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The determination of two emerging perfluoroalkyl substances and related halogenated sulfonic acids and their significance for the drinking water supply chain†

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In the present study analytical methodologies were developed for two newly emerging polar perfluorinated alkyl substances (PFAS), namely F_3-MSA, and HFPO-DA, in order to assess the occurrence and levels of these PFAS in Dutch and Belgian waters. Two separate methods were needed for analysing F_3-MSA and HFPO-DA. A mixed-mode and a reversed phase C18 method were developed for F_3-MSA and HFPO-DA, respectively, using a high resolution Orbitrap Fusion mass spectrometer for detection, yielding satisfactory LOD and LOQ results for both analytes. A sample campaign was performed collecting single grab samples from various locations and different stages of the drinking water production chain. Whereas both PFAS were absent in groundwaters, they were found to be present in surface waters, river bank and dune infiltrates, process water, and drinking water, demonstrating the persistence and mobility of both compounds. Based on provisional health-based guideline values (0.15 μg L^{-1} for HFPO-DA, 11.9 mg L^{-1} for F_3-MSA), the current levels in drinking water from the suppliers involved in this study do not pose a health risk for the human population. Common removal processes used in drinking water production appeared to remove these polar compounds at most partially. At locations close to potential sources of these chemicals (*e.g.* fluoropolymer production sites), the quality of surface water or river bank filtrate abstracted for production of drinking water must therefore be monitored.

Environmental significance statement

The present study demonstrates the presence of two new perfluorinated substances in source waters and drinking water. These substances are highly mobile, and the present work shows that they can easily cross both natural and technological barriers typically used in drinking water production, such as river banks, disinfection and active carbon filtration. One of the products, HFPO-DA is used as a substitute for a recently regulated perfluorinated substance (PFOA), while the other, F_3-MSA, is a catalyst in the production of hydrophobic polymers, which was recently discovered in the aquatic environment. Without further control, the emissions of both substances into the environment are expected to increase.

Introduction

Perfluoroalkyl substances (PFAS) have recently gained interest from drinking water suppliers. In particular perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) are notorious because of the multitude of data demonstrating their persistence in the environment and their occurrence in sources of drinking water.[1,2] PFOA and PFOS are poorly removed in the drinking water production chain by conventional purification processes[3] but can be removed with active carbon filtration[3] or by reverse osmosis.[4] Major producers in Europe and the United States have already reduced production and emissions of PFOA and PFOS either on a voluntary basis or by regulation and, as a consequence, have implemented short-chain or alternative PFAS.[5,6] In some countries (*e.g.* China) PFOS and PFOA continue to be produced.[7] For some of the short-chain perfluoro alkanoic and alkyl sulfonic acids such as PFBA (PF butanoic acid) and PFBS (PF butane sulfonic acid) removal by active carbon is less efficient and incomplete.[3] Recent studies have shown that substitutes of PFOA, including fluorinated ether heptafluoro propoxypropanoic acid (HFPO-DA, also known as FRD-903), which is one of the constituents of GenX (see Table SI-1†) have been observed in locations where PFOA has previously been reported to be present, among others in surface waters collected in the river Rhine delta,[8–11] in a fluoro impacted river in the USA[12] and in Chinese rivers.[13]

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HFPO-DA is a polar persistent compound with an estimated log *D* value of 1.34 (at pH 7.4, see Table SI-1†), an aqueous solubility of 7.1 g L^{-1} [14] to infinite[15] and a half-life in water of more than 1 y.[16] According to REACH dossiers[17] HFPO-DA is produced annually in volumes between 10 and 100 tons. HFPO-DA (FRD-903) is used to manufacture the ammonium salt FRD-902, which is applied as a processing aid in the production of fluoropolymers. This manufacturing process is referred to as the GenX technology. In 2016 in river water downstream of a production location in The Netherlands, HFPO-DA was observed in concentrations up to 800 ng L^{-1}.[9] In the same study drinking water samples from different locations in The Netherlands were analysed and a maximum concentration of 11 ng L^{-1} was reported.[9] In 2017, in a collaborative study by the Dutch water suppliers, HFPO-DA was found in drinking water prepared from river bank filtrate originating from the river Beneden-Merwede near the same production location, and levels amounted up to 30 ng L^{-1}.[10]

Trifluoromethane sulfonic acid (F_3-MSA see Table SI-1†), also known as triflic acid, is another relatively poorly known PFAS that has been observed recently in the aquatic environment at several locations in Europe. F_3-MSA is a member of the group of highly persistent halogenated methane sulfonic acids that have been reported to occur in groundwater, surface waters and drinking water.[18] F_3-MSA is an effective oligomerisation/polymerisation catalyst. It is one of the strongest acids known, is thermally stable, does not release fluoride in the presence of strong nucleophiles, and resists both oxidation and reduction. It has been used for the synthesis of highly hydrophobic polymers[19] and in liquid crystals and batteries.[20]

F_3-MSA is registered under REACH with an annual production volume of more than 100 tons. It is a highly persistent compound with an estimated log *D* value of −3.88 (see Table SI-1†). In European groundwater and surface waters levels over 1 μg L^{-1} have been reported, and concentrations of F_3-MSA in drinking water between 10 and 1000 ng L^{-1} have been observed.[18] Other halogenated MSAs (HMSAs) have also recently been encountered in several types of water.[21]

The polarity and persistence of HFPO-DA and F_3-MSA and the findings in aqueous environments mentioned above, together with the LOQ levels of ≤ 1 ng L^{-1} required for the reliable determination of expected low levels in tapwater, spurred the development and operationalisation of analytical methodologies for both substances. In addition, a sampling campaign was organised to assess the occurrence of the substances in relevant raw waters (including groundwater, surface waters and dune infiltrates, partly obtained from locations in the vicinity of a fluoropolymer manufacturing plant) and in corresponding drinking water, and to evaluate their removal efficiency in various drinking water treatment processes. Human toxicity data and (provisional) health-based drinking water guidelines were collected from the literature and databases to allow a toxicological evaluation of the campaign findings. The present study describes the methodologies developed, presents the results of the sampling campaign and summarises the toxicological information available.

