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Underestimated burden of per- and polyfluoroalkyl substances in global surface waters and groundwaters

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Per- and polyfluoroalkyl substances (PFAS) are a class of fluorinated chemicals used widely in consumer and industrial products. Their human toxicity and ecosystem impacts have received extensive public, scientific and regulatory attention. Regulatory PFAS guidance is rapidly evolving, with the inclusion of a wider range of PFAS included in advisories and a continued decrease in what is deemed safe PFAS concentrations. In this study we collated PFAS concentration data for over 45,000 surface and groundwater samples from around the world to assess the global extent of PFAS contamination and their potential future environmental burden. Here we show that a substantial fraction of sampled waters exceeds PFAS drinking water guidance values, with the extent of exceedance depending on the jurisdiction and PFAS source. Additionally, current monitoring practices probably underestimate PFAS in the environment given the limited suite of PFAS that are typically quantified but deemed of regulatory concern. An improved understanding of the range of PFAS embodied in consumer and industrial products is required to assess the environmental burden and develop mitigation measures. While PFAS is the focus of this study, it also highlights society's need to better understand the use, fate and impacts of anthropogenic chemicals.

Per- and polyfluoroalkyl substances (PFAS) constitute a class of over 14,000[1] chemicals extensively used in industrial applications and consumer products because of their distinct water and oil repellent properties and high heat tolerance. PFAS are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom[2]. This includes fluoropolymers (for example, Teflon), some fluorinated insecticides (for example, Fludioxonil) and pharmaceuticals (for example, Bicalutamide)[3]. PFAS are referred to as 'forever chemicals'[4] because of their persistence in the environment. Perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), two of the highest-profile PFAS, were added to the Stockholm Convention for the protection of human health and the environment from persistent organic pollutants (POPs)[5] in 2009 and 2019, respectively, limiting their use and production. This also coincided with a shift from 'legacy PFAS' towards novel PFAS[6] (Extended Data Table 1).

Regulators worldwide have proposed or regulated varying concentrations for PFAS in drinking water. One of the most restrictive recommendations for drinking water is Health Canada's, with the sum of all PFAS being less than 30 ng l^{-1} (ref. 7), whereas the European Union recommends the sum off all PFAS being less than 500 ng l^{-1} or the sum of 20 select PFAS being less than 100 ng l^{-1} (ref. 8). It is noted, however, that currently Health Canada only requires quantification of either at least 18 PFAS or using US Environmental Protection Agency (EPA) methods 533 and/or 537.1[9]. The US EPA has proposed drinking water

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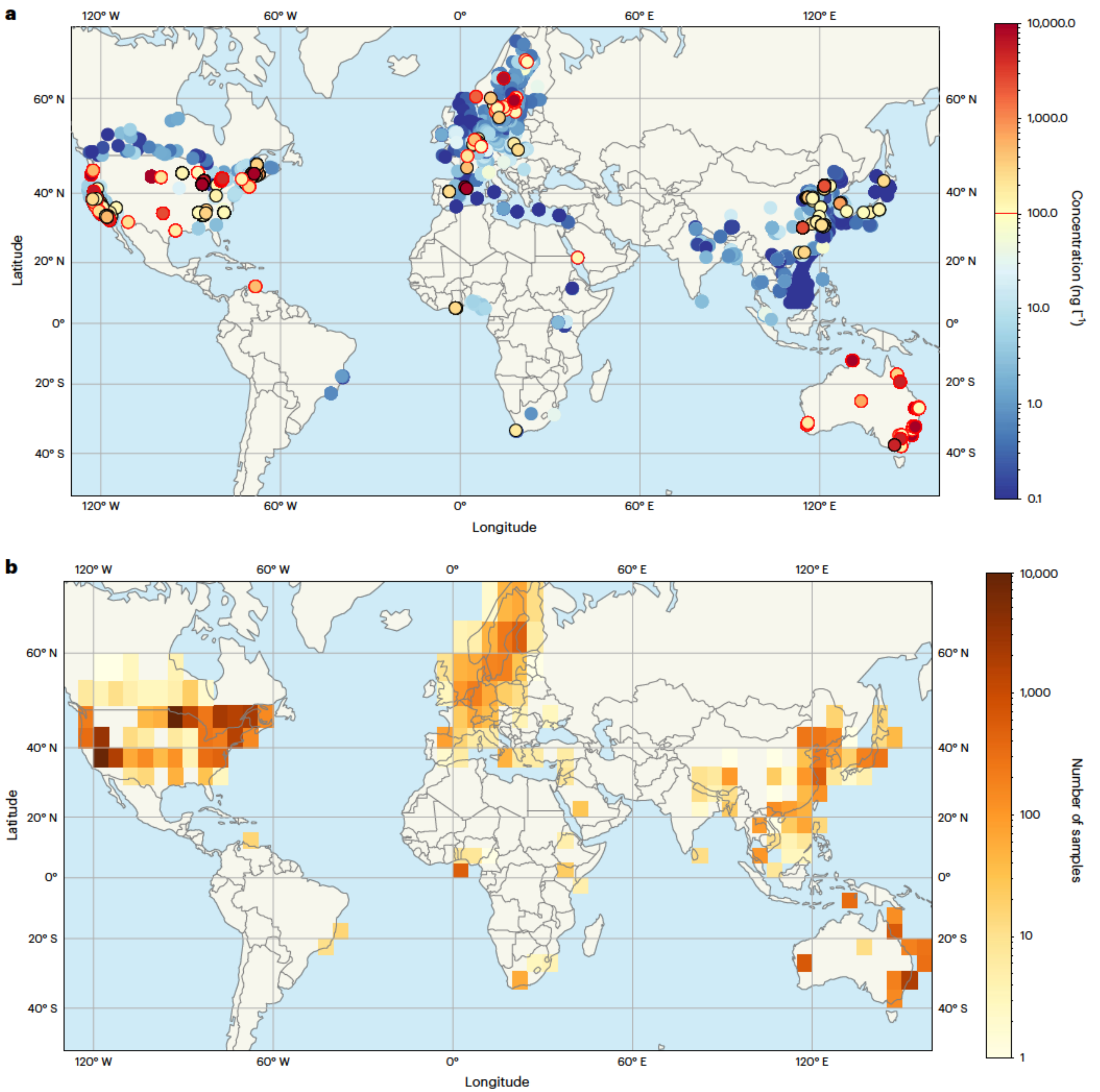

Fig. 1 | Global map of PFAS concentration in water. a, Sum of concentration of 20 PFAS subject to EU guidance in surface water, groundwater and drinking water samples. Those above the EU drinking water limit of 100 ng l^{-1} (marked red on scale bar) are circled in red (for known contamination sources (for example, AFFF or non-AFFF)) or black (unknown sources). **b**, Number of PFAS samples available on a 5° longitude/latitude grid worldwide.

concentration limits of 4 ng l^{-1} for PFOS and PFOA in their National Primary Drinking Water Regulation and limits on perfluorononanoic acid (PFNA), perfluorobutanesulfonic acid (PFBS), perfluorohexanesulfonic acid (PFHxS) and hexafluoropropylene oxide dimer acid (GenX) through the hazard index (HI)[10].

Toxicity concerns increase with fluorinated chain length (FCL), because long-chain PFAS (FCL > 6) usually take longer to be excreted from the body due to their lower water solubility, higher affinity for serum proteins and enterohepatic recirculation, which increase their elimination time from plasma and tissue[11–13]. All perfluoroalkyl carboxylic acids (PFCA) with a FCL ≥ 7 are currently candidates for potential inclusion on the Stockholm Convention for the protection of human health and the environment from POPs[5].

Certain PFAS degrade to terminal perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs) and are referred to as precursors[14] (Supplementary Table 1 and Supplementary Fig. 1). Precursors are used extensively in the manufacture of consumer products such as cosmetics, surface treated paper, waterproof textiles, insecticides, food packaging and firefighting foams[15]. Whereas there are too many PFAS precursors to list individually, they are generally

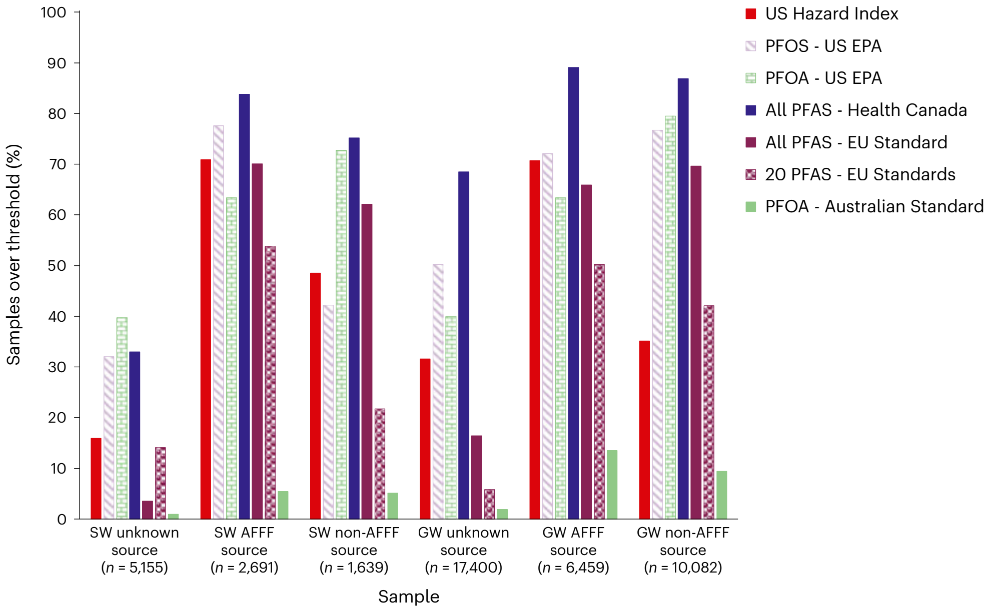

Fig. 2 | Incidence of exceedance of PFAS regulatory standards or advisories. For samples where PFAS concentrations were below detection limits, a PFAS concentration was randomly assigned between zero and the detection limit.

separated into three major groupings: fluorotelomers, sulfonamides and polyfluorinated alkyl phosphate esters (PAPs).

Whereas studies have estimated PFAS production globally[16,17] and quantified PFAS in commercial and industrial products, their fate is still unknown. Numerous studies have investigated PFAS extent in environmental compartments, including one that suggests that four select PFAS exceed the planetary boundary[18]. Studies have also assessed or compared aqueous phase PFAS concentrations in select regions[19,20]. Whereas it is widely acknowledged that PFAS are globally pervasive, the extent of PFAS in global surface (SW) and groundwater (GW) is unknown, as is the extent to which PFAS concentrations exceed proposed or implemented PFAS drinking water guidelines.

Here we investigate the extent and distribution of PFAS surface and groundwater contamination globally. We assess PFAS concentrations with respect to current and proposed PFAS drinking water regulations or advisories. Finally, we investigate the source of PFAS contamination, including the distribution of PFAS used in various consumer products, providing insights into the global pervasiveness of PFAS and the ability to predict the future environmental burden of PFAS.

Extent of global PFAS water contamination

To assess the global extent and importance of PFAS in the environment, an extensive global dataset was developed from 273 environmental studies since 2004, which include data for over 12,000 SW and 33,900 GW samples. As PFAS are not naturally occurring[21], any PFAS found in the environment was introduced from a range of consumer and industrial products.

PFAS are pervasive in SW and GW worldwide (Fig. 1). Note that, while the mapped data suggest Australia, China, Europe and North America are PFAS hotspots relative to the world (Fig. 1a), when comparing against the number of samples collected (Fig. 1b), it implies that these are high-sampling zones, potentially skewing the representation of actual distribution. If research were undertaken in more locations worldwide at sites with high aqueous film forming foam (AFFF) usage, such as major airports, comparable PFAS contamination levels would probably be found. Additionally, high PFAS contamination in Fig. 1a is not limited to areas near manufacturing sites but also high-use areas. For example, Australia has no PFAS manufacturing facilities[22,23] but has highly contaminated PFAS sites from firefighting activities. Furthermore, sampled locations could have higher PFAS concentrations compared to unsampled areas, as research efforts tend to concentrate on locations where PFAS presence is likely. Given this, the occurrence of surface and groundwater with large PFAS concentrations estimated in this study may be high.

