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# New Framework To Diagnose the Direct Disposal of Prescribed Drugs in Wastewater – A Case Study of the Antidepressant Fluoxetine

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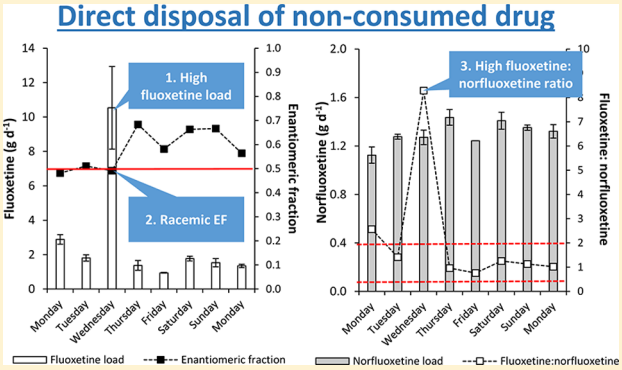
Supporting Information

**ABSTRACT:** Intentional or accidental release (direct disposal) of high loads of unused pharmaceuticals into wastewater can go unnoticed. Here, direct disposal of a pharmaceutical drug via the sewer network was identified for the first time using wastewater analysis. An irregularly high load of the antidepressant fluoxetine in raw wastewater ($10.5 \pm 2.4$ g $d^{-1}$) was up to 11 times greater than any other day. National prescription data revealed a predicted daily fluoxetine load for the studied treatment works to be 0.4–1.6 g $d^{-1}$. Enantio-selective analysis showed the high load of fluoxetine was present as a racemic mixture, which is typical for fluoxetine in dispensed formulations. As fluoxetine undergoes stereoselective metabolism within the body, a racemic mixture in wastewater suggests a nonconsumed drug was the major contributor of the high load. This was confirmed by its major metabolite norfluoxetine whose load did not increase on this day. Considering the most commonly prescribed formulation of fluoxetine, this increased load accounts for the disposal of ~915 capsules. Furthermore, as fluoxetine is prescribed as one capsule per day, disposal is unlikely to be at the patient level. It is postulated that direct disposal was from a facility which handles larger quantities of the drug (e.g., a pharmacy).




## 1. INTRODUCTION

In 2001, wastewater analysis has been first proposed for community wide estimation of drug use.[1] This approach has been applied in numerous studies to date, mainly for illicit drug use estimates throughout Europe.[2,3] The same approach has been applied to pharmaceuticals.[4,5] However, notable discrepancies between consumption estimates from wastewater analysis and prescription information have been observed for some compounds.[4,5] For example, the study of 12 prescription drugs at a wastewater treatment works (WwTW) in the UK found consumption estimates from wastewater analysis can range from 12 to 514% of what is expected from prescription data.[4] Possible reasons for inaccurate pharmaceutical drug consumption estimates from wastewater analysis includes the abuse of counterfeit drugs,[6] the unavailability of information on drugs dispensed in hospitals, spatial differences in prescription/use (where national prescription information is used), prescribed drugs going unused, or drugs being directly disposed into the wastewater system.[7]

Several studies have found direct disposal of unused pharmaceutical drugs to the sewer system as a viable route into wastewater at both the patient[8,9] and pharmacy level.[10] These studies rely on patients and pharmacies completing questionnaires on their disposal practices. However, to date there has been very little/no evidence of direct disposal of pharmaceutical drugs identified through wastewater analysis. This is because observing directly disposed drugs at the patient level is unlikely to provide a significant change to the composition of the wastewater itself. Observing direct disposal will be strongly dependent on the pharmacokinetics of the pharmaceutical in question, the extent of its usage within the population and the size of the receiving WwTW. On the other hand, direct disposal by a pharmacy will only be observed fortuitously as it is likely to occur infrequently. Furthermore, if observed by wastewater analysis, other than a high compound load there may not be further supporting evidence to adequately diagnose direct disposal. If the pharmaceutical is only available via prescription, national prescription information can be used to estimate the load of that drug in wastewater.

Enantio-selective analysis is an indispensable tool for resolving certain environmental problems. It can be used to identify the source of chiral drug loads found in wastewater. Directly disposed drug loads can be distinguished from consumed drug

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loads by determining the enantiomeric distribution of the chiral drug in question.[7] This relies on the pharmaceutical drug in question being dispensed in a known enantiomeric form and it undergoing stereoselective changes within the body during metabolism. Vazquez-Roig et al.[11] used enantioselective analysis to tentatively propose direct disposal of atenolol where a moderately higher average daily load was observed. Monitoring human metabolites of the compound in question can also be used to help distinguish between directly disposed and consumed drugs.[12] The clearest case of direct disposal identified through wastewater analysis was by Emke et al.[7] Here, high daily loads of the illicit stimulant 3,4-methylenedioxymethamphetamine (MDMA) or ecstasy were found to be present in wastewater as a racemic mixture. This was observed following a police raid of an illegal production facility within the catchment.[7] Nevertheless, to date there have been no cases with strong supportive evidence of the direct disposal of a pharmaceutical drug using wastewater analysis.

Directly disposed drugs can also have a significant impact upon the receiving environment if they are not sufficiently removed during wastewater treatment. The antidepressant fluoxetine has been identified as a compound of risk for the aquatic compartment in some studies.[13,14] This is due to it being detected in river waters or predicted to be present in river waters at concentrations above predetermined predicted-no-effect-concentrations (PNECs). Oakes et al.[13] proposed a fluoxetine PNEC of 0.012 $\mu$g $L^{-1}$. This was derived using a lowest observed effect concentration (LOEC) of $\leq$0.6 $\mu$g $L^{-1}$ for the chlorophyte *Desmodesmus subspicatus* and an assessment factor of 50.[13] In freshwater ecosystems globally, fluoxetine has been reported at median concentrations of 0.020 $\mu$g $L^{-1}$.[15] Considering the small differences between the proposed PNEC and concentrations observed in the environment, direct disposal of the drug can influence whether or not the PNEC of fluoxetine is exceeded.

In our study, during an eight day sampling period of raw wastewater at a municipal WwTW in South-West England, a high load of the antidepressant fluoxetine was observed. It was postulated that this was the result of direct disposal of the drug rather than increased consumption. Therefore, the aim of this study was to diagnose this high load of fluoxetine as direct disposal. This was assessed by investigating the following:

i) UK prescription information for fluoxetine

ii) The enantiomeric distribution of fluoxetine in raw wastewater

iii) The relationship between fluoxetine and its major metabolite norfluoxetine

These findings were compared to a seven day sampling period at the same WwTW where no direct disposal was suspected. This study is the first to demonstrate with sufficient supporting evidence the direct disposal of a prescribed pharmaceutical drug using wastewater analysis. Using this information, we propose a new framework to distinguish between consumed and nonconsumed (directly disposed) drug loads in wastewater. Finally, the risk posed by direct disposal in the environment was evaluated by applying established environmental risk assessment calculations.

