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Sewage Exfiltration As a Source of Storm Drain Contamination during Dry Weather in Urban Watersheds

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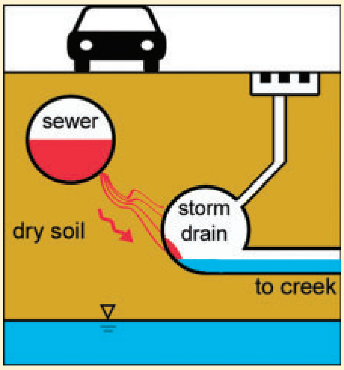
Supporting Information



ABSTRACT: Separating storm drains and sanitary sewers is expected to control sewage pollution, for example, from combined sewer overflows, and to reduce excessive stormwater flow to wastewater treatment plants. However, sewage contamination has been found in such separated storm drain systems in urban areas during dry-weather flow. To determine whether transmission of sewage is occurring from leaking sanitary sewers directly to leaking separated storm drains, field experiments were performed in three watersheds in Santa Barbara, CA. Areas with high and low risks for sewage exfiltration into storm drains were identified, and rhodamine WT (RWT) dye pulses were added to the sanitary sewers. RWT was monitored in nearby storm drain manholes using optical probes set up for unattended continuous monitoring. Above-background RWT peaks were detected in storm drains in high-risk areas, and multiple locations of sewage contamination were found. Sewage contamination during the field studies was confirmed using the human-specific *Bacteroidales* HF183 and *Methanobrevibacter smithii nifH* DNA markers. This study is the first to provide direct evidence that leaking sanitary sewers can directly contaminate nearby leaking storm drains with untreated sewage during dry weather and suggests that chronic sanitary sewer leakage contributes to downstream fecal contamination of coastal beaches.

INTRODUCTION

Modern cities use networks of sanitary sewers to transport municipal and industrial wastewater to centralized wastewater treatment plants. However, sewer leakage is a known problem in many cities worldwide and can be due to structural defects caused by aging, excessive demand, insufficient rehabilitation, and poor construction and materials.[1] Sewage exfiltration (i.e., loss of wastewater from the sewer system) can contaminate underlying groundwater and has been extensively described in the literature.[1−4] Published exfiltration rates vary greatly, and the overall extent of exfiltration is difficult to estimate because of differences in measurement methods and experimental designs[5,6] A literature review suggested likely sewer exfiltration rates in the range of 0.01−0.1 L/s per kilometer for the United Kingdom and countries with similar sewer networks.[1] In the United States, an exfiltration rate of 19000 m^3 per day was estimated in Albuquerque, NM, corresponding to an exfiltration rate of about 2 L/s per kilometer.[7] Sewage exfiltration can contaminate groundwater,[8−10] drinking water wells,[8] and even drinking water distribution systems during pressure-loss events.[11] The detection of sewage contamination often relies on monitoring a variety of sewage tracer chemicals,[8,9,12] fecal indicator bacteria,[10] or viruses.[8] The risks for human health upon exposure to sewage are mainly associated with pathogenic viruses and bacteria, although toxic chemicals can pose a risk as well.[7,13]

In addition to sanitary sewers and drinking water infrastructure, most cities in the West and Northeast of the United States also have separate municipal storm drains to transport stormwater runoff from impervious surfaces to oceans or lakes and to avoid combined sewer overflows and overloading of treatment plants. However, storm drains can be contaminated by sewage through illicit connections and discharges[14−16] and possibly through exfiltration from leaky sanitary sewers,[17−19] although the latter has not been directly confirmed.

The goal of this study was to determine whether there are direct hydrological connections between leaking sanitary sewers and storm drains. The urban watersheds in Santa Barbara, CA, were selected based on recent (unpublished) data and a previous study[17] that showed sewage contamination from unidentified sources in storm drains during dry weather. We hypothesize that sewage exfiltrating from sanitary sewers travels through unsaturated soil during dry weather and infiltrates into nearby leaky storm drains. To test for the hypothesized hydrological connections, rhodamine WT fluorescent dye was dosed into sanitary sewers at multiple locations and monitored in nearby storm drains downstream of the dosing locations.

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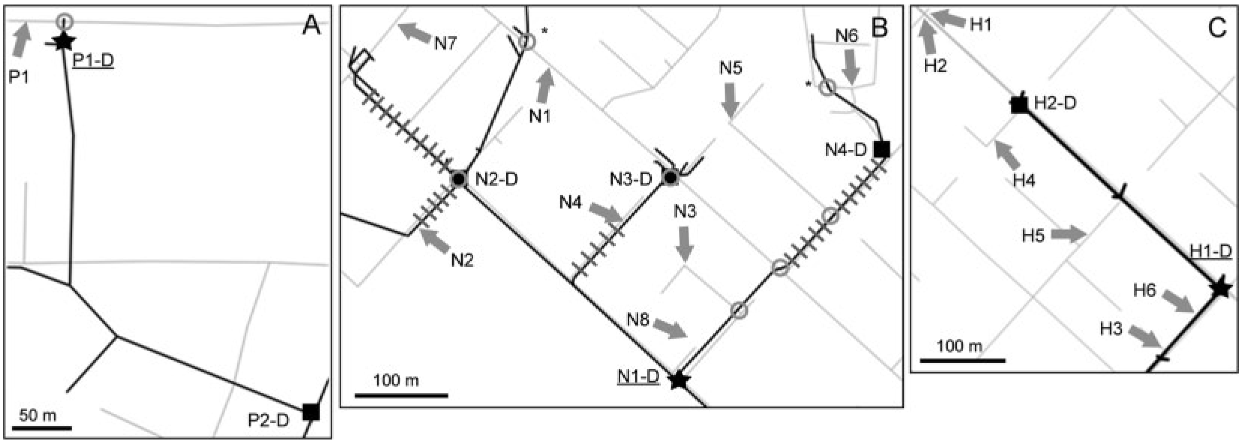

Figure 1. Infrastructure details of field sites, locations of sampling, and locations of rhodamine WT (RWT) dye addition and detection for field studies (A) 1, (B) 2, and (C) 3. Storm drains are indicated as black lines; sanitary sewers as gray lines. Numbered symbols are the RWT dye injection locations in sanitary sewers (gray arrows), the RWT dye detection locations in storm drains (black stars, underlined text), and the RWT dye injection or sampling locations in storm drains (black squares). In panel B, gray hatched lines indicate where sanitary sewers and storm drains are laterally parallel and at the same depth; gray open circles are where sanitary sewers cross over storm drains. (Asterisks indicate where the relative depths of sewers and storm drains could not be determined.)