Threshold regulatory PFAS concentration limits are used to benchmark the PFAS global extent in SW and GW (Extended Data Table 2). PFAS sources were divided into three categories: known non-AFFF (for example, production facilities using or producing PFAS, landfills), known AFFF (for example, firefighting training area) or unknown. A higher proportion of samples exceeded threshold limits when associated with a known source of PFAS contamination compared with an unknown source (Fig. 2 and Extended Data Figs. 1–6). For GW samples with known AFFF contamination, 71, 72 and 63% exceeded the proposed US EPA HI ($n = 6{,}312$) or their proposed PFOS ($n = 6{,}442$) and PFOA ($n = 6{,}447$) drinking water regulation, respectively. However, when there was no known source, the incidence of exceedance of these criteria was still elevated (31, 50 and 40% for the US EPA HI ($n = 14{,}905$), PFOS ($n = 15{,}351$) and PFOA ($n = 15{,}499$) drinking water regulation, respectively). Given that guidance on PFAS threshold concentrations vary globally, the proportion of samples that are deemed of concern also varies. Groundwater with no known contamination source exceeded Health Canada's criteria in 69% of samples whereas only 6% of these samples exceeded the EU's sum of all PFAS criteria (500 ng l^{-1}) ($n = 16{,}151$). If the alternate EU sum of 20 PFAS criteria is considered, 16% of groundwater samples with no known contamination source were in exceedance ($n = 16{,}143$). Regardless of the regulatory threshold considered, a large fraction of groundwater samples would be considered unacceptable for drinking water consumption. For known AFFF source SW samples, the proportion exceeding regulatory thresholds is similar to GW samples. However, when there was no known PFAS source, or a known non-AFFF source, the incidence of SW samples exceeding regulatory thresholds was lower. This is expected as residence times in surface waters are lower than for groundwater. For this analysis, samples that were below detection limits (BDL) were randomly assigned a concentration between zero and the detection limit. To assess potential bias, particularly for low-threshold criteria jurisdictions (for example, PFOA < 4 ng l^{-1} US EPA), this analysis was repeated with PFAS concentrations with BDL set to zero (Extended

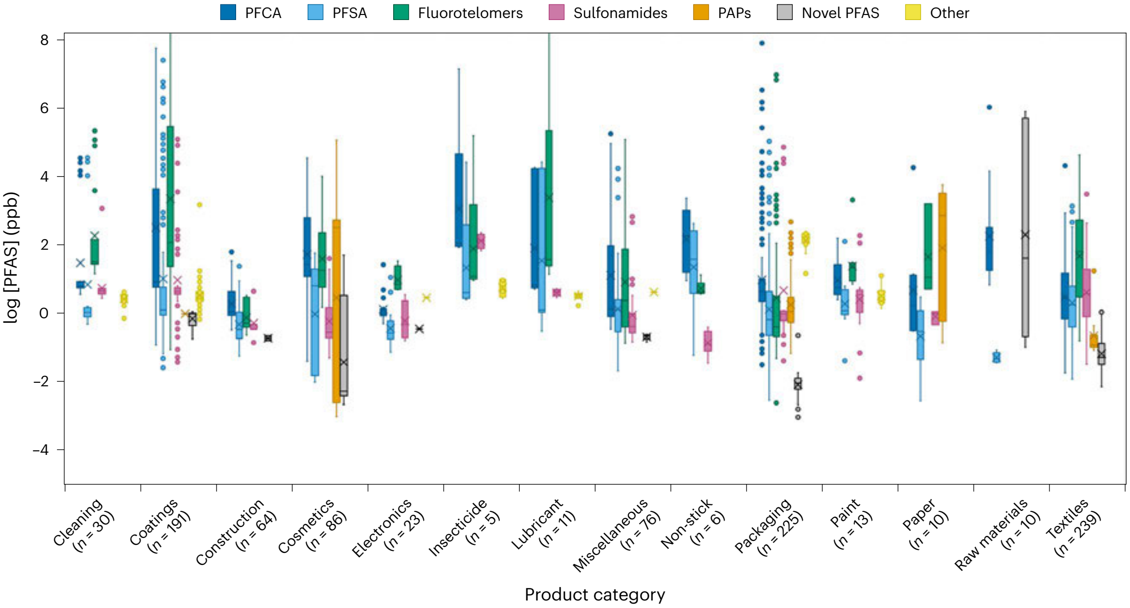

Fig. 3 | Box plot of total PFAS concentration identified in various consumer and industrial product categories. Box dimensions show the span between quartiles 1 and 3 (interquartile range, IQR). Outliers are defined as values greater than 1.5× the IQR. Whiskers extend from these quartiles to the largest (quartile 3) or smallest (quartile 1) non-outlier value (that is, <1.5× the IQR). *Y*-axis units are ng ml^{-1} or μg kg^{-1} equivalent to ppb.

Data Table 3 and Supplementary Figs. 2–8). Whereas assumptions made dealing with detection limits impact results, both approaches conclude that an important fraction of samples exceeds regulatory threshold levels. As method-detection limits continually decrease, the extent of exceedances will be better informed.

Where does PFAS come from

To assess PFAS sources to the environment, consumer and industrial products containing PFAS were divided into those used for AFFF and non-AFFF. AFFF applications typically result in high concentration point sources of PFAS, as do industrial manufacturing sites that synthesize or use PFAS. The latter are considered known (non-AFFF) sources in this study.

Non-AFFF consumer and industrial products

PFAS in 943 non-AFFF consumer products in 15 categories were characterized from 38 literature studies since 2010. In these studies, 113 PFAS were quantified, although at most 60 PFAS were analysed in any given study[24]. Comparison of PFAS classes in consumer products is challenging as the same suite of PFAS are not quantified in each study. For example, at least two PFCAs or PFSAs were measured in 89% and 69% of all non-AFFF product samples, respectively, whereas only 49%, 35%, 20%, 12% and 15% of studies quantified at least two fluorotelomers, sulfonamides, PAPs, novel or other PFAS, respectively. When measured, however, fluorotelomers and traditional PFCAs represented the dominant PFAS subclass in most of the product categories investigated (for example, coatings, cosmetics and textiles) (Fig. 3). Fluorotelomers represented a median of 72% of the total measured PFAS by mass in consumer products, whereas PFCAs represented 25%. PAPs and sulfonamides were also relevant when measured with a median of 14% and 7%, respectively. Interestingly, PFSAs were typically much lower, accounting for a median of 4% of the total quantified PFAS mass.

Different jurisdictions worldwide provide guidance, or regulate, differing ranges of PFAS, with no standard approach to quantify PFAS. For example, the US EPA has three methods to measure PFAS in aqueous samples, methods 533, 537.1 and 8327, with an additional non-drinking aqueous method (1633) in development. EPA method 537 and its revisions have been the most used since 2009, quantifying 14 PFAS. In 2018, this method was revised as 537.1 to include four additional PFAS. All other EPA methods were developed in 2019 or later and quantify a total of 32 PFAS, including seven PFSA, 11 PFCA, three fluorotelomers, three sulfonamides and eight novel PFAS (Extended Data Table 2). In this study, EPA draft method 1633 is used as a benchmark as EPA methods are commonly used globally and method 1633 is the most comprehensive. In doing so, this provides a preliminary assessment of the extent to which the most comprehensive EPA method captures PFAS mass and the extent of unaccounted PFAS.

If only the PFAS listed in draft method 1633 were used to quantify PFAS in consumer products within this dataset, the total embodied PFAS would be substantially underestimated (Fig. 4) and the PFAS distribution would completely change. For example, the median concentration of PFAS regulated in the United States (sum of PFBS, PFHxS, PFOS, PFOA, PFNA and GenX) in textiles ($n = 227$) and coatings ($n = 167$) is two and three orders of magnitude smaller than the median of all PFAS quantified. Across all products, EPA method 1633 suggests a median distribution of 73% PFCA ($n = 781$), 11% PFSA ($n = 750$), 16% fluorotelomers ($n = 353$), 10% sulfonamides ($n = 242$) and 0.1% novel PFAS ($n = 27$), with phosphate-based PFAS not being quantified with this method. This results in the proportion of PFCAs, PFSAs and sulfonamides being overestimated by a factor of 2.8, 2.8 and 4.2, respectively, whereas fluorotelomers would be underestimated by a factor of 25. A median of 4% of the PFAS mass in consumer products is currently subject to the Stockholm Convention ($n = 976$), increasing to 18% with the inclusion of candidate PFAS (PFCAs with FCL ≥ 7) ($n = 976$). The average amount of long-chain PFAS within this dataset, including PFCAs, is 66% ($n = 976$), indicating that long-chain PFAS are dominant in consumer products.

As previously mentioned, fluorotelomers represent the largest contributor to PFAS mass in consumer products. Fluorotelomers are comprised of numerous subgroups including fluorotelomer sulfonates (FTS), fluorotelomer alcohols (FTOH), fluorotelomer iodides, fluorotelomer acrylates, fluorotelomer methacrylates, fluorotelomer mercaptoalkyl phosphate diester, fluorotelomer unsaturated carboxylic acids (FTUCA) and fluorotelomer carboxylic acids (FTCA). FTS represent a median 2% ($n = 338$) of the total PFAS in consumer products when two or more PFAS classes are quantified and are the only fluorotelomers

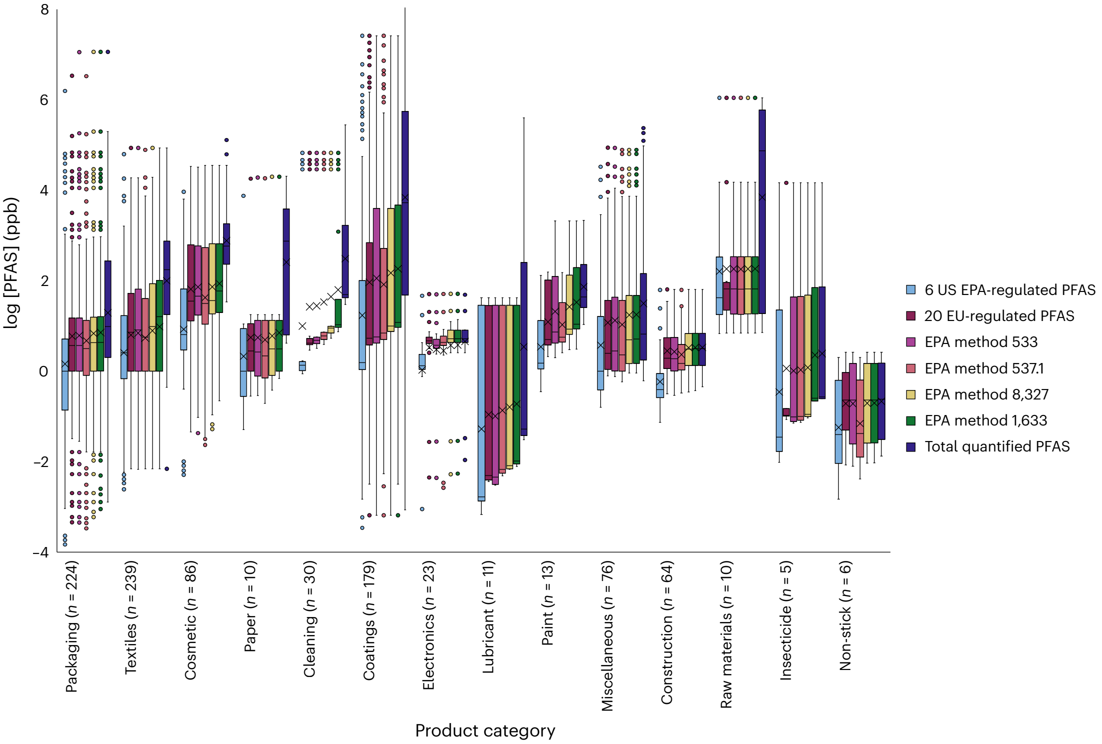

Fig. 4 | Box plot of PFAS in consumer/industrial products that would be quantified with EPA methods or regulated in the US/EU. PFAS concentrations are in ng ml^{-1} or μg kg^{-1} equivalent to ppb. Box dimensions show the span between quartiles 1 and 3 (IQR). Outliers are defined as values greater than 1.5× the IQR. Whiskers extend from these quartiles to the largest (quartile 3) or smallest (quartile 1) non-outlier value (that is, <1.5× the IQR).

quantified using the US EPA methods. FTOH require a different analytical method to most other PFAS and were not often analysed. However, when two or more PFAS in this subclass were quantified, they represented an important proportion (median of 58% ($n = 365$)) of the total PFAS in consumer products.