Materials and methods

Several analytical methods can be found in the literature for F_3-MSA and other halogenated MSAs[18,22,23] on the one hand and HFPO-DA[8,9,24] on the other. These analytical methods were used as a basis for the method development reported here. One of the objectives for method development was to obtain sufficiently low LOQs (<1 ng L^{-1}) for F_3-MSA and HFPO-DA in drinking water, groundwater and surface waters, in order to detect relevant concentrations during the sampling campaign.

The following LC-columns were tested:

- Nucleodur HILIC, 2 × 150 mm, 1.8 μm (Macherey-Nagel, Duren, Germany)
- Dionex Acclaim Mixed-mode WAX-1, 2.1 × 150 mm, 3 μm (ThermoFisher, Ermelo, The Netherlands)
- Obelisc N, 2.1 × 150 mm, 5 μm (SIELC, Wheeling, IL, USA)
- Xbridge C18 XP, 2.1 × 150 mm, 2.5 μm (Waters, Etten-Leur, Netherlands)

Analytical conditions were optimised as part of the study and are described in the results section below. Details of the final methodologies used are provided in the ESI.†

Sampling

A sampling campaign for the determination of F_3-MSA and HFPO-DA was conducted in September 2017. A total of 53 grab samples (see Table SI-2†) were obtained from eleven water suppliers in The Netherlands and Belgium and included the following water types: drinking water (DW, $n = 22$), surface water (SW, $n = 13$), river bank filtrate (RBF, $n = 7$), groundwater (GW, $n = 5$) and process water (PW, $n = 6$). Furthermore, two drinking water treatment processes (reverse osmosis and UV/H_2O_2) were studied by analyzing samples collected at various stages of the process.

Instrumental analysis

For the detection of F_3-MSA and HFPO-DA a high resolution (HR) Orbitrap Fusion mass spectrometer (ThermoFisher) was used equipped with a heated ESI source. A high resolution Orbitrap was used for the quantification of F_3-MSA and HFPO-DA instead of a QqQ MS, due to the screening capabilities of this system, which also provided an excellent sensitivity compared to the available QqQ system. Two separate MS methods were developed for F_3-MSA and HFPO-DA, respectively, because of the two different liquid chromatography methods (see Results section). The method developed for F_3-MSA allows one to simultaneously monitor the presence of other MSAs and a suspect screening for HMSAs (see ESI†) was performed using the raw data files obtained by the HRMS instrument.

Sample pre-treatment

In order to achieve sufficiently low LOQs for F_3-MSA and HFPO-DA, optimised sample pre-treatment using solid phase extraction (SPE) is needed. Since both HFPO-DA and F_3-MSA are strong acids they can be extracted from water using weak anionic exchange (WAX) SPE cartridges.[8,9,18,24] A sample volume of 500 mL was loaded upon the cartridge and concentrated in order to achieve a sufficient concentration factor (500×) to reach the required LOQs. For desorbing HFPO-DA and F_3-MSA from the SPE cartridge, a final volume of 10 mL of methanol containing 0.25% ammonium hydroxide was used. The eluent was further concentrated using heated nitrogen until a volume of 250 μL was reached and was then reconstituted to 1 mL of ultrapure water : methanol 75 : 25 (v/v). In the end satisfactory recoveries for HFPO-DA and F_3-MSA were obtained with the optimised sample pre-treatment method (for details, see ESI†).

Quality assurance

The ESI† provides details about the method recoveries, compound stability and method validation (Tables SI-3–SI-5†). During the sample pre-treatment extra precautions were taken in order to avoid fluoropolymer materials, which can contain PFAS used as processing aids in the production of the polymer.[25] For sample handling only glass and high quality plastics such as polypropylene and nylon were used. Due to the nature of the sampling campaign, only single samples were obtained for each water type at each location.

Toxicological evaluation

Toxicological information and (provisional)health-based guideline values (GLVs) for drinking water were collected from the literature and risk assessment reports by the European Food Safety Authority (EFSA), European Chemicals Agency (ECHA), US Environmental Protection Agency (EPA), and the Dutch National Institute for Health and Environment (RIVM). Additional information was collected from toxicological databases (TOXNET), International Toxicity Estimates for Risk (ITER), International Programme on Chemical Safety (IPCS), and OECD eChemPortal. *In vitro* data and structural alerts were obtained from the ToxCast database (US-EPA) and OECD QSAR Toolbox v3.4.0.17, respectively. Provisional GLVs (pGLVs) were derived by applying default ECHA assessment factors to derive tolerable daily intake levels and using a default 20% allocation of the total exposure to drinking-water, an adult body weight of 70 kg and a standard drinking water consumption of 2 L per day.[26]

Results

LC method optimisation

Initially, efforts were targeted at optimising a single HPLC method that could detect both analytes despite the large difference in hydrophobicity between F_3-MSA and HFPO-DA (see Table SI-1†). Because F_3-MSA is highly polar, it is not possible to analyse this compound quantitatively using C18 reversed phase chromatography, due to a lack of retention. Both analytes are strong acids (see Table SI-1†), meaning that they are always negatively charged (*i.e.* independent of the actual pH of the waters sampled), which is a property that can be used for chromatographic separation. Consequently, for method development only analytical columns were considered which have anion exchange as primary or secondary interaction for chromatographic separation. To that end three different chromatographic columns were tested and included a Nucleodur HILIC, a Mixed mode WAX-1 and a zwitterionic Obelisc N column.

