Environmental Science Advances

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal

Cite this: DOI: 10.1039/d5va00054h

PFAS in drinking water, wastewater and surface water in Reykjavik, Iceland†

María J. Gunnarsdóttir, *[a] Hrund Ó. Andradóttir,[a] Kristín Ólafsdóttir, [b] Ásta Ósk Hlödversdóttir,[a] Roland Kallenborn, [c] Erik Magnus Ræder,[c] Jan Ludvig Lyche,[c] Jitka Becanova [d] and Rainer Lohmann [d]

Per- and polyfluoroalkyl substances (PFAS) are persistent contaminants with global environmental and health implications. This study evaluated PFAS concentrations in drinking water, wastewater, and surface water in Reykjavik, Iceland, focusing on seasonal variability and potential pollution sources. Thirty-three samples from groundwater, wastewater, and surface water were analysed for up to 54 PFAS. Results reveal that PFAS concentrations in Reykjavik's drinking water were minimal, which most compounds below detection limits, and the sum of 18 PFAS below 0.5 ng L^{-1}. These levels were significantly below EU Drinking Water Directive and European Food Safety Authority health limits, indicating effective source water protection. In contrast, elevated PFAS levels were detected in wastewater and surface water, with concentrations reaching 14 ng L^{-1} for sum 18 PFAS. The most prevalent compound was perfluorobutanoic acid (PFBA). The highest contamination occurred at firefighting training sites, particularly at Reykjavik Airport, where PFAS concentrations exceeded 2000 ng L^{-1}, dominated by PFOS. A comparison to prior results implied an about 10-fold decrease of PFOS in Reykjavik's wastewater treatment plant since 2017. These findings emphasize the need for continued monitoring, and further investigation into historical and active contamination sources to safeguard environmental and public health in Iceland. Given the presence of PFAS-contaminated sites in Iceland, targeted PFAS management strategies are needed to prevent contamination of drinking water resources.

Received 27th February 2025
Accepted 2nd June 2025

DOI: 10.1039/d5va00054h

rsc.li/esadvances

Environmental significance

The persistent and widespread contamination of PFAS has recently been recognized as a major threat to the environment and public health. There are very limited measurements of PFAS in Icelandic environment, so these results are valuable as a first step in the process of investigating status. They are also valuable information into the limited knowledge of PFAS in the Arctic environment. The AFFF site results from Reykjavik Airport fire training site show significant contamination, while the results of drinking water source at Heidmörk for all the capital region, serving 64% of Icelandic population, show clean water. The latter supports the importance of strong water protection policy as practiced in Heidmörk and laid down in the EU Water Framework Directive.

Introduction

Since the 1950s, per- and polyfluoroalkyl substances (PFAS), a large group of synthetic organic compounds, have been used in a wide range of commercial and industrial applications. They have been shown to be released from various sources and to be highly persistent in the environment, stored in soil and reach surface water and groundwater. They travel long distances with water- and air currents and are ultimately found even in the most remote places on Earth, such as in glacier melt and the Arctic biota.[1–4] PFAS pollution results from a combination of long-range transport with air and ocean currents, and local contamination such as emission from airports, fire-fighting training sites, wastewater facilities, municipal solid waste landfills, municipal incinerators and industries.[5,6] Application of biosolids to agricultural land is another potential pathway of human and environmental exposure to PFAS.[7] Some PFAS have been shown to bioaccumulate in animals and humans, with increasing concentrations up the food chain having an adverse effect on the biota and humans, and they are ubiquitously detected in human blood serum.[8–11] Several PFAS compounds cause toxic effects in humans, including dysfunctions in immune and thyroid function, liver disease, lipid and insulin dysregulation, kidney and testicular cancers, and developmental effects on unborn children.[12,13]

[a]Faculty of Civil and Environmental Engineering, University of Iceland, Iceland. E-mail: mariag@hi.is
[b]Dept. Pharmacology and Toxicology, University of Iceland, Iceland
[c]Norwegian University of Life Sciences (NMBU), Norway
[d]University of Rhode Island (URI), USA

† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d5va00054h

PFAS are used in nearly all branches of industry and in many consumer products because of their unique chemical and physical properties, such as water and grease repellence, temperature and chemical resistance, and surfactant properties.[14] PFAS have been used in aqueous firefighting foams (AFFFs), non-stick cookware, paper food packaging, creams and cosmetics, textiles for furniture, outdoor clothing, paints, photography, chrome plating, pesticides and pharmaceuticals.[12] More than 4700 PFAS were identified in 2018 to be either on the global market or likely to be on it. For many of these, there are no analytical standards or information on adverse health effects.[15] Glüge *et al.*[14] reported that over 1400 different PFAS are used in more than 200 use categories. Airports, military bases and fire-fighting training sites around the world have become significant PFAS contamination hot-spots due to extensive use of firefighting foam, with perfluorooctanesulfonic acid (PFOS) and perfluorohexanesulfonic acid (PFHxS) as the predominant substances.[16,17]

There was no legally binding limit for PFAS in drinking water in the EU until 2021. In the new EU Drinking Water Directive (EU DWD 2020/2184) on the quality of drinking water, the limit for the sum of 20 PFAS was set to 100 ng L^{-1}. The European Commission asked the European Food Safety Authority (EFSA) for a scientific evaluation of the risk to human health related to PFAS in food.[18] EFSA performed a risk assessment for the total amount of four PFAS (PFHxS, PFOA PFNA, PFOS) (PFAS-4) that are currently considered the main threat to human health due to their widespread occurrence and their toxic potential. The EFSA assessment determined a tolerable weekly intake (TWI) of 4.4 ng per g per kg weight per week, based upon the documented toxic consequences of PFAS exposure on the immune system of a 1-year-old child. Based on EFSA's opinion from 2020, the Danish DTU National Food Institute established the health-based limit for PFAS-4 in drinking water to be 2 ng L^{-1}. The limit was derived from EFSA's TWI in 1-year-old children and assuming that 10% of the daily intake of PFAS-4 is from drinking water.[19] This limit was incorporated into the Danish drinking water regulation in 2021 (BEK 2361/2021) and is currently the strictest PFAS criteria worldwide in protecting drinking water quality. Sweden recently established a limit of 4 ng L^{-1} for the total amount of PFAS-4 in drinking water.[20] Additionally, Sweden has expanded its regulation to include 21 PFAS compounds, as the fluorotelomer 6:2 FTS has been added to the 20 EU PFAS with the EU DWD limit of 100 ng L^{-1}. Denmark has recently added two PFAS into an updated regulation (BEK 940/2024), perfluorooctanesulfonamide (FOSA) and 6:2 FTS. Denmark has also recently issued a ban on the import, sale and re-use of PFAS-containing fire extinguishing foam concentrate on fire training sites (BEK 1360/27/11/2023) and has prohibited the use of specific type of PFAS in food packaging.[21]

The Stockholm Convention, which Iceland has signed, regulates the use of persistent organic pollutants (POPs) to protect the environment and human health (**http://www.pops.int**). Twenty-eight chemicals are regulated, including four PFAS (PFOS, PFOA, PFHxS and PFOSF). After this phase-out, manufacturing has shifted from the long-chain PFAS to shorter-chain alternatives, which are presumed to be safer. However, recent research confirmed that the substitute short-chain PFASs also have the potential to induce adverse health effects[22] and hence must be considered as regrettable replacements. Long-chain perfluorocarboxylic acids (PFCAs), along with their salts and related compounds, have been proposed by Canada to be added to the Stockholm Convention list for POPs.[23] In January 2023, authorities in Denmark, Germany, the Netherlands, Norway and Sweden submitted a restriction proposal for PFAS to the European Chemical Agency (ECHA), which is currently under evaluation in the EU. The aim of the restriction proposal is a comprehensive ban on all PFAS to reduce the risks to human health and the environment. The proposal focuses on the entire group of PFAS to avoid one PFAS being replaced by another, following the principle of replacing PFAS with non-PFAS alternatives where feasible or where the alternatives will soon be available. The initiative aims for a complete phase-out of PFAS substances (**https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas**).

The EU Water Framework Directive (EU WFD 2000/60/EC) aims at enforcing an EU wide strategy to prevent deterioration in the chemical quality of water and promote sustainable water management. The EU Directive 2013/39, amending the EU WFD for priority substances in the field of water policy, specifies an Annual Average Environmental Quality Standard (AA-EQS) for PFOS in inland surface water, setting a limit of 0.65 ng L^{-1}. The implementation process of EU-WFD is ongoing in Iceland and measuring priority substances, including PFOS, is part of that process. The Environmental Agency of Iceland has developed an action and monitoring plan for Iceland 2022–2027 (ref. 24) where 22 water bodies have been classified as possibly at risk and two at risk (1 groundwater and 1 lake). Analytic results including PFOS are now available for 14 water bodies in Iceland, of which 4 are from the capital area (2 surface water, 1 wastewater, 1 coastal sea sample). The results from 2017 of the two surface waters from the capital area – Tjornin (a lake in the city centre) and Kopavogslaekur (a stream in Kopavogur) showed PFOS concentrations of 30.7 ng L^{-1} and 5.2 ng L^{-1} respectively[24,25] while the results for PFOS in the ten water bodies from outside the capital area were largely below the method detection limit (MDL < 0.13 ng L^{-1}). In a Nordic project, PFOS was measured at 0.61 ng L^{-1} in lake Ellidavatn on the outskirts of Reykjavik in 2017; this was one of the lowest levels measured in thirteen lakes in the Nordic countries.[10]

Iceland is a sparsely populated island country in the middle of the North Atlantic Ocean (2024: 394 000 inhabitants; 103 000 km^2; 64°N latitude). The country's major income is related to fishing, aluminium smelting industry and tourism. There are no known production sites of PFAS in Iceland. However, there are 12 airports around Iceland with regular scheduled domestic flights requiring rescue and fire service on site, three of which are international. And there are 32 fire brigades operating in the country serving 64 municipalities. All required to do regular training. Though there are indications of some PFAS pollution in surface bodies within the most densely populated capital region, no systematic investigation has been conducted on how widespread it is and what is the source of the pollution. No measurements have been taken of PFAS before this research in

the drinking water supply in Reykjavík, which is generally very pristine,[26] or elsewhere.

The overarching goal of this research was to assess concentrations and trends of PFAS in drinking water, wastewater and surface water collected from representative locations in the capital region of Iceland. The particular focus was on resolving concentrations during different times of the year to capture varying weather conditions prone to contribute to water pollution and human activities. The underlying research questions were: (1) How abundant are PFAS in Iceland's water, and how do PFAS concentration in drinking water (groundwater) for the capital area compare to the new EU DWD and the health limits based on the new EFSA risk assessment, (2) How does the concentration of PFAS in wastewater effluent vary over different conditions over the year and to similar cities elsewhere, and (3) Is runoff water contaminated with PFAS and is there a certain polluting activity in the area of drainage that can indicate the source of pollution.

