Levels of perfluorinated compounds (PFCs) in groundwater around improper municipal and industrial waste disposal sites in Thailand and health risk assessment
Chanidaporn Hongkachok, Suwanna Kitpati Boontanon, Narin Boontanon, Shigeo Fujii, Shuhei Tanaka and Yuji Suzuki

ABSTRACT
The aims of this study were to examine the levels of perfluorinated compounds (PFCs) in groundwater around improperly developed municipal and industrial waste disposal sites, including estimating non-cancer risk and cancer risk from ingestion of the groundwater. A total of 27 groundwater samples were collected from two cities in Thailand, Ayutthaya and Chonburi. Seven target compounds were extracted by solid phase extraction (SPE) and analyzed by high-performance liquid chromatography–tandem mass spectrometer (HPLC–MS/MS). The results showed that the total PFCs in groundwater around municipal waste disposal sites (MWDSs) varied from 1.68 to 7.75 ng/L. In groundwater around the industrial waste disposal site (IWDS), total PFCs varied from 2.64 to 42.01 ng/L, which were significantly different from those found in groundwater around the MWDSs at $p < 0.01$. PFOS and PFOA were ubiquitous in both areas, while perfluorohexane sulfonate (PFHxS) was frequently found in the samples around IWDS. The findings possibly suggest that PFHxS has been introduced for use as an alternative substance for most current C8 and higher due to it having shorter chain length and shorter half-lives. The results for both non-cancer risk and cancer risk in all samples were acceptable.

Key words | groundwater, health risk assessment, perfluorinated compounds, Thailand, waste disposal sites

INTRODUCTION
Perfluorinated compounds (PFCs) are anthropogenic chemicals which were first synthesized in the early 1940s and nowadays are being massively reported in all environments in term of concentrations, sources of contamination, and implications. The most prevalent ones are perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). Due to their unique characteristics: stability, surfactivity, hydrophobicity, and lipophobicity; they have been commonly used in a variety of consumer products, e.g. textiles and leather, metal plating, paper and packaging, coating additives, cleaning products, and pesticides (Prevedouros et al. 2006). Besides their useful properties, their persistency, toxicity and bioaccumulative nature have caused many environmental and human health problems (Jahnke & Berger 2009). Some researchers have revealed that exposure to PFCs may affect the reproductive function in women and cause thyroid disease in the general public (Knox et al. 2011; Melzer et al. 2010). Aquatic environments are potentially expected to be their sink disposal in the environment because of their high water solubility and low volatility. Therefore, they are frequently detected in wastewater, drinking water, tap water, surface water, and groundwater.

Groundwater is an important freshwater resource in rural areas in Thailand because it is fresh and clean water that is easily extracted. However, groundwater pollution may not be avoidable owing to there being many potential sources, especially improperly developed waste disposal sites. Furthermore, in Thailand, landfill burning has been occurring often in dumps set up for illegal disposal of garbage, especially involving toxic waste. In addition, over 50% of industrial waste is not being properly treated, but is illegally dumped at legal and illegal landfills. These sites
are suspected to be important sources of PFCs contamination. Other suspected sources of contamination could be leachate from landfills near groundwater wells. The study of trace elements such as PFCs in Thailand’s groundwater has been limited. Therefore, it was necessary to undertake such a study in order to provide information for further study and for developing environmental standards and regulation. This study aimed to analyze and compare the existence of PFCs in groundwater around municipal waste disposal sites (MWDSs) and an industrial waste disposal site (IWDS), as well as estimate health risks of non-carcinogenic and carcinogenic effects from drinking groundwater.

**MATERIALS AND METHODS**

**Standards and reagents**

In this study, there are seven PFCs standards: perfluorohaptonic acid (PFHpA), perfluorooctanoic acid (PFOA), perfluorooctanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnA), perfluorohexane sulfonate (PFHxS), and perfluorooctane sulfonate (PFOS) were selected. Methanol HPLC grade (>99.99%) and methanol ACS grade, acetonitrile HPLC grade (>99.8%), and ammonium acetate (98%) were purchased from Merck KGaA (Millipore, Germany). Ultrapure water was produced by a RiOs-DI® Water Purification System (Millipore, Germany). Potassium Hydrogen Phthalate (KHP) was used to prepare a standard curve for dissolved organic carbon (DOC) analysis.