For the HILIC column, chromatographic conditions described by Zahn *et al.*[18] were used as starting conditions: 95% acetonitrile + 5 mM ammonium formate at pH 3.0. These resulted in almost unretained peaks. Other mobile phase conditions were also tested, including adjusting the ammonium formate concentration and starting percentage of acetonitrile, but no improvement in retention was obtained. Furthermore the column also showed severe column bleeding which resulted in a high background during mass spectrometry analysis. The Nucleodur HILIC column was thus found unsuitable for F_3-MSA or HFPO-DA analysis.

The Dionex Acclaim Mixed-mode WAX column consists of hydrophobic alkyl chains to which an ionisable terminus is attached that provides weak anion exchange properties, which should be suited for retaining both F_3-MSA and HFPO-DA. With low buffer concentrations (*i.e.* 5 mM ammonium acetate) both compounds were retained strongly, resulting in long retention times and broad peaks. When the buffer concentration was increased above 20 mM, reasonable retention was obtained, but unsatisfactory peak shape was observed for F_3-MSA. This column also showed substantial bleeding during analysis. The Dionex Acclaim Mixed-mode WAX column was thus found unsuitable for F_3-MSA or HFPO-DA analysis.

The third column that was tested was the SIELC Obelisc N column. Obelisc N is a zwitterionic column which has positively and negatively charged functional groups attached to hydrophobic alkyl chains. This column was tested extensively using different organic modifiers such as acetonitrile and methanol, varying ammonium acetate buffer concentrations and in both reversed phase and HILIC modes. The best results for F_3-MSA were obtained by using the column in reversed phase mode and using methanol as organic modifier with ammonium acetate as buffer and 0.05% formic acid. While the chromatographic retention and peak shape were sufficient for HFPO-DA under these conditions, the sensitivity decreased substantially (>10×) due to the presence of formic acid. When no formic acid was added, F_3-MSA could not be detected. The SIELC Obelisc N column was thus found unsuitable for simultaneous F_3-MSA or HFPO-DA analysis.

The findings from these experiments led to the decision that two separate methods were needed for analysing both F_3-MSA and HFPO-DA. The Obelisc N method was further optimised for F_3-MSA only, and a new method was developed for HFPO-DA using a C18 column.

Because no isotope-labeled internal standard was available of F_3-MSA, PFBA-$^{13}C_3$ was used as internal standard for quantification. The final mobile phase composition for mobile phase A was ultrapure water with 10 mM ammonium acetate plus 0.05 v/v% formic acid. Mobile phase B consisted of methanol with 10 mM ammonium acetate plus 0.05 v/v% formic acid. The applied gradient (0.3 mL min^{-1}) started at 20% B and increased to 90% B in 12 min, and was subsequently held at 90% B for 7 min, then returned to initial conditions in 1 min and was held for 6 min. These conditions led to satisfactory chromatographic separation and peak shape for both the analyte and the internal standard (see Fig. 1).

Most of the methods for the determination of HFPO-DA described in the literature deploy regular C18 columns with a mobile phase consisting of MeOH and an ammonium acetate buffer.[8,9,24] Therefore an XBridge BEH C18 XP column was chosen for method development using the aforementioned mobile phase. For method development different concentrations of ammonium acetate were tested, and an optimal concentration of 5 mM was determined. As internal standard the isotopically labeled HFPO-DA-$^{13}C_3$ was used. The final mobile phase composition consisted of solvent A (ultrapure water) and solvent B (methanol), both containing 5 mM ammonium acetate. The applied gradient (0.25 mL min^{-1}) started at 25% B and increased to 100% B in 10 min, then held at 100% B for 4 min followed by return to initial conditions in 0.5 min and held for 3.5 min. These conditions resulted in satisfactory chromatography as illustrated in Fig. 2.

HR-MS optimisation

For F_3-MSA little variability in sensitivity was observed during optimisation of the source parameters (*i.e.* gas and temperature settings). The acquisition method consisted of a full-scan with a scan range of 120–500 *m*/*z* in the negative ionisation mode at a resolution of 120 000 FWHM, which is used for the quantification of F_3-MSA and suspect screening. The quantification of F_3-MSA was performed on the accurate mass of deprotonated molecular ion (*m*/*z* 148.9526), with a mass accuracy of 5 ppm. For the unambiguous confirmation of F_3-MSA a MS/MS spectrum of product ion *m*/*z* 149.95 at a high collision dissociation energy (HCD) of 50%, was continuously recorded at a resolution of 15 000 FWHM.

Varying the source parameters led to substantial improvement in sensitivity in the case of HFPO-DA. By using low temperatures for the ion transfer tube (250 °C) and vaporizer temperature (200 °C), a fivefold increase in sensitivity was achieved. With the applied heated electrospray source considerable in-source fragmentation was observed in negative ionisation mode, causing a low intensity for the deprotonated molecular ion. Therefore the quantification of HFPO-DA was performed on a specific fragment $[C_5HOF_{11}–H]^-$detected at *m*/*z* 284.97790, with a mass accuracy of 5 ppm. The acquisition method consisted of a full-scan with a scan range of 150–500 *m*/*z* in the negative ionisation mode at a resolution of 120 000 FWHM, which is used for the quantification of HFPO-DA and suspect screening. For the unambiguous confirmation of HFPO-DA a MS/MS spectrum of product ion *m*/*z* 284.98 at a HCD of 30% was continuously recorded at a resolution of 15 000 FWHM.

For non-target screening purposes also data dependent MS/MS scans were triggered of the highest detected ions of each full scan cycle at a resolution of 15 000 FWHM. The final mass spectrometry settings for F_3-MSA and HFPO-DA are described in detail in the ESI.†

Sampling campaign

An overview of results of the sampling campaign for F_3-MSA, HFPO-DA in surface water, river bank/dune filtrate, groundwater and drinking water is presented in Table 1. All concentration data can be found in Table SI-6† and represent concentrations in single grab samples.