Although most PFAS in consumer products may not be currently regulated, many will transform to regulated PFAS in the environment (Supplementary Tables 1 and 2). Studies that have used the total oxidizable precursor (TOP) assay found a notable increase in PFCAs following oxidation. This suggests that traditional EPA-based methods do not adequately capture PFAS embodied in consumer products and their potential environmental burden[24–27].

AFFF

Eleven literature studies characterize PFAS in 148 AFFF samples from different suppliers and synthesis methods sold since 1980. These studies quantified 69 PFAS with a maximum of 40 PFAS being measured in any given study[28]. PFAS for AFFF applications have been synthesized by two synthesis processes: electrochemical fluorination and telomerization[21]. These processes result in a range of products with electrochemical fluorination-producing PFOS and telomerization-producing fluorotelomers[21,29]. Depending on the manufacturer and year produced, AFFF has different formulations (Supplementary Table 3). PFOS represents a median 51% of the PFAS in historic 3M AFFF ($n = 14$), with other PFSAs and sulfonamides also forming important contributions. All other PFAS in historic 3M AFFF had low concentrations, when measured. Fluorotelomers and PFCAs, were the dominant PFAS in Angus AFFF ($n = 28$), with a median of 64% and 36%, respectively. Several other AFFF have been investigated, however, the supplier's name was not provided or PFCA and PFSA concentrations were not quantified. In these samples, fluorotelomers represented the dominant PFAS (median = 93%, $n = 83$). Of these fluorotelomers, important subclasses include FTS (median = 73% of total PFAS, $n = 69$) and FTOH (median = 10% of total PFAS, $n = 38$). Comparison of PFAS quantified using EPA method 1633 to the sum of all PFAS quantified suggests that exclusively reporting PFAS quantified using EPA method 1633 underrepresents total PFAS in AFFF by a median factor of 2.8. A median 60% of the PFAS mass in historic 3M AFFF is subject to the Stockholm Convention whereas Angus AFFF has no PFAS subject to the Stockholm Convention. For non-3M AFFF ($n = 134$), including candidate PFAS, 0.6% of the PFAS mass would be subject to the Stockholm Convention, increasing to 1% if long-chain PFAS are considered. This analysis of AFFF formulations suggests that known PFAS in AFFF presents a large environmental burden, with an important fraction either currently subject to regulatory oversight, or likely in future. However, an undetected fraction of PFAS in AFFF probably exists[30]. It is important to note that many of these studies quantify a limited number of PFAS, similar to non-AFFF product studies. Therefore, it is challenging to predict the AFFF environment burden because not all PFAS are quantified. Furthermore, when the TOP assay is applied to AFFF samples, considerable increases in total PFAS mass has been reported[31,32], as noted in non-AFFF consumer product studies.

Finding the missing piece in FTOH and other under measured PFAS

Across the 33,940 groundwater samples, 57 distinct PFAS were quantified. On average, 16 distinct PFAS (maximum of 38 PFAS) were quantified and an average of 15 PFAS within the suite of proposed US EPA method 1633. PFCAs, PFSAs and sulfonamides were routinely quantified (at least two PFCAs, PFSAs and sulfonamides were quantified in 91%, 89% and 54% of studies, respectively). Whereas at least two fluorotelomers were quantified in 26% of the groundwater studies, this was almost exclusively FTS, with FTCA and FTUCA quantified to a lesser extent and no studies quantifying FTOH. This is despite the fact that FTOH are an important PFAS present in consumer products, when quantified. It is important to note that existing EPA aqueous methods (EPA methods 533, 537, 1633) are liquid chromatography with tandem mass spectrometry (LC-MS/MS) based. Analysis of FTOH requires gas chromatography tandem mass spectrometry (GC-MS/MS), with no US EPA GC/MS/MS methods for aqueous PFAS in existence. With regards to surface water, PFCAs, PFSAs and fluorotelomers were quantified to a similar extent as groundwater samples, with FTS representing the dominant fluorotelomers quantified. Unlike groundwater studies, four of the surface water studies quantified FTOH[33–36], with only two also quantifying PFCAs, PFSAs or both, facilitating an assessment of the relative importance of FTOH. In the 16 urban river samples in China[34] and eight river samples in Bangladesh[33], FTOH represented a median of 53% of the total PFAS (range of 46 to 62%) and 2% (ranging from 0.9 to 34%), respectively. It is difficult to draw definitive conclusions from two studies with relatively few samples, however, coupled with the FTOH prevalence in consumer products, it suggests that FTOH could be an important class of unquantified PFAS. Because only a limited suite of PFAS are typically quantified, any estimate of PFAS environmental burden is likely to be an underestimate, and a broader suite of PFAS needs to be quantified.

Wastewater treatment plants (WWTPs) and landfills are focal point receptors of anthropogenic activity. Hence, representing an opportunity for quantification of the diverse PFAS suite that has or may be dispersed into the environment. Unfortunately, studies investigating WWTP influent and landfill leachate provide limited insights. Whereas landfill leachate studies quantify more PFAS than surface and groundwater studies, they have focused on the same range of PFAS (PFCAs, PFSAs, FTS and select sulfonamides) with no studies directly measuring FTOH[37]. However, studies have reported atmospheric FTOH emissions at landfill sites and WWTPs[38]. One Chinese study reported FTOH represented 8% of the PFAS WWTP influent mass[39]. FTOH could enter the wastewater system through various sources, including laundering of textiles[40].

Studies using the TOP assay to WWTP effluent report a considerable PFAS fraction that go undetected using EPA methods[41,42]. Similarly, studies that oxidized landfill leachate reported minimum to moderate changes in PFAS concentrations, suggesting that unknown PFAS transformed biotically or abiotically in landfill cells[43,44]. Whereas limited studies have applied the TOP assay to surface and groundwater, some report considerable increases in PFAS concentrations, although the increases are not consistent in the literature[41,45,46]. A major drawback of the TOP assay is that not *all* PFAS undergo oxidation to PFCAs or PFSA, particularly the perfluoroether class which transform into unmonitored terminal PFAS[47]. Furthermore, there is no standardized TOP assay method, and results from the variants available can differ greatly, with too harsh conditions leading to mineralization of terminal target PFAS[48]. These findings suggest that TOP assay results may underrepresent future PFAS' environmental burden. Given the relatively limited suite of PFAS that have been quantified in surface and groundwater, it is not possible to reliably discuss the extent to which current PFAS methods adequately capture the range of PFAS and mass in these systems.

Overall, this study suggests that a large fraction of surface and groundwaters globally exceed PFAS international advisories and regulations and that future PFAS environmental burden is likely underestimated. Because PFAS definition continues to evolve, the extent of underestimation will be a function of PFAS definition. Additional work is needed to develop analytical techniques to quantify PFAS in environmental matrices, conduct a more systematic sampling regime of water sources globally and quantify human and ecological impacts of the broad range of PFAS in the environment.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-024-01402-8.

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Methods

This study reviewed and collated 48,985 samples from 367 published papers and government websites to build a comprehensive database to determine PFAS global distribution in surface and groundwater (Supplementary Table 4). This study is therefore limited to PFAS tested in previous studies, the analytical instruments and methods used and the locations that were sampled. The data were collated, compared and analysed and statistically validated using Python scripts and MS Excel.

PFAS is reported in ng l^{-1} for aqueous concentrations. When investigating PFAS concentrations in products, all data were converted to parts per billion (ppb) using appropriate area to mass conversions as the data include PFAS from an array of sources in different compartments and measured with different instruments and sample-preparation techniques.

The data available were converted into an Excel file using an online open-source portable document format converter when required. All data was then saved as a comma-separated values or Microsoft Excel spreadsheet document before analysis with Python. To check the data, an initial screening was done using a Python script, followed by manual checks. When analytes were reported as below detection limits (BDL) or not detected, a random value between 0 and the detection limit was assigned using a loop in Python and the detection limit provided in each study. Even though there are specific statistical methods for handling censored data, they assume a specific data distribution not applicable in this case and as there are less than 60% of samples below the detection limit, substitution was suitable[49]. Randomizing the substitution reduces clustering of data around a specific value and biasing of results. To represent data on a map, the latitude and longitude of the sampling location was used. Where no location was specified other than the country, a random major city in that country was assigned to capture the sample's location.

A list of the PFAS analytes, their major PFAS class and fluorinated chain length are included in Supplementary Table 1. The PFAS classes considered include those that form as terminal products, that is, perfluorocarboxylates (PFCA), perfluorosulfonates (PFSA) and precursors to these terminal products. Precursors included are fluorotelomers, sulfonamides and polyfluorinated alkyl phosphate esters (PAPs). Within the fluorotelomer PFAS class subclasses include: alcohols (FTOH), sulfonates (FTS), iodides, n:2 saturated/unsaturated carboxylates (FTCA/FTUCA), acrylates and betaines. Finally, novel PFAS (which predominantly encapsulate the ether PFAS sub-group) were considered.

Data availability

Sources of data used to compile the database are provided in Supplementary Table 4. The data analysed and used to generate the figures and tables in this study are available in the following Zenodo data repository: https://doi.org/10.5281/zenodo.10616840. Source data are provided with this paper.

Code availability

Python scripts used to summarize data will be provided upon request.

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Author contributions

Conceptualization: conceived by D.M.O. and refined by all authors. Methodology: D.A.G., D.G., A.M.J., T.C.G.K. and D.M.O. Data collection: D.A.G., D.G. and J.H. Data analysis: D.A.G., D.G., A.M.J., T.C.G.K. and D.M.O. Validation: D.A.G., D.G. and A.M.J. Supervision: A.M.J., M.J.L. and D.M.O. Writing: D.A.G., A.M.J. and D.M.O. with input from all authors.

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Competing interests

The authors declare no competing interests.