**Sampling sites and sample collection**

Study areas in this work were based on information obtained from the Department of Groundwater Resources (DGR 2015) and Pollution Control Department (PCD) of Thailand. The sampling points were chosen in two cities in Thailand, which were reported to have a large amount of accumulated waste; the maps are shown in Figure 1. The groundwater samples were collected from domestic groundwater wells around Bang Chai MWDS (Figure 1, 1(a)) and Sena MWDS (Figure 1, 2(a)), Ayutthaya province (n = 12) and Map Phai IWDS (Figure 1(b)), Chonburi province (n = 15). The samples were directly collected from faucets connected to the groundwater well and pumping system by using PET
bottles with screw caps, which were rinsed with methanol and dried prior to use. The containers were rinsed by the water samples three times to prepare the same conditions as the samples before collection. After sampling, the samples were stored in a cooler box and brought back to the Water Quality Analysis Laboratory, Mahidol University. The samples were filtered by GF/B glass filter. Glass bottles and glass equipment were avoided during the experiment because target compounds may bind to the glass in aqueous solutions. Teflon equipment was also avoided because interferences may be introduced to the samples of extracts (Hansen et al. 2002; Yamashita et al. 2004).

Sample extraction and PFC analysis

PFCs were extracted by solid phase extraction (SPE) technique. SPE has become a more popular sample preparation compared to liquid–liquid extraction (LLE) and has been applied in many studies. The reasons that it has surpassed LLE is low consumption of organic solvents and ease of operation (Zhao et al. 2007). A 1,500 mL water sample was filtered into PrecepC-Agri (C18) cartridges using concentrators at a flow rate of 10 mL/min. Before loading, the concentrators were washed by methanol at a flow rate of 10 mL/min for 5 min, followed by milli-Q water at a flow rate of 10 mL/min for 10 min and the cartridges were preconditioned by 10 mL of methanol, followed by two times of 10 mL milli-Q water. After that, target analytes were eluted by 4 mL of methanol, followed by 2 mL of acetonitrile. Eluents were gently purged by nitrogen gas and reconstituted with 0.5 mL of 30% acetonitrile. Analysis of target PFCs was performed by using Agilent 1200SL HPLC. The target compounds were quantified using Agilent 6400 MS/MS, in negative mode of electrospray ionization. The analytical parameters are listed in Table 1. Mobile phases consisted of (A) 10 mM ammonium acetate in ultrapure water and (B) 100% acetonitrile (HPLC/MS grade). The initial mobile phase was 50% acetonitrile, and then ramped up to 60% acetonitrile at 16.5 min, and kept for 3.5 min. At 23 min, acetonitrile went up to 70%, and then linearly ramped up from 70% to 90% at 26 min. After that, the mobile phase gradient ramped down again to 30% acetonitrile for 4 min. The total running time was 30 min.

Quality assurance

Five points of a calibration curve covering 0.1 to 10 μg/L were prepared with the regression coefficient (R²) > 0.999. Limit of detection (LOD) and limit of quantification (LOQ) of the measurement method were defined as the concentration with signal-to-noise ratios (S/N) equal to 3:1 and 10:1, respectively. Recovery experiments were done by spiking 10 μg/L of each PFC standards into the samples before the extraction process. A blank sample using Milli-Q water was prepared and analyzed with the same procedure as the spiked samples. The recoveries of the seven PFCs in groundwater matrix were 95.9 ± 2.86% for PFHpA, 106.94 ± 7.14% for PFOA, 99.02 ± 1.81% for PFNA, 91.56 ± 3.39% for PFDA, 83.82 ± 7.06% for PFUnA, 100.87 ± 1.69% for PFHxS, and 93.16 ± 4.74% for PFOS, which are displayed in Table 2.

Dissolved organic carbon analysis

Five points of a standard curve were prepared by potassium hydrogen phthalate (KHP). A 25 mL of water sample was filtered by 1 μm GF/B glass fiber filter coupled with vacuum filtration apparatus. Then, the DOC was automatically analyzed by a total organic carbon analyzer (TOC-VCSH/ASI-V/SSM-5000A, Shimadzu, Japan) using the non-purgeable organic carbon (NPOC) method.