While HFPO-DA was not observed in groundwater samples, it was detected in 77% and 86% of the samples from surface waters and river bank/dune filtrate, respectively. HFPO-DA was also detected (≥0.2 ng L^{-1}) in 46% of the 22 drinking water samples collected. The average concentration of HFPO-DA in drinking water is relatively low (2.9 ng L^{-1}). Substantial concentrations (*i.e.* above 4 ng L^{-1}) of HFPO-DA were observed in drinking water from suppliers that abstract surface water and RBF in the vicinity of a production facility that uses HFPO-DA in the production process of perfluorinated polymers. The highest concentration of HFPO-DA was detected at Lekkerkerk-Tiendweg with a concentration of 59 ng L^{-1} in RBF and 28 ng L^{-1} in the corresponding drinking water. These values are

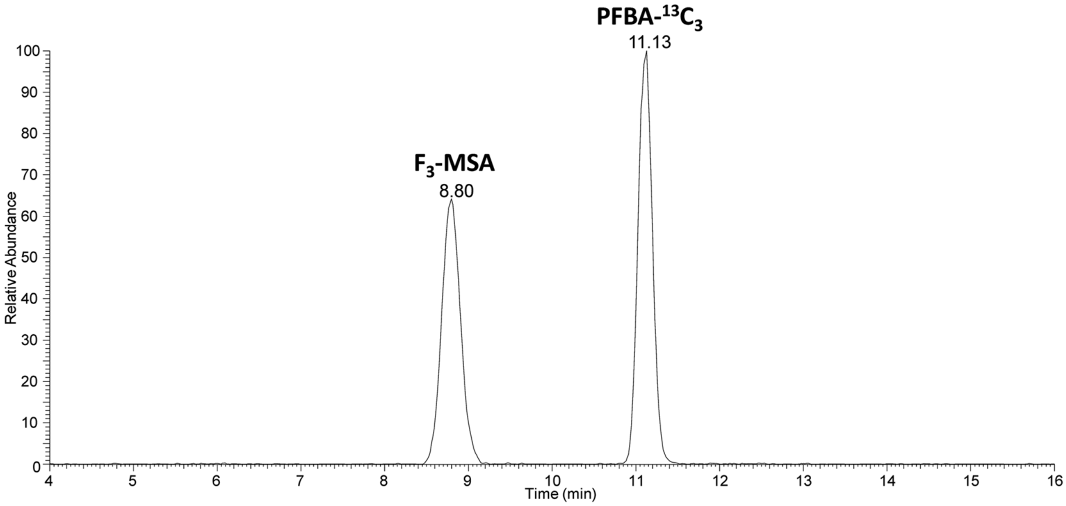

Fig. 1 Extracted ion chromatogram of F_3-MSA (*m*/*z* [M−H]: 148.9526) and PFBA-$^{13}C_3$ (*m*/*z* [M−H]: 215.9893) reference standards (2.5 μg L^{-1}) obtained with SIELC Obelisc N column.

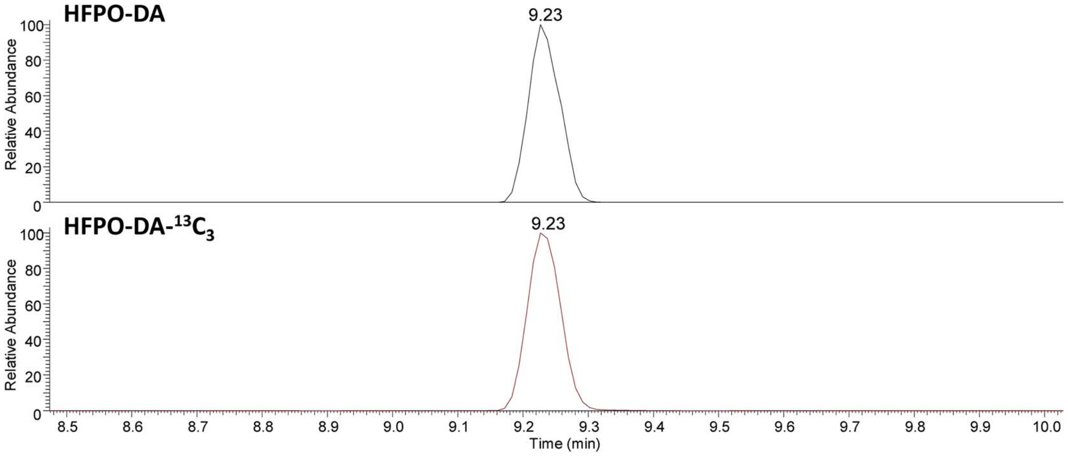

Fig. 2 Extracted ion chromatograms of HFPO-DA (0.1 μg L^{-1}; m/z [$C_5HF_{11}O-H$]: 284.9779) and HFPO-DA-$^{13}C_3$ reference standards (25 μg L^{-1}, m/z [$C_3{}^{13}C_2H_{11}O-H$]: 286.9846) obtained with an XBridge C18 column.

in close agreement with earlier literature data from the same region.[10] Both the literature values and the results of the present sampling campaign suggest that HFPO-DA is only partly removed by drinking water treatment (see below).

F_3-MSA was not detected in any of the sampled groundwaters. However, the compound was found to be present in all surface water and river bank/dune filtrate samples. F_3-MSA was also detected ($\geq$1.0 ng L^{-1}) in 68.2% of the 22 drinking water samples collected. The average concentration of F_3-MSA in drinking-, surface-, and riverbank/dune infiltrate samples was 24, 42 and 78 ng L^{-1}, respectively. The highest concentrations for F_3-MSA were detected at location Heel (RBF 230 ng L^{-1} and SW 150 ng L^{-1}), which are substantially higher than other source waters that were analysed. This could indicate that there is a local emission (point source) of F_3-MSA in the vicinity of Heel. The results of the sampling campaign reveal that relatively high concentrations of this newly emerging compound are detected in various water matrices (except for groundwater). This confirms earlier studies where F_3-MSA was observed in similar types of water from Spain, Germany, France and The Netherlands.[18,21] The results also suggest that F_3-MSA is only partly removed by drinking water treatment.