Methods

Sampling sites

The capital area including Reykjavík is a 762 km^2 area which consists of 6 municipalities (see Fig. 1) totalling 244 000 inhabitants in 2024. The city has a maritime cold climate, with frequent rain and freeze–thaw cycles in winter.[27] The highest pollutant concentrations in runoff typically occur after a long dry period, allowing particulates and compounds to accumulate on streets or in snow.[28]

The drinking water source for most of the capital is in Heidmörk, serving 64% of the population of Iceland.[29] Heidmörk area is approximately 4 km east of the built-up nearest area. The area is mostly in a postglacial porous lava field with thin volcanic strata and limited surface water, as most water seeps into the ground and the groundwater source is abundant. The 250 km^2 Heidmörk area is protected according to the EU WFD (Directive, 2000/60/EC) and divided into four protection zones (9 km^2 water intake, 100 km^2 primary, 141 km^2 distant and safety zones).[30] Average annual production of Veitur Utility serving three municipalities (Reykjavík, Seltjarnarnes and Mosfellsbaer), is 739 L s^{-1} from 18 boreholes in three water intake zones: Gvendarbrunnar–Jadar (G–J), Myllulaekur (ML) and Vatnsendakrikar (VK) (Table S-1†). In some boreholes the groundwater level is close to the surface and therefore more vulnerable to contamination, especially at production zones G–J and ML.[29] Total cell count (TCC) is measured at all water intake zones with a fully automatic flow cytometer (FCM).

Three WWT plants preliminary treat the municipal wastewater in the capital area *via* mechanical methods before discharging it to the open ocean. The largest WWT plant is Klettagardar (64.1556°N, −21.8729°W) operated by Veitur Utilities, which treats 60% of the wastewater from the greater capital area of Reykjavík totalling 320 thousand BOD (biological oxygen demand) people equivalents.[31,32] The raw wastewater is diluted with both heating- and stormwater, which is reflected by a low BOD (50–100 mg L^{-1}) and a high annual average flowrate of 1650 L s^{-1},[33] ranging from 1300 to 2000 L s^{-1} during sampling (Table S-2†). The outflow from the WWT plant is pumped 4–5 km out into Faxaflói Bay where further dilution and biodegradation occurs. According to Veitur Utility, 10% (summer) to 36% (winter) of the wastewater is estimated to be return water from the district heating system, mostly

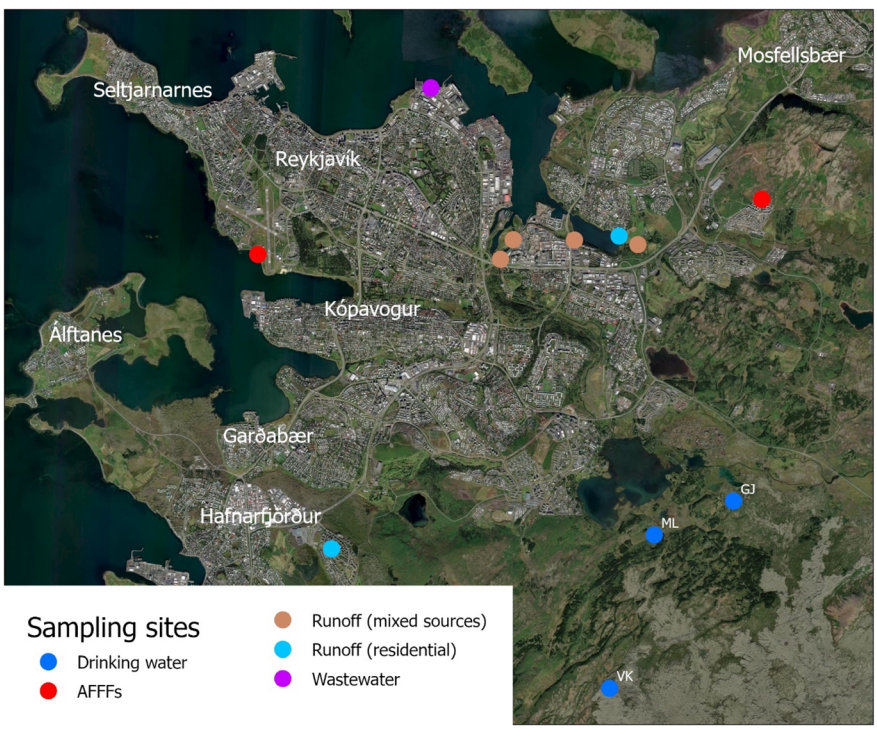

Fig. 1 The capital area with sampling locations.

geothermal water. The total flow in 2023 through Klettagardar was 53 Mio m^3 per year.

The choice of surface water sampling sites was based on different land usage within the urban area and interviews with local health inspection officials on possible contaminated sites (Table S-3†). In all, four different sites were targeted, based on historical land use: two residential sites developed at different times (in the 1980s, and from 2015); four mixed areas including highway, commercial and light industrial activities; and two runoff AFFFs sites, a former training site for the Capital Region Fire Brigade and a AFFFs fire training site at Reykjavik Airport. The sampling sites are shown on Fig. 1.

Choice of sampling sites and targeting different season and weather conditions are shown in the ESI chapter.†

Sampling program

Sampling procedure. Sample collection was performed according to guidelines from the laboratories at the Norwegian University of Life Sciences (NMBU) and the University of Rhode Island (URI), Narragansett, USA. All equipment, materials and containers were rinsed with high-purity water and methanol before use, using HDPE plastic bottles, 2 L for drinking water samples, 1 L for all others and 200 ml for blanks. The blank samples were filled with deionized water. A total of 33 grab water samples were collected in the period 2022–2024. The number of PFAS analysed in samples varied from 21 to 54 (Table 1).

Sample preparation at UI before shipment. With the exception of the drinking water and drinking water blanks, samples were acidified upon arrival to the lab with 1 ml 6 N HCl and stored cold until extraction. Oasis® WAX (500 mg, 6 cm^3, 60 μm, Waters, Milford MA, USA) was conditioned with 4 ml of 0.1% ammonium hydroxide in methanol, followed by 4 ml methanol and 4 ml Millipore water. Wastewater and runoff samples were centrifuged (3000 rpm for 10 min) and the supernatant transferred to a clean bottle before loading the samples on the wax columns. Isotopically labelled internal PFAS standard was added to the first litre of sample. About 2 L of drinking water was filtered for each sample and about 1 L for wastewater and runoff. Loading was done with a speed of 1–3 drops per sec in a vacuum manifold. The sample amount was determined by weighing bottles before and after loading. After loading, the SPE-WAX columns were washed with 4 ml of 2 M ammonium acetate pH 4, dried under vacuum for 15 min and stored at 4–8 °C until shipment to the analytical laboratories NMBU and URI.

Laboratory analysis at URI. Water phases were extracted using a modified EPA Method 1633. The water sample was spiked with isotopically labelled internal PFAS standard (used for extraction efficiency correction) and passed through 150 mg Oasis WAX SPE cartridges. The SPE columns were then eluted with 2% ammonium hydroxide in LC-MS methanol. Methanol extracts were concentrated with a gentle stream of nitrogen to a final volume of 0.5 ml. Water samples from field samples were also spiked with a mass-labelled recovery standard solution prior to preparation for instrumental analysis. Instrumental Analysis & QA/QC 40 μL aliquots of methanol extracts from either extraction process were diluted by a factor of 2.5 into

Table 1 Number of samples and PFAS substances analysed in each sample

Laboratory	Year of sampling/analysing	WS – water supply Heidmörk	WW – wastewater Klettagardar	WT – runoff ind. & residential	WT – runoff AFFFs	SUM all samples	No. PFAS substances analysed
URI	2022	2	2	0	0	4	44
URI	2024	0	0	0	1	1	54
NMBU	2023	3	2	4	2	11	21
NMBU	2023–2024	3	4	9	1	17	33
SUM		**8**	**8**	**13**	**4**	**33**	

a final 100 μL solution of 40:60 LC-MS methanol : 10 mM ammonium acetate in LC water. This solution was injected into a SCIEX ExionLC AC UHPLC system coupled to a SCIEX X500R quadrupole time-of-flight tandem mass spectrometer (QTOF MSMS), and the results were analysed in Sciex data processing software.

Laboratory analysis at NMBU. The columns were eluted with 10 ml 2% NH_4OH in methanol. The eluent was concentrated to almost dryness with N_2 at 50 °C and reconstituted in 1 ml 50% methanol. Finally, the samples were filtered using centrifuge filters. The samples were analysed on an Agilent 6495 HPLC–MS/MS using an Acquity BEH C18 2.1 μm × 100 mm column. The injection volume was 2.5 μl. Mobile phases were: A: water with 10% methanol and B: methanol, both with 2 mM ammonium acetate added.

Quality control procedures

QA/QC procedures are detailed in the ESI† for both universities. Briefly, the quantification of all targeted PFAS in samples and quality control (QC) samples was based on the isotope dilution method, using a 1/*x*-weighted linear regression calibration curve with an r^2 value above 0.99. The concentrations of target compounds were recovery-corrected using a set of mass-labelled surrogate standards, which were spiked into each sample prior to extraction. Due to different sampling dates, the samples analysed at NMBU were separated into two separate batches. Blank values and limits of detection were established separately for the two sets of samples. For all samples the levels found in the blanks were subtracted from the environmental samples.

Results and discussion

The overall range of results showed varied PFAS concentrations and detection frequency in the aquatic environment tested in Reykjavik (Table 2 and Appendix Tables 3–7). The groundwater source at Heidmörk, the drinking water source for the capital, is in good status, with the lowest detection frequency of PFAS. The runoff water from residential and industrial areas was nearly identical, whereas the PFAS concentration and detection frequency was higher in wastewater at Klettagardar WWT plant. The sites with historical use of firefighting foams had the highest detection frequency and stood out as heavily contaminated at Reykjavík Airport, with the PFAS concentration more than 500 times higher than the other runoff sites in the three groups of PFAS. The site at the former firefighting training station at Leirtjörn was much less contaminated than Skeljanes – Reykjavik Airport, though still having high detection frequency for PFAS-4 as in Skeljanes (see Table 7). The group of 6 PFAS were not analysed in all samples as shown in Table 2.

PFAS in drinking water

Results reveal that PFAS concentrations in drinking water in the capital area of Iceland were minimal and significantly below both EU-DWD and the strictest health base limit for PFAS-4 in Denmark (Fig. 2). The highest concentrations of all 24 PFAS

Table 2 SUM PFAS concentration, range of concentration, count detected, and detection frequency in each category

Type of site	Matrix	No. PFAS analysed	No. of samples tested	Median ng L^{-1} (without <MDL)	Range of sum of PFAS ng L^{-1}	Count detected >MDL/sum chemicals tested	Detection frequency %
Drinking water WS	3 intake zones	PFAS-4[a]	8	0.14	<MDL–0.14	1/32	3%
		18 PFAS[b]	8	0.18	<MDL–0.41	11/144	8%
		6 PFAS[c]	5	0.17	<MDL–0.19	4/30	13%
Wastewater WWT	Kletta-gardar	PFAS-4	8	2.31	1.57–4.21	29/44	91%
		18 PFAS	8	9.00	7.28–14.11	81/144	56%
		6 PFAS	6	2.28	0.84–24.4	23/32	64%
Surface water	Residential	PFAS-4	7	0.34	0.03–0.53	7/16	44%
		18 PFAS	4	4.07	3.11–5.69	23/72	32%
		6 PFAS	2	0.11	0.10–0.11	4/12	33%
	Industry	PFAS-4	9	0.35	<MDL–0.96	14/36	39%
		18 PFAS	9	4.57	3.23–7.48	51/162	31%
		6 PFAS	7	0.32	0.11–1.50	15/42	33%
	AFFFs	PFAS-4	4	796	2.13–1622	16/16	100%
		18 PFAS	4	1039	6.38–2152	49/72	68%
		6 PFAS	2	971	500–1442	11/12	92%

[a] PFAS-4 = PFHxS, PFOA, PFNA, PFOS. [b] 18 PFAS = PFBA, PFBS, PFHxA, PFHpA, PFHxS, PFOA, PFNA, PFOS, PFDA, PFUnDA, PFDoDA, PFTrDA, PFTeDA, PFPeA, PFPeS, PFHpS, PFNS, PFDS. [c] Additional 6 PFAS = FBSA, FHxSA, 4:2 FTS, 6:2 FTS, 8:2 FTS, FOSA.