Statistical analysis

A difference of mean PFC levels in the groundwater around the MWDSs and the IWDS was analyzed by the independent sample t-test using IBM® SPSS® Statistics 20 to illustrate whether there was significance. Correlations between DOC and individual PFCs concentrations were performed by Pearson Product Moment.
Health risk assessment

Health risk assessment has been considered as the probability of harmful effects to human health resulting from exposure to chemical contaminants. Ever since PFCs have become new emerging contaminants, several countries have developed standard criteria to promote an acceptable level of PFCs that humans can be exposed to without any adverse effects. However, no PFC levels were ever recommended in Thailand, therefore, the thresholds and input parameters for assessment in this study were derived from the United States Environmental Protection Agency (US EPA) model and information provided by the New Jersey Department of Environmental Protection (US EPA 2011, 2016a, 2016b; NJDEP 2015). The baseline information for the parameters are provided in Table 3.

Calculation of PFCs daily intake

The magnitude of the chemical exposures, typically represented as the contaminant daily intake (CDI), was estimated from frequency and duration of human exposure over a lifetime, as shown in Equation (1) for the parameters in the risk assessment.

\[
CDI_{\text{oral}} = \frac{(C_{\text{water}} \times IR_{\text{oral}} \times EF \times ED)}{BW \times AT} \tag{1}
\]

where \(CDI_{\text{oral}}\), \(C_{\text{water}}\), \(IR_{\text{oral}}\), \(BW\), and \(AT\) represent chronic daily intake (mg/kg/day), concentration of PFCs in ground-water (ng/L), intake rate (L/day), body weight (kg), and averaging time (day), respectively.

Risk characterization

Typically, the health risk can be expressed in terms of a non-carcinogenic risk and a carcinogenic risk.

The non-carcinogenic risk

The non-carcinogenic risk was determined from CDI and reference dose (RfD) to produce a hazard quotient (HQ). The HQ is the ratio of exposure of hazardous chemicals and their reference dose (RfDs) (Equation (2)), if the HQ value is equal to or less than one, the risk is not considered significant to human health.

\[
HQ = \frac{CDI}{\text{RfD}} \tag{2}
\]
where HQ is the hazard quotient (unit-less), CDI is the chronic daily intake (mg/kg/day), and RfD is a reference dose.

**The carcinogenic risk**

The carcinogenic risk was estimated through multiplying the CDI by cancer slope factor (CSF), given in Equation (3). CSF represents a probability of developing cancer during an individual lifetime. The carcinogenic risk which does not exceed $10^{-6}$ has been accepted. This benchmark was adopted by the US EPA (US EPA 2000) and is commonly used worldwide.

$$\text{Carcinogenic risk} = \text{CDI} \times \text{CSF}$$

where CDI is the chronic daily intake (mg/kg/day) and CSF is cancer slope factor (mg/kg/day).

**RESULTS AND DISCUSSION**

**PFCs concentrations and their distributions in groundwater around the municipal waste disposal sites (MWDSs) and industrial waste disposal site (IWDS)**

As can be seen in Figures 2, 1(a) and 2(a), six of the seven PFCs were detected in groundwater around the MSWDs, which were PFHxP, PFOA, PFNA, PFUnA, PFHpA, and PFOS; however, PFHxS was found in only one sample at a very low level. PFDA was absent from any of the groundwater around the MWDSs. The total PFC levels in the samples around the MWDSs varied from 1.68 ng/L to 7.75 ng/L. Among them PFOA and PFOS were outstanding. PFOA made major contributions that ranged from 21.84% up to 80.20%, followed by PFOS (8.78% to 78.16%), PFHpA (11.52% to 21.36%), PFUnA (6.37% to 20.21%), PFNA (4.65% to 21.68%), and the remainder was PFHxS (1.64%). Figure 2, 1(b) and 2(b) show the PFCs concentrations and their distribution profiles in groundwater around the MWDSs, in which all the PFCs compounds were measured. The total PFCs around the MWDSs was quantified at concentrations of 2.64 ng/L to 42.01 ng/L, which were much higher than those around the MWDSs. Similar to those found in the groundwater around MWDSs the prevalent ones were PFOA and PFOS. PFOA showed the highest distribution in groundwater around IWDS with a frequency that ranged from 23.71% to 86.75%, followed by PFOS (7.77% to 68.75%), PFHpA (1.46% to 16.10%), PFNA (1.09% to 14.04%), PFHxS (0.51% to 12.64%), PFUnA (0.68% to 10.42%), and PFDA (0.62% to 5.41%), respectively. In addition to PFC variations in the groundwater, this could be mainly influenced by leachate components and properties which resulted from many factors such as rain input, waste arrangement, waste filling procedure, age and waste composition, etc. (Eschauzier et al. 2013; Yan et al. 2015).