Removal efficiency

In order to further investigate the efficiency of drinking water treatment for removal of these two emerging PFAS, the results were evaluated by grouping the raw and corresponding drinking water results for each location where possible. Fig. 3 shows that F_3-MSA is not or incompletely removed by the majority of drinking water purification processes applied. These typically include aeration, softening, sand filtration, disinfection (by *e.g.* ozone or UV/peroxide) and activated carbon (AC). The only exception is the reverse osmosis process which leads to an almost complete removal of F_3-MSA in permeate water (see Fig. 3, location Lekkerkerk).

A similar comparison made for HFPO-DA (see ESI, Fig. S-1†) shows that for this compound the same observation can be made: it is incompletely removed by the majority of drinking water purification processes applied, with the exception of reversed osmosis that achieves an almost complete removal of HFPO-DA in permeate water.

To study the efficiency of two drinking water treatment processes for removal of HFPO-DA and F_3-MSA in more detail, process water samples were collected from a UV/peroxide disinfection process combined with AC filtration, and reverse osmosis, respectively. Single samples were taken at various sequential steps in the purification process in order to observe the removal efficiency. Table 2 presents the concentrations of both analytes in the various stages of each process train. Because the sampling campaign allowed us to obtain only individual samples from each step, the results provide an

Table 1 Frequency of detection and concentrations of F_3-MSA and HFPO-DA in various water types

	Drinking water		Groundwater		Surface water		River bank/dune filtrate	
	F_3-MSA	HFPO-DA	F_3-MSA	HFPO-DA	F_3-MSA	HFPO-DA	F_3-MSA	HFPO-DA
Number of samples (n)	22	22	5	5	13	13	7	7
Detected (n)[b]	15	10	—	—	13	10	7	6
Detected (n) >1 ng L^{-1}	11[a]	5	—	—	10[a]	3	6[a]	3
Detected (%)	68.2	45.5	—	—	100.0	76.9	100.0	85.7
Average conc. (ng L^{-1})	24	2.9	—	—	42	2.2	78	10.2
Highest conc. (ng L^{-1})	165	28	—	—	150	10.2	230	59

[a] >10 ng L^{-1}. [b] LOQs (see ESI): 1.0 ng L^{-1} (F_3-MSA); 0.2 ng L^{-1} (HFPO-DA).

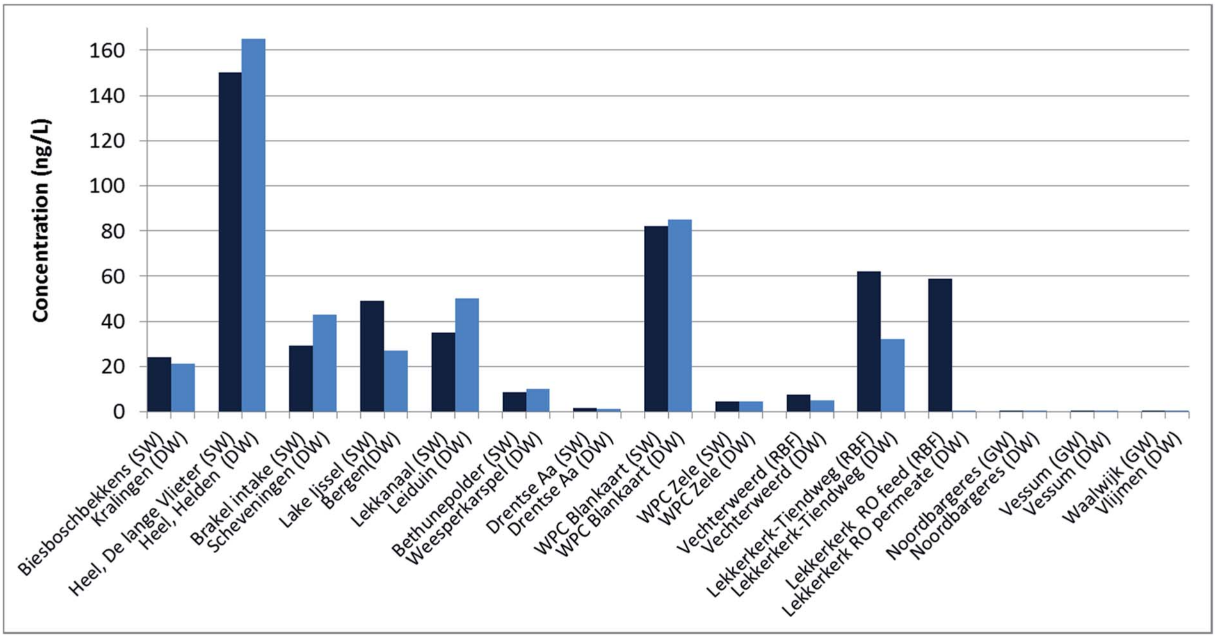

Fig. 3 Concentrations of F_3-MSA detected in raw water and the corresponding tapwater from several locations (single samples). Dark blue: raw water; light blue: drinking water; side-to-side bars reflect corresponding water works (*i.e.* water from same source before and after treatment). SW, surface water; DW, drinking water; RBF, river bank filtrate; GW, groundwater; RO, reverse osmosis.

indication of the behaviour of the two substances, and do not allow for a statistical evaluation of treatment efficiencies.

