, in Danish/Greenlandic.
36 Kommune Kujalleq, *Spildevandsplan 2018–2024 [Wastewater Plan 2018–2024]*, 2020, in Danish/Greenlandic.
37 Kommuneqarfik Sermersooq, *Spildevandsplan 2014–2024 [Wastewater Plan 2014–2024]*, 2013, in Danish/Greenlandic.
38 Qeqqata Kommunia, *Spildevandsplan 2021-2026 [Wastewater Plan 2021-2026]*, 2021, https://pilersaarut.qeqqata.gl/media/1683/spildevandsplan-samlet-dk.pdf, in Danish.
39 Environment Agency Iceland (EIA), *Stöðuskýrsla Fráveitumála 2022 [Status Report on Wastewater Issues 2022], Report No. UST-2023:14, Reykjavík: Umhverfisstofnun*, 2023, In Icelandic.
40 Statistics Iceland, Iceland population on Jan. 1. 2015-2022 by municipality [Data file] [Internet], https://www.hagstofa.is/talnaefni/ibuar/mannfjoldi/sveitarfelog-og-byggdakjarnar/, Accessed September 2023, in Icelandic.
41 Icelandic Tourist Board, *Arrivals of Cruise Ships to the Six Largest Harbours in Iceland 2017–2023 [Internet]*, Reykjavik: Icelandic Tourist Board, 2023, Available from: https://www.ferdamalastofa.is/is/rannsoknir/greiningar/skemmtiferdaskip-2023, in Icelandic.
42 Statistics Norway, Data table [Internet], https://www.ssb.no/statbank/table/07459/tableViewLayout1/, Accessed October 2023, in Norwegian.
43 Norwegian Environment Agency, Wastewater treatment plants [Internet], https://www.norskeutslipp.no/en/Wastewater-treatment-plants-/?SectorID=100, Accessed February 2025.
44 Statistics Norway, *Kommunale Avløp 2021: Ressursinnsats, Gebyrer, Utslipp, Rensing Og Slamdisponering [Municipal Wastewater 2021: Resources, Fees, Emissions, Treatment and Sludge Disposal] [Internet], ISSN 1892-7513*, 2022, Available from: https://www.ssb.no/natur-og-miljo/vann-og-avlop/artikler/kommunale-avlop-2021.ressursinnsats-gebyrer-utslipp-rensing-og-slamdisponering/, in Norwegian.
45 Cruise Northern Norway Svalbard, Statistics report, https://cnns.no/wp-content/uploads/2022/11/Statistic.pdf, Accessed September 2024.
46 Roshydromet, *The Russian Federal Service for Hydrometeorology and Environmental Monitoring, Review of the State and Pollution of the Environment in the Russian Federation for 2022, [Report]*, 2023, p. 170, in Russian.
47 Rosstat, *The Federal State Statistics Service, Environmental Protection in Russia, Statistical Digest*, 2022, p. 111, in Russian.
48 Rosstat, *The Federal State Statistics Service, Regions of Russia. Socio-Economic Indicators. Statistical Digest*, 2022, p. 453, in Russian.
49 Rosstat, *The Federal State Statistics Service, Information on the Operation of Sewerage (Separate Sewerage Networks) in the Constituent Entities of the Russian Federation in 2022 [Report]*, 2022, in Russian.
50 Statistics Sweden, Sweden statistics database [Internet], https://www.statistikdatabasen.scb.se, Accessed September 2024, in Swedish.
51 The European Parliament, *Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 Concerning Urban Wastewater Treatment*, 2024.
52 US EPA, The Clean Water Act (CWA), 33 U.S.C. §1251 et seq. (1972), https://www.epa.gov/laws-regulations/summary-clean-water-act, Accessed June 2025.
53 Alaska Department of Environmental Conservation, Chapter 72 on Wastewater treatment and disposal, law on environmental conservation, 18 AAC 72 as amended through October 1, 2023 [Internet], https://dec.alaska.gov/media/k3zjcdo4/18-aac-72.pdf, Accessed October 2024.
54 J. A. Crum, Wastewater treatment and trends in Alaska's coastal communities, *J. Water Pollut. Control Fed.*, 1989, **61**, 446–448.
55 Anchorage Water and Wastewater Utility, Wastewater treatment [Internet], https://www.awwu.biz/water-quality/wastewater-treatment, Accessed April 2024.
56 Government of Canada, Frequently asked questions: Fisheries Act pollution prevention provisions [Internet], https://www.canada.ca/en/environment-climate-change/services/managing-pollution/fisheries-act-registry/frequently-asked-questions.html, Accessed April 2024.