MATERIALS AND METHODS

Study Sites and Infrastructure Details. Field experiments were performed in three watersheds in Santa Barbara, CA (Figure S1A, Supporting Information). Field study 1 (Figure 1A) was performed as a proof of concept at a location where field observations, canine scent tracking,[20] and other measurements had shown severe sewage pollution in the storm drain. Surcharge flow occurred in the sanitary sewer every 15–30 min, because of pump operation at an upstream lift station. At the time of surcharge flow, liquid was heard trickling into the storm drain upstream of site P1-D. In addition, sewage odor was observed at the storm drain manhole P1-D. The storm drain section was located upstream from a storm drain where significant but intermittent sewage contamination had previously been observed[17] and where a low-flow diversion was installed to transfer runoff to the sanitary sewer for treatment.

Field study 2 (Figure 1B) was performed upstream of a location (N1-D) where sewage contamination had recently been observed, based on detection of human-specific markers in water samples collected from storm drains.[21] However, the exact origin of the contamination had not been identified. Sanitary sewers were mostly vitrified clay pipes from the 1950s or older, although some sections had been rehabilitated in poly(vinyl chloride) (PVC) since the 1990s. The storm drain pipes in this area are located mostly at depths below those of the sanitary sewer pipes. Locations for which a high risk for sewage exfiltration into the leaking storm drains was assumed had the following characteristics: sanitary sewers made of vitrified clay, sanitary sewers positioned above storm drains, and sanitary sewers crossing storm drains or running parallel within 5 m. Multiple high-risk locations were identified, as shown in Figure 1B. Detailed information about the infrastructure at the high-risk locations of field study 2 is provided in Table S1 and Figure S1B (Supporting Information). In summary, in the case of parallel sanitary sewers and storm drains, pipes were at a horizontal distance of 1.2–5.2 m and a vertical distance of 0.2–5.2 m (sewer inverts above storm drain inverts). In the case of crossing sanitary sewers and storm drains, sewer inverts were 0.9–2.5 m above storm drain inverts, except for two cases (indicated with asterisks in Figure 1A). In the latter cases, geospatial data were insufficiently accurate to indicate whether sanitary sewers were just above or just below storm drains. A high potential for sewage exfiltration into the storm drains was assumed in this area.

Field study 3 (Figure 1C) was also performed at a location where human-specific *Bacteroidales* marker concentrations suggested sewage pollution, with unknown origin,[17] and where sanitary sewers were mostly vitrified clay pipes from the 1950s or older. In contrast to field study 2, the storm drains in this area were all above the sanitary sewers. Upstream of H1-D, two sewer mains ran parallel to the storm drain. The closest sanitary sewer (1.8–2.7-m horizontal distance) ran 1.5–1.8 m deeper than the storm drain, and the farthest sanitary sewer (3.4–4.7 m horizontal distance) ran 0.3–1.5 m deeper than the storm drain. The sanitary sewers crossed the storm drain at two locations, but running 0.2–0.5 m deeper. High-risk areas for sewage exfiltration into the storm drains were not identified in this area, and a low potential for sewage exfiltration into the storm drains was assumed.

RWT Dosing. In field study 1, one sanitary sewer crossed the storm drain upstream of P1-D, and the first sanitary sewer manhole upstream of the suspected contamination area was selected for dosing with RWT (Figure 1A). For field study 2, the locations for dosing RWT were selected based on the identification of areas with a high risk for sewage exfiltration into leaking storm drains, as described above. RWT was dosed into all sanitary sewer manholes with at least one location downstream that was at high risk for sewage exfiltration into storm drains (Figure 1B). RWT dosed to those sanitary sewer manholes was hypothesized to flow through the high-risk locations and make its way into the storm drains. In field study 3, locations with high risk for sewage exfiltration into storm drains were not identified. However, RWT was dosed into sanitary sewers to determine whether sewage exfiltrates into leaking storm drains in areas with assumed low risk. RWT was dosed into all sanitary sewer manholes with at least one location downstream where sanitary sewers ran parallel or crossed the storm drains (Figure 1C). The details of RWT dosing are

Table 1. Details on Rhodamine WT Dye Injection for All Field Studies[a]

experiment	date (month/day/year)	location(s)	no. of RWT pulses (interval)	RWT conc (ppm)	RWT vol (L)
field 1	06/11/10	P1	2 (0.5 h)	800	10
field 2a	07/01/10	N1, N2	1	800	10
	07/06/10	N3, N4	1	400	10
	07/09/10	N5−N8	1	800	10
field 2b	07/22/10	N1	2 (1 h)	800	10
		N2	3 (1 h)	800	10
		N3	4 (1 h)	800	10
		N4	5 (1 h)	800	10
field 2c	09/16/10	N2-D	1	100	0.05
	09/17/10	N2-D	1	1000	0.05
	09/21/10	N3-D	1	100	0.05
	09/22/10	N3-D	1	1000	0.05
	09/17/10	N4-D	1	1000	0.05
field 3	09/07/10	H1−H3	1	2,000	10
	09/08/10	H4−H6	1	2,000	10

[a] RWT was added into the sanitary sewers in all experiments, except in field study 2c, for which RWT was added into the storm drains.

reported in Table 1. In field study 1, RWT was added twice at a 0.5-h interval. Field studies 2 and 3 were more complex, and RWT pulses were added once or more to multiple sanitary sewer manholes. RWT was dosed to the sanitary sewers in all studies except field study 2c, in which RWT was dosed to the storm drains.

