Evaluation of PFCA removal by SAT using a pilot-scale reactor

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Abstract

Wastewater reuse using soil aquifer treatment (SAT) is a rational and realistic solution in countries and regions with limited freshwater resources. The behaviour and removal of perfluoroalkyl carboxylic acids (PFCAs) under long hydraulic retention times (HRTs) in SAT may warrant further investigation. In this study, actual treated effluent from a wastewater treatment plant (WWTP) was continuously treated using a pilot-scale SAT reactor with a designed HRT of 30 days, located in the WWTP; PFCA removal characteristics were investigated based on a 14-month monitoring period. Continuous SAT reactor operations were accomplished for 30 months under the designed HRT (28 days, as calculated by a tracer test); stable treatments were achieved during the period, represented by dissolved organic matter removal from 3.94 mgC/L to 0.701 mgC/L. Removal of PFCAs by SAT under an HRT of 28 days was found to be difficult, as indicated by perfluorooctanoic acid level from 18.4 to 19.0 ng/L. In addition, PFCA concentrations may be increased after SAT, probably due to the influences of PFCA precursors; this is indicated by the increase in perfluorononanoic acid from 11.6 to 14.1 ng/L. Based on the guideline values, further removal of PFCAs in SAT-treated effluent may be required.

Key words: arid regions, indirect potable reuse, perfluorinated carboxylic acids, pilot-scale reactor, soil aquifer treatment

INTRODUCTION

Fresh water is an essential and limited resource in many countries and regions in the world. Water resources management is needed in these countries and regions, and wastewater reuse using soil aquifer treatment (SAT) is a rational and realistic solution. Advantages of water reuse by SAT include greater potential for water quality improvement through infiltration, low cost and usage of the aquifer zone as underground storage. In addition, the system is widely applied in arid regions in countries such as the U.S., Israel and South Africa for the purpose of indirect potable reuse and agricultural and landscape irrigation (Asano et al. 2007).

Water purification and improvement of the quality of treated effluent from wastewater treatment plants (WWTPs) are important uses of SAT. Schriks et al. (2010) compared the maximum
concentrations of chemicals in surface water and/or groundwater based on the concentrations specified in the (provisional) guidelines for toxicological assessment of drinking water. In addition, they suggested that the chemicals for which the ratios of the maximum concentrations in the surface and/or groundwater to those specified in the guidelines exceed 0.2 may warrant further investigation.

In the case where treated effluent from WWTPs is reused after SAT for potable purposes, the treated wastewater is a source of potable water. Therefore, in cases of chemicals present in treated wastewater with the ratios of the maximum concentrations to those specified in the guidelines exceeding 0.2, the behaviour and the removal characteristics of the chemicals by SAT must be evaluated.

Perfluorinated surfactants, including perfluoroalkyl carboxylic acids (PFCAs), are used in numerous products such as surfactants, fire retardants and paper and textile coatings (Murakami et al. 2008). Perfluorooctanoic acid (PFOA) is widely known to be one of the main products in PFCAs; the U.S. Environmental Protection Agency (USEPA) has recently released lifetime health advisories for concentrations of PFOA and perfluorooctane sulfonate in drinking water at 70 ng/L (USEPA 2016). In addition, PFOA monitoring levels have been established in the U.K. (300 ng/L; U. K. Drinking Water Inspectorate 2009) and by health-based drinking water guidance in New Jersey, U.S. (40 ng/L; State of New Jersey Department of Environmental Protection 2007). Murakami et al. (2008) reported that PFOA in secondary treated effluent ranged from 10 to 68 ng/L in Japan; this implies that the ratio of the maximum concentration to the lifetime health advisories in USEPA, the monitoring level in U. K. and the health-based drinking water guidance in New Jersey exceeded 0.2. In addition, the maximum concentrations of PFOA in treated effluents in the U.S. (1,050 ng/L; Sinclair & Kannan 2006) and Canada (180 ng/L, based on the maximum value of average concentrations from seven WWTPs; D’eon et al. 2009) exceed 0.2 with respect to the values in USEPA, U.K. and New Jersey. Moreover, the maximum concentrations of PFOA in treated effluents in Switzerland (35 ng/L, based on the maximum value of average concentrations from seven WWTPs; Huset et al. 2008) exceed 0.2 with respect to the lifetime health advisories in USEPA and the health-based drinking water guidance in New Jersey. Therefore, it can be inferred that the behaviour and the removal characteristics of PFCAs, including PFOA, should be investigated in SAT for potable reuse of treated water.