57 Government of Canada, Wastewater systems effluent regulations SOR/2012-139 [Internet], http://laws-lois.justice.gc.ca/eng/regulations/SOR-2012-139/FullText.html, Accessed April 2024.
58 Canadian Council of Ministers of the Environment (CCME), Canada-wide strategy for the management of municipal wastewater effluent. Winnipeg (MB), 2009, https://ccme.ca/en/res/mwwe_strategy_e.pdf, Accessed June 2025.
59 Environment and Climate Change Canada (ECCC), *Wastewater Systems Effluent Regulations 2016 Status report, Ottawa (ON)*, 2016, Cat No.: En14-376/2016E-PDF, ISBN: 978-0-660-30526-4.
60 Canadian Council of Ministers of the Environment (CCME), Guidance document for the beneficial use of municipal biosolids, municipal sludge and treated septage, Winnipeg (MB), 2012, https://www.publications.gc.ca/site/eng/443732/publication.html, Accessed June 2025.
61 International Maritime Organization, International Convention for the Prevention of Pollution from Ships (MARPOL) [Internet], London: IMO, 2024, https://www.imo.org/en/about/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx, Accessed June 2024.
62 Marine Environment Protection Committee (MEPC), *Recommendation on standards for the rate of discharge of untreated sewage from ships, Annex 14, Resolution MEPC*, 2006, vol. 157, supp. 5.
63 International Maritime Organization (IMO), Resolution MEPC.2(VI) - Recommendation on international effluent standards and guidelines for performance tests for sewage treatment plants (adopted on 3 December 1976) [Internet], London: IMO, 2024, https://imorules.com/MEPCRES_2.VI.html, Accessed June 2024.
64 Government of Canada, *New Environmental Measures for Cruise Ships in Waters under Canadian Jurisdiction – 2022 Season. SSB No.: 10/2022*, 2022.
65 Alaska Department of Environmental Conservation, Large cruise ship general permit [Internet], Alaska.gov, 2014, https://dec.alaska.gov/water/cruise-ships/cruise-general-permit/, Accessed May 2024.
66 Alaska Department of Environmental Conservation, Cruise ship program [Internet], https://dec.alaska.gov/water/cruise-ships, Accessed July 2024.
67 State of Alaska, Laws of Alaska 2017: AN ACT relating to regulation of wastewater discharge from small commercial passenger vessels in state waters; and providing for an effective date, 2017, https://www.akleg.gov/basis/Bill/Text/30?Hsid=SB0003A, Accessed June 2024.
68 Cruise Line Industry Association, Wastewater [Internet], 2024, https://akcruise.org/safetyenvironment/wastewater, Accessed June 2024.
69 Friends of the Earth (FOE), Cruise Ship Report Card 2022 [Internet], https://foe.org/wp-content/uploads/2022/07/CruiseShipReportCard_2022_final-July-25.pdf, Accessed June 2024.
70 Inatsisartut, Inatsisartutlov nr. 15 af 8. juni 2017 om beskyttelse af havmiljøet [no. 15 of 8 June 2017 on the protection of the marine environment] [Internet], Nuuk, Government of Greenland, 2017 Jun 8, https://nalunaarutit.gl/groenlandsk-lovgivning/2017/l-15-2017?sc_lang=da, Accessed June 2024, in Danish.
71 Norwegian Maritime Authority, Regulations of 30 May 2012 No. 488 on environmental safety for ships and mobile offshore units, https://www.sdir.no/siteassets/engelske-forskrifter-pdf/30-may-2012-no.-488-environmental-safety-for-ships-and-mobile-offshore-units.pdf, Accessed June 2024.
72 Government of the Faroe Islands, *Kunngerð um spillivatn, Nr. 111, 7. Sept. 2009 [Regulation on wastewater, No. 111]*, 2009, in Faroese.
73 Government of the Faroe Islands, *Kunngerð um spillvatnsevju, sum broytt við kunngerð nr. 90 frá 28. september 2007, Nr. 186, 5. nov. 1993 [Regulation on wastewater sludge. No. 186 with updates from 2007*, 1993, in Faroese.
74 Government of Finland, *Decree on Municipal Wastewater, 888/2006*, 2006, https://finlex.fi/fi/lainsaadanto/saadoskokoelma/2006/888, in Finnish.
75 Government of Finland, *Decree on the Treatment of Domestic Wastewater in Areas outside the Sewerage Network, 157/2017*, 2017, https://www.finlex.fi/fi/lainsaadanto/saadoskokoelma/2017/157, in Finnish.
76 Environmental Protection Agency, Denmark, *Udrednings- og pilotprojekt vedr. håndtering af miljøproblemer som følge af spildevand i de grønlandske byer [Investigation and pilot project on handling environmental problems due to wastewater in Greenlandic towns], Dokument nr. P-059371-A-1, Copenhagen (Denmark)*, COWI consultants, 2005, in Danish.
77 Inatsisartut, *Landstingsforordning Nr. 12 Af 22. December 1988 Om Beskyttelse Af Miljøet [County Council Ordinance No. 12 of 22 December 1988 on the Protection of the Environment]*, Nuuk, Government of Greenland, 1988, in Danish.
78 Inatsisartut, *Selvstyrets Bekendtgørelse Nr. 10 Af 12. Juni 2015 Om Bortskaffelse Af Latrin Og Spildevand [Self-Government Executive Order No. 10 of 12 June 2015 on the Disposal of Latrine and Wastewater], Greenland*, 2015, in Danish.
79 Naalakkersuisut, *Retningslinjer for Udarbejdelse Af VVM-Redegørelse (Vurderinger Af Virkning På Miljøet) for Mineraludnyttelse I Grønland [Guidelines for Preparing an EIA Report (Environmental Impact Assessment) for Mineral Exploitation in Greenland]*, 2015, in Danish.
80 Icelandic Tourist Board, Tourism in figures – January 2024: Summary for the year 2023, https://www.ferdamalastofa.is/is/um-ferdamalastofu/frettir/ferdathjonusta-i-tolum-januar-2024-samantekt-fyrir-arid-2023, Accessed January 2025.
81 Government of Iceland, *Reglugerð um fráveitur og skólp 798/1999 [Regulation on wastewater systems and sewage 798/1999]*, 1999, In Icelandic.

