

Perfluorinated compounds contamination in tap water and bottled water in Bangkok, Thailand

Chinagarn Kunacheva, Shigeo Fujii, Shuhei Tanaka, Suwanna Kitpati Boontanon, Somrutai Poothong, Thana Wongwatthana and Binaya Raj Shivakoti

ABSTRACT

Perfluorinated compounds (PFCs) such as perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) have been detected in the environment, in biota and in humans. The exposure pathways of these chemicals to humans are unclear. Tap water and bottled water are two possible pathways of PFCs occurrence in human blood. The major objectives of the study were to identify the occurrences of PFCs in tap and bottled water and to evaluate conventional water treatment processes performance on removal of PFCs. Solid phase extraction coupled with HPLC-ESI-MS/MS were used for the analysis of ten PFCs. PFCs were detected in all tap water samples and bottled water samples. The average PFOS and PFOA concentrations in tap water were 0.17 and 3.58 ng l⁻¹, respectively. PFOS and PFOA were not similarly distributed in all areas in the city. PFCs concentrations were higher in bottled water than in tap water. Moreover, the current treatment processes were not effective in removing PFCs in aqueous phase. Nevertheless, PFCs in particulate phase were effectively removed by primary sedimentation and rapid sand filtration. Based on the guideline from the New Jersey Department of Environmental Protection, PFOA concentrations in tap water and bottled water found in Bangkok were not expected to cause any health risks.

Key words | bottled water, perfluorinated compounds, PFOA, PFOS, tap water, water treatment plant

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INTRODUCTION

Perfluorinated compounds (PFCs), especially perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), have been found not only in the environment but also in wildlife and human blood (Hansen *et al.* 2002; Kannan *et al.* 2004). The toxicity of PFOS has been studied for many years. PFOS has been shown to be toxic in rats and rabbits in the laboratory. The lowest observed adverse effect level (LOAEL) was 0.4 mg kg⁻¹ bw/day and the no observed adverse effect level (NOAEL) of PFOS was estimated to be 0.1 mg kg⁻¹ bw/day (OECD 2002). Toxicology studies for PFOA have also been conducted.

LOAEL was estimated to be 1 mg kg⁻¹ bw/day (Butenhoff *et al.* 2002) and NOAEL was calculated as 1.6 mg kg⁻¹ bw/day (Sibinski 1987). Based on NOAEL concentration, the State of New Jersey Department of Environmental Protection reported the guideline value of PFOA in bottled water to be 40 ng l⁻¹ (State of New Jersey 2009).

PFCs in tap and bottled water could be of a great concern. Researchers have reported PFCs contamination in raw water (river), tap water and bottled water in Japan (Saito *et al.* 2004; Takagi *et al.* 2008), the USA (Hansen *et al.* 2002; Boulanger *et al.* 2004) and Europe

(Skutlarek *et al.* 2006; Ericson *et al.* 2008). Unfortunately, the study of PFCs contamination in tap (or bottled water) water is very limited in South-east Asian countries, especially in Thailand. A comprehensive survey of PFCs in tap water and bottled water in the country is necessary for better understanding the risk of exposure to PFCs in humans. In the meantime, evaluation of conventional water treatment (or purification) processes is also important for understanding the behaviour and removal of PFCs during treatment. The purposes of this study were: (1) to identify the occurrence of PFCs in tap water and bottled water in Bangkok city; (2) to evaluate conventional water treatment processes performance on the removal of PFCs; and (3) to compare PFCs contamination with other Asian cities.

MATERIALS AND METHODS

Sampling location

There are four water treatment plants (WTPs) (W1–W4) in Bangkok City providing tap water for more than 8 million people. The source of water for W1, W2 and W3 is Chao Phraya River, which is the largest river in Thailand. Chao Phraya River runs from the north of Thailand to the Gulf of Thailand (river outlet) in a southerly direction. The river passes through Bangkok City receiving wastewater from industrial and domestic activities. The pumping station is located in Pathum Thani province, north of Bangkok. Raw water is pumped to ‘East Water Canal’ and flows to W1 and W2. W3 is located in the west side of Bangkok, which is separated by Chao Phraya River. There is a pumping station in the East Water Canal to transfer raw water from the east

side to W3 across Chao Phraya River. W4 is located in the west side of Bangkok, taking raw water from Mae Klong River, which is located 107 km west from W4. West Water Canal was built to transfer raw water from Mae Klong River to W4. A conventional treatment process is used in all four treatment plants as shown in Figure 1. The conventional quality parameters of the water sources and tap water from the four WTPs are shown in Table 1.

Sampling was conducted in all four WTPs in January 2009. Raw water, clarifier effluents, rapid sand filter effluents and tap water samples were collected in each WTP to identify the performance of the treatment processes. Tap water samples (T1–T14) from each treatment plant were also collected from gas stations around Bangkok to estimate PFCs contamination in tap water for human consumption. Tap water sampling was conducted on the same day of each WTP sampling. Furthermore, ten bottles of water from five commercial companies, whose raw water has different origins, were also purchased from nearby convenient stores. Sampling points are shown in Figure 2.