It has been reported that biodegradation of PFCAs was not expected in WWTPs (Shivakoti et al. 2010) in which the hydraulic retention time (HRT) is generally less than 1 day. Meanwhile, SAT is operated at a HRT to the order of months (e.g. the retention time shall be no less than two months for indirect potable reuse after SAT with surface application (State Water Resources Control Board 2015), and little is known about the removal characteristics of PFCAs by SAT under long HRT.

In the present study, actual treated effluent from a WWTP was continuously treated using a pilot-scale SAT reactor with a designed HRT of one month, located in the WWTP. Organic matter and nutrients were monitored to evaluate the stability of SAT. In addition, PFCA removal characteristics were investigated based on long-term monitoring over a period of 14 months.

**MATERIALS AND METHODS**

**Treated effluent**

Treated effluent of an anaerobic-anoxic-oxic (A2O) process before chlorination, which is mainly used to treat domestic wastewater, in a WWTP in Kyoto City, Japan, was used for SAT. The A2O-treated effluent was collected from a 100 cm depth in the final sedimentation tank by using a hose consisting of a 0.05 cm mesh such that large particles in the A2O-treated effluent are not collected. Annual median (minimum–maximum) values of suspended solids and chemical oxygen demand in FY2012 were 1 (1–3) mg/L and 7.2 (6.2–10) mg/L, respectively (Kyoto City Waterworks Bureau 2013). Median (minimum–maximum) pH and dissolved oxygen (DO) during operation period of the SAT
reactor, described below, was 6.58 (6.16–7.67) and 3.36 (1.12–6.70) mg-O₂/L, respectively (Takabe et al. 2014).

A tank made of polyethylene was set near the pilot-scale SAT reactor (see Figure 1). The collected A2O-treated effluent was stored in the tank and flowed into the SAT reactor through tubes. The widest dimension of the tank was 62 cm × 93 cm × 60 cm, and the effective volume was 100 L. The tank had two water level sensors installed at a height of 12 cm and 37 cm from the bottom. When the water level in the tank decreased to 12 cm from the bottom, collection of the A2O-treated effluent from the sedimentation tank by a pump (PC-831B, Sanso, Japan) was initiated. When the water level in the tank increased to 37 cm from the bottom, the collection was stopped. The A2O-treated effluent in the tank was pumped up to the SAT reactor and the flow rate was regulated using a flow meter equipped with a needle valve.

Pilot-scale SAT reactor

A stainless-steel pilot-scale SAT reactor was installed in WWTP A; the flow in the reactor is shown in Figure 1. The reactor was cuboidal and the inner width, depth and height were 150, 150 and 300 cm, respectively. The outlet port was located 220 cm from the bottom of the reactor. Fine sand, collected from Shiga Prefecture, Japan, was used. Sand characteristics measured before filling in the pilot reactor are shown in Table 1. A 0.5 m³ bag filled with the sand was set at the top of the SAT reactor. The bottom of the bag was cut, and the sand was packed in the reactor up to a height of 250 cm in order to obtain a 30 cm vadose zone and a 220 cm saturated zone. However, the sand layer began to sink immediately after the reactor operation started; this is partly because of the removal of void air. After a month, the surface sinkage stopped at 237 cm from the bottom. Therefore, the reactor operation was conducted with a 17 cm vadose zone and a 220 cm saturated zone. The reactor has a window on its side to allow the water level in the reactor to be visually checked.

The A2O-treated effluent was dripped without interruption using a port, which was located 60 cm from the centre of the sunken sand surface. Based on the volume of the saturated zone (4.95 × 10⁶ cm³)
and the effective porosity (43.5%) described in Table 1, the inflow rate of the A2O-treated effluent was set as 70 L/day to obtain an HRT of one month (i.e. 30 days).

The reactor operation was initiated on October 2011.