82 Visit Svalbard Statistics, Guest nights per sector development between 2012-2023, 2023, Available from: https://www.visitsvalbard.com/dbimgs/%C3%85rsstatistikk2023.pdf, Accessed June 2024.
83 Klima-og miljødepartementet, Norge, Pollution Control Regulations (Pollution Regulations, 2004, Available from: https://lovdata.no/dokument/SF/forskrift/2004-06-01-931?q=forurensningsforskriften, Accessed June 2024.
84 Klima-og miljødepartementet, *Forskrift Om Begrensning Av Forurensning, Del 4. Avløp [Pollution Control Regulations, Part 4. Sewage]*, 2007, https://lovdata.no/dokument/SF/forskrift/2004-06-01-931/KAPITTEL_4#KAPITTEL_4, in Norwegian.
85 Russian Federation, *Amendment Active from January 1, 2022 to the Water Code of the Russian Federation (N 11211284-7)*, 2022, https://www.interfax-russia.ru/main/gosduma-prinyala-zakon-o-nulevom-sbrose-stochnyh-vod-na-ledniki-v-arktike, in Norwegian.
86 The Swedish Agency for Marine and Water Management (SwAM), Havs- och vattenmyndighetens allmänna råd om små avloppsanordningar för hushållsspillvatten [The Swedish Marine and Water Authority's general advice on small sewage systems for domestic wastewater, *HVMFS*, 2016, **17**, 2016, in Swedish.
87 M. Olshammar, *Data Collection about Technologies Used in On-Site Wastewater Treatment [Report], SMED Report No 28*, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden, 2021, in Swedish.
88 United States Environmental Protection Agency (USEPA), *Wastewater Technology Fact Sheet Package Plants [Report]*, United States Environmental Protection Agency, Office of Water, Washington, D.C., 2000, No. EPA 832-F-00-016.
89 E. Johannessen, A. S. Eikum, M. Ek, T. Krogstad and C. Junestedt, Performance of prefabricated package plants for on-site wastewater treatment in the Vansjø- and Hobøl watershed (Morsa), Norway, *Vatten J. Water Manag. Res*, 2012, **68**, 107–114.
90 M. Hübinette, Minireningsverk renar sämre än väntat – Få anläggningar renade avloppsvattnet i den utsträckning som fabrikanten angav [Small-scale treatment plants perform worse than expected – Few installations treated wastewater as the manufacturer claimed, *VANN*, 2010, **03**, 414–427, in Swedish.
91 C. M. Ragush, J. J. Schmidt, W. H. Krkosek, G. A. Gagnon, L. Truelstrup-Hansen and R. C. Jamieson, Performance of municipal waste stabilization ponds in the Canadian Arctic, *Ecol. Eng.*, 2015, **83**, 413–421.
92 K. Johnson, Dawson City digs deep for sewage treatment, *Western Canada Water Magazine*, 2009, 44–45.
93 K. Johnson, The social context wastewater management in remote communities, *Western Canada Water Magazine*, 2018, 32–33.
94 K. Johnson, Advancing wastewater treatment in Inuit regions of Canada, in *Proceedings of Western Canada Water Conference; 60th Annual WCWWA Conference and Trade Show, September 23–26 2008, Regina, Saskatchewan*, 2008, p. 12.
95 Statistics Norway, Avløp og kloakk på kartet [Sewage and wastewater on the map], 2017, https://www.ssb.no/natur-og-miljo/artikler-og-publikasjoner/avlop-og-kloakk-pa-kartet, Accessed June 2024, in Norwegian.
96 Rosstat, The Federal State Statistics Service, *Comprehensive Observation of Living Conditions of the Population*, Statistical Digest, 2022, Table 76.1, in Russian.
97 A. A. Dudarev and A. V. Dozhdikov, Comparative analysis of living conditions and environmental factors related to the population demography, well-being and health in urban and rural areas of Nenets Autonomous Okrug (Arctic Russia): 2000–2019, in *Thematic Network (TN) on Geopolitics and Security of the University of the Arctic*, ed. L. Heininen, H. Exner-Pirot and J. Barnes, 2022, p. 21.
98 J. Hayward, R. Jamieson, L. Boutilier, T. Goulden and B. Lam, Treatment performance assessment and hydrological characterization of an Arctic natural tundra wetland receiving primary treated municipal wastewater, *Ecol. Eng.*, 2014, **73**, 786–797.
99 L. Bach, A. Fischer and J. Strand, Local anthropogenic contamination affects the fecundity and reproductive success of an Arctic amphipod, *Mar. Ecol.: Prog. Ser.*, 2010, **419**, 121–128.
100 V. Vzyatysheva, How GPS sensors flushed down the toilet floated up in the Gulf of Finland and who needs it, Gazeta [Paper], 2014, https://paperpaper.io/dirty-gps/, Accessed February 2024, in Russian.
101 C. Morandi and H. Steinmetz, How does greywater separation impact the operation of conventional wastewater treatment plants?, *Water Sci. Technol.*, 2019, **79**, 1605–1615.
102 P. D. Jenssen and R. L. Siegrist, Technology assessment of wastewater treatment by soil infiltration systems, *Water Sci. Technol.*, 1990, **22**, 83–92.
103 E. Marino, D. White, P. Schweitzer, M. Chambers and J. Wisniewski, Drinking water in Northwestern Alaska: using or not using centralized water systems in two rural communities, *Arctic*, 2009, **62**, 75–82.
104 K. Daley, H. Castleden, R. Jamieson, C. Furgal and L. Ell, Water systems, sanitation, and public health risks in remote communities: Inuit resident perspectives from the Canadian Arctic, *Soc. Sci. Med.*, 2015, **135**, 124–132.
105 J. J. Schmidt, C. M. Ragush, W. H. Krkosek, G. A. Gagnon and R. C. Jamieson, Characterizing phosphorus removal in passive waste stabilization ponds in Arctic communities, *Arctic Sci.*, 2016, **2**, 1.
106 J. Hayward and R. Jamieson, Derivation of treatment rate constants for an Arctic tundra wetland receiving primary treated municipal wastewater, *Ecol. Eng.*, 2015, **82**, 165–174.
107 M. Dam, A. Guðjón Auðunsson, H. H. Poulsen, I. A. Berg, L. Kristensen, J. Stenersen, F. N. Joensen, V. K. Davidsen and S. B. Petersen, *Micropollutants in wastewater in four Arctic cities – is the treatment sufficient?*, TemaNord, 2017:550, 2017.
108 European Environment Agency, Population connected to at least secondary wastewater treatment, 2024, Available from: https://www.eea.europa.eu/en/european-zero-