Additional information

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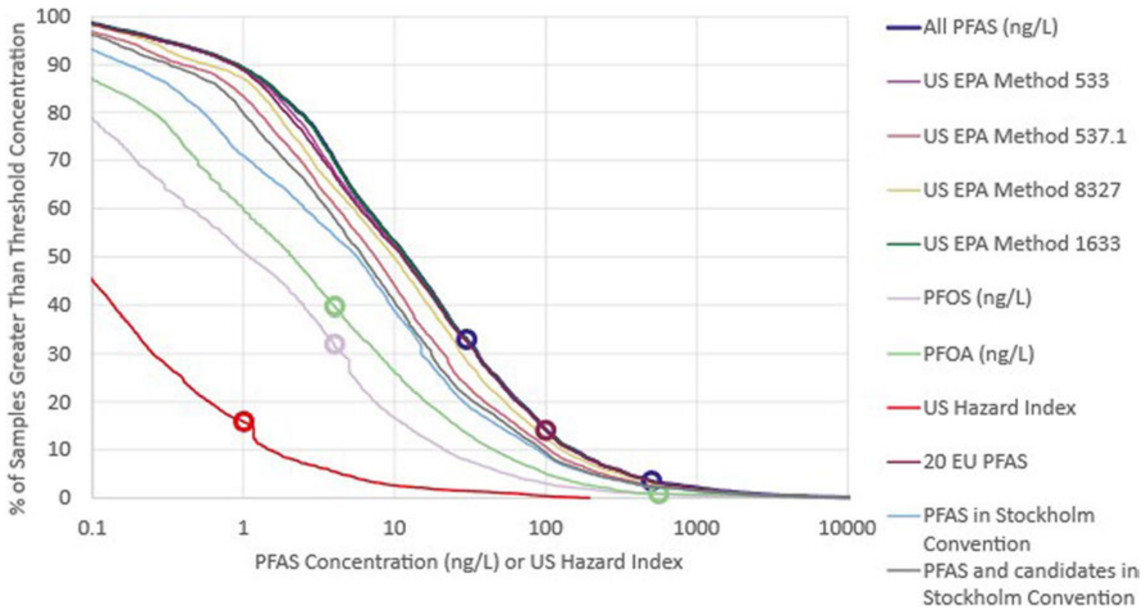
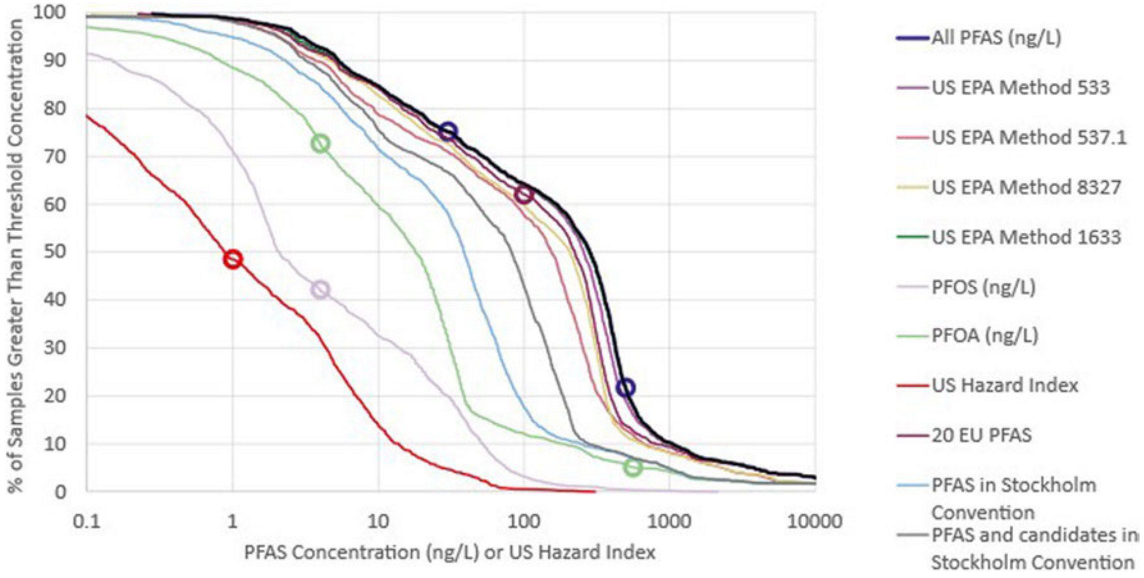
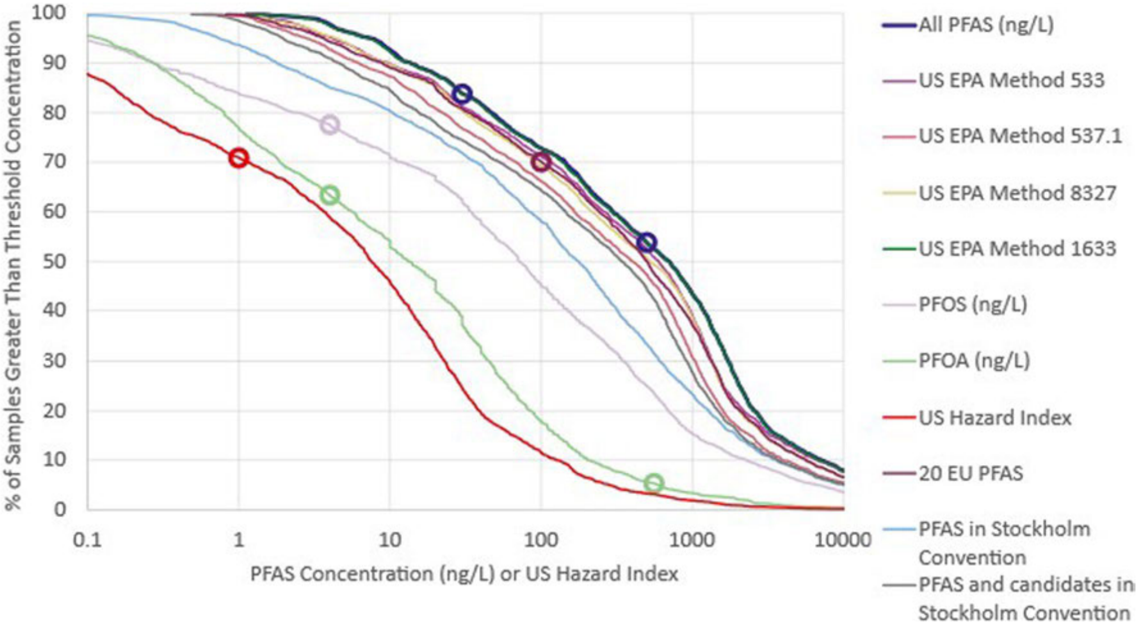


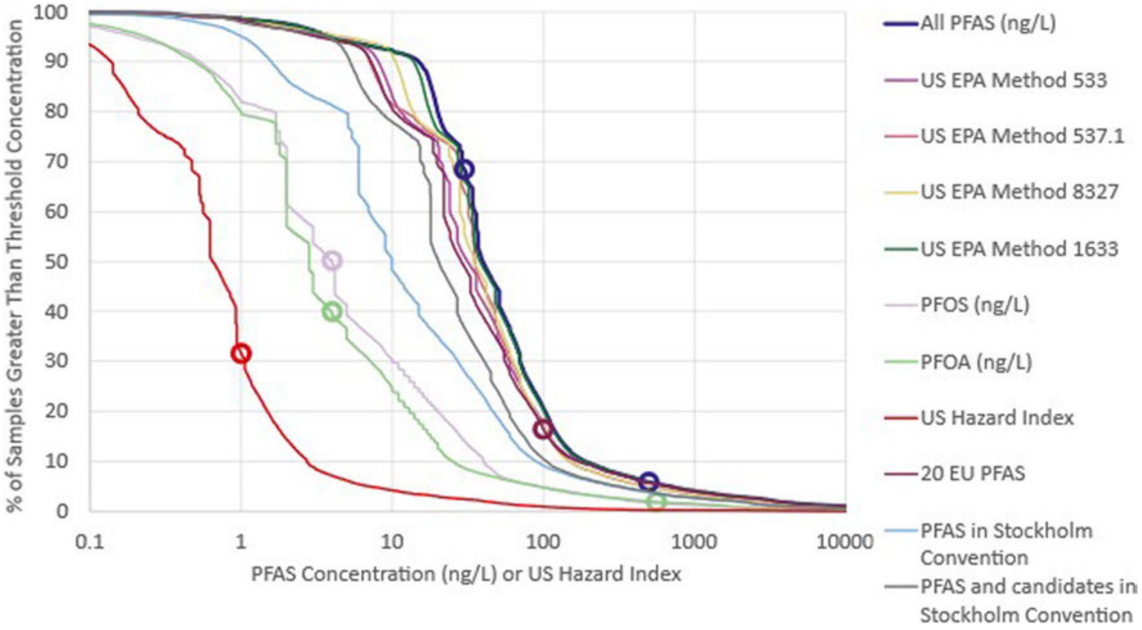
Extended Data Fig. 1 | Cumulative distribution of surface water samples from an unknown source that exceed a given PFAS concentration. Circles indicate relevant PFAS drinking water guidance values. For samples where PFAS concentrations were below detection limits a PFAS concentration was randomly assigned between zero the detection limit.



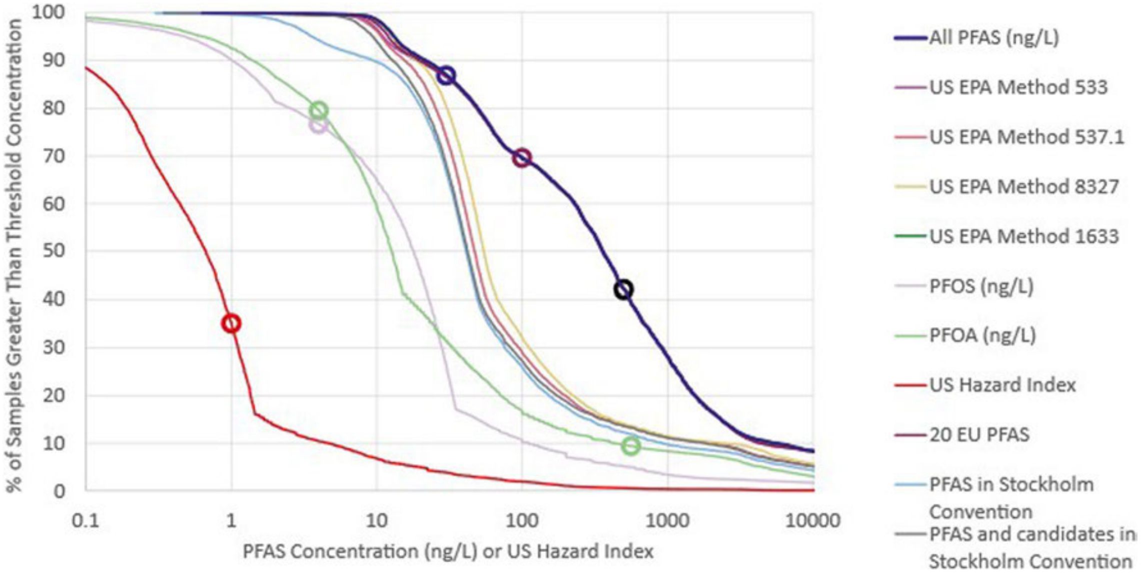
Extended Data Fig. 2 | Cumulative distribution of surface water samples from a known non AFFF source that exceed a given PFAS concentration. Circles indicate relevant PFAS drinking water guidance values. For samples where PFAS concentrations were below detection limits a PFAS concentration was randomly assigned between zero the detection limit.



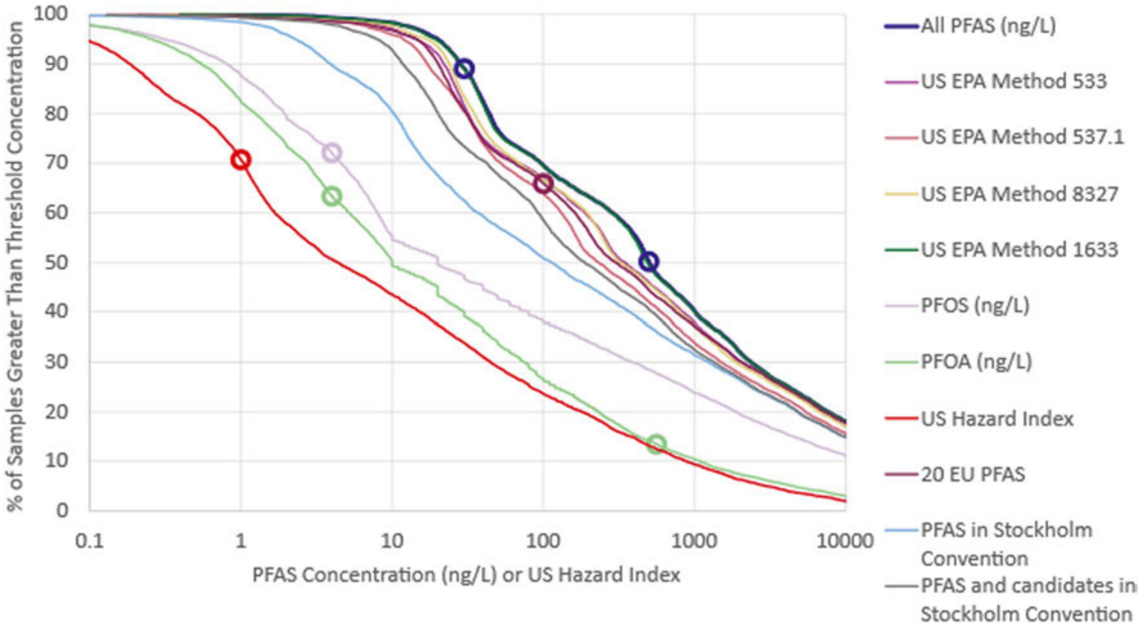
Extended Data Fig. 3 | Cumulative distribution of surface water samples from a known AFFF source that exceed a given PFAS concentration. Circles indicate relevant PFAS drinking water guidance values. For samples where PFAS concentrations were below detection limits a PFAS concentration was randomly assigned between zero the detection limit.