Sample collection

WTP and tap water samples were collected by direct grab-sampling from the faucet. Bottled water samples were purchased in 2-l PET bottles from convenient stores. New 1.5-l narrow-neck PET bottles with screw caps were used as sampling containers. PET bottles were washed with methanol and dried before use. Containers were also rinsed three times with the sample before collection. After sampling, the samples were brought back to the laboratory and stored at 4°C, with sample pre-treatment in the same day.

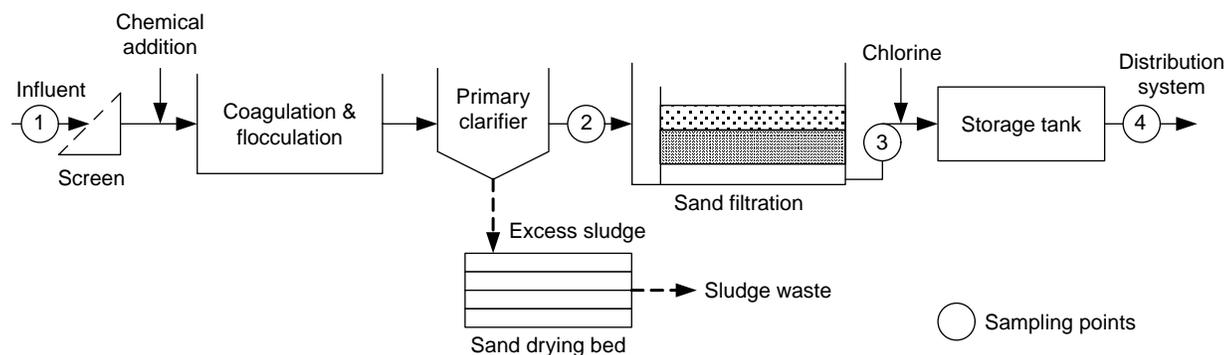


Figure 1 | Sampling points in WTPs.

Table 1 | Quality of water sources (East Water Canal and West Water Canal) and tap water from water treatment plants (W1, W2, W3 and W4) (Source: Metropolitan Waterworks Authority, <http://www.mwa.co.th>)

Parameter	Water sources		Tap water			
	East water Canal	West water Canal	W1	W2	W3	W4
Turbidity (NTU)	24.4	10.8	0.82	0.59	0.93	0.58
DO (mg l^{-1})	4.3	7.05	NA	NA	NA	NA
Conductivity ($\mu\text{m/cm}$)	288	207	269	264	269	217
Alkalinity (mg l^{-1})	120	114	80	77	82	94
pH	7.42	7.58	7.10	7.18	7.30	7.41
Coliform bacteria (MPN/100 ml)	1,700	170	ND	ND	ND	ND
Fecal coliform bacteria (MPN/100 ml)	200	20	ND	ND	ND	ND

Note: NA = not available; ND = not detected.

Sample preparation

Collected samples were directly loaded into the cartridge except for influent and primary sedimentation tank effluent in WTP samples, in which suspended solids were separated by using $1\ \mu\text{m}$ GF/B glass fibre filter. The suspended solid sample in the filter was then further analysed by using accelerated solvent extraction (ASE-200, Dionex, Japan).

The aqueous phase sample (1,000 ml) was passed through a PresepC-Agri (C18) cartridge (Wako, Japan) connected inline to Oasis[®]HLB (Waters, Japan), which were preconditioned by 10 ml of LC/MS-grade methanol followed by 20 ml *Milli-Q* water manually. PFCs mass labelled internal standards ($^{13}\text{C}_2$ -PFHxA, $^{13}\text{C}_4$ -PFOA, $^{13}\text{C}_2$ -PFDA and $^{13}\text{C}_4$ -PFOS) were spiked ($10\ \text{ng l}^{-1}$) into