pollution-dashboards/indicators/population-connected-to-at-least-secondary-wastewater-treatment.

109 UN Water, Progress on the proportion of domestic and industrial wastewater flowssafely treated, United Nations, 2024, https://www.unwater.org/publications/progress-wastewater-treatment-2024-update, Accessed February 2025.

110 A. Mohammed, V. Bense, B. Kurylyk, R. Jamieson, L. Johnston and A. Jackson, Modelling reactive solute transport in permafrost-affected groundwater systems, *Water Resour. Res.*, 2022, **17**, 124036.

111 J. Lywood, M. Robertson, S. Leavitt, C. Diallo and R. Jamieson, Development of a linear program to optimize sludge management planning in Nunavut, Canada, *J. Cold Reg. Eng.*, 2015, **29**, 04014016.

112 Statistics Norway, Kommunlt Avløp, Disponering av avløpsslam (F) 2002-2023 [Municipal discharge, Handling of wastewater sludge 2002.2023], https://www.ssb.no/statbank/table/05279, Accessed March 2025, in Norwegian.

113 Klima-og miljødepartementet and Norge. Gjødselvareforskriften. Forskrift om produksjon, omsetning og import av gjødselvarer av organisk opphav og visse uorganiske gjødselvarer (gjødselvareforskriften) [Regulations on the production, trade and import of fertilizers of organic origin and certain inorganic fertilizers (Fertilizer Regulations)], 2025, Accessed February 2025.

114 EU, *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy*, 2000.

115 C. Cromey, K. Black, A. Edwards and I. Jack I, Modelling the deposition and biological effects of organic carbon from marine sewage discharges, *Estuarine, Coastal Shelf Sci.*, 1998, **47**, 295–308.

116 L. Taylor, P. Chapman, R. Miller and R. Pym, The effects of untreated municipal sewage discharge to the marine environment off Victoria, British Columbia, Canada, *Water Sci. Technol.*, 1998, **38**, 285–292.

117 Y. Chen, M. Lin and D. Zhuang, Wastewater treatment and emerging contaminants: bibliometric analysis, *Chemosphere*, 2022, **297**, 133932.

118 T. Pearson and R. Rosenberg, *Macrobenthic succession in relation to organic enrichment and pollution of the marine environment*, 1978, vol. 16, pp. 229–311.

119 C. Schaefer, D. Deslauriers and K. Jeffries, The truncate soft-shell clam, Mya truncata, as a biomonitor of municipal wastewater exposure and historical anthropogenic impacts in the Canadian Arctic, *Can. J. Fish. Aquat. Sci.*, 2022, **79**, 367–379.

120 S. Jewett, L. Clough, A. Blanchard, W. Ambrose, H. Feder, M. Hoberg and A. Whiting, Nearshore macrobenthos of northern Kotzebue Sound, Alaska, with reference to local sewage disposal, *Polar Biol.*, 2009, **32**, 1665–1680.

121 L. Bach and I. Dahllöf, Local contamination in relation to population genetic diversity and resilience of an Arctic marine amphipod, *Aquat. Toxicol.*, 2012, **114–115**, 58–66.

