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Water quality in rural Greenland - acceptability and safety

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ABSTRACT

The low proportion of households with piped drinking water in Greenlandic settlements – and elsewhere in the Arctic, leads to improvised methods of household water storage and water saving practices that could present a risk for public health.

This interview-based study investigated the perceptions of safety and acceptability of the water supply in rural Greenlandic households. The bacterial quality of the water distributed by the public supply before and after storage in the homes, of alternative water sourced from nature by the users themselves, and of shared handwash basins used in un-piped homes, was analyzed.

The treated water distributed by the rural Greenlandic water supply was acceptable to most users, although half of them expressed concerns about its quality, and distrusted the state of the infrastructure delivering piped water. For drinking, most respondents preferred untreated water from nature, but a majority used mainly piped water for practical reasons of access. The microbial quality of the public water supply met legislative requirements in most cases, but was found to deteriorate during both distribution to some taps, and storage in the homes, which constitutes a challenge to the reliable provision of safe water to users. Water from alternative sources showed slightly higher heterotrophic plate counts (HPC) than piped water, but no *Escherichia coli*. As for washbasins, they were found to have high levels of contamination in all three bacterial parameters investigated (HPC, coliforms and *E. coli*), indicating a possible transmission route for pathogens.

In conclusion, while the quality of treated water was overall good at distribution, the water saving and storage practices developed to compensate for the lack of piping may threaten public health. Alternative water sources are culturally important and trusted by users, although the possible impact of changes in climate and land use on the reliability of their quality is unknown.

Introduction

Water and sanitation systems are essential to sustainable development in general (UN 2021), and critical to human health and wellbeing in particular (WHO 2022). Yet much remains to be done, as the UN admits that “the world is not on track to achieve SDG 6″ (UN-Water 2021) – a fact made more obvious lately by the vulnerabilities exposed during the covid-19 pandemic, which led to recent UN recommendations to strengthen water and sanitation services (UN 2021). It is also becoming more urgent, as climate change is expected to bring new threats to water systems (UNESCO, UN-Water 2020).

The UN definition of safe water access is achieved when drinking water is physically accessible, in sufficient amounts, safe, acceptable, and affordable (Van de Lande, 2015). Maréchal et al. (Maréchal et al., 2022) showed that water in Greenlandic settlements is predominantly both physically accessible and affordable. Sufficiency is, however, challenged by the lack of piping, and in some places by the limited capacity of raw water resources. It was also documented that many residents actively chose to use untreated water from nature, even in settings with piped water access on the premises (Maréchal et al., 2022). Together, the limited sufficiency of piped water and acceptability of treated water may lead to potentially unsafe methods of household water storage, water use, and water saving practices.

In Greenland, most water supplies are operated in isolation, as localities are not connected by roads, due to the distances in between, and the icecap covering most of the surface of the country (Hendriksen and Hoffmann, 2018). This makes communities vulnerable to any incident or emergency, as illustrated in Jensen et al. (Jensen et al., 2022). Treatment and supply systems in many settlements are aging, and while being most often of relatively simple nature, implementing some kind of filtration and UV-treatment, boil advisories due to microbial contamination have been commonly issued. The Greenland water supply company

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Nukissiorfiit has therefore begun, since 2017, to deploy a new modular systems for the treatment of drinking water, to increase water safety by replacing aging equipment and enabling monitoring from a distance. These systems are designed to be easy to transport and install, and on the longer run, the installation of identical systems in most settlements will facilitate exchange of staff, knowledge and equipment, especially in times of emergency. The replacement was prioritized in the locations with most boil advisories, with the first system implemented in 2017 and fully functional in 2018, and, by 2020, eight of these modular systems were in place across the country.

In rural Greenland (i.e., in settlements <500 inhabitants), however, the vast majority of households (80%) live in un-piped homes, collecting treated drinking water from public taps – as well as untreated alternative water from natural sources (Maréchal et al., 2022). The public taps (known as taphouses), although distributed across the settlements, are on average 90 m away from the homes (Maréchal et al., 2022). The burden of water collection off the premises is known to be a limiting factor in household water consumption (Cassivi et al., 2018). Indeed as a result of the limited piping in the Greenlandic settlements, and despite access to taphouses, the amount of water used daily in un-piped households is on average 13 L/d/cap, with showers and laundry typically taking place in a service house (aka “washeteria” in Alaska (Mattos et al., 2021)) outside the home, adding up to an extra 10 L/d/cap (Maréchal et al., 2022). This qualifies as basic level according to a recent WHO report (Howard et al., 2020). Such low water quantities have, in Alaska, been linked with the use of shared basins for hand washing (Chambers et al., 2008), which presents a risk of pathogen transmission for users.

The water is typically collected from public taphouses in semi-opaque white plastic jugs, and stored within the household until use, either inside those same jugs, or transferred into a bucket or metal tank (Maréchal et al., 2022). On some occasions, tanks are filled by connecting them to the taphouse with a hose. As a result of these methods, household water transport and storage could present a risk of contamination, and lead to deterioration of water quality in the households (Maréchal et al., 2022), despite the efforts by Nukissiorfiit to secure quality at the point of delivery.

Indeed, such practices have been linked, in other parts of the Arctic, to a number of health conditions. Some are caused by the deficiency in hygiene measures, due to the limited amounts of water available (Gessner, 2008; Hennessy et al., 2008; Wenger et al., 2010), and therefore known as water-washed diseases - they include infections such as respiratory tract infections and skin diseases (Bressler and Hennessy, 2018). In addition, the deterioration of the water quality during household water storage has been shown to result in oral transfer of pathogens during water usage (Bressler and Hennessy, 2018; Martin et al., 2007). This would be referred to as water-borne diseases (Daley et al., 2018). Several studies from Nunavut (Canada) and Alaska (USA) observed household water storage containers to contain higher microbial levels than the water at the collection sites (Mattos et al., 2021; Martin et al., 2007; Daley et al., 2018). No data on water quality are available at this time to estimate the impact of this practice on public health in Greenland.

As for alternative sources of water, which users were found to prefer and collect directly from nature (Maréchal et al., 2022), according to a traditional practice similarly observed in Canada and Alaska (Daley et al., 2018; Thomas et al., 2016), it may be collected from either a river, a lake, or pieces of floating ice from iceberg break offs (known as “nilak”) that are then melted inside the house. This is a common practice, even for persons living in piped homes (Maréchal et al., 2022). These alternative sources are neither treated nor monitored, hence no data is available at this point on water quality of those alternative sources.

To secure the microbial safety of potable water, thresholds for acceptable contents of bacterial indicators are embedded in the drinking water regulations worldwide. For Greenland the current legislation calls for the absence of *Escherichia coli*, coliforms, fecal *Enterococcus* sp. and H_2S-producing clostridia in 100 ml of drinking water leaving the treatment plant and taps (Government of Greenland 2021). Coliform bacteria have historically been used as indicators of fecal contamination in water supplies, but they are a heterogeneous group that includes species naturally occurring in the environment, and therefore no longer regarded as conclusive for this purpose (WHO, Regional office for Europe 2017). Therefore, their presence in water nowadays serves only as a preliminary warning of fecal contamination, which needs to be confirmed or inferred by *E. coli* tests. *E. coli* is considered an indicator of fecal contamination, because of their prevalence in feces of warm-blooded animals, their rarity in uncontaminated water, and how unlikely they are to grow in the conditions of low temperature and nutrients typically found in drinking water supplies (WHO, Regional office for Europe 2017). While coliforms can also serve as indicators of the integrity of the system, the total heterotrophic bacteria plate count (HPC) is considered preferable to coliforms for this purpose (WHO, Regional office for Europe 2017).

Together, the limited sufficiency of piped water and acceptability of treated water may lead to potentially unsafe methods of household water storage, water use, and water saving practices. The aim of this study was to explore the subject of water perception among residents, focussing on two factors from the UN definition of water access: safety and acceptability. The study also aimed to examine the water quality throughout the drinking water delivery systems in a selection of Greenlandic settlements, from source, treatment and distribution point, to the point-of-use after various methods of household water storage and usage, by analysing the content of the bacteriological indicator organisms *E. coli*, coliforms and HPC.