RWT Monitoring. RWT was monitored using a 600 OMS V2 sonde equipped with temperature and conductivity sensors and a rhodamine WT optical probe (YSI Incorporated, Yellow Springs, OH). The sonde was programmed for unattended monitoring, at 1- or 2-min intervals. The sonde was calibrated using a two-point calibration curve (0 and 100 ppb) and had a detection limit of 1 ppb and a linear range of 1−200 ppb. RWT was purchased as Keyacid rhodamine WT liquid and consisted of 20% true dye concentration (Keystone Aniline Corporation, Chicago, IL). Background signals were collected during a period of 20 days in field study 2 and 8 days in field study 3.

Flow Rate Calculations. Flow rates in sanitary sewers were calculated based on Manning's equation, assuming a roughness coefficient n of 0.014.[22] Slopes were calculated from manhole invert depths and spatial information contained in a GIS (geographic information system) database from the City of Santa Barbara.

Water Sampling and Microbiological Analyses. One or more water samples were taken in the storm drains during each of the three field studies. Storm drain samples were taken at P1-D and P2-D (field study 1), N1-D and N2-D (field study 2), and H1-D and H2-D (field study 3). One sewage sample was collected from the nearby El Estero wastewater treatment plant influent, on 06/11/2010. Water samples (2 L) were collected using a sterile plastic beaker and filtered through Miracloth (20−25-μm pore size) into a sterile plastic bottle in the field. Samples were stored on ice in the dark until being filtered in the laboratory through 0.22-μm filters (within 6 h).

DNA was extracted from the archived filters (−20 °C) using the PowerWater DNA Isolation kit (MoBio Laboratories, Carlsbad, CA) according to the manufacturer's instructions, and then subjected to ethanol precipitation in a final volume of 50 μL. Polymerase chain reaction (PCR) inhibition was tested by using salmon testes DNA from *Oncorhynchus keta* as an internal control, based on the protocol of Morrison et al.[23] The PCR conditions were as previously described,[23] except for an annealing temperature of 62 °C and the addition of 0.2 mg/mL bovine serum albumin and deoxyribonucleotide triphosphate (dNTP) concentrations of 0.2 mM each. A separate Sybr Green quantitative PCR (qPCR) reaction was run after addition of 0.25 ng of salmon testes DNA to each sample reaction (in duplicate) and a no-sample control (in quadruplicate). At first, 2.5 μL of 1:5 diluted DNA template was run. Samples were considered inhibited if the average threshold cycle value (Ct) of samples exceeded the average plus 3 times standard deviation of the blank control with salmon testes DNA. Samples were diluted 2-fold until inhibition was removed. Concentrations of human-specific HF183 *Bacteroidales* markers were determined using SybrGreen qPCR, based on a previously described protocol.[17,24] A volume of 2.5 μL of DNA template was used per 25 μL of qPCR reaction, with the template dilution based on the inhibition assay (i.e., 1:5 or higher). All qPCR reactions were run in an iQ5 thermocycler (Bio-Rad, Hercules, CA), using the qPCR Core Kit for Sybr Green I (Eurogentec, San Diego, CA). The presence or absence of the *Methanobrevibacter smithii nifH* gene was determined by two rounds of PCR, using the protocol of Ufnar et al.[25] The DNA template in round 1 consisted of 1 μL of diluted template DNA (per salmon testes DNA inhibition assay), and that in round 2 consisted of 1 μL of 1:10 diluted PCR product from round 1. PCR reactions were performed in 25 μL reaction volumes, using a Hybaid PCR Sprint thermocycler and the Taq PCR Core Kit including Q-mix (Qiagen, Valencia, CA).

RESULTS AND DISCUSSION

Field Study 1: Leaking Sanitary Sewer Due to Surcharge Conditions (Proof of Concept). In field experiment 1 (Figure 1A), field observations, canine scent tracking,[20] and video recording of the storm drain pipe indicated that the storm drain was receiving leakage from a sanitary sewer that was under surcharge conditions at regular intervals, leading to an opportunistic chance for a proof of concept. Additional quantitative evidence was obtained by detection of two RWT peaks in the storm drain at P1-D, after dosing of two separate pulses of RWT

Table 2. Microbial Source Tracking Results: Human-Specific *Bacteroidales* HF183 concentrations and Presence (+) or Absence (−) of the *Methanobrevibacter smithii nifH* Gene

experiment	location	date (month/day)	HF183[a,b] (copies/L)	HF183 (% sewage)	*M. smithii nifH*
sewage	WWTP	06/11	8.8×10^7 (4.2×10^6)	100	+
field 1	P1-D	06/09	6.3×10^6 (6.0×10^5)	7	+
	P2-D	06/09	1.5×10^7 (1.8×10^5)	17	+
field 2	N2-D	07/01	nd	nd	+
	N2-D	07/06	3.9×10^3 (5.9×10^2)	0.004	−
	N2-D	07/09	1.7×10^4 (1.1×10^3)	0.02	+
	N1-D	07/01	1.3×10^5 (6.8×10^3)	0.15	+
	N1-D	07/06	nd	nd	−
	N1-D	07/09	5.3×10^4 (3.4×10^3)	0.06	+
field 3	H2-D	09/08	nd	nd	−
	H2-D	09/13	nd	nd	−
	H2-D	09/20	nd	nd	−
	H1-D	09/08	nd	nd	−
	H1-D	09/13	nd	nd	−
	H1-D	09/20	nd	nd	−

[a] Standard errors for analytical replicates ($n = 3$) in parentheses. [b] nd: not detected.

in the sanitary sewer at P1, during surcharge conditions [Table 1, Figure S2 (Supporting Information)]. The time of travel of RWT between dosing and detection was 20−30 min. Based on an estimated flow of 0.1 m^3/s in the sanitary sewer (Manning's equation), an RWT dosing rate of 0.17×10^{-3} m^3/s, and the assumption of no longitudinal dispersion, a 1-min pulse of 1.3 ppm RWT occurred in the sanitary sewer after mixing of RWT with the sewage flow. A maximum of 0.25 ppm RWT was detected in the storm drain (Figure S2, Supporting Information), suggesting ∼20% sewage in the storm drain shortly after surcharge conditions in the sanitary sewer. Concentrations of HF183 indicated approximately 7% sewage at P1-D (Table 2), agreeing well with the estimates based on RWT concentration. The detection of the *M. smithii nifH* marker (Table 2) also confirmed sewage pollution.

