QUANTIFYING SUB-SURFACE DISCHARGES FROM INDIVIDUAL SEWER DEFECTS

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ABSTRACT

The California Regional Water Quality Control Board, Santa Ana Region (RWQCB) required wastewater collection agencies in Orange County to report discharges from “pipe breaks, leaking sewer pipes and joints, and other subsurface discharges of wastewater.” The Orange County Sanitation District (OCSD), in conjunction with a research team from University of California, Irvine (UCI), developed a device to quantify the subsurface discharge of individual sewer defects. The instrument developed to measure discharge rates of individual sewer defects has been named the “Exfiltrometer.” Soil adjacent to each sewer defect tested for exfiltration was tested for the presence of wastewater. Indicators of wastewater used in this study include: E. coli and total coliform bacteria, caffeine, and major anions. A variety of sewer defect types were tested. Some of the same defect types exhibited similar exfiltration rates. Others did not. Ultimately, a greater number of exfiltration tests need to be performed to draw more statistically significant conclusions about a wastewater collection system’s sub-surface discharge of wastewater.

KEYWORDS

Exfiltration, sewer, wastewater, subsurface discharge, sewer defects.

INTRODUCTION

On April 26, 2002 the California Regional Water Quality Control Board, Santa Ana Region (RWQCB) established a Monitoring and Reporting Program as part of its General Waste Discharge Requirements for Wastewater Collection Agencies in Orange County. It included a requirement to develop a methodology to report discharges from “pipe breaks, leaking sewer pipes and joints, and other subsurface discharges of wastewater.” Orange County Sanitation District (OCSD), as the lead agency in the compliance effort, receives wastewater from satellite systems serving 24 cities and 7 special districts. Approximately 400 miles of interceptors and trunk lines and 175 miles of local small diameter sewers are OCSD owned, and about 5,500 miles of local sewers owned and operated by their satellites. The OCSD service area covers about 470 square miles and overlies a deep underground aquifer along the Santa Ana River.
basin. This aquifer serves as a major source of drinking water. The sanitary sewers in the region are up to 100 years old and are mostly made of clay and vitrified clay pipe materials.

OCSD and its satellite partners retained Brown and Caldwell to assist in reviewing the Orders requirements, and the Water Quality and Treatment Laboratory at University of California, Irvine, to develop a methodology to quantify exfiltration from individual locations in sewers. OCSD has submitted a report to the Regional Board titled: Status Report on the Development of a Reporting Methodology for Subsurface Discharges of Sewage covering this effort.

A survey of the literature found that the available methods to measure exfiltration fall into three broad categories. The first is based on placing a sewer with a defect in a box above ground and determining the rate of leakage. It provides a result that does not take into account the retarding effect attributed to the soil outside the defect, such as soil clogging, etc. The second method requires isolation of a sewer reach, surcharging the reach, and recording the rate of water level drop in the manhole. This method significantly overestimates the rate of exfiltration because it includes flows in the upper part of the sewer, while most small diameter sewers flow less than one-half full. The third method relies on area-wide mass balances or tracers, but the reported results have been difficult to quantify.

**METHODS**

In order to quantify leakage rates through sewer defects for this study, an Exfiltrometer has been developed. When a sewer defect was selected for study, the Exfiltrometer was taken out into the field, placed into the sewer, and exfiltration measurements were made. There are a number of test procedures that were utilized to ensure that the exfiltration measurements are reliable.

An Exfiltrometer prototype (Gifford, 2006) was produced prior to this study.

The main components of the Exfiltrometer (Figures 1, 2, 3, & 4) are the inflatable plugs, water-depth sensors, reservoir, controller, atmospheric float, and umbilical cord.