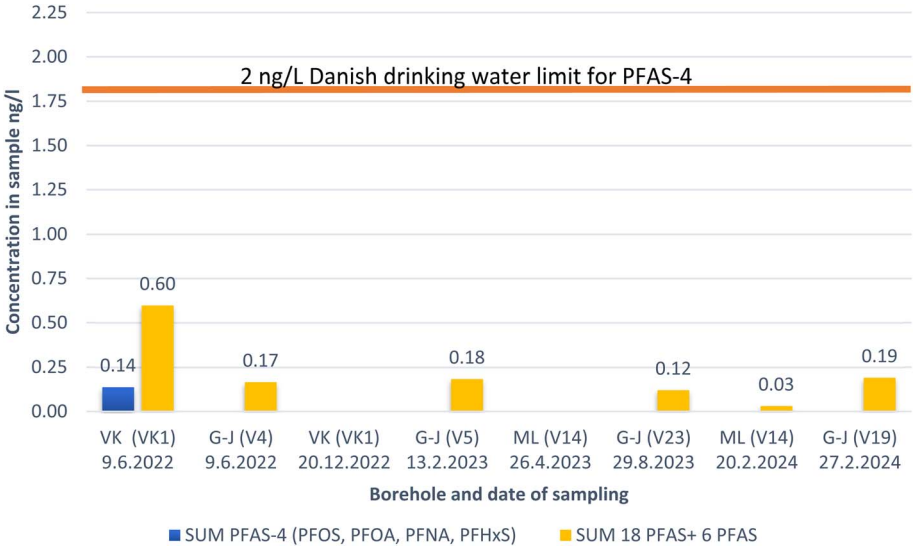

Fig. 2 SUM PFAS-4, SUM 24 PFAS (18 PFAS + 6 PFAS) including PFAS-4 in groundwater in Heidmörk. The Danish health limit for PFAS-4 is 2 ng L^{-1}. 6 PFAS were not measured in three samples on 20.12.2022, 13.2.2023, 26.4.2023, so only 18 PFAS for those samples are shown.

were at borehole VK1 on 9 June 2022 in light rain, 0.6 ng L^{-1}. Otherwise, PFAS were very low 0.03–0.19 ng L^{-1} or below detection limits (see Table 3 in Appendix). Weather conditions appeared to have limited influence on PFAS concentration in groundwater probably due to limited number of samples. The only positive correlation was between PFAS and air temperature. PFAS concentration did not correlated with total cell count (TCC), which is an indicator of surface water intrusions into the groundwater aquifer. It should be noted that the number of samples was only eight, taken at different sites, which could explain low correlation (see Table S-1†).

In an international comparison, the Icelandic drinking water was found to have low concentration of PFAS. For example, the median concentration of twenty PFAS in 59 water supplies globally was 3.7 ng L^{-1} with a maximum of 44 ng L^{-1},[34] whereas in Heidmörk the samples never exceeded 1 ng L^{-1} (Fig. 2) and the median was 0.18 ng L^{-1} (Table 3). In Reykjavik, the highest detection frequency in drinking water was for PFBA, which was detected over the detection limit in four out of eight drinking water samples (DF = 50%) with a maximum at 0.12 ng L^{-1} (Table 3), whereas in Kaboré *et al.*[34] the 59 water supplies the detection frequency of PFBA was 92% and maximum at 3.6 ng L^{-1}.

Similarly, a more recent study of 11 PFAS in 580 drinking water supplies in Sweden showed that 15 water supplies serving 2.2 million people had PFAS concentrations exceeding 10 ng L^{-1}. The highest levels detected in two supplies were 40 ng L^{-1}, that still is below the EU DWD (100 ng L^{-1}).[20] However, the majority of water supplies in the Swedish study had averaged total PFAS concentrations below 5 ng L^{-1}, with a maximum of 30 ng L^{-1}. These levels greatly exceeded the 2 ng L^{-1} Danish limit mentioned before or the 4 ng L^{-1} in the Swedish regulation. Bointeux *et al.*[35] showed that only nanofiltration was able to remove the analysed PFASs whereas conventional drinking water treatments such as aeration, sand, or granular activated carbon filtration, ozonation or chlorination did not efficiently remove PFAS.

PFAS in wastewater and surface water runoff from residential and industrial sites

Median concentrations of 18 PFAS above the detection limit in water from industrial runoff, residential runoff and wastewater are shown in Fig. 3. Among the three sources, wastewater most often showed the highest detection rate and concentrations for PFAS. Certain substances, such as FHxSA, PFDS, PFNS, PFPeS, PFHxS, PFUnDA, were only detected in wastewater. An exception to this trend was PFBA, which was predominant in runoff from residential and industry areas at nearly twice the concentration than that in wastewater.

For comparison PFOS and PFOA were monitored in effluent from 609 wastewater treatment works in England and Wales in 2015–2020 and the median concentrations were 1.8 ng L^{-1} and 2.6 ng L^{-1} respectively.[36] These concentrations are higher than in water samples from the WWT plant at Klettagardar, especially the PFOA results that are more than six times higher.

In a Nordic project, PFAS effluents (dissolved + particle phases) from fourteen Nordic wastewater treatment (WWT) plants were measured, two of which are in Iceland (Hafnarfjördur and Klettagardar), where PFOS was detected at 8.3 and 14.8 ng L^{-1} respectively. The PFOS median was 8.1 ng L^{-1} for the fourteen WWT and ranged from 2.1 to 24.9 ng L^{-1}.[10]

Bossi *et al.*[37] measured five PFAS (PFOS, PFHxS, PFOA, PFNA and PFDA) in effluent from six WWT plants in Denmark at an average of 4.7 ng L^{-1} (0.8–13 ng L^{-1}), while the same substances in Klettagardar were on average 2.7 ng L^{-1} (1.6–4.3 ng L^{-1}). The lower PFAS concentration in wastewater in Reykjavik at Klettagardar can partly be explained by that some of the effluent (10–30%) being return water from district heating (geothermal water). The influence of return water from district heating

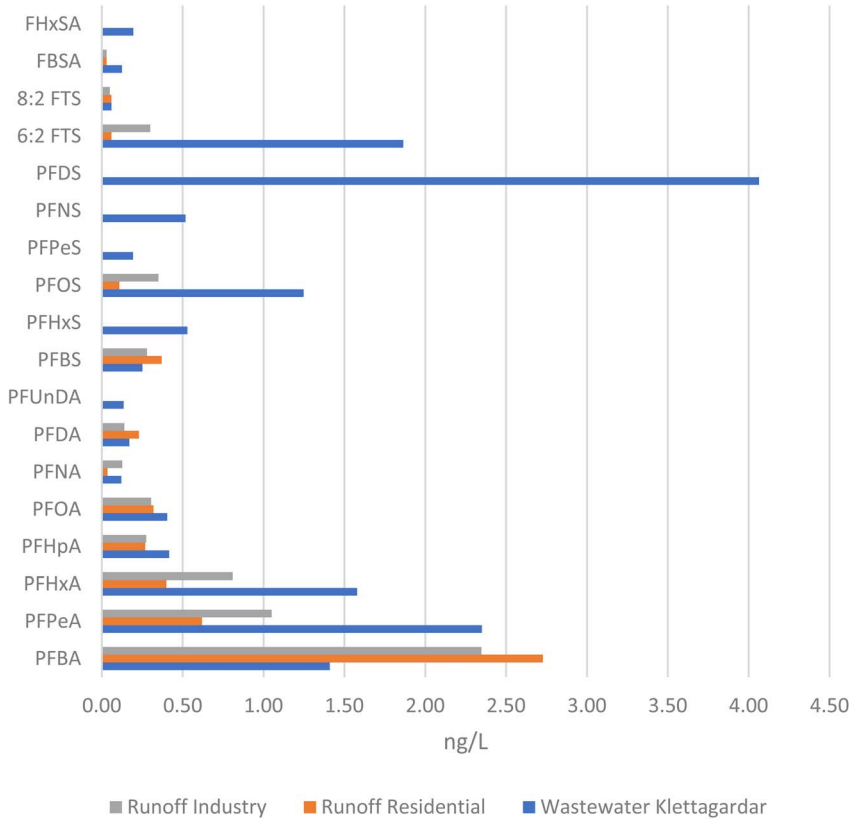

Fig. 3 18 PFAS medians ng L^{-1} in wastewater and runoff water from residential and industrial/commercial areas detected above MDL.

diluting concentrations of PFAS is further supported by the fact that the highest concentrations in Klettagardar of the four PFAS (4.3 ng L^{-1}) were in sample collected in June when heating is minimal though more research is needed to support that claim.

There are studies showing that PFAS such as PFOS and PFOA can be formed in WWT plants through transformation of precursor compounds (*i.e.*, various fluorotelomer- and perfluoroalkyl sulfonamide-based compounds), usually in the secondary treatment, and there is growing concern that re-use of contaminated sewage sludge could be a source of PFAS contamination, mainly in groundwater.[37] Vo *et al.*[38] conducted a comprehensive review of PFAS occurrence in wastewater, which indicated that even modern WWT plants cannot completely remove PFAS.

