



WASTEWATER EFFLUENT, COMBINED SEWER OVERFLOWS, AND OTHER SOURCES OF ORGANIC COMPOUNDS TO LAKE CHAMPLAIN¹

P. Phillips and A. Chalmers²

ABSTRACT: Some sources of organic wastewater compounds (OWCs) to streams, lakes, and estuaries, including wastewater-treatment-plant effluent, have been well documented, but other sources, particularly wet-weather discharges from combined-sewer-overflow (CSO) and urban runoff, may also be major sources of OWCs. Samples of wastewater-treatment-plant (WWTP) effluent, CSO effluent, urban streams, large rivers, a reference (undeveloped) stream, and Lake Champlain were collected from March to August 2006. The highest concentrations of many OWCs associated with wastewater were in WWTP-effluent samples, but high concentrations of some OWCs in samples of CSO effluent and storm runoff from urban streams subject to leaky sewer pipes or CSOs were also detected. Total concentrations and numbers of compounds detected differed substantially among sampling sites. The highest total OWC concentrations (10-100 $\mu\text{g}/\text{l}$) were in samples of WWTP and CSO effluent. Total OWC concentrations in samples from urban streams ranged from 0.1 to 10 $\mu\text{g}/\text{l}$, and urban stream-stormflow samples had higher concentrations than baseflow samples because of contributions of OWCs from CSOs and leaking sewer pipes. The relations between OWC concentrations in WWTP-effluent and those in CSO effluent and urban streams varied with the degree to which the compound is removed through normal wastewater treatment. Concentrations of compounds that are highly removed during normal wastewater treatment [including caffeine, Tris(2-butoxyethyl)phosphate, and cholesterol] were generally similar to or higher in CSO effluent than in WWTP effluent (and ranged from around 1 to over 10 $\mu\text{g}/\text{l}$) because CSO effluent is untreated, and were higher in urban-stream stormflow samples than in baseflow samples as a result of CSO discharge and leakage from near-surface sources during storms. Concentrations of compounds that are poorly removed during treatment, by contrast, are higher in WWTP effluent than in CSO, due to dilution. Results indicate that CSO effluent and urban stormwaters can be a significant major source of OWCs entering large water bodies such as Burlington Bay.

(KEY TERMS: organic chemicals; environmental sampling; urban areas; point source pollution.)

Phillips, P. and A. Chalmers, 2009. Wastewater Effluent, Combined Sewer Overflows, and Other Sources of Organic Compounds to Lake Champlain. *Journal of the American Water Resources Association* (JAWRA) 45(1):45-57. DOI: 10.1111/j.1752-1688.2008.00288.x

INTRODUCTION

Most studies of the occurrence of organic wastewater compounds (OWCs) in surface waters have focused on the concentrations in wastewater treat-

ment-plant (WWTP) effluent and receiving waters (Fono and Sedlak, 2005). The first large-scale examination of OWCs in the United States (U.S.) (Kolpin *et al.*, 2002) measured OWC concentrations in streams with multiple potential contaminant sources, including WWTPs; subsequent investigations have

¹Paper No. JAWRA-07-0175-P of the *Journal of the American Water Resources Association* (JAWRA). Received December 11, 2007; accepted September 24, 2008. © 2008 American Water Resources Association. **Discussions are open until August 1, 2009.**

²Respectively, Hydrologist, U.S. Geological Survey, 425 Jordan Road, Troy, New York 12180; and Hydrologist, U.S. Geological Survey, P.O. Box 628, U.S. Post Office and Courthouse, Montpelier, Vermont 05601 (E-Mail/Phillips: pjphilli@usgs.gov).

largely focused on the occurrence of OWCs in streams directly below WWTPs (Kolpin *et al.*, 2004; Glassmeyer *et al.*, 2005). Several studies have focused also on the role of WWTPs as sources of OWCs entering surface waters, and on technologies to remove these compounds from the wastewater effluent (Carballa *et al.*, 2005; Clara *et al.*, 2005; Andresen and Bester, 2006; Reemtsma *et al.*, 2006; Heidler and Halden, 2007). Most recently, researchers have begun to study the removal of these compounds during drinking-water treatment of source waters contaminated with OWCs (Andresen and Bester, 2006; Stackelberg *et al.*, 2007). This concern is especially important in areas where wastewater is recycled for potable reuse, such as the Southwestern U.S. (Snyder *et al.*, 2004; Drewes *et al.*, 2005).

The discharge of untreated wastewater to streams and rivers by combined sewer overflows (CSOs) during storms can result in elevated concentrations of bacteria, nutrients, and OWCs in receiving waters. This is particularly important in areas of the Northeastern and Great Lakes regions of the U.S., which frequently have combined sanitary and storm systems. In Europe, Buerge *et al.* (2006) found that caffeine loads in receiving waters in Switzerland were higher than in WWTP effluents and that caffeine loads in the streams increased with precipitation – an indication that CSOs were a major source of caffeine found in nearby streams and lakes. Wilkison *et al.* (2002) found an increase in caffeine, 4-nonylphenol diethoxylate (NP2EO), and triclosan concentrations in stormflows of an urban stream receiving CSO discharge but no WWTP effluent; they also reported increased concentrations of the fecal indicators cholesterol and coprostanol in urban streams during storms, and a decrease in the concentration of the plant sterol stigmastanol. Fono and Sedlak (2005) concluded that the OWCs in untreated sewage were derived from leaky sewers and CSOs, and that bypass flow of untreated sewage may have a disproportionately large effect on concentrations of compounds that are well removed by wastewater-treatment processes (such as caffeine and ibuprofen). Boyd *et al.* (2004) found that concentrations of ibuprofen and triclosan in stormwater canals receiving flow from both sanitary and storm sewers in New Orleans increased after storms with rainfall of 7 cm or more, and attributed the occurrence of these compounds to untreated sewage; they also detected these analytes in adjacent Lake Pontchartrain and identified these stormwater canals as the source.

Although it is commonly assumed that OWC concentrations are highest during baseflow, when sewage effluent dominates streams, these results suggest that concentrations of some OWCs might be highest during stormflows due to CSO contributions

of untreated sewage. Fono and Sedlak (2005) concluded that the dilution effect during stormflows could be less important than the effect of raw sewage discharges to receiving waters because of high concentrations of many OWCs in untreated wastewater, and that this trend could be further enhanced by a decrease in removal efficiency at WWTPs during CSO events. Benotti and Brownawell (2007) developed a simple model of freshwater discharge for CSO events based on differing ratios of CSO and WWTP discharges, and concluded that concentrations of OWCs (including nicotine and acetaminophen) that are highly removed by WWTPs can increase during CSO events, as the lack of treatment becomes more important than dilution by storm runoff not affected by raw sewage. Concentrations of OWCs that are not well removed by WWTPs (including carbamazepine and codeine), by contrast, can be expected to decrease during CSO events, due to dilution by storm runoff.

In 2006, the U.S. Geological Survey (USGS) began a six-month study to document the occurrence of OWCs in the Lake Champlain Basin, specifically at Burlington, Vermont; St. Albans, Vermont; and Plattsburgh, New York (Figure 1, Table 1). This study area contains a variety of hydrologic, land use, and other settings for assessing the sources and sinks of OWCs within this large basin. The sampling sites include five WWTPs, a CSO, three urban streams, two large rivers that receive agricultural runoff and wastewater during storms, and a reference stream dominated by forested land use. Lake Champlain itself was also sampled for OWCs. This lake is large (1,142 km²), and its urban centers receive contaminants from all of the aforementioned contaminant sources. The three urban streams receive untreated wastewater from leaky sewerpipes and/or CSOs during storms, but no treated wastewater inputs. The study entailed collection of 30 samples from 17 sites and analysis of these samples for more than 60 compounds (Table 2) and therefore provides (1) a comprehensive overview of OWC pathways to surface waters of the Lake Champlain Basin and to the lake itself, and (2) an assessment of the role of CSO effluent and urban-stream stormflow relative to that of WWTP effluent in the transport of OWCs to large receiving waters.