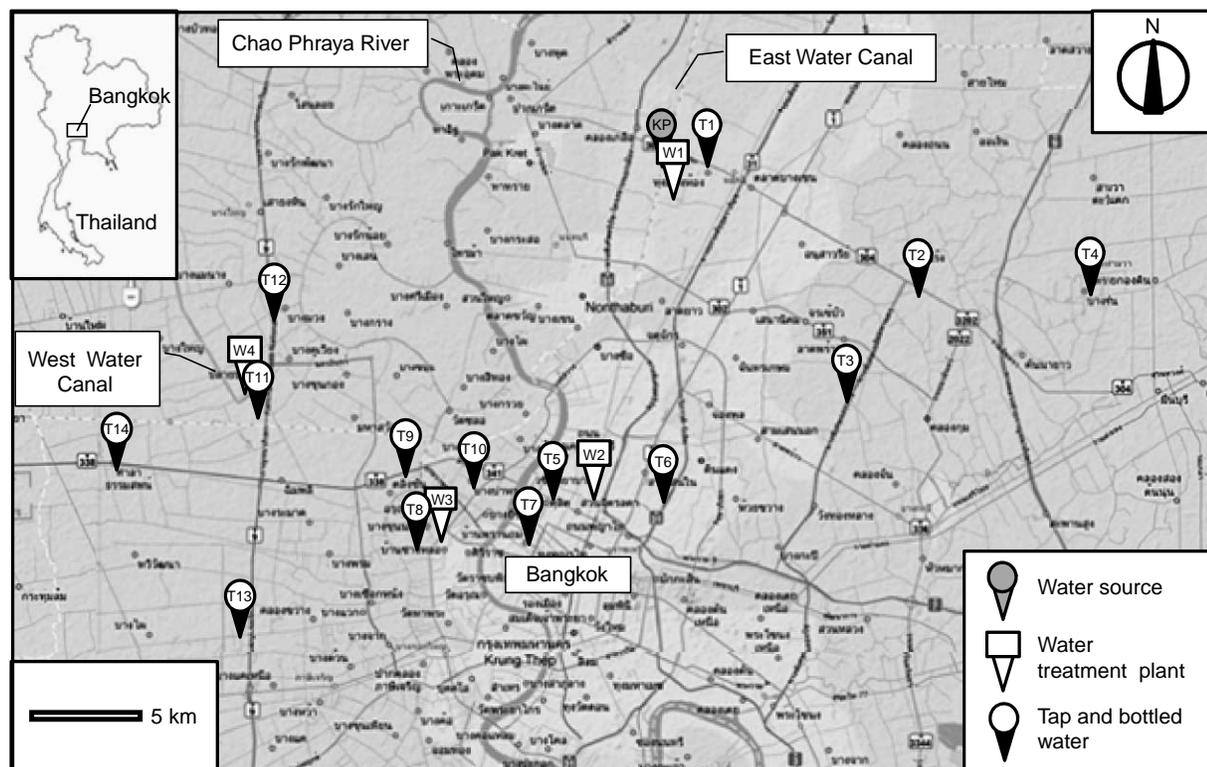


Figure 2 | Sampling locations for raw water, WTPs, tap and bottled water samples (source: Google Maps).

a sample before loading to find their recovery rates. A flow rate of 5 ml min^{-1} was maintained through the cartridge. The above procedures were completed in Thailand and the cartridges were brought back to Japan for further analysis. In Japan, each cartridge was dried completely under vacuum. Then, the target compounds were eluted with 2 ml LC/MS-grade methanol followed by 2 ml LC/MS grade acetonitrile into a polypropylene tube, evaporated to dryness with nitrogen gas, and reconstituted into LC/MS mobile phase (40% LC/MS-grade acetonitrile) to a final volume of 2 ml. PFCs in filtrates were concentrated by a factor of 500 times.

The suspended solids phase was separated by GF/B filter (filtered volume: 1,000 ml). The filters were air dried and inserted in ASE cells (volume: 33 ml) for extraction. The internal standards were spiked into the duplicated cell before extraction. The extraction was done using methanol as a solvent. The extraction was run for three cycles (15 min per one cycle) using pressure 2,000 psi and temperature 100°C . The final extracted volume was 60–80 ml. Then, the extracted sample was diluted with LC/MS-grade *ultrapure* water to 1 l, loaded into a PresepC-Agri (C18) cartridge, continuing with the same procedure as liquid phase samples. A duplicate sample was performed for each sampling point.

Table 2 | Analytical parameters of each PFC by HPLC/MS/MS analysis

Compound	No. of carbon	Parent ion (m/z)	Daughter ion (m/z)	CE (eV)	Retention time (min)	LOD (ng l^{-1})	LOQ (ng l^{-1})
PFPA	C5-A	263	219	5	1.9	0.02	0.05
PFHxA	C6-A	313	269	5	2.8	0.01	0.02
PFHpA	C7-A	363	319	5	4.7	0.01	0.03
PFOA	C8-A	413	369	5	7.2	0.01	0.03
PFNA	C9-A	463	419	5	9.9	0.01	0.02
PFDA	C10-A	513	469	5	12.7	0.01	0.04
PFUnA	C11-A	563	519	5	15.4	0.07	0.22
PFDoA	C12-A	613	569	5	18.0	0.07	0.22
PFHxS	C6-S	399	80	55	7.9	0.01	0.03
PFOS	C8-S	499	80	55	13.8	0.01	0.04
$^{13}\text{C}_2$ -PFHxA	C6-A	315	271	5	2.8	0.01	0.02
$^{13}\text{C}_4$ -PFOA	C8-A	417	373	5	7.2	0.01	0.03
$^{13}\text{C}_2$ -PFDA	C10-A	515	471	5	12.7	0.01	0.03
$^{13}\text{C}_4$ -PFOS	C8-S	503	80	55	13.8	0.01	0.04

Note: CE = collision energy; S = perfluorinated sulfonates (PFCs); A = perfluorinated carboxylic acids (PFCAs).