The boxplot in Fig. 4 shows PFAS concentrations in wastewater, runoff water and the AFFFs site at Leirtjörn, but not at Skeljanes – Reykjavik Airport (shown later), both as PFAS-4 and the sum of 24 PFAS. The PFAS-4 compounds show Leirtjörn with the highest concentration, which might indicate the impact of AFFFs used there. PFAS-4 in wastewater is the highest of the remaining three in PFAS-4. The same applies to 24 PFAS, where the highest concentration is found in wastewater; for instance,

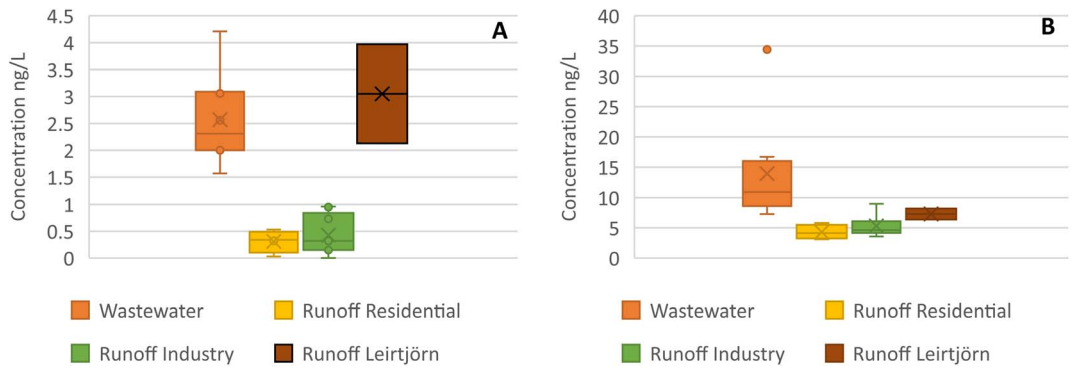

Fig. 4 Concentration of PFAS in all samples except drinking water and AFFFs at Skeljanes – Reykjavik Airport, (A) PFAS-4 and (B) 24 PFAS. 6 PFAS were not measured in 8 samples (see Tables 3–7).

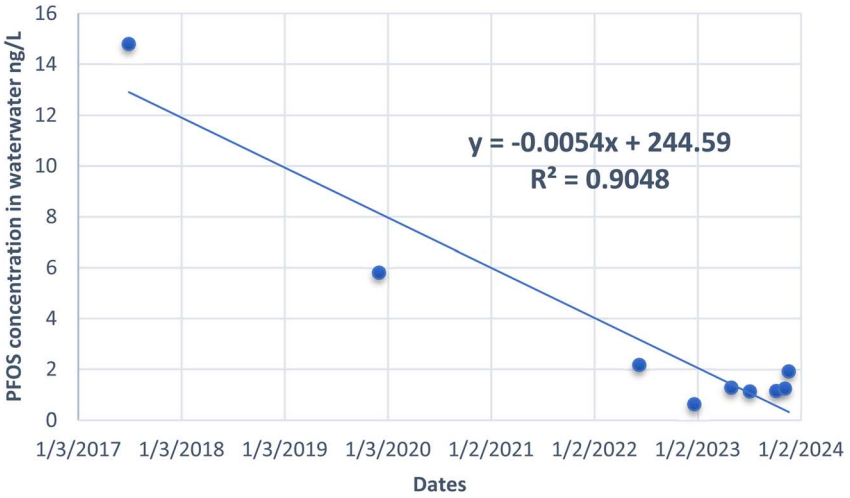

Fig. 5 Comparison of 5 available PFOS measurements in Klettagardar wastewater treatment station (ng L^{-1}).

the concentration of one outlier in wastewater is 35 ng L^{-1}, including 23 ng L^{-1} of 6:2 FTS.

The explanation of low concentrations at Leirtjörn relative to other AFFF-impacted sites (see below) could be that the lakes are heavily influenced by rainfall, as they dry up during drought and groundwater flows downhill away from the lakes towards the sea. It would probably have been more appropriate to carry out soil sampling at the training site or from a groundwater borehole that is downhill from the AFFFs site.

PFOS has been phased out, as mentioned earlier, and some research has shown a decline in PFOS concentrations, for instance in human blood levels in the USA.[39] In Australia, a decline in blood serum was shown in metropolitan firefighters following workplace interventions that involved the removal of PFAS-containing foams.[40] However, people may be exposed to other PFAS replacements that can be hazardous to health.

There is an indication of a decline in PFOS in wastewater in Klettagardar by about 90% since 2017, though with limited data prior to 2020, as shown in Fig. 5. Gewurtz *et al.*[41] collected data for PFAS from 48 WWT plants in Canada to include in time-trend analysis for the period 2009 to 2021. Concentrations of long-chain PFAS generally decreased over time, which is attributable to industrial production phase-outs and regulations, whereas short-chain PFAS were widely detected, which reflects the use of the latter to replace the long-chained PFAS. Concentrations of PFOS did not decrease over time in wastewater media in Canada and in general, elevated concentrations of several PFAS were observed at WWT plants that receive landfill leachate. Gewurtz *et al.*[41] concluded that upstream risk management is the most effective method to remove PFAS, as treatment processes are often not designed to remove PFAS. They suggested continued monitoring to assess the impact of the Canadian government's intent to phase out PFAS.

PFAS in runoff water from AFFFs sites

Analytical results from the two separate samples collected at the same time and location at Skeljanes – Reykjavik Airport are shown in Fig. 6, are with high concentrations in both samples, 2652 ng L^{-1} by NMBU and 3512 ng L^{-1} by URI. PFOS and PFHxS, known to be the main indication of AFFFs, dominated at concentrations of about 1200 ng L^{-1} and 350 ng L^{-1}. Other

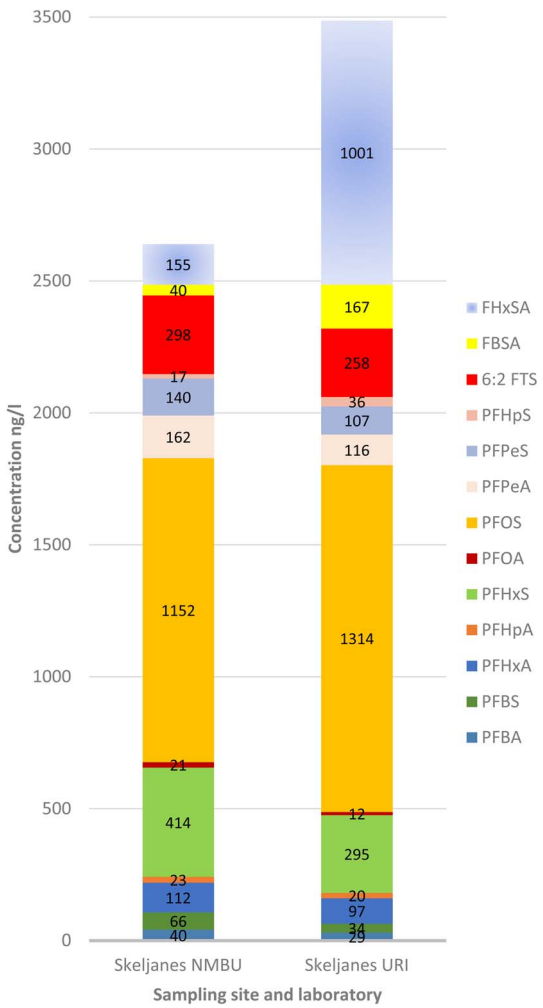

Fig. 6 PFAS detected over 10 ng L^{-1} at the AFFFS sites at Skeljanes Reykjavik Airport.

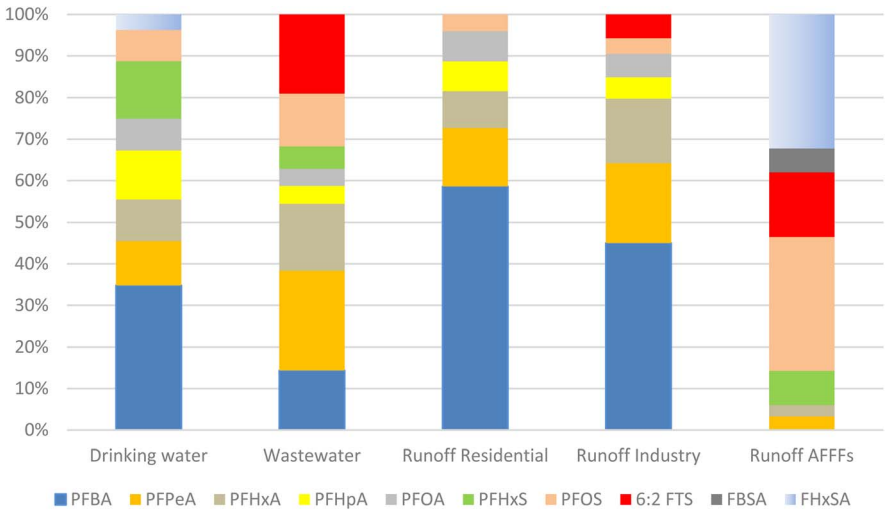

Fig. 7 Composition profile of 10 PFAS. Calculated from mean values of samples over detection limits. PFAS substances with concentrations <3% are not shown.

main PFAS detected at Skeljanes-Reykjavik Airport were FHxSA and 6:2 FTS. While PFOS containing AFFFs have been phased out, fluorotelomer based substances such as 6:2 FTS may have been used as replacements and detection of FHxSA indicates PFHxS precursors.[42] There was very good agreement between both analysis for almost all compounds, except for FHxSA and FBSA that were 4–6 times greater in the URI analysis. This might reflect elution problems during the analysis at NMBU.

In Sweden, the largest local sources of contaminated drinking water were firefighting sites, such as airstrips, military installations and industrial, national and municipal rescue services, where AFFFs have been used. In many cases, PFAS concentration were so high that water supplies have had to be closed, or expensive purification measures were put in place.[20] Gyllenhammar *et al.*[16] presented monitoring results for PFAS-4 in drinking water in Uppsala in Sweden near a military station at 99–1250 ng L^{-1}. Filipovic *et al.*[17] measured water at a closed-down military airport in Stockholm, where PFAS (PFOS, PFHxS, PFOA, PFHxA) ranged from 738 to 51 000 ng L^{-1} in groundwater. Samples were collected nearly twenty years after the airport had been closed. In a study of waterbodies in Alaska high PFAS concentration has been detected near Anchorage airport where PFAS is ranging from 583.3–952.2 ng L^{-1} in two popular lakes.[43]

Composition profiles of PFAS

The detection of PFAS differed between water bodies, except that runoff from residential and industrial areas were similar, though 6:2 FTS was only present in samples from the industrial sites. The dominant substances in both categories were PFBA, PFPeA and PFHxA (Fig. 7). The dominant substances in wastewater were the same as in industrial runoff. PFOA was detected (>2%) at all sites except in AFFF- impacted samples. The PFAS substances in runoff from AFFFs sites were dominated by PFOS, PFHxS and the fluorotelomers 6:2 FTS, FBSA and FHxSA. The fluorotelomers were not measured by NMBU at the AFFFs site at Leirtjörn.

These results are in line with other studies, such as an earlier report from Svalbard, where the dominant compound in runoff water was PFBA.[5] The results also comply with other studies, as PFOS and PFHxS have been known to be the main indicators of AFFFs contamination. Similar composition profiles can be seen for wastewater and runoff from residential and light industry in Sweden.[44] Langberg *et al.*[45] investigated the distribution of PFAS contamination at a military site and civil airport in Bodö, Norway, analysing up to 30 PFAS in aqueous samples and the marine biota. The dominant substances in runoff water were PFOS, 6:2 FTS, PFPeA, PFHxA and PFHxS, which were detected at maximum concentrations of 1010, 921, 738, 194 and 142 ng L^{-1} respectively. These are similar results and concentrations to those seen at the Skeljanes – Reykjavik Airport AFFFs site, as can be seen in Table 7.