High concentrations of fecal indicator bacteria have been recorded over many years at location P2-D, leading to the installation of a low-flow diversion to transfer dry-weather runoff to a nearby sanitary sewer pipe. Sewage contamination was confirmed in 2005 at P2-D based on elevated HF183 concentrations,[17] validating the need for the low-flow diversion, although the exact origin of the sewage inputs was not found. The results of the current study suggest that most of the sewage contamination originates from the branch at P1-D, receiving the sewage exfiltrate, because the HF183 concentrations were similar at the two locations (Table 2). After the sanitary sewer pipe was repaired, follow-up monitoring did not detect any HF183 and *M. smithii nifH* markers at P2-D (data not shown).

Field study 1 indicated that lift station operation and surcharge conditions in sanitary sewers can lead to exfiltration and severe contamination of nearby leaking storm drains. Continuous monitoring of RWT in the storm drains appeared to be a promising approach for obtaining direct evidence of such contamination.

Field Study 2: Storm Drains Located Deeper than Sanitary Sewers. Background RWT concentrations were consistently between −1 and 2 ppb, and no peaks could be distinguished (Figure 2A). After RWT addition to the sanitary sewer in phase 2a, two above-background RWT peaks were observed in the storm drain at N1-D, 2 days after the second RWT pulse and 10 days after the third RWT pulse (Figure 2B). The first peak was detected after dosing of RWT at N1−N4; the second, after dosing at all manholes. Therefore, at least one RWT peak could be attributed to RWT dosing at N1−N4, and phase 2b focused on the latter manholes. Multiple RWT peaks were detected during phase 2b, but not at 1-h intervals (i.e., not at the time interval between pulses at each manhole) (Figure 2C). Therefore, the approach of dosing multiple pulses into each manhole was effective in detecting sewer-to-storm-drain contamination in this area, but did not allow for better localization of the contamination origin. In addition, the detection of multiple RWT peaks suggested multiple locations of sewage exfiltration into the leaking storm drains. Detection of HF183 and *M. smithii nifH* markers at two storm drain locations during phase 2a confirmed the occurrence of sewage contamination during RWT testing (Table 2). HF183 concentrations were 2−3 orders of magnitude lower than during field study 1 and corresponded to sewage concentrations between 0.004% and 0.15%. These lower concentrations were due to the higher dilution of sewage infiltrate in storm drain baseflow originating from sump pumps, irrigation runoff, and groundwater seepage. Based on RWT dosing concentrations in sewage of 200−4000 ppm and an observed RWT peak concentration of 5 ppb, the sewage dilution at N1-D was 10^4−10^6. This corresponds to approximately 10^2−10^4 HF183 copies/L, which is on the low end of the concentration range observed (10^4−10^5 copies/L). Because of possible RWT adsorption in soil[26,27] and longitudinal dispersion in the sanitary sewer, estimates of sewage contamination in storm drains based on RWT might be lower than estimates based on HF183 concentrations.

During phase 2c, RWT was injected at three storm drain locations (Figure 1B) to determine travel times for the different storm drain branches with confluent at N1-D. After dosing of 100 and 1000 ppm RWT at N2-D, where continuous low flow was present, RWT was observed at N1-D, 150 m downstream, within 2 h (Figure 3A). After dosing of the same concentrations at N3-D, one small RWT peak was observed 74 h after the second dosing and after the storm drain had been flushed with clean

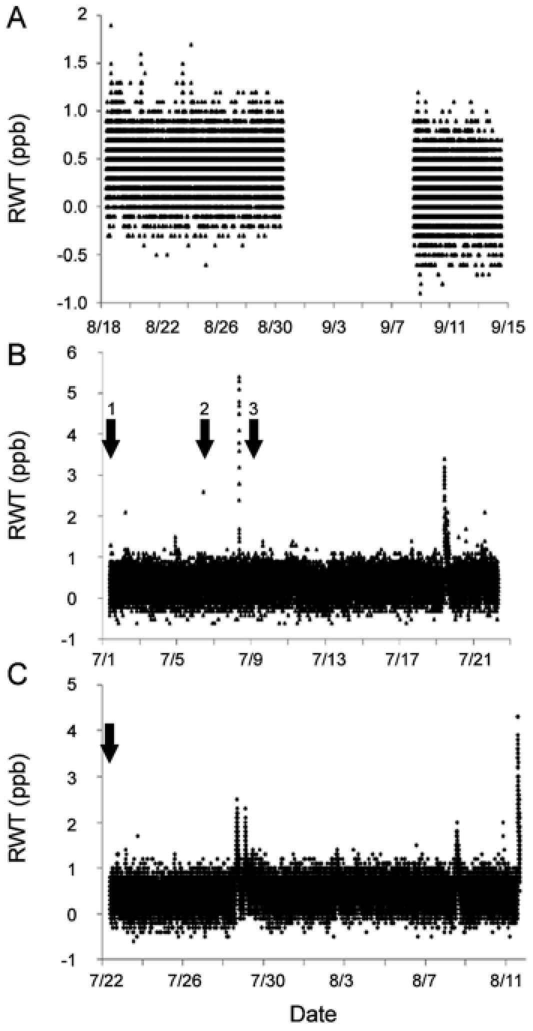

Figure 2. RWT concentrations at N1-D. (A) Background. (B) Phase 2a: one RWT pulse in each sanitary sewer manhole (indicated by arrows). Pulse 1, N1 and N2; pulse 2, N3 and N4; pulse 3, N5−N8. (C) Phase 2b: multiple RWT pulses in each sanitary sewer manhole (timing indicated by arrow).