Materials and methods

Data collection and selection of study sites

There are five administrative regions in Greenland, known as municipalities, all of which were included in the study, i.e., from North to South: Avannaata Kommunia, Kommune Qeqertalik, Qeqqata Kommunia, Kommuneqarfik Sermersooq (divided into West and East coast), and Kommune Kujalleq (Fig. 1).

In a desktop study, data were collected for all Greenlandic settlements, i.e., communities of fewer than 500 inhabitants – as opposed to towns which usually have a larger population (the town of Ittoqortormiit, despite its population size <500, has a town status and therefore was excluded from this study).

Data on the raw water sources, treated and distributed as drinking water by the public water supply, and on boil water advisories (BWA) – warnings on water quality – were provided by Nukissiorfiit, which is the company in charge of the water supply in all Greenlandic towns and settlements. Excluded from service by Nukissiorfiit at the time of data collection were the sheep farms, three airports and their neighboring settlements, and some seafood factories.

Visits were organized in five settlements representative of different water sources, treatments and regions of Greenland (Tasiusaq in Kujalleq, Itilleq, Sarfannguit, Qaarsut and Saattut), and the town of Nanortalik, which served as a reference site in which most households are piped. The location of the study sites is shown in Fig. 1, and the characteristics of each study site are described in Table 1.

Interviews for qualitative assessment

The qualitative data on acceptability is based on 21 interviews with residents. Informal interviews were conducted during a preliminary visit to Sarfannguit in August 2019. A meeting was called to inform the residents of the research about to take place. They were encouraged to ask questions and express their wishes about the focus of the project, to ensure that the results of this research project would address as closely as possible the interests of the local population. This revealed specific

Fig. 1. Location of the study sites and other localities in Greenland. The regions named in blue are the five municipalities, and the North East Greenland National Park.

concerns shared by the residents, including the quality of untreated water sources from nature, the possible deterioration of tap water quality during household storage, and the taste and safety of public water obtained by desalination/reverse osmosis (RO) treatment of seawater. These concerns were therefore included as research topics in the final design of the study. A questionnaire was developed on water perceptions and use, adapted in part from previous work by Wright et al. (2018a). Formal interviews based on this questionnaire were later conducted in Greenlandic, with the help of a translator, at the home of respondents, selected on a mixture of voluntary basis and impromptu visits – please refer to Maréchal et al. (2022) for more details on the community research method. While there were no formal requirements to receive an ethics approval for this kind of study, an informed consent was obtained through discussion and written consent forms, and the research team has remained in contact with – and made themselves reachable for – the interviewees afterwards.

Microbial water quality assessment

Sampling and temperature measurements

Samples (n = 54) from four communities (Itilleq, Nanortalik, Tasiusaq and Qaarsut) were used for analysis of microbial content and temperature measurements. The samples were taken from all points of the system: water treatment plant (n = 1), taphouses (n = 12), hot taps (n = 3) and cold taps (n = 3) of a public service house and two piped homes, hot taps (n = 5) and/or cold taps (n = 4) of five households with a tank, jugs (n = 10) and a bucket (n = 1) used for storing treated water from the public supply, two buckets and a jug containing alternative water from nature, and 12 washbasins. In addition, temperature was measured in another 30 samples. The samples from piped homes came from households that agreed to a visit.

The water samples were broken into four categories:

- **piped water** = delivered by a public tap (either directly outside the treatment plant, or at a taphouse), or piped all the way into residential and other buildings. In Greenland, most public taps/taphouses are found strewn around the settlements, away from the waterworks, so the water collected there has typically gone through a similar amount of piping as water piped to the buildings themselves.
- **stored water** (household water storage) = collected by the user from the public taps, and subsequently stored in jugs, buckets and tanks inside or outside their home. There is a wide variety of both tanks and jugs/buckets used for water storage in rural Greenland, and delineation is not straight forward. Some tanks are more similar in size to some of the buckets than to other tanks. Both can be found inside the homes in a variety of rooms, with various ambient temperatures. When relevant in the results section, the storage containers have been separated into categories based mostly on the material used (metal for tanks, vs. plastic for jugs and buckets), and the fact that the water stored in tanks is extracted through pipes/taps, including a hot tap.
- **alternative water** = collected from a natural source, untreated, and stored inside or outside the home
- **washbasin** = sampled from the shared basins used for hand washing in un-piped homes

The samples were taken in sterile semi opaque plastic bottles, which were rinsed three times with the sample and then filled to the brim. In the case of washbasin samples, the small amounts of water available in these basins meant that the three-step rinsing was done with very small

Table 1
Characteristics of the study sites for sampling and interviews on drinking water in Greenland.

Region	Study site	Location	Popula-tion	Water source use by the supply	Treatment (2020)	Distribution	Sampling dates	Data collected	Water samples	
								Inter-views	Tempera-ture	Biological tests
Qeqqata	**Sarfannguit**	66.90 N; 52.86 W	96	Lake	Sand filter, UV	Piped to buildings or taphouses	August 2019	Informal inter-views (groups)	16	
				Sea	Desalination (RO), UV		March 2020		14	-
Avannaata	**Qaarsut**	70.73 N; 52.64 W	174	River	Bag filter, UV	Piped to buildings or taphouses, tank (self-filled)	January 2021	9	23	
	Saattut	70.81 N; 51.64W	226	Sea	Desalination (RO), UV	Taphouses	February 2021	3	-	
Qeqqata	**Itilleq**	66.58 N; 53.50W	89	Groundwater well	Sand filter, bag filter, UV	Piped to buildings or taphouses	October 2021	3	11	
Kujalleq	**Nanortalik**	60.14 N; 45.24 W	1185	Lake	Pressurized filter with pH adjustment, UV, chlorination	Piped to buildings or taphouses, tank (truck-hauled)	February 2022	4	13	
	Tasiusaq	60.19 N; 44.82 W	63	Lake	Bag filter, UV	Taphouses, tank (self-filled)	March 2022	2	7	

amounts of sample, spun energetically around the bottles to compensate for the limited quantity.

The temperature of the samples was measured at the sampling site to evaluate the conditions at point of delivery. It was measured with a total immersion thermometer (VWR). For high temperatures, when the sampling bottle was too short to immerse the thermometer up to the required level (meniscus at the top of the column´s liquid level), the thermometer was immersed in the flow of running tap water itself. The samples were then brought back, in a thermos bag (to keep them from freezing since the outside air temperature during fieldworks was usually below zero, and never above 10 °C), to the field laboratory within 1–2 h, or 6 h for Itilleq, and analyzed immediately. This procedure was followed to avoid any significant biological activity from taking place between sampling and analysis.

The temperature results are presented in a boxplot, with boxes extending vertically from the first quartile (25th percentile) to the third quartile (75th percentile), crosses representing the mean value, and horizontal lines representing the median value. Whiskers represent the minimum and maximum values excluding outliers, and the dots represent the outliers. The N-value is shown on top of each column.

Microbial testing

Microbial water quality was tested using two types of 3M™ Petrifilm™ (supplied by VWR International). Aqua Heterotrophic Count Plates (AQHC) were used for total heterotrophic bacteria counts, while E. coli/coliforms (EC) 3M™ Petrifilm™ were used for counts of total coliforms and *E. coli*.

During the fieldwork phase of this study, an indoor space was dedicated to laboratory work, except for Itilleq, where samples were brought back to the laboratory at the DTU campus in Sisimiut. In all cases, a table surface was sterilized with disinfection wipes, and the samples for each session were ordered according to the time of sampling at each site, keeping gray waters (from washbasins) to be processed last to avoid contamination of later samples.

Water samples (other than greywater) were filtered (99 mL) through a sterile mixed cellulose ester membrane filter (pore size: 0.45 µm, diameter: 47 mm, Pall Corporation, MI, USA) placed in a clean graduated magnetic filter funnel and filter holder (Pall Corporation). The membrane filters were then aseptically placed onto a Petrifilm™ plate, which was hydrated with the remaining 1 mL of the sample to allow for analysis of the bacterial content in 100 ml sample volumes.