METHODS

Sampling Network and Sample Handling

Samples were collected from 17 sites in the Lake Champlain basin from March to August of 2006

TABLE 1. Name, Description, USGS Site-Identification Number, Drainage Area, and Sample-Collection Periods for the 17 Sites Sampled in Lake Champlain Basin, 2006.

Site Code	Site Name	USGS Site Identifier	Drainage Area (km ²)	Sample-Collection Date (2006)
Lake Sites				
LBB	Burlington Bay in Lake Champlain at Burlington, Vermont	442829073135401	na	April, August
LCB	Cumberland Bay near Plattsburgh, New York	444204073250501	na	July
LLC	Lake Champlain at State Line, near Burlington	442816073175701	na	April
LMB	Missisquoi Bay near Highgate Springs, Vermont	450048073102601	na	July, August
LSB	St. Albans Bay near St. Albans, Vermont	444707073094401	na	July
Large River/Reference Stream Sites				
SMR	Missisquoi River at Rt. 78, Swanton, Vermont	04294000	2,202	June, July
SWR	Winooski River at Rt. 127, Colchester, Vermont	04290566	2,748	May, July 12, July 31
SRB	Ranch Br. at Ranch Camp, near Stowe, Vermont	04288230	10	May, July
Urban Streams				
SEB	Englesby Brook at Burlington	04282815	2	March, June, July
SPB	Potash Brook at Queen City Park Road near Burlington	04282813	19	April, June, July
SSB	Stevens Brook at Lower Newton St. at St. Albans	04292775	10	June, July
Wastewater Effluent				
WBW	Burlington Main WWTP outflow at Burlington	442818073131801	na	April, May
WBN	Burlington North End WWTP outfall near Burlington	443142073160601	na	April
WBR	Burlington Riverside WWTP outflow at Burlington	442916073113601	na	April
WPL	Plattsburgh WWTP at Plattsburgh	444154073265001	na	June
WSA	St. Albans WWTP outfall near St. Albans	444947073051401	na	May
Combined Sewer Overflow				
WBC	Burlington Main CSO, at Burlington	442818073131802	na	May, June

Notes: na, not applicable.

Locations are shown in Figure 1.

Bay (LBB) are the two sites within the large-river and lake categories that are most affected by wastewater discharges. The Winooski River receives the largest amount of wastewater of any stream-sampling site and receives 10 times as much wastewater as the Missisquoi River, which has approximately the same discharge. The Burlington Bay lake site, which is near the Burlington Main WWTP outflow, also receives 10 times as much wastewater as the Missisquoi River site. Flows for the plants sampled range from around 23 to 110 meters cubed per second (or 1-5 millions of gallons per day).

Two of the samples collected from the two urban streams that discharge into Burlington Bay (Englesby and Potash Brooks) were collected during storms that resulted in significant increases in streamflow and CSO discharge at the Burlington Main WWTP, so that these samples reflect CSO inputs into the streams. The first stormflow sample from Englesby Brook was collected in March during high flow resulting from rainfall (1.3 cm) and snowmelt, and the first stormflow sample from Potash Brook was collected after a 3-cm rainfall in April, and the final stormflow samples from these streams were collected after a storm with rainfall of nearly 5 cm in June (NOAA, 2007).

Sites were classified into one of five groups, and these classifications are used to group site data in

tables and plots. Lake sites include the five sites sampled on Lake Champlain. The Large River/Reference Sites includes two large (greater than 2,000 km² in drainage area) rivers and the small reference (10 km²) site dominated by forested land use with no wastewater discharges. The other three site types include the three small streams dominated by urban land use (Urban Streams), the five WWTP sites (Wastewater Effluent), and the CSO site; these three site types reflect either treated or untreated sewage.

Samples were collected in accordance with standard USGS trace-organic analysis protocols (Wilde *et al.*, 2004; USGS, 2006). Standard width-incremental and depth-integrated techniques were used for stream and river samples. All analytical methods used in this study were devised for filtered samples; therefore, all samples were filtered through 0.7- μ m glass fiber filters.

Analytical Method

All 30 samples included in this study were analyzed for 62 analytes representing a wide range of compound types or uses (Table 2). These analyses were conducted at the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado. Analytes were extracted through disposable

TABLE 2. List of Analytes.

Compound Class/Compound	RL	Detected in Water Samples?
Wastewater Method		
Detergent Degradates		
4-Cumylphenol	0.14	Y
4- <i>n</i> -Octylphenol	0.16	Y
4-Nonylphenol diethoxylate (NP2EO)	5	Y
4-Octylphenol diethoxylates (OP2EO)	1	Y
4-Octylphenol monoethoxylates (OP1EO)	1	Y
4- <i>tert</i> -Octylphenol	0.10	Y
<i>p</i> -Nonylphenol	1.8	Y
Organosphosphate Esters		
Tributyl phosphate (TBP)	0.2	Y
Triphenyl phosphate (TPP)	0.16	Y
Tris(2-butoxyethyl)phosphate (TBEP)	0.5	Y
Tris(2-chloroethyl)phosphate (TCEP)	0.18	Y
Tris(dichlorisopropyl)phosphate (TDIP)	0.18	Y
Fragrance/Flavorants		
3-Methyl-1(<i>H</i>)-indole (Skatol)	0.08	Y
Acetophenone	0.10	Y
Camphor	0.10	Y
Galaxolide (HHCB)	0.5	Y
Isoquinoline	0.4	Y
Tonalide (AHTN)	0.5	Y
Pesticides		
Anthraquinone	0.16	Y
Bromacil	0.4	Y
Carbaryl	1.0	Y
Chlorpyrifos	0.20	N
Diazinon	0.16	N
D-Limonene	0.14	Y
Indole	0.14	Y
Metalaxyl	0.2	N
Metolachlor	0.16	Y
<i>N,N</i> -diethyl-meta-toluamide	0.2	Y
Prometon	0.4	N
PAHs		
1-Methylnaphthalene	0.10	Y
2,6-Dimethylnaphthalene	0.2	Y
2-Methylnaphthalene	0.08	Y
Anthracene	0.08	Y
Benzo[<i>a</i>]pyrene	0.12	N
Fluoranthene	0.08	Y
Naphthalene	0.10	N
Phenanthrene	0.08	Y
Pyrene	0.08	Y
Sterols		
3- β -Coprostanol	1.6	Y
β -Sitosterol	2	Y
β -Stigmastanol	2	Y
Cholesterol	1.4	Y
Other Compounds		
1,4-Dichlorobenzene	0.08	Y
3- <i>tert</i> -Butyl-4-hydroxy anisole (BHA)	0.6	Y
5-Methyl-1 <i>H</i> -benzotriazole	1.8	Y
Benzophenone	0.18	Y
Bisphenol A**	0.4	N
Bromoform	0.08	Y
Caffeine	0.2	Y
Carbazole	0.08	Y
Cotinine	0.4	Y
Isoborneol***	0.06	Y

TABLE 2. (Continued)

Compound Class/Compound	RL	Detected in Water Samples?
Isophorone	0.14	Y
Isopropylbenzene	0.10	Y
Menthol***	0.2	Y
Methyl salicylate	0.18	Y
<i>p</i> -Cresol	0.18	Y
Pentachlorophenol*	2	Y
Phenol	0.4	N
Tetrachloroethylene	0.18	Y
Triclosan	0.2	Y
Triethyl citrate (ethyl citrate)	0.4	Y

Notes: RL, reporting level.