Besides the concentration, PFHxS was frequently observed in the samples around IWDS, which might indicate that it has been used as an alternative substance to long-chain perfluorinated compounds in industrial processes due to it having a shorter chain length, or it might be from the degradation product of other alternative compounds such perfluorohexane sulfonyl fluoride (PFHxSF, C6F13SO2F)-based and their derivatives (Wang et al. 2013). The statistical analysis result indicates that the difference between the total PFCs concentrations in groundwater around the MWDSs and the IWDS was statistically significant at $P < 0.01$. However, this was not a big surprise. It is similar to the previous research, which reported that high PFCs concentrations were found in the industrial wastewater treatment plant effluent compared to the municipal wastewater treatment plant effluent in Taiwan (Lin et al. 2010). Additionally, the contamination of PFCs in groundwater in this study were found to be higher than the concentrations in tap water as well as river water in Thailand reported in previous studies (Kunacheva 2009; Kunacheva et al. 2009; Boontanon et al. 2012).

**Comparison of PFCs contaminations in groundwater in this study and those from other countries**

Table 4 shows the concentration ranges of PFCs in groundwater around the MWDSs and IWDS compared to those found in other countries. When compared to the levels found in other studies, PFHpA and PFHxS detected in this study were comparable to, while PFOA, PFNA and PFOS were quite higher compared to those previously reported in Vietnam. The PFCs concentrations in Japan and China groundwater were reported in greater quantity than this study. Surprisingly, the study in Tokyo, Japan reported that high PFCs concentration in groundwater was caused by pollution from street runoff and a leaking sewer pipe (Murakami et al. 2009). Extremely high PFC levels in groundwater were detected around a fire-training area in Northern Michigan, USA. The groundwater contained various PFCs concentrations in the μg/L level, even 5 years after fire-training had last been conducted at that site.
Figure 2 | Total PFCs concentrations (1a and 1b) and their distribution profiles (2a and 2b) in groundwater around the MWDSs and the IWDS, respectively.

Table 4 | Comparison of PFCs contaminations (ng/L) in groundwater in this study and those from other countries

<table>
<thead>
<tr>
<th>Study location</th>
<th>PFHpA</th>
<th>PFOA</th>
<th>PFNA</th>
<th>PFHxS</th>
<th>PFOS</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thailand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Around MWDSs, Ayutthaya</td>
<td>&lt;LOQ-0.91</td>
<td>0.65–6.22</td>
<td>N.D.-0.80</td>
<td>N.D.-0.07</td>
<td>&lt;LOQ-3.15</td>
<td>This study</td>
</tr>
<tr>
<td>Around IWDS, Chonburi</td>
<td>N.D.-1.98</td>
<td>0.80–34.96</td>
<td>N.D.-2.14</td>
<td>N.D.-3.73</td>
<td>1.39–25.88</td>
<td>This study</td>
</tr>
<tr>
<td>Vietnam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanoi</td>
<td>N.D.-1.3</td>
<td>N.D.-2.5</td>
<td>N.D.-0.45</td>
<td>N.D.</td>
<td>N.D.-0.64</td>
<td>Duong et al. (2015)</td>
</tr>
<tr>
<td>Ho Chi Minh</td>
<td>N.D.-0.58</td>
<td>N.D.-4.5</td>
<td>N.D.-0.36</td>
<td>N.D.-6.0</td>
<td>N.D.-8.2</td>
<td>Duong et al. (2015)</td>
</tr>
<tr>
<td>Japan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tokyo</td>
<td>0.47–60</td>
<td>&lt;0.1–20</td>
<td>0.1–94</td>
<td>N.A.</td>
<td>0.28–133</td>
<td>Murakami et al. (2009)</td>
</tr>
<tr>
<td>China</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eastern China</td>
<td>&lt;0.5–99.7</td>
<td>&lt;0.1–475</td>
<td>&lt;0.1–22</td>
<td>&lt;0.5–1.9</td>
<td>&lt;0.5–94.9</td>
<td>Chen et al. (2016)</td>
</tr>
<tr>
<td>USA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michigan</td>
<td>N.A.</td>
<td>N.D.-105,000</td>
<td>N.A.</td>
<td>9,000–120,000</td>
<td>4,000–110,000</td>
<td>Moody et al. (2005)</td>
</tr>
<tr>
<td>The Netherlands</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The central part</td>
<td>&lt;LOQ-320</td>
<td>0.5–1,800</td>
<td>&lt;LOQ-0.1</td>
<td>&lt;LOQ-99</td>
<td>N.A.</td>
<td>Eschauzier et al. (2013)</td>
</tr>
</tbody>
</table>