The results obtained for the advanced oxidation water treatment UV/H_2O_2-AC show that the UV/H_2O_2 process itself has no or negligible effect on the removal of F_3-MSA and HFPO-DA (comparing influent and effluent levels). Dune infiltration neither has an effect on the removal of F_3-MSA and HFPO-DA. In the end, both F_3-MSA and HFPO-DA are incompletely removed by the applied water treatment. Water treatment using RO leads to a complete removal (lower than LOQ) of F_3-MSA and HFPO-DA from feed water and a concomitant enrichment of the compounds in the concentrate. In a recent study RO was also found to completely remove F_3-MSA and other HMSAs.[21] The results demonstrate that RO is a very effective purification process for the removal of F_3-MSA and HFPO-DA.

Table 2 Concentrations of HFPO-DA and F_3-MSA in various stages of UV/H_2O_2-AC and reverse osmosis water treatment (single samples)

	HFPO-DA, ng L^{-1}	F_3-MSA, ng L^{-1}
Supplier 1 (UV/H_2O_2-AC)		
Lake Ijsselmeer (raw)	0.28	49
Effluent from intake station Pr. Juliana	0.30	46
Influent UV/H_2O_2-AC	0.22	39
Effluent UV/H_2O_2-AC	0.22	39
After dune filtration	0.22	45
Drinking water Bergen	0.20	27
Supplier 2 (RO)		
Reverse osmosis feed	5.3	59
Reverse osmosis permeate	<0.20	<1.0
Reverse osmosis concentrate	28	165

Halogenated methanesulfonic acids

Apart from F_3-MSA, other HMSAs have been shown to be present in source waters and drinking water.[18] A suspect screening was performed for six HMSAs (see Table S-7†) using the data set (HRMS spectra) from the sampling campaign recorded with the F_3-MSA analytical method. The results are presented in Fig. 4 (see Table SI-8† for estimated concentrations and sampling locations). Since the concentrations of HMSAs are calculated using F_3-MSA as calibration standard, the results presented here are an indication of the actual environmental concentrations. F_3-MSA is shown as reference in Fig. 4. The identities of all HMSAs detected were confirmed at a Schymanski identification level of 2b,[27] by annotation of the HR MS2 spectrum, except for BrCl-MSA which was confirmed at level 3. Confirmation to level 2a was not possible, because no reference MS2 spectra were available. The identity of these HMSAs can only be confirmed unambiguously when reference standards are available.[21] HMSAs are recently discovered[18,21] disinfection byproducts of water treatment for drinking water production.

Toxicological evaluation

EFSA[28] based its toxicological evaluation of HFPO-DA on toxicity data for FRD-902. Read-across from FRD-902 data is considered justified for HFPO-DA, since the effects of both substances are caused by the anion 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy) propanoate and in organisms, absorption and distribution of this anion are expected to be similar after dissolution and

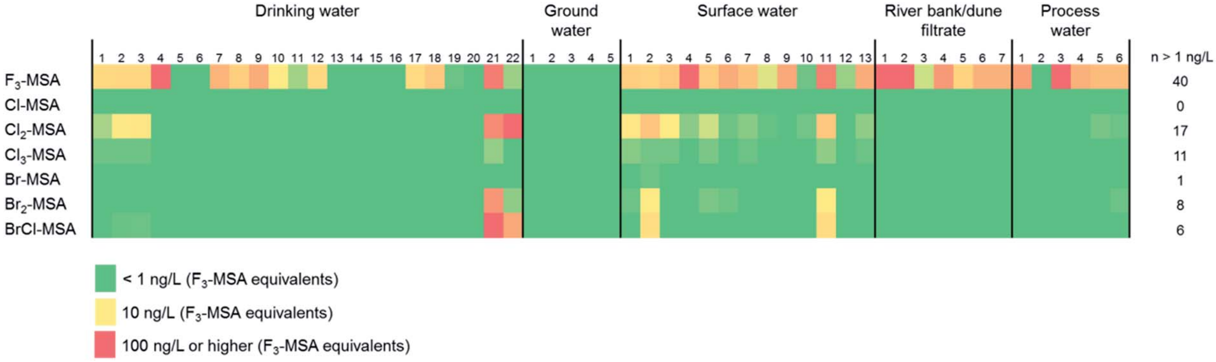

Fig. 4 Heat map of suspect screening results for HMSAs in various water types. All concentrations of HMSAs were calculated using F_3-MSA as calibration standard and are indicative. Results of F_3-MSA were added as reference. Numbers of sampling locations refer to the locations listed in Table SI-8.†

dissociation of the acid (HFPO-DA) and the salt (FRD-902).[29] An overview of toxicity studies for FRD-902 documented in its REACH registration dossier has been provided by RIVM.[29] FRD-902 appears not to be mutagenic or genotoxic and adverse effects on reproduction or development are not expected. The OECD QSAR Toolbox does report structural alerts for DNA binding and *in vivo* genotoxicity for both HFPO-DA and FRD-902, but retrieves predominantly negative genotoxicity test results for FRD-902 as well (see Table SI-9†). RIVM concludes that FRD-902 and HFPO-DA should be classified as suspected non-genotoxic carcinogens in humans because carcinogenicity has been observed in experimental animals. US-EPA is currently working on a toxicity assessment for HFPO-DA (a Public Comment draft is available[29]).

A provisional oral Tolerable Daily Intake (TDI) level of 21 ng kg^{-1} body weight per day for FRD-902 was derived by RIVM[30] (see ESI†). Additional information on the bioaccumulation of FRD-902 in humans, which is currently lacking, would allow derivation of an improved exposure limit. It should be noted that potential carcinogenic effects have not been incorporated in this TDI level. The provisional TDI of 21 ng kg^{-1} bw per day was converted to a pGLV for FRD-902 of 0.15 μg L^{-1} (for derivation, see ESI†). This value also applies to HFPO-DA and the anion, and to the sum of the three substances.[31]

For F_3-MSA no toxicity studies and health risk assessments could be retrieved from the consulted authorities, databases and literature (for more details, see the ESI†). A short-term repeated dose oral exposure study in rats (OECD TG-407) is reported in the REACH registration dossier for F_3-MSA.[31] The reported no-adverse-effect level (NOAEL) is 1000 mg kg^{-1} bw. Local effects are observed at lower doses (over 40 mg kg^{-1} bw) but these effects are considered to be non relevant for human physiology.

