Short Communication

Toxicity of Perfluorooctane Sulfonate and Perfluorooctanoic Acid to Plants and Aquatic Invertebrates

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ABSTRACT: Acute toxicities of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) were tested on four freshwater species and three plant species. PFOS was more toxic than PFOA for all species tested in this study. Similar time-response patterns of PFOS and PFOA toxicity were observed for each tested species. Values of the 48-h LC_{50} of PFOS for all test species ranged from 27 to 233 mg/L and values of the 96-h LC_{50} for three of the species ranged from 10 to 178 mg/L. Values of the 48-h LC_{50} of PFOA for all test species ranged from 181 to 732 mg/L and values of the 96-h LC_{50} for three of the species ranged from 337 to 672 mg/L. The most sensitive freshwater species to PFOS was green neon shrimp (*Neocaridina denticulate*) with a 96-h LC_{50} of 10 mg/L. Of the aquatic organisms tested, the aquatic snail (*Physa acuta*) always has the highest resistance to PFOS or PFOA toxicity over each exposure period. Both PFOS and PFOA had no obvious adverse effect on seed germination for all three plant species. Five-day EC_{50} of root elongation was more sensitive to LC_{50} of seed germination in this study. Based on EC_{10}, EC_{50}, and NOECs, the 5-day root elongation sensitivity of test plants to both PFOS and PFOA was in the order of lettuce (*Lactuca sativa*) > pakchoi (*Brassica rapa* chinensis) > cucumber (*Cucumis sativus*). Based on the results of this study and other published literature, it is suggested that current PFOS and PFOA levels in freshwater may have no acute harmful ecological impact on the aquatic environment. However, more research on the long-term ecological effects of PFOS and PFOA on aquatic fauna are needed to provide important information to adequately assess ecological risk of PFOS and PFOA. Environ Toxicol 24: 95–101, 2009.

Keywords: perfluorooctanoic acid; perfluorooctane sulfonate; *Physa acuta*; *Daphnia magna*; root elongation

INTRODUCTION

Perfluorinated chemicals are emerging contaminants with growing environmental concerns. The strong polarity of carbon-fluorine bonds make perfluorinated compounds more thermally and chemically stable than the analogue hydrocarbons. In the past half-century, perfluorinated chemicals have been widely found in numerous commercial and industrial applications as active ingredients, impurities, or as degradation products of derivatives (Giesy and Kannan, 2002; Beach et al., 2006). However, it was not discovered until the late 1990s that these widely used perfluorinated compounds were becoming widespread in the environment, animals and humans (Giesy and Kannan,

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2002; Walters and Santillo, 2006). Because of the unique chemical properties of perfluorinated compounds, these chemicals are resistant to both chemical and biological degradation under normal environmental conditions and are expected to be highly persistent in the environment (Beach et al., 2006). Therefore, the potential ecological and health effects of these chemicals have attracted much research attention recently.

Among perfluorinated substances, perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) are two major environmentally persistent chemicals representing final environmental degradation or metabolism compounds of other perfluorinated products, and they have been extensively found in various environmental media, biota, and human tissues (Giesy and Kannan, 2002; Hekster et al., 2003; Lehmler, 2005). PFOS and related chemicals are often used as ingredients in fire fighting foams, flame retardants and fire-prevention agents, pesticides, cleaning agents, aircraft hydraulic fluids, antireflective or photoresist agents in semiconductor photolithography, and antistatic surfactants or adhesion control agents in photographic processes (Lehmler, 2005; OECD, 2005). PFOA is primarily applied as process aid in the manufacture of various fluoropolymers and commonly used fluoropolymer products including nonstick cookware, electric wire insulators, and weatherproof clothing (Lehmler, 2005). Therefore, high levels of PFOS and PFOA have often been detected near fluorochemical manufacturing facilities and after accidental release of fire-fighting foam at high ng/L levels to ug/L levels (Moody et al., 1999, 2002). In contrast, general surface water levels of these two compounds were found to be less than 1 ng/L to tens or hundreds ng/L range (Hansen et al., 2002; Rostkowski et al., 2006; Wilson et al., 2007).