The Exfiltrometer quantifies the amount of water that leaks through a sewer defect utilizing a mass balance. First, the two plugs are inflated to isolate the sewer section containing a known defect (Figure 1). The controller is then programmed to pump water from the reservoir to maintain a constant water depth in the test section of the sewer. If water leaks through the sewer defect in question, the water level in the test section drops. The water level is monitored by a water-depth sensor in the test section and its output is received by the controller. When/if the water level in the test section drops below the programmed level, typically 2 mm, the controller switches on a pump that delivers water from the reservoir. When the water level in the test section returns to the programmed level, the controller turns the pump drawing water from the reservoir off. The volume of water used from the reservoir versus the time period of the test is then plotted to show the leakage rate of the sewer defect and, thus, the defect’s exfiltration rate.
The reservoir is used to provide a measurable supply of water to the sewer test section. It is a 5-foot-tall, 5 ¾-inch ID, clear polycarbonate tube. It is plugged at the bottom by a 6-inch pipe plug. The plug has been modified to introduce a water-level-depth sensor into the bottom of the reservoir. This sensor transmits data to the controller/data-logger about the water level in the reservoir.

The stand that supports the reservoir also incorporates a small pump and solenoid-actuated valve (Figure 3). The pump, when turned on by the controller, delivers water to the isolated sewer test section through 220 feet of LLDPE (Linear Low-Density Polyethylene) tubing. Normally closed to prevent leakage of water from the reservoir into the test section, the solenoid-actuated valve is opened at the same time the pump is switched on to permit flow.
Figure 2. The UCI Exfiltrometer.

Figure 3. Pump and solenoid valve of reservoir.

Figure 4. The business end of the Exfiltrometer.
The Exfiltrometer’s umbilical cord is comprised of the necessary water, air, and electrical lines that need be supplied to the sewer test section. The umbilical cord consists of:

- Air line for inflatable plug directly attached to umbilical cord (Plug A)
- Air line for free plug (plug not directly attached to umbilical cord—Plug B)
- Water line to fill sewer test section from reservoir
- Integral cable of sewer water-depth sensor
- Multi-conductor cable that provides power to sewer video camera and lights

The umbilical cord is sheathed in helical 1-inch-OD cable-bundle wrap for protection. Portions of the bundle wrap are also covered with large-diameter heat-shrink tubing for further abrasion protection.

The atmospheric float references the air above the water in the sewer test section to atmospheric pressure. As water is pumped into the test section, the volume of air above the water is compressed. If this compressed air were not allowed to evacuate, the sewer water-depth sensor would give erroneous readings. The atmospheric float simply allows the compressed air to escape out of the test section, ensuring that the air above the water in the test section equalizes to atmospheric pressure.

The atmospheric float can be referenced to the atmosphere through either inflatable plug. Each plug has an atmospheric air line with a quick-connect coupling that mates with the atmospheric float. This allows flexibility in the way the Exfiltrometer is fished into a sewer. Since either plug can provide the atmospheric reference, either plug can be downstream in the test section. This capability enables the Exfiltrometer to be fished into the manhole which is the shortest distance from the sewer defect of interest.

The sewer plug used can be inflated to obstruct pipes with inside diameters from 4.7 to 8.25 inches, making them ideal for use in 6-8 inch I.D. sewer lines. Inflated to the recommended pressure of 35 PSI, the plug can obstruct pipes with fluids exerting as much as 15 PSI on the plug. 15 PSI is equivalent to more than 34 feet of head for water, so there'd have to be a considerable back-up of sewage on the upstream plug in order for the plug to fail.
Before placing the Exfiltrometer in the sewer, its functionality is tested. A clear polycarbonate tube, 8 feet in length and 5 inches in diameter, is brought along to the test site for this purpose. The Exfiltrometer is pulled into the middle of the tube, where there is a valve used to simulate a sewer leak (exfiltration). The inflatable plugs are inflated to 30 p.s.i.

The controller is set to maintain a water level in the test section between 2 and 3 inches and begins pumping water from the reservoir to the test pipe’s test section. When the test section’s water level has stabilized at the set level, the height of the water level in the reservoir is measured with measuring tape and noted. The depth level reading from the reservoir’s pressure transducer is also noted. The valve used to simulate a sewer leak is then opened. The flow from the valve is collected in a graduated cylinder.

