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Occurrence and removal of pharmaceutically active compounds in sewage treatment plants with different technologies

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Occurrence of eight selected pharmaceutically active compounds (PhACs; caffeine, carbamazepine, triclosan, gemfibrozil, diclofenac, ibuprofen, ketoprofen and naproxen) were investigated in effluents from fifteen sewage treatment plants (STPs) across South Australia. In addition, a detailed investigation into the removal of these compounds was also carried out in four STPs with different technologies (Plant A: conventional activated sludge; plant B: two oxidation ditches; plant C: three bioreactors; and plant D: ten lagoons in series). The concentrations of these compounds in the effluents from the fifteen STPs showed substantial variations among the STPs, with their median concentrations ranging from 26 ng/L for caffeine to 710 ng/L for carbamazepine. Risk assessment based on the "worst case scenario" of the monitoring data from the present study suggested potential toxic risks to aquatic organisms posed by carbamazepine, triclosan and diclofenac associated with such effluent discharge. With the exception of carbamazepine and gemfibrozil, significant concentration decreases between influent and effluent were observed in the four STPs studied in more detail. Biodegradation was found to be the main mechanism for removing concentrations from the liquid waste stream for the PhACs within the four STPs, while adsorption onto sludge appeared to be a minor process for all target PhACs except for triclosan. Some compounds (*e.g.* gemfibrozil) exhibited variable removal efficiencies within the four STPs. Plant D (10 lagoons in series) was least efficient in the removal of the target PhACs; significant biodegradation of these compounds only occurred from the sixth or seventh lagoon.

Introduction

Pharmaceutically active compounds (PhACs) and their possible environmental impacts are an emerging environmental issue.[1–3] The presence of PhACs in surface waters is well documented in the literature.[4–10] A major route of the PhACs into the aquatic environment is through sewage treatment plants (STPs) following excretion in faeces and urine after their intended use and disposal of unused medications into the toilet.[11–17]

Increased attention in recent years has been paid to the removal of micropollutants including PhACs in STPs due to an increasing concern of their potential negative impact to the environment[3,18–21] and a growing water shortage in select regions worldwide.[22] To compensate for such water shortages, treated wastewater is increasingly being used directly or indirectly for drinking water production. Discharge of treated effluent by STPs can substantially contribute to the river flow approaching 100% in select areas.[23,24] Although much is yet to be understood pertaining to ecological and health effects posed by low environmental concentrations by PhACs, increasing research suggests that such effects are possible.[20,21]

Current STPs were not specifically designed to remove PhACs from the waste stream. Thus, it is of no surprise that incomplete removal of these compounds has been reported.[11,12,25] To date, most research on the removal of PhACs during waste treatment has been in conventional activated sludge treatment plants.[11,26] In recent years, membrane bioreactors and other advanced treatment technologies such as ozonation also have been studied in comparison with conventional activated sludge treatment plants in terms of removal efficiency for PhACs in wastewater.[14,27–30] In addition, modelling has been used to predict the concentrations and fate of PhACs in activated sludge treatment.[31–33] Less research, however, has been conducted on the effectiveness of other technologies such as oxidation ditches, bioreactors, and lagoon treatment in the removal of PhACs.

The objectives of this study were to: (1) investigate the concentrations of eight commonly used PhACs (caffeine, carbamazepine, triclosan, gemfibrozil, diclofenac, ibuprofen, ketoprofen and naproxen) in the final effluents from 15 STPs across South Australia, (2) examine the removal and fate of these compounds at various treatment stages within four selected STPs that use a range of treatment technologies (conventional activated sludge, oxidation ditches, bioreactors, and lagoon treatment), and (3) determine potential implications of effluent discharge into surface waters based on the toxicity data available in the literature. The target analytes include compounds that range from high removal rates (caffeine) to those with exceedingly low removal rates (carbamazepine). In addition, the inclusion of samples collected from those plants other than

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activated sludge plants will help indicate whether the results presented in other studies can apply to other technologies.