Both PFOS and PFOA have been found to cause acute toxic effects on aquatic organisms at comparatively high concentrations, based on the limited information mainly published by the industry (Hekster et al., 2003; Allsopp et al., 2005). Although acute toxic effects of aquatic animals for these two compounds often occur only at levels higher than those expected to be encountered at environment levels based on current information available, it is still possible that some species may be more sensitive than others (Allsopp et al., 2005). For example, MacDonald et al. (2004) found that PFOS was about three orders of magnitude more toxic to the aquatic midge *Chironomus tentans* than to most other aquatic organisms reported in the literature. In fact, the information in current literature about toxicities of perfluorinated compounds is rather sparse, and more studies on aquatic toxicity of PFOS and PFOA are critically needed before sufficient information to evaluate the full impact of these two chemicals in environment is available.

In this study, different plants and aquatic animals were used to evaluate acute toxicity for PFOA and PFOS. Four aquatic invertebrates were selected, including primary consumers (zooplankton and snails) or detritus consumers (freshwater shrimp and planarian), are pivotal trophic components of freshwater food webs and play a vital role in transporting energy and nutrients in aquatic ecosystems. Furthermore, the freshwater planarian (*Dugesia japonica*), green neon shrimp (*Neocaridina denticulate*), and a freshwater snail (*Physa acuta*) were chosen as study species in the present study because of their common presence in the aquatic environment of Taiwan and other parts of the Asia. Three commercially important plants from three important vegetable classes were also selected to examine toxic effects of PFOS or PFOA on seed germination and root elongation. The results of this study can provide some useful information about acute toxicity of PFOS and PFOA and help to assess potential effects of PFOS and PFOA in aquatic ecosystems.

MATERIALS AND METHODS

Chemicals and Stock Solution

PFOS (heptadecafluorooctanesulfonic acid potassium salt; >98%) was obtained from Fluka (Steinheim, Switzerland). PFOA (pentadecafluorooctanoic acid ammonium salt; >98%) was obtained from Sigma-Aldrich (St. Louis, MO). All stock solution of testing chemicals were prepared in dechlorinated tap water using polymethyl pentene (PMP) containers, because these two chemicals can be adsorbed onto glass surface (Boudreau et al., 2003). Water solubility for PFOS was 550 mg/L at 24–25°C (OECD, 2002) and for PFOA was 3400 mg/L at 25°C (USEPA, 2002). In this study, stock solution of PFOS and PFOA were no greater than 400 mg/L and 2000 mg/L, respectively.

Test Organisms

Freshwater planarians, *Dugesia japonica*, were collected from Nanshi stream located in Wulai, Taipei prefecture, Taiwan in 2004. Since then, the planarians have been maintained in dechlorinated tap water at our laboratory. Animals were fed raw chicken liver once a week. Culture medium was renewed after weekly feeding. Freshwater snails, *Physa acuta*, were collected from a ditch located in Shilin of Taipei City in June 2005. Snails were fed with lettuce and half of the culture medium was changed with dechlorinated water every 2 weeks. In addition, water flea (*Daphnia magna*) and green neon shrimps (*Neocaridina denticulate*) were purchased from local suppliers and acclimated in the laboratory for at least 7 days prior to the experiments. Water fleas were fed with green water and half of the medium was renewed with dechlorinated water once a week and green neon shrimps were fed with commercial fry food T850S of Hai Feng Feed Company and half of their culture medium was renewed with dechlorinated water every week.

Daphnia Immobilization Bioassay

Daphnia immobilization bioassay was performed according to the OECD test guideline 202 (OECD, 1984) with slight modifications. In brief, water fleas (*Daphnia magna*) were exposed to five concentrations of the testing chemical or to dechlorinated tap water alone as solvent control using polyprolene test vessels. Water quality parameters including water pH, conductivity, and dissolved oxygen were measured at the beginning and at the end of each test. Initial values of pH were 7.82 ± 0.12 and 7.91 ± 0.03 after 48 h. At the start of the bioassays, dissolved oxygen and specific conductivity were 67.7 ± 6.8% and 101.8 ± 6.8 μs/cm, respectively. After the 48-h testing period, dissolved oxygen and specific conductivity were 55.6 ± 1.26% and 109.1 ± 3.5 μs/cm, respectively. Based on water solubility of test chemicals and preliminary toxicity results, nominal test concentrations were in the range of 10–400 mg/L for PFOS and 31–250 mg/L for PFOA. For each concentration, six animals were kept in 50 mL of test solution for water fleas (younger than 24 h) with five replication in a temperature incubator at (25 ± 2)°C with 12-h illumination. Each treatment was conducted three different times and a total of 540 animals were used for PFOS or PFOA toxicity testing. The animals were not fed and were inspected at 24 and 48 h after the beginning of bioassays. The organism was considered immobile if it was not able to swim within 15 s after gentle stirring. None of the control animals became immobile at the end of the bioassays.