Conclusions and recommendations

This research has shown that the metropolitan region of Reykjavik displays a wide range of PFAS concentrations. The groundwater source in Heidmörk, serving 64% of the population of Iceland, is very low in PFAS, and the PFAS substances sporadically detected there are probably mainly originating from atmospheric long-range transport. PFAS concentrations in Reykjavik's drinking water were far below the EU DWD and the Danish regulations. These results support and show the importance of strong water protection, as practised in Heidmörk and laid down in the EU WFD.

Wastewater from Klettagardar shows lower or similar PFAS contamination in effluent as elsewhere, for instance in the Nordic study[10] though lower than from larger populated areas—this could partly be explained by return geothermal water from the district heating system in Reykjavik. Runoff sites from residential and industrial areas tested were also in line with what can be seen elsewhere. While sampling targeted different climatic conditions (before and after rain events), no firm

conclusions can be drawn given the overall low PFAS concentrations and limited number of samples.

The main PFAS contaminated site detected in this study is from the fire-training site at Skeljanes – Reykjavik Airport, which is more than 500 times greater than the six runoff sites tested. There is an indication that the former fire-fighting training site at Leirtjörn is contaminated and further investigations are needed. While the majority of the investigated waters from the Greater Reykjavik region were very clean relative to other European sites, the presence of PFAS hotspots in Iceland serves as a reminder that source remediation is important. The recommended next step would be to investigate systematically fire-training sites in Iceland, both those in use and former training sites, in light of the persistence of the PFAS contamination. It is especially important to investigate if a drinking water source is close to these sites. Other sites in Iceland with possible PFAS pollution are largely unknown and should be mapped, such as runoff from landfill or industry.

Data availability

The data results are all presented in the paper and can be used if cited.

Conflicts of interest

There are no conflicts of interest to declare.

Appendix

Table 3 27 PFAS in groundwater in Heidmork[a] (ng L^{-1})

	Labratory		URI	URI	NMBU	NMBU	NMBU	NMBU	NMBU	NMBU				
	Sample number		URI-1	URI-2	S-1	S-2	S-10	S-12	S-23 (S-20)	S-26 (S-22)				
	Sample site (ID)		VK-1 Vatnsenda-kriki	V-4 Jadar	VK-1 Vatnsenda-kriki	V-5 Jadar	V-14 Myllulækur	V-23 Gvendarbr	V-14 Myllulækur	V-19 Gvendarbr				
	Sample size (g)		492.44	497.27	2079.00	2021.00	2084.00	2215.00	2238.00	1607.00				
	Date of sampling		09/06/2022	09/06/2022	20/12/2922	13/02/2023	26/04/2023	29/08/2023	20/02/2024	27/02/2024				
	Analytes	Included in EU 2020/2184	Light rain and warm	Light rain and warm	Dry and cold	Snowmelt, rain, flooding	Light rain and cold	Rain after long drought	Wet and melting snow	Heavy rain	Count detected	Detection frequency %	Max ng L^{-1}	Median ng L^{-1}
1	PFBA	1	0.11	<0.10	<0.10	0.12	<0.10	0.12	<0.09	0.12	4	50%	0.12	0.12
2	PFBS	1	<0.03	<0.03	<0.03	0.06	<0.03	<0.02	0.03	0.06	3	38%	0.06	0.06
3	PFHxA	1	0.05	<0.04	<0.03	<0.03	<0.03	<0.06	<0.06	<0.06	1	13%	0.05	0.05
4	PFHpA	1	0.05	<0,02	<0.02	<0.02	<0.02	<0.12	<0.12	<0.12	1	13%	0.05	0.05
5	PFHxS	1	<0.02	<0.09	<0.09	<0.09	<0.09	<0.04	<0.04	<0.04	0	0%		
6	PFOA	1	0.14	<0.04	<0.03	<0.03	<0.19	<0.16	<0.16	<0.16	1	13%	0.14	0.14
7	PFNA	1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.19	<0.19	<0.19	0	0%		
8	PFOS	1	<0.04	<0.04	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0	0%		
9	PFDA	1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0	0%		
10	PFUnDA	1	<0.01	<0.01	<0.02	<0.02	<0.02	<0.17	<0.17	<0.17	0	0%		
11	PFDoDA	1	<0.01	<0.01	<0.03	<0.03	<0.03	<0.02	<0.02	<0.02	0	0%		
12	PFTrDA	1	<0.01	<0.01	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0	0%		
13	PFTeDA		<0.04	<0.04	<0.01	<0.01	<0.01	<0.02	<0.02	<0.02	0	0%		
14	PFPeA	1	0.06	<0.03	<0.20	<0.20	<0.20	<0.05	<0.05	<0.05	1	13%	0.06	0.06
15	PFPeS	1	<0.02	<0.02	<0.25	<0.25	<0.25	<0.14	<0.14	<0.14	0	0%		
16	PFHpS	1	<0.03	<0.03	<0.04	<0.04	<0.04	<0.02	<0.02	<0.02	0	0%		
17	PFNS	1	<0.04	<0.04	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0	0%		
18	PFDS	1	<0.05	<0.05	<0.20	<0.20	<0.20	<0.04	<0.04	<0.04	0	0%		
	SUM 18 PFAS		**0.41**	**<DL**	**<DL**	**0.18**	**<DL**	**0.12**	**0.03**	**0.18**	**11**	**8%**	**0.41**	**0.18**
19	FBSA		<0.06	<0.056	n.a.	n.a.	n.a.	<0.01	<0.01	<0.01	0	0%		
20	FHxSA		<0.02	<0.08	n.a.	n.a.	n.a.	<0.01	<0.01	0.01	1	20%	0.01	0.01
21	4:2 FTS		0.098	<0.072	n.a.	n.a.	n.a.	<0.01	<0.01	<0.01	1	20%	0.10	0.10
22	6:2 FTS		0.091	0.165	n.a.	n.a.	n.a.	<0.01	<0.01	<0.01	2	40%	0.17	0.13
23	8:2 FTS		<0.01	<0.01	n.a.	n.a.	n.a.	<0.01	<0.01	<0.01	0	0%		
24	FOSA		<0.11	<0.11	n.a.	n.a.	n.a.	<0.01	<0.01	<0.01	0	0%		
	SUM 6 PFAS		**0.19**	**0.17**	**n.a.**	**n.a.**	**n.a.**	**<DL**	**<DL**	**0.01**	**4**	**13%**	**0.19**	**0.17**
	SUM 24 PFAS		**0.60**	**0.17**	**<DL**	**0.18**	**<DL**	**0.12**	**0.03**	**0.19**	**15**	**9%**	**0.60**	**0.17**
19	PFUdS	1	n.a.	n.a.	n.a.	n.a.	n.a.	<0.06	<0.06	<0.06				
20	PFDoDS	1	n.a.	n.a.	n.a.	n.a.	n.a.	<0.04	<0.04	<0.04				
21	PFTrDS	1	n.a.	n.a.	n.a.	n.a.	n.a.	<0.05	<0.05	<0.05				
		20						**<DL**	**<DL**	**<DL**				
5	PFHxS	1	<0.02	<0.09	<0.09	<0.09	<0.09	<0.04	<0.04	<0.04	0	0%		
6	PFOA	1	0.14	<0.04	<0.03	<0.03	<0.19	<0.16	<0.16	<0.16	1	13%	0.14	0.14
7	PFNA	1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.19	<0.19	<0.19	0	0%		
8	PFOS	1	<0.04	<0.04	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0	0%		
	SUM PFAS 4	4	**0.14**	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**	**1**	**3%**	**0.14**	**0.14**

[a] n:a. = not analyzed.

Table 4 27 PFAS at Klettagardar WWT plant[a] (ng L^{-1})

	Labratory		URI	URI	NMBU	NMBU	NMBU	NMBU	NMBU	NMBU				
	Sample number		URI-3	URI-4	S-3	S-11	S-14	S-17	S-18	S-19				
	Sample site (ID)		No. 1 Kletta-gardar	No. 2 Kletta-gardar	Kletta-garðar	Kletta-garðar	Kletta-garðar	Kletta-garðar	Kletta-garðar	Kletta-garðar				
	Sample size (g)		501.51	508.08	927.00	1007.00	1008.00	1034.00	1054.00	1015.00				
	Date of sampling		10/06/2022	10/06/2022	21/12/2022	01/05/2023[b]	06/07/2023	07/10/2023	07/11/2023	20/11/2023				
	Analytes	Included in EU 2020/2184	Light rain warm	Light rain warm	Dry and frost	Dry	Warm and dry period	Dry and light rain	Light rain and snow	Wet and windy	Count detected	Detection frequency %	Max ng L^{-1}	Median ng L^{-1}
1	PFBA	1	0.83	0.64	1.58	1.59	1.54	1.28	0.90	1.73	8	100%	1.73	1.41
2	PFBS	1	0.29	0.45	0.18	0.34	0.21	<0.17	<0.17	0.17	6	75%	0.45	0.25
3	PFHxA	1	1.59	1.43	1.36	1.25	2.01	1.73	1.57	2.26	8	100%	2.26	1.58
4	PFHpA	1	0.44	0.39	0.29	0.38	0.48	0.39	0.46	0.57	8	100%	0.57	0.42
5	PFHxS	1	0.63	0.45	0.66	0.81	0.56	0.42	0.45	0.50	8	100%	0.81	0.53
6	PFOA	1	0.67	0.53	0.30	0.43	0.38	0.30	0.32	0.45	8	100%	0.67	0.41
7	PFNA	1	0.12	0.10	<0.02	0.06	<0.13	0.14	<0.13	0.20	5	63%	0.20	0.12
8	PFOS	1	2.79	2.03	0.62	1.27	1.12	1.14	1.23	1.91	8	100%	2.79	1.25
9	PFDA	1	0.06	0.07	<0.02	0.04	<0.17	0.30	0.27	0.30	6	75%	0.30	0.17
10	PFUnDA	1	<0.01	<0.01	<0.04	<0.04	<0.12	0.13	<0.12	0.14	2	25%	0.14	0.14
11	PFDoDA	1	<0.01	<0.01	<0.05	<0.05	<0.37	<0.37	<0.37	<0.37	0	0%		
12	PFTrDA	1	<0.01	<0.01	<0.04	<0.04	<0.15	<0.15	<0.15	<0.15	0	0%		
13	PFTeDA		<0.01	<0.01	<0.03	<0.03	<0.20	<0.20	<0.20	<0.20	0	0%		
14	PFPeA	1	1.73	1.27	2.31	2.40	3.13	2.04	2.57	2.79	8	100%	3.13	2.35
15	PFPeS	1	0.26	0.13	<0.51	<0.51	<0.67	<0.67	<0.67	<0.67	2	25%	0.26	0.20
16	PFHpS	1	<0.03	<0.03	<0.08	<0.08	<0.13	<0.13	<0.13	<0.13	0	0%		
17	PFNS	1	0.38	0.66	<0.06	<0.06	<0.28	<0.28	<0.28	<0.28	2	25%	0.66	0.52
18	PFDS	1	4.32	3.81	<0.05	<0.05	<0.35	<0.35	<0.35	<0.35	2	25%	4.32	4.06
	SUM 18		**14.11**	**11.95**	**7.28**	**8.56**	**9.43**	**7.87**	**7.77**	**11.02**	**81**	**56%**	**14.11**	**9.00**
19	FBSA		0.16	0.15	n.a.	n.a.	0.11	0.08	0.10	0.14	6	100%	0.16	0.13
20	FHxSA		0.22	0.17	n.a.	n.a.	0.21	0.10	0.18	0.22	6	100%	0.22	0.20
21	4:2 FTS		<0.01	<0.01	n.a.	n.a.	<0.04	<0.04	<0.04	<0.04	0			
22	6:2 FTS		2.15	1.58	n.a.	n.a.	1.49	0.60	2.47	23.64	6	100%	23.64	1.86
23	8:2 FTS		0.07	0.06	n.a.	n.a.	<0.02	0.06	0.06	0.39	5	83%	0.39	0.06
24	FOSA		<0.01	<0.01	n.a.	n.a.	<0.03	<0.03	<0.03	<0.03	0			
	SUM 6 PFAS		**2.60**	**1.96**	**n.a.**	**n.a.**	**1.81**	**0.84**	**2.81**	**24.39**	**23**	**64%**	**24.39**	**2.28**
	SUM 24 PFAS		**16.71**	**13.90**			**11.24**	**8.71**	**10.58**	**35.41**	**104**	**58%**	**35.41**	**12.57**
25	PFUdS	1	n.a.	n.a.	<0.05	<0.05	<0.22	<0.22	<0.22	<0.22				
26	PFDoDS	1	n.a.	n.a.	<0.04	<0.04	<0.21	<0.21	<0.21	<0.21				
27	PFTrDS	1	n.a.	n.a.	<0.01	<0.01	<0.31	<0.31	<0.31	<0.31				
		20	**n.a.**	**n.a.**	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**				
5	PFHxS	1	0.63	0.45	0.66	0.81	0.56	0.42	0.45	0.50	8	100%	0.81	0.53
6	PFOA	1	0.67	0.53	0.30	0.43	0.38	0.30	0.32	0.45	8	100%	0.67	0.41
7	PFNA	1	0.12	0.10	<0.01	0.06	<0.13	0.14	<0.13	0.20	5	63%	0.20	0.12
8	PFOS	1	2.79	2.03	0.62	1.27	1.12	1.14	1.23	1.91	8	100%	2.79	1.25
	SUM PFAS-4	4	**4.21**	**3.10**	**1.57**	**2.56**	**2.06**	**2.00**	**2.00**	**3.06**	**29**	**91%**	**4.21**	**2.31**