Samples of greywater from washbasins were tested by placing aliquots of 1-mL of the sample directly onto the Petrifilm™ plates. When necessary, serial dilutions (1/10 and 1/100) were made in refrigerated boiled tap water. Testing of this water on all types of Petrifilm™ plates was used as negative control samples to rule out cross-contamination during the microbial analysis. When necessary, enrichments of washbasin samples were performed by keeping the sample 24 h at 4 °C before re-testing.

All Petrifilm™ plates were readied for incubation following the instructions from the manufacturer, and then incubated at 37 °C in a transportable electric incubator, in stacks of 5 to 10. Heterotrophic counts provide an early indication of a deterioration in water quality (Bartram et al., 2003), and are well suited to identify distribution systems and raw water resources where the conditions are favorable to bacterial growth, including for pathogens if present. While the new Greenlandic regulation no longer mentions incubation at 37 °C (Thomas et al., 2016), the enumeration of "colony counts at 37 °C (…) is still considered to be of some value (Bartram et al., 2003). Moreover HPC at 37 °C have been shown to be mainly composed of mesophilic *Enterobacteriaceae* and *Citrobacter* spp., species primarily associated with fecal contamination, as opposed to the dominance of the environmental *Pseudomonadaceae* and *Aeromonadaceae* observed for HPC at 22 °C (Gensberger et al., 2015). After 24 h for coliforms on EC plates, and 48 h for AQHC plates and *E. coli* on EC plates, the Petrifilm™ plates were read for CFUs/100 mL or CFUs/mL (greywater) of sample. Enumeration of

Table 2
Types of raw water sources in use in each region (the numbers represent settlements where this type of water resource is currently in use).

Region	Number of settlements using each type of raw water resources				
	Surface water (lake)	Surface water (river)	Spring	Ground water (well)	Seawater (RO)
Avannaata	9	5			5
Qeqertalik	6			1	1
Qeqqata	4			1 (1 as secondary source)	1 (+ 1 as secondary source)
Sermersooq West coast	3				
Kujalleq	6	1 (+1 as secondary source)	1		1
Sermersooq East coast	4	1			

E. coli (blue colonies) and total coliforms (red and blue colonies) on EC followed the manufacturer's instructions. Technical replicates were regularly performed to check the consistency of equipment and handling.

The funnel, filter base, tweezers, spreader, thermometer and sampling bottles and caps were sterilized after each day, by soaking the equipment overnight in a 3% chlorine solution. Alcohol disinfection napkins and rinsing with water were used between samples.

Bacterial counts results were log transformed, and are shown in superimposed scatter plots, with means for each category of water samples or bar graphs. Figures were prepared in GraphPad Prism, version 9.5.0 and Microsoft Excel. The results have been reported back to the inhabitants who had provided samples.

Results

Data on the raw water sources of Greenlandic settlements are shown in Table 2 (more detail is available in Appendix A) for each Greenlandic region. In all regions, surface water was either the only or the main water source (lakes in 33 settlements, rivers in 9, and spring in 1), with seawater desalinated by reverse osmosis (RO) being the second most used resource (in place in 9 settlements), and ground water used in only two locations (one of them as a secondary source).

Secondary sources, when present, mean that a system was in place all year long, but only used when water availability of the primary source was limited, typically due to seasonal variations in technical failures.

At the time of this study, none of the visited localities had yet received the new modular water treatment system. The methods of water treatment (described in Table 1) were filtration in three settlements and the town, and RO in one settlement. The last settlement, visited twice, used filtration during the first visit, and RO during the second. All water received UV disinfection, but only the town used chlorination. Chlorine is generally not used for water treatment in the Greenlandic settlements because the potential health risk of wrong dosing was evaluated to be higher than that of microbial recontamination of the treated water. This, however, means that the drinking water is not protected from recontamination during distribution and storage. *E. coli* were only detected in gray water samples (washbasins).

Water acceptability – summary results from the interviews

Most respondents (17 of 21) agreed that the water supply was the responsibility of Nukissiorfiit, while one thought the responsibility lied with the municipality, and three didn´t know. One mentioned being unsure of whether Nukissiorfiit "was here", and another thought that Nukissiorfiit ought to be, but was not "taking responsibility".

On the topic of safety, about half (10 of 21) expressed worries about the quality of treated water, both regarding the presence of pathogens and chemicals. More specifically, their concerns were directed at the state and maintenance of the distribution system – mostly the old piping (8 of 21), and temperature of the water supply (1 of 21) – and not at the treatment, in which they expressed more confidence; as one respondent put it, because "it is automated". Overall, 16 of 21 respondents said people in their household never got sick because of the water, 2 of 21 sometimes, while the remaining three didn´t know – although one wondered. However, 4 of 21 would say that they would sometimes hear of people in the settlement getting sick because of the water. When monitoring came up, it was slightly more common to express trust (4 of 7) rather than distrust (3 of 7) in the authorities in charge.

On their overall preferences and practices, about 76% of respondents found the public water good (12 of 21) or acceptable (4 of 21), and a majority (16 of 21) reported it as their main drinking water source. When questioned more specifically, however, half of respondents deemed it unstable (12 of 21), and mentioned variability in color (12 of 21), taste (7 of 21), smell (4 of 21) and temperature (1 of 21), and had observed these fluctuations to be influenced by season, weather (rain), and/or tides for groundwater. One respondent related that "you can see the taste by the color". Even within the group that favored the public water as their source of drinking water, a third of them (5 of 16) admitted they disliked the taste of it.

When drinking piped water, over half of respondents (14 of 21) did nothing to treat it, while 6 of 21 boiled it first (albeit one only when it smelled, one only in the summer, and the third one only for their baby), and one only drank it when mixed with a flavoring, or only when alternative water was not available. In two households, only specific inhabitants drank the piped water, while the others only drank alternative or bottled water.

Alternative water was the only source of drinking water for 5 of 21 respondents, who reportedly disliked public water and never drank it. In fact, on regular basis, 71% of the respondents (15 of 21) reported also using an alternative source of water from nature at least sometimes, including half of those "often" or "always". Over half of respondents (12 of 21) said they would rely entirely on alternative water for drinking if they could, including two who did not have access to it: one single parent was unable to collect it, and one elderly person had relied on a now deceased spouse to collect it during his fishing outings. Most respondents (18 of 21) stated that they both preferred its taste, and trusted its quality, over those of public water – only two mentioned instabilities in taste and/or color for river water, yet still trusted this source better. *Nilak* was unanimously reported as stable, "*nilak* never changes". Alternative water was never boiled before drinking. The only safety concern expressed was about flies – otherwise, as stated by one respondent, they "trust nature to be clean".

Only one in 21 respondents, however, reported never using public water at all, and relying entirely on self-hauled water from a natural source. This was despite her estimation that she lived at a "very close" distance to the taphouse (about 130 m of relatively flat and easy terrain), and needed large quantities for her work as *piniartup nulia* ("hunter´s wife") in processing the skins.