122 B. Holte, S. Dahle, B. Gulliksen and K. Næs, Some macrofaunal effects of local pollution and glacier-induced sedimentation, with indicative chemical analyses, in the sediments of two Arctic fjords, *Polar Biol.*, 1996, **16**, 549–557.

123 K. J. Kreissig, J. S. Sørensen, P. E. Jensen and L. T. Hansen, Bacterial communities on Fucus sp. harvested in tidal zones with or without exposure to human sewage in Greenland, *Reg. Stud. Mar. Sci.*, 2023, **62**, 102928.

124 D. Y. Back, S.-Y. Ha, B. Else, M. Hanson, S. Jones, K. H. Shin, A. Tatarek, J. M. Wiktor, N. Cicek, S. Alam and C. J. Mundy, On the impact of wastewater effluent on phytoplankton in the Arctic coastal zone: a case study in the Kitikmeot Sea of the Canadian Arctic, *Sci. Total Environ.*, 2021, **759**, 143861.

125 N. Michelutti, M. Hermanson, J. Smol, P. Dillon and M. Douglas, Delayed response of diatom assemblages to sewage inputs in an Arctic lake, *Aquat. Sci.*, 2007, **69**, 523–533.

126 D. Antoniades, N. Michelutti, R. Quinlan, J. M. Blais, S. Bonilla, M. S. Douglas, R. Pienitz, J. P. Smol and W. F. Vincent, Cultural eutrophication, anoxia, and ecosystem recovery in Meretta Lake, High Arctic Canada, *Limnol. Oceanogr.*, 2011, **56**, 639–650.

127 L. Gallant, L. Kimpea, K. Hargan and J. Blais, Tracking the history of 20th century cultural eutrophication in High Arctic waterbodies, *Anthropocene*, 2020, **31**, 100250.

128 M. F. Meyer, T. Ozersky, K. H. Woo, K. Shchapov, A. W. E. Galloway, J. B. Schram, E. J. Rosi, D. D. Snow, M. A. Timofeyev, D. Y. Karnaukhov, M. R. Brousil and S. E. Hampton, Effects of spatially heterogeneous lakeside development on nearshore biotic communities in a large, deep, oligotrophic lake, *Limnol. Oceanogr.*, 2022, **67**, 2649–2664.

129 A. Kalinowska, K. Jankowska, S. Fudala-Ksiazek, M. Poerpaoli and A. Luczkiewicz, The microbial community, its biochemical potential, and the antimicrobial resistance of Enterococcus spp. in Arctic lakes under natural and anthropogenic impact (West Spitsbergen), *Sci. Total Environ.*, 2021, **769**, 142998.

130 A. Tiwari, A. Krolicka, T. Tran, K. Räisänen, A. Asmundsdottir, O.-G. Wikmark, R. Lood and T. Pitkänen, Antibiotic resistance monitoring in wastewater in the Nordic countries: A systematic review, *Environ. Rev.*, 2024, **246**, 118052.

131 L. Khmelevtsoval, I. Sazykin, T. Azhogina and M. Sazykina, The dissemination of antibiotic resistance in various environmental objects, *Environ. Sci. Pollut. Res.*, 2020, **27**, 43569–43581.

132 K. Neudorf, Y. Huang, C. Ragush, C. Yost, R. Jamieson and L. Truelstrup-Hansen, Antibiotic resistance genes in municipal wastewater treatment systems and receiving waters in Arctic Canada, *Sci. Total Environ.*, 2017, **598**, 1085–1094.

133 M. Starks, C. M. Schaefer, K. M. Jeffries, D. Deslauriers, K. H. Luong, C. S. Wong, M. L. Hanson and C. W. Knapp, Presence of antibiotic resistance genes in the receiving