[a] n:a. = not analyzed. [b] National holiday.

Table 5 27 PFAS in runoff water from residential[a] area (ng L^{-1})

	Labratory		NMBU	NMBU	NMBU	NMBU				
	Sample number		S-4	S-7	S-13	S-20 (S-26)				
	Sample site (ID)		Grafarvogur	Urriðaholt	Urriðaholt	Grafarvogur				
	Sample size (g)		916.00	1011.00	836.00	915.00				
	Date of sampling		20/01/2023	20/01/2023	26/08/2023	20/11/2023				
	Analytes	Included in EU 2020/2184	Heavy rain on snow	Heavy rain and snow	Rain after long dry period	Wet and windy	Count detected	Detection frequency %	Max ng L^{-1}	Median ng L^{-1}
1	PFBA	1	2.93	2.73	<0.9	1.70	3	75%	2.93	2.73
2	PFBS	1	<0.06	<0.06	0.37	<0.17	1	25%	0.37	0.37
3	PFHxA	1	0.40	0.20	<0.54	0.56	3	75%	0.56	0.40
4	PFHpA	1	0.22	0.16	0.32	0.33	4	100%	0.33	0.27
5	PFHxS	1	<0.19	<019	<0.15	<0.15	0	0%		
6	PFOA	1	0.39	<0.23	0.32	0.23	3	75%	0.39	0.32
7	PFNA	1	0.04	0.03	<0.13	0.13	3	75%	0.13	0.04
8	PFOS	1	0.11	<0.06	<0.39	<0.39	1	25%	0.11	0.11
9	PFDA	1	0.04	<0.02	0.42	<0.17	2	50%	0.42	0.23
10	PFUnDA	1	<0.04	<0.04	<0.12	<0.12	0	0%		
11	PFDoDA	1	<0.05	<0.05	<0.37	<0.37	0	0%		
12	PFTrDA	1	<0.04	<0.04	<0.15	<0.15	0	0%		
13	PFTeDA		<0.03	<0.03	<0.20	<0.20	0	0%		
14	PFPeA	1	0.44	<0.41	4.26	0.62	3	75%	4.26	0.62
15	PFPeS	1	<0.51	<0.51	<0.67	<0.67	0	0%		
16	PFHpS	1	<0.08	<0.08	<0.13	<0.13	0	0%		
17	PFNS	1	<0.06	<0.06	<0.28	<0.28	0	0%		
18	PFDS	1	<0.05	<0.05	<0.35	<0.35	0	0%		
	SUM 18 PFAS		**4.56**	**3.11**	**5.69**	**3.57**	**23**	**32%**	**5.69**	**4.07**
19	FBSA		n.a.	n.a.	<0.03	0.03	1	50%	0.03	0.03
20	FHxSA		n.a.	n.a.	<0.02	<0.02	0	0%		
21	4:2 FTS		n.a.	n.a.	<0.04	<0.04	0	0%		
22	6:2 FTS		n.a.	n.a.	0.05	0.07	2	100%	0.07	0.06
23	8:2 FTS		n.a.	n.a.	0.06	<0.02	1	50%	0.06	0.06
24	FOSA		n.a.	n.a.	<0.03	<0.03	0	0%		
	SUM 6 PFAS		**n.a**	**n.a.**	**0.11**	**0.10**	**4**	**33%**	**0.11**	**0.11**
	SUM 24 PFAS				**5.80**	**3.67**	**27**	**32%**	**5.80**	**4.74**

25	PFUdS	1	<0.05	<0.05	<0.22	<0.22
26	PFDoDS	1	<0.04	<0.04	<0.21	<0.21
27	PFTrDS	1	<0.01	<0.01	<0.31	<0.31
		20	**<DL**	**<DL**	**<DL**	**<DL**

5	PFHxS	1	<0.19	<0.19	<0.15	<0.15	0	0%		
6	PFOA	1	0.39	<0.23	0.32	0.23	3	75%	0.39	0.32
7	PFNA	1	0.04	0.03	<0.13	0.13	3	75%	0.04	0.04
8	PFOS	1	0.11	<0.06	<0.39	<0.39	1	25%	0.11	0.11
	SUM PFAS-4	4	**0.53**	**0.03**	**0.32**	**0.36**	**7**	**44%**	**0.53**	**0.34**

[a] n:a. = not analyzed.

Table 6 27 PFAS in runoff water from industrial[a] area (ng L^{-1})

	Labratory		NMBU	NMBU	NMBU	NMBU	NMBU	NMBU	NMBU	NMBU	NMBU				
	Sample number		S-5	S-6	S-15	S-16	S-22 (S-28)	S-21 (S-27)	S-27 (S-23)	S-28 (S-24)	S-29 (S-25)				
	Sample site (ID)		Grafar-lækur	Stórhöfði	Grafar-lækur	Stórhöfði	Grafar-lækur	Stórhöfði	Set pond small Elliðavogur	Set pond large Elliðavogur	Set pond Ártúnsbr				
	Sample size (g)		885.00	955.00	745.00	960.00	838.00	652.00	942.00	1000.00	958.00				
	Date of sampling		20/01/2023	20/01/2023	01/09/2023	01/09/2023	20/11/2023	20/11/2023	08/03/2024	08/03/2024	08/03/2024				
	Analytes	Included in EU 2020/2184	Heavy rain on snow	Heavy rain on snow	Warm runoff	Warm runoff	Wet and windy	Wet and windy	Light rain earlier in the day 7 °C	Light rain earlier in the day 7 °C	Light rain earlier in the day 7 °C	Count detected	Detection frequency	Max ng L^{-1}	Median ng L^{-1}
1	PFBA	1	2.60	2.35	1.44	2.35	1.80	1.39	1.84	2.47	3.62	9	100%	3.62	2.35
2	PFBS	1	<0.06	<0.06	<0.17	<0.17	<0.17	<0.17	<0.17	0.28	<0.17	1	11%	0.28	0.28
3	PFHxA	1	0.71	0.50	1.27	0.81	0.91	0.75	1.30	1.36	0.72	9	100%	1.36	0.81
4	PFHpA	1	0.22	0.26	0.28	<0.23	0.26	0.27	0.31	0.46	0.38	8	89%	0.46	0.28
5	PFHxS	1	<0.19	<0.19	<0.19	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	0	0%		
6	PFOA	1	0.29	0.39	0.36	0.32	0.15	<0.10	0.15	0.36	0.18	8	89%	0.39	0.31
7	PFNA	1	0.02	0.23	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	2	22%	0.23	0.13
8	PFOS	1	0.07	0.11	0.60	<0.39	<0.39	<0.39	<0.39	0.59	<0.39	4	44%	0.60	0.35
9	PFDA	1	<0.04	0.05	0.23	<0.13	<0.17	<0.17	<0.17	<0.17	<0.17	2	22%	0.23	0.14
10	PFUnDA	1	<0.05	<0.04	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	0	0%		
11	PFDoDA	1	<0.04	<0.05	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	0	0%		
12	PFTrDA	1	<0.03	<0.04	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	0	0%		
13	PFTeDA		<0.03	<0.03	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0	0%		
14	PFPeA	1	0.65	<0.41	1.10	0.69	1.00	0.82	1.99	1.96	1.37	8	89%	1.99	1.05
15	PFPeS	1	<0.51	<0.51	<0.67	<0.67	<0.67	<0.67	<0.67	<0.67	<0.67	0	0%		
16	PFHpS	1	<0.08	<0.08	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.15	0	0%		
17	PFNS	1	<0.06	<0.06	<0.28	<0.28	<0.28	<0.28	<0.28	<0.28	<0.28	0	0%		
18	PFDS	1	<0.05	<0.05	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	0	0%		
	SUM 18 PFAS		**4.57**	**3.89**	**5.28**	**4.17**	**4.12**	**3.23**	**5.59**	**7.48**	**6.27**	**51**	**31%**	**7.48**	**4.57**
19	FBSA		n.a.	n.a.	<0.03	<0.03	<0.03	<0.03	0.03	0.08	0.03	3	43%	0.08	0.03
20	FHxSA		n.a.	n.a.	<0.02	<0.02	<0.02	<0.02	<0.02	0.03	<0.02	1	14%	0.03	0.03
21	4:2 FTS		n.a.	n.a.	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	0	0%		
22	6:2 FTS		n.a.	n.a.	0.28	0.40	0.30	0.31	0.08	1.34	0.18	7	100%	1.34	0.30
23	8:2 FTS		n.a.	n.a.	0.04	0.06	<0.02	0.05	<0.02	0.05	<0.02	4	57%	0.06	0.05
24	FOSA		n.a.	n.a.	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0	0%		
	SUM 6 PFAS		**n.a.**	**n.a.**	**0.32**	**0.46**	**0.30**	**0.36**	**0.11**	**1.50**	**0.21**	**15**	**36%**	**1.50**	**0.32**
	SUM 24 PFAS				**5.60**	**4.63**	**4.42**	**3.59**	**5.70**	**8.98**	**6.48**	**66**	**32%**	**8.98**	**5.60**
25	PFUdS	1	<0.05	<0.05	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22				
26	PFDoDS	1	<0.04	<0.04	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21				
27	PFTrDS	1	<0.01	<0.01	<0.31	<0.31	<0.31	<0.31	<0.31	<0.31	<0.31				
		20	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**	**<DL**				
5	PFHxS	1	<0.19	<0.19	<0.19	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	0	0%		
6	PFOA	1	0.29	0.39	0.36	0.32	0.15	<0.10	0.15	0.36	0.18	8	89%	0.39	0.31
7	PFNA	1	0.02	0.23	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	2	22%	0.23	0.13
8	PFOS	1	0.07	0.11	0.60	<0.39	<0.39	<0.39	<0.39	0.59	<0.39	4	44%	0.60	0.35
	SUM PFAS-4	4	**0.39**	**0.73**	**0.96**	**0.32**	**0.15**	**<DL**	**0.15**	**0.95**	**0.18**	**14**	**39%**	**0.96**	**0.35**

[a] n:a. = not analyzed.