96-h Acute Toxicity Test

Acute toxicity tests on shrimp were performed according to the Taiwan EPA standard protocol (Taiwan EPA, 2005) with slight modifications. In brief, test animals were exposed to five concentrations or to dechlorinated tap water alone as solvent control using polyprolene test vessels. Water quality parameters including water pH, conductivity, and dissolved oxygen were measured at the beginning and at the end of each test. All acute toxicity experiments were conducted in a temperature incubator at 25 ± 2°C with 12 h illumination. Each treatment included one control and at least five testing concentrations using polyethylene test vessels. Nominal test concentrations of PFOS were in the range of 5–200 mg/L for both planarian and neon green shrimp, and in the range of 25–300 mg/L for freshwater snails. For PFOA, nominal test concentrations were in the range of 150–750 mg/L for planaria, 50–1000 mg/L for neon green shrimp, and 100–1000 mg/L for freshwater snails. For each concentration, 10 animals were kept in 50 mL of test solution for planaria (body length 0.9 ± 0.1 cm) with three replications for each treatment, whereas six animals were kept in 1000 mL of test solution for freshwater snails (shell length 0.6 ± 0.2 cm) and green neon shrimp (body length 1.3 ± 0.2 cm) with five replications for each treatment. Each treatment was conducted three different times and a total of 540 animals were used for PFOS or PFOA toxicity testing. The animals were not fed and were inspected every 24 h for mortality during the entire experimental period. Organisms without detectable movement were considered dead and removed from the test solution. No animal died in control groups for all acute toxicity tests, although there was 10% mortality of control green neon shrimp for one treatment.

Seed Germination and Root Elongation Test

Lettuce (*Lactuca sativa*), cucumber (*Cucumis sativus*), and pakchoi (*Brassica rapa* chinensis) seeds were surface-sterilized with a 10% bleach solution for 30 min and rinsed three times with distilled water before use in toxicity bioassay. The seed germination and root elongation test was performed according to the Ecological Effects Test Guidelines OPPTS 850.4200 (USEPA, 1996) with slight modifications. Each test consisted of six dilutions and a control group (dechlorinated tap water for controls) with five replicates. Tested concentrations were 6.25, 12.5, 25, 50, 100, and 200 mg/L for PFOS, and were 62.5, 125, 250, 500, 1000, and 2000 mg/L for PFOA. A total of five seeds were placed on a Whatman No 1 filter paper containing 5 mL of test solution in a plastic Petri dish. Each test was conducted three different times for each plant species. A total of 450 seeds were used for each test chemical. The average percentage of seed germination in control groups from three treatments were 89.3 ± 11.5% for cucumber, 85.3 ± 18.5% for lettuce, and 98.7 ± 2.3% for pakchoi, respectively. After 120 h of incubation in the dark at 25 ± 1°C, the root elongation of each seed from different treatments was measured to 1 mm.

Data Analysis

The nominal concentrations that were lethal to 50% of the aquatic organisms (LC_{50}) or were caused 50% of daphnia immobilization (EC_{50}) at different exposure periods were calculated using trimmed Spearman-Karber analysis (Hamilton et al., 1977). Trimmed Spearman-Karber analyses were made using trimmed Spearman-Karber Program (version 1.5) which was obtained from Environmental Monitoring Systems Laboratory (USEPA, Cincinnati, Ohio). In addition, the nominal concentrations that were produced successful germination of the 50% test seeds (LC_{50}) were also analyzed by trimmed Spearman-Karber analysis. The inhibition of root length data relative to PFOS or PFOA concentrations were fitted to two-parameter Gompertz model using nonlinear regression with an EXCEL VBA macro program BIOASSAY97 (Onofri, 2005). The effective concentrations that were inhibited 10% (EC_{10}) or 50% (EC_{50}) of root length growth for each test plant were calculated by

TABLE I. LC_{50} and NOEC (mg/L) from 24 to 96 h for aquatic organisms and EC_{50} and NOEC (mg/L) from 24 to 48 h for water flea exposed to PFOA and PFOS