Extended Data Fig. 4 | Cumulative distribution of groundwater samples from an unknown source that exceed a given PFAS concentration. Circles indicate relevant PFAS drinking water guidance values. For samples where PFAS concentrations were below detection limits a PFAS concentration was randomly assigned between zero the detection limit.



Extended Data Fig. 5 | Cumulative distribution of groundwater samples from a known non AFFF source that exceed a given PFAS concentration. Circles indicate relevant PFAS drinking water guidance values. For samples where PFAS concentrations were below detection limits a PFAS concentration was randomly assigned between zero the detection limit.



Extended Data Fig. 6 | Cumulative distribution of groundwater samples from a known AFFF source that exceed a given PFAS concentration. Circles indicate relevant PFAS drinking water guidance values. For samples where PFAS concentrations were below detection limits a PFAS concentration was randomly assigned between zero the detection limit.

Extended Data Table 1 | Summary of all PFAS identified in this study

Abbreviation	Name	CAS number	Class/Sub-class	Fl.Chain Length	Chemical Formula
TFA	Trifluoroacetate	14477-72-6	PFCA	1	$C_2F_3O_2$
PfPrA	Perfluoropropanoicacid	422-64-0	PFCA	2	$C_3HF_5O_2$
PFBA	Perfluorobutanoicacid	375-22-4	PFCA	3	$C_4HF_7O_2$
PFPeA	Perfluoropentanoicacid	2706-90-3	PFCA	4	$C_5HF_9O_2$
PFHxA	Perfluorohexanoicacid	307-24-4	PFCA	5	$C_6HF_{11}O_2$
PFHpA	Perfluoroheptanoicacid	375-85-9	PFCA	6	$C_7HF_{13}O_2$
PFOA	Perfluorooctanoicacid	335-67-1	PFCA	7	$C_8HF_{15}O_2$
PFNA	Perfluorononanoicacid	375-95-1	PFCA	8	$C_9HF_{17}O_2$
ip-PFNA	Perfluoro-7-methyloctanoicacid	15899-31-7	PFCA	7	$C_9HF_{17}O_2$
PFDA	Perfluorodecanoicacid	335-76-2	PFCA	9	$C_{10}HF_{19}O_2$
PFUnDA	Perfluoroundecanoicacid	2058-94-8	PFCA	10	$C_{11}HF_{21}O_2$
PFDoDA	Perfluorododecanoicacid	307-55-1	PFCA	11	$C_{12}HF_{23}O_2$
PFTrDA	Perfluorotridecanoicacid	72629-94-8	PFCA	12	$C_{13}HF_{25}O_2$
PFTeDA	Perfluorotetradecanoicacid	376-06-7	PFCA	13	$C_{14}HF_{27}O_2$
PFPeDA	Perfluoropentadecanoicacid	141074-63-7	PFCA	14	$C_{15}HF_{29}O_2$
PFHxDA	Perfluorohexadecanoicacid	67905-19-5	PFCA	15	$C_{16}HF_{31}O_2$
PFHpDA	Perfluoroheptadecanoicacid	57475-95-3	PFCA	16	$\underline{C_{17}HF_{33}O_2}$
PFOcDA	Perfluorooctadecanoicacid	16517-11-6	PFCA	17	$C_{18}HF_{35}O_2$
PFNDA	Perfluorononadecanoicacid	133921-38-7	PFCA	18	$C_{19}HF_{37}O_2$
PFCoA	Perfluoroeicosanoicacid	68310-12-3	PFCA	19	$C_{20}HF_{39}O_2$
PFHCoA	Perfluoroheneicosanoicacid	-	PFCA	20	$C_{21}HF_{41}O_2$
PFDoCoA	Perfluorodocosanoicacid	-	PFCA	21	$C_{22}HF_{43}O_2$
PFTRrCoA	Perfluorotricosanoicacid	-	PFCA	22	$C_{23}HF_{45}O_2$
PFTeCoA	Perfluorotetracosanoicacid	-	PFCA	23	$C_{24}HF_{47}O_2$
PFPeCoA	Perfluoropentacosanoicacid	-	PFCA	24	$C_{25}HF_{49}O_2$
TFMS	Trifluoromethanesulfonicacid	1493-13-6	PFSA	1	CHF_3O_3S
PFEtS	Perfluoroethanesulfonate	354-88-1	PFSA	2	$C_2HF_5O_3S$
PFPrS	Perfluoropropanesulfonate	423-41-6	PFSA	3	$C_3HF_7O_3S$
PFBS	perfluorobutanesulfonate	375-73-5	PFSA	4	$C_4HF_9O_3S$
PFPeS	perfluoropentanesulfonate	2706-91-4	PFSA	5	$C_5HF_{11}O_3S$
PFHxS	perfluorohexanesulfonate	355-46-4	PFSA	6	$C_6HF_{13}O_3S$
PFHpS	perfluoroheptanesulfonate	375-92-8	PFSA	7	$C_7HF_{15}O_3S$
PFOS	perfluorooctanesulfonate	1763-23-1	PFSA	8	$C_8HF_{17}O_3S$
PFNS	perfluorononanesulfonate	68259-12-1	PFSA	9	$C_9HF_{19}O_3S$
PFDS	perfluorodecanesulfonate	335-77-3	PFSA	10	$C_{10}HF_{21}O_3S$
PFDoDS	perfluorododecanesulfonate	79780-39-5	PFSA	12	$C_{12}HF_{25}O_3S$
6:2FTA	6:2Fluorotelomeracrylate	17527-29-6	Flurotelomer/FTA	6	$C_{11}H_7F_{13}O_2$
8:2FTA	8:2Fluorotelomeracrylate	27905-45-9	Flurotelomer/FTA	6	$C_{13}H_7F_{17}O_2$
10:2FTA	10:2Fluorotelomeracrylate	17741-60-5	Flurotelomer/FTA	10	$C_{15}H_7F_{21}O_2$
5:1:2FTB	5:1:2Fluorotelomerbetaine	171184-02-4	Flurotelomer/FTB	5	$C_{12}H_{13}F_{12}NO_2$
7:1:2FTB	7:1:2Fluorotelomerbetaine	34455-29-3	Flurotelomer/FTB	7	$C_{14}H_{13}F_{16}NO_2$
9:1:2FTB	9:1:2Fluorotelomerbetaine	171184-04-6	Flurotelomer/FTB	9	$C_{16}H_{13}F_{20}NO_2$
5:3FTB	5:3Fluorotelomerbetaine	171184-14-8	Flurotelomer/FTB	5	$C_{12}H_{14}F_{11}NO_2$
7:3FTB	7:3Fluorotelomerbetaine	278598-45-1	Flurotelomer/FTB	7	$C_{14}H_{14}F_{15}NO_2$
9:3FTB	9:3Fluorotelomerbetaine	171184-16-0	Flurotelomer/FTB	9	$C_{16}H_{14}F_{19}NO_2$
4:2FTCA	4:2fluorotelomercarboxylicacid	70887-89-7	Flurotelomer/FTCA	4	$C_6H_3F_9O_2$
6:2FTCA	6:2fluorotelomercarboxylicacid	53826-12-3	Flurotelomer/FTCA	6	$C_8H_3F_{13}O_2$
8:2FTCA	8:2fluorotelomercarboxylicacid	27854-31-5	Flurotelomer/FTCA	8	$C_{10}H_3F_{17}O_2$
10:2FTCA	10:2fluorotelomercarboxylicacid;	53826-13-4	Flurotelomer/FTCA	10	$C_{12}H_3F_{21}O_2$
3:3FTCA	3:3fluorotelomercarboxylicacid	356-02-5	Flurotelomer/FTCA	3	$C_6H_5F_7O_2$
4:3FTCA	4:3fluorotelomercarboxylicacid	80705-13-1	Flurotelomer/FTCA	4	$C_7H_5F_9O_2$
5:3FTCA	5:3fluorotelomercarboxylicacid	914637-49-3	Flurotelomer/FTCA	5	$C_8H_5F_{11}O_2$
7:3FTCA	7:3fluorotelomercarboxylicacid	812-70-4	Flurotelomer/FTCA	7	$C_{10}H_5F_{15}O_2$
9:3FTCA	9:3fluorotelomercarboxylicacid	-	Flurotelomer/FTCA	9	$C_{12}H_5F_{19}O_2$
4:2FTUCA	4:2fluorotelomerunsaturatedcarboxylicacid	70887-90-0	Flurotelomer/FTUCA	4	$C_6H_2F_8O_2$
6:2FTUCA	6:2fluorotelomerunsaturatedcarboxylicacid	70887-88-6	Flurotelomer/FTUCA	6	$C_8H_2F_{12}O_2$
8:2FTUCA	8:2fluorotelomerunsaturatedcarboxylicacid	70887-84-2	Flurotelomer/FTUCA	8	$C_{10}H_2F_{16}O_2$
10:2FTUCA	10:2fluorotelomerunsaturatedcarboxylicacid	70887-94-4	Flurotelomer/FTUCA	10	$C_{12}H_2F_{20}O_2$
6:2FTI	6:2Fluorotelomeriodide	2043-57-4	Flurotelomer/FTI	6	$C_8H_4F_{13}I$
8:2FTI	8:2Fluorotelomeriodide	2043-53-0	Flurotelomer/FTI	8	$C_{10}H_4F_{17}I$
10:2FTI	10:2Fluorotelomeriodide	2043-54-1	Flurotelomer/FTI	10	$C_{12}H_4F_{21}I$
6:2FTMA	6:2Perfluoroctylmethacrylate	2144-53-8	Flurotelomer/FTMA	6	$C_{12}H_9F_{13}O_2$
8:2FTMA	8:2Perfluoroctylmethacrylate	1996-88-9	Flurotelomer/FTMA	8	$C_{14}H_9F_{17}O_2$
6:2FTMAP	6:2fluorotelomermercaptoalkylphosphatediester	-	Flurotelomer/FTMAP	6	$C_{17}HF_{26}O_3S_2P$
6:2/8:2FTMAP	6:2/8:2fluorotelomermercaptoalkylphosphatediester	-	Flurotelomer/FTMAP	8	$C_{18}HF_{30}OS_2P$
8:2FTMAP	8:2fluorotelomermercaptoalkylphosphatediester	-	Flurotelomer/FTMAP	8	$C_{19}HF_{34}OS_2P$
8:2/10:2FTMAP	8:2/10:2fluorotelomermercaptoalkylphosphatediester	-	Flurotelomer/FTMAP	10	$C_{20}HF_{38}OS_2P$