Instrumental analysis and quantification

Separation of PFCs was performed using Agilent 1200 SL high-performance liquid chromatography (HPLC) (Agilent, Japan). A $10 \mu\text{l}$ extract was injected into a $2.1 \times 100 \text{ mm}$ ($5 \mu\text{m}$) Agilent Eclipse XDB-C₁₈ column. Mobile phase consisted of (A) 5 mM ammonium acetate in *ultrapure* water (LC/MS-grade) and (B) 100% acetonitrile (LC/MS-grade). At a flow rate of 0.25 ml min^{-1} , the separation process started with an initial condition of 30% (B), increased to 50% (B) at 16.5 min, then to 70% (B) at 16.6, held at 70% (B) for 3.4 min, up to 90% (B) at 21 min, kept at 90% (B) for 1 min, and then ramped down to 30% (B). The total running time was 34 min for each sample. For quantitative determination, the HPLC was interfaced with an Agilent 6400 Triple Quadrupole (Agilent, Japan) mass spectrometer (MS/MS). The mass spectrometer was operated in the electrospray ionization (ESI) negative mode. The analyte ions were monitored using multiple reaction monitoring (MRM) mode. The analytical parameters of each PFC are shown in Table 2.

Calibration and validation

The calibration curves for quantification, consisting of seven points covering 0.05 to $25 \mu\text{g l}^{-1}$ (0.2 to 100 ng l^{-1})

Table 3 | PFCs concentration in raw water, water treatment plant (WTP), tap water and bottled water samples

Type of sample	n	PFCs concentrations (ng l ⁻¹)									
		PFPA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUnA	PFDoA	PFHxS	PFOS
Raw water	2	2.88 ± 0.08	0.43 ± 0.01	1.65 ± 0.04	16.54 ± 2.10	ND	ND	< LOQ	ND	ND	4.29 ± 0.19
WTP:											
Influent	8	2.23 ± 1.53	0.17 ± 0.04	0.68 ± 0.29	9.57 ± 2.41	ND	ND	< LOQ	ND	ND	5.02 ± 3.32
Clarifier	8	1.14 ± 0.62	0.15 ± 0.15	0.70 ± 0.33	9.08 ± 2.67	ND	ND	< LOQ	ND	ND	6.28 ± 3.58
Rapid sand filter	8	1.20 ± 0.48	ND	ND	1.43 ± 1.26	ND	ND	< LOQ	ND	ND	0.68 ± 0.33
Effluent	8	1.11 ± 0.71	ND	ND	1.79 ± 2.13	ND	ND	< LOQ	ND	ND	0.73 ± 0.43
Tap water	28	1.84 ± 1.72	0.13 ± 0.07	0.28 ± 0.14	3.60 ± 4.15	ND	ND	< LOQ	ND	ND	0.18 ± 0.27
Bottled water	20	0.28 ± 0.34	0.34 ± 0.30	0.25 ± 0.18	10.55 ± 9.58	ND	ND	ND	ND	ND	0.22 ± 0.37

Note: n = number of samples; A = perfluorinated carboxylic acids (PFCAs); S = perfluorinated sulfonates (PFCs); ND = not detected; < LOQ = lower than limit of quantification.

with concentrated factor), generally provided linearity, with determination coefficients (R^2) of more than 0.999 in every compound. The limit of detection (LOD) for HPLC/MS/MS was defined as concentration with signal to noise ratio (S/N) equal to 3:1. Practically, the limit of quantification (LOQ) was used for quantifying analyte, which was defined by S/N 10:1 (Saito *et al.* 2004; Lien 2007) (Table 2). Duplicated analysis was also performed on all samples, and coefficients of variation (CV) of concentrations were below 20%. During the sample collection and analysis, analytical blanks ($n = 2$) were performed using *ultrapure* water. PFCs concentrations were less than the LOQ, indicating no contamination during the process.

The recovery rates were calculated by spiking PFCs internal standards into samples. For aqueous phase samples, internal standards were spiked before loading to the cartridges, while the standards were spiked into ASE cells before extraction for particulate phase analysis. The ranges (average ± SD) of recovery rates of ¹³C₂-PFHxA, ¹³C₄-PFOA, ¹³C₂-PFDA and ¹³C₄-PFOS were 61–136% (95% ± 0.22), 79–125% (105% ± 0.11), 74–124% (101% ± 0.13) and 73–126% (98% ± 0.12), respectively.