Tracer test

A tracer test using bromide (Br\textsuperscript{−}) as a tracer was conducted to evaluate the HRT in the reactor. The median (minimum–maximum) Br\textsuperscript{−} concentration in usual A2O-treated effluent was 0.0945 (0.0460–0.175) mg-Br/L (n = 33). In the tracer test, on 15 February 2014, potassium bromide (KBr) was added to approximately 100 L of A2O-treated effluent in the storage tank to obtain 50 times higher Br\textsuperscript{−} concentrations than in usual effluent (measured concentration: 4.86 mg-Br/L). The A2O-treated effluent with KBr was discharged to the SAT reactor for 1 day (i.e. 24 hours). After that, the inflow to the reactor was changed to the usual A2O-treated effluent. The SAT-treated effluent was continuously collected using a fraction collector at six hour intervals after the termination of the high Br\textsuperscript{−} injection. The Br\textsuperscript{−} concentration in the SAT-treated effluent was measured for 100 days (from 14 February to 23 May 2014). After filtration using GF/B with a pore size of 1 μm (Whatman, USA), the Br\textsuperscript{−} concentration was measured by ion chromatography (Dionex, ICS-1100, Thermo Scientific, USA).

Water quality monitoring

DOC, UV\textsubscript{254}, nitrogen compounds and dissolved total phosphorus

Dissolved organic carbon (DOC), UV\textsubscript{254}, nitrogen compounds [dissolved total nitrogen (DTN), NH\textsubscript{4}\textsuperscript{+}, NO\textsubscript{2\textsuperscript{−}}, NO\textsubscript{3\textsuperscript{−}}, organic N (given as the difference between the DTN and the total inorganic N)] and dissolved total phosphorus (DTP) in the A2O-treated effluent and SAT-treated effluent were continuously measured for 30 months (from October 2011 to May 2014). Before analysis, the water samples were filtered by GF/B. The pH of and DO in the water samples are described in a previous study (Takabe \textit{et al.} 2014). Simply, pH in the SAT-treated effluent (5.64) was slightly lower than that in the A2O-treated effluent (6.58) possibly due to ion exchanges by the packed sand. DO in the SAT-treated effluent was 4.52 mg-O\textsubscript{2}/L, and the SAT in the reactor was operated under aerobic conditions (Takabe \textit{et al.} 2014).

DOC and UV\textsubscript{254} were measured by TOC-L (Shimadzu, Japan) and Multi-Spec-1500S (Shimadzu, Japan), respectively. DTN and DTP were measured by AACS-II (Bran + Luebbe, Germany). NH\textsubscript{4}\textsuperscript{+} was measured by AA-II (Bran + Luebbe, Germany). NO\textsubscript{2\textsuperscript{−}} and NO\textsubscript{3\textsuperscript{−}} were measured by AA-III (Bran + Luebbe, Germany). The specific ultraviolet absorbance (SUVA) was calculated by dividing the UV\textsubscript{254} value by DOC.

PFCAs

PFCAs concentrations in the A2O-treated and SAT-treated effluent were monitored for 14 months (from October 2011 to January 2013). Target PFCAs included perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA),

<table>
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<tr>
<th>Table 1</th>
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<tr>
<td>ignition loss (−)</td>
<td>TOC (−)</td>
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<tr>
<td>0.0136</td>
<td>0.000094</td>
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<tr>
<td>Water content (−)</td>
<td>Specific surface (m\textsuperscript{2}/g)</td>
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<td>0.00567</td>
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PFOA, perfluorononoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnDA), perfluorododecanoic acid (PFDoDA), perfluorotridecanoic acid (PFTrDA) and perfluorotetradecanoic acid (PFTeDA). PFAC-MXB (Wellington laboratories, Canada) was used as the standard solution.

Measurements of PFCAs were conducted as described in a previous study (Takemine et al. 2014). A 100 mL sample was filtered using GF/B; solid-phase extraction was then conducted using Presep PFC-II (Wako, Japan). The cartridge was cleaned with 10 mL of 0.1% ammonia (Wako, Japan)/methanol (Wako, Japan) and 15 mL of ultra-purified water. The cleanup spike (MPFAC-MXA; Wellington laboratories, Canada) and 10 μL of formic acid were added to the water samples. The samples were loaded into a clean cartridge at 10 mL/min. The target chemicals were eluted by 5 mL of 0.1% ammonia/methanol. The elute was concentrated to 1 mL using N2 gas, and a syringe spike (13C8 PFOA, Cambridge isotope laboratories, U.S.) was added.