Table 7 27 PFAS in runoff water from[a] AFFFs sites (ng L^{-1})

	Labratory		NMBU	NMBU	NMBU	URI				
	Sample number		S-8	S-9	S-24 (S-21)	S-25 (S-21)				
	Sample site (ID)		Leirtjörn smaller	Leirtjörn larger	Skeljanes	Skeljanes				
	Sample size (g)		1026.00	964.00	1063.00	1031.00				
	Date of sampling		26/04/2023	26/04/2023	22/02/2024	22/02/2024				
	Analytes	Included in EU 2020/2184	Light rain 2 °C	Light rain 2 °C	Sun, calm −3 °C	Sun, calm −3 °C	Count detected	Detection frequency %	Max ng L^{-1}	Median ng L^{-1}
1	PFBA	1	1.96	1.69	40.29	29.03	4	100%	40.29	15.49
2	PFBS	1	0.08	0.08	65.99	33.97	4	100%	65.99	17.02
3	PFHxA	1	0.52	0.77	112.16	96.94	4	100%	112.16	48.86
4	PFHpA	1	0.74	0.70	22.65	20.18	4	100%	22.65	10.46
5	PFHxS	1	0.79	1.86	413.89	295.10	4	100%	413.89	148.48
6	PFOA	1	0.28	0.36	20.74	12.14	4	100%	20.74	6.25
7	PFNA	1	0.17	0.17	1.36	0.47	4	100%	1.36	0.32
8	PFOS	1	0.88	1.58	1152.07	1314.20	4	100%	1314.20	576.83
9	PFDA	1	<0.02	<0.02	1.30	0.41	2	50%	1.30	0.85
10	PFUnDA	1	<0.04	<0.04	0.38	0.25	2	50%	0.38	0.31
11	PFDoDA	1	<0.05	<0.05	<0.37	0.20	1	25%	0.20	0.20
12	PFTrDA	1	<0.04	<0.04	<0.15	<0.003	0	0%		
13	PFTeDA		<0.03	<0.03	<0.20	<0.009	0	0%		
14	PFPeA	1	0.95	0.99	162.26	116.00	4	100%	162.26	58.50
15	PFPeS	1	<0.51	<0.51	140.17	107.40	2	50%	140.17	123.79
16	PFHpS	1	<0.08	<0.08	17.18	35.68	2	50%	35.68	26.43
17	PFNS	1	<0.06	<0.06	1.02	3.67	2	50%	3.67	2.34
18	PFDS	1	<0.05	<0.05	0.69	4.18	2	50%	4.18	2.43
	SUM 18 PFAS		**6.38**	**8.20**	**2152.15**	**2069.81**	**49**	**68%**	**2152**	**1039**
19	FBSA		n.a.	n.a.	40.23	166.50	2	100%	166.50	103.37
20	FHxSA		n.a.	n.a.	154.63	1001.00	2	100%	1001.00	577.82
21	4:2 FTS		n.a.	n.a.	0.04	<0.07	1	50%	0.04	0.04
22	6:2 FTS		n.a.	n.a.	297.76	258.40	2	100%	297.76	278.08
23	8:2 FTS		n.a.	n.a.	4.87	6.45	2	100%	6.45	5.66
24	FOSA		n.a.	n.a.	2.54	9.77	2	100%	9.77	6.15
	SUM 6 PFAS		n.a.	n.a.	**500.07**	**1442.12**	**11**	**92%**	**1442**	**971**
	SUM 24 PFAS				**2652.22**	**3511.93**	**60**	**71%**	**3512**	**3082**
25	PFUdS	1	<0.05	<0.05	<0.22	n.a.				
26	PFDoDS	1	<0.04	<0.04	<0.21	n.a.				
27	PFTrDS	1	<0.01	<0.01	<0.31	n.a.				
		20	**<DL**	**<DL**	**<DL**	**n.a.**				
5	PFHxS	1	0.79	1.86	413.89	295.10	4	100%	413.89	148.48
6	PFOA	1	0.28	0.36	20.74	12.14	4	100%	20.74	6.25
7	PFNA	1	0.17	0.17	1.36	0.47	4	100%	1.36	0.32
8	PFOS	1	0.88	1.58	1152.07	1314.20	4	100%	1314.20	576.83
	SUM PFAS-4	4	**2.13**	**3.97**	**1588.06**	**1621.91**	**16**	**100%**	**1622**	**796**

[a] n:a. = not analyzed.

Acknowledgements

The authors thank Reykjavik Energy's Research Fund (VOR22-11) and the Icelandic Road and Coastal Administration for financial support for this project and Fulbright Iceland for supporting Professor and Fulbright Specialist Rainer Lohmann for this work. Lohmann and Becanova acknowledge support from SERDP (ER20-1293) and the National Institute for Environmental Health Sciences STEEP Center (P42ES027706). We express our gratitude to Sigrún Tómasdóttir, Hlöðver Stefán Þorgeirsson, Sædís Ólafsdóttir and Sverrir Guðmundsson at Veitur Utility, Stefanía Valdimarsdóttir at University of Iceland, and Páll Höskuldsson at EFLA Consulting for providing information on the system and assistance with sampling. Furthermore, the authors would also like to express their gratitude to Reykjavik Public Health for guidance in choosing sampling sites in the capital area.

References

1 C. M. Butt, U. Berger, R. Bossi and G. T. Tomy, Levels and trends of poly-and perfluorinated compounds in the arctic environment, *Sci. Total Environ.*, 2010, **408**(15), 2936–2965, DOI: **10.1016/j.scitotenv.2010.03.015**.

2 W. F. Hartz, M. K. Björnsdotter, L. W. Yeung, A. Hodson, E. R. Thomas, J. D. Humby, C. Day, I. E. Jogsten, A. Kärrman and R. Kallenborn, Levels and distribution profiles of Per-and Polyfluoroalkyl Substances (PFAS) in a high Arctic Svalbard ice core, *Sci. Total Environ.*, 2023, **871**, 161830, DOI: **10.1016/j.scitotenv.2023.161830**.

3 R. Lohmann, K. Abass, E. C. Bonefeld-Jørgensen, R. Bossi, R. Dietz, S. Ferguson, K. J. Fernie, P. Grandjean, D. Herzke, M. Houde and M. Lemire, Cross-cutting studies of per-and polyfluorinated alkyl substances (PFAS) in Arctic wildlife and humans, *Sci. Total Environ.*, 2024, **18**, 176274, DOI: **10.1016/j.scitotenv.2024.176274**.

4 D. Muir, M. J. Gunnarsdóttir, K. Koziol, F. A. von Hippel, D. Szumińska, N. Ademollo, S. Corsolini, A. De Silva, G. Gabrielsen, R. Kallenborn, Ż. Polkowska, E. Krümmel and K. Vorkamp, Local sources *versus* long-range transport of organic contaminants in the Arctic: future developments related to climate change, *Environ. Sci.: Adv.*, 2025, DOI: **10.1039/D4VA00240G**.

5 J. S. Skaar, E. M. Ræder, J. L. Lyche, L. Ahrens and R. Kallenborn, Elucidation of contamination sources for poly-and perfluoroalkyl substances (PFASs) on Svalbard (Norwegian Arctic), *Environ. Sci. Pollut. Res.*, 2019, **26**, 7356–7363, DOI: **10.1007/s11356-018-2162-4**.

6 S. Liu, S. Zhao, Z. Liang, F. Wang, F. Sun and D. Chen, Perfluoroalkyl substances (PFASs) in leachate, fly ash, and bottom ash from waste incineration plants: Implications for the environmental release of PFAS, *Sci. Total Environ.*, 2021, **795**, 148468, DOI: **10.1016/j.scitotenv.2021.148468**.

7 L. R. Kim, Y. J. Choi, M. L. Mashtare and L. S. Lee, Characterizing and comparing per-and polyfluoroalkyl substances in commercially available biosolid and organic non-biosolid-based products, *Environ. Sci. Technol.*, 2020, **54**(14), 8640–8648, DOI: **10.1021/acs.est.9b07281**.

8 R. Vestergren and I. T. Cousins, Tracking the pathways of human exposure to perfluorocarboxylates, *Environ. Sci. Technol.*, 2009, **43**(15), 5565–5575.

9 S. Hansen, R. Vestergren, D. Herzke, M. Melhus, A. Evenset, L. Hanssen, M. Brustad and T. M. Sandanger, Exposure to per-and polyfluoroalkyl substances through the consumption of fish from lakes affected by aqueous film-forming foam emissions—A combined epidemiological and exposure modeling approach. The SAMINOR 2 Clinical Study, *Environ. Int.*, 2016, **94**, 272–282, DOI: **10.1016/j.envint.2016.05.030**.

10 A. Kärrman, T. Wang, R. Kallenborn, A. M. Langseter, S. M. Grönhovd, E. M. Ræder, J. L. Lyche, L. Yeung, F. Chen, U. Eriksson, R. Aro and F. Fredriksson, *PFASs in the Nordic Environment: Screening of Poly- and Perfluoroalkyl Substances (PFASs) and Extractable Organic Fluorine (EOF) in the Nordic Environment*, Nordic Council of Ministers, 2019, **https://norden.diva-portal.org/smash/get/diva2:1296387/fulltext01.pdf**.

11 A. M. Roos, M. Gamberg, D. Muir, A. Kärrman, P. Carlsson, C. Cuyler, Y. Lind, R. Bossi and F. Rigét, Perfluoroalkyl substances in circum-Arctic Rangifer: caribou and reindeer, *Environ. Sci. Pollut. Res.*, 2022, **1**, 1–5, DOI: **10.1007/s11356-021-16729-7**.

12 EEA-European Environment Agency, Emerging chemical risks in Europe— "PFAS." Copenhagen, Denmark, [cited 2024 November 16]. 2019. Available from: **https://www.eea.europa.eu/publications/emerging-chemical-risks-in-europe/emerging-chemical-risks-in-europe**.