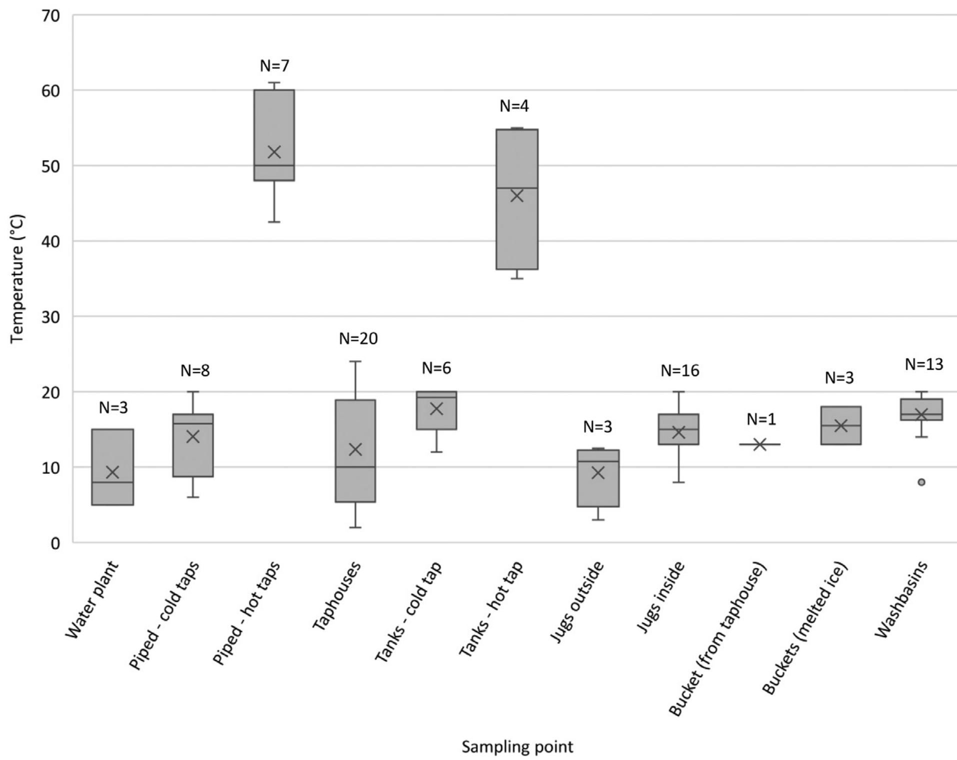

Fig. 2. Temperature of water at sampling point, in °C. The number of samples (N) in each category is shown above the columns.

Of the 11 respondents who expressed an opinion on bottled water, all liked and trusted it, but only one suggested that it was his preferred choice of drinking water. Alternative water from nature was therefore the preferred and most trusted water source for the majority of respondents, across piped and un-piped homes alike.

On the topic of water treatment and how it is perceived by the residents, two points are worth mentioning, namely the uses of reverse osmosis and chlorine disinfection.

Complaints on water obtained through RO were made by five respondents (including two in informal interviews). Three found it "salty". One remarked that rust formed in the pipes when using this treatment method – which was used in this location as a secondary source in cases of emergency, when awaiting maintenance on the surface water pipes. Two mentioned resorting to water from nature for their household drinking water whenever the public supply switched from lake water to RO.

As for chlorine, close to half of respondents expressed either distrust (6 of 21) or dislike (3 of 21) for it, with at least two saying they wouldn´t drink chlorinated water. One respondent said they used to use chlorine in their household, but over time realized that "less is more" and stopped using it, because it was "not good for health". Only one respondent expressed a positive outlook on chlorine, while the other half (11 of 21) expressed no clear opinion.

As for reported hygiene practices, most respondents having access to a service house reported using it for showers and laundry (12 of 15). This usage included a respondent, who had a tank in their home. The other three respondents used the water in their own homes for personal hygiene and laundry, including two with tanks and one without.

Most respondents (18 of 21) reported using a washbasin in their home for handwashing "always" (16) or "sometimes" (2), including one house with a tank. The water was shared by the household and guests in most cases (13), and only by the members of the household in four cases. The last respondent, who had a tank in the house, reported using this type of basin only in specific cases, that is., for the hunter in the family, "when he has blood on his hands", and no one else. Of the 17 households that used one regularly (i.e., excluding the one where the basin was linked to a specific activity), the content of the basin was reportedly changed at least daily, and in most cases several times a day (14). The factors influencing the frequency of change included visible cleanliness/turbidity of the water, number of people present in the house, and occasional uses that required more soap (for instance the processing of a recent seal catch that would leave the hands greasy). Only one respondent cited the quantity of water available to the household as a limiting factor in the frequency of change.

The topic of Covid-19 was brought up in the interviews held in 2020–2022 (Table 1), and while most people stated it had not changed their habits (13 of 21), or were unsure (2 of 21), a few did mention taking specific measures to address the risk (6 of 21). These measures included washing hands more often, using disinfection spray, changing the basin water and cleaning the basin itself more often, and generally following the recommended safety measures. It is, however, important to note here that strict measures had been put in place early on in Greenland to protect the settlements from the virus, which had therefore not reached them at the time of these interviews. One respondent stated, to this point, that they had not changed their handwashing habits because of Covid-19 since they were "vaccinated now, and there was no corona here before the vaccine".

Water characteristics along the supply chain

Temperature

Water temperature (shown in Fig. 2, detailed results in Appendix B) varied according to the point of sampling in the system, with the highest temperatures measured at the hot taps (52 ± 6 °C for piped, 46 ± 9 °C for tanks). Cold water showed an increase in temperature from the treatment facility (9 ± 4 °C) to the taphouses (12 ± 7 °C), and then to the cold taps, especially when those taps were connected to tanks (18 ± 3 °C) rather than to the piped water supply (14 ± 5 °C). Temperature of stored water samples was lower in jugs kept outside temporarily until used for drinking (9 ± 4 °C) than in those kept inside the homes (15 ± 3 °C for jugs, and 15 ± 2 °C for buckets). Most washbasin water was found to be between 14 and 20 °C at the time of sampling,

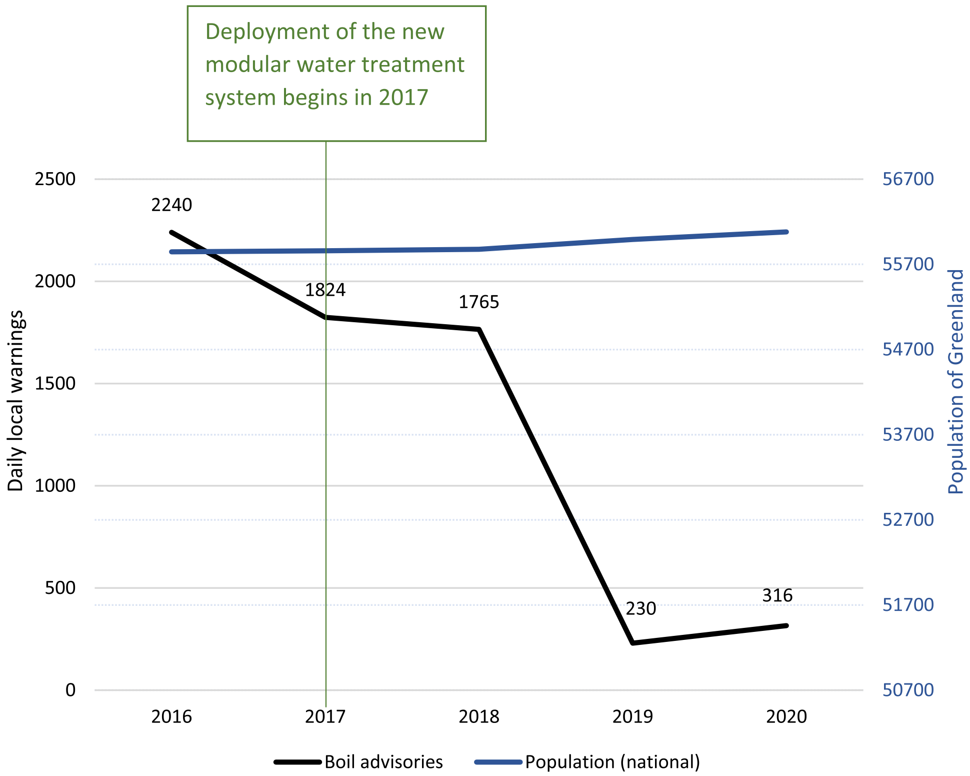

Fig. 3. Yearly number of boil water advisories (BWA) in Greenland. One unit is one day of BWA in one location. The national population is shown on the secondary axis.

except for one at 8 °C, with an average of 17 ± 3 °C – overall higher than the water found in the jugs. This suggests that the water, after being poured into the washbasins, had been left in the basins long enough to adjust partly to the indoor air temperature.