RESULTS AND DISCUSSION

Occurrences of PFCs in WTP, tap water and bottled water

The concentration of ten PFCs in raw water, WTPs, tap water and bottled water samples are summarized in Table 3

and Figure 3. PFCs were detected in all tap water and bottled water samples, revealing that they contaminate most tap and bottled water in the city. PFPA, PFHxA, PFHpA, PFOA, and PFOS were detected in most samples, while the other five PFCs (PFNA, PFDA, PFUnA, PFDoA, and PFHxS) were not detected (ND) or were lower than the limit of quantification (< LOQ). PFCs concentration ranges in the samples were 0.28–2.88 ng l⁻¹ for PFPA, ND–0.43 ng l⁻¹ for PFHxA, ND–1.65 ng l⁻¹ for PFHpA, 1.43–16.54 ng l⁻¹ for PFOA and 0.22–6.28 ng l⁻¹ for PFOS. The average combined concentration of the ten PFCs in the samples ranged from 3.31 to 25.79 ng l⁻¹.

PFOS and PFOA concentrations in raw water (originated from Chao Phraya River) were 4.29 ng l⁻¹ and 16.54 ng l⁻¹, respectively. These values were comparable to the previous reported PFCs concentrations in Chao Phraya River, which were in the range 0.19–2.20 ng l⁻¹

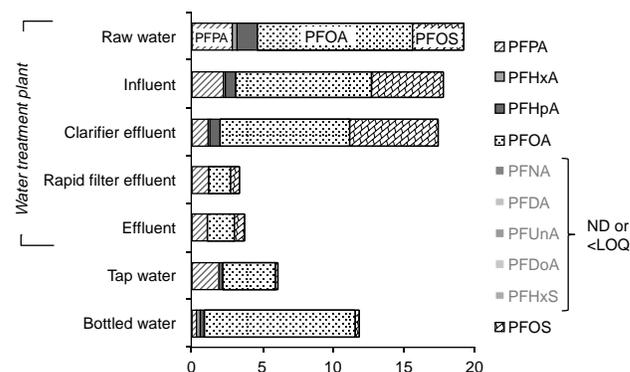


Figure 3 | Average PFCs concentrations in raw water, water treatment plant, tap water and bottled water samples (Note: ND = not detected, < LOQ = less than limit of quantification).

PFOS and $1.10\text{--}20.40\text{ ng l}^{-1}$ PFOA (Lien 2007). The highest concentration of PFCs was detected in raw water with a concentration of 25.79 ng l^{-1} while the average combined concentration of the ten PFCs in the effluent was 3.63 ng l^{-1} , indicating that there was some removal of PFCs by conventional water treatment processes. Detailed discussions on PFCs removal are given below.

Tap water was collected from 14 sampling points around Bangkok City. The average combined concentration of ten PFCs was found to be 6.03 ng l^{-1} . The concentration was much higher compared with the WTP effluent samples (finally treated tap water, 3.63 ng l^{-1}). Although the reason for the higher concentrations of PFCs in tap water is not well understood, it might be possible that PFCs contamination was fluctuating. A comprehensive study using composite samples or multiple samplings should be done.

In this survey, five brands of bottled water samples were purchased from tap water sampling locations in Bangkok. The sources of bottled water were in different places, not only in Bangkok. Advanced treatment processes such as reverse osmosis, ozonation and UV radiation were used for bottled water production. However, PFCs were still detected in all samples. Average PFCs concentrations in bottled water ranged from 0.22 to 10.55 ng l^{-1} , with PFOA occurring in the highest concentrations of all the PFCs. PFCs were found in much higher concentration in bottled water than in tap water. It appears that the advanced treatment processes were not effective in removing PFCs in large-scale application. The result in our study was similar to an earlier report from Osaka, Japan (Takagi *et al.* 2008).

Figure 3 shows average PFCs concentrations in different samples. The concentrations of PFCs in the raw water and WTP samples followed the general trends of PFOA > PFOS > PFPA. PFOA (57%), PFOS (19%) and PFPA (15%) were the dominant PFCs in raw water. PFHxA and PFHpA were detected as a lower percentage, 8% and 2%, respectively, while other PFCs were not detected in all samples. The relative abundance of PFCs in influent and clarifier effluent samples also showed a similar relation. The rapid sand filter effluent and WTP effluent samples showed different proportions with PFOA > PFPA > PFOS, while PFHxA and PFHpA were not detected. The results showed that the rapid sand filter has some effect on PFCs removal.

PFOA was the dominant PFC in tap water (60%) and bottled water (90%). This result was also shown in Ericson *et al.* (2008).

PFOS and PFOA contamination in tap water

Sampling was conducted in Bangkok City. Fourteen sampling points were selected. There were four tap water sampling points each in the W1 and W4 area, which produce a total tap water volume of 4.4 million m^3/d . Three tap water samples were collected each in the W2 and W3 area, which are the smaller WTPs producing a total of 870,000 m^3/d . Table 4 shows PFOS and PFOA concentrations and loadings in tap water. The average PFOS and PFOA concentrations in tap water were 0.17 and 3.58 ng l^{-1} , respectively. Average loading of PFOS and PFOA were 0.36 g/d and 2.58 g/d, respectively.