	LC_{50}[a] (95% CI; mg/L)				NOEC[b] (mg/L)			
Species	24 h	48 h	72 h	96 h	24 h	48 h	72 h	96 h
PFOS								
Planarian	34 (30–38)	27 (24–31)	26 (23–29)	23 (20–25)	25	10	10	10
Shrimp	>200	57 (43–75)	20 (17–24)	10 (9–12)	100	25	25	5
Snail	271	233 (226–241)	208 (197–219)	178 (167–189)	200	100	100	100
Water flea	193 (177–209)	63 (58–69)	–	–	100	20	–	–
PFOA								
Planarian	352 (331–374)	345 (325–366)	343 (324–364)	337 (318–357)	150	150	150	150
Shrimp	>1000	712 (663–764)	546 (502–594)	454 (418–494)	500	250	250	250
Snail	856 (768–954)	732 (688–779)	697 (661–735)	672 (635–711)	500	500	500	250
Water flea	298 (278–321)	181 (166–198)	–	–	125	125	–	–

[a] Determined using trimmed Spearman-Karber analysis.
[b] Determined using Dunnett's test.

two-parameter Gompertz model with lower and upper asymptotes constrained. The NOECs (no observed effect concentrations) were determined by Dunnett's multiple comparison procedure ($p \leq 0.05$) using the Minitab Statistical Program (version 13.2).

RESULTS

Toxicity of PFOS and PFOA to Aquatic Invertebrates

LC_{50} or EC_{50} values of PFOS and PFOA for four aquatic species tested are summarized in Table I. PFOS was more toxic than PFOA for all species tested in this study. Similar time-response patterns of PFOS and PFOA toxicity were observed for each tested species. For example, planaria rapidly responded to PFOS or PFOA toxicity in the first 24 h, but no obvious toxicity increased from 48 to 96 h. On the other hand, water fleas continued to respond PFOS or PFOA toxicity from 24 to 48 h. In addition, green neon shrimps were more tolerant to PFOS and PFOA toxicity in the first 24 h than other tested species, but started to increase their sensitivity to PFOS or PFOA toxicity from 48 to 96 h.

Values of the 48-h LC_{50} of PFOS for test species ranged from 27 to 233 mg/L and values of the 96-h LC_{50} for three species ranged from 10 to 178 mg/L (Table I). At 48 h of exposure, sensitivity of the aquatic invertebrates to PFOS was in the order of planarian > green neon shrimp > water flea > freshwater snail. At 96 h of exposure, the sensitivity of the aquatic invertebrates to PFOS was in the order of green neon shrimp > planarian > freshwater snail.

Values of the 48-h LC_{50} of PFOA for test species ranged from 181 to 732 mg/L and values of the 96-h LC_{50} for three species ranged from 337 to 672 mg/L (Table I). At 48-h of exposure, the sensitivity of the aquatic invertebrates to PFOA was in the order of water flea > planarian > green neon shrimp = freshwater snail. At 96-h of exposure, the sensitivity of the aquatic invertebrate to PFOA was in the order of planarian > green neon shrimp > freshwater snail. Among the different aquatic organisms tested, freshwater snails always had the greatest resistance to PFOS or PFOA toxicity at each exposure period.

Values of the 48-h NOECs of PFOS for four test species ranged from 10 to 100 mg/L and values of the 96-h NOECs for three species ranged from 5 to 100 mg/L (Table I). The 24-h NOECs of the aquatic invertebrates to PFOS was in the order of freshwater snail > water flea = green neon shrimp > planarian and the 96-h NOECs was in the order of freshwater snail > planarian > green neon shrimp. Values of the 48-h NOECs of PFOA for the four test species ranged from 125 to 500 mg/L and values of the 96-h NOECs for three species ranged from 150 to 250 mg/L (Table I). Following 24 h of exposure, the NOECs of the aquatic invertebrates to PFOA was in the order of water flea > planarian > freshwater snail = green neon shrimp. After 96-h of exposure, the 96-h NOECs was in the order of green neon shrimp = freshwater snail > planarian.