Piped water quality

Overall, the status of the microbiological quality of drinking water in the settlements can be explored by looking at the frequency of BWAs issued by the Greenland authorities in charge of monitoring water quality. Boil advisories will remain in place until the water is tested with a satisfying result. The annual sum of days in any locality with standing BWAs (Fig. 3) has gone down about tenfold between 2016 and 2020, thus indicating that the overall water quality as delivered by the water works of rural Greenland has improved significantly during recent years. One key reason for this improvement is believed to be the aforementioned gradual deployment since 2017 of a new modular system of water treatment, prioritizing settlements with high occurrences of boil water advisories.

Indeed, of all samples taken, piped water (including taphouses) was where the lowest bacterial counts were found, with some heterotrophic bacteria (Fig. 4a) present in 15 of 19 taps, coliforms detected in only one instance (Fig. 4b), and no *E. coli* detected in any sample (<1 CFU/100 mL water, Appendix B).

The range of heterotrophic bacterial counts was one order of magnitude higher in the piped building taps compared to the waterworks, and another two orders of magnitude in the taphouses compared to the piped building taps. While the order of magnitude of heterotrophic count was usually no higher than 10^1 CFU/100 mL (for 9 of 12 taphouses, the waterworks, and all three piped buildings), three taphouses in three different communities showed heterotrophic counts in the thousands (Fig. 4a). Two of these seemed to be never or rarely used (according to users' testimony and their placement relative to other buildings), but the third one was in regular use by at least some residents. Coliforms were only detected in one taphouse sample.

Notably, of all the taphouses in use, those with heterotrophic counts in the tens or more CFU/100 mL were all found in one settlement, where the temperature of the water sampled at the taphouses was between 20 and 24 °C. In comparison, the water sampled at the treatment plant of the same settlement, at 5 °C, had a heterotrophic count of only 6 CFU/100 mL. In all other settlements, the water distributed through taphouses in use was coming out at a temperature of 2–10 °C, and never showed heterotrophic counts higher than 3 CFU/100 mL. In the settlements visited, most respondents (16 of 21) reported never having experienced a boil advisory, another four only rarely, and one did not know. One had experienced boil advisories only during their stay in a nearby city. Of those with BWA experience, only 1 of 5 reported feeling concerned about the advisory. In response to the warning, 3 of 5 respondents started boiling the water before drinking it – for one respondent this was only the case if a summer seasonal alternative water source was unavailable. The last respondent said it made no change to their habits, as they "already boiled it anyway".

Stored water quality

Various methods of water storage were observed in the interviewed households, and specific habits of water use were reported by the interviewees (detailed results of the interviews are available in Appendix C). Two main types of containers were used for domestic storage of water:

White semi opaque plastic jugs, typically around 10 L each, were usually kept on the floor – sometimes on a countertop when in use. These jugs (Fig. 5a) were said to be generally kept inside the house, especially during the winter to prevent the water from freezing. In the summer, the jugs containing water specifically for drinking were reported to be stored outside to keep the water cool. All jugs were usually kept closed by a lid (15 of 18), except in some cases for the jug currently in use. They were reportedly only refilled when empty, and cleaned or replaced regularly. It was reported to be difficult to clean the inside of the jugs, because of the small size of the opening at the top. The users, however, testified to having devised a wide range of ingenious practices for cleaning their containers, often involving some strategy to scrub the inside of the jugs by filling them with water and some sort of solid material, then shaking to induce abrasion and the removal of biofilm or dirt (Fig. 5b). The

Table 3
Maintenance of household items for water collection and storage.

Number of users		Hot water	Cold water	Rice	Salt	Stones	Sand	Soap	Towel wrapped around a stick
2	Combinations of methods used by the residents		x	x					
1		x				x			
3		x							
1		x					x		
1			x				x		
1			x			x			
2			x		x				
3		x						x	
1		x						x	x
1			x					x	
4			x						

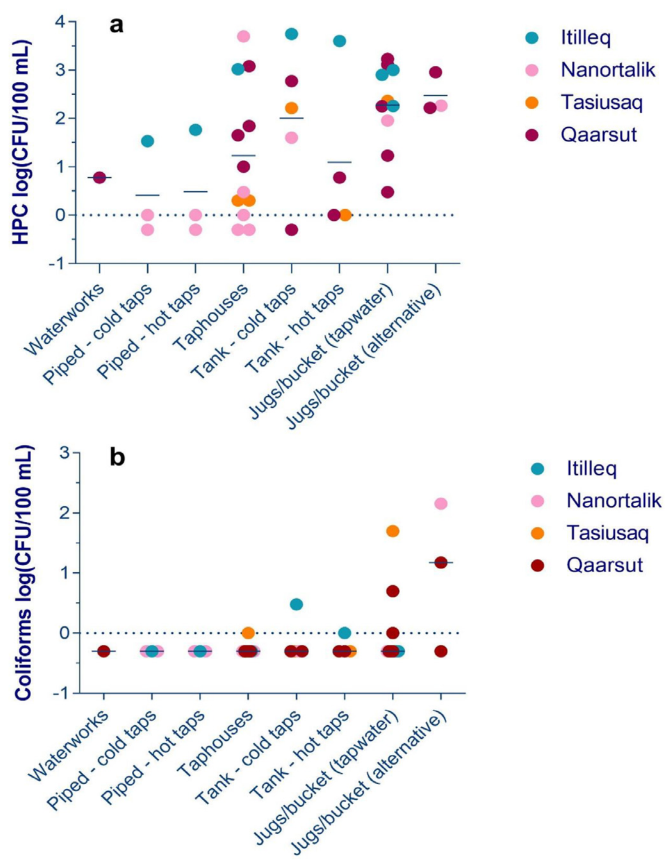

Fig. 4. Heterotrophic plate counts (HPC) (a) and coliform counts (b) in water samples retrieved along the public supply distribution system, and after storage in various household containers in four Greenland settlements. The quality of alternative water sources stored in jugs and buckets is also shown. The detection limit was 1 CFU/100 mL (0 log CFU/100 mL), shown as the dotted horizontal line. Non-detects are shown as $\frac{1}{2}$ the detection limit (−0.301 log CFU/100 mL). Means within each category of water samples are indicated by the short full horizontal line.

variety and popularity of the tools used for this purpose are summarized in Table 3 (more detail in Appendix C).

Opaque plastic buckets (Fig. 5c), with a capacity of around 60 L, were used to store larger amounts of water inside the house, and in particular, to melt and store water from frozen lake or ice flows (*nilak*). Of those using *nilak*, half report rinsing the surface of the ice first with tap water, before leaving it to melt. A noticeable brown deposit could be found at the bottom of the bucket where lake water was melted, as illustrated in Fig. 5d. Buckets were kept closed in three out of five cases, always inside the house at indoor temperatures, and specifically in the kitchen in two out of three homes that gave an answer. The water was retrieved by plunging a small plastic jug into the water, also shown in Fig. 5e.

The exact frequency of cleaning varied greatly between users, from “every refill” to “yearly”, and in three cases “when dirty”. Two respondents said they didn´t clean their containers at all.

Of all samples collected, stored water had the highest levels of HPC – up to 10^3 CFU/100 mL in five out of 20 samples, counts below the detection limit (1 CFU/100 mL) in only one sample, and any order of magnitude in between in the remaining 14 samples (Fig. 4a). Stored water also contained higher amounts of coliforms (Fig. 4b) than piped water – with detection of coliforms in 25% of the samples, albeit in relatively low numbers (a few CFU/100 mL in four samples, and 50 CFU/100 mL in the last). *E. coli* was not detected in any stored water sample (Appendix B).

No significant correlation (p>0.05) was found between the temperature and HPC content of stored water. Temperature was thus clearly not the only factor in stored water contamination, and the role of other factors (such as the quality of the specific water source and methods of collection, storage, cleaning habits and use) needed further exploring.

Alternative water

Heterotrophic counts of alternative water samples (Fig. 4a) were somewhat comparable to those of household storage samples: presence in all samples, in hundreds of CFU/100 mL, though never reaching the highest level detected in the stored water samples.