*Five samples with data.

**10 samples with data.

***24 samples with data.

polypropylene solid-phase-extraction cartridges that contain polystyrene-divinylbenzene phase, and compound concentrations were measured by capillary-column gas chromatography-mass spectrometry (GC-MS) as described by Zaugg *et al.* (2002). Nearly all of the analytes tested by this method are associated with wastewater sources, although a few (including the herbicide metolachlor) are associated with other sources; therefore, all analytes tested by this method are herein referred to as OWCs because wastewater is the predominant source of these compounds.

Reporting Limits (RL) were calculated for analytes by Zaugg *et al.* (2002) according to procedures detailed in USEPA (1997) and are updated annually (Childress *et al.*, 1999). Several detections that are discussed herein were below the RL. The method's enhanced analyte-identification capabilities allow reporting of compound concentrations below the RL (Childress *et al.*, 1999; Stackelberg *et al.*, 2006), especially when these data are qualified on the basis of quality-assurance data obtained from blank and replicate samples. Compound detections were reported only if they met qualitative GC-MS (chromatographic retention time, mass spectrometric ion abundance ratios, and mass spectra) criteria before being quantified according to a five-point calibration curve (Zaugg *et al.*, 2002). Calibration standards for the wastewater-method are included at concentrations well below the RL (Table 2) and allow for accurate quantification of concentrations below the RL (Zaugg *et al.*, 2002). Sample replicate data (discussed in subsequent sections) showed good agreement between replicates (generally 15% or less) for detections less than the RL, an indication that the method produced reliable results at these low concentrations for a variety of compounds. Because qualitative identification is

required before a concentration is reported, data from this method is not restricted by censoring all measurements below the RL. Data below the RL are reported as estimated, and so have greater uncertainty than data reported above the RL.

Quality Assurance

Six analytes (naphthalene, phenanthrene, benzo-phenone, bisphenol A, methyl salicylate, and *N,N*-diethyl-meta-toluamide) were detected in at least one of the four blanks analyzed during the study. When detected in blanks, concentrations of the five analytes ranged from 0.010 to 0.023 $\mu\text{g}/\text{l}$, except for bisphenol A (0.16 $\mu\text{g}/\text{l}$). All reported concentrations within five times of those in the field blank were considered to be nondetected and were censored. In addition, data reported in other studies (Phillips *et al.*, 2005) indicate that the analytes phenol and triphenyl phosphate commonly occur at low concentrations in blanks analyzed using the same analytical method; therefore, all phenol concentrations below 1.5 $\mu\text{g}/\text{l}$, and all triphenyl phosphate concentrations below 0.08 $\mu\text{g}/\text{l}$, were censored.

One replicate sample yielded comparisons for 12 compounds. Concentration differences ranged from 5.1 to 46%, with a median of 13%; most (75%) of the replicate differences were 25% or less. All concentrations in all replicate samples were low ($<0.08 \mu\text{g}/\text{l}$) – an indication that concentrations reported below the RL are reliable estimates. These replicate differences are similar to those reported by Phillips *et al.* (2005) for the same method.

Annual Load Calculations

Annual loads of selected analytes from the several sources were estimated through simple first-order methods because the concentration database was relatively small. Loads for Englesby and Potash Brook were calculated as the mean daily high-flow discharges multiplied by the average of the two high-flow concentrations, plus the mean daily low-flow discharges multiplied by the low-flow concentration. The high-flow discharges include all days with mean daily discharge greater than or equal to the minimum discharge of the two storm samples. The low-flow discharges included all mean daily flows less than the minimum discharge of the two storm samples. In practice, calculating loads for each stream site was relatively easy because most measured concentrations were associated with high flows, so that low flow loads were frequently zero for most analytes. If concentrations for OWCs were not detected, the

concentration and daily load were set to zero. The calculated loads were used to indicate order-of-magnitude differences in loads to Burlington Bay and therefore are not conclusive indicators of the sources, although they can be used to indicate which types of sites are most likely to contribute the largest amount of organic compounds.

The loads calculated for the Burlington CSO effluent and the Burlington Main WWTP represent the mean concentrations for the samples from each site multiplied by the annual discharge at each site. Annual flow data were provided by plant personnel for both plants and represent calendar year 2006. Error estimates of loads were not calculated due to the first-order approach and the limited number of samples.

RESULTS AND DISCUSSION

Of the 62 compounds analyzed by the wastewater method, 37 were detected in more than half of the WWTP samples or in both of the CSO effluent samples, or in more than half of the urban-stream samples (Table 3). Some of the most commonly detected compounds in WWTP and CSO samples were detergent degradates, organophosphate esters, and sterols. The concentrations of most compounds in the WWTP and CSO samples were similar to those found by Glassmeyer *et al.* (2005) in WWTP samples collected across the U.S. The higher concentrations of sterols reported by Glassmeyer *et al.* (2005) than the WWTP samples in this study can be attributable to the use of unfiltered samples in Glassmeyer's study, in contrast to the use of filtered samples in this study, because sterols are highly sorbed to particles and therefore have generally lower concentrations in filtered samples than in unfiltered samples.

Total concentrations and numbers of compounds detected varied substantially among the types of sites studied. (Total concentration for each sample was calculated as the sum of concentrations for all analytes in the wastewater method, with nondetected values set to zero.) The highest total concentrations (10-100 $\mu\text{g}/\text{l}$) and the largest numbers of compounds detected (20 or more) were in samples from the WWTP sites and CSOs (Figure 2). From 4 to 28 compounds were detected in samples from the urban streams, where total concentrations ranged from 0.05 to 10 $\mu\text{g}/\text{l}$. The concentration and number of OWCs were higher in stormflow samples collected in urban streams than in baseflow samples (Figure 2). The lowest concentrations ($\leq 0.3 \mu\text{g}/\text{l}$) and lowest number

TABLE 3. Range of Concentrations for Compounds Detected by Wastewater Method in Samples of CSO Effluent, and Median and Maximum Concentrations for Compounds Detected in WWTP Effluent and Urban-Stream Stormflow Samples, 2006.