environment of Iqaluit's wastewater treatment plant in water, sediment, and clams sampled from Frobisher Bay, Nunavut: a preliminary study in the Canadian Arctic, *Arctic Sci.*, 2023, 919–927.
134 L. G. Chaves-Barquero, K. Hoang Luong, C. J. Mundy, C. W. Knapp, M. L. Hanson and C. S. Wong, The release of wastewater contaminants in the Arctic: a case study from Cambridge Bay, Nunavut, Canada, *Environ. Pollut.*, 2016, **218**, 542–550.
135 M. Gromola, J. Neufeld and B. McConkey, Monitoring microbial populations and antibiotic resistance gene enrichment associated with Arctic waste stabilization, *Appl. Environ. Microbiol.*, 2021, **87**, e02914–e02920.
136 J. Hayward, A. Jackson, J. Yost, L. Truelstrup-Hansen and R. Jamieson, Fate of antibiotic resistance genes in two Arctic tundra wetlands impacted by municipal wastewater, *Sci. Total Environ.*, 2018, **642**, 1415–1428.
137 A. M. S. Mortensen, S. J. Poulsen, M. Á. F. Berbisá and A. Djurhuus, Distribution of antibiotic resistant bacteria and genes in sewage and surrounding environment of Tórshavn, Faroe Islands, *Front. Environ. Sci.*, 2024, **12**, 1336318.
138 L. Perez-Bou, B. Munoz-Palazon, J. Gonzalez-Lopez, A. Gonzalez-Martinez and D. Correa-Galeote, Deciphering the role of wastewater treatment plants in cold environments as hotspots for the dissemination of antibiotic resistance genes, *Microbial. Ecol.*, 2024, **87**, 14.
139 N. Makowska-Zawierucha, J. Mokracka, M. Malecka, P. Balazy, M. Chelchowski, D. Ignatiuk and K. Zawierucha, Quantification of class 1 integrons and characterization of the associated gene cassettes in the high Arctic – interplay of humans and glaciers in shaping the aquatic resistome, *Ecol. Indic.*, 2022, **145**, 109633.
140 L. Tan L, L. Li, N. Ashbolt, X. Wang, Y. Cui, X. Zhu, Y. Xu, Y. Yang, D. Mao and Y. Luo, Arctic antibiotic resistance gene contamination, a result of anthropogenic activities and natural origin, *Sci. Total Environ.*, 2018, **621**, 1176–1184.
141 Russian Code of Practice, Sewerage, Pipelines and wastewater treatment plantsk, SP 32.13330.2018, SNiP 2.04.03-85 (with Amendments No 1, 2, 3), Effective from Dec 25, 2018/Jun 2019, Available from: https://docs.cntd.ru, Accessed in February 2025.
142 Unilos Astra, 2025, https://www.uni-los-astra.ru/katalog/skarabej-stantsii-glubokoj-biologicheskoj-ochistki-yunilos, Accessed February 2025.
143 Bio Terra, Autonomous sewage systems for the North, 2025, Available from: https://bio-terra.ru/press-tsentr/avtonomnaya_kanalizatsiya/kanalizatsiya_dlya_severa/, Accessed February 2025.
144 R. L. Siegrist, E. J. Tyler and P. D. Jenssen, Design and performance of onsite soil absorption systems, *White Paper Prepared for National Needs Research Conference, Risk Based Decision Making for Onsite Wastewater Treatment, 2000 May 19–20*, Washington University, St. Louis, MO, 2000, p. 48.