In contrast, alternative water harbored the highest counts of coliforms of all categories of samples - with coliforms present in two out of three samples, in tens and hundreds of CFU/100 mL (Fig. 4b), but no *E. coli* (<1 CFU/100 mL).

Tracking water quality from taphouse to household storage

In some cases (Qaarsut, Itilleq, Nanortalik and Tasiusaq), it was possible to track water from its supply to its point-of-use inside a home, and witness the evolution of water quality from tap to household container (tank, jug or bucket).

Fig. 6 illustrates the deterioration of water quality from taphouse to household tank in three out of four households, with higher bacterial counts in the cold tap samples than in the ones from hot taps. This was especially true for the tanks of households B and C, which had hot water temperatures as high as 55 and 54 °C, respectively, and showed a decrease of 2 orders of magnitude in HPC in hot water samples relative to that from the cold tap. In comparison, water from the hot tap of household D only had a temperature of 35 °C, and HPCs from cold and hot taps were in the same order of magnitude (3.6 and 3.7 log(CFU/100 mL), respectively).

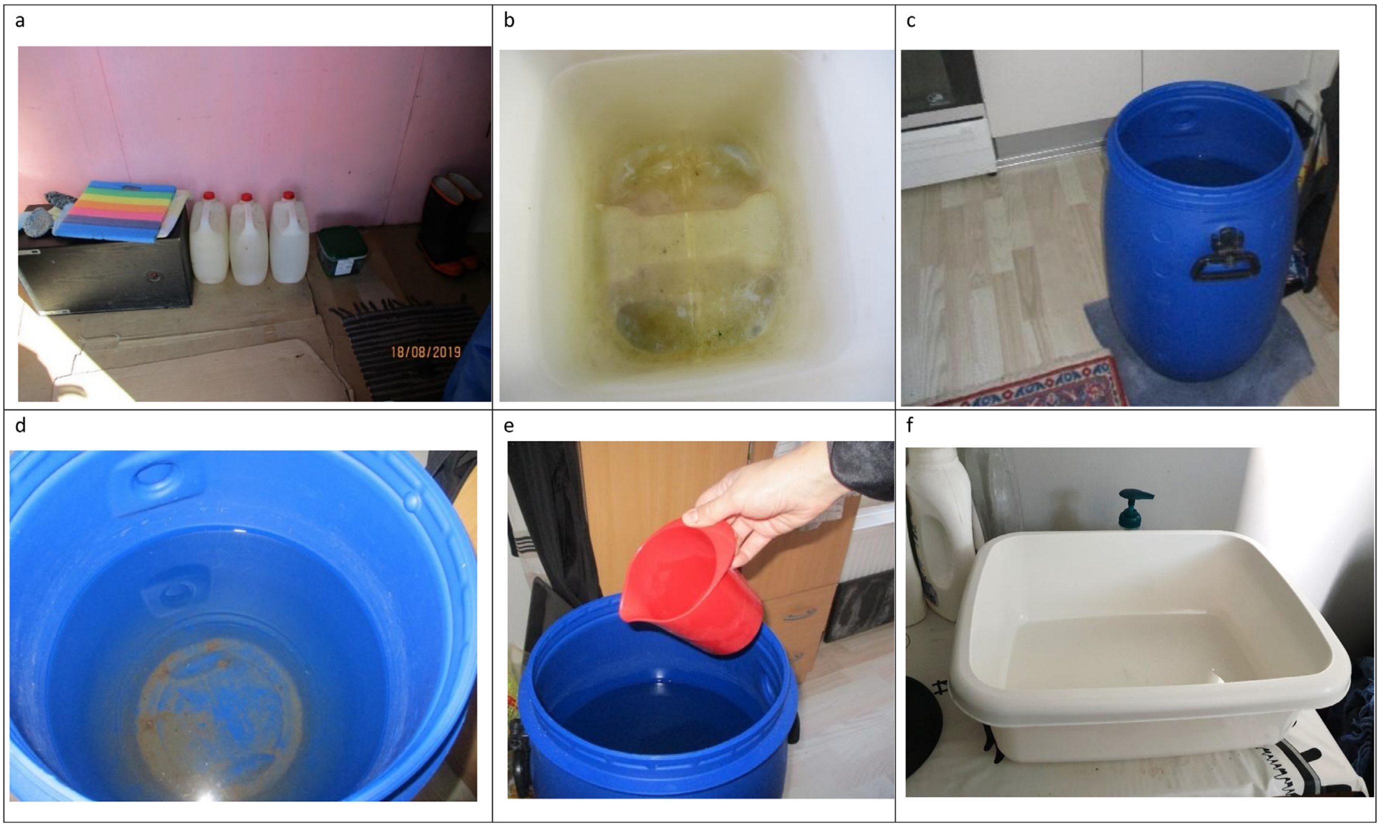

Fig. 5. Plastic jugs used for collecting and storing water in the household, here inside the unheated hallway of the house (a), and the bottom inside such a jug, showing the film that may develop after extended use (b). A bucket where water from the frozen lake is collected for use in the house (c), the impurities at the bottom after melting ice (d), and the jug used to take out the water (e). A basin used for handwashing, containing water and soap (f) - the hands are dipped in and rubbed with soapy water and then dried directly without rinsing.

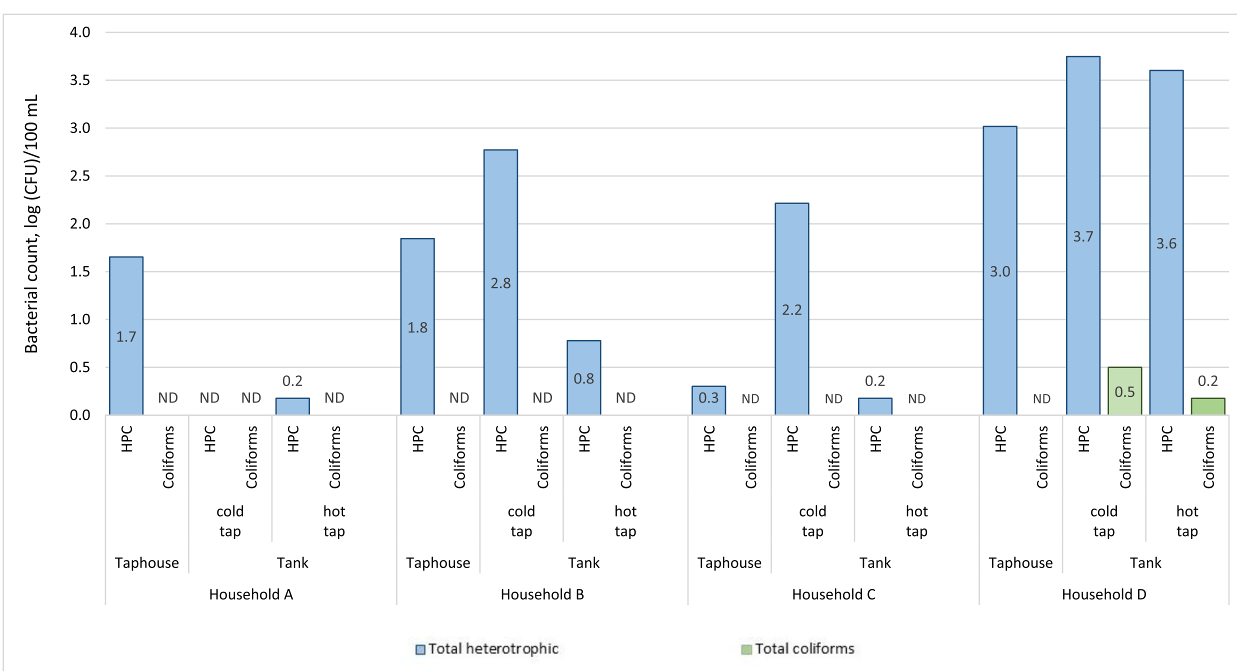

Fig. 6. Tracking microbiological water quality from tap to point-of-use household tanks; showing total heterotrophic and total coliform counts log (CFU/100 mL) for water sampled at the taphouse, and then in the household storage tanks. Values, when detected, have been log transformed. The mention “ND” represents the absence of detection in 100 mL of sample.