**Analyte	Range in CSO Concentration	Median/Maximum Concentration*	
		WWTP Effluents	Urban-Stream Stormflow
Detergent Degradates			
4-Nonylphenol diethoxylate	2.4-7.7	11/23	1.1/2.0
4-Octylphenol diethoxylates	nd	0.59/1.4	0.15/0.29
4-Octylphenol monoethoxylates	nd-0.35	0.28/1.6	nd/0.073
4- <i>tert</i> -octylphenol	nd	0.12/0.91	nd/0.046
<i>p</i> -Nonylphenol	1.1-2.4	2.5/14	nd/0.77
Organosphosphate Esters			
Tributyl phosphate	nd-0.056	0.15/0.65	nd/0.038
Triphenyl phosphate	0.14-0.17	0.13/0.64	nd/0.082
Tris(2-butoxyethyl)phosphate	1.0-9.2	0.87/19	0.43/0.68
Tris(2-chloroethyl)phosphate	0.082-0.085	0.18/0.58	nd/0.057
Tris(dichloroisopropyl)phosphate	0.092-0.11	0.19/0.84	nd/0.053
Fragrance/Flavorants			
3-Methyl-1(<i>H</i>)-indole	nd	0.037/1.3	0.030/0.053
Camphor	0.18-0.36	nd/0.78	0.072/0.16
Galaxolide	0.37-0.43	1.25/3.7	nd/nd
Tonalide	nd-0.11	0.20/0.46	nd/nd
Pesticide			
Anthraquinone	0.19-0.30	nd/0.53	0.23/0.71
Metolachlor	nd	nd/0.034	nd/0.11
<i>N,N</i> -Diethyl-meta-toluamide	nd-1.24	nd/0.75	nd/0.22
Polycyclic Aromatic Hydrocarbons (PAHs)			
1-Methylnaphthalene	0.024-0.026	nd/0.017	nd/0.45
2,6-Dimethylnaphthalene	0.006-0.025	nd/0.010	nd/0.11
2-Methylnaphthalene	0.035-0.040	nd/0.016	nd/0.21
Fluoranthene	0.067-0.082	0.0067/0.10	0.071/0.16
Phenanthrene	0.067-0.13	nd/nd	0.086/0.26
Pyrene	0.041-0.048	0.012/0.016	0.035/0.12
Sterols			
3- β -Coprostanol	1.58-1.68	0.20/0.49	nd/0.54
β -Sitosterol	1.09-1.98	nd/0.85	nd/1.08
β -Stigmastanol	nd-1.38	nd/0.94	nd/1.44
Cholesterol	5.2-6.8	0.43/1.0	0.50/1.1
Other Compounds			
1,4-Dichlorobenzene	0.078-0.15	0.15/0.52	nd/nd
Caffeine	11-12	nd/2.4	0.28/2.2
Carbazole	0.045-0.13	nd/0.63	0.061/0.18
Cotinine	0.25-0.33	0.34/1.8	nd/0.21
Isophorone	0.039-0.057	nd/0.040	nd/0.025
<i>p</i> -cresol	0.36-1.2	0.69/1.3	0.18/2.1
Triclosan	nd	0.52/1.5	nd/nd
Triethyl citrate (ethyl citrate)	0.060-0.16	0.38/0.58	nd/nd

Notes: nd, not detected.

*Concentrations in micrograms per liter.

**Compounds include those that were detected in five or more instances from the 13 total samples collected from CSO (two samples), WWTP (six samples), and urban storm samples (five samples).

of detected compounds (≤ 5) were found in samples from Lake Champlain, the Large River/Reference Sites. The only sample with no OWC detection was a sample from the reference stream. The high total OWC concentrations for CSO samples reflect the large contribution of bromoform (30-40 $\mu\text{g}/\text{l}$), which results from disinfection (through bromination) of the CSO effluent discharge to Burlington Bay.

Organic Wastewater Compounds Effectively Removed by Wastewater Treatment

Comparisons of the concentrations of OWCs among WWTP effluent, CSO effluent, and the urban streams indicate that urban streams contribute substantial amounts of OWCs to the lake during storms from untreated sewage sources. This is because the

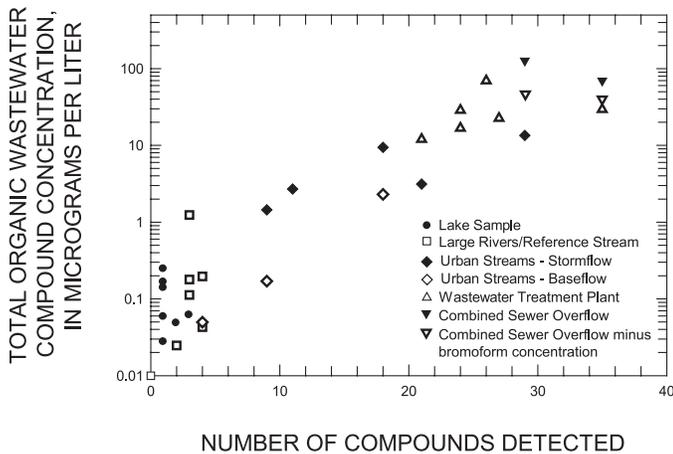


FIGURE 2. Total Concentration and Number of Compounds Detected, by Site Type and Flow Conditions (for urban stream samples), for Samples Collected From Lake Champlain Basin, 2006.

watersheds of two of the streams (Englesby and Potash Brooks) are underlain by old sewerpipes, combined sewers, and storm sewers, all of which may leak, especially during storms, releasing untreated sewage to streams. Thus, OWCs are found in greater concentrations and greater numbers in stormflow samples from these streams than in baseflow samples. Total OWC concentrations in stormflow samples from these streams ranged from 1.5 to 9.4 $\mu\text{g}/\text{l}$, whereas those in baseflow samples ranged from 0.05 to 0.17 $\mu\text{g}/\text{l}$ (Figure 2). Similarly, total OWC concentrations in stormflow and baseflow samples in the other urban stream (Stevens Brook) were 13.5 and 2.3 $\mu\text{g}/\text{l}$, respectively.

Some of the best evidence that urban stream water contains untreated sewage is illustrated through a comparison of the concentrations of three compounds in WWTP effluent – caffeine, cholesterol, and Tris(2-butoxyethyl)phosphate (TBEP) – with those in CSO effluent and stormflow of urban streams. Removal of these three compounds by activated-sludge wastewater treatment is highly effective and ranges from 99% for caffeine (Buerge *et al.*, 2006) to greater than 95% for cholesterol (Phillips *et al.*, 2005) to 90% for TBEP (Andresen and Bester, 2006). For each of these compounds, concentrations in urban storm samples and CSO samples are either greater than (for caffeine) or comparable (for cholesterol and TBEP) with those found in WWTP effluent samples (Figure 3). By contrast, concentrations of these compounds in baseflow samples from urban streams are lower than in stormflow samples, and baseflow urban sample concentrations are similar to those found in samples collected in Lake Champlain and the Large River/Reference Sites (Figure 3). These results correspond with the conclusion of Fono and Sedlak (2005) that bypassing of sewage treatment is more important than dilution

caused by rainfall for compounds that are well removed by secondary wastewater treatment processes, resulting in higher concentrations in CSOs than treated effluent.

Concentrations of caffeine were highest in CSO-effluent samples ($\sim 10 \mu\text{g}/\text{l}$), ranged from 0.2 to 2.2 $\mu\text{g}/\text{l}$ in urban stream-stormflow samples (Figure 3), and were undetected in all WWTP samples except those from the St. Albans WWTP (Figure 3). The elevated concentrations of caffeine in stormflow samples from all three urban streams, and its non-detection or low concentrations in baseflow samples (Figure 3) is consistent with untreated sewage from leaky sewer pipes and CSOs as a source of caffeine. The detection of caffeine at the St. Albans WWTP, which is the only WWTP not using activated sludge for biological treatment, further indicates that the type of treatment used at WWTPs can affect removal amounts of caffeine, a finding similar to that reported by Phillips *et al.* (2005).

The foregoing evidence that caffeine is effectively removed through biological treatment at all of the WWTPs except for St. Albans is supported by other research. A study by Buerge *et al.* (2006) in the Greifensee region of Switzerland found that (1) WWTPs discharged little caffeine because caffeine is effectively removed (up to 99%) by biological treatment, and (2) caffeine concentrations in surface waters of that region were higher than in WWTP effluent because these waters received CSO discharges, which contained large amounts of caffeine. These findings are consistent with the elevated caffeine concentrations in the Burlington CSO and urban stream storm samples, which can be attributed to the presence of untreated or poorly treated wastewater. The decreasing trend in caffeine concentrations from CSO to urban storm samples thus reflects progressively greater amounts of dilution of untreated sewage by rainfall. Caffeine was also detected in low concentrations in samples from Lake Champlain near Burlington and in Burlington Bay (about 0.02 $\mu\text{g}/\text{l}$) and in samples from the two large rivers (about 0.03 $\mu\text{g}/\text{l}$) (Figure 3), which suggests that poorly treated or untreated sewage may be the source of caffeine at these sites.