145 P. D. Jenssen, S. Jonasson and A. Heistad, *Naturbasert rensing av avløpsvann – en kunnskapssammenstilling med hovedvekt på norske erfaringer [Natural systems for wastewater treatment – a knowledge compilation with emphasis on Norwegian results]. VA-forsk [Rapport]*, VA-Forsk, No. 20, Stockholm, 2006, p. 87.
146 P. D. Jenssen, T. Krogstad and K. Halvorsen, Community wastewater infiltration at 69° northern latitude – 25 years of experience, in *Proceedings of Soil Science Society of America Onsite Wastewater Conference, Albuquerque NM, 7–8 April 2014*, 2014, https://dl.sciencesocieties.org/publications/meetings/browse/sssa/2014OWT.
147 D. C. Boratto, Treatment performance assessment and modeling of a soil-based wastewater treatment system in northern Canada, MSc thesis, Dalhousie University, Halifax (NS), 2024.
148 D. Boratto, B. Kurylyk and R. Jamieson, Modeling a rapid infiltration basin for wastewater treatment in the Arctic under various operating conditions, *J. Contam. Hydrol.*, 2025, **6**, 104601.
149 R. Z. Riznyk, J. Rockwell, L. C. Reid and S. L. Reid, Peat leachmount treatment of residential wastewater in sub-Arctic Alaska, *Water, Air, Soil Pollut.*, 1993, **69**, 165–177.
150 Ionics Worldwide Headquarters, Alaskan lodge uses a membrane bioreactor (MBR) system to meet its wastewater treatment needs, *Filtr. Sep.*, 2004, **41**, 20–22.
151 S. Turtumøygard and G. R. Hensel, *WebGIS avløp, fagsystem for avløp fra private renseanlegg [WebGIS sewage, technical system for sewage from private treatment plants]*, 2021, vol. 7, iss. 31, in Norwegian.
152 E. P. Y. Tang, W. F. Vincent, D. Proulx, P. Lessard and J. De la Noüe, Polar cyanobacteria versus green algae for tertiary wastewater treatment in cool climates, *J. Appl. Phycol.*, 1997, **9**, 371–381.
153 E. Bridson-Pateman, R. Jamieson and C. Lake, Geotextile biofiltration of primary treated municipal wastewater under simulated Arctic summer conditions, *Geotext. Geomembr.*, 2016, **44**, 824–831.
154 R. K. Chhetri, E. Klupsch, H. R. Andersen and P. E. Jensen, Treatment of Arctic wastewater by chemical coagulation, UV and peracetic acid disinfection, *Environ. Sci. Pollut. Res.*, 2018, **25**, 32851–32859.
155 C. M. Ragush, J. M. Poltarowicz, J. Lywood, G. A. Gagnon, L. Truelstrup Hansen and R. C. Jamieson, Environmental and operational factors affecting carbon removal in model Arctic waste stabilization ponds, *Ecol. Eng.*, 2017, **98**, 91.
156 N. A. Kashulin, T. P. Skuf'ina, V. A. Dauvalter and V. A. Kotelnikov VA, Ustoychivoye vodopol'zovaniye v Arktike [Sustainable water management in the Arctic], *Arctic: Ecology and Economy*, 2018, **4**, 15–22.
157 S. Eikås, Biodiesel from microalgae: enhanced sustainability of biodiesel production by cultivating microalgae with urine as fertilizer and CO2 addition from power plant emissions, Master's thesis, Norwegian University of Life Sciences (NMBU), Norway, 2007, p. 36.