From the reported NOAEL, a tolerable daily intake can be calculated using the following assessment factors:[32] 6 for extrapolation to chronic exposure, 4 for allometric scaling of interspecies differences and 2.5 for other interspecies differences, and 10 for intraspecies differences (resulting in an overall assessment factor of 600). A pGLV of 11.9 mg L^{-1} would be derived from the reported NOAEL.

All concentrations observed for F_3-MSA and HFPO-DA in drinking water samples from the sampling campaign are substantially below their respective provisional drinking water guideline values. The concentrations detected therefore give no cause of concern for adverse health effects from lifetime consumption of tap water produced by the water suppliers involved in the present study. It must however be noted that the GLVs are provisional and may be adapted when additional toxicological information becomes available.

Final observations

During the present study the presence of FOSA (1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluoro-1-octanesulfonamide) in the samples collected during the sampling campaign was also evaluated (for method, see ESI†). In none of the 53 samples taken FOSA was observed (LOD: 0.25 ng L^{-1}), except in the RO concentrate where a level of 0.92 ng L^{-1} was observed. The latter value demonstrates that FOSA is probably present in RO feed water, albeit at concentrations below the LOD.

In the present study two LC-Orbitrap-MS methods were developed for the analysis of F_3-MSA and HFPO-DA in drinking and surface water. Single grab samples were obtained from different locations in The Netherlands and Belgium. Both analytes were shown to be present in low concentration levels in drinking water from several water suppliers. The persistence and mobility of the two compounds is demonstrated by their presence in samples of river bank filtrate and their incomplete removal during drinking water processing, unless reverse osmosis is applied. Both F_3-MSA and HFPO-DA were absent in the groundwater samples collected in the present study, indicating that their major routes to the environment probably involve (industrial) wastewaters, rather than *e.g.*, landfills. The concentrations detected in drinking water give no immediate reason for concern for adverse health effects by drinking tap water produced by the water suppliers involved in the present study. However, concentrations may increase if discharges continue to be permitted. Available toxicological information for both substances is however incomplete. In addition, a recent study in the Netherlands[11] concluded that HPFO-DA findings suggest that the change in production to a less bioaccumulating but, therefore, more water-soluble fluorinated alternative for PFOA only causes a shift to a different environmental compartment and may not be a solution for the pressure on the environment as a whole.[33] Because common removal processes used in drinking water production incompletely remove these newly emerging PFAS, a problem shared with other mobile persistent chemicals,[34] vigilance and frequent monitoring of these substances is required.

Conflicts of interest

All authors declare there are no conflicts of interest.

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References

1 M. S. McLachlan, K. E. Holmstrom, M. Reth and U. Berger, Riverine discharge of perfluorinated carboxylates from the European continent, *Environ. Sci. Technol.*, 2007, **41**, 7260–7265.

2 A. Möller, L. Ahrens, R. Surm, J. Westerveld, F. van der Wielen, R. Ebinghaus, *et al.*, Distribution and sources of polyfluoroalkyl substances (PFAS) in the river Rhine watershed, *Environ. Pollut.*, 2010, **158**, 3243–3250.

3 C. Eschauzier, E. F. Beerendonk, P. Scholte-Veenendaal and P. de Voogt, Impact of treatment processes on the occurrence of perfluoroalkyl acids in the drinking water production chain, *Environ. Sci. Technol.*, 2012, **46**, 1708–1715.

4 V. Albergamo, B. Blankert, E. Cornelissen, B. Hofs, W. J. Knibbe, W. van der Meer, *et al.*, Removal of polar organic micropollutants by pilot-scale reverse osmosis drinking water treatment, *Water Res.*, 2019, **148**, 535–545.

5 Z. Wang, I. T. Cousins, M. Scheringer and K. Hungerbühler, Fluorinated alternatives to long-chain perfluoroalkyl carboxylic acids (PFCAs), perfluoroalkane sulfonic acids (PFSAs) and their potential precursors, *Environ. Int.*, 2013, **60**, 242–248.

6 Z. Wang, J. C. DeWitt, C. P. Higgins and I. T. Cousins, A never ending story of per- and polyfluoroalkyl substances (PFAS)?, *Environ. Sci. Technol.*, 2017, **51**, 2508–2518.

7 T. Wang, R. Vestergren, D. Herzke, J. Yu and I. T. Cousins, Levels, Isomer Profiles, and Estimated Riverine Mass Discharges of Perfluoroalkyl Acids and Fluorinated Alternatives at the Mouths of Chinese Rivers, *Environ. Sci. Technol.*, 2016, **50**, 11584–11592.

8 F. Heydebreck, J. Tang, Z. Xie and R. Ebinghaus, Alternative and legacy perfluoroalkyl substances: differences between European and Chinese river/estuary systems, *Environ. Sci. Technol.*, 2015, **49**, 8386–8395.

9 W. Gebbink, L. van Asseldonk and S. P. J. van Leeuwen, Presence of emerging per- and polyfluoroalkyl substances (PFASs) in river and drinking water near a fluorochemical production plant in The Netherlands, *Environ. Sci. Technol.*, 2017, **51**, 11057–11065.

10 J. M. Versteegh and P. de Voogt, *Risicoduiding en vóórkomen van FRD-903 in drinkwater en drinkwaterbronnen bij een selectie van drinkwaterwinningen in Nederland [Interpretation of risks associated with the occurrence of FRD-903 in raw and drinking water from selected drinking water production sites in The Netherlands]*, Bilthoven. RIVM, Report no. 2017-0175 (in Dutch with English summary), 2015, p. 22.