2. Experimental section

Site selection and sampling

Sample collection for this study was conducted in two phases. Phase I was conducted in 2004 and represented a screening of PhACs in effluents in 15 Australian STPs. The technologies used in these STPs included activated sludge, biological filters, oxidation ditches, bioreactors and lagoons, with different designs and performance parameters. Phase II was conducted in 2005 and consisted of sampling at four STPs in South Australia with different treatment technologies[34] to provide a more detailed investigation into the removal of the target PhACs. Information on the plants, including influent and effluent chemical characteristics, can be found in Table 1. Plant A is a large conventional, municipal, activated sludge treatment plant with primary sedimentation, secondary activated sludge process, and tertiary stage of six lagoons. Final effluent from plant A is discharged into the sea or reused for irrigation. The other three plants (B, C and D) are small, rural STPs. Final effluents from the three rural STPs are discharged to small creeks. Plant B uses a biological process with two oxidation ditches followed by chlorination. Plant C uses an activated sludge process with three bioreactors followed by UV disinfection and chlorination. Plant D is composed of 10 lagoons operated in series: 2 parallel anaerobic lagoons followed by 8 aerobic lagoons with only lagoon 3 aerated.

For Phase I, effluent samples (1 L each) were collected in 4 replicates using pre-cleaned, 1-L brown glass bottles and preserved by acidifying to pH 3 with 5M sulfuric acid. All samples were collected using 24-h composite samplers (ISCO 6712 Full-size portable sampler from TELEDYNE ISCO, Lincoln, Nebraska, USA). The effluent samples were collected on an equal proportion in each hour without consideration of the flow rate. After collection, all samples were transported on ice to the analytical laboratory and then stored in a cold room (4 °C) until extraction. Such extraction of effluent samples took place within a week of collection. Two blank samples filled with Milli-Q water and two quality control samples spiked with known concentrations of the target compounds also were included during the sampling and extraction process. For Phase II, wastewater samples were collected using 24-h composite samplers at different stages of treatment for each of the four STPs. For plant B with a long hydraulic retention time (40 hours), 2-days composite samples were collected. During the wastewater sampling, sludge samples also were collected from the four STPs.

Sample analysis

Eight pharmaceutically active compounds (PhACs) that are extensively used in Australia were selected for study (Table 2). The triclosan standard was purchased from Fluka (Sydney, Australia) while $^{13}C_{12}$-triclosan used as internal standard (IS) was obtained from Wellington Laboratories through Novachem Pty Ltd (Melbourne, Australia). Standards for ibuprofen, naproxen, and diclofenac were obtained from Alltech (Mebourne, Australia), while all other standards including caffeine and its IS $^{13}C_3$-caffeine, carbamazepine and its IS dihydroxycarbamazepine, mecoprop-d_3 (IS for acidic drugs), gemfibrozil and ketoprofen were purchased from Sigma-Aldrich (Sydney, Australia). High-performance liquid chromatography (HPLC) grade hexane, acetone, methanol, and acetonitrile were obtained from BDH (Melbourne, Australia). Stock solutions (100 mg/L) of each standard as well as mixtures were prepared in methanol. *N*-Methyl-*N*-(trimethylsilyl)-trifluoroacetamide (MSTFA, derivatization grade) was obtained from Sigma-Aldrich (Sydney, Australia). Solid-phase extraction cartridges (Oasis HLB, 500 mg sorbent) were obtained from Waters Australia (Melbourne, Australia).

Effluent samples (1 L each) were filtered through GF/C glass fibre filter papers (1.2 μm, Whatman, Adelaide, Australia). Internal standards ($^{13}C_3$-caffeine for caffeine, dihydroxycarbamazepine for carbamazepine, triclosan-$^{13}C_2$ for triclosan, and mecoprop-d_3 for acidic drugs) were added to 1-L of the filtered water at a concentration of 100 ng/L each. The aqueous samples were passed through Waters Oasis HLB cartridges (6 cc, 500 mg sorbent), which were preconditioned by using 5 ml of methanol and 5 ml of Milli-Q water. The cartridges were washed with water containing 10% methanol (50 ml, v:v) and the target compounds were eluted from the cartridges with organic solvent (2 × 4 ml of methanol). The extracts were taken to dryness by a gentle stream of nitrogen gas, and re-dissolved in 1 ml of

Table 1 Information on the four sewage treatment plants sampled during Phase II.[a]

Plant Treatment process	A Activated sludge with 6 lagoons	B 2 oxidation ditches	C 3 bioreactors with UV	D 10 lagoons in series
Population served	1,300,000	5,000	7,377	3,300
Daily treatment volume (Mega litres)	135	0.96	1.77	0.76
HRT (hours) [b]	15	40	30	N/A
SRT (days) [c]	3	2	14	70
Influent BOD [d] (mg/L)	430	320	320	150
Influent SS [e] (mg/L)	380	200	480	160
Influent ammonia (NH_3–N) (mg/L)	42	37	46	55
Effluent BOD (mg/L)	3	<2	2	10
Effluent SS (mg/L)	4	<1	2	22
Effluent ammonia (NH_3–N) (mg/L)	0.3	1.5	3.3	35

[a] Influent and effluent data in the table are 24-h averages. [b] Hydraulic retention time. [c] Sludge retention time. [d] Five-day biochemical oxygen demand. [e] Suspended solids.