The concentration of PFOS was lower than that reported in Lien (2007), who reported that the average PFOS in tap water in Bangkok City was 5.29 ng l^{-1} in 2006, while PFOA concentration was comparable (4.19 ng l^{-1}). Recent studies have shown declining concentration of PFOS in tap water, environmental and blood samples following the phase-out of PFOS production (Renner 2008; Takagi *et al.* 2008).

W1 and W2 are located in the east side of Bangkok, distributing tap water to 82% of the population in the city. The average PFOS concentrations distributed from W1 and W2 were 0.33 and 0.17 ng l^{-1} , respectively. PFOA concentration in tap water samples were 0.94 ng l^{-1} from W1 and 0.97 ng l^{-1} from W2. A total loading of 1.31 mg/d PFOS and 4.06 mg/d PFOA were distributed from W1 and W2, respectively. For western Bangkok, W3 and W4 produce 970,000 m^3/d of tap water to 18% of the Bangkok population. PFOS and PFOA were found to be 0.04 ng l^{-1} and 5.84 ng l^{-1} , respectively, in tap water samples from W3. The higher concentrations were identified in W4, which produces tap water covering 82% of the western area, with 0.15 ng l^{-1} of PFOS and 6.56 ng l^{-1} of PFOA. PFOS and PFOA loadings were 0.13 mg/d and 6.24 mg/d, respectively. The result shows that PFOS and PFOA were not evenly distributed in all areas in the city. In this case, PFOA was detected at higher concentrations in the western area, while PFOS concentration was quite similar in all areas. PFOS

Table 4 | PFOS and PFOA concentrations and loading in tap water

Water treatment plant	Flow rate (m ³ /d)	Sample	Concentration (ng l ⁻¹)		Loading (g/d)	
			PFOS	PFOA	PFOS	PFOA
W1	3,600,000	T1	0.56 ± 0.06	1.62 ± 0.09	2.02 ± 0.22	5.83 ± 0.32
		T2	0.25 ± 0.32	0.55 ± 0.11	0.90 ± 1.15	1.98 ± 0.40
		T3	0.25 ± 0.15	0.80 ± 0.21	0.90 ± 0.54	2.88 ± 0.76
		T4	0.24 ± 0.15	0.80 ± 0.27	0.86 ± 0.54	2.88 ± 0.97
		<i>Ave</i>	0.33	0.94	1.19	3.38
W2	700,000	T5	ND	0.72 ± 0.13	ND	0.50 ± 0.09
		T6	0.06 ± 0.09	0.82 ± 0.13	0.04 ± 0.06	0.57 ± 0.09
		T7	0.45 ± 0.04	1.36 ± 0.29	0.32 ± 0.03	0.95 ± 0.20
		<i>Ave</i>	0.17	0.97	0.12	0.68
W3	170,000	T8	ND	1.43 ± 0.57	ND	0.24 ± 0.10
		T9	ND	10.37 ± 0.53	ND	1.76 ± 0.09
		T10	0.11 ± 0.16	5.71 ± 1.42	0.02 ± 0.03	0.97 ± 0.24
		<i>Ave</i>	0.04	5.84	0.01	0.99
W4	800,000	T11	ND	1.04 ± 0.19	ND	0.83 ± 0.15
		T12	ND	9.00 ± 4.20	ND	7.20 ± 3.36
		T13	0.04 ± 0.06	6.03 ± 0.10	0.03 ± 0.05	4.82 ± 0.08
		T14	0.56 ± 0.79	10.15 ± 8.16	0.45 ± 0.63	8.12 ± 6.53
		<i>Ave</i>	0.15	6.56	0.12	5.25

Note: ND = not detected; Ave = average.

and PFOA concentrations are based on many factors such as source of water, treatment process and pipelines. A comprehensive study of PFOS and PFOA concentration in the city is needed for the further study of risk assessment in the city. Currently, there is no standard or guideline value for PFOS and PFOA in Thailand. However, based on the value reported by the [State of New Jersey Department of Environmental Protection \(2009\)](#), PFOA concentrations in tap water found in Bangkok are not expected to cause any health risks.

Water treatment plant processes performance

The aqueous phase and particulate phase concentrations of PFOS and PFOA in different samples in four WTPs are illustrated in [Figure 4](#). PFOS and PFOA were detected in particulate phase in most samples (influent and clarifier effluent samples). W1, W2 and W3 have the same water source. PFOS and PFOA concentrations were detected in much higher concentrations in the particulate phase than

the liquid phase, with a ratio of 9.5:1. In contrast, W4, which has a different raw water source, had a much lower particulate: liquid ratio of 0.94:1 indicating that this ratio was dependent on the sources of the water. It seemed that PFOS and PFOA in the particulate phase were effectively removed by rapid sand filtration in W1, W2 and W3, while PFOS and PFOA in W4 were effectively removed by the primary sedimentation.