MWDS, represents municipal waste disposal site; IWDS, represents industrial waste disposal site; N.A., represents not analyzed; N.D., represents not detected; <LOQ, represents less than limit of quantification.
A study in the Netherlands showed the PFCs concentration was much higher than detected in this study. They found that PFCs contamination in groundwater had originated from a former landfill, a military camp, and an urban area (Eschauzier et al. 2013) similar to those findings in the USA and Sweden. Those studies indicated that high PFC levels were observed in urbanized and industrialized areas which strongly support the results of this study.

**Relationship between PFCs concentrations and DOC concentrations**

When considering the total PFCs in groundwater and DOC, which is presented in Figure 3, the relationship between total PFCs and DOC showed a direct variation. It should be noticed that in the sampling points where higher PFC levels were observed, DOC levels were also found to be higher in those samples. This could be significant evidence to support the hypothesis that the groundwater has been contaminated by the waste disposal sites, particularly the IWDS due to industrial activity and manufacturing processes, suggesting that industrial waste disposal plays an important role in PFCs contamination in groundwater.

Due to a long-term leaching behavior as well as the complexity of PFCs movement, the mobility and contamination of PFCs is not only dependent on their physical-chemical properties, but also their associations with solution-specific properties such as organic carbon content. Statistically positive correlations between DOC and concentration of some PFCs compounds were observed, high correlations ($P < 0.01$) were found for PFNA ($r = 0.610$) and PFDA ($r = 0.606$). A moderate correlation ($P < 0.05$) was found for PFHpA ($r = 0.478$), while a non-statistically significant and small correlations were found for PFOA ($r = 0.241$), PFUnA ($r = 0.034$), PFHxS ($r = 0.087$), and PFOS ($r = 0.107$). Similar findings have been previously reported by Gallen et al. (2017), where significant correlations between PFCs and organic carbon were also found. This is consistent with the association between hydrophobicity properties and the potential of hydrophobic partitioning with organic carbon. The sorption of PFCs to natural sediments is highly influenced by sediment-specific parameters, in which the organic carbon content resulted from the importance of hydrophobic interactions (Higgins & Luthy 2006). Since PFCs are hydrophobic and lipophobic, they could interact with the hydrophilic surface of minerals and be absorbed. Therefore, this could be one factor contributing to the PFCs concentrations in a water environment.

**Human health risk assessment**

Although, those PFC levels did not exceed the health advisory levels for drinking purpose (70 ng/L for individual PFOA and PFOS or combined) (US EPA 2016a, 2016b), the long term consumption of the groundwater without any water treatment may cause unexpected adverse effects. Therefore, evaluation of health risk is necessary to ensure whether consumption of this water is safe.