The two other OWCs mentioned previously that are effectively removed through wastewater treatment – TBEP and cholesterol – were highest in CSO samples, and had urban storm samples concentrations comparable with those of WWTP effluent. Concentrations of TBEP in WWTP effluent generally ranged from 0.2 to 19 $\mu\text{g}/\text{l}$ (Figure 3), those in CSO effluent ranged from 1 to 9 $\mu\text{g}/\text{l}$, and those in the five urban storm samples generally ranged from 0.2 to 0.7 $\mu\text{g}/\text{l}$; concentrations at other sites were all $< 0.2 \mu\text{g}/\text{l}$. Concentrations of cholesterol exceeded

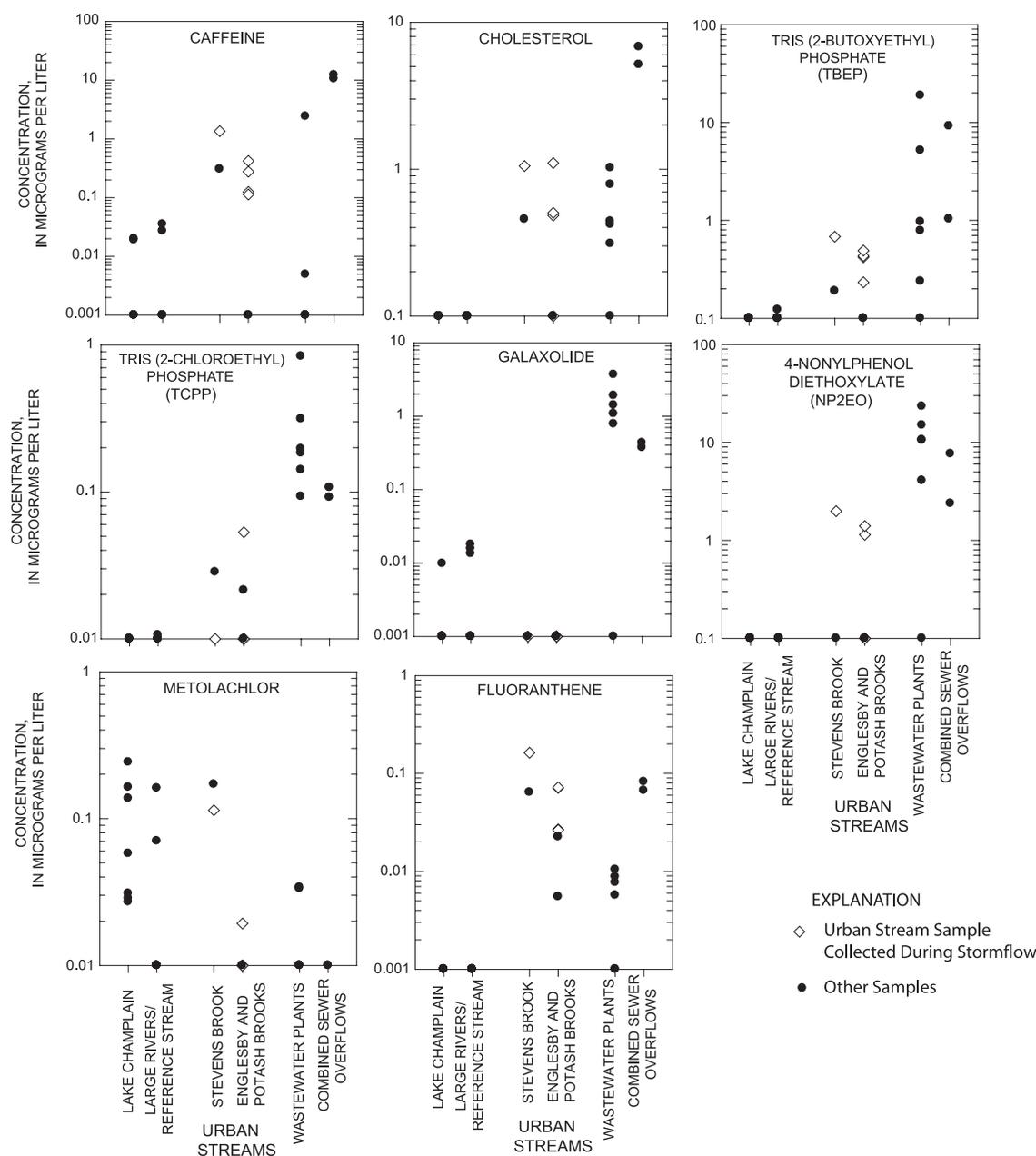


FIGURE 3. Concentrations of Selected OWCs, by Site Type in Lake Champlain Basin Study Area, 2006.

0.4 $\mu\text{g}/\text{l}$ in most WWTP effluent samples, as well as in both CSO samples, and most urban storm samples. Cholesterol was not detected in Lake Champlain, Large River/Reference Sites, and most urban stream baseflow samples (Figure 3).

Annual Caffeine, Cholesterol, and TBEP Loads. Loads of these three compounds to Burlington Bay are either higher at the CSO and two urban streams (for caffeine) than the Burlington Main WWTP, or comparable among the CSO, urban streams and Burlington Main plant (cholesterol and TBEP), indicating the importance of untreated sew-

age as a source of these compounds to Burlington Bay (Figure 4). Annual loads from each source were calculated, but were based on one or two samples from each site and therefore are best considered first-order estimates and indicate likely loading differences among sources of OWCs entering Lake Champlain in the vicinity of Burlington.

The largest loads for caffeine (9 kg/year), cholesterol (5 kg/year), and TBEP (5 kg/year) enter from the CSO outflow (Figure 4). Caffeine and TBEP loads from Potash Brook stormflow (0.7 and 2 kg/year) slightly exceed those from the Burlington Main WWTP (0 and 0.7 kg/year, respectively). Cholesterol