For the liquid phase samples, PFOS and PFOA concentrations were quite similar during the treatment processes in most WTPs except PFOA in W3 and W4. The removal rate of PFOA in W3 and W4 were 100% and 45%, respectively. However, the average removal rates of PFOS and PFOA in aqueous phase were 45% and -4%, respectively. These removal rates were comparable to the earlier report of [Takagi *et al.* \(2008\)](#), which supports the breakdown of precursors to PFOS and PFOA during the treatment processes. Although some percentages of PFOS can be removed by the current treatment processes, the removal rates of PFCs were lower than 50% in most WTPs.

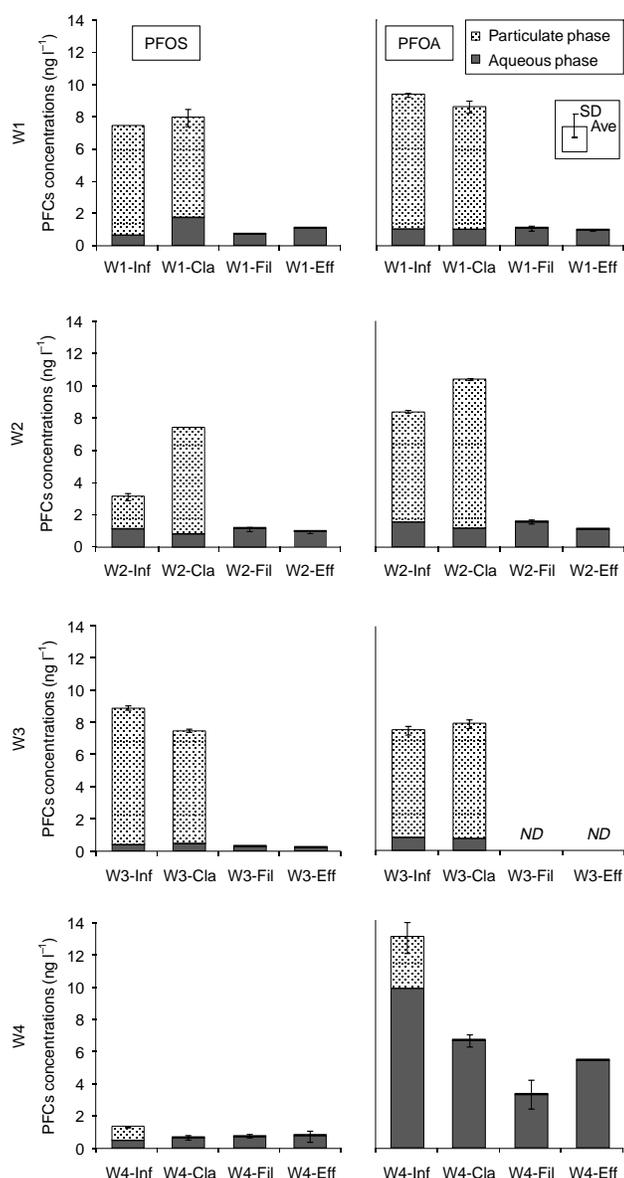


Figure 4 | PFOS and PFOA concentrations in four WTPs (Inf = influent of WTP, Cla = effluent of primary clarifier, Fil = effluent of rapid sand filtration, Eff = effluent of WTP).

Figure 5 shows the relationship between PFOS and PFOA concentrations in aqueous phase of influent of WTP and tap water. Eighty per cent of PFOS plots and 88% of PFOA plots were varied around the linear line 1:1, suggesting that the treatment process did not remove PFCs completely. There was a limitation on removal of PFCs in aqueous phase samples. In general, it can be concluded that the current treatment processes were not

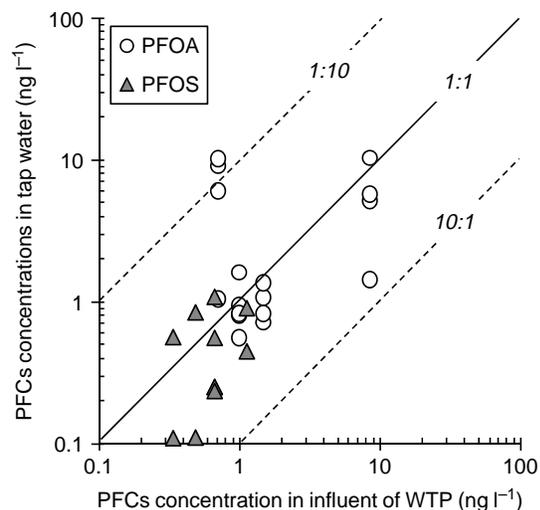


Figure 5 | Relationship between PFOS and PFOA concentrations in aqueous phase of influent of WTP and tap water.

effective in removing PFCs completely. Nevertheless, PFCs in particulate phase were effectively removed by rapid sand filtration.