## 2. MATERIAL AND METHODS

**2.1. Materials.** *R*/*S*-(±)-Fluoxetine and norfluoxetine (Table S1) were purchased from Sigma-Aldrich (Gillingham, UK) and the internal standard *R*/*S*-(±)-fluoxetine-D5 from TRC (Toronto, Canada). Methanol (MeOH) was HPLC grade and purchased from Sigma-Aldrich (Gillingham, UK). Water ($H_2O$) was of 18.2 MΩ quality (Elga, Marlow, UK). All glassware was deactivated using 5% dimethylchlorosilane in toluene (Sigma-Aldrich, Gillingham, UK). Ammonium acetate ($NH_4OAc$), formic acid (HCOOH), and acetic acid (1.0 M) used in the preparation of mobile phases were also purchased from Sigma-Aldrich. Oasis HLB (60 mg, 3 mL) solid phase extraction (SPE) cartridges were purchased from Waters (Manchester, UK).

**2.2. Analytical Methodologies.** Briefly, samples for SPE were brought to room temperature and filtered (0.7 $\mu$m), and 50 mL aliquots were spiked with 50 ng of fluoxetine-D5. These were loaded onto preconditioned Oasis HLB cartridges, dried, and eluted using 4 mL of MeOH. Extracts were then dried under nitrogen and reconstituted in 500 $\mu$L of 80:20 $H_2O$:MeOH for the determination of whole drug concentrations. A fully validated method utilizing ultraperformance liquid chromatography tandem mass spectrometry using a Waters Acquity UPLC system (Manchester, UK) coupled to a Xevo TQD Triple Quadrupole Mass Spectrometer (Waters, Manchester, UK) was applied. A full description of the method is available in Petrie et al.[16] Recoveries of fluoxetine and norfluoxetine ranged from 95 to 111%, with method quantitation limits of 2.1 to 2.5 ng $L^{-1}$ (Tables S2 and S3).

To investigate the enantiomeric fraction (EF) of fluoxetine, SPE cartridges were prepared in the same way. However, following elution and drying of MeOH extracts, reconstitution was in 500 $\mu$L of the appropriate mobile phase used for enantioselective separation (4 mM $NH_4OAc$ in MeOH containing 0.005% HCOOH). For separation, a Chirobiotic V column (100 × 2 mm; 5 $\mu$m internal diameter) was used, as described in Evans et al.[17] The EF of fluoxetine was calculated according to eq 1

$$\mathrm{EF} = \frac{S(+)}{[S(+) + R(-)]} \quad (1)$$

where EF is the enantiomeric fraction, $S(+)$ is the peak area of *S*-(+)-fluoxetine accounting for the response of *S*-(+)-fluoxetine-D5, and $R(-)$ is the peak area of *R*-(−)-fluoxetine accounting for *R*-(−)-fluoxetine-D5. The uncertainty of EF measurement for fluoxetine in raw wastewater was <0.05.[17]

**2.3. Wastewater Treatment Works.** A trickling filter WwTW in South-West England was studied. This receives mainly municipal wastewater with a population equivalent (PE) of 105,847. Raw wastewater was collected during an eight day monitoring campaign in December 2014 (08/12/14 to 15/12/14) and a seven day monitoring campaign in June 2015 (03/06/15 to 09/06/15). Samples were collected post primary screens but before primary sedimentation tanks. Volume paced composites were operated with a mean sampling frequency of 15 min (i.e., 96 subsamples throughout 24 h). This conservative sampling frequency was selected to ensure sampling error distributions were unbiased and <20%.[18] The number of toilet flushes or "pulses" (p) per day estimated for fluoxetine in this WwTW was ∼6600 (>100 p $d^{-1}$ is required for representative information using volume-paced composites with a 15 min collection frequency).[18] Subsamples were cooled on collection to <4 °C to limit biological activity. On the first Monday of the December sampling campaign (08/12/14), hourly grab samples were also collected between 8:00 and 0:00 ($n$ = 17). Upon collection, all samples were filtered and subject to SPE immediately.



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**2.4. Environmental Risk Assessment.** Environmental risk assessment of fluoxetine in receiving river water was undertaken with reference to the Guideline on the Environmental Risk Assessment of Medicinal Products for Human Use.[19] The ratio between the predicted environmental concentration (PEC) and PNEC was calculated as means of quantifying the risk posed. Ratios >1 require further evaluation of the fate of the drug and/or its metabolites in the aquatic environment. The PEC ($\mu$g $L^{-1}$) was calculated using the following equations with prescription information (2) and wastewater analysis (3), respectively

$$\mathrm{PEC}_{\mathrm{Prescription}} = \frac{\mathrm{Load}_{\mathrm{PRES}} \times S \times R}{Q \times \mathrm{PE} \times \mathrm{DF}} \quad (2)$$

$$\mathrm{PEC}_{\mathrm{Waste\ water\ analysis}} = \frac{\mathrm{Load}_{\mathrm{INF}} \times R}{Q \times \mathrm{PE} \times \mathrm{DF}} \quad (3)$$

Here $\mathrm{Load}_{\mathrm{PRES}}$ is the maximum predicted load based on prescription information (accounting for the % dose excreted unchanged) ($\mu$g $d^{-1}$), $\mathrm{Load}_{\mathrm{INF}}$ is the daily load of fluoxetine in the aqueous phase of influent wastewater ($\mu$g $d^{-1}$), $S$ is the correction factor to account for the fraction of fluoxetine bound to suspended particulate matter (0.49),[4] $R$ is the correction factor to account for the known removal of fluoxetine during wastewater treatment at the site in question (0.673), $Q$ is the total quantity of wastewater per inhabitant (L $inh^{-1}$ $d^{-1}$), PE is the population size contributing to the wastewater, and DF is the dilution factor of effluent into the river. The PNEC of fluoxetine was determined according to

$$\mathrm{PNEC} = \frac{\mathrm{Tox.}}{\mathrm{AF}} \quad (4)$$

Here Tox. is the lowest available toxicity data (effect concentration ($EC_{50}$), lethal concentration ($LC_{50}$), LOEC, no observed effect concentration (NOEC)) considering at least three species type, and AF is the assessment factor (1000 for $EC_{50}$ and $LC_{50}$ and 10 for LOEC and NOEC).