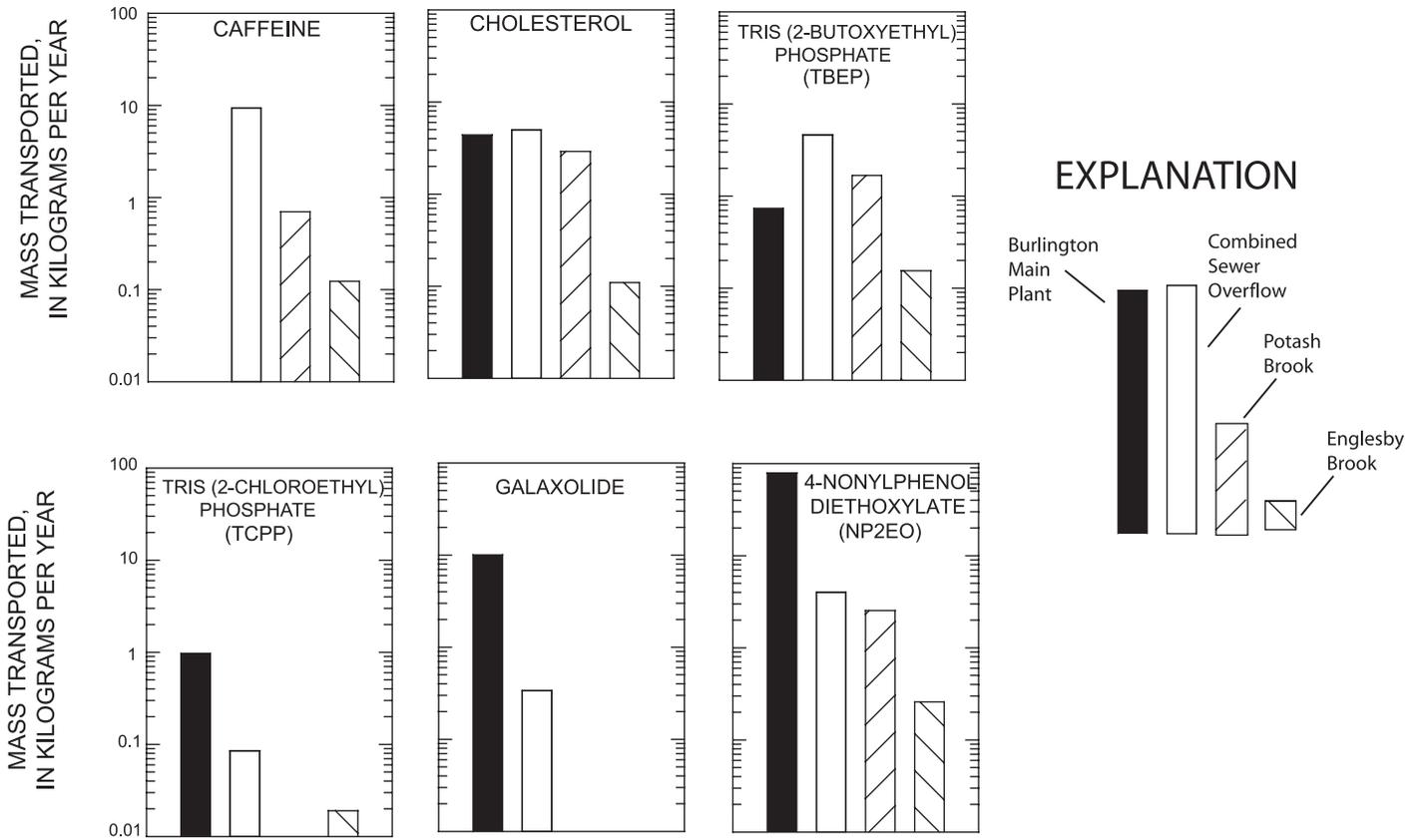


FIGURE 4. 2006 Annual Mass Loads for Select OWCs for Burlington Main Wastewater Treatment Plant, Combined Sewer Overflow, and Englesby and Potash Brooks.

loads from the Burlington Main WWTP (4 kg/year) are similar to those from the CSO outflow (5 kg/year) and Potash Brook (3 kg/year). Loads for Englesby Brook are generally lower than those for the other sites (0.1 kg/year for caffeine, 0.2 kg/year for TBEP, and 0.1 kg/year for cholesterol), probably because of the small size of this watershed (2 km²). The Burlington Main WWTP contributes from 0 (caffeine) to 40% (cholesterol) of the OWC loads from these three sources to Burlington Bay, whereas CSO effluent contributes from 40 (cholesterol) to 90% (caffeine), and the two urban streams together contribute from 10 (caffeine) to 30% (TBEP).

The results of comparison of concentrations and loads among sites around Burlington agree with the hypothesized correlation between degree of OWC removal and magnitude of sewage contributions to the lake from CSOs and urban streams made by Fono and Sedlak (2005) and Benotti and Brownawell (2007). For compounds that are effectively removed by the wastewater-treatment process, inputs of untreated sewage overcome the dilution effect from rainfall runoff during stormflows, resulting in elevated concentrations and loads in CSOs and urban streams. Additional samples need to be collected over

a variety of flow conditions to substantiate the relations indicated by these data.

Organic Wastewater Compounds Poorly Removed by Wastewater Treatment

OWCs that are not well removed by wastewater treatment – including tris(dichloroisopropyl)phosphate (TCPP), galaxolide, and NP2EO – have highest concentrations in WWTP effluent samples, and lower concentrations in CSO samples, reflecting the importance of treated sewage as a source of these compounds to Burlington Bay. The higher concentrations of the OWCs that are poorly removed by WWTP in WWTP effluent than in CSO or urban stream storm samples corresponds with the model of dilution of poorly removed OWCs in CSO effluent suggested by Benotti and Brownawell (2007). Thus, concentrations of poorly removed compounds are diluted in CSO wastewater, due to its concentration acting in response only to dilution by rainwater.

Tris(dichloroisopropyl)phosphate removal by activated sludge WWTPs is negligible (Meyer and Bester, 2004), whereas removal for galaxolide in activated-sludge

WWTPs has been estimated at 40% (Carballa *et al.*, 2005). The fate and removal efficiency of nonylphenol ethoxylates such as NP2EO in activated-sludge systems is complex because these compounds are a component of detergent degradates as well as detergents. One estimate of NP2EO indicates negligible removal for NP2EO in activated-sludge systems (Esperanza *et al.*, 2004), whereas another study has indicated highly variable rates of removal of this compound by this process (Clara *et al.*, 2005).

Concentrations of TCPD were highest (0.093–0.84 $\mu\text{g}/\text{l}$) in WWTP effluent samples, and somewhat lower in CSO effluent (~ 0.1 $\mu\text{g}/\text{l}$) samples. Tris (dichloroisopropyl)phosphate was not commonly detected in urban storm or urban baseflow samples, and when detected, concentrations of TCPD were <0.06 $\mu\text{g}/\text{l}$. With the exception of one sample from site SWR, no Lake Champlain and none of the sites in the Large River/Reference category had a detection for this compound (Figure 3). Similarly, concentrations of galaxolide were highest in WWTP samples, and generally ranged from 1 to 3.7 $\mu\text{g}/\text{l}$ (Figure 3), although one WWTP sample (from site WPL) did not have a detection for this compound. Concentrations in the CSO samples were lower (about 0.4 $\mu\text{g}/\text{l}$), and those in urban-stream samples collected during baseflow and stormflow conditions were below detection limits. Galaxolide was detected at low concentrations (<0.02 $\mu\text{g}/\text{l}$) in all three samples from the Winooski River (site SWR, Figure 1) and in one sample (<0.01 $\mu\text{g}/\text{l}$) from Burlington Bay (Figure 3), likely reflecting the high amounts of treated wastewater discharged to these two sites.

Concentrations of NP2EO were highest in WWTP samples (generally from 4 to 23 $\mu\text{g}/\text{l}$), and were lower in CSO samples (from 2.4 to 7.7 $\mu\text{g}/\text{l}$). 4-Nonylphenol diethoxylate was detected in most urban stream storm samples, and concentrations in these samples (<2 $\mu\text{g}/\text{l}$) were generally lower than in the WWTP and CSO samples (Figure 3). Relations between NP2EO concentrations and site types were similar to those of the other four commonly detected detergent degradates addressed in this study (Table 3), all of which had maximum concentrations in WWTP samples. These results indicate that within the Lake Champlain basin, the detergent degradates behave similarly to other compounds that are poorly removed by secondary removal in WWTP by activated sludge.

Annual TCPD, Galaxolide, and NP2EO Loads. The largest estimated loadings of the three compounds with poor removal by wastewater treatment were from the Burlington Main WWTP, and ranged from 80 kg/year for NP2EO, to 10 kg/year for galaxolide, and 1 kg/year for TCPD (Figure 4). Unlike well removed compounds, which had approximately

equal loads for the Burlington Main WWTP and CSO sites, loads for these compounds in CSO effluent were $<10\%$ of those at the Burlington Main Plant (4 kg/year for NP2EO, 0.3 kg/year for galaxolide, and 0.1 kg/year for TCPD). Similarly, loads for TCPD and galaxolide were low or zero for the two urban streams. Loads for NP2EO for the Potash Brook site were similar to that for the CSO site (Figure 4), but overall, nearly all of the combined load to Burlington Bay for these three compounds is from the Burlington Main WWTP (from 90% for TCPD to nearly 100% for galaxolide).

Although these results are based on limited samples, they indicate that the mixture of untreated sewage and rainfall runoff found in CSO effluent and urban stream-stormflow results in a dilution of concentrations of poorly removed compounds compared with treated sewage samples, similar to that suggested by Benotti and Brownawell (2007). Thus, the major source of poorly removed compounds to Lake Champlain is likely from treated wastewater effluent. Further studies are needed that include sampling of WWTP and CSO effluents, as well as both baseflow and stormflow samples at urban streams discharging to Burlington Bay during different seasons and flow conditions; these results would allow for greater confidence in load estimates of these different sources to Burlington Bay.

Organic Wastewater Compounds Not Associated With Wastewater

Compounds including the pesticide metolachlor and polycyclic aromatic hydrocarbons (PAHs) had maximum concentrations at sites other than the WWTP or CSO outfall – an indication that these compounds originated from a nonwastewater source. The highest concentrations (0.03–0.3 $\mu\text{g}/\text{l}$) of metolachlor (an agricultural herbicide) were found in samples from Lake Champlain (Figure 3); this pattern is consistent with agricultural runoff as the source of pesticides in the lake. Both samples from the Missisquoi River had metolachlor concentrations >0.05 $\mu\text{g}/\text{l}$ and were the only two metolachlor detections in the samples collected from the Large River/Reference group. The detection of metolachlor in the Missisquoi River samples is consistent with the large amount of agricultural land in this river's basin (about 20%); this also is the highest percentage of agricultural land of all watersheds sampled in this study. Metolachlor was also detected in some of the urban-stream samples and in one WWTP sample, but the concentrations in nonwastewater samples were higher than in the WWTP or CSO-effluent samples (Figure 3).

Concentrations of PAHs were generally higher in samples from urban streams and in CSO effluent than in samples from the WWTP sites. Concentrations of fluoranthene ranged from 0.01 to 0.16 $\mu\text{g}/\text{l}$ in urban stream samples, but were $<0.02 \mu\text{g}/\text{l}$ in samples from WWTP effluents (Figure 3), indicating the importance of nonwastewater sources; patterns of concentrations of other PAHs (including 1-methylnaphthalene, 2,6-dimethylnaphthalene, 2-methylnaphthalene, fluoranthene, phenanthrene, and pyrene) are generally similar. The highest stream concentrations of PAHs were in samples from Stevens Brook, where the watershed contains an abandoned coal yard with documented PAH contamination in soils. Polycyclic aromatic hydrocarbons are also present in asphalt and are a byproduct of a variety of combustion processes. Polycyclic aromatic hydrocarbons were not detected in the Lake Champlain samples or Large River/Reference samples. Except for the point source at Stevens Brook, the data from most sites indicate a broad diffuse source of PAHs in the urban watersheds. The elevated concentrations of PAHs in the CSO-effluent samples probably reflect the contributions from street runoff in urban areas. These results are similar to the observations of Wilkinson *et al.* (2002), who found that nonpoint sources of PAHs contributed greater amounts of PAHs to metropolitan Kansas City streams during storms than CSOs.

SUMMARY AND CONCLUSIONS

The distribution and concentrations of OWCs in surface waters within the Lake Champlain basin were investigated in a 2006 study that entailed sampling of wastewater-treatment-plant (WWTP) effluent, CSO effluent, and storm runoff from urban streams, two large rivers, and a reference site with no wastewater discharges. The concentrations at these sampling sites reflect the geographical distribution of OWC sources and confirm that CSO effluent and urban storm runoff contributes OWCs to the lake.

The correlation between OWC concentrations in WWTP effluent and those in CSO effluent and urban storm runoff reflect the degree of OWC removal by the wastewater-treatment process. OWCs that are effectively removed through wastewater treatment (including caffeine, TCP, and cholesterol) were found in CSO effluent at concentrations similar to or greater than in WWTP effluents; this is consistent with the removal of these compounds from WWTP effluent and the lack

of treatment for CSO effluent. These three compounds had higher mass loadings in CSO effluent than in the WWTP effluent. Conversely, OWCs that undergo little removal through normal wastewater treatment (including TCP, galaxolide, and NP2EO) were found in higher concentrations in WWTP effluent than in CSO effluent; this is attributed to dilution of CSO effluent by stormwater unaffected by untreated sewage. These three compounds had higher loadings in the Burlington WWTP than in the CSO effluent. Stormflow in urban streams contained many OWCs, and the correlations with degree of removal by WWTPs were similar to those of CSO effluent. OWCs that are effectively removed through normal wastewater treatment were found in urban stream-stormflows at concentrations similar to or greater than those in WWTP effluents, whereas OWCs that are poorly removed through wastewater treatment were found in lower concentrations than in WWTP effluent.

This study shows CSOs and urban stream-stormflows are significant contributors of OWCs to large receiving waters such as Burlington Bay in Lake Champlain. This in turn indicates that efforts to decrease the amounts of OWCs entering large receiving waters need to identify and treat waters that bypass normal wastewater-treatment processes. Future evaluations of the annual contributions from these sources will require sampling of WWTP effluents, CSO effluents, and urban streams under differing seasons and flow conditions.

ACKNOWLEDGMENTS

This project was funded by the USGS Lake Champlain program. Operators and employees of all the wastewater plants sampled in this study are thanked. The manuscript was greatly improved by comments made by Dr. Mark Benotti, Southern Nevada Water Authority/Las Vegas Valley Water District, and Neil Kamman, State of Vermont, David Eckhardt and Paul Stachelberg of the U.S. Geological Survey.

LITERATURE CITED

- Andresen, J. and K. Bester, 2006. Elimination of Organophosphate Ester Flame Retardants and Plasticizers in Drinking Water Purification. *Water Research* 40(3):621-629, doi:10.1016/j.watres.2005.11.022.
- Benotti, M.J. and B.J. Brownawell, 2007. Distribution of Pharmaceuticals in an Urban Estuary During Both Dry- and Wet-Weather Conditions. *Environmental Science and Technology* 41(16):5795-5802, doi: 10.1021/es0629965.
- Boyd, G.R., J.M. Palmeri, S. Zhang, and D.A. Grimm, 2004. Pharmaceutical and Personal Care Products and Endocrine Disrupting Chemicals in Stormwater Canals and Bayou St. John in New Orleans, Louisiana, US. *Science of the Total Environment* 333:137-148, doi:10.1016/j.scitotenv.2004.03.018.

- Buerge, I.J., T. Poiger, M.D. Muller, and H.-R. Buser, 2006. Combined Sewer Overflows to Surface Waters Detected by the Anthropogenic Marker Caffeine. *Environmental Science and Technology* 40(13):4096-4102, doi:10.1021/es052553l.
- Carballa, M., F. Omil, J.M. Lema, M. Llompart, C. Garcia-Jares, I. Rodriguez, M. Gomez, and T. Ternes, 2005. Behavior of Pharmaceuticals and Personal Care Products in a Sewage Treatment Plant of Northwest Spain. *Water Science and Technology* 52(8):29-35.
- Childress, C.J., W.T. Foreman, B.F. Connor, and T.J. Malone, 1999. New Reporting Procedures Based on Long-Term Method Detection Levels and Some Considerations for Interpretations of Water Quality Data Provided by the U.S. Geological Survey National Water Quality Laboratory. U.S. Geological Survey Open-File Report 99-193, 19 pp. <http://pubs.er.usgs.gov/usgspubs/ofr/ofr99193>, accessed December 1, 2008.
- Clara, M., B. Strenn, O. Gans, E. Martinez, N. Kreuzinger, and H. Krois, 2005. Removal of Selected Pharmaceuticals, Fragrances and Endocrine Disrupting Compounds in a Membrane Bioreactor and Conventional Wastewater Treatment Plants. *Water Research* 39(19):4797-4807, doi:10.1016/j.watres.2005.09.015.
- Drewes, J.E., C. Bellona, M. Oedekoven, P. Xu, T.-U. Kim, and G. Amy, 2005. Rejection of Waste-Water Derived Micropollutants in High-Pressure Membrane Applications Leading to Direct Potable Reuse. *Environmental Progress* 24(4):400-409, doi:10.1002/ep.10110.
- Esperanza, M., M.T. Suidan, F. Nishimura, Z.-M. Wang, and G.A. Sorial, 2004. Determination of Sex Hormones and Nonylphenol Ethoxylates in the Aqueous Matrices of Two Pilot-Scale Municipal Wastewater Treatment Plants. *Environmental Science and Technology* 38(11):3028-3035, doi:10.1021/es0350886.
- Fono, L.J. and D.L. Sedlak, 2005. Use of the Chiral Pharmaceutical Propranol to Identify Sewage Discharges Into Surface Waters. *Environmental Science and Technology* 39(23):9244-9252, doi:10.1021/es047965t.
- Glassmeyer, S.T., E.T. Furlong, D.W. Kolpin, J.D. Cahill, S.D. Zaugg, S.L. Werner, M.T. Meyer, and D.D. Kryak, 2005. Transport of Chemical and Microbial Compounds From Known Wastewater Discharges: Potential for Use as Indicators of Human Fecal Contamination. *Environmental Science and Technology* 39(14):5157-5169, doi:10.1021/es048120k.
- Heidler, J. and R.U. Halden, 2007. Mass Balance Assessment of Triclosan Removal During Conventional Sewage Treatment. *Chemosphere* 66(2):362-369, doi:10.1016/j.chemosphere.2006.04.066.
- Kolpin, D.W., E.T. Furlong, M.T. Meyer, E.M. Thurman, S.D. Zaugg, L.B. Barber, and H.T. Buxton, 2002. Pharmaceuticals, Hormones, and Other Organic Wastewater Contaminants in U.S. Streams, 1999–2000: A National Reconnaissance. *Environmental Science and Technology* 36(6):1202-1211, doi:10.1021/es011055j.
- Kolpin, D.W., M. Skopec, M.T. Meyer, E.T. Furlong, and S.D. Zaugg, 2004. Urban Contribution of Pharmaceuticals and Other Organic Wastewater Contaminants to Streams During Differing Flow Conditions. *Science of the Total Environment* 328:119-130, doi:10.1016/j.scitotenv.2004.01.015.
- Meyer, J. and K. Bester, 2004. Organophosphate Flame Retardants and Plasticizers in Wastewater Treatment Plants. *Journal of Environmental Monitoring* 6:599-605, doi:10.1039/b403206c.
- NOAA, 2007. DS3240 – Precipitation Data, Hourly – US & Some non-US-, Burlington Vermont Airport (Station 43108102). National Climatic Data Center. <http://www.ncdc.noaa.gov/oa/ncdc.html>, accessed December 2007.
- Phillips, P., B. Stinson, S.D. Zaugg, E.T. Furlong, D.W. Kolpin, K. Esposito, B. Bodniewicz, R. Pape, and J. Anderson, 2005. A Multidisciplinary Approach to the Removal of Emerging Contaminants in Municipal Wastewater Treatment Plants in New York State, 2003–2004. Water Environment Federation WEF-TEC 78th Annual Technical Exhibition and Conference, Conference Proceedings. Washington DC, November 2005, pp. 5095-5124.
- Reemtsma, T., S. Weiss, J. Mueller, M. Petrovic, S. Gonzalez, D. Barcelo, F. Ventura, and T. Knepper, 2006. Polar Pollutants Entry Into the Water Cycle by Municipal Wastewater: A European Perspective. *Environmental Science and Technology* 40(17):5451-5458, doi:10.1021/es060908a.
- Snyder, S.A., P. Westerhoff, Y. Yeomin, and D.L. Sedlak, 2004. Pharmaceuticals, Personal Care Products, and Endocrine Disruptors in Water: Implications for the Water Industry. *Environmental Engineering Science* 20(5):449-469, doi:10.1089/109287503768335931.
- Stackelberg, P.E., E.T. Furlong, M.T. Meyer, A.K. Henderson, and D.B. Reissmann, 2006. Response to Comment on 'Persistence of Pharmaceutical Compounds and Other Organic Wastewater Contaminants in a Conventional Drinking Water Treatment Plant'. *Science of the Total Environment* 354:93-97, doi:10.1016/j.scitotenv.2005.04.012.
- Stackelberg, P.E., J. Gibs, E.T. Furlong, M.T. Meyer, S.D. Zaugg, and R.L. Lippincott, 2007. Efficiency of Conventional Drinking-Water-Treatment Processes in Removal of Pharmaceuticals and Other Organic Compounds. *Science of the Total Environment* 377:255-272, doi:10.1016/j.scitotenv.2007.01.095.
- USEPA (U.S. Environmental Protection Agency), 1997. Guidelines Establishing Test Procedures for the Analysis of Pollutants (App. B, Part 136, Definition and Procedures for the Determination of the Method Detection Limit). U.S. Code of Federal Regulations, Title 40, revised as of July 1, 1997, pp. 265-267.
- USGS (U.S. Geological Survey), 2006. Collection of Water Samples (ver. 2.0): U.S. Geological Survey Techniques of Water-Resources Investigations. book 9, chap. A4. <http://pubs.water.usgs.gov/twri9A4/>, accessed December 1, 2008.
- Wilde, F.D., D.B. Radtke, J. Gibs, and R.T. Iwatsubo (Editors), 2004. Processing of Water Samples (Version 2.1): U.S. Geological Survey Techniques of Water-Resources Investigations. book 9, chap. A5. <http://pubs.water.usgs.gov/twri9A5/>.
- Wilkison, D.H., D.J. Armstrong, and D.W. Blevins, 2002. Effects of Wastewater and Combined Sewer Overflows on Water Quality in the Blue River Basin, Kansas City, Missouri and Kansas, July 1998–October 2000. USGS WRIR 02-4107, 162 pp. <http://pubs.er.usgs.gov/usgspubs/wri/wri024107>, accessed December 1, 2008.
- Zaugg, S.D., S.G. Smith, M.P. Schroeder, L.B. Barber, and M.R. Burkhardt, 2002. Methods of Analysis by the U.S. Geological Survey National Water Quality Laboratory, Determination of Wastewater Compounds by Polystyrene-Divinylbenzene Solidphase Extraction and Capillary-Column Gas Chromatography/Mass Spectrometry. U.S. Geological Survey Water-Resources Investigations Report, 01-4186, 37 pp. <http://pubs.er.usgs.gov/usgspubs/wri/wri20014186>, accessed December 1, 2008.