Comparing PFOS and PFOA concentrations among other Asian cities

Previous studies have reported PFOS and PFOA concentrations in tap water and bottled water from Asian cities including Kuala Lumpur, Singapore, Hanoi, Shenzhen, Taipei, Osaka and Tokyo (Lien 2007; Tanaka *et al.* 2008; Takagi *et al.* 2008). Figure 6 shows PFOS and PFOA concentrations in Bangkok and other Asian cities. PFOS concentrations varied from 0.18 to 7.34 ng l⁻¹. Bangkok tap water and bottled water samples had lower average PFOS concentration among those reported, while the highest was detected in Taipei. PFOS detected in tap water in the South-east Asian cities (Bangkok, Kuala Lumpur, Singapore and Hanoi) were lower than Shenzhen, Taipei, Osaka and Tokyo. The trends of PFOS concentrations were comparable to those in surface waters, which are the sources of tap water.

PFOA concentrations ranged from 2.50 to 14.75 ng l⁻¹. Concentration of PFOA in Bangkok City was the highest among the other cities in South-east Asia. Average PFOA concentration in tap water in Bangkok City was comparable

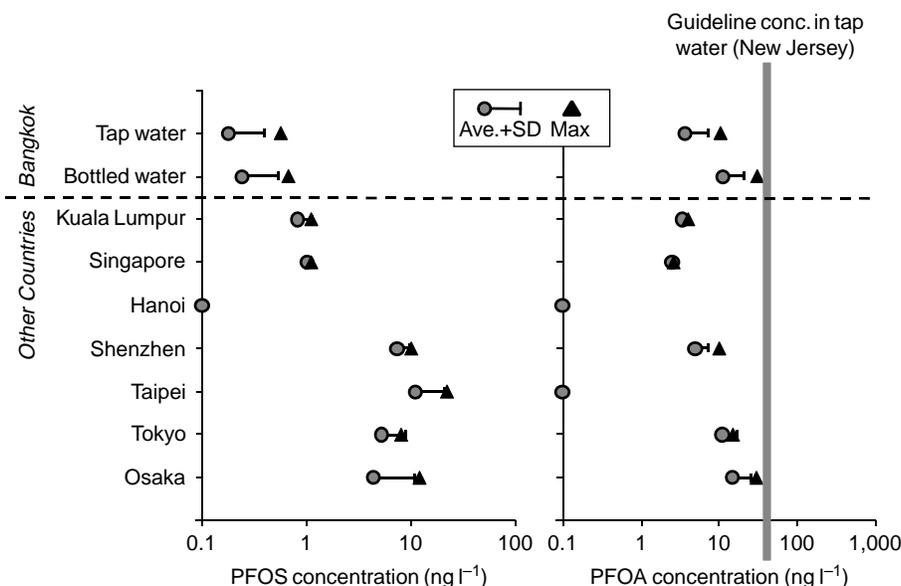


Figure 6 | Comparison of PFOS and PFOA concentrations with other Asian cities (source: Kuala Lumpur, Singapore, Hanoi, Shenzhen and Taipei: Tanaka et al. 2008; Tokyo: Lien 2007; Osaka: Takagi et al. 2008).

to Shenzhen but much lower than Osaka and Tokyo, which were at the same level as PFOA detected in bottled water in this study.

CONCLUSIONS

PFCs were detected in all tap water and bottled water samples. PFPA, PFHxA, PFHpA, PFOA and PFOS were detected in most samples, while the other five PFCs (PFNA, PFDA, PFUnA, PFDoA and PFHxS) were not detected (ND) or lower than the limit of quantification ($< \text{LOQ}$). The concentrations of PFCs in the raw water and WTP samples followed the general trends of $\text{PFOA} > \text{PFOS} > \text{PFPA}$. PFOS and PFOA concentrations in raw water were found to be 4.29 ng l^{-1} and 16.54 ng l^{-1} , respectively. The average PFOS and PFOA concentrations in tap water were 0.17 and 3.58 ng l^{-1} , respectively. The tap water results also showed that PFOS and PFOA were not similarly distributed in all areas in the city. In this case, PFOA was detected at a higher level in the western area, while PFOS concentration was quite similar in all areas. PFCs were found in much higher concentrations in bottled water than in tap water.

Furthermore, the average removal rates of PFOS and PFOA in aqueous phase were 45% and -4% , respectively. In general, it can be concluded that the current treatment

processes were not effective in removing PFCs. Nevertheless, PFCs in particulate phase were effectively removed by primary sedimentation and rapid sand filtration. Currently, there is no standard or guideline value for PFOS and PFOA in Thailand. However, based on the value reported by the State of New Jersey Department of Environmental Protection (2009), PFOA concentrations in tap water and bottled water found in Bangkok were not expected to cause any health risks.

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