The analyses were performed using liquid chromatography (LC; ACQUITY UPLC, Waters, U.S.)/mass spectrometry (MS)/MS (XEVO TQ MS, Waters, U.S.). The LC/MS/MS operating conditions and the quantification and confirmation ions are described in a previous study (Takemine et al. 2014). The instrumental detection limits of the target chemicals were 1.0 ng/L.

Recovery ratios (average ± standard deviation) of MPFBA, MPFHxA, MPFOA, MPFNA, MPFDA, MPFUnDA and MPFDoDA were 83.5 ± 24.9%, 85.2 ± 24.7%, 84.6 ± 24.4%, 77.4 ± 26.5%, 71.2 ± 29.4%, 60.8 ± 28.6% and 60.1 ± 26.6%, respectively.

Statistical analysis

The Wilcoxon rank-sum test was used to examine the statistical significance between the target chemical concentrations in the water samples; a significance level of 0.05 was used for all tests.

RESULTS AND DISCUSSION

HRT in pilot-scale SAT reactor

The result of the tracer test is shown in Figure 2. Recovery of the injected Br− in the tracer test is calculated by Equation (1), and the recovery ratio was 110%.

\[
RR = \sum_{i=1}^{295} \frac{(C_i + C_{i+1}) / 2 \times C_{u} \times (t_{i+1} - t_i)}{(C_t - C_{u}) \times Q \times t_{fit}} \times 100
\]

where RR is recovery ratio (%), C is Br− concentration in the SAT-treated effluent (g-Br/m³), Cu is Br− concentration in the usual A2O-treated effluent (g-Br/m³), Ct is Br− concentration in the A2O-treated

**Figure 2** | Br− concentrations during the tracer test.
effluent during the tracer test (g-Br/m³), Q is the inflow rate (m³/d), t is time (days), \( t_\text{tt} \) is the tracer test period (days) and i is the sampling number (−). \( C_\text{tu} \), \( C_\text{tt} \), Q and \( t_\text{tt} \) are 0.0945 g-Br/m³, 4.86 g-Br/m³, 0.07 m³/d and 1 d, respectively.

The one-dimensional advection dispersion equation and its analytical solution for the pulse injection are expressed as Equations (2) and (3), respectively, and, the pore-water velocity (\( u \): m/d) is expressed as Equation (4).

\[
\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} \tag{2}
\]

\[
C(x, \ t) = \frac{\Delta M}{2 \varphi_e A \sqrt{\pi Dt}} \exp \left( -\frac{(x - ut)^2}{4Dt} \right) \tag{3}
\]

\[
u = \frac{Q}{\varphi_e A} \tag{4}
\]

where \( D \) is the dispersion coefficient (m²/day), \( x \) is the distance (m), \( \Delta M \) is the amount of pulse-injected chemical (g-Br), \( \varphi_e \) is the effective porosity (−) and \( A \) is the cross-section area (m²).

Sand, which was used in this study, was separately packed in a sand column having an inner diameter and height of 5 cm and 40 cm, respectively, with 30 cm of vadose zone, and an HRT in the vadose zone of 48–82 min (Suzuki et al. 2015). Considering that the height of the vadose zone was 17 cm, the HRT in the vadose zone was quite shorter than that of the designed HRT (30 days) in the SAT reactor. Infiltration in the vadose zone was ignored, and the effective porosity and dispersion coefficient were parameter-fitted to the measured Br⁻ concentration in the SAT-treated effluent (Figure 2) based on Equations (3) and (4) by Mathematica (version 10, Wolfram Research, USA). The calculated effective porosity and dispersion coefficient were 0.37 and 0.0052 m²/day, respectively, and the pore-water velocity was calculated as 0.080 m/day by Equation (4). The parameter-fitted effective porosity was 0.85 times the porosity measured before the SAT reactor operation (Table 1). The sinking of the sand layer after the start of the operation might contribute to the decrease in the effective porosity. Based on the parameter-fitted coefficients, HRTs in the reactor were calculated as 28 days, a value similar to the designed HRT. Therefore, it was clear that the SAT reactor was successfully operated under the designed HRT.

**Removal of organic matter, nitrogen compounds and DTP by SAT**

Temporal changes of DOC concentrations in the A2O-treated and SAT-treated effluent are shown in Figure 3. In addition, distributions of DOC, UV₂₅₄, SUVA, nitrogen compounds and DTP concentrations are shown in Figure 4. DOC concentrations in the SAT-treated effluent were stable after the start of operation. DOC concentrations significantly decreased (\( p = 7.27 \times 10^{-28} \)) from the A2O-treated effluent (median value: 3.94 mgC/L) to the SAT-treated effluent (0.701 mgC/L). The DOC removal ratio was 82.1%, and it was demonstrated that these ratios were similar in case of SAT with a 21-day HRT (76%) (Drewes & Fox 1999) and a 28.8-day HRT (79%) (Zhang et al. 2012).