Extended Data Table 1 (continued) | Summary of all PFAS identified in this study

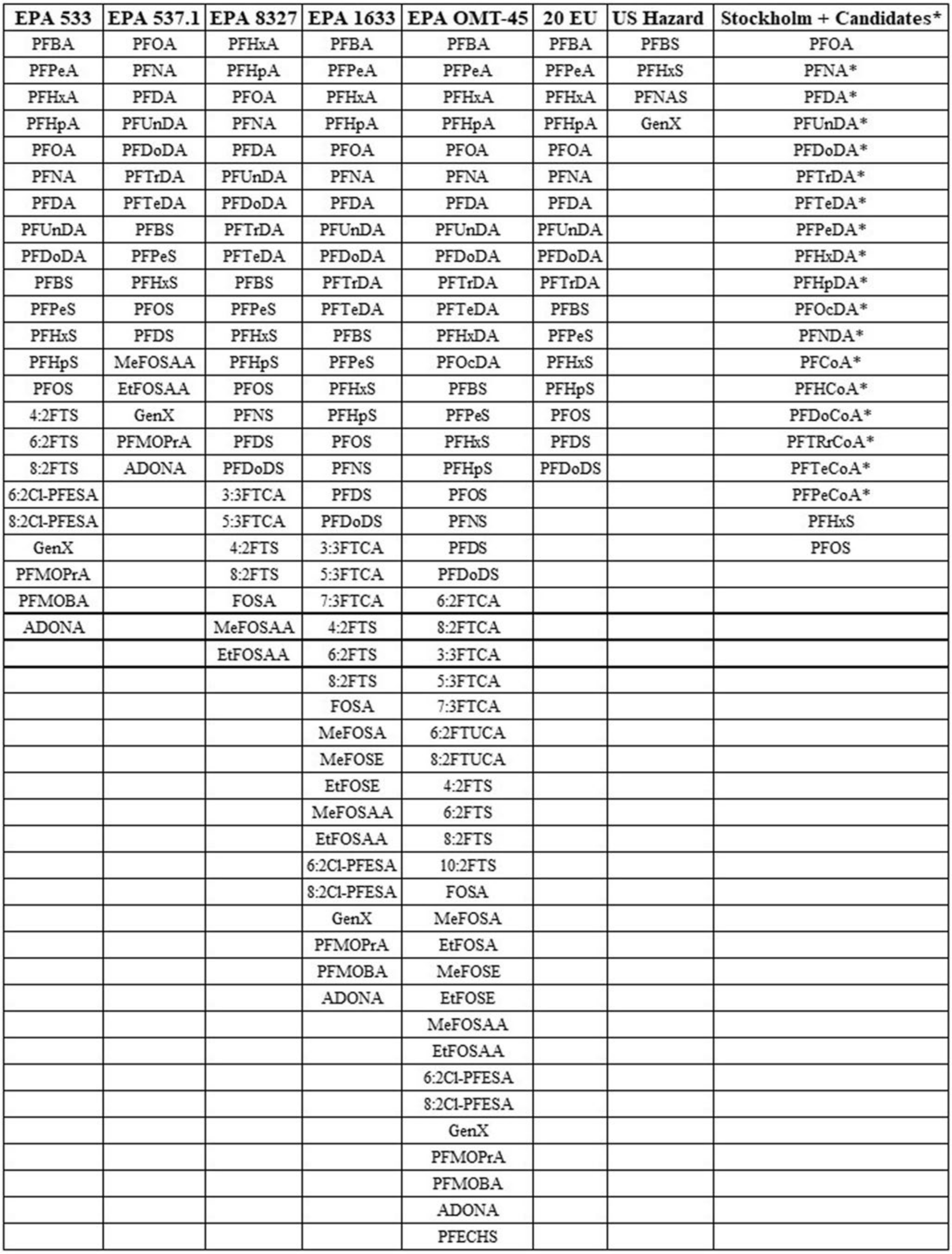
10:2FTMAP	10:2fluorotelomermercaptoalkylphosphatediester	-	Flurotelomer/FTMAP	10	$C_{21}HF_{42}OS_2P$
6:2FTO	6:2fluorotelomerolefin	25291-17-2	Flurotelomer/FTO	6	$C_8H_3F_{13}$
8:2FTO	8:2fluorotelomerolefin	21652-58-4	Flurotelomer/FTO	8	$C_{10}H_3F_{17}$
10:2FTO	10:2fluorotelomerolefin	30389-25-4	Flurotelomer/FTO	10	$C_{12}H_3F_{21}$
12:2FTO	12:2fluorotelomerolefin	67103-05-3	Flurotelomer/FTO	12	$C_{14}H_3F_{25}$
4:2FTOH	4:2Fluorotelomeralcohol	2043-47-2	Flurotelomer/FTOH	4	$C_6H_5F_9O$
6:2FTOH	6:2Fluorotelomeralcohol	647-42-7	Flurotelomer/FTOH	6	$C_8H_5F_{13}O$
7:2sFTOH	7:2Secondaryfluorotelomeralcohol	24015-83-6	Flurotelomer/FTOH	7	$C_9H_5F_{15}O$
8:2FTOH	8:2Fluorotelomeralcohol	678-39-7	Flurotelomer/FTOH	8	$C_{10}H_5F_{17}O$
10:2FTOH	10:2Fluorotelomeralcohol	865-86-1	Flurotelomer/FTOH	10	$C_{12}H_5F_{21}O$
12:2FTOH	12:2Fluorotelomeralcohol	39239-77-5	Flurotelomer/FTOH	12	$C_{14}H_5F_{25}O$
14:2FTOH	14:2Fluorotelomeralcohol	60699-51-6	Flurotelomer/FTOH	14	$C_{16}H_5F_{29}O$
16:2FTOH	16:2Fluorotelomeralcohol	65104-67-8	Flurotelomer/FTOH	16	$C_{18}H_5F_{33}O$
18:2FTOH	18:2Fluorotelomeralcohol	65104-65-6	Flurotelomer/FTOH	18	$C_{20}H_5F_{37}O$
4:2FTS	4:2Fluorotelomersulfonate	757124-72-4	Flurotelomer/FTSA	4	$C_6H_5F_9O_3S$
6:2FTS	6:2Fluorotelomersulfonate	27619-97-2	Flurotelomer/FTSA	6	$C_8H_5F_{13}O_3S$
8:2FTS	8:2Fluorotelomersulfonate	39108-34-4	Flurotelomer/FTSA	8	$C_{10}H_5F_{17}O_3S$
10:2FTS	10:2Fluorotelomersulfonate	120226-60-0	Flurotelomer/FTSA	10	$C_{12}H_5F_{21}O_3S$
12:2FTS	12:2Fluorotelomersulfonate	149246-64-0	Flurotelomer/FTSA	12	$C_{14}H_5F_{25}O_3S$
14:2FTS	14:2Fluorotelomersulfonate	1377603-17-2	Flurotelomer/FTSA	14	$C_{16}H_5F_{29}O_3S$
6:2FTSaAm	6:2fluorotelomersulfonamidoamine	-	Flurotelomer/FTSaAm	6	$C_{19}H_{17}F_{25}O_2N_2S$
8:2FTSaAm	8:2fluorotelomersulfonamidoamine	-	Flurotelomer/FTSaAm	8	$C_{21}H_{17}F_{29}O_2N_2S$
4:2FTAoS	4:2fluorotelomerthioetheramidosulfonate	-	Flurotelomer/FTAoS	4	$C_{10}H_{14}F_7NO_2$
6:2FTAoS	6:2fluorotelomerthioetheramidosulfonate	171184-14-8	Flurotelomer/FTAoS	6	$C_{12}H_{14}F_{11}NO_2$
8:2FTAoS	8:2fluorotelomerthioetheramidosulfonate	171184-15-9	Flurotelomer/FTAoS	8	$C_{14}H_{14}F_{15}NO_2$
4:2FTSAB	4:2fluorotelomersulfonamidealkylbetaine	34455-27-1	Flurotelomer/FTSAB	4	$C_{13}H_{19}F_9N_2O_4S$
6:2FTSAB	6:2fluorotelomersulfonamidealkylbetaine	34455-29-3	Flurotelomer/FTSAB	6	$C_{15}H_{19}F_{13}N_2O_4S$
8:2FTSAB	8:2fluorotelomersulfonamidealkylbetaine	34455-21-5	Flurotelomer/FTSAB	8	$C_{17}H_{19}F_{17}N_2O_4S$
10:2FTSAB	10:2fluorotelomersulfonamidealkylbetain	34455-35-1	Flurotelomer/FTSAB	10	$C_{19}H_{19}F_{21}N_2O_4S$
12:2FTSAB	20:2fluorotelomersulfonamidealkylbetain	278598-45-1	Flurotelomer/FTSAB	12	$C_{21}H_{19}F_{25}N_2O_4S$
6:2FtTHN	2-hydroxy-N,N,N-trimethyl-3-[(-tridecafluorooctyl)thio]propan-1-aminiumchloride	88992-46-5	Flurotelomer/other	6	$C_{14}H_{19}F_{13}NOS+$
FBSA	Perfluorobutanesulfonamide	30334-69-1	Sulfonamide/PSA	4	$C_4H_2F_9NO_2S$
MeFBSA	n-Methylperfluorobutanesulfonamide	68298-12-4	Sulfonamide/PSA	4	$C_5H_4F_9NO_2S$
FHxSA	perfluorohexanesulfonamide	41997-13-1	Sulfonamide/PSA	6	$C_6H_2F_{13}NO_2S$
FOSA	Perfluorooctanesulfonamide	754-91-6	Sulfonamide/PSA	8	$C_8H_2F_{17}NO_2S$
MeFOSA	n-Methylperfluorooctanesulfonamide	31506-32-8	Sulfonamide/PSA	8	$C_9H_4F_{17}NO_2S$
FBSE	2-(Perfluorobutanesulfonamido)ethanol	34454-99-4	Sulfonamide/PSE	4	$C_6H_6F_9NO_3S$
EtFOSA	n-Ethylperfluorooctanesulfonamide	4151-50-2	Sulfonamide/PSE	8	$C_{10}H_6F_{17}NO_2S$
MeFBSE	n-Methylperfluorobutanesulfonamideethanol	34454-97-2	Sulfonamide/PSE	4	$C_7H_8F_9NO_3S$
EtFBSE	n-Ethylperfluorobutanesulfonamideethanol	34449-89-3	Sulfonamide/PSE	4	$C_8H_{10}F_9NO_3S$
MeFOSE	n-Methylperfluorooctanesulfonamideethanol	24448-09-7	Sulfonamide/PSE	8	$C_{11}H_8F_{17}NO_3S$
EtFOSE	n-Ethylperfluorooctanesulfonamideethanol	1691-99-2	Sulfonamide/PSE	8	$C_{12}H_{10}F_{17}NO_3S$
FBSAA	Perfluorobutanesulfon-amidoaceticacid	347872-22-4	Sulfonamide/PSAA	4	$C_6H_4F_9NO_4S$
FPeSAA	Perfluoropentanesulfonamidoaceticacid	647-43-8	Sulfonamide/PSAA	5	$C_7H_4F_{11}NO_4S$
FHxSAA	Perfluorohexanesulfonamidoaceticacid	1003193-99-4	Sulfonamide/PSAA	6	$C_8H_4F_{13}NO_4S$
FHpSAA	Perfluoroheptanesulfonamidoaceticacid	1003194-00-0	Sulfonamide/PSAA	7	$C_9H_4F_{15}NO_4S$
FOSAA	perfluorooctanesulfonamideaceticacid	2806-24-8	Sulfonamide/PSAA	8	$C_{10}H_4F_{17}NO_4S$
MeFPeSAA	Methylperfluoropentanesulfonamidoaceticacid	1003194-04-4	Sulfonamide/PSAA	5	$C_8H_6F_{11}NO_4S$
MeFHxSAA	Methylperfluorohexanesulfonamidoaceticacid	715646-50-7	Sulfonamide/PSAA	6	$C_9H_6F_{13}NO_4S$
MeFHpSAA	Methylperfluoroheptanesulfonamidoaceticacid	1910057-77-0	Sulfonamide/PSAA	7	$C_{10}H_6F_{15}NO_4S$
MeFOSAA	n-Methylperfluorooctanesulfonamideaceticacid	2355-31-9	Sulfonamide/PSAA	8	$\underline{C_{11}H_6F_{17}NO_4S}$
EtFBSAA	Ethylperfluorobutanesulfonamidoaceticacid	68957-33-5	Sulfonamide/PSAA	4	$C_8H_8F_9NO_4S$
EtFPeSAA	Ethylperfluoropentanesulfonamidoaceticacid	68957-31-3	Sulfonamide/PSAA	5	$C_9H_8F_{11}NO_4S$
EtFHxSAA	Ethylperfluorohexanesulfonamidoaceticacid	68957-32-4	Sulfonamide/PSAA	6	$C_{10}H_8F_{13}NO_4S$
EtFHpSAA	Ethylperfluoroheptanesulfonamidoaceticacid	68957-63-1	Sulfonamide/PSAA	7	$C_{11}H_8F_{15}NO_4S$
EtFOSAA	n-Ethylperfluorooctanesulfonamideaceticacid	2991-50-6	Sulfonamide/PSAA	8	$C_{12}H_8F_{17}NO_4S$
MeFPrSAA	N-methylperfluoropropanesulfonamidoaceticacid	-	Sulfonamide/PSAA	3	$C_6H_6F_7O_4NS$
MeFBSAA	N-methylperfluorobutanesulfonamidoacetate	159381-10-9	Sulfonamide/PSAA	4	$C_7H_6F_9O_4NS$
N-AP-FHxSA	N-(3-(dimethylaminopropan-1-yl)perfluoro-1-hexanesulfonamide	50598-28-2	Sulfonamide/PSAA	6	$C_{11}H_{13}F_{13}N_2O_2S$
PFBSAm	N-(3-(dimethylamino)propyl)-nonafluorobutane-1-sulfonamide	68555-77-1	Sulfonamide/PSAm	4	$C_9H_{13}F_9N_2O_2S$
PFPeSAm	N-(3-(dimethylamino)propyl)-undecafluoropentane-1-sulfonamide	68555-78-2	Sulfonamide/PSAm	5	$C_{10}H_{13}F_{11}N_2O_2S$
PFHxSAm	N-(3-(dimethylamino)propyl)-tridecafluorohexane-1-sulfonamide	50598-28-2	Sulfonamide/PSAm	6	$C_{11}H_{13}F_{13}N_2O_2S$
PFHpSAm	N-(3-(dimethylamino)propyl)-pentadecafluoroheptane-1-sulfonamide	67584-54-7	Sulfonamide/PSAm	7	$C_{12}H_{13}F_{15}N_2O_2S$
PFOSAm	N-(3-(dimethylamino)propyl)-heptadecafluorooctane-1-sulfonamide	13417-01-1	Sulfonamide/PSAm	8	$C_{13}H_{13}F_{17}N_2O_2S$
PFBSAmA	3-(N-(3-(dimethylamino)propyl)-perfluorobutylsulfonamido)propanoicacid	-	Sulfonamide/PSAmA	4	$C_{10}H_{13}F_9O_4N_2S$
PFPeSAmA	3-(N-(3-(dimethylamino)propyl)-perfluoropentylsulfonamido)propanoicacid	-	Sulfonamide/PSAmA	5	$C_{11}H_{13}F_{11}O_4N_2S$
PFHxSAmA	3-(N-(3-(dimethylamino)propyl)-perfluorohexylsulfonamido)propanoicacid	-	Sulfonamide/PSAmA	6	$C_{12}H_{13}F_{13}O_4N_2S$
PFHpSAmA	3-(N-(3-(dimethylamino)propyl)-perfluorohepylsulfonamido)propanoicacid	-	Sulfonamide/PSAmA	7	$C_{13}H_{13}F_{15}O_4N_2S$
PFOSAmA	3-(N-(3-(dimethylamino)propyl)-perfluorooctylsulfonamido)propanoicacid	-	Sulfonamide/PSAmA	8	$C_{14}H_{13}F_{17}O_4N_2S$