Toxicity of PFOS and PFOA to Plants

LC_{50} values of seed germination and EC_{50} values of root elongation on three test plants after 5-day exposure to PFOS or PFOA are summarized in Table II. LC_{50} and NOEC values of PFOS to seed germination were greater than 200 mg/L for all three plant species. PFOA had no adverse effect on cucumber seed germination, and both LC_{50} and NOEC values of seed germination were greater than 2000 mg/L. LC_{50} and NOEC values of PFOA to seed germination were 1734 and 1000 mg/L for lettuce, and 579 and 250 mg/L for pakchoi, respectively. As expected, EC_{50}

TABLE II. LC_{50} and NOEC (mg/L) of seed germination and EC values and NOEC (mg/L) of root elongation for three tested plants after 5 days exposure PFOA and PFOS

	Seed Germination		Root Elongation			
	LC_{50}[a] (95% CI)	NOEC[b]	EC_{10}[c] (95% CI)	EC_{50}[c] (95% CI)	NOEC[b]	Gompertz Model Parameters
PFOS						
Cucumber	>200	>200	–[d]	>200	>200	No convergence
Lettuce	>200	>200	24 (16–33)	99 (88–110)	50	Slope = 1.3379 Inflection point =131
Pakchoi	>200	>200	71 (56–85)	130 (119–141)	50	Slope = 3.088 Inflection point =147
PFOA						
Cucumber	>2000	>2000	812 (527–1097)	1254 (1026–1482)	250	Slope = 4.3307 Inflection point=1365
Lettuce	1734 (1342–2240)	1000	5 (0–11)	170 (88–252)	< 62.5	Slope = 0.5199 Inflection point =344
Pakchoi	579 (530–632)	250	155 (108–203)	278 (236–320)	125	Slope = 3.2355 Inflection point =311

[a] Determined using trimmed Spearman-Karber analysis.
[b] Determined using Dunnett's test.
[c] Calculated using nonlinear regression analysis fitted to two-parameter Gompertz model with lower and upper asymptotes constrained.
[d] Not calculated.

of root elongation was more sensitive to LC_{50} of seed germination in this study. EC_{50} values of PFOS for three test species ranged from 99 to >200 mg/L and EC_{50} values of PFOA ranged from 263 to 1254 mg/L (Table II). EC_{10} values of PFOS for lettuce and pakchoi were 24 and 71 mg/L, and EC_{10} values of PFOA for three test species ranged from 5 to 812 mg/L (Table II). NOEC value of PFOS to root elongation was greater than 200 mg/L in cucumber. In fact, PFOS had no effect on the root growth of cucumber seed and there was still ~90% of root elongation at 200 mg/L group compared to the control group after 5-day exposure. On the other hand, PFOA almost completely inhibited lettuce and pakchoi root growth at or above 1000 mg/L. NOECs of PFOA to root elongation for the three test species ranged from <62.5 to 250 mg/L. Based on EC_{10}, EC_{50} and NOECs, the 5-day root elongation sensitivity of the three test plants to both PFOS and PFOA was in the same order of lettuce > pakchoi > cucumber.

DISCUSSION

PFOS is moderately toxic to aquatic invertebrates, with acute toxicity values in the range of 10–300 mg/L in the present study. There is only very limited information on the acute toxicity of PFOS due to the scarcity of freshwater species tested. Only four species of freshwater invertebrate have previously been used for PFOS toxicity testing – water flea (both *Daphnia magna* and *Daphnia pulicaria*), aquatic midge (*Chironomus tentans*) and freshwater mussel (*Unio complamatus*) (OECD, 2002; Boudreau et al., 2003; MacDonald et al., 2004). Compared with the published data on acute toxicity of PFOS, the 48-h EC_{50} of 63 mg/L found for *Daphnia magna* in this study is very similar to the value of 67.2 mg/L for *Daphnia magna* in the study of Boudreau et al. (2003). Based on LC_{50} values obtained in this study, both freshwater planarian and green neon shrimp were more sensitive to PFOS toxicity than *Daphnia magna* after 48 h exposure. In addition, the 96-h LC_{50} of 10 and 23 mg/L found for green neon shrimp and planarian in this study are lower than the 96-h LC_{50} of 59 mg/L for the freshwater mussel (*Unio complamatus*), as cited in OECD (2002). It is important to further examine whether physiological and ecological adaptations of test species could explain toxicity difference, since snails and water flea are phytophagous, whereas planaran or shrimp are detritivorous. Furthermore, MacDonald et al. (2004) reported a 10-day LC_{50} of 0.045 mg/L for survival of the aquatic midge (*Chironomous tentans*). This suggests that diverse species of freshwater invertebrates should be used in PFOS toxicity tests and that PFOS might be pose toxic effects to some uncommon aquatic test species under chronic conditions.