Median UV₂₅₄ and SUVA were 0.087 cm⁻¹ and 0.023 L/mgC/cm and 0.019 cm⁻¹ and 0.028 L/mgC/cm in the A2O-treated and the SAT-treated effluent, respectively. UV₂₅₄ significantly decreased from the A2O-treated to the SAT-treated effluent (\( p = 8.39 \times 10^{-26} \)), suggesting effective removal of aromatic compounds by SAT. Meanwhile, SUVA significantly increased after SAT (\( p = 0.0152 \)), therefore suggesting that non-aromatic components were preferentially removed by SAT, which demonstrates the same tendency shown by actual SAT systems in a previous study (Quanrud et al. 2003).
Median DTN, NO$_3^-$ and organic N concentrations were 5.02, 3.90 and 0.74 mgN/L in the A2O-treated effluent and 4.96, 4.27 and 0.36 mgN/L in the SAT-treated effluent, respectively. NH$_4^+$ and NO$_2^-$ concentrations were low in both the A2O-treated and SAT-treated effluent. There were no significant differences in DTN concentrations between two types of treated effluent ($p = 0.379$). Continuous DO measurement in the SAT reactor suggested that aerobic conditions were dominant in the SAT reactor (Takabe et al. 2014), and it was likely that denitrification did not occur in the SAT reactor. Meanwhile, organic N concentrations significantly decreased from the A2O-treated effluent to the SAT-treated effluent ($p = 8.89 \times 10^{-5}$) and NO$_3^-$ concentrations significantly increased ($p = 4.27 \times 10^{-3}$). It was likely that organic matter in the A2O-treated effluent was firstly biodegraded, and generated NH$_4^+$ was subsequently oxidized to NO$_3^-$ due to domination of aerobic conditions in the SAT reactor (Takabe et al. 2014). Therefore, transformation from organic N to NO$_3^-$ by microbial activities was
expected to partly contribute to the observed decrease in organic N and increase in NO$\textsubscript{3}^-$ concentrations in the SAT reactor.

Median DTP concentrations were 0.153 mgP/L in the A2O-treated effluent; meanwhile, DTP was seldom detected in the SAT-treated effluent. A pre-experiment in which 3 g of the autoclaved sand before the packing and 40 mL of the A2O-treated effluent were shaken for 24 h revealed that DTP in the A2O-treated effluent was partly decreased (from 0.064 to 0.018 mgP/L) by sorption on the sand surface. Therefore, it was likely that the sorption partly contributed to the decrease of DTP concentrations in the SAT reactor.

The formation of the clogging layer is a problem in long-term SAT operation (Asano et al. 2007). Meanwhile, an increase in the water level in the SAT reactor was not visually observed during the experimental period. Based on the results obtained in this study, it was determined that continuous SAT reactor operations were accomplished for 30 months under the designed HRT, and stable treatments were achieved during the period. In addition, PFCA removal by SAT was monitored during the stable period.

**Removal of PFCAs by SAT**

The behaviour and removal of chemicals that are frequently detected (frequency: >92%), including PFBA, PFPeA, PFHxA, PFHpA, PFOA and PFNA, are discussed in this section.

Figure 5 shows the changes in each compound in the A2O-treated effluent and SAT-treated effluent for a period of 14 months. PFCAs, except for PFNA, were detected in the SAT-treated effluent just after the start of operation; meanwhile, the concentrations of PFNA in the SAT-treated effluent were quite lower than those in the A2O-treated effluent during the first three months. After three months, the concentrations sharply increased and seemed to attain stable levels. Higgins & Luthy (2006) revealed the sorption of perfluorinated surfactants, including PFNA, on sediment, which were dominated by sediment organic carbon. The packed sand had organic content (see Table 1) and it is probable that PFNA adsorbed on the sand surface during the first three months, causing the subsequent breakthrough to occur.