Extended Data Table 1 (continued) | Summary of all PFAS identified in this study

6:2monoPAP	6:2Fluorotelomerphosphatemonoester	57678-01-0	PAPs	6	$C_8H_6F_{13}O_4P$
8:2monoPAP	8:2Fluorotelomerphosphatemonoester	57678-03-2	PAPs	8	$C_{10}H_6F_{17}O_4P$
4:2diPAP	4:2Polyfluoroalkylphosphoricaciddiesters	135098-69-0	PAPs	4	$C_{12}H_9F_{18}O_4P$
4:2/6:2diPAP	4:2/6:2Polyfluoroalkylphosphoricaciddiesters	-	PAPs	6	$C_{14}H_9F_{30}O_4P$
6:2diPAP	6:2Polyfluoroalkylphosphoricaciddiesters	57677-95-9	PAPs	6	$C_{16}H_9F_{26}O_4P$
6:2/8:2diPAP	6:2/8:2Polyfluoroalkylphosphoricaciddiesters	943913-15-3	PAPs	8	$C_{18}H_9F_{30}O_4P$
6:2/10:2diPAP	6:2/10:2Polyfluoroalkylphosphoricaciddiesters	-	PAPs	10	$C_{20}H_9F_{34}O_4P$
6:2/12:2diPAP	6:2/12:2Polyfluoroalkylphosphoricaciddiesters	68412-69-1	PAPs	12	$C_{22}H_9F_{38}O_4P$
6:2/14:2diPAP	6:2/14:2Ppolyfluoroalkylphosphoricaciddiesters	-	PAPs	14	$C_{24}H_9F_{42}O_4P$
8:2diPAP	8:2Polyfluoroalkylphosphoricaciddiesters	678-41-1	PAPs	8	$C_{20}H_9F_{34}O_4P$
8:2/10:2diPAP	8:2/10:2Polyfluoroalkylphosphoricaciddiesters	1158182-60-5	PAPs	10	$C_{22}H_9F_{38}O_4P$
8:2/12:2diPAP	8:2/12:2Polyfluoroalkylphosphoricaciddiesters	-	PAPs	12	$C_{24}H_9F_{42}O_4P$
10:2diPAP	10:2Polyfluoroalkylphosphoricaciddiesters	1895-26-7	PAPs	10	$C_{24}H_9F_{42}O_4P$
SAmPAP	Bis(2-{ethyl[(perfluorooctyl)sulfonyl]amino}ethyl)hydrogenphosphate	2965-52-8	PAPs	8	$C_{24}H_{19}F_{34}N_2O_8PS_2$
diSAmPAP	perfluorooctanesulfonamidoethanol-basedphosphateester	30381-98-7	PAPs	8	$C_{24}H_{22}F_{34}N_3O_8PS_2$
OBS	perfluorousnonenoxybenzenesulfonate	70829-87-7	NovelPFAS/etherPFAS	3	$C_{15}H_4F_{17}O_4SNa$
4:2Cl-PFESA	4:2Chlorinatedpolyfluoroalkylethersulfonate	-	NovelPFAS/etherPFAS	4	$C_6HClF_{12}O_4S$
6:2Cl-PFESA	6:2Chlorinatedpolyfluoroalkylethersulfonate;F-53B;9-Cl-PF3ONS	73606-19-6	NovelPFAS/etherPFAS	6	$C_8HClF_{16}O_4S$
8:2Cl-PFESA	8:2Chlorinatedpolyfluoroalkylethersulfonate; 11-Cl-PF3OUdS	763051-92-9	NovelPFAS/etherPFAS	8	$C_{10}HClF_{20}O_4S$
10:2Cl-PFESA	10:2Chlorinatedpolyfluoroalkylethersulfonate	-	NovelPFAS/etherPFAS	10	$C_{12}HClF_{24}O_4S$
8Cl-PFOS	Sodium8-chloroperfluoro-1-octanesulfonate	2481740-05-8	NovelPFAS/etherPFAS	8	$C_8HClF_{16}O_3S$
Cl-PFECA(1;0)	7-Cl-dodecafluoro-3,5-dioxadodecanoate	-	NovelPFAS/etherPFAS	3	$C_7ClF_{12}O_4$
Cl-PFECA(0;1)	8-Cl-tetradecafluoro-3,6-dioxanonanoate	-	NovelPFAS/etherPFAS	3	$C_8ClF_{14}O_4$
Cl-PFECA(2;0)	9-Cl-hexadecafluoro-3,5,7-trioxadodecanoate	-	NovelPFAS/etherPFAS	3	$C_9ClF_{16}O_5$
Cl-PFECA(1;1)	10-Cl-dodecafluoro-3,6,8-trioxaundecanoate	-	NovelPFAS/etherPFAS	3	$C_{10}ClF_{18}O_5$
Cl-PFECA(0;2)	11-Cl-eicosanfluoro-3,6,9-trioxapentadecanoate	-	NovelPFAS/etherPFAS	3	$C_{11}ClF_{20}O_5$
Cl-PFECA(3;0)	11-Cl-eicosanfluoro-3,5,7,9-tetraoxadodecanoate	-	NovelPFAS/etherPFAS	3	$C_{11}ClF_{20}O_6$
Cl-PFECA(2;1)	12-Cl-docosanfluoro-3,6,8,10-tetraoxatridecanoate	-	NovelPFAS/etherPFAS	3	$C_{12}ClF_{22}O_6$
Cl-PFECA(1;2)	13-Cl-tetracosanfluoro-3,6,8,11-tetraoxatetradecanoate	-	NovelPFAS/etherPFAS	3	$C_{13}ClF_{24}O_6$
Cl-PFECA(4;0)	13-Cl-tetracosanfluoro-3,5,7,9,11-pentaoxadodecanoate	-	NovelPFAS/etherPFAS	3	$C_{13}ClF_{24}O_7$
Cl-PFECA(0;3)	14-Cl-hexacosanfluoro-3,6,9,12-tetraoxapentadecanoate	-	NovelPFAS/etherPFAS	3	$C_{14}ClF_{26}O_6$
GenX/HFPO-DA	2,3,3,3-Tetrafluoro-2-(heptafluoropropoxy)-propanoicacid	13252-13-6	NovelPFAS/etherPFAS	3	$C_6HF_{11}O_3$
HFPO-TA	Hexafluoropropyleneoxidetrimeracid	13252-14-7	NovelPFAS/etherPFAS	3	$C_9HF_{17}O_4$
HFPO-TeA	hexafluoropropyleneoxidetetrameracid	51445-02-4	NovelPFAS/etherPFAS	3	$C_{12}H_2F_{23}NO_4$
PFMOAA	Perfluoro-2-methoxyaceticacid	674-13-5	NovelPFAS/etherPFAS	1	$C_3HF_5O_3$
PFO2HxA	Perfluoro-(3,5-dioxahexanoic)acid,	39492-88-1	NovelPFAS/etherPFAS	1	$C_4HF_7O_4$
PFMOPrA	Perfluoro-3-methoxy-propanoicacid	377-73-1	NovelPFAS/etherPFAS	2	$C_4HF_7O_3$
PFO3OA	Perfluoro-(3,5,7-trioxaoctanoic)acid	39492-89-2	NovelPFAS/etherPFAS	1	$C_5HF_9O_5$
PFO4DA	Perfluoro-(3,5,7,9-tetraoxadecanoic)acid	39492-90-5	NovelPFAS/etherPFAS	1	$C_6HF_{11}O_6$
PFO5DoDA	Perfluoro-3,5,7,9,11-pentaoxadodecanoicacid	39492-91-6	NovelPFAS/etherPFAS	1	$C_7HF_{13}O_7$
PFMOBA	Perfluoro-4-methoxy-butanicacid	863090-89-5	NovelPFAS/etherPFAS	3	$C_5HF_9O_3$
NfBP1	NafionByproduct1,C7HF13SO5	29311-67-9	NovelPFAS/etherPFAS	3	$C_7HF_{13}O_5S$
NfBP2	NafionByproduct2,C7H2F14SO5	749836-20-2	NovelPFAS/etherPFAS	3	$C_7H_2F_{14}O_5S$
ADONA	dodecafluoro-3H-48-dioxanonanoate	958445-44-8	NovelPFAS/etherPFAS	3	$C_7H_5F_{12}NO_4$
PFECHS	Perfluoroethylenecyclohexanesulfonate	67584-42-3	NovelPFAS/cylcicPFAS	6	$C_8F_{15}KO_3S$
PFEtCHxS	Perfluoro-4-ethylcyclohexanesulfonicacid	335-24-0	NovelPFAS/cylcicPFAS	6	$C_8H_2F_{15}KO_3S$
7H-PFHpA	7H-Perfluoroheptanoicacid	1546-95-8	NovelPFAS/modifiedPFCA	6	$C_7H_2F_{12}O_2$
BTFBB	1,3-Bis(trifluoromethyl)-5-bromo-benzene	328-70-1	NovelPFAS/cylcicPFAS	6	$C_8H_3BrF_6$
1:2H-PFESA	hexafluoro-4H-3-oxabutasulfonate	-	NovelPFAS/etherPFAS	2	$C_3HF_6O_2S$
2:2H-PFESA	octafluoro-5H-3-oxapentasulfonate	-	NovelPFAS/etherPFAS	2	$C_4HF_8O_2S$
3:2H-PFESA	decafluoro-6H-3-oxahexasulfonate	-	NovelPFAS/etherPFAS	3	$C_5HF_{10}O_2S$
4:2H-PFESA	dodecafluoro-7H-3-oxaheptasulfonate	-	NovelPFAS/etherPFAS	4	$C_6HF_{12}O_2S$
6:2H-PFESA	hexadecafluoro-9H-3-oxanonasulfonate	-	NovelPFAS/etherPFAS	6	$C_8HF_{16}O_2S$
PFDI	Perfluorodecyliodide	423-62-1	Perfluoroiodides	10	$C_{10}F_{21}I$
PFDoI	Perfluorododecyliodide	307-60-8	Perfluoroiodides	12	$C_{12}F_{25}I$
PFBuDiI	Octafluoro-1,4-diiodobutane	375-50-8	Perfluoroiodides	4	$C_4F_8I_2$
PFHxDiI	Dodecafluoro-1,6-diiodohexane	375-80-4	Perfluoroiodides	6	$C_6F_{12}I_2$
PFoDiI	Hexadecafluoro-1,8-diioctane	335-70-6	Perfluoroiodides	8	$C_8F_{16}I_2$
PFHxPA	Perfluorohexylphosphonicacid	40143-76-8	Phosphonic/phinic acids	6	$C_6H_2F_{13}O_3P$
PFOPA	Perfluorooctylphosphonicacid	40143-78-0	Phosphonic/phinic acids	8	$C_8H_2F_{17}O_3P$
PFDPA	Perfluorodecylphosphonicacid	52299-26-0	Phosphonic/phinic acids	10	$C_{10}H_2F_{21}O_3P$
C4C4-PFPiA	C4/C4Perfluoroalkylphosphinicacid;bis(nonafluorobutyl)phosphinicacid	52299-25-9	Phosphonic/phinic acids	4	$C_8HF_{18}O_2P$
C6C6-PFPiA	C6/C6Perfluoroalkylphosphinicacid;bis(perfluorohexyl)phosphinicacid	40143-77-9	Phosphonic/phinic acids	6	$C_{12}HF_{26}O_2P$
C6C8-PFPiA	C6-C8Perfluoroalkylphosphinicacid;perfluorohexylperfluorooctylphosphinicacid	610800-34-5	Phosphonic/phinic acids	8	$C_{14}HF_{30}O_2P$
C8C8-PFPiA	C8/C8Perfluoroalkylphosphinicacid;bis(heptadecafluorooctyl)phosphinicacid	40143-79-1	Phosphonic/phinic acids	8	$C_{16}HF_{34}O_2P$
Cl-PFHxPA	6-Chloroperfluorohexylphosphonicacid	-	Phosphonic/phinic acids	6	$C_6H_2ClF_{12}O_3P$
Cl-PFOPA	8-Chloroperfluorooctylphosphonicacid	2252239-09-9	Phosphonic/phinic acids	8	$C_8H_2ClF_{16}O_3P$