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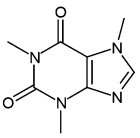
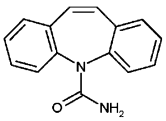
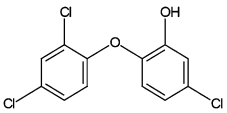
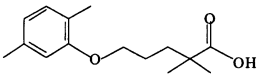
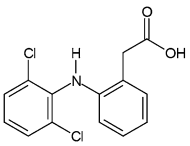
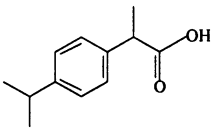
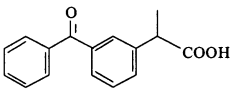
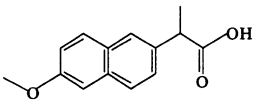
Table 2 Chemical structure and classification of the eight target pharmaceutically active compounds (PhACs)[a]

Generic Name	Structure	Chemical data[b]	Classification
Caffeine		MF: $C_8H_{10}N_4O_2$ MW: 194.19 CAS: 58-08-2 pK_a: 6.1 log K_{ow}: <0	Psychoactive Stimulant
Carbamazepine		MF: $C_{15}H_{12}N_2O$ MW: 236.27 CAS: 298-46-4 pK_a: <2 log K_{ow}: 2.45	Antiepileptic
Triclosan		MF: $C_{12}H_7Cl_3O_2$ MW: 289.54 CAS: 3380-34-5 pK_a: 7.9 log K_{ow}: 4.76	Antimicrobial Agent
Gemfibrozil		MF: $C_{15}H_{22}O_3$ MW: 250.33 CAS: 25812-30-0 pK_a: 4.7 log K_{ow}: 4.77	Lipid Regulator
Diclofenac		MF: $C_{14}H_{11}Cl_2NO_2$ MW: 296.15 CAS: 15307-86-5 pK_a: 4.15 log K_{ow}: 4.51	Anti-inflammatory Drug and Analgesic
Ibuprofen		MF: $C_{13}H_{18}O_2$ MW: 206.30 CAS: 15687-27-1 pK_a: 4.91 log K_{ow}: 3.97	Anti-inflammatory Drug and Analgesic
Ketoprofen		MF: $C_{16}H_{14}O_3$ MW: 254.28 CAS: 22071-15-4 pK_a: 4.45 log K_{ow}: 3.12	Anti-inflammatory Drug and Analgesic
Naproxen		MF: $C_{14}H_{14}O_3$ MW: 230.26 CAS: 22204-53-1 pK_a: 4.15 log K_{ow}: 3.18	Anti-inflammatory Drug and Analgesic

[a] MF: Molecular Formula; MW: Molecular Weight; CAS: Chemical Abstracts Service Registry Numbers; pK_a: -$\log_{10}$ of K_a (acid dissociation constant); log K_{ow}: logarithm of octanol/water partition coefficient. [b] Chemical data were compiled from Ref. 15, 32, 35

acetonitrile. The extracts were stored in a refrigerator before analysis.

The target compounds in the extracts were converted into their trimethylsilyl derivatives by MSTFA using the following conditions: 0.1ml of each extract and 0.1 ml of MSTFA reacted at 80 °C for 1hr. The derivatives were determined by gas chromatography-mass spectrometer (GC-MS) (Agilent 6890 GC and 5972 MSD) with electron impact mode (EI). The instrument was equipped with HP-5MS capillary column (30 m × 0.25 mm ID, film thickness 0.25 μm). Helium was used as carrier gas at a flow rate of 1.1 ml/min. Oven temperature was programmed as follows: 80 °C (1 min) to 150 °C at 10 °C/min, to 215 °C at 3 °C/min, then to 280 °C (10 min) at 10 °C/min. The injector and interface temperatures were set at 280 °C, while MS quad was set at 150 °C and MS source set at 230 °C. Selected ion mode (SIM) was used to analyse the extracts, and the ions for quantification were as follows: *m*/*z* 194 for caffeine, 193 for carbamazepine, 200 for triclosan, 201 for gemfibrozil, 214 for diclofenac, 263 for ibuprofen, 282 for ketoprofen, and 243 for naproxen. Two or three confirmation ions for each compound were used in the analysis, and the response ratio with quantification ion had to be met within 20% of variation for each target compound. The method detection limits for the selected compounds using GC-MS ranged from 1 to 6 ng/L based on the standard deviations of the lowest concentration in the calibration, but due to complex matrix interferences in wastewater samples the reporting method limits of quantification (LOQ) for the analytical method were set to 5 ng/L for caffeine and triclosan, 10 ng/L for carbamazepine, diclofenac, ibuprofen and ketoprofen and 20 ng/L for gemfibrozil and naproxen based on 10 times standard deviation of the lowest concentration of each compound. The reproducibility of each compound within a day was better than 5%. Recoveries determined for effluent samples