PFOA is only slightly toxic to aquatic invertebrates, with acute toxicity values in the range of 100–1000 mg/L in the present study. There is even less published data on acute toxicity with PFOA than those with PFOS. Only one freshwater species, *Daphnia magna,* was reported, with 48-h EC_{50} values ranged from 126 to >1000 mg/L as cited in USEPA (2002). In this study, *Daphnia magna* with a 48-h EC_{50} value of 181 mg/L is more sensitive to PFOA exposure compared with other freshwater species tested, with 48-h LC_{50} values ranging from 345 to 732 mg/L. The result of this study showed that PFOA was less toxic than PFOS to aquatic invertebrates, and this finding is in a good

agreement with those previous studies (MacDonald et al., 2004; Sanderson et al., 2004).

Both PFOS and PFOA are very persistent chemicals that are difficult to break down by either chemical or biological processes. Several studies have demonstrated that PFOS or PFOA concentrations had no significant reduction in test water column during 35 days experiment periods (Sanderson et al., 2003; Hanson et al., 2005a). In this study, a lack of linearity with time in planarian exposed to PFOS or PFOA was probably not due to decrease of PFOS or PFOA concentration in test solutions, because it was expected that there was no significant dissipation of PFOS or PFOA during the 48-h or 96-h testing periods of the present study. However, it is still necessary to interpret these LC_{50}/EC_{50} values with some caution due to lack of analytical confirmation in the present study. It will of interest to investigate physiological characters of various aquatic organisms to affect their different responses to PFOS and PFOA toxicity.

With concentrations up to 200 mg/L, PFOS had no effect on seed germination, but affected the root elongation of all three plant species tested. EC_{50} values of 5-day root elongation on lettuce or pakchoi exposed to PFOS ranging from 99 to 130 mg/L was in a range similar to 96-h LC_{50} values of three aquatic animals exposed to PFOS in the present study. On the other hand, EC_{50} values of 5-day root elongation on lettuce or pakchoi had slightly lower values than the 96-h LC_{50} values of three aquatic animals exposed to PFOA in the present study. This observation suggests that root elongation of some plants and survival of aquatic organisms exhibit similar sensitivity to PFOS and PFOA. Based on the EC_{50} values of 5-day root elongation, PFOS was more toxic than PFOA, as observed in aquatic macrophytes in the studies of Hanson et al. (2005a,b).

In general, environmental PFOS levels are at least one order of magnitude higher than PFOA levels in surface water (Hansen et al., 2002; Rostkowski et al., 2006; Wilson et al., 2007), although that PFOA was found at higher concentrations than PFOS in freshwater bodies of New York State (Sinclair et al., 2006) and in the Yangtze River of China (So et al., 2007). PFOS typically occurs in freshwater at low ng/L levels, ranging up to hundreds of ng/L (Hansen et al., 2002; Rostkowski et al., 2006; Wilson et al., 2007); whereas PFOA usually occurs in freshwater at hundreds of pg/L levels, ranging up to tens or hundreds of ng/L (Hansen et al., 2002; Rostkowski et al., 2006; Sinclair et al., 2006; So et al., 2007; Wilson et al., 2007). In relation to ecological effects of measured PFOS or PFOA levels, the risk assessment defines the predicted no-effect concentration (PNEC), which is based on standard toxicity data on LC_{50} or NOEC with the application of a safety factor, can be used to evaluate possible ecological effects. The 96-h NOEC values of PFOS and PFOA found in this study were in the range of 5–100 mg/L and 150–250 mg/L, respectively (Table I). Using these acute toxicity NOECs divided by a safety factor of 10 to calculate PNECs, the PNECs were determined to be in the range of 0.5–10 mg/L for PFOS and 15–25 mg/L for PFOA. Based on the results of this study together with other published literature, it is suggested that current PFOS and PFOA levels in the freshwater environment may have no acute harmful impact on the aquatic environment. However, few published studies have investigated chronically sublethal effects of PFOS and PFOA on freshwater animals. The potential of PFOS and/or PFOA for endocrine disruption and other chronically ecotoxicological effects at lower concentrations may be of great concern for aquatic fauna and merit further investigation (Oakes et al., 2005; Liu et al., 2007). Information on the long-term ecological effects of PFOS and PFOA on aquatic fauna will provide important data to adequately assess the ecological risks of PFOS and PFOA.

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