Summary of all PFAS identified in this study. Most of the novel PFAS considered are classified as single H- or Cl- substituted perfluoroalkyl carboxylic acids and perfluorosulfonic acids, or per and poly-fluoro-ether acids.

Extended Data Table 2 | Table of PFAS present in this study incorporated in methods or regulations



EPA 533	EPA 537.1	EPA 8327	EPA 1633	EPA OMT-45	20 EU	US Hazard	Stockholm + Candidates*
PFBA	PFOA	PFHxA	PFBA	PFBA	PFBA	PFBS	PFOA
PFPeA	PFNA	PFHpA	PFPeA	PFPeA	PFPeA	PFHxS	PFNA*
PFHxA	PFDA	PFOA	PFHxA	PFHxA	PFHxA	PFNAS	PFDA*
PFHpA	PFUnDA	PFNA	PFHpA	PFHpA	PFHpA	GenX	PFUnDA*
PFOA	PFDoDA	PFDA	PFOA	PFOA	PFOA		PFDoDA*
PFNA	PFTrDA	PFUnDA	PFNA	PFNA	PFNA		PFTrDA*
PFDA	PFTeDA	PFDoDA	PFDA	PFDA	PFDA		PFTeDA*
PFUnDA	PFBS	PFTrDA	PFUnDA	PFUnDA	PFUnDA		PFPeDA*
PFDoDA	PFPeS	PFTeDA	PFDoDA	PFDoDA	PFDoDA		PFHxDA*
PFBS	PFHxS	PFBS	PFTrDA	PFTrDA	PFTrDA		PFHpDA*
PFPeS	PFOS	PFPeS	PFTeDA	PFTeDA	PFBS		PFOcDA*
PFHxS	PFDS	PFHxS	PFBS	PFHxDA	PFPeS		PFNDA*
PFHpS	MeFOSAA	PFHpS	PFPeS	PFOcDA	PFHxS		PFCoA*
PFOS	EtFOSAA	PFOS	PFHxS	PFBS	PFHpS		PFHCoA*
4:2FTS	GenX	PFNS	PFHpS	PFPeS	PFOS		PFDoCoA*
6:2FTS	PFMOPrA	PFDS	PFOS	PFHxS	PFDS		PFTRrCoA*
8:2FTS	ADONA	PFDoDS	PFNS	PFHpS	PFDoDS		PFTeCoA*
6:2Cl-PFESA		3:3FTCA	PFDS	PFOS			PFPeCoA*
8:2Cl-PFESA		5:3FTCA	PFDoDS	PFNS			PFHxS
GenX		4:2FTS	3:3FTCA	PFDS			PFOS
PFMOPrA		8:2FTS	5:3FTCA	PFDoDS			
PFMOBA		FOSA	7:3FTCA	6:2FTCA			
ADONA		MeFOSAA	4:2FTS	8:2FTCA			
		EtFOSAA	6:2FTS	3:3FTCA			
			8:2FTS	5:3FTCA			
			FOSA	7:3FTCA			
			MeFOSA	6:2FTUCA			
			MeFOSE	8:2FTUCA			
			EtFOSE	4:2FTS			
			MeFOSAA	6:2FTS			
			EtFOSAA	8:2FTS			
			6:2Cl-PFESA	10:2FTS			
			8:2Cl-PFESA	FOSA			
			GenX	MeFOSA			
			PFMOPrA	EtFOSA			
			PFMOBA	MeFOSE			
			ADONA	EtFOSE			
				MeFOSAA			
				EtFOSAA			
				6:2Cl-PFESA			
				8:2Cl-PFESA			
				GenX			
				PFMOPrA			
				PFMOBA			
				ADONA			
				PFECHS			

Table of PFAS present in this study incorporated in methods or regulations.

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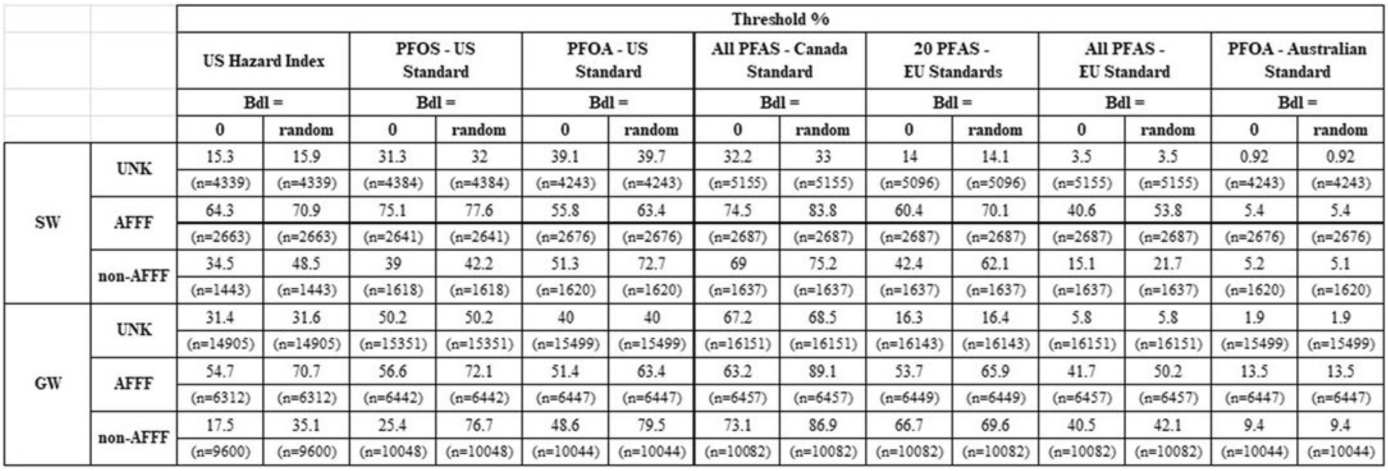
Extended Data Table 3 | Threshold percent based on cumulative distribution of surface and groundwater samples from an unknown or known AFFF or non-AFFF source that exceeds a given PFAS concentration



		Threshold %													
		US Hazard Index		PFOS - US Standard		PFOA - US Standard		All PFAS - Canada Standard		20 PFAS - EU Standards		All PFAS - EU Standard		PFOA - Australian Standard	
		Bdl =		Bdl =		Bdl =		Bdl =		Bdl =		Bdl =		Bdl =	
		0	random	0	random	0	random	0	random	0	random	0	random	0	random
SW	UNK	15.3	15.9	31.3	32	39.1	39.7	32.2	33	14	14.1	3.5	3.5	0.92	0.92
		(n=4339)	(n=4339)	(n=4384)	(n=4384)	(n=4243)	(n=4243)	(n=5155)	(n=5155)	(n=5096)	(n=5096)	(n=5155)	(n=5155)	(n=4243)	(n=4243)
	AFFF	64.3	70.9	75.1	77.6	55.8	63.4	74.5	83.8	60.4	70.1	40.6	53.8	5.4	5.4
		(n=2663)	(n=2663)	(n=2641)	(n=2641)	(n=2676)	(n=2676)	(n=2687)	(n=2687)	(n=2687)	(n=2687)	(n=2687)	(n=2687)	(n=2676)	(n=2676)
	non-AFFF	34.5	48.5	39	42.2	51.3	72.7	69	75.2	42.4	62.1	15.1	21.7	5.2	5.1
		(n=1443)	(n=1443)	(n=1618)	(n=1618)	(n=1620)	(n=1620)	(n=1637)	(n=1637)	(n=1637)	(n=1637)	(n=1637)	(n=1637)	(n=1620)	(n=1620)
GW	UNK	31.4	31.6	50.2	50.2	40	40	67.2	68.5	16.3	16.4	5.8	5.8	1.9	1.9
		(n=14905)	(n=14905)	(n=15351)	(n=15351)	(n=15499)	(n=15499)	(n=16151)	(n=16151)	(n=16143)	(n=16143)	(n=16151)	(n=16151)	(n=15499)	(n=15499)
	AFFF	54.7	70.7	56.6	72.1	51.4	63.4	63.2	89.1	53.7	65.9	41.7	50.2	13.5	13.5
		(n=6312)	(n=6312)	(n=6442)	(n=6442)	(n=6447)	(n=6447)	(n=6457)	(n=6457)	(n=6449)	(n=6449)	(n=6457)	(n=6457)	(n=6447)	(n=6447)
	non-AFFF	17.5	35.1	25.4	76.7	48.6	79.5	73.1	86.9	66.7	69.6	40.5	42.1	9.4	9.4
		(n=9600)	(n=9600)	(n=10048)	(n=10048)	(n=10044)	(n=10044)	(n=10082)	(n=10082)	(n=10082)	(n=10082)	(n=10082)	(n=10082)	(n=10044)	(n=10044)

Threshold percent based on cumulative distribution of surface and groundwater samples from an unknown or known AFFF or non-AFFF source that exceeds a given PFAS concentration. For samples where PFAS concentrations were below detection limits (BDL), a PFAS concentration was set to zero or a random value between zero and the detection limit. n represents the number of samples. For both SW and GW samples with no known PFAS source, the incidence of threshold exceedance changed little (< 1.3% for all criteria). For samples with a known source, the incidence of threshold exceedance decreased, with the greatest decrease for groundwater with an AFFF source using Health Canada's 30 ng/L sum of all PFAS criteria (from 89% to 63%).