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spiked with 50 ng/L of each standard were all more than 70% ($n = 4$). No recovery correction was made for the analytical data. The blank samples taken to the field showed no contamination during the sampling and extraction processes.

Risk assessment

The potential environmental risk of the target PhACs was assessed based on the "worst case scenario" in accordance with the Technical Guidance Document (TGD) on risk assessment.[36] Risk quotients (RQ) were calculated between the predicted environmental concentrations (PEC) or measured environmental concentrations (MEC) and the predicted no effect concentrations (PNEC), which are the concentrations for which adverse effects are not expected to occur for these substances. PNEC values were derived from the literature.[19,37–44] According to the TGD, the PNEC values were calculated from the lowest acute LC_{50}, EC_{50} or IC_{50} values (concentrations causing 50% death, effect or inhibition) divided by the assessment factor of 1000. If chronic NOEC (no observed effect concentration) values for one, two, or three trophic levels were available, the assessment factor 100, 50 or 10 was used correspondingly for PNEC calculations.[45] Specifically, the PNEC values for caffeine, gemfibrozil, ibuprofen, ketoprofen, and naproxen were calculated using the assessment factor 1000 from the acute toxicity data of the literature,[37,38,43,44] while the PNEC values for triclosan and diclofenac were derived from the chronic toxicity data using the assessment factor 10.[19,39–42] For carbamazepine, Ferrari *et al.*[41] estimated the PNEC value from the NOEC values and a statistical extrapolation model providing an estimate of hazardous concentration for 5% of the species (HC_5). Maximum concentrations measured for the analytes for all sites were used to represent MECs.

Results and discussion

Concentrations in effluents and risk assessment

Phase I showed that PhACs were routinely present in the effluents from the 15 STPs sampled. There were, however, large variations in their measured concentrations (Fig. 1). The greatest variations

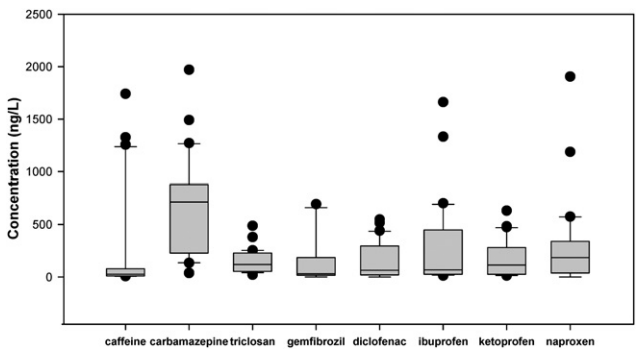

Fig. 1 Concentration ranges (box plot) for pharmaceutically active compounds (PhACs) in the final effluents from 15 sewage treatment plants sampled in Phase I. A boxplot depicts groups of numerical data through their five-number summaries (the smallest observation, lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation). A boxplot also indicates which observations, if any, might be considered outliers (big black dots in the graph).

were observed for caffeine, carbamazepine, ibuprofen, and naproxen with two orders of magnitude differences between the maximum and minimum concentrations. Variability in concentrations for the eight target PhACs also was seen in the effluent samples collected from the four STPs in South Australia for Phase II (Fig. 2). During Phase II, concentrations of caffeine, triclosan, diclofenac and ketoprofen did not generally exceed 300 ng/L, whereas concentrations of carbamazepine, gemfibrozil, ibuprofen, and naproxen generally ranged from 300 ng/L to 1000 ng/L.

During Phase I, carbamazepine was found in the highest concentrations followed by naproxen, caffeine, triclosan, and ketoprofen (Fig. 1). Measured concentrations ranged from ng/L to μg/L, with 94% being below 1000 ng/L. The concentration ranges determined for the target PhACs in both Phase I and II are consistent with previous investigations.[11,26,41,44,46]

In Australia, most STP effluents are discharged into aquatic environments, which may lead to negative impact on the aquatic ecosystems. During dry seasons, effluent could account for almost 100% of a river's flow in Australia.[23,24] Based on the measured effluent concentrations from this study and limited ecotoxicity data available in the literature, a potential risk assessment was conducted for the "worst case scenario" (100% of stream flow derived from effluent and using the highest measured concentrations of target PhACs). The RQ values for carbamazepine, triclosan, and diclofenac were more than 1 (Table 3), indicating potential risks to the aquatic organisms. Biological tests showed toxicological effects of carbamazepine, triclosan, and diclofenac on various aquatic organisms. Chronic toxicity tests on carbamazepine showed the NOEC values of 25 μg/L in *C. dubia* (7 days), 377 μg/L in the rotifer *B. calyciflorus* (2 days), and 25 mg/L in early life stages of zebrafish.[41] Orvos *et al.*[39] conducted toxicity tests for triclosan with LC_{50} values for fish ranging from 260 to 840 μg/L and a NOEC of 34 μg/L in an early life stage test for rainbow trout (*Oncorhynchus mykiss*). Algal species were found to be very sensitive to triclosan with a NOEC value of 0.5 μg/L for *Scenedesmus subspicatus*.[39,40] A recent study by Veldhoen *et al.*[47] found that exposure to low levels (as low as 0.15 μg/L) of triclosan disrupted thyroid hormone-associated gene expression and could alter the rate of thyroid hormone-mediated postembryonic anuran development. Based on the traditional toxicity tests, the NOEC value for diclofenac was 1000 μg/L for *C. dubia* (7 days), which is three orders of magnitude higher than the measured effluent concentrations. But a recent study demonstrated chronic histopathological effects in rainbow trout after 28 days of exposure. At the LOEC (lowest observed effect concentration) of 5 μg/L, both renal lesions and alterations of the gills occurred in rainbow trout[19] and cytological alterations in liver, kidney and gills at 1 μg/L.[42]

The RQ values for caffeine, gemfibrozil, ibuprofen, ketoprofen, and naproxen were less than 1 (Table 3), indicating no potential risks. However, risk levels may change when chronic toxicity data for these compounds are available. Mixture effects of pharmaceuticals and their degradation products in effluent should also be considered in the future risk assessment.

Removal within sewage treatment plants

Distribution of the eight PhACs in each of the four STPs sampled for Phase II clearly showed that caffeine, gemfibrozil, ibuprofen,

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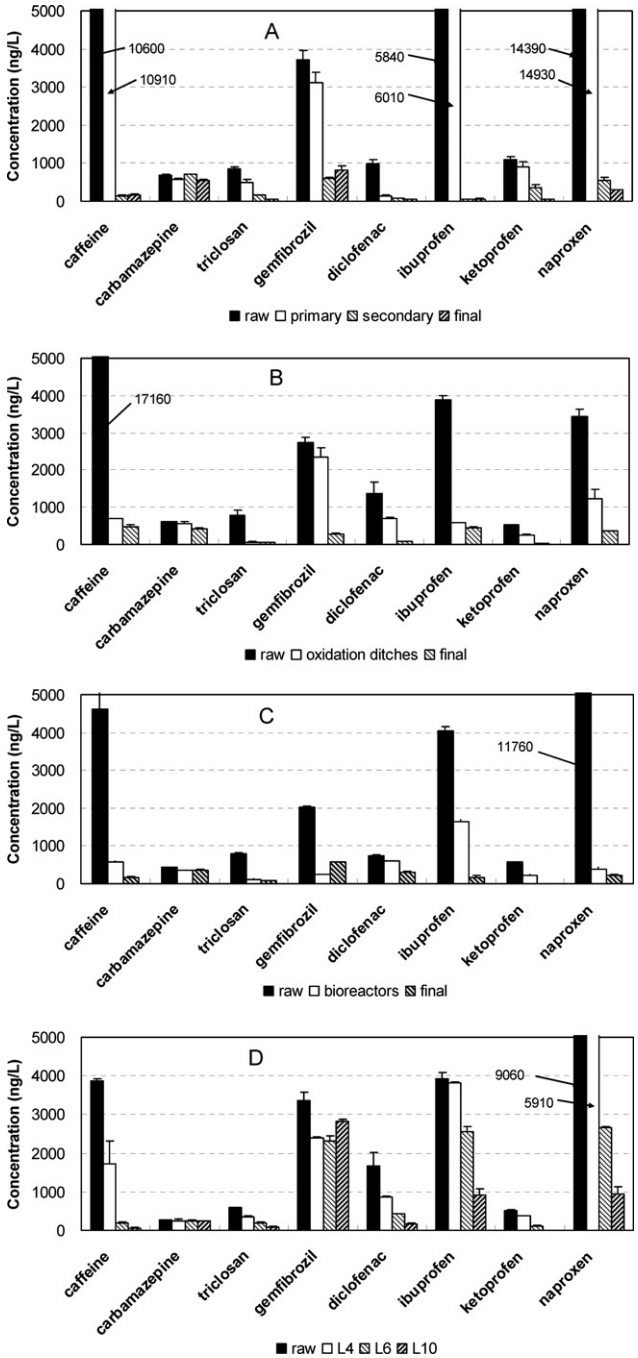

Fig. 2 Fate of pharmaceutically active compounds (PhACs) in the four sewage treatment plants sampled in Phase II. Concentrations in wastewaters at different stages of treatment (raw wastewater, primary effluent, secondary effluent, and final effluent) were shown in order for plant A with conventional activated sludge treatment. For plant B with oxidation ditches and plant C with biological reactors, concentrations were shown for raw wastewater samples from sewage inlet, combined clarifier and final outlet. For plant D with 10 lagoons in series, concentrations were shown for raw wastewater samples from sewage inlet and three aerobic lagoons (L4, L6, and L10). The error bars in the graph indicate standard deviation of four replicates.

and naproxen had relatively high concentrations (exceeding 2000 ng/L, with maximum concentrations exceeding 33000 ng/L) in the influents, while carbamazepine, triclosan, diclofenac, and ketoprofen had relatively low concentrations (less than 2000 ng/L with maximum concentrations as low as 270 ng/L) in these influents (Fig. 2). These results are consistent with the consumption in Australia. Caffeine is a widely consumed stimulant. Many beverages (tea, coffee and soft drinks as well as chocolates) contain caffeine. The average Australian consumes about 2.8 kilograms of coffee and 5.8 kilograms of chocolate each year. The six pharmaceuticals (carbamazepine, gemfibrozil, diclofenac, ibuprofen, ketprofen and naproxen) are listed among the Australian top-50 dispensed pharmaceuticals by mass.[31] The annual dispensed mass for these pharmaceuticals in 1998 are as follows in a decreasing order: 22,850 kg (naproxen), 20,042 kg (gemfibrozil), 14,200 (ibuprofen), 9,980 kg (carbamazepine), 4,440 kg (ketoprofen) and 4,390 kg (diclofenac). This order is similar to the order of influent concentrations for these six PhACs (Fig. 2). Differences are likely a reflection of local use patterns compared to the national use data. Triclosan is an antimicrobial agent used in many personal and hospital healthcare products. There are no statistical data available on the consumption of triclosan. The concentrations in raw wastewater reflect the consumption of these products as wastewater is likely a major disposal path for these compounds.

Table 3 Highest measured environmental concentrations in effluents (MEC) and predicted no effect concentrations (PNEC) and risk quotients (RQ) of each pharmaceutical compound

Pharmaceutical Compound	MEC(effluent) (ng/L)	PNEC (ng/L) [b]	RQ [a]
Caffeine	1740	182,000[44]	0.01
Carbamazepine	1970	420[41]	4.69
Triclosan	490	50[39,40]	9.76
Gemfibrozil	2860	10,000[43]	0.29
Diclofenac	550	100[19,41,42]	5.48
Ibuprofen	1660	9,100[37]	0.18
Ketoprofen	630	15,600[38]	0.04
Naproxen	1910	21,200[38]	0.09

[a] RQ = MEC/PNEC. [b] Refe. 19, 37–44.

The concentrations of individual target PhACs in the influents varied from plant to plant, but there were no statistically significant differences (ANOVA, $p > 0.05$) among the four STPs if considering all eight compounds together. Significant changes in concentrations of the PhACs at different process stages were observed in each of the four STPs, except for carbamazepine having no significant decreases and gemfibrozil in plant D (Fig. 2). Unlike the other three STPs, plant A has a primary sedimentation stage. However, significant decreases in concentrations were only found for diclofenac ($F = 40$, $p < 0.05$) and triclosan ($F = 163$, $p < 0.05$) at this stage. Significant decreases (ANOVA, $p < 0.05$) in concentrations for most of the compounds analysed in this study were observed at biological steps in plants A, B and C. Plant D performed with the least efficiency in removing the PhACs in wastewater (Fig. 2). Plant D is a rural sewage treatment plant with 2 anaerobic lagoons followed by 8 aerobic lagoons in series. Plant D had the lowest treatment efficiency as indicated by operating parameters such as biochemical oxygen demand (BOD), sewage suspended solids, and ammonia (Table 1). Interestingly, a detailed investigation into the lagoons treatment in plant D showed that most of the

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target compounds started to degrade significantly ($F = 17$, $p < 0.05$) in the sixth or seventh lagoon (Fig. 3). Sludge and solids sedimentation occurred in the first several lagoons, suggesting that adsorption onto solids is not important in the removal of these PhACs in this STP. It also suggests that anaerobic degradation played little role in eliminating those compounds in plant D.

Overall aqueous removal efficiencies from the liquid wastewater for each compound in each STP, calculated by comparing influent and effluent concentrations, are given in Table 4. Similar to previous studies,[13,44] high removal efficiencies were determined for caffeine in the four STPs (Table 4). In contrast, little removal (6–31%) of carbamazepine was observed. The results are consistent with the low or no removal efficiencies previously reported.[11,13,14,28] Carbamazepine also has been found to be persistent in aquatic environments,[5,25,46] suggesting that it can be used as an anthropogenic marker of sewage contamination. The observed removal rates for triclosan ranged from 85 to 93% (Table 4), which are in the range identified previously.[14,26,48]

The five acidic pharmaceuticals (gemfibrozil, diclofenac, ibuprofen, ketoprofen, and naproxen) had variable removal rates in the four STPs (Table 4). The removal efficiencies for gemfibrozil ranged from 15% in plant D to 90% in plant B. A similar wide range in removal efficiencies for gemfibrozil previously has been reported, with removal rates of <10 to 75% in seven conventional activated sludge treatment plants of five European countries.[26] Removal efficiencies of more than 60% were found for diclofenac, ibuprofen, ketoprofen, and naproxen, indicating that these four anti-inflammatory drugs are less persistent than gemfibrozil (a lipid regulator) in the STPs investigated. The lowest removal efficiency (61%) for diclofenac occurred in plant C with bioreactors, while the lowest removal efficiency (77%) for ibuprofen was found in plant D with lagoon treatment. Variable removal efficiencies (<10–80%) for diclofenac previously have been reported, with most reported efficiencies being less than 70%.[11,13,15,26,29,49] Laboratory experiments showed little adsorption onto sludge and slow biodegradation of diclofenac in activated sludge systems.[29,50] Higher removal efficiencies observed for diclofenac for this study are likely due to the relatively high hydraulic retention times in these four STPs. In general, plant D had the lowest efficiency in wastewater treatment, but it still exhibited substantial removal efficiencies (>77%) for most of the PhACs except for carbamazepine (6%) and gemfibrozil (15%). This study demonstrates that, with the exception of carbamazepine and gemfibrozil, the four STPs with different technologies are capable of removing a substantial portion of the target PhACs from the liquid waste stream. However, even for compounds with the greatest removal rates, discharge to the aquatic environment is still taking place.

Two processes (adsorption onto sludge and biodegradation) are often responsible for the aqueous removal of PhACs in an STP.[28,29,51–53] Preliminary analyses of sludge samples found no or only trace amounts of these PhACs except for triclosan with concentrations of up to 17 mg/kg.[53] Triclosan is a hydrophobic compound with a sorption coefficient (K_d) of 20,000 L/kg on sludge.[40] Bester[48] found that adsorption onto sludge accounted for about 30% of the removal for triclosan in a German sewage treatment. Adsorption onto sludge played a role in the removal of triclosan in the STPs, although biological degradation was believed to be the predominant removal mechanism for triclosan in the STPs.[48,53] Similar results for pharmaceuticals were found in sludge samples from Japanese, Swiss, German, and US sewage treatment plants.[28,29,51,52] The pharmaceutical compounds including caffeine have sorption coefficients (K_d) of less than 300 L/kg,[28] indicating that adsorption onto sludge is not a major factor in the removal process. This also can be explained by the physiochemical properties of these pharmaceutical compounds (Table 2). Caffeine and carbamazepine are hydrophilic compounds with low log K_{ow} values. Acidic pharmaceuticals such as gemfibrozil, diclofenac, ibuprofen, ketoprofen, and naproxen have pK_a values ranging from 4.1 to 4.9; these compounds occur as ions at neutral pH and have little tendency