158 V. P. Haritonov, Energy saving water disposal technology for Arctic regions, *Energosberezheniye*, 2021, **5**, 41, **https://www.abok.ru/for_spec/articles.php?nid=7876**.
159 R. Gunnarsdóttir, S. Heiske, P. E. Jensen, J. E. Schmidt, A. Villumsen and P. D. Jenssen, Effect of anaerobiosis on indigenous microorganisms in blackwater with fish offal as co-substrate, *Water Res.*, 2014, **63**, 24971812.
160 R. Gunnarsdóttir, K. Müller, P. E. Jensen, P. D. Jenssen and A. Villumsen, Effect of long-term freezing and freeze-thaw cycles on indigenous and inoculated microorganisms in dewatered blackwater, *Environ. Sci. Technol.*, 2012, **46**, 12408–12416.
161 K. A. Hickel, A. Dotson, T. K. Thomas, M. Heavener, J. Hébert and J. A. Warren, The search for an alternative to piped water and sewer systems in the Alaskan Arctic, *Environ. Sci. Pollut. Res. Int.*, 2018, **25**, 32873–32880.
162 K. J. Mattos, J. Warren, M. Heavener and K. R. Linden, Rethinking water and sanitation in challenging environments: lessons learned from installing portable, adaptable, mid-tech household systems, in *Proceedings of the Regional Conference on Permafrost, International Cold Regions Engineering Conference*, 2021.
163 B. Tartakovsky and Y. Kleiner, M. Manuel Bioelectrochemical anaerobic sewage treatment technology for Arctic communities, *Environ. Sci. Pollut. Res.*, 2018, **25**, 32844–32850.
164 D. W. Smith and J. A. Crum, Wastewater Treatment, Section 10, in *The Cold Regions Utilities Monograph*, ed. D. W. Smith, ASCE, Reston, Virginia, 3rd edn, 1996.