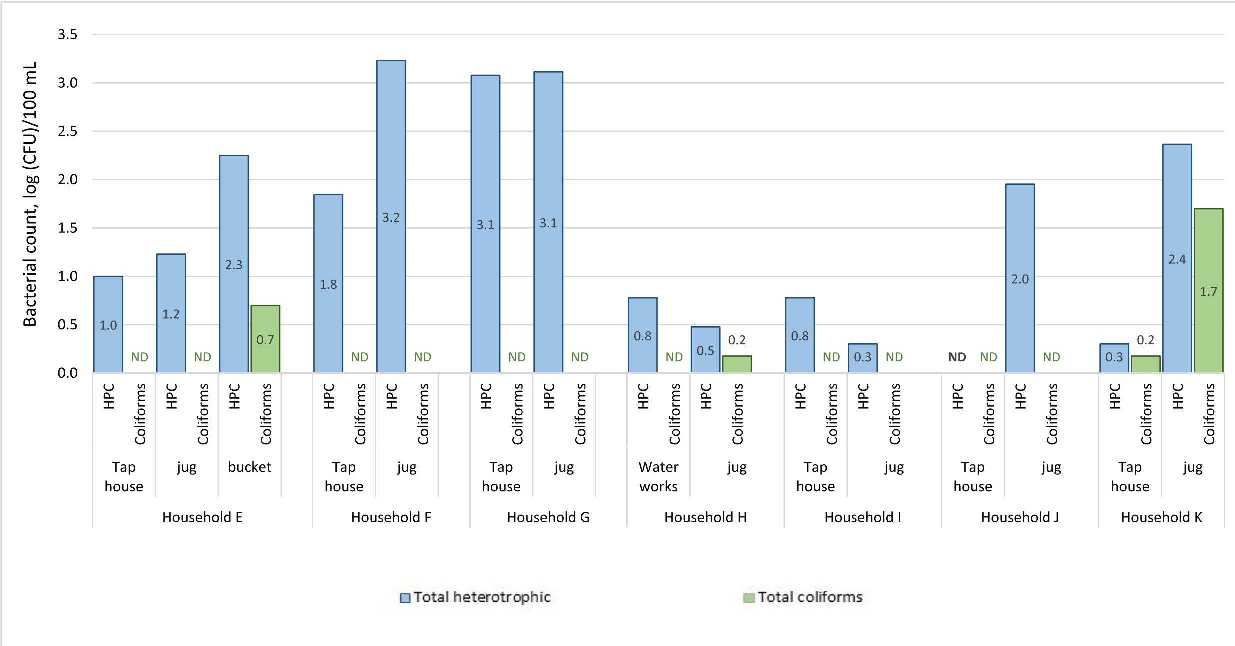

Fig. 7. Tracking water quality from tap to point-of-use household storage: jugs and buckets; showing total heterotrophic and total coliform counts (CFU/100 mL) for water sampled at the taphouse, and then in the household storage jugs or buckets. Values, when detected, have been log transformed. The mention "ND" represents the absence of detection in 100 mL of sample.

In contrast, the tank of household A showed very similar counts from both taps, but in this case the count was very low (<1 and 1 CFU/100 mL, respectively, for cold and hot taps), and lower than HPCs obtained at the taphouse from which the water was sourced. While this last element could only be explained by a deterioration in water quality at the taphouse since the last tank refill (the residents did not report using any disinfection), the overall cleanliness and frequency of cleaning of the tank water may be main factors that differed from the other tanks tested. Tank A was reportedly cleaned monthly, while the other tanks tested were never cleaned. Storage temperature was also investigated as a factor in the stability of water quality in Household A, but the tank was located in a heated cellar, and the water from the cold tap came out at 20 °C, a temperature similar to that of the other tanks.

Fig. 7 shows the changes in water quality in household storage jugs and buckets in five out of seven households, where bacterial counts overall increased in household storage containers, including in three cases the detection of coliforms.

More precisely, the first example (household E) showed the changes in microbiological quality of water from a single taphouse after storage in a closed jug outside the house and cleaned twice weekly, and in an open bucket inside the house. The heterotrophic plate count in the jug water showed little change compared to the taphouse (HPC increased from 10 to 17 CFU/100 mL), while the bucket water showed an increase of HPC of over one order of magnitude (from 10 to 178 CFU/100 mL), and the appearance of coliforms. In the case of household F, water from a taphouse gained two orders of magnitude in HPC while stored in a jug that was cleaned every trimester. Coliforms were detected after storage in household H, where the water from the treatment plant was stored in a jug that was reportedly never cleaned. In household J, using water from a taphouse where no HPC were detected, HPCs were detected in the hundreds CFU/100 mL after the water was stored in a jug that was rinsed at every refill, but never cleaned. In household K, water from the taphouse (the only one with a presence of coliforms) was stored in a jug cleaned twice a year. This jug-stored water contained heterotrophic and coliform counts, which were two and one orders of magnitude higher, respectively, than the water coming from the taphouse.

In the remaining two households, there was no or almost no deterioration of the microbiological water quality. The jugs of households G and I were reportedly cleaned regularly, jug G at every refill/daily and jug I weekly. This could explain why water quality was more stable in these two jugs (and jug E above, cleaned twice weekly) than in the other four – of which two are never cleaned, and the other two are cleaned only twice and four times a year. This confirms that proper maintenance of household water storage containers plays an important role in ensuring lasting water quality.

Washbasins

In un-piped homes, the usual method for handwashing was to fill a plastic basin, then kept either in the sink or on the countertop in the kitchen or the bathroom, with water and soap (Fig. 5f). The users would rub this soapy water on their hands, and then directly dry them without rinsing due to the lack of running water. The water was shared by all users.

Microbiological analysis of the washbasins from 12 un-piped homes in Qaarsut, Itilleq, Tasiusaq and Nanortalik revealed high HPCs (Fig. 8a), all in the order of 10^2 to 10^5 CFU/mL, with presence of total coliforms in varying orders of magnitude (Fig. 8b) – from absence in one sample (and presence after enrichment in two), to 10^5 CFU/mL in five samples. *E. coli* was detected in four out of 12 samples, all in a range of 2 to 5 CFU/mL (Fig. 8c).

While indoors temperature provided a favorable environment for bacterial growth, no significant correlation (p>0.05) was found between temperature and bacterial levels, so other factors such as the quality of the water source and use in the household were likely more influential.

Discussion

Acceptability of water was found to be an important factor, confirming observations made in the US and Canadian Arctic (C.J. Wright et al., 2018a; Marino et al., 2009; Goldhar et al., 2013; Daley et al., 2014; Hanrahan et al., 2014). A clear preference for alternative sources was expressed by a significant portion of the Greenlandic population, as well

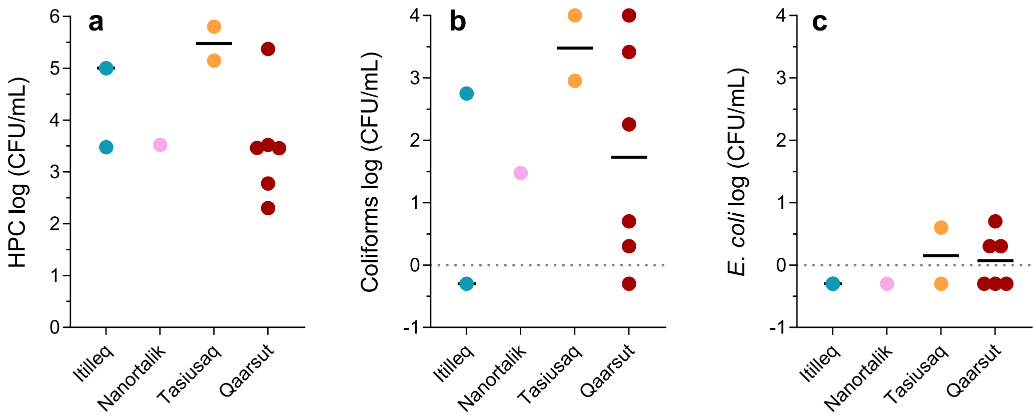

Fig. 8. Microbiological quality of water in washbasin in four Greenland localities. Heterotrophic plate counts (HPC) (a), coliform (b) and *Escherichia coli* (c) counts are shown. The detection limit was 1 CFU/mL (0 log CFU/mL), shown as the dotted horizontal line in (b) and (c). Non-detects are shown as $\frac{1}{2}$ the detection limit (−0.301 log CFU/mL). Means within each settlement are indicated by the short full horizontal line.