![Figure 3](https://iwaponline.com/wst/article-pdf/2017/2/457/216912/wst2017020457.pdf)
As mentioned above, health risk assessment was estimated only for exposure by drinking, although the water has been being consumed for showering; but in the general population, dermal absorption of PFCs is extremely slow and not a significant exposure pathway (US EPA 2016c; NCEH 2017). Table 5 shows the estimation of non-cancer risk and cancer risk of PFOA, PFNA, and PFOS from drinking groundwater. The non-carcinogenic risk was represented by the HQs which were calculated by the total daily intake and RfDs. There is no instance in which the combined HQ for non-cancer risk of those samples exceeded one, which means the risks were all acceptable. It could be concluded that they were observed as having less potential for non-carcinogenic toxicity.

In terms of the carcinogenic risk, it has only been focused on PFOA because of limited CSF data. The estimated carcinogenic risks of all samples were lower than \(10^{-6}\) (benchmark level), so the risks were all acceptable; suggesting that drinking the groundwater might not induce an unexpected cancer risk, nor would it increase the probability of developing cancer during a person’s lifetime.

<table>
<thead>
<tr>
<th>Sample</th>
<th>CDI (mg/kg/day)</th>
<th>Non-carcinogenic risk</th>
<th>Carcinogenic risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PFOA</td>
<td>PFNA</td>
<td>PFOS</td>
</tr>
<tr>
<td>MW_BC01</td>
<td>1.06E-08</td>
<td>–</td>
<td>3.78E-08</td>
</tr>
<tr>
<td>MW_BC02</td>
<td>1.98E-08</td>
<td>–</td>
<td>4.69E-08</td>
</tr>
<tr>
<td>MW_BC03</td>
<td>1.83E-08</td>
<td>–</td>
<td>1.29E-08</td>
</tr>
<tr>
<td>MW_BC04</td>
<td>9.68E-09</td>
<td>–</td>
<td>1.58E-08</td>
</tr>
<tr>
<td>MW_SN01</td>
<td>5.80E-08</td>
<td>1.20E-08</td>
<td>8.66E-09</td>
</tr>
<tr>
<td>MW_SN02</td>
<td>1.77E-08</td>
<td>5.95E-09</td>
<td>–</td>
</tr>
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<td>MW_SN03</td>
<td>2.31E-08</td>
<td>–</td>
<td>1.86E-08</td>
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<td>MW_SN04</td>
<td>5.60E-08</td>
<td>–</td>
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<td>MW_SN05</td>
<td>3.08E-08</td>
<td>–</td>
<td>1.90E-08</td>
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<td>MW_SN06</td>
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<td>1.76E-08</td>
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<td>MW_SN07</td>
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<tr>
<td>MW_SN10</td>
<td>1.83E-08</td>
<td>5.90E-09</td>
<td>1.01E-08</td>
</tr>
</tbody>
</table>

*Concern risk <10^{-6} is acceptable.*
CONCLUSIONS

In this study, the contamination of PFCs in groundwater was investigated in order to understand their contamination and their potential harmfulness to the consumers. All target PFCs were detected in most samples particularly in the groundwater around the IWDS. Among them, PFOS and PFOA were predominant in the samples both around MWDSs and IWDSs, which could confirm that PFOS and PFOA are still being used. Moreover, this study also found that total target PFCs have highly contaminated the groundwater around the industrial waste disposal site (IWDS) compared to those quantified in the groundwater around the municipal waste disposal sites (MWDSs) with statistical significance, which could be remarked that the IWDS might be a potentially serious source of contamination. In comparison to the recommendation levels, the concentrations did not exceed the health advisory levels for drinking purposes suggested by the US EPA; however, regular measurements by government agencies for the reduction of PFCs in groundwater in sensitive areas around waste disposal sites are necessary. Furthermore, strict law enforcement should be used to control and eliminate illegal waste disposal. In terms of the relationship of total PFCs and DOC, they showed a direct correspondence. This could be noteworthy evidence to support the idea that groundwater has been contaminated by the waste disposal sites, particular the IWDS. In addition, positive correlations between some PFCs and DOC were observed, indicating the associations of hydrophobicity of PFCs chain and organic matter. By health risk assessment, the estimated risk for the non-carcinogenic effects as well as the carcinogenic risk were not observed in any groundwater samples. However, continuous monitoring should be important to follow up their contaminations since they are persistent and bioaccumulative. Further investigation on PFCs sorption potential on soil particles would be beneficial for waste management in order to understand their movement mechanism and to evaluate their potential release to the surrounding environment, especially groundwater.

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