11 S. H. Brandsma, J. C. Koekkoek, M. J. M. van Velzen and J. de Boer, The PFOA substitute GenX detected in the environment near a fluoropolymer manufacturing plant in the Netherlands, *Chemosphere*, 2019, **220**, 493–500.

12 J. McCord and M. Strynar, Identification of per- and polyfluoroalkyl substances in the Cape Fear river by high resolution mass spectrometry and nontargeted screening, *Environ. Sci. Technol.*, 2019, **53**, 4717–4727.

13 Y. Pan, H. Zhang, Q. Cui, N. Sheng, L. W. Y. Yeung, Y. Sun, *et al.*, Worldwide Distribution of Novel Perfluoroether Carboxylic and Sulfonic Acids in Surface Water, *Environ. Sci. Technol.*, 2018, **52**, 7621–7629.

14 M. I. Gomis, Z. Wang, M. Scheringer and I. T. Cousins, A modeling assessment of the physicochemical properties and environmental fate of emerging and novel per- and polyfluoroalkyl substances, *Sci. Total Environ.*, 2015, **505**, 981–991.

15 W. B. Nixon and F. J. Lezotte, *Determination of the water solubility and vapor pressure of H-28307*, Technical Report, DuPont de Nemours and Company, Maryland, 2008.

16 R. L. Van Hoven and W. B. Nixon, *H-28308: An evaluation of hydrolysis as a function of pH*, Technical Report, DuPont de Nemours and Company, Maryland, 2008.

17 ECHA dossier, https://echa.europa.eu/registration-dossier/-/registered-dossier/2679/4/8, accessed 20-05-2019.

18 D. Zahn, T. Froemel and T. P. Knepper, Halogenated methanesulfonic acids: A new class of organic micropollutants in the water cycle, *Water Res.*, 2016, **101**, 292–299.

19 H. Suzuki, M. Takeishi and I. Narisawa, Synthesis of polysiloxane-grafted fluoropolymers and their hydrophobic properties, *J. Appl. Polym. Sci.*, 2000, **78**, 1955–1963.

20 Solvay company, https://www.solvay.com/en/product/triflic-acid-ta, accessed August 2019.

21 D. Zahn, R. Meusinger, T. Froemel and T. P. Knepper, Halomethanesulfonic acids: a new class of polar disinfection byproducts: standard synthesis, occurrence, and indirect assessment of mitigation options, *Environ. Sci. Technol.*, 2019, **53**, 8994–9002.

22 N. Köke, D. Zahn, T. P. Knepper and T. Froemel, Multi-layer solid-phase extraction and evaporation enrichment methods for polar organic chemicals from aqueous matrices, *Anal. Bioanal. Chem.*, 2018, **410**, 2403–2411.

23 R. Montes, J. Aguirre, X. Vidal, R. Rodil, R. Cela and J. B. Quintana, Screening for polar chemicals in water by trifunctional mixed-mode liquid chromatography-high resolution mass spectrometry, *Environ. Sci. Technol.*, 2017, **51**, 6250–6259.

24 Y. Pan, H. Zhang, Q. Cui, N. Sheng, L. W. Y. Yeung, Y. Guo, *et al.*, First report on the occurrence and bioaccumulation of hexafluoropropylene oxide trimer acid: an emerging concern, *Environ. Sci. Technol.*, 2017, **51**, 9553–9560.

25 R. C. Buck, J. Franklin, U. Berger, J. M. Conder, I. T. Cousins, P. de Voogt, *et al.*, Perfluoroalkyl and polyfluoralkyl substances (PFASs) in the environment: terminology, classification, and origins, *Integr. Environ. Assess. Manage.*, 2011, **7**, 513–541.

26 WHO, *Guidelines for drinking-water quality*, World Health Organisation, Geneva, 3rd edn, vol. 1 Recommendations, 2018.

27 E. L. Schymanski, J. Jeon, R. Gulde, K. Fenner, M. Ruff, H. P. Singer, *et al.*, Identifying small molecules *via* high resolution mass spectrometry: Communicating confidence, *Environ. Sci. Technol.*, 2014, **48**, 2097–2098.

28 EFSA, Scientific Opinion of the Panel on food contact materials, enzymes, flavourings and processing aids (CEF) on 24th list of substances for food contact materials, *EFSA J.*, 2009, **1157–1163**, 1–28.

29 US-EPA, Washington, https://www.epa.gov/pfas/genx-and-pfbs-draft-toxicity-assessments, 2018.

30 P. Janssen, *Derivation of a lifetime drinking-water guideline value for 2,3,3,3-tetrafluoro-2- (heptafluoropropoxy)propanoic acid (FRD-902)*, Advice of 17 November 2016 to Ministry of Infrastructure and Environment, RIVM, Bilthoven, 2016, Project M/300007/16/PF.

31 ECHA, *Trifluoromethanesulphonic acid Registration Dossier*. Available at https://echa.europa.eu/registration-dossier/-/registered-dossier/5311/1, accessed 19-08-2019, 2017.

32 ECHA, *Guidance on Information Requirements and Chemical Safety Assessment*, European Chemicals Agency, Helsinki, Ch. R.8: Characterisation of dose[concentration]-response for human health. Guidance for the implementation of REACH, 2008.

33 European Commission, *New research suggests that alternatives to legacy PFASs may be no safe*, Brussels, http://ec.europa.eu/environment/integration/research/newsalert/pdf/new_research_suggests_that_alternatives_to_legacy_pfas_may_be_no_safer_517na4_en.pdf, 2018.

34 T. Reemtsma, U. Berger, H. P. H. Arp, H. Gallard, T. P. Knepper, M. Neumann, *et al.*, Mind the Gap: Persistent and Mobile Organic Compounds—Water Contaminants That Slip Through, *Environ. Sci. Technol.*, 2016, **50**, 10308–10315.