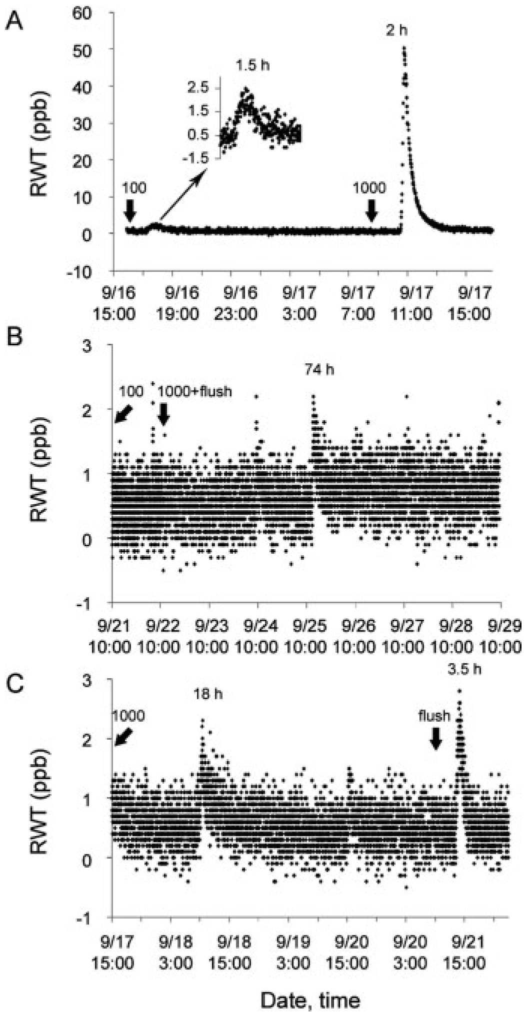

Figure 3. Detection of RWT at N1-D after dosing into storm drains in (A) N2-D, (B) N3-D, and (C) N4-D. RWT pulse volumes (100 or 1000 mL) are indicated with each injection, as well as flushes with water but without RWT (flush). The time of travel between the injection and detection locations is indicated for each peak.

water (Figure 3B). A trickle flow was observed during the first dosing, but no flow was observed during the second dosing. After dosing of 1000 ppm RWT at N4-D, where flow was absent, RWT pooled in the manhole. Still, a small RWT peak was observed at N1-D after 18 h, indicating that intermittent flow occurred (Figure 3C). After the storm drain had been flushed, a second RWT peak was observed at N1-D after 4 h. Overall, the results from phase 2c indicate that the travel time of water in the storm drains in this area is on a scale of hours when flow is present, but can increase to days or weeks due to periods without flow. The time of travel of RWT in storm drains is unpredictable and is unlikely to provide useful information regarding the location of exfiltration and storm drain pollution in this case. However, intermittent flow patterns, as observed before in other storm drains in Santa Barbara,[21] can explain why the times between RWT dosing and detection in phases 2a and 2b were not reproducible. Because the HF183 concentrations at N2-D and N1-D were similar, the area near N2-D should contribute significantly to the sewage pollution downstream.

Detection of RWT in storm drains after dosing in sanitary sewers during field study 2 indicated that the experimental approach is useful for obtaining direct evidence of sewage exfiltration into leaking storm drains with relatively low concentrations of sewage contamination (<0.15%). Exact localization of the source of contamination using RWT tracing is challenging because of variable travel times in storm drains. However, HF183 concentrations were helpful in localizing at least one of the contamination locations.

Field Study 3: Storm Drains Located Shallower than Sanitary Sewers. Background RWT concentrations in this area were mostly between −1 and 1 ppb (Figure S3A, Supporting Information). However, multiple RWT spikes up to 5 ppb, but consisting of only one data point, were observed (Supporting Information, Figure S3A, inset A1 for detail). Storm drain flow at this location was usually very low, with water levels below 3 cm, although episodes of increased flow occurred at regular intervals. Sand bags were used to dam the flow and provide enough water depth for submerging the probe during low-flow episodes. Because sufficient water levels could not always be sustained, the probe was not submerged at times, as evident from decreased conductivity at regular intervals (Supporting Information, Figure S3A, inset A1). Only one small RWT peak consisting of multiple data points was observed (Supporting Information, Figure S3A, inset A2) and should be considered part of the background signal.

One small RWT peak could be observed at H1-D, 13−14 days after RWT had been dosed into the sanitary sewers at six locations (Supporting Information, Figure S3B, inset). However, this peak could not be reliably distinguished from the background signal, even though it was somewhat higher than the background peak in inset A2 of Figure S3A (Supporting Information). Multiple one-data-point peaks were also observed and were considered background, perhaps due to incomplete submersion of the probe. Human-associated markers were not detected at H1-B and H2-B. Therefore, both RWT and microbiological data suggest no or low sewage contamination due to exfiltration from sanitary sewers in this area. More experiments with higher RWT dosing concentrations are recommended in this area to determine whether the small peaks observed could be related to sewage pollution.

Importance of Exfiltration to Storm Drain Water Quality. Studies on the impact of exfiltration on the environment or human health have mostly focused on potential contamination of groundwater.[8−10] However, this study provided multiple lines of evidence that storm drains, and therefore surface waters and oceans, can be contaminated directly by sewer exfiltration as well. Poor condition of the sanitary sewer infrastructure and sufficient depth with respect to groundwater increase the susceptibility for sewer exfiltration in the U.S.[7] It has been suggested that especially arid urban areas are at risk, such as in Arizona and New Mexico.[7] However, this study demonstrates exfiltration and contamination of surface waters through leaking storm drains in a small city along the California coast. Given that large parts of California are highly urbanized and have a climate and separated sewer infrastructure similar to those of Santa Barbara, it can be reasonably assumed that similar contamination scenarios occur elsewhere.

In the case of the sewage exfiltration under surcharge conditions (study 1), transport from the sanitary sewer to the storm drain was fast, and sewage concentrations were in the range of 7−20%. The surcharge conditions caused a flow rate of about 1 L/min in the storm drains based on visual observations, approximately three times per hour and lasting for 2 min each, corresponding to a load on the order of 14 L of fresh sewage per day. In the case of the diffuse sewage exfiltration (study 2), a maximum loading estimate of 120 L of sewage per day was obtained, based on an estimated storm drain flow of 55 L/min (Manning's equation) and 0.15% sewage concentration. Based on the results of the current study, over 100 L of sewage enters the storm drains per day, but this quantity will likely increase if more storm drains are investigated. To assess the risk to human health, it is important to consider that sewage properties can be altered by transport through soil, for example, through reductions in virus and bacterial concentrations.[28,29] For instance, after exfiltration near N2-D, filtration of sewage through soil is expected to take several days.

RWT Dye Studies for Localizing Sewage Exfiltration Pollution. This study shows that RWT dosing experiments combined with unattended monitoring are a promising method for assessing the occurrence of direct sewage exfiltration into leaking storm drains. The methods are within reach of communities and municipalities, as screening watersheds requires no other equipment than the optical probe setup (∼$7,000) and a PC or laptop. The experiments were approved by the local public works department, and the RWT concentrations used in this study did not affect operation of the wastewater treatment plant. Although tracers such as bacteriophage PRD-1 can be detected to very low concentrations and might be more relevant for pathogen transport in the environment,[26,30] the inability to use unattended monitoring makes their use very impractical. Commonly used nonreactive tracers such as bromide did not provide sufficiently low detection limits for this study (results not shown).

Our data suggest that spatial information can be used to estimate the risk for sewage exfiltration into leaking storm drains, as most contamination occurred in an area with all risk factors present: aged vitrified clay sanitary sewer pipes, sanitary sewers above storm drains, and multiple locations where sanitary sewers and storm drains cross or run parallel within 5 m. In the area where one of these factors was missing (i.e., storm drains were above the sanitary sewers), evidence for sewage exfiltration into storm drains was lacking. Therefore, identifying all areas that match the above criteria should be a first step for preliminary assessment of the contamination potential or for the design of field studies. The latter will require a spatial database with age, construction material, and depth of sanitary sewers and storm drain infrastructure. Based on the detection of sewage exfiltration pollution in multiple storm drain locations in this study, more research is recommended in other urban areas to assess the magnitude of the problem of sanitary sewers, and potentially private laterals, leaking into storm drains.

■ ASSOCIATED CONTENT

S Supporting Information. Details about sanitary sewer and storm drain configurations and RWT concentrations measured in storm drains. This information is available free of charge via the Internet at http://pubs.acs.org/ .

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■ REFERENCES

(1) Chisala, B. N.; Lerner, D. N. Distribution of sewer exfiltration to urban groundwater. *Proc. Inst. Civ. Eng.: Water Manage.* **2008**, *161*, 333–341.

(2) Blackwood, D. J.; Ellis, J. B.; Revitt, D. M.; Gilmour, D. J. Factors influencing exfiltration processes in sewers. *Water Sci. Technol.* **2005**, *51*, 147–154.

(3) DeSilva, D.; Burn, S.; Tjandraatmadja, G.; Moglia, M.; Davis, P.; Wolf, L.; Held, I.; Vollertsen, J.; Williams, W.; Hafskjold, L. Sustainable management of leakage from wastewater pipelines. *Water Sci. Technol.* **2005**, *52*, 189–198.

(4) Ellis, J. B.; Revitt, D. M.; Lister, P.; Willgress, C.; Buckley, A. Experimental studies of sewer exfiltration. *Water Sci. Technol.* **2003**, *47*, 61–67.

(5) Rutsch, M.; Franz, T.; Krebs, P. Transferability of exfiltration rates from sewer systems. *J. Soils Sediments* **2007**, *7*, 69–74.

(6) Rutsch, M.; Rieckermann, J.; Cullmann, J.; Ellis, J. B.; Vollertsen, J.; Krebs, P. Towards a better understanding of sewer exfiltration. *Water Res.* **2008**, *42*, 2385–2394.

(7) Amick, R. S.; Burgess, E. H. *Exfiltration in Sewer Systems*; Report EPA/600/R-01/034; U.S. Environmental Protection Agency: Cincinnati, OH, 2000.

(8) Hunt, R. J.; Borchardt, M. A.; Richards, K. D.; Spencer, S. K. Assessment of sewer source contamination of drinking water wells using tracers and human enteric viruses. *Environ. Sci. Technol.* **2010**, *44*, 7956–7963.

(9) Fenz, R.; Blaschke, A. P.; Clara, M.; Kroiss, H.; Mascher, D.; Zessner, M. Monitoring of carbamazepine concentrations in wastewater and groundwater to quantify sewer leakage. *Water Sci. Technol.* **2005**, *52*, 205–213.

(10) Paul, M.; Wolf, L.; Fund, K.; Held, I.; Winter, J.; Elswirth, M.; Gallert, C.; Hotzl, H. Microbiological condition of urban groundwater in the vicinity of leaky sewer systems. *Acta Hydrochim. Hydrobiol.* **2004**, *32*, 351–360.

(11) Teunis, P. F. M.; Xu, M.; Fleming, K. K.; Yang, J.; Moe, C. L.; LeChevallier, M. W. Enteric virus infection risk from intrusion of sewage into a drinking water distribution network. *Environ. Sci. Technol.* **2010**, *44*, 8561–8566.

(12) Wolf, L.; Eiswirth, M.; Hotzl, H. Assessing sewer−groundwater interaction at the city scale based on individual sewer defects and marker species distributions. *Environ. Geol.* **2006**, *49*, 849–857.

(13) Soller, J. A.; Bartrand, T.; Ashbolt, N. J.; Ravenscroft, J.; Wade, T. J. Estimating the primary etiologic agents in recreational freshwaters impacted by human sources of faecal contamination. *Water Res.* **2010**, *44*, 4736–4747.

(14) Hoes, O. A. C.; Schilperoort, R. P. S.; Luxemburg, W. M. J.; Clemens, F.; de Giesen, N. C. V. Locating illicit connections in storm water sewers using fiber-optic distributed temperature sensing. *Water Res.* **2009**, *43*, 5187–5197.

(15) Field, R.; Pitt, R.; Lalor, M.; Brown, M.; Vilkelis, W.; Phackston, E. Investigation of dry weather pollutant entries into storm drainage systems. *J. Environ. Eng.* **1994**, *120*, 1044–1066.

(16) Li, T.; Zhou, Y. C.; Li, H. Quantifying non-stormwater discharges to stormwater systems with model analysis. *J. Environ. Eng.* **2008**, *134*, 928–932.

(17) Sercu, B.; Van De Werfhorst, L. C.; Murray, J.; Holden, P. A. Storm drains are sources of human fecal pollution during dry weather in three urban Southern California watersheds. *Environ. Sci. Technol.* **2009**, *43*, 293–298.

(18) Ana, E. V.; Bauwens, W. Modeling the structural deterioration of urban drainage pipes: The state-of-the-art in statistical methods. *Urban Water J.* **2010**, *7*, 47–59.

(19) Fenner, R. A. Approaches to sewer maintenance: A review. *Urban Water* **2000**, *2*, 343–356.

(20) Murray, J. *Canine Scent and Microbial Source Tracking in Santa Barbara, CA*; Report U2R09; Water Environmental Research Foundation: Alexandria, VA, 2001.

(21) Steets, B.; Smith, R.; Patterson, M.; Louie, A. *Laguna Watershed Study and Water Quality Improvement Feasibility Analysis*; Geosyntec Consultants: Santa Barbara, CA, 2009; http://www.santabarbaraca.gov/NR/rdonlyres/B6A274E7-3D46-4E51-B7F8-C04334477829/0/LagunaWatershedStudyFINAL.pdf (accessed July, 2011).

(22) Parmley, R. O. *Hydraulics Field Manual*, 2nd, ed.; McGraw-Hill Professional: New York, 2001.

(23) Morrison, C. R.; Bachoon, D. S.; Gates, K. W. Quantification of enterococci and bifidobacteria in Georgia estuaries using conventional and molecular methods. *Water Res.* **2008**, *42*, 4001–4009.

(24) Seurinck, S.; Defoirdt, T.; Verstraete, W.; Siciliano, S. D. Detection and quantification of the human-specific HF183 *Bacteroides* 16S rRNA genetic marker with real-time PCR for assessment of human faecal pollution in freshwater. *Environ. Microbiol.* **2005**, *7*, 249–259.

(25) Ufnar, J. A.; Wang, S. Y.; Christiansen, J. M.; Yampara-Iquise, H.; Carson, C. A.; Ellender, R. D. Detection of the *nifH* gene of *Methanobrevibacter smithii*: A potential tool to identify sewage pollution in recreational waters. *J. Appl. Microbiol.* **2006**, *101*, 44–52.

(26) Harden, H. S.; Chanton, J. P.; Rose, J. B.; John, D. E.; Hooks, M. E. Comparison of sulfur hexafluoride, fluorescein and rhodamine dyes and the bacteriophage PRD-1 in tracing subsurface flow. *J. Hydrol.* **2003**, *277*, 100–115.

(27) Smart, P. L.; Laidlaw, I. M. S. Evaluation of some fluorescent dyes for water tracing. *Water Resour. Res.* **1977**, *13*, 15–33.

(28) Hua, J. M.; An, P. L.; Winter, J.; Gallert, C. Elimination of COD, microorganisms and pharmaceuticals from sewage by trickling through sandy soil below leaking sewers. *Water Res.* **2003**, *37*, 4395–4404.

(29) Horswell, J.; Hewitt, J.; Prosser, J.; Van Schaik, A.; Croucher, D.; Macdonald, C.; Burford, P.; Susarla, P.; Bickers, P.; Speir, T. Mobility and survival of *Salmonella typhimurium* and human adenovirus from spiked sewage sludge applied to soil columns. *J. Appl. Microbiol.* **2010**, *108*, 104–114.

(30) Blanford, W. J.; Brusseau, M. L.; Yeh, T. C. J.; Gerba, C. P.; Harvey, R. Influence of water chemistry and travel distance on bacteriophage PRD-1 transport in a sandy aquifer. *Water Res.* **2005**, *39*, 2345–2357.

Supporting Information

Sewage exfiltration as a source of storm drain contamination during dry weather in urban watersheds

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5 pages
1 table
3 figures

Table S1. Sanitary sewer (SS) and storm drain (SD) infrastructure details for all high risk location indicated in Fig. S1B. DHor: horizontal distance between pipes, DVert: vertical distance between pipe inverts. Locations with crossing pipes are C1 - C7, locations with parallel pipes are P1 - P4.

	Age		Size (in.)		Elevation (ft)		DHor (m)	DVert[a] (m)
	SS	SD	SS	SD	SS[b]	SD[c]		
C1	1921	1921	6	30	NA[d]	69.0	NR[e]	NA
C2	1917	1976	8	27	38.8	31.8	NR	2.1
C3	1921	1976	6	24	42.6	39.5	NR	0.9
C4	2002	1976	6	33	16.9	13.1	NR	1.2
C5	1921	1960	8	33	26	17.9	NR	2.5
C6	1925	1960	6	33	30.3	24.8	NR	1.7
C7	1926	1997	6	24	NA	60	NR	NA
P1	1917	1976	8	27	48.8-60	31.7-59.3	1.7-2.2	0.2-5.2
P2	1917	1976	8	30	38.8-41.8	31.8-34.7	4.2-5.2	2.1-2.2
P3	1921	1976	6	24	27-31	21.8-29.7	3.0-4.0	0.4-1.6
P4	1917	1960	6	33	25-30	20-31.8	1.2-3.6	0.5-1.5

[a] Vertical distance is SS – SD elevation.

[b] SS elevations above sea level were calculated using invert depth information from GIS (accuracy 0.2-2ft depending on location) and surface elevations on storm drain atlas. When interpolations were required, straight pipes were assumed.

[c] SD elevations above sea level were calculated from the storm drain atlas, with interpolations assuming straight pipes.