as some concerns about taste and appearance of public water in some cases, related to either season (thaw-melt) or technology (reverse osmosis in particular). The alternative sources, when used, were neither treated nor monitored by water professionals, and hence constituted an unknown in the general water system and its possible impact on human health. This water, however, received more trust from users, who almost unanimously valued it higher than public water for its quality, its taste, and the reliability of both. Those who had this alternative water supply in their homes had it by choice, rather than necessity. It is important to note the cultural and social importance of these sources in terms of well-being, as they are preferred by the users, provide them with a sense of safety, and participate in self-reliance – as also mentioned in Canada by Anderson et al. (2013) and Goldhar et al. (2014) . Based on informal conversations – and similar to observations made by Goldhar et al. (2014), it emerges that a rich traditional knowledge is associated with this practice, regarding the choice of natural sources and their respective potential health benefits – although this is beyond the scope of this study. Upon testing, alternative water sources were found to contain some coliforms, but no *E. coli*. This is aligned with findings in Nunavik, Canada, and Alaska, USA (Mattos et al., 2021; Martin et al., 2007), who noted the generally good quality of the alternative water sources chosen by residents. The quality of these sources, however, could be at risk of degradation under the influence of climate change induced changes in biodiversity and preferred wildlife paths (UNESCO, UN-Water 2020; Gagnon et al., 2020; Peeters et al., 2019). These could threaten to disqualify the knowledge inherited through generations on the quality of water from nature by bringing new risks of zoonotic threats, from which the waters are not protected. Urbanization and increased human activity further add to the risks with anthropogenic contamination of the sources. We recommend these risks be further studied and quantified in order to enable sufficient protection of public health in times of rapid changes.

As for treated drinking water, its microbial quality in the public supplies of rural Greenland improved tremendously overall after the water treatment plants in the eight most problematic settlements were replaced by the new modular system – with boil advisories going down by 86% from 2016, before the first replacement was made, to 2020 (Fig. 3). However, none of the settlements visited in this study had received this modular system at the time of the visit.

Nevertheless, examination of the microbial water quality of the public water as delivered by Nukissiorfiit in the four settlements visited showed that the water quality requirements were met for most samples at the time of the visit: no taps, neither public nor private, tested positive for *E. coli*. Only one taphouse tested positive for total coliforms, however with a count that was at the limit of regulation of 1 CFU/100 mL (Thomas et al., 2016). Three taphouses stood out with HPC (37 °C) levels that were two orders of magnitude higher than any other taphouse. Two of them were not (or probably not) in use and thus stagnant, while the third was at the end of the pipe, and near the border of the settlement, and therefore probably used by few people and stagnant part of the time. This underlines the importance of flushing the pipes regularly, and especially before collecting water for drinking. Taphouses in a settlement with higher water temperature at delivery had higher bacterial counts, highlighting the importance of maintaining proper temperature in the system.

In household water storage, although requirements were still met in most samples, water quality showed signs of deterioration – with HPC increasing by one to two orders of magnitude in half of the household containers (jugs, buckets and tanks), indicating either the presence of a biofilm, contamination during handling (supported by the appearance of coliforms in a quarter of containers), and/or indoors temperature favorable to bacterial growth. Similar concerns were raised in Canada in previous studies by Martin et al. (2007) and Wright et al. (2018b). This illustrates how widespread the issue of water quality is for Arctic residents, as we observe a pattern of water quality deterioration during storage in household containers.

The observed increase in bacterial numbers along the distribution system appears to be closely linked to maintenance habits, as also observed in Canada by Martin et al. (2007). Both tanks and jugs are, however, notoriously difficult to clean. Cleaning a tank often requires climbing into it, a difficult exercise that not all can perform, and jugs have small openings and complex shapes that makes it challenging to reach and clean their inside surface thoroughly. While chlorine could be offered as a household water treatment method, its reception is likely to require outreach first, as perceptions are rather negative – as also observed in other parts of the Arctic (Martin et al., 2007; C.J. Wright et al., 2018a; Ritter et al., 2014; Daley et al., 2015). While outreach to raise awareness on waterborne and water-washed diseases has been shown to lead to better maintenance of water-related equipment in the households, and improved hygiene practices (Roche et al., 2012; Hennessy and Bressler, 2016; Sohns et al., 2019), and could be a promising measure to implement, special care would then have to be put on providing a training for chlorine use, as appropriate dosing and monitoring can be difficult to achieve in individual households, and misuse could compromise health (WHO 2019). However, considering the residents' dislike for chlorine, it is more appropriate to, instead, recommend developing containers for water storage that are easier to clean and maintain.

As for washbasins, they presented high bacterial counts in all three categories, including the presence of *E. coli*. This indicates that the prerequisites for bacterial survival and even growth in the washbasins are present, turning these basins into vectors of transmission when someone having pathogenic organisms on their hands uses a basin shared with other users. The transfer may occur orally by direct contact (hand to mouth), or indirectly via, e.g., food items. While soap can inhibit or kill bacteria, this effect depends on the concentration in the water. The finding of live *E. coli* in some washbasins indicates sub lethal soap concentrations and therefore the possibility of transmission of *E. coli* and possibly other fecal pathogens – of which *E. coli* is an indicator organism – among users. This confirms concerns expressed in Chambers et al. (Howard et al., 2020) about transmission of fecal bacteria through washbasins in un-piped homes. Thus, what was originally devised as a hygiene measure (implementation of a handwashing system in the home) could end up constituting a public health hazard by creating a culture of pathogens, and a route of transmission between users – a remark also recently made in an Alaskan study by Mattos et al. (2021).

To better protect the public health of the rural population in Greenland, in-home running water could seem like an obvious priority. However, this would require costly investments, and some localities have limited raw water resources (Maréchal et al., 2022), which may not be able to support the increased water usage to be expected if all homes were piped. Therefore, other measures to improve hygiene and water access should also be explored.

In conclusion, the public water supply was under control and provided overall safe and acceptable water to its users. However, most users preferred untreated and unprotected water for drinking, trusted based on inherited knowledge and experience. Changed in the environment and climate could represent a threat to the quality of these sources. As for treated water, its quality showed signs of deterioration within the system when used improperly (stagnant taphouses) and during household water storage, although cleaning of storage containers appeared to be a determining factor in mitigating this effect. Furthermore, the use of shared basins for handwashing is a matter of concern in terms of disease transmission. While these challenges are being assessed and solutions investigated, our overall recommendations are: 1) to ensure that all taphouses are regularly used or flushed, and monitored, or alternatively shut down; 2) to develop solutions for household water storage that are easy to clean, and provide information on maintenance; 3) to create an in-home running water point for hand washing in unpiped homes; and 4) to investigate the risk of deterioration of the quality of untreated water sources used for drinking. Since the responsibility of Nukissiorfiit ends at the public tap (for taphouses) or at the main (for piped households), some of these solutions will have to be explored at another level. Also, further research should explore concerns expressed in the interviews regarding the taste and corrosivity of desalinated water, and the observation of rust in piped and desalinated water samples.

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Data availability

A summary of the data supporting the results can be found in the Appendices A, B, and C. The data supporting the results is available upon reasonable request.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Ethics and consent

All participants in interviews have given consent to the use of their answers in this research, and all results were anonymized in order to ensure that no participant could be identified through this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.heha.2023.100065.

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