In addition to being executed before the Exfiltrometer is placed into the sewer for exfiltration testing, the functionality test described is executed after the Exfiltrometer has been pulled out of the sewer. An example of the data collected during the functionality checks is shown in Table 1.

<table>
<thead>
<tr>
<th>Volume Measurement</th>
<th>Change in Parameter</th>
<th>Change in Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graduated Pitcher</td>
<td></td>
<td>0.82 L</td>
</tr>
<tr>
<td>Change in Reservoir Height (Tape Measurer)</td>
<td>4.9 cm</td>
<td>0.82 L</td>
</tr>
<tr>
<td>Change in Reservoir Height (Water Level Sensor)</td>
<td>4.82 cm</td>
<td>0.81 L</td>
</tr>
</tbody>
</table>

An abbreviated exfiltration test procedure is as follows:
1) A plug is inserted into the upstream sewer of the upstream manhole to block flow of wastewater into the subject sewer reach. The next manhole upstream is monitored throughout the test for back-up of wastewater. If the sewer backs-up to a predetermined level, the wastewater is pumped out by a Vactor truck and reintroduced to the collection system downstream of the subject sewer reach.

2) The subject sewer line is jetted clean. A rope is attached to the jetting equipment and run from manhole to manhole. The Exfiltrometer is pre-calibrated above ground during this time.

3) The Exfiltrometer is pulled into the sewer with the rope.

4) The defect is located by means of a visual indication on the umbilical cord. Usually, masking tape is wrapped around the umbilical cord at a distance from the upstream plug to the manhole equivalent to that of the distance from the sewer defect to the manhole. The Exfiltrometer’s video camera then assists in more accurately positioning the Exfiltrometer at the defect in question.

5) The upstream plug is inflated. Any remaining wastewater drains out of the test section after a short period of time.

6) The downstream plug is inflated.

7) The sewer water depth is filled to the level input on the controller. Usually, the depth is initially low (about 1 inch) and is raised once or twice (maybe to 2, 3, or 4 inches—whatever is appropriate for the geometry of the defect) later during the test.

8) Data is collected with the controller/data logger when Step 6 begins. If the sewer defect exhibits exfiltration, water will leak out of the sewer test section and the controller will pump water from the reservoir to replace it. If there is no exfiltration, no water will leak out of the sewer test section and, therefore, the controller will not pump any water to the sewer test section.

9) The Exfiltrometer is calibrated again above ground after completion of the test.

The accuracy of the Exfiltrometer is limited primarily by the accuracy of the sewer water-depth sensor. The sensor is designed to measure a maximum depth of 1 meter and has a net accuracy of 0.1% of full scale. The 0.1% accuracy figure represents the maximum sum of the most significant DC-sensor errors: non-linearity, non-repeatability, and hysteresis. Zero-measurand-output error, the output from the sensor when no pressure is applied, was nulled before each test. The temperature of the water in the sewer test section was assumed to be constant. Temperature-drift errors should be insignificant.
There is one meter between the inflatable plugs in the sewer test section. Since the majority of the sewer defects tested was in 8-inch-diameter (8 inches = 0.2038 m) pipes, the inaccuracy in the exfiltration measurement can be estimated. The tolerance of the volume in the sewer test section is estimated when there is the greatest potential for error—when the sewer test section is half full. The tolerance is given by: (full scale of sensor)(net accuracy at full scale)(length of sewer test section)(width of sewer test section) = (1 m)(0.1%)(1 m)(0.2038 m) = 0.2 L. Therefore, for any exfiltration test, the volume tolerance of the sewer test section is 0.2 L.

If, over the course of a 1-hour exfiltration test, there is no recorded exfiltration, the measured exfiltration rate error is (± 0.2 L)/(1 hr.) = ± 0.2 L/hr. The longer the exfiltration test, the less significant this measurement error becomes.