Based on the data obtained after establishing the stable levels of PFNA, the median (minimum–maximum) concentrations of PFBA, PFPeA, PFHxA, PFHpA, PFOA and PFNA were 4.71 (n.d.–10.7), 3.67 (n.d.–6.56), 5.57 (2.72–16.7), 3.72 (2.65–6.57), 18.4 (11.1–34.4) and 11.6 (6.01–25.3) ng/L, respectively, in the A2O-treated effluent. The concentrations in this study were comparatively lower than those found in secondary treated effluent in Japan in a previous study (PFHpA: 4.7–37, PFOA: 10–68 and PFNA: 17–94 ng/L; Murakami et al. 2008). The concentration ranges of PFBA, PFPeA, PFHxA, PFHpA, PFOA and PFNA were 5.11 (1.19–11.6), 4.64 (2.92–8.84), 6.61 (3.93–10.5), 5.19 (2.91–7.63), 19.0 (12.6–29.6) and 14.1 (7.29–25.2) ng/L, respectively, in the SAT-treated effluent. The Wilcoxon rank-sum test indicated no significant differences in PFBA (p = 0.283) and PFOA (p = 0.283) concentrations between the A2O-treated and SAT-treated effluent. Meanwhile, the concentrations of PFPeA (p = 7.11 $\times$ 10$^{-3}$), PFHxA (p = 1.97 $\times$ 10$^{-2}$), PFHpA (p = 3.02 $\times$ 10$^{-2}$) and PFNA (p = 5.70 $\times$ 10$^{-3}$) in the SAT-treated effluent were significantly higher than those in the A2O-treated effluent. Some precursors, such as fluorotelomer alcohols (FTOHs), fluorotelomer carboxylates (FTCAs) and polyfluoroalkyl phosphates, are biodegraded and transformed to PFCAs (Wang et al. 2009; Lee et al. 2010), and the precursors most likely result in increases in PFCAs in WWTPs. Distributions of the precursors in treated effluent were also investigated (Suzuki et al. 2014; Ye et al. 2014). It was reported that 8:2 FTCa was not detected in treated effluent (Ye et al. 2014); meanwhile, Suzuki et al. (2014) reported that 6:2 FTOH and 8:2 FTOH were detected in the effluent from the final sedimentation tank (8:2 FTOH: influent: 77 ng/L, effluent: 14 ng/L). It is known that microbes in soil transform FTOHs to PFCAs (Wang et al. 2009). In addition, it was reported that activated sludge biodegraded 8:2 FTOH and generated PFCAs, specifically significant increase of PFHpA, PFOA and
PFNA under the aerobic condition (Yu et al. 2016), and similar microbial metabolic patterns were observed between the activated sludge and sand surface layer, which has the highest microbial activities, in the SAT reactor (Takabe et al. 2014). Therefore, there is a possibility that the increase in PFCAs in the SAT reactor might be attributable to the biodegradation of residual precursors of PFCAs in the A2O-treated effluent by SAT, specifically surface layer.

The present results suggest that it would be difficult to remove PFCAs by SAT under an HRT of 28 days. In addition, it appears that, in some cases, PFCA concentrations might be increased by SAT because of the influences of PFCA precursors. Moreover, the maximum concentration ratio for PFOA in the SAT-treated effluent relative to the lifetime health advisories in USEPA (0.42; USEPA 2016) and health-based drinking water guidance in New Jersey (0.74; State of New Jersey Department of Environmental protection 2007) still exceeded 0.2. Therefore, where treated wastewater is reused after SAT for potable purposes and PFCAs should be removed, additional treatment such as activated carbon adsorption (Takagi et al. 2008) might be required in the drinking water treatment plants.

Figure 5 | Changes of PFCA concentrations over time.
CONCLUSIONS

The tracer test conducted in this study revealed that the HRT of the pilot-scale SAT reactor was 28 days, and the SAT reactor was successfully and continuously operated for 30 months with no increase of water level in the SAT reactor. The monitoring of organic matter and nutrient removals suggested that stable treatments were achieved in the SAT reactor. Measurements taken over a 14-month period revealed that it would be difficult to remove PFCAs by SAT under an HRT of 28 days. In addition, there was a possibility that PFCA concentrations would be increased by SAT; this is probably due to the influences of PFCA precursors. In cases where treated wastewater is reused with SAT for potable purposes and PFCAs should be removed, additional treatment such as activated carbon adsorption in the drinking water treatment plants might be required.

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