## 3. RESULTS AND DISCUSSION

**3.1. Daily Profile of Fluoxetine and Norfluoxetine in Raw Wastewater.** *3.1.1. Predicted and Measured Daily Loads of Fluoxetine.* On Wednesday of the December sampling campaign, a fluoxetine load of 10.5 ± 2.4 g $d^{-1}$ was observed (Figure 1). This was considerably greater than any other day (up to 11 times). The consumption of fluoxetine is not expected to vary greatly throughout the week as it is unlikely to be used as a drug of abuse which may result in recreational usage. Furthermore, no significant rainfall or increased wastewater flows were recorded on this day which could have resulted in an increased load of fluoxetine flushed from the sewer network (Table S4). Therefore, it was postulated that the high load of fluoxetine on Wednesday was a result of direct disposal. Using UK prescription information, the daily load of fluoxetine predicted to be observed at a 105,847 PE WwTW in England during December 2014 was 0.4−1.6 g $d^{-1}$ (Table 1). This was calculated according to eq 5

$$\mathrm{Load}_{\mathrm{PREDICTED}} = \frac{\mathrm{PRES.} \times \left(\frac{\mathrm{Excretion}}{100}\right) \times \left(\frac{(100 - \mathrm{part.})}{100}\right) \times \left(\frac{\mathrm{WwTW\ PE}}{\mathrm{Pop.}}\right)}{d} \quad (5)$$

Here PRES. is the quantity of drug prescribed nationally during a calendar month as the free base (g) (Table 1), Excretion is the quantity of drug excreted unchanged following consumption (%) (Table 1), part. is the sorption of drug to suspended particulate matter (%) (Table 1), WwTW PE is the population equivalent of the wastewater treatment works, Pop. is the population size to which the prescription information relates (57,000,000), and $d$ is the number of days in the month studied. It should be noted that comparison of prescription information with measured drug loads in raw wastewater can have discrepancies. For example, a detailed study by Baker et al.[4] at a 3,400,000 PE WwTW in England showed the difference between calculated fluoxetine loads and estimated loads from prescription data to be 57%. Furthermore, prescription data used in our study is at a national scale, and the WwTW studied here (105,847) represents <2% of the population. Therefore, there are uncertainties associated when comparing prescription data with wastewater analysis (e.g., possible spatial trends in prescription behavior). Nevertheless, a 10.5 g $d^{-1}$ observed on Wednesday of the December sampling campaign was +650% of the maximum predicted load (Figure 1, Table 1). On all other days, calculated loads ranged from 70 to 180% of the maximum predicted load.

During a seven day sampling period in June 2015 at the same WwTW where no significant contributions from direct disposal were suspected, daily loads ranged from 0.6 to 0.9 g $d^{-1}$ ($\mathrm{Load}_{\mathrm{PREDICTED}}$ = 0.3−1.4 g $d^{-1}$) (Figure 1, Table 1). Here no significant contribution of the fluoxetine load is suspected from direct disposal as the predicted load was not exceeded. This uniformity of daily fluoxetine load is in good agreement with previous observations for prescription drugs,[4,25,26] including fluoxetine.[4] This supports the hypothesis that the irregularly high load of fluoxetine on Wednesday of the December sampling campaign was caused by direct disposal of a large quantity of the drug. To investigate this further, enantioselective analysis was undertaken to measure the enantiomeric distribution of fluoxetine in raw wastewater.

*3.1.2. Enantio-Selective Analysis as a Tool To Distinguish between Consumed and Directly Disposed Unused Drugs.* Enantio-selective analysis can be used to help distinguish between consumed drugs and those directly disposed.[7] This is reliant on the drugs in question being chiral, dispensed in a known enantiomeric form, and subject to stereoselective changes to their composition during human metabolism. Fluoxetine satisfies these criteria as it is dispensed as a racemic mixture, and human metabolism results in the enrichment of *S*-(+)-fluoxetine. This is due to *R*-(−)-fluoxetine undergoing faster metabolism in the body than *S*-(+)-fluoxetine.[22] Consequently, an EF of >0.5 would be expected in raw wastewater containing the consumed drug. Between Thursday and Monday of the December sampling campaign (11/12/14 to 15/12/14), EFs ranged from 0.56 to 0.68 (Figure 1). Here fluoxetine loads were <1.8 g $d^{-1}$ (estimated load from prescription data = 0.4−1.6 g $d^{-1}$) demonstrating fluoxetine was consumed, and no notable direct disposal is suggested. This is in good agreement with data obtained in June where loads were ≤0.9 g $d^{-1}$ ($\mathrm{Load}_{\mathrm{PREDICTED}}$ = 0.3−1.4 g $d^{-1}$) and EFs ranged from 0.66 to 0.70 (Figure 1).

On Monday (08/12/14), Tuesday, and Wednesday of the December sampling campaign where loads were >1.8 g $d^{-1}$, EFs were in the range 0.48 to 0.51 (Figure 1). Enantiomeric fractions close to racemic (0.50) here suggest a large contribution of the fluoxetine load observed in raw wastewater on these days is



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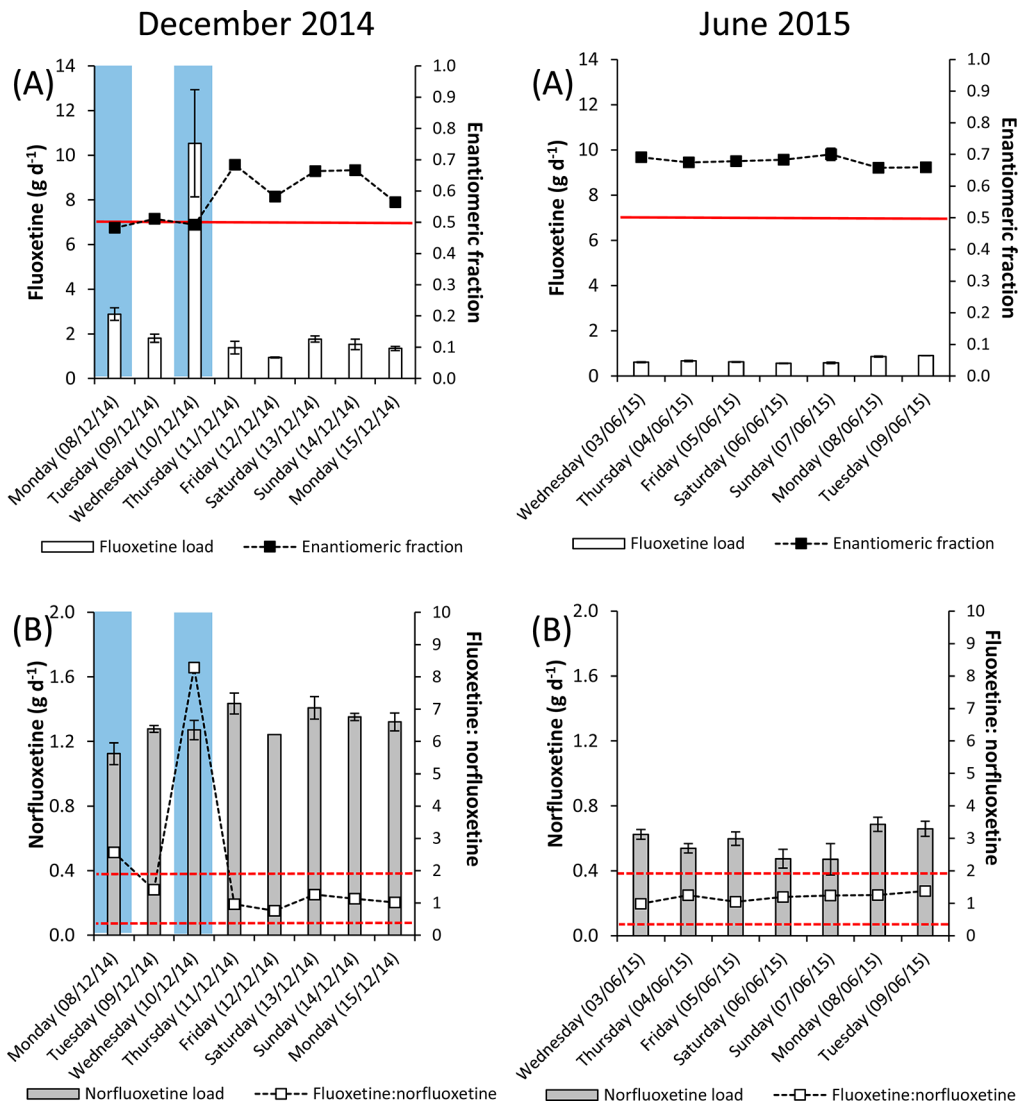


**Figure 1.** Daily fluoxetine load and EF (A) and norfluoxetine load and the fluoxetine:norfluoxetine ratio (B) during week long sampling campaigns in December 2014 and June 2015, respectively. The solid *red line* outlines a racemic EF (i.e., 0.5), and the broken *red line* shows the predicted fluoxetine:norfluoxetine ratio range for consumed fluoxetine (see Table 1). Days where direct disposal has been identified are highlighted with a *blue* background.

**Table 1. Prescription, Metabolism, and Predicted Daily Loads of Fluoxetine and Norfluoxetine at a 105,847 Population Equivalent WwTW in the UK during December 2014 and June 2015**

| | fluoxetine prescribed as free base (kg) | | | | | | $Load_{PREDICTED}$[g] (g $d^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| compound | Dec 2014 | June 2015 | excretion of fluoxetine dose (%) | known metabolites | enantiomeric distribution in urine (human) | partitioning to influent solids (%) | Dec 2014 | June 2015 | predicted fluoxetine:norfluoxetine ratio |
| fluoxetine | 488[a] | 430[b] | 2.5−11[c,d] | norfluoxetine[e] | enriched with *S*-(+) enantiomer, EF > 0.5[e] | 51[f] | 0.4−1.6 | 0.3−1.4 | |
| norfluoxetine | | | 7−10[c,d] | | | 62[f] | 0.8−1.2[h] | 0.7−1.1[h] | 0.3−1.9 |

[a]National Health Service.[20] [b]National Health Service.[21] [c]Caccia t al.[22] [d]Taylor et al.[23] [e]Bergstrom et al.[24] [f]Baker et al.[4] [g]Aqueous phase only, see eq 5 for calculation. [h]To calculate the predicted load of norfluoxetine, the difference in molecular weight between norfluoxetine and fluoxetine is considered as % excretion considers number of moles over mass.

nonconsumed drugs. This provides further support that the high load of fluoxetine on Wednesday was caused by direct disposal. Furthermore, EFs close to 0.50 on Monday and Tuesday suggest that direct disposal also occurred on these days. Interestingly, due to inherent discrepancies in comparing prescription data with measured drug loads,[4,5] direct disposal would not have been suspected on either Monday (8/12/14) or Tuesday of the December sampling campaign without enantioselective analysis.

*3.1.3. Distinguishing between Consumed and Non-consumed Drugs by Metabolite Profiling.* A further piece of



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evidence which can help distinguish between consumed and nonconsumed drugs in raw wastewater are their metabolites. Metabolites are excreted together with the parent drug in known quantities relative to one other following consumption. The main metabolite of fluoxetine is norfluoxetine.[22] The relationship between fluoxetine and norfluoxetine in raw wastewater can therefore be used to help distinguish between consumed and nonconsumed fluoxetine drug loads. Daily loads of norfluoxetine ranged from 1.1 ± 0.1 to 1.4 ± 0.1 g $d^{-1}$ during the eight day sampling period in December ($Load_{PREDICTED}$ = 0.8−1.2 g $d^{-1}$) (Figure 1). No relationship was observed between fluoxetine and norfluoxetine loads which could have suggested increased consumption resulted in the high loads of fluoxetine observed. The predicted ratio of fluoxetine to norfluoxetine expected in the aqueous phase of raw wastewater following consumption is 0.3−1.9 (Table 1). On days where no significant direct disposal was proposed, the fluoxetine:norfluoxetine ratios ranged from 0.8 to 1.3. This is in agreement with the June sampling period where fluoxetine:norfluoxetine ratios were between 1.0 and 1.4. However, on both Monday (08/12/14) and Wednesday of the December sampling campaign the fluoxetine:norfluoxetine ratio was ≥2.6 providing further support that fluoxetine was directly disposed on these days (Figure 1B). Most notably, the fluoxetine:norfluoxetine ratio on Wednesday was 8.3.

**3.2. Hourly Variations of Fluoxetine and Norfluoxetine in Raw Wastewater.** During the first Monday (08/12/14) of the December sampling campaign, hourly grab samples were collected between 8:00 and 0:00 h ($n$ = 17). This provided the opportunity to investigate the hourly variability in fluoxetine and norfluoxetine load during a day where direct disposal of the parent drug was suspected. Here the measured load was greater than the predicted daily load (2.9 g $d^{-1}$ versus 0.4−1.6 g $d^{-1}$); an EF close to 0.50 and a fluoxetine:norfluoxetine ratio of 2.6 all indicated direct disposal had occurred within the catchment on this day (Figure 1). Grab sampling revealed that the hourly load of fluoxetine varied from 0.06 to 0.64 g $h^{-1}$, with highest loads generally observed between 08:00 and 15:00 h (Figure 2A). During these times, an enrichment of *S*-(+)-fluoxetine was not observed, and the EF of fluoxetine was ∼0.50 ± 0.02 (Figure 2A). This suggests a large contribution of the fluoxetine load at these times was nonconsumed drugs. This was supported by the behavior of norfluoxetine which did not show such high variability in load indicating a constant (or unchanged) level of fluoxetine consumption in the studied population. Norfluoxetine loads varied from 0.04 to 0.07 g $h^{-1}$ throughout the day (Figure 2B). Considering fluoxetine typically has a single daily dose and a half-life of between 2 and 3 days,[27] this low variability in metabolite load is not surprising. Between 08:00 and 15:00 h the fluoxetine:norfluoxetine ratio was >1.9 supporting the proposal that fluoxetine loads observed at these times were mainly present as nonconsumed drugs. From 16:00 h onward, fluoxetine and norfluoxetine loads as well as EFs were indicative of consumption only (Figure 2). The length of time wastewater takes to travel from the point of entry into the sewer network (i.e., a household) within the catchment to the WwTW can vary from <30 min to ∼6 h. Consequently, it is difficult to predict exactly when direct disposal took place on this day other than it being prior to 08:00 h.

**3.3. A New Framework To Distinguish between Consumed and Nonconsumed (Directly Disposed) Drugs in Wastewater.** Only a few studies reported in the literature have proposed evidence for the direct disposal of drugs (Table 2).[7,11,12] There are a number of reasons for this: (i) direct disposal at the patient level (e.g., of a daily dose) is unlikely to have sufficient impact upon a 24 h composite sample collected from a medium to large sized WwTW, particularly if the drug in question is a high usage compound (and has a high excretion rate as the unchanged drug following consumption), (ii) the infrequent disposal of larger quantities of drugs by a patient (weekly or monthly dose), hospital, or pharmacy cannot be predicted and will only be observed fortuitously, and (iii) due to analytical or other limitations, the disposed drug may itself not be studied or (iv) further supporting evidence of direct disposal (e.g., enantiomeric distribution and determination of metabolites) may not be attainable.

Andrés-Costa et al.[12] observed high loads of the illicit stimulant cocaine during a week-long sampling event at a WwTW in Spain. This corresponded with a higher than anticipated parent drug:metabolite ratio. Cocaine:benzoylecgonine ratios ranged from 1.6 to 2.0 and are considerably greater than the expected ratio of 0.2−0.5 (Table 2).[12] This was supported by newspaper reports of police raiding an illegal production facility within the catchment. Similarly, higher than

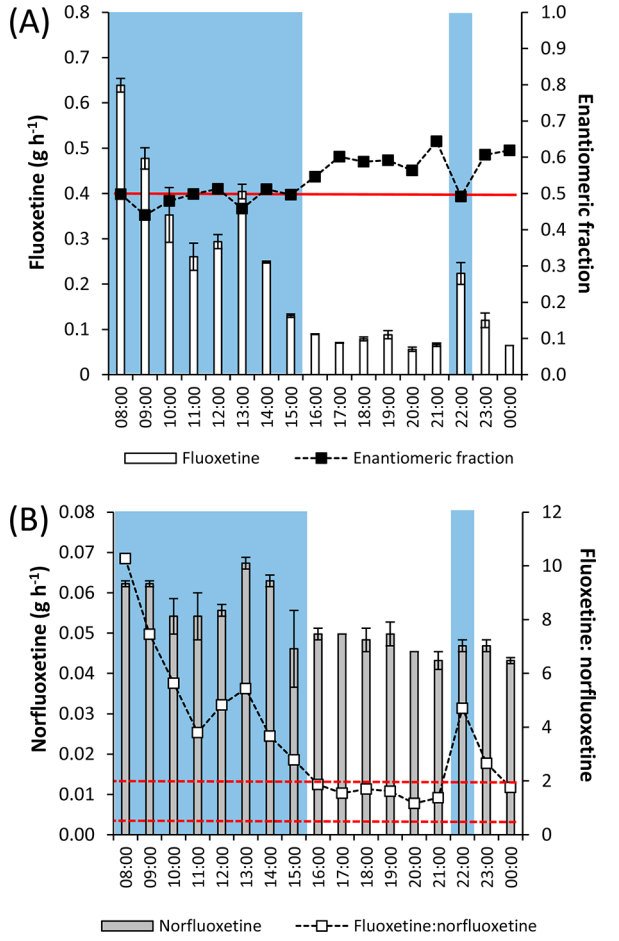


**Figure 2.** Hourly variability of fluoxetine load and EF (A) and norfluoxetine load and the fluoxetine:norfluoxetine ratio (B) during the first Monday (08/12/14) of the December 2014 sampling campaign from Figure 1. The solid *red line* outlines a racemic EF (i.e., 0.5), and the broken *red line* shows the predicted fluoxetine:norfluoxetine ratio range for consumed fluoxetine (see Table 1). Times where direct disposal has been identified are highlighted with a *blue* background.



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Table 2. Suspected Direct Disposal of Drugs Reported in the Literature[a]

| drug | class of drug | direct disposal proposed | | | | baseline information used for comparison (no direct disposal suspected) | | | | further information | ref |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | duration | Load (g d$^{-1}$) | EF | parent drug: metabolite | duration | Load (g d$^{-1}$) | EF | parent drug: metabolite | | |
| fluoxetine | antidepressant | Mon-Mon (Dec 2014) | 0.95−10.54 | 0.48−0.68 | 0.8−8.3 | Wed-Tues (June 2015) | 0.58−0.91 | 0.67−0.70 | 1.0−1.4 | predicted daily load using Dec 2014 prescription data = 0.4−1.6 g d$^{-1}$ | this study |
| atenolol | beta-blocker | one week (2012) | 1.3[b] | 0.50 | | one week (2012, different WwTW) | 1.0[b] | >0.50 | | | Vazquez-Roig et al.[11] |
| MDMA | illicit stimulant | one week (2011) | 184 | 0.50 | | one week (2010) | 9.3 | >0.57 | | police raid illegal production facility within catchment | Emke et al.[7] |
| amphetamine | illicit stimulant | one week (2011) | 1431 | 0.52 | | one week (2010) | 99 | 0.52 | | | Emke et al.[7] |
| cocaine | illicit stimulant | Fri and Sun at two separate WwTWs (2013) | 375−3292 | | 1.6−2.0 | several weeks (2011 and 2012) | 110−464 | | 0.2−0.5 | police shutdown illegal production facility within catchment | Andrés-Costa et al.[12] |

[a]Abbreviations: EF, enantiomeric fraction; WwTW, wastewater treatment works. [b]g d$^{-1}$ 1000$^{-1}$ inhabitants.

typical MDMA loads (~20 times) at a WwTW in The Netherlands coincided with a police raid of an illegal production facility (Table 2).[7] In this case, enantioselective analysis was used to help diagnose the direct disposal of MDMA. EFs of MDMA was ~0.50 (racemic mixture) when high loads were observed. Where consumption is assumed during a baseline week for comparison purposes EFs were >0.57.[7] In the literature, only one study provides some evidence for direct disposal of a pharmaceutical drug. Vazquez-Roig et al.[11] reported average daily loads for the beta-blocker atenolol of 1.3 g d$^{-1}$ 1000$^{-1}$ inhabitants. This was higher than other WwTWs studied in the area which received loads of 1.0 g d$^{-1}$ 1000$^{-1}$ inhabitants. Higher loads were again supported with racemic EFs (Table 2). However, no previous study which has postulated direct disposal from wastewater analysis has been able to provide strong supportive evidence of drug use information (e.g., prescription data), parent drug/metabolite relationships, and enantiomeric determinations. These parameters were used to establish a framework for distinguishing between consumed and nonconsumed (directly disposed) prescription drugs using wastewater analysis (Figure 3). This framework can be applied to findings from routine 24 h composite sampling to help identify directly disposed drug loads. Applying this framework in our study, direct disposal was confirmed on Monday (08/12/14) and Wednesday of the December sampling period. Direct disposal could not be confirmed on Tuesday as the fluoxetine:norfluoxetine ratio did not exceed the predicted ratio of 0.3−1.9 based on consumption (Table 1). Application of this framework requires care as it will not be directly applicable to all chiral drugs. For example, ibuprofen can be dispensed in more than one enantiomeric form - as a racemic mixture or in the enantiomerically pure form. This makes it difficult to predict the enantiomeric form expected in wastewater. On the other hand, the metabolite of a parent drug can also be dispensed as a separate pharmaceutical (e.g., desvenlafaxine). Therefore, the framework should act as a starting point for investigating the disposal of pharmaceutical drugs and adapted for the specific drug under investigation.

Using the data obtained on Wednesday, the quantity of drug formulations estimated to be directly disposed was calculated using eq 6

$$\text{No. of formulations} = \frac{(\text{Load} - \text{Load}_{\text{PREDICTED}}) \times \left(\frac{100}{(100 - \text{part.})}\right)}{\text{Dose}} \quad (6)$$

Here Load is the calculated daily load at the WwTW (g), $\text{Load}_{\text{PREDICTED}}$ is the highest predicted daily load based on eq 5 (g), part. is the sorption of drug to suspended particulate matter (%, note that partitioning to suspended particulate matter could be concentration dependent), and Dose is the dose of drug per formulation (g). The most widely dispensed formulation of fluoxetine in the UK is capsules containing 20 mg of active ingredient.[20] This formulation accounted for 96% of all fluoxetine items prescribed during December 2014. Using this information, the number of capsules estimated to be directly disposed of on Wednesday is ~915 capsules. Furthermore, as the prescribed dose is one capsule per day, this number of capsules accounts for an individual's prescription of >2.5 years. This suggests direct disposal is unlikely to be at the patient level. Disposal of such a large number of capsules



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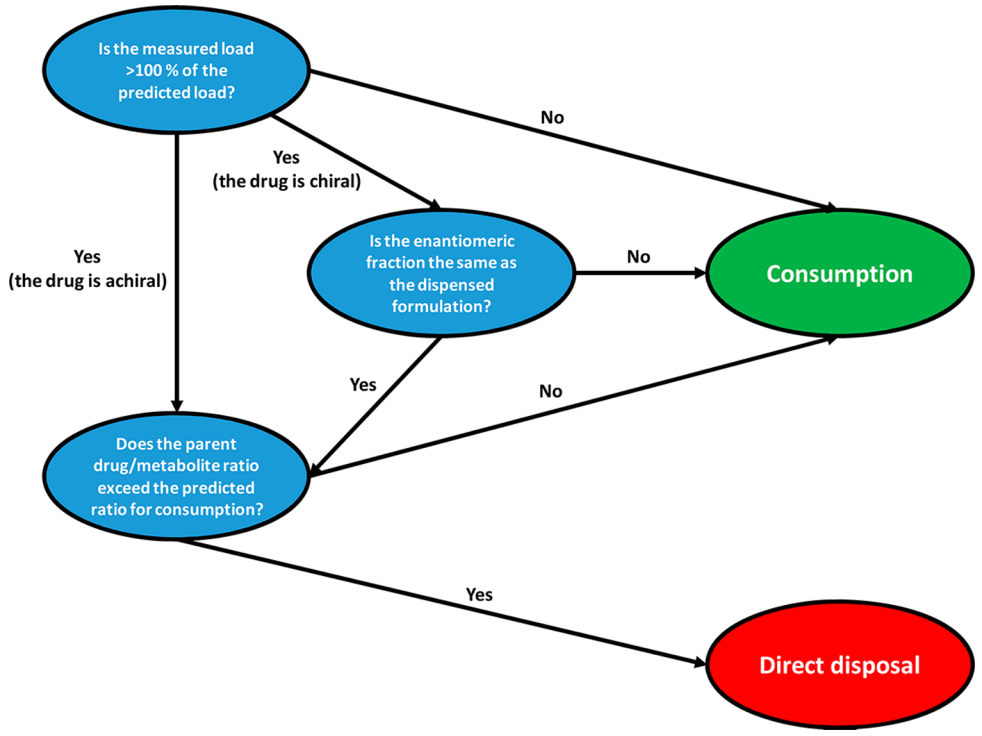


**Figure 3.** Proposed framework to distinguish between consumed and directly disposed prescription drugs in wastewater.

on 1 day is more likely to be by a facility which handles and dispenses a large quantity of pharmaceutical drugs (e.g., a pharmacy). In this catchment there are no registered pharmaceutical production companies. A study by Tong et al.[10] found that 3.2% of 285 community pharmacies in New Zealand disposed of unused solid medications via the toilet or sink. Although this may not be directly comparable to current disposal practices in the UK, this is a possible route of entry for the relatively large quantity of unconsumed fluoxetine observed on Wednesday. Current EU directives only outline that member states shall ensure that appropriate collection systems are in place for medicinal products that are unused or have expired.[28]

**3.4. Environmental Risk Assessment.** To assess the potential impact of fluoxetine in the environment, established environmental risk assessment protocols were applied.[19] It should be noted that current environmental risk assessment can be inaccurate as it does not consider the impact of mixtures of a number of different compounds or the enantio-specific toxicity of chiral drugs. For example, enantio-specific toxicity has been observed for fluoxetine toward some aquatic species.[29,30] Nevertheless, these established environmental risk assessment calculations have been applied here to compare the possible environmental impact of consumed and directly disposed drug loads. PECs were calculated taking into account site specific flow data (wastewater and receiving river). This was calculated using prescription data and wastewater analysis from December 2014 and June 2015. Using available toxicity data in the literature, the lowest derived PNEC was calculated to be 0.010 $\mu$g L$^{-1}$ (Table S5). This was determined using toxicity data from studies using racemic fluoxetine. Therefore, there will be a degree of uncertainty here as directly disposed and consumed fluoxetine will have different enantiomeric distributions when entering the environment, and, as discussed previously, enantio-specific toxicity of fluoxetine is known to occur.[29,30]

The PEC of fluoxetine for the load observed on Wednesday (December 2014) where direct disposal was identified was 0.0044 $\mu$g L$^{-1}$ (Table 3). This corresponded to a PEC/PNEC of 0.44, and therefore low risk is assumed despite a high load of the drug observed. This is attributed to the high dilution in wastewater (354 L inh$^{-1}$ d$^{-1}$) and in the receiving river (44 times) at this site during winter. No seasonal bias is expected for the direct disposal of fluoxetine. Therefore, if the directly disposed load (10.5 g d$^{-1}$) is applied to June conditions at the same WwTW (wastewater volume of 235 L inh$^{-1}$ d$^{-1}$ and a riverine dilution factor of 18), the PEC/PNEC is 1.59 (Table 3). The action limit of 1 is exceeded, and further investigation is needed. It should be noted that many WwTWs have similar or lower wastewater and river dilution ratios than those reported here. For example, seven of 16 WwTWs previously studied in the UK had river dilution factors of $\leq$7, with two of these sites having dilution factors of one (i.e., no dilution).[31] Therefore, directly disposed drugs are expected to have an even greater environmental impact here. On the other hand, the PEC will be lower at sites which employ other wastewater treatment options (e.g., activated sludge) which are considered more effective in removing fluoxetine than trickling filters. However, greater stereoselective changes may be observed which need to be taken into account.

Finally, if the PEC of fluoxetine is calculated using UK prescription data and default conditions (wastewater volume of 200 L inh$^{-1}$ d$^{-1}$ and a riverine dilution factor of 10)[19] as a means of prioritizing compounds for investigation, a concentration of 0.005 $\mu$g L$^{-1}$ is derived (Table 3). Thus, the PEC/PNEC of fluoxetine is determined to be 0.50. This is similar to a study by Oakes et al.[13] where a PEC/PNEC ratio of 0.83 was calculated from prescription data for Sweden. In both cases the PEC/PNEC action limit of 1 is not exceeded, and this compound may not be prioritized for further investigation here. However, if the directly disposed load is applied to default


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Table 3. PEC/PNEC of Fluoxetine during December 2014 and June 2015 in the Receiving River at the Studied WwTW (105,847 Population Equivalent) and in Default Dilution Conditions under Normal and Direct Disposal Events[a]

| conditions | fluoxetine load | influent wastewater load[b] (g d$^{-1}$) | wastewater volume (L inh$^{-1}$ d$^{-1}$) | riverine dilution factor | PEC ($\mu$g L$^{-1}$) | PEC/PNEC |
|---|---|---|---|---|---|---|
| Dec 2014 | prescription data | 1.6[c] | 354 | 43 | 0.0007 | 0.07 |
| | wastewater analysis (no direct disposal) | 1.4[d] | | | 0.0006 | 0.06 |
| | wastewater analysis (direct disposal) | 10.5[e] | | | 0.0044 | 0.44 |
| June 2015 | prescription data | 1.4[f] | 235 | 18 | 0.0022 | 0.22 |
| | wastewater analysis (no direct disposal) | 0.7[g] | | | 0.0010 | 0.10 |
| | wastewater analysis (direct disposal) | 10.5[e] | | | 0.0159 | 1.59 |
| default | prescription data | 1.6[c] | 200[h] | 10[h] | 0.0050 | 0.50 |
| | wastewater analysis (no direct disposal) | 1.4[d] | | | 0.0038 | 0.38 |
| | wastewater analysis (direct disposal) | 10.5[e] | | | 0.0335 | 3.35 |

[a]Abbreviations: PEC, predicted environmental concentration; PNEC, predicted no effect concentration. [b]Aqueous phase. [c]Maximum load based on December 2014 prescription information.[20] [d]Average daily load from 11/12/14 to 15/12/14 ($n$ = 5). [e]Daily load from 10/12/14 ($n$ = 1). [f]Maximum load based on June 2015 prescription information.[21] [g]Average daily load from 03/06/15 to 09/06/15 ($n$ = 7). [h]EMEA.[19]

dilution conditions[19] (to a 105,847 population equivalent WwTW), the PEC/PNEC is calculated to be 3.35 (Table 3). Therefore, the environmental risk posed by pharmaceutical drugs cannot be fully appreciated by calculating PECs on prescription data alone (or by applying default dilution ratios). It is recommended that future environmental risk assessment must consider the possibility of directly disposed drugs entering wastewater (and their stereoselective composition), even though the frequency of these events and their severity in terms of total drug quantity disposed are difficult to predict. Consequently, a more integrated approach toward environmental risk assessment may be needed by considering disposal practices of patients, hospitals, and pharmacies (and their number/size, etc.) within the catchment area under study.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b00291.