Soil samples were taken adjacent to each sewer defect tested for exfiltration. The soils were analyzed for the presence of wastewater tracers in an attempt to validate exfiltration results. If wastewater leaked through a sewer defect, evidence of its presence should be found in the surrounding soil. Bacterial tracers analyzed were \textit{E. coli} and total coliform. Chemical tracers include: chloride, nitrate, sulfate, and caffeine. Soil moisture content was also quantified. Parasto Azami and Sara Huber, members of the Exfiltration Team, performed the chemical analyses.

Soil cores were taken 9-12 inches from the centerline of the sewer pipes and down to 20 feet below the surface. Drilling and sampling of soils were performed using a Direct-Push rig. Soil cores were cut into 1-foot segments, numbered, and transferred to the laboratory for analyses.

A septic tank site was selected to test the adequacy of the soil sampling and chemical testing program at a location where wastewater is known to flow. Septic systems are designed to deliver wastewater to the underlying soil, so evidence of the presence of wastewater should be found there. The site consists of a system that serves a city maintenance yard and an adjacent single family home. Sewage flowing into the septic system first encounters a septic tank, where the majority of solids are removed. From the septic tank, the treated wastewater flows into a distribution box. The distribution box delivers the wastewater to four leach pits. Each of the leach pits is 36 inches in diameter and approximately 21 feet deep.

The collected soil samples were analyzed for the presence of chemical wastewater tracers: chloride, nitrate, sulfate, and caffeine. Caffeine proved to be the most reliable wastewater tracer.

The minimum quantitative detection limit at present is about 0.25 µg/per sample (either 1 liter of wastewater or 50 grams of wet soil), but lower values can be determined semi-quantitatively. For example, the results from the sample C4-24 collected at location C4 and 24 feet below the surface are shown in Figure 2-4 is estimated to be approximately 0.05 µg in the 50 gram wet soil. Work is continuing on improving the detection limit and a new HPLC/MS-MS system with enhanced sensitivity is being installed.
Fecal coliforms are indicators of fecal pollution caused by warm-blooded animals, including humans. They have been used as wastewater indicators in water studies (Paul et al., 1995). However, a potential limitation with using fecal coliforms as a tracer may be the lack of transport in soils that some research indicates (Environmental Protection Agency /625/R, 2002). Based on the referenced EPA report, coliform concentration below a septic tank drops to zero detected after 0.6 m transport in the soil.

The following test protocol was used to test for bacteriological traces of sewage in soil. Approximately 10 grams of soil are weighed and transferred to a sterilized 150 mL beaker. 50 mL of a sterile, phosphate-buffered solution (PBS with NaCl (8.0 g/l), KCl (0.2 g/l), Na2PO4 (1.15 g/l), and KH2PO4 (0.2 g/l) is added to the beaker and the beaker is placed on a stirring table at 140 r.p.m. for 30 minutes. The phosphate-buffered solution is utilized to liberate bacteria that adsorb to negatively charged soil particles.

After the beakers have been on the stirring table for 30 minutes, they are removed and the suspended soil particles are allowed to settle. The coliforms in the supernatant are then enumerated by USEPA Standard Method 10029-Bacteriological Test for Drinking Water.

Escherichia coli (E. coli) is the species of primary interest for this study because it is present in abundant numbers in untreated sewage. Once the bacteria have been enumerated, their concentration, per unit soil, is determined. For example, if 18 E. coli bacteria were counted on a filter that had 5 mL of soil/buffered solution passed through it and the mass of the soil in the soil/buffered solution is 3.463 grams, the E. coli concentration would be:
Results and Discussion

Seven defects, representing different sewer types, defects, and soil conditions were selected for the investigation. The results are presented in a summary form in Table 1. The amount of exfiltration can be determined within +/- 0.2 L per test. With a three hour test interval, this corresponds to 0.067 L/hr or 160 gal per year (assuming a uniform rate).

\[
\frac{18 \text{ E. coli bacteria}}{(3.463 \text{ gm soil}) \left( \frac{5 \text{ mL solution used}}{50 \text{ mL of total solution in beaker}} \right)} = 52 \text{ E. coli/gm soil}
\]