[d] NA: not available

[e] NR: not relevant

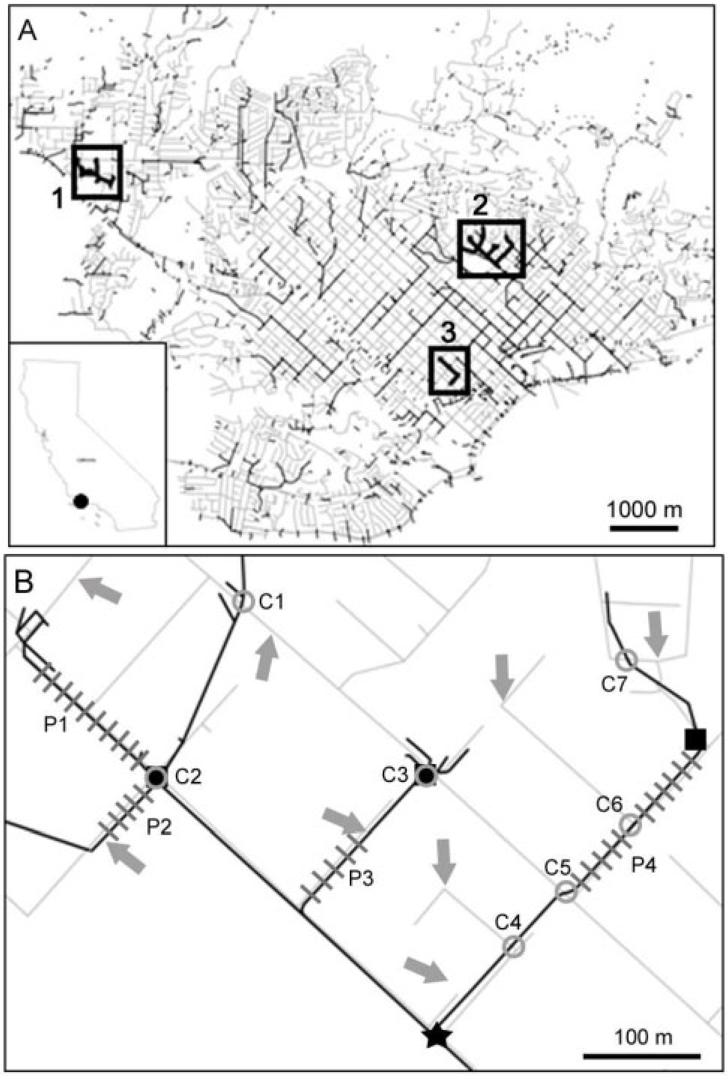

Fig. S1. A. Location of Santa Barbara, CA (lower left inset, black circle) and map of the downtown area sewer infrastructure with field study locations (numbered squares) and dense black lines indicating storm drains. B. Field study 2: locations of high-risk locations where sanitary sewers and storm drains cross (C1 – C7, grey open circles) or run parallel within 5 m (P1 – P4, gray hatched lines). Locations of RWT injection (grey arrows), detection (black star) and sampling (black squares) are indicated as well, as in Fig. 1B.

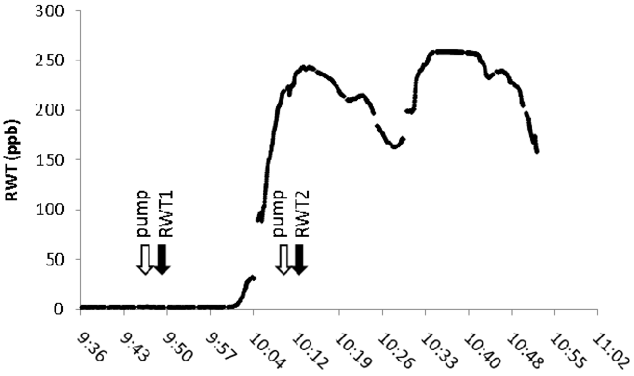

Fig. S2. Detection of RWT at P1-D after dosing into sanitary sewers P1. Arrows indicate start of surcharge flow (open arrows) and RWT dosing (black arrows) in the sanitary sewer.

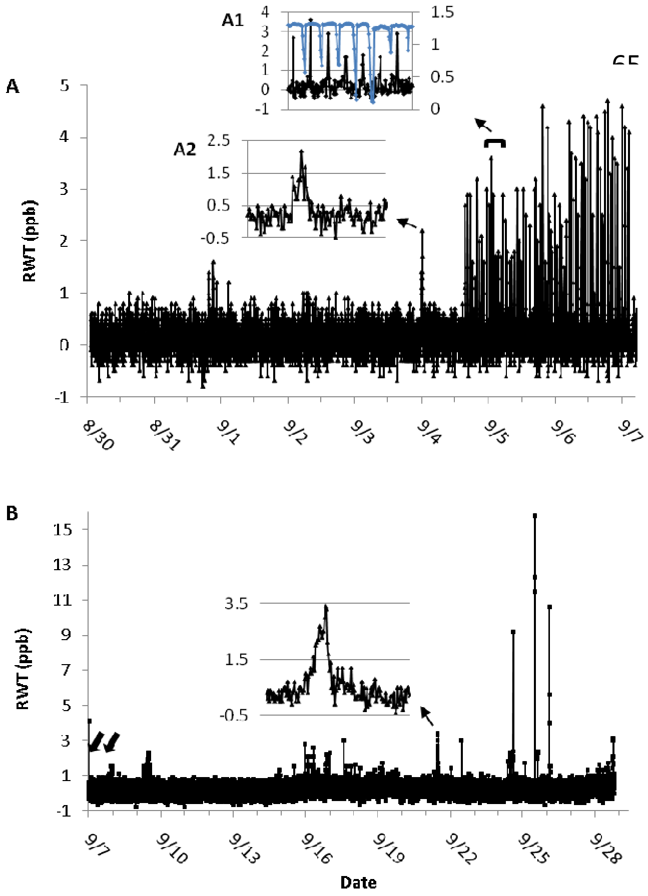

Fig. S3. RWT concentrations at H1-D. A. Background. Inset A1 shows detail with conductivity in blue lines on right y-axis. Inset A2 shows detail of RWT peak. B. RWT concentrations after dosing one RWT pulse in each sanitary sewer manhole (dosing times indicated by arrows).