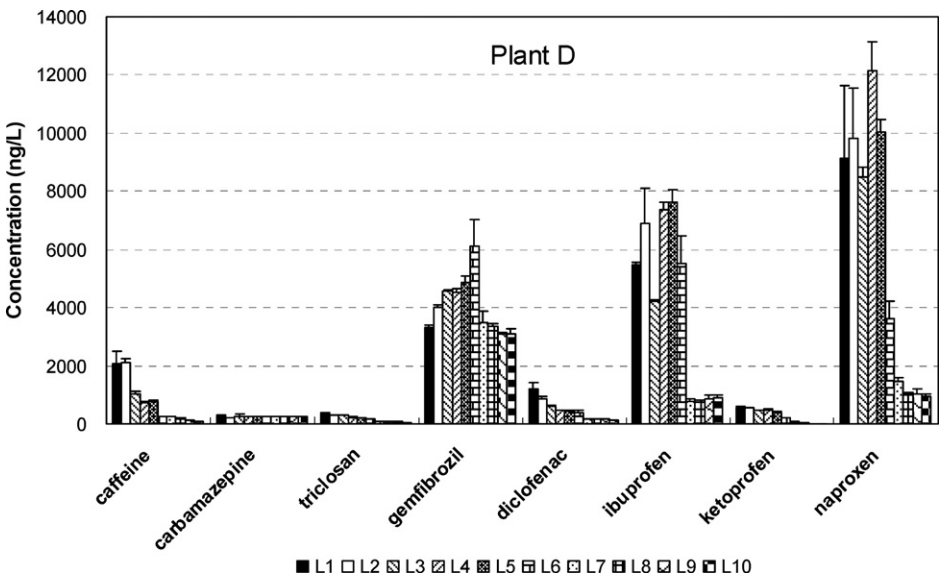

Fig. 3 Concentration changes of pharmaceutically active compounds (PhACs) in plant D with a series of lagoons. Concentration levels were shown for PhACs in the wastewater samples from each lagoon (L1 to L10). The error bars in the graph indicate standard deviation of four replicates.

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Table 4 Removal efficiencies (%) of pharmaceutically active compounds in the four sewage treatment plants

Plant Treatment process	A Activated sludge with 6 lagoons	B 2 oxidation ditches	C 3 bioreactors with UV	D 10 lagoons in series	Literature Data [a]
Caffeine	98	97	96	98	38–86 [c] 94 [e]
Carbamazepine	20	31	17	6	7 [a] <10–53 [b] 30 [e]
Triclosan	93	92	89	85	55–95 [b] 58 [e] 95–96 [f]
Gemfibrozil	78	90	72	15	69 [a] <10–75 [b] 75 [e]
Diclofenac	95	94	61	90	69 [a] <10–80 [b] 9–60 [d] 22 [e]
Ibuprofen	99	89	96	77	90 [a] 52–99 [b] 78–100 [d] 96 [e]
Ketoprofen	96	93	100	100	38–67 [c] 51–100 [d] 65 [e]
Naproxen	98	90	98	90	66 [a] 42–93 [b] 55–98 [d] 93 [e]

[a] Data from literature: a. 11; b. 26; c. 19; d. 15; e. 13; f. 48.

of adsorption to the sludge. At neutral pH of wastewater, pharmaceuticals occur mainly in the dissolved phase within STPs. Therefore, biodegradation is likely the main elimination process for the PhACs in the STPs.

However, photolysis may also play a role in the removal of the PhACs in the STPs, especially for plant C with UV treatment and plant D with lagoons exposed to sunlight. In plant C, UV treatment and chlorination are followed after bioreactors. About 37 to 40% of removal for diclofenac, ibuprofen and ketoprofen occurred at the last stage (UV and chlorination). Partial removal of these acidic compounds in plant C and plant D could be attributed to the photochemical transformation as these compounds can undergo photolysis in water.[54] But further research is needed to clarify the role played by UV treatment.

For those relatively recalcitrant compounds such as carbamazepine and gemfibrozil, advanced treatment technologies such as activated carbon, ozonation, and nanofiltration may be required to more efficiently remove them from wastewater.[27,55] However this may also increase the wastewater treatment cost.

Conclusions

Based on the investigations into the 15 STPs, we can conclude that the eight select pharmaceuticals were detected in the final effluents at significantly variable concentrations. In the worst case scenario with the effluent accounting for 100% of the stream water, carbamazepine, triclosan and diclofenac in the effluent could pose potential risk to the aquatic organisms in the streams while caffeine, gemfibrozil, ibuprofen, ketoprofen and naproxen pose no potential risks based on the toxicity data available.

Significant removal in the four STPs with different technologies was demonstrated for all the eight pharmaceutical compounds except for carbamazepine, which was found mainly due to the biological degradation processes in the plants. Plant D with lagoon treatment was the least efficient among the four STPs in the removal of the pharmaceuticals, especially carbamazepine and gemfibrozil, from the wastewater.

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