13 S. E. Fenton, A. Ducatman, A. Boobis, J. C. DeWitt, C. Lau, C. Ng, J. S. Smith and S. M. Roberts, Per-and polyfluoroalkyl substance toxicity and human health review: Current state of knowledge and strategies for informing future research, *Environ. Toxicol. Chem.*, 2021, **40**(3), 606–630, DOI: **10.1002/etc.4890**.

14 J. Glüge, M. Scheringer, I. T. Cousins, J. C. DeWitt, G. Goldenman, D. Herzke, R. Lohmann, C. A. Ng, X. Trier and Z. Wang, An overview of the uses of per-and polyfluoroalkyl substances (PFAS), *Environ. Sci.: Processes Impacts*, 2020, **22**(12), 2345–2373, DOI: **10.1039/D0EM00291G**.

15 OECD I, *Toward a New Comprehensive Global Database of Per-And Polyfluoroalkyl Substances (PFASs): Summary Report on Updating the OECD 2007 List of Per- and Polyfluoroalkyl Substances (PFASs)*, Organisation for Economic Cooperation and Development (OECD), 2018.

16 I. Gyllenhammar, U. Berger, M. Sundström, P. McCleaf, K. Eurén, S. Eriksson, S. Ahlgren, S. Lignell, M. Aune, N. Kotova and A. Glynn, Influence of contaminated drinking water on perfluoroalkyl acid levels in human serum–A case study from Uppsala, Sweden, *Environ. Res.*, 2015, **140**, 673–683, DOI: **10.1016/j.envres.2015.05.019**.

17 M. Filipovic, A. Woldegiorgis, K. Norström, M. Bibi, M. Lindberg and A. H. Österås, Historical usage of aqueous film forming foam: A case study of the

widespread distribution of perfluoroalkyl acids from a military airport to groundwater, lakes, soils and fish, *Chemosphere*, 2015, **129**, 39–45, DOI: 10.1016/j.chemosphere.2014.09.005.

18 EFSA-European Food Safety Authority- Panel on Contaminants in the Food Chain (EFSA CONTAM Panel), Scientific Opinion on the risk to human health related to the presence of perfluoroalkyl substances in food, *EFSA J.*, 2020, **18**(9), 391, DOI: 10.2903/j.efsa.2020.6223.

19 A. M. Vinggaard, and P. T. Olesen, (2021). Sundhedsmæssige konsekvenser af at indtage PFOS kontamineret drikkevand, No. DTU DOC nr.: 21/1035548, 3 p. (Accessed 26.2.2025) https://backend.orbit.dtu.dk/ws/files/257666871/2021_Sept_1_Notat_Drikkevand_og_sundhedseffekter.pdf.

20 E. Livsmedelsverket. Lindfeldt, I. Gyllenhammar, S. Strandh and E. Halldin Ankarberg, *L-2021 Nr 21: Kartläggning Av Per- Och Polyfluorerade Alkylsubstanser (PFAS) I Sveriges Kommunala Rå- Och Dricksvatten*, Livsmedelsverkets rapportserie, Uppsala, 2021.

21 E. C. Cowan, J. Allan, T. Seppälä, E. Krümmel, F. de Leon and T. Maes, On Thin Ice–a review of the multi-level governance regarding Chemicals of Emerging Arctic Concern (CEAC), *Environ. Sci.: Adv.*, 2025, **4**, 584–594, DOI: 10.1039/D4VA00369A.

22 Y. Rericha, L. Truong, C. Leong, D. Cao, J. A. Field and R. L. Tanguay, Dietary perfluorohexanoic acid (PFHxA) exposures in juvenile zebrafish produce subtle behavioral effects across generations, *Toxics*, 2022, **10**(7), 372, DOI: 10.3390/toxics10070372.

23 Government of Canada, 2021, Per- and polyfluoroalkyl substances (PFAS), https://www.canada.ca/en/health-canada/services/chemical-substances/other-chemical-substances-interest/per-polyfluoroalkyl-substances.html.

24 UST – Umhverfisstofnun (The Environmental Agency of Iceland). 2022. Vatnaáætlun Íslands 2022-2027 (River Basin Management Plan for Iceland) https://ust.is/haf-og-vatn/stjorn-vatnamala/vatnaaaetlun-2022-2027/.

25 UST- Umhverfisstofnun (The Environmental Agency of Iceland). (2022). Tjörnin Í Reykjavík Niðurstöður, Frumgreining Og Viðbrögð Við Mælingum Forgangsefna (F1). https://ust.is/library.

26 M. J. Gunnarsdottir, S. M. Gardarsson, G. S. Jonsson and J. Bartram, Chemical quality and regulatory compliance of drinking water in Iceland, *Int. J. Hyg Environ. Health*, 2016, **219**(8), 724–733, DOI: 10.1016/j.ijheh.2016.09.011.

27 H. Ó. Andradóttir, A. R. Arnardóttir and T. Zaqout, Rain on snow induced urban floods in cold maritime climate: Risk, indicators and trends, *Hydrol. Process.*, 2021, **35**(9), e14298.

28 H. Ó. Andradóttir and G. E. Vollertsen, Temporal variability of heavy metals in suburban road runoff in a rainy cold climate, *J. Environ. Eng.*, 2015, **141**(3), 04014068, DOI: 10.1061/(ASCE)EE.1943-7870.0000894.

29 M. J. Gunnarsdóttir, S. Tómasdóttir, O. Örlygsson, H. Ó. Andradóttir and S. M. Gardarsson, Impact of wildfires on the drinking water catchment for the capital area of Iceland–a case study, *Environ. Sci.: Adv.*, 2025, **4**, 606–618, DOI: 10.1039/D4VA00352G.

30 Verkfræðistofan Vatnaskil. Vatnsvernd á höfuðborgarsvæðinu. Greinargerð um heildarendurskoðun Reykjavík. 2015: (Report on Water protection in the capital area) https://ssh.is/images/stories/Hofudborgarsvaedid_2040/vatnsvernd_heildarendurskodun_greinargerd_Utgafa_18052015.pdf.

31 G. Friðriksson, *Cloacina: Saga Fráveitu*, Veitur ehf, Reykjavík, 2021, ISBN 978-9935-24-902-9.

32 EEA-Environment Agency Iceland. Stöðuskýrsla fráveitumála 2022 (English: Status Report on Wastewater 2022). Report nr. UST-2023:14, Reykjavík: Umhverfisstofnun, https://www.ust.is/library/sida/haf-og-vatn/Stoduskyrsla_fraveitumala_2022_2.pdf.

33 S. Ólafsdóttir and H. S. Þorgeirsson, Sýnatökur og efnagreiningar fráveitu: Árleg yfirlitsskýrsla vegna rannsókna ársins 2023 (English: Sampling and chemical analysis of wastewater: Annual summary report for the year 2023). Report nr. 2024-007. Reykjavík: Veitur ehf, 2024. Available at https://www.veitur.is/utgefid-efni/fraveita.

34 H. A. Kaboré, S. V. Duy, G. Munoz, L. Méité, M. Desrosiers, J. Liu, T. K. Sory and S. Sauvé, Worldwide drinking water occurrence and levels of newly-identified perfluoroalkyl and polyfluoroalkyl substances, *Sci. Total Environ.*, 2018, **616**, 1089–1100, DOI: 10.1016/j.scitotenv.2017.10.210.

35 V. Boiteux, X. Dauchy, C. Bach, A. Colin, J. Hemard, V. Sagres, C. Rosin and J. F. Munoz, Concentrations and patterns of perfluoroalkyl and polyfluoroalkyl substances in a river and three drinking water treatment plants near and far from a major production source, *Sci. Total Environ.*, 2017, **583**, 393–400, DOI: 10.1016/j.scitotenv.2017.01.079.

36 Environment Agency England and Wales, *Poly- and Perfluoroalkyl Substances (PFAS): Sources, Pathways and Environmental Data*, Environment Agency, 2021, https://www.pfasfree.org.uk/wp-content/uploads/EA-PFAS-Research-Report-Final-2019.pdf.

37 R. Bossi, J. Strand, O. Sortkjær and M. M. Larsen, Perfluoroalkyl compounds in Danish wastewater treatment plants and aquatic environments, *Environ. Int.*, 2008, **34**(4), 443–450, DOI: 10.1016/j.envint.2007.10.002.

38 H. N. Vo, H. H. Ngo, W. Guo, T. M. Nguyen, J. Li, H. Liang, L. Deng, Z. Chen and T. A. Nguyen, Poly-and perfluoroalkyl substances in water and wastewater: A comprehensive review from sources to remediation, *J. Water Proc. Eng.*, 2020, **36**, 101393, DOI: 10.1016/j.jwpe.2020.101393.

39 ATSDR Agency for Toxic Substances and Disease Registry. *Per- and Polyfluoroalkyl Substances (PFAS) and Your Health - PFAS in the U.S. Population. Agency for Toxic Substances and Disease Registry*, Centres for Disease Control and Prevention, 2022.

40 Y. M. Tefera, S. Gaskin, K. Mitchell, D. Springer and S. Mills, Temporal decline in serum PFAS concentrations among metropolitan firefighters: Longitudinal study on post-exposure changes following PFAS foam cessation, *Environ. Int.*, 2023, **179**, 108167, DOI: 10.1016/j.envint.2023.108167.

41 S. B. Gewurtz, A. S. Auyeung, A. O. De Silva, S. Teslic and S. A. Smyth, Per-and polyfluoroalkyl substances (PFAS) in Canadian municipal wastewater and biosolids: Recent patterns and time trends 2009 to 2021, *Sci. Total Environ.*, 2024, **912**, 168638, DOI: **10.1016/j.scitotenv.2023.168638**.

42 L. A. D'Agostino and S. A. Mabury, Certain perfluoroalkyl and polyfluoroalkyl substances associated with aqueous film forming foam are widespread in Canadian surface waters, *Environ. Sci. Technol.*, 2017, **51**(23), 13603–13613, DOI: **10.1021/acs.est.7b03994**.

43 ACAT. Alaska Community Water Quality Report: PFAS contamination of municipality of Anchorage and Fairbanks north star borough waters, 2023. Available from: **https://www.akaction.org/publications/pfas/alaska-community-water-quality-report-pfascontamination-of-municipality-of-anchorage-and-fairbanks-north-star-borough-waters/**.

44 L. Gobelius, J. Hedlund, W. Dürig, R. Troger, K. Lilja, K. Wiberg and L. Ahrens, Per-and polyfluoroalkyl substances in Swedish groundwater and surface water: implications for environmental quality standards and drinking water guidelines, *Environ. Sci. Technol.*, 2018, **52**(7), 4340–4349, DOI: **10.1021/acs.est.7b05718**.

45 H. A. Langberg, G. D. Breedveld, H. M. Grønning, M. Kvennås, B. M. Jenssen and S. E. Hale, Bioaccumulation of fluorotelomer sulfonates and perfluoroalkyl acids in marine organisms living in aqueous film-forming foam impacted waters, *Environ. Sci. Technol.*, 2019, **53**(18), 10951–10960.