Additional information, physicochemical properties of fluoxetine and norfluoxetine (Table S1); mass spectrometry detail (Table S2), method validation data (Table S3), wastewater flows and rainfall data (Table S4), toxicological information for fluoxetine (Table S5); and additional references (PDF)

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### Notes

The authors declare no competing financial interest.

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**Supporting information**

# A new framework to diagnose the direct disposal of prescribed drugs in wastewater – a case study of the antidepressant fluoxetine

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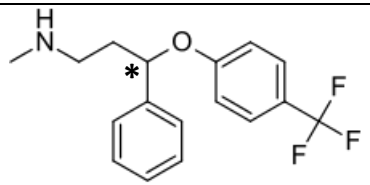
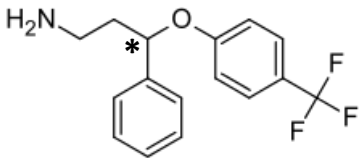
The supporting information is eight pages in length and contains five tables:

**Table S1. Physico-chemical properties of fluoxetine and norfluoxetine**

| Drug/metabolite | Molecular weight (g mol$^{-1}$) | Chemical structure | Water Solubility (mg L$^{-1}$)[i] | Log Kow[ii] | Log Koc[iii] | Log Dow[iv] | Henry's Law Constant (atm m$^3$mol$^{-1}$)[v] | Vapour Pressure (Torr)[vi] | pKa (Most basic)[vii] |
|---|---|---|---|---|---|---|---|---|---|
| Fluoxetine | 309.33 |  | 60.3 | 4.65 | 8.90E-08 | 1.92 | 8.90E-08 | 1.88E-06 | 10.05±0.10 |
| Norfluoxetine | 295.30 |  | - | - | - | 1.54 | - | 5.21E-06 | 9.05±0.13 |

[i]As calculated by EPI Suite[1] at 25°C
[ii]As calculated by EPI Suite[1] (KOWWIN v1.68 estimate)
[iii]As calculated by EPI Suite[1] based on Log Kow
[iv]As calculated by Marvin Beans[2] at pH 7.5
[v]As calculated by EPI Suite[1] based on Bond SAR method
[vi]As stated on Scifinder calculated using Advanced Chemistry Development (ACD/Labs) Software v11.02 (©1994-2015 ACD/Labs)[3]
[vii]As stated on Scifinder calculated using Advanced Chemistry Development (ACD/Labs) Software v11.02 (©1994-2015 ACD/Labs) at 25°C[3]
*Denotes chiral centre

**Table S2. Mass spectrometry information for the determination of fluoxetine and norfluoxetine**

| Drug/metabolite | Molecular ion (m/z) | Daughter 1 (m/z) | Cone voltage (V) | Collision energy (eV) | Daughter 2 (m/z) | Cone voltage (V) | Collision energy (eV) | Ion ratio | Internal standard |
|---|---|---|---|---|---|---|---|---|---|
| Fluoxetine | 310.2 | 44.1 | 34 | 10 | 148.1 | 34 | 10 | 14.9 | Fluoxetine D5 |
| Norfluoxetine | 296.1 | 134.1 | 18 | 6 | - | - | - | - | Fluoxetine D5 |

**Table S3. Method validation parameters for fluoxetine and norfluoxetine in influent wastewater**

| Drug/metabolite | IDL (ng $L^{-1}$) | IQL (ng $L^{-1}$) | Recovery (%) | Matrix suppression (%) | MDL (ng $L^{-1}$) | MQL (ng $L^{-1}$) |
|---|---|---|---|---|---|---|
| Fluoxetine | 0.01 | 0.05 | 111 | 54 | 0.50 | 2.52 |
| Norfluoxetine | 0.01 | 0.05 | 95 | 55 | 0.42 | 2.12 |

**Table S4. Wastewater flow data and rainfall during December 2014 and June 2015 sampling campaigns**

| Measured variable | Day of week | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Mon** | **Tues** | **Wed** | **Thurs** | **Fri** | **Sat** | **Sun** | **Mon** | **Tues** |
| | | | | | *December 2014* | | | | |
| Wastewater flow ($m^3$ $d^{-1}$) | 32,444 | 36,843 | 34,363 | 42,651 | 38,857 | 40,247 | 38,266 | 36,369 | - |
| Rainfall (mm) | 0.0 | 1.0 | 3.7 | 15.9 | 0.0 | 0.2 | 0.2 | 0.4 | - |
| | | | | | *June 2015* | | | | |
| Wastewater flow ($m^3$ $d^{-1}$) | - | - | 26,284 | 23,891 | 23,652 | 22,915 | 22,529 | 29,163 | 25,695 |
| Rainfall (mm) | - | - | 1.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**Table S5. Toxicological information for fluoxetine towards aquatic test species**

| Trophic level | Test species | EC50 (mg $L^{-1}$) | LC50 (mg $L^{-1}$) | LOEC (µg $L^{-1}$) | NOEC (µg $L^{-1}$) | Reference | PNEC (µg $L^{-1}$) |
|---|---|---|---|---|---|---|---|
| Algae | *Dunaliella tertiolecta* | 0.170 | - | - | - | DeLorenzo and Fleming[4] | 0.170 |
| | *Pseudokirchneriella subcapitata* | 0.024 | - | - | - | Brooks et al[5] | 0.024 |
| | *Desmodesmus subspicatus* | - | - | ≤0.6 | <0.6 | Oakes et al[6] | 0.060 |
| Fish | *Gambusia affinis* | - | 0.546 | - | - | Henry and Black[7] | 0.546 |
| | *Pimephales promelas* | - | 0.705 | - | - | Brooks et al[5] | 0.705 |
| Crustacean | *Ceriodaphnia dubia* | - | 0.234 | - | - | Brooks et al[5] | 0.234 |
| | *Ceriodaphnia dubia* | - | 0.510 | - | - | Henry et al[8] | 0.510 |
| | *Daphnia magna* | - | 0.820 | - | - | Brooks et al[5] | 0.820 |
| | *Gammarus pulex* | - | - | 0.100 | - | De Lange et al[9] | 0.010 |
| | *Hyallea azteca* | - | - | 100 | 33 | Péry et al[10] | 3.30 |
| | *Daphnia magna* | - | - | 31 | 8.9 | Péry et al[10] | 0.890 |
| | *Daphnia magna* | - | - | 135 | <60 | Oakes et al[6] | 6.00 |
| Mollusc | *Potamopyrgus antipodaram* | - | - | 69 | 13 | Péry et al[10] | 0.130 |
| | *Potamopyrgus antipodaram* | - | - | - | 0.47 | Nentwig[11] | 0.047 |

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