<table>
<thead>
<tr>
<th>Site</th>
<th>NASSCO Sewer Defect Code</th>
<th>Soil Type</th>
<th>Hydraulic Conductivity (cm/s)</th>
<th>Measured Exfiltration Rate (short term) (L/hr)</th>
<th>Equivalent Annual Exfiltration Rate (gal/yr)</th>
<th>Caffeine</th>
<th>E. Coli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Sites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Septic Tank</td>
<td>n/a</td>
<td>Sand</td>
<td>1.0 E-2</td>
<td>~25</td>
<td>~56,000</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>1</td>
<td>BSV</td>
<td>Clay</td>
<td>1.0 E-7</td>
<td>4.2 ± 0.1</td>
<td>9,700</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

2 | FC | Clayey Sand | 3.4 E-4 | ND | ND | < 0.7 | ND | < 1,600 | No | No |
| 3 | JO | Clayey Silt | 1.0 E-5 | ND | ND | < 0.1 | ND | < 230 | No | No |
| 4A | CL | Clay | 1.2 E-5 | 0.37 ± 0.2 | 860 | No | No |
| 4B | FC | Clay | 1.2 E-5 | -26 ± 0.2 | -60,000 | Infiltration | |
| 5 | CL | Clayey Sand | 1.0 E-3 | 0.26 ± 0.2 | 600 | Yes | No |
| 6 | CL | Clayey Sand | 1.0 E-3 | 0.92 ± 0.6 | 2,100 | Yes | Yes |
| 7 | JO | Silty Clay | 1.0 E-7 | ND | ND | < 0.08 | ND | < 190 | No | No |

* Assumes sewer is 1/2 full for entire year and the exfiltration rate is constant
* Not representative of a typical sewer defect. Defect has never been exposed to wastewater
* Value at a soil depth above the sewer defect. Sample at defect disturbed
* No exfiltration detected. Minimum detectable flow rate shown (depends on length of test)
* Estimated from 20 persons @ 20gal/d to three leach pits (one observed to be dry)
* Typical value from Appendix 9
* Sites 4A & B located between the same two manholes, but Site 4A was tested before the rainy season
The measured rates range from an infiltration rate of 26 L/hr (60,000 gal/yr) to an exfiltration rate of 18.8 L/hr (44,000 gal/yr) with three sites showing no exfiltration despite visual observation of defects. The test results suggest that the rate of exfiltration depends, as expected, on the type and size of the defect, and also, on the soil type outside each defect. The results of testing for *E. coli* and the major anions in the soil outside the defect did not show clear indications of an exfiltration effect. However, caffeine was detected at two of the three sites where exfiltration was quantified.

The exfiltration rates summarized in Table 1 are probably greater than the actual rates occurring at the sites because they are measured at a water level corresponding to the sewers flowing \( \frac{1}{2} \) full. Water levels can be expected to vary throughout the day, but most of the time sewers tested were observed flowing less than half full, and water level marks observed on the inside of the tested sewers showed the maximum water levels mostly to be significantly below \( \frac{1}{2} \) full.

Because of the time required to test individual defects (~ 3 to 5 hrs), and the number of factors that appear to affect exfiltration rates, a statistical approach is needed to estimate the overall exfiltration within a service area. The averages from these tests, used in combination with databases of defects (obtained from CCTV surveys) and knowledge of soil type and soil moisture content, can then provide a reasonable estimate of the total exfiltration in the service area.

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Special thanks go to Matthew Chuang of Ninyo & Moore, Alyssa Beach of Brown & Caldwell, and Luke Lee, an undergraduate research assistant at UC-Irvine. Matthew arranged and conducted all of the geotechnical field work, Alyssa assisted with most of the sewer tests in the field, and Luke helped with the hydraulic-conductivity testing. Without their assistance, this study would not have been possible.

This study’s success also has much to do with a key member of the Exfiltration Team, Parasto Azami. She analyzed the soil samples for the chemical sewage tracers and a summary of her caffeine findings have been presented in this report, along with the exfiltration results, to provide a more complete picture of the scope of this study.

REFERENCES:


