Case Study

Information Content of Wastewater Flowmeter Data before and during a Surcharge

William C. Klingensmith III[1] and David C. Mays, Ph.D., P.E., M.ASCE[2]

Abstract: When local sanitary sewers discharge to regional treatment systems, flow monitoring is performed for billing purposes, but the information content of these flow data is often overlooked. Wastewater flow data provide information to: (1) quantify rainfall-derived infiltration and inflow, (2) detect flow spikes that could indicate improperly connected sump pumps, and (3) observe long-term increases in peak flow that threaten a surcharge (i.e., when the sewer fills completely). These points are illustrated through a case study from the Mansfield Heights Water & Sanitation District, Arapahoe Country, Colorado using simple methods including novel refinements. It is shown how prophylactic analysis of wastewater flow data might have predicted a surcharge that resulted in public exposure to waterborne pathogens and extensive property damage. Anecdotal estimates from the Denver, Colorado metropolitan region suggest that approximately 80% of sanitation perform flow monitoring, but essentially none evaluates these data routinely. Considering the value of flowmeter data, it is recommended that such data should be analyzed at least annually. **DOI: 10.1061/(ASCE)EE.1943-7870.0001415.**

Introduction

The United States alone has approximately 1,000,000 km (600,000 mi) of sanitary sewers that annually suffer tens of thousands of overflows (Shelton et al. 2011). These overflows threaten both public health, through exposure to microbial pathogens, and environmental quality, through the extreme biochemical oxygen demand of raw sewage. Sanitary sewer overflows often result from rainfall-derived infiltration and inflow (RDII), which increases linearly with rainfall volume (Zhang 2007), so accordingly the consequences of sanitary sewer overflows are expected to worsen with the increasing frequency of extreme precipitation driven by climate change (Nasrin et al. 2017). A concern is basement flooding by raw sewage, which occurs when sanitary sewers surcharge (i.e., when sewers fill completely causing flow as pressurized conduits rather than open channels), which can drive sewage backward through residential service lines (Sandink 2016).

To investigate the source of RDII in residential neighborhoods, Pawlowski et al. (2014) performed a field test in which they injected dyed water into suspected residential conduits for RDII including service laterals, downspouts, cleanouts, foundation drains, sump pumps, and yard drains. They found that service laterals and stormwater downspouts accounted for a significant fraction of RDII, with 59% of homes tested generating RDII from service laterals (especially those built before 1950), and 28% of homes tested generating RDII from stormwater downspouts (especially in-ground downspouts and those built before 1940). However, their study placed less emphasis on other conduits such as sump pumps.

[1]Board Member, Mansfield Heights Water and Sanitation District, 7995 East Prentice Ave., Greenwood Village, CO 80111. Email: bill.klingensmith@mac.com

[2]Associate Professor, Dept. of Civil Engineering, Univ. of Colorado Denver, Campus Box 113, PO Box 173364, Denver, CO 80217-3364 (corresponding author). Email: david.mays@ucdenver.edu

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The standard method to determine RDII (e.g., Pawlowski et al. 2014) assumes that wastewater flow is the sum of sanitary flow and RDII, such that RDII can be determined by subtracting the sanitary flow from the wastewater flow. The sanitary flow is assumed equal to the dry weather flow in the absence of rain. This standard method can be implemented with the Sanitary Sewer Overflow Analysis and Planning Toolbox (SSOAP) provided by the USEPA (Vallabhaneni et al. 2007; Lai 2008; Vallabhaneni 2012). However, Zhang of the University of North Carolina (Zhang 2005) notes that estimating RDII is notoriously difficult for several reasons, which prompted the development of statistical autoregression techniques to calculate RDII from wastewater flow data (Zhang 2005) or wastewater flow data coupled with rainfall data (Zhang 2007). More recently, Zhang of Tsinghua University and colleagues (Zhang et al. 2017) used a statistical partitioning method, specifically the self-organizing map, to estimate RDII and suggested that overflows could be prevented by carefully using the storage capacity of sewage pumping stations and wastewater treatment plants (Zhang et al. 2017). An alternative approach to estimate RDII uses concentrations of chemical markers for sewage such as total nitrogen (Shelton et al. 2011). Each of these techniques has advantages over the standard method, but each comes with its own shortcomings: autoregression techniques generate models with hundreds of parameters requiring thousands of data for calibration (Zhang 2005, 2007); self-organizing maps require specialty training (Zhang et al. 2017); and sewage markers require measurements of concentration over time. These limitations underscore Zhang's (2007) observation that measuring RDII is not trivial.

To address these shortcomings, this study presents simplified methods to estimate RDII that can be easily implemented by even small sanitation districts. It is hoped that the availability of simplified methods will increase the frequency and accuracy with which wastewater flow data are evaluated. To demonstrate the value of more frequent evaluation, a case study is presented with 11 years of wastewater flow data from the Mansfield Heights Water & Sanitation District (Mansfield), Arapahoe Country, Colorado. This case study illustrates how simple evaluation of wastewater flow data can improve the operation of a sanitation system by (1) measuring the amount of rainwater in the system,

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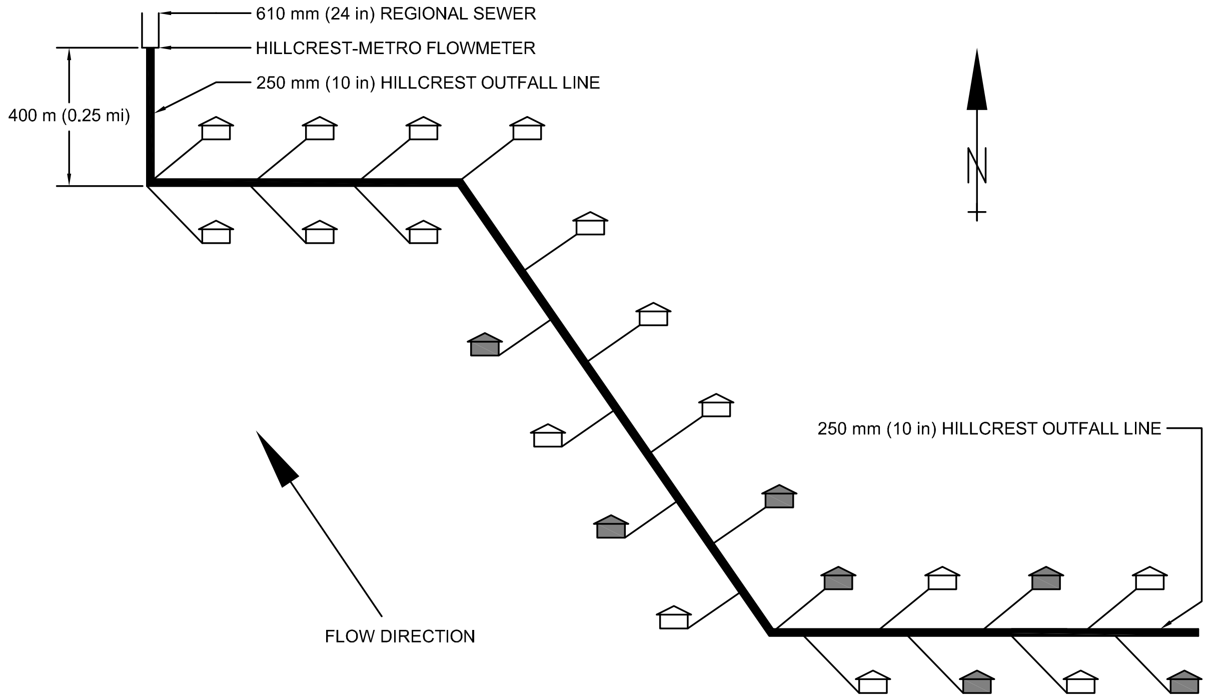

Fig. 1. Schematic diagram of the Hillcrest Outfall Line. The relative locations of the seven flooded houses on June 12, 2015, are shown in gray. Not all houses or connector lines are shown, and the drawing is not to scale.

(2) identifying significant inflow from the presence of sudden spikes in flowmeter rates, and (3) detecting an increase in the risk of a surcharge from a trend of increasing magnitudes of spikes in wastewater flow.

Background

The Mansfield Heights Water & Sanitation District of Cherry Hills Village, Colorado provides wastewater collection for 162 single family homes within the Denver metropolitan area. Residential structures in metropolitan Denver often have basements whose floors are generally constructed at a higher elevation than the sanitary or storm sewer. Mansfield is part of a five-district group that shares a single outfall line known as the Hillcrest Outfall Line (Fig. 1). Together the five districts contain 757 homes. The number of homes has shown little change for at least 11 years and it was assumed that there was no significant variation in the amount of sanitary flow generated per day during the years under study.

The Hillcrest Outfall Line was constructed in the late 1950s and extends for 3.6 km (2.25 mi) from its origin to the point it connects to a 610 mm (24 in.) line that conveys wastewater to the Metro Wastewater Reclamation District (Metro), which provides regional wastewater collection and treatment for the Denver metropolitan area. The five-district group draining to the Hillcrest Outfall Line uses 100 mm (4 in.) service lines, 200 mm (8 in.) connector lines, and the 250 mm (10 in.) Hillcrest Outfall Line. As shown on Fig. 1, connecting lines and some residential service lines join the outfall line along its first 3.2 km (2 mi). The maximum capacity of the outfall line is 57 L/s (1.3 million gal./day or mgd). A flowmeter is located at the junction of the Hillcrest Outfall Line and the Metro conveyance line, which is 400 m (0.25 mi) downstream from the last residential connection. The flowmeter has a temporal resolution of 15 min. Rainfall data are not available in or near the basin served by the Hillcrest Outfall Line.

After several days of greater-than-usual rain, a heavy rainstorm resulted in a surcharge of the Hillcrest Outfall Line on June 12, 2015, that lasted for approximately 5 h. Toward the end of the surcharge, the manholes along the outfall line were inspected revealing surcharge conditions reaching as high as 300 mm (1 ft) below the top of the manholes. There was no evidence of a mechanical obstruction within the sewer system.

Sewage backed up into seven homes, all of which connected directly to the outfall line (Fig. 1). The flooding depth varied from 25 to 910 mm (1–36 in.) in the seven homes depending primarily on the elevation of the basement floor. The estimated total damage was approximately $400,000. In the case of the home with 910 mm (3 ft) of flooding, the fire department shut off the gas and electricity, and the residents were required to evacuate for 3 days.

Methods

Flowmeter Data

Upon request from Mansfield, Metro provided plots of wastewater flow data versus time at the Hillcrest–Metro meter, which were digitized using the shareware utility DataThief III (Tummers 2006). These data included measurements every 15 min (i.e., 15-min data) for the typical low-flow month of January 2015 (Fig. 2) and for the period of the surcharge from June 9, 2015, through June 23, 2015 (Fig. 3). To place these measurements in context, the data also included the 8-h data from January 1, 2015, through June 18, 2015 (Fig. 4), and the 24-h data for the 11 years from January 1, 2005, through December 31, 2015 (Fig. 5). In addition, Metro provided daily high, average, and low flow data from January 1, 2010, through December 31, 2015, in numeric form. Daily highs, averages, and lows were confirmed by comparison to the 15-min data from January 2015.

J. Environ. Eng., 2018, 144(9): 05018004

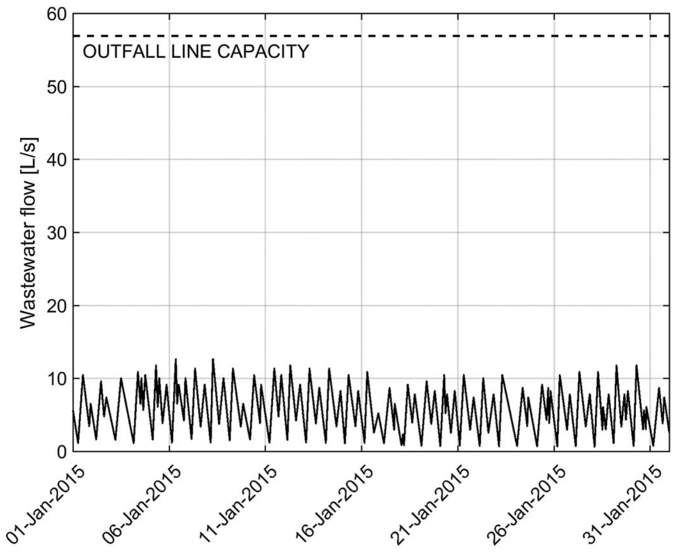

Fig. 2. Wastewater measured at the Hillcrest–Metro meter at the end of the Hillcrest Outfall Line during the dry month of January 2015. The vertical scale has been chosen to match the subsequent figures.

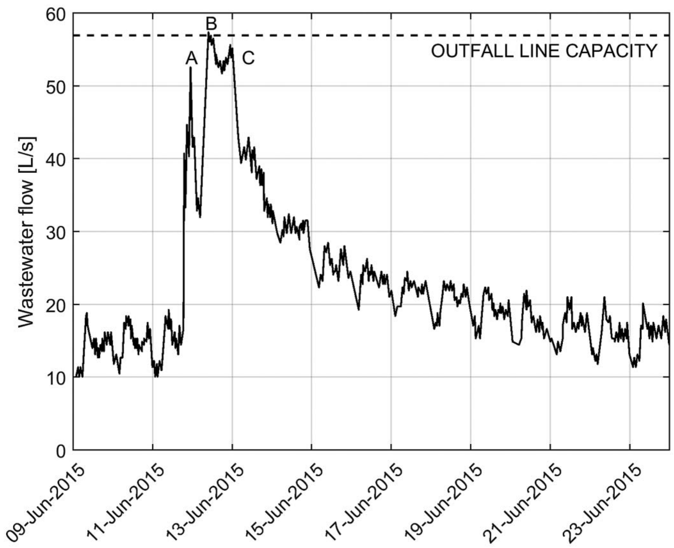

Fig. 3. Wastewater flow from June 2015, where A indicates the Thursday evening storm of June 11, 2015; B indicates the Friday morning storm of June 12, 2015; and C indicates the Friday evening storm of June 12, 2015. A surcharge during heavy rainfall occurred at B. The characteristic daily flow pattern of wastewater can be identified.

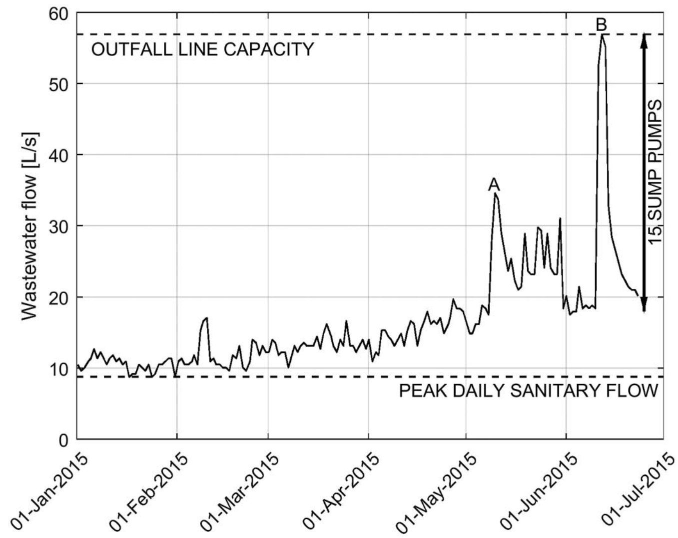

Fig. 4. Wastewater flow from January to June 2015, where A indicates the storm of May 10, 2015; and B indicates the storm of June 12, 2015.

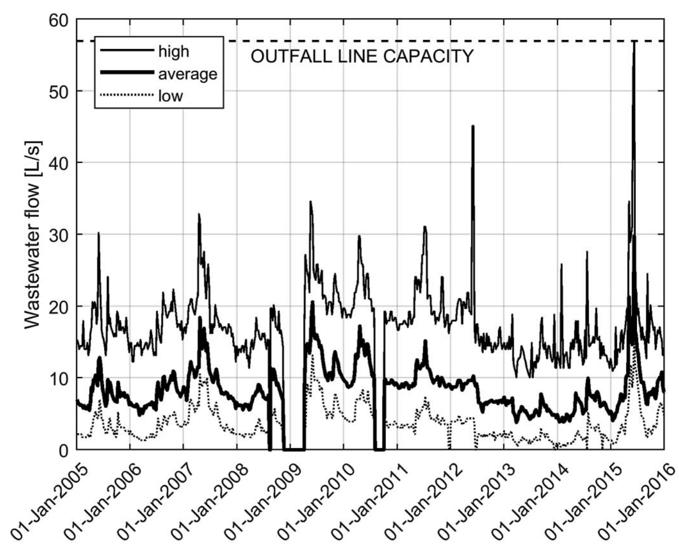

Fig. 5. Daily high, average, and low wastewater flow from 2005 to 2015. Zeros indicate periods during which flow data are unavailable.

Analysis

The wastewater flow data were analyzed to determine the percent RDII during the 6 years of 2010 through 2015 using four methods (wastewater derived from lawn irrigation was treated as RDII). All methods assumed that wastewater flow is the sum of sanitary flow and RDII, and that total daily sanitary flow throughout the year is relatively constant. In the first three methods RDII was estimated by assuming that a lowest flow time period represented 100% sanitary flow, recognizing that this approach would probably overestimate sanitary flow and therefore underestimate RDII [Fig. 6(a)]. Each of these three methods used a different dry or low flow period: Method 1 uses the month with the lowest average monthly flow in each of the 6 years, Method 2 uses the day with the lowest average daily flow in each of the 6 years, and Method 3 uses the day with the lowest average daily flow in all 6 years.

In Method 4, RDII is estimated by assuming that the low daily flow, typically in the middle of the night, is RDII rather than sanitary flow [Fig. 6(b)]. Then the lowest low daily flow for all 6 years was subtracted from the lowest average daily flow in all 6 years, recognizing that this approach would probably underestimate sanitary flow and therefore overestimate RDII. This fourth method represents a modification of the third method and the results of third and fourth methods together define the possible range of the true value of sanitary flow and therefore the true percent of wastewater flow that represents RDII.

In addition, the constancy of Method 4 (the difference between the average daily flow and low daily flow) as a function of increasing average wastewater flow, and of the difference between the high

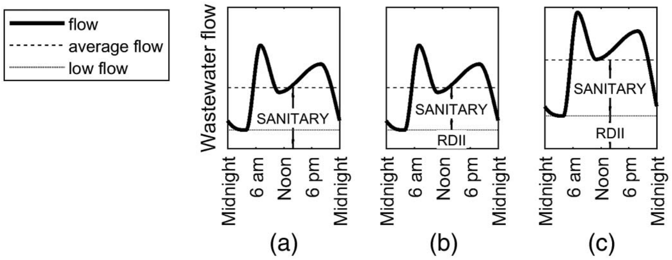

Fig. 6. Schematic showing the diurnal variation of wastewater flow, daily average flow, and daily low flow: (a) Methods 1–3; (b) Method 4 with low RDII; and (c) Method 4 with increased RDII.

daily and low daily flow as a function of increasing average wastewater flow were evaluated [Fig. 6(c)]. If either of these measurements is constant as average daily flow increases, the measurement could be useful in calculating the percent RDII in wastewater when no dry period is available. For this evaluation the average daily flow points were a representative subset of all data points (Table 1). Specifically, starting with the lowest average flow in all 6 years a series of average flow amounts was created by increasing the first and lowest average flow value by one unit, then two units, etc. For the final value a small range of values around the otherwise single value was used to ensure a representative sampling. Thus, there is oversampling for the lower values, but relatively constant sampling from a percentage increase point of view.

Evidence of inflow, e.g., improperly connected sump pumps discharging directly to the sanitary sewer, was determined by evaluating the graphs for sharp spikes in flow. It was assumed that infiltration, even from an intense rainstorm, would not cause a large abrupt increase and decrease in outfall line flow because the stormwater pulse would be attenuated as it moved through the soils overlying the sanitary sewer. Temporal trends in wastewater flow, such as trends in the fraction of RDII in the outfall line, or in the frequency and magnitude of flow spikes consistent with inflow, were also evaluated by analysis of the relevant time series.

Sanitation District Practices at Time of Surcharge

A limited survey was conducted to collect anecdotal data relative to the percentage of sanitation districts in the Denver metropolitan region that (1) have a flowmeter at the end of their outfall line; (2) that routinely analyze the data to evaluate the above parameters, i.e., fraction of RDII, evidence of sudden inflow, and temporal trends; and (3) that present the results to their board of directors. Answers to these questions were obtained from the Mansfield administrator, who manages approximately 50 sanitation districts in the Denver metropolitan region (S. Blair, Community Resource Services of Colorado, LLC, personal communication, 2017), and from the Mansfield civil engineer who in conjunction with a colleague consults for 13 water and sanitation districts in the Denver metropolitan region (L. Schwien, Kennedy/Jenks Consultants, personal communication, 2017).

Results

Quality of Flowmeter Data

The sharp definition and typical repetitive shape of the daily sanitation flow as recorded by the flowmeter in the relatively dry month of January 2015 suggests that the flowmeter is relatively accurate and stable with good temporal resolution (Fig. 2). Specifically, the curve demonstrates the expected pattern of wastewater flow during a 24-h period with a low around 4:00 a.m. and a high around 7:00 a.m. There is also a secondary low point at about 11:00 a.m. and a secondary high point at about 8:00 p.m. This characteristic pattern primarily reflects the synchronization effect of work and school requirements on domestic water usage (Zhang 2005). In addition, a perceptible mild loss of definition during the weekend was noticeable, and is attributed to decreased synchronization from much less work and school.

Percent Rainwater in Sanitation System

Table 2 shows the analysis of percent RDII in the sanitation system by each of the four methods: (1) the lowest average monthly flow in each of the 6 years, (2) the lowest average daily flow in each of the 6 years, (3) the lowest average daily flow in all 6 years, and (4) the lowest average daily flow minus the lowest low daily flow of all 6 years (Fig. 7). Note that the days of minimum average daily flow and minimum low daily flow were different days.

Table 2 and Fig. 7 demonstrate that when the lowest average monthly flow of each year (Method 1) or the lowest average daily flow of each year (Method 2) is used to estimate sanitary flow, a nonsensical result is generated in which the percent RDII tends to decrease as the total wastewater flow increases. Why is this? Increases in annual wastewater flow are assumed to be secondary to effects resulting from increases in annual rainfall. Accordingly, years with high wastewater flow may have no dry month or day, and therefore, the estimate of sanitary flow will be too high and the calculation of percent rainwater in the wastewater will be too low. This result is nonsensical because in general increasing wastewater flow will be a proxy for increasing RDII. Conversely, when the lowest average daily flow of all 6 years (Method 3) or the lowest average daily flow minus the lowest low daily flow for all 6 years (Method 4) is used to estimate sanitary flows, the percent RDII increases as the wastewater flow in the sanitary sewer increases.

In general, use of any constant number for sanitary flow will give an increasing percent RDII versus wastewater flow, i.e., the curve will asymptotically approach 100%. Therefore, an appropriately shaped curve in itself does not indicate that the estimated sanitary flow or the estimated RDII is correct. But the analysis does suggest that in calculating the percent RDII it is preferable to use the best available single estimate of sanitary flow over multiple years providing the sanitary sewer serves a stable residential district. Also of note is that the lowest average daily flow for all 6 years occurred in three of the 6 years including the two driest years, but not in the two wettest years (Table 2).

If we assume that the lowest daily flow (at approximately 4:00 a.m.) is entirely sanitary flow (Method 3), then sanitary flow is the same as the lowest average daily flow or 3.5 L/s (0.08 mgd). Alternatively, if we assume that the lowest daily flow is entirely RDII (Method 4), then sanitary flow would be the difference between the average and lowest daily flows or 3.1 L/s (0.07 mgd). Most likely the lowest daily flow on the days with the lowest average flow includes both sanitary flow and RDII. Thus, the actual amount of sanitary flow is constrained between the narrow range of 3.1 to 3.5 L/s (0.07–0.08 mgd). When a low average flow day in absolute terms is available, it makes little difference from an operational point of view whether sanitary flow is estimated at 3.1 L/s (0.07 mgd), 3.5 L/s (0.08 mgd), or somewhere in between.

Fig. 8 shows the relationship of average (total) daily flow minus low daily flow (Method 4) and high daily flow minus low daily flow to average daily flow. Both the average minus low flow difference and, to a greater extent, the high minus low flow difference increase with increasing average daily flow. The slopes of the two

Table 1. Daily average–low flow and high–low flow versus average flow

	2010	2011	2012	2013	2014	2015	
	Annual flow (m^3/year)						
Flow category	345,000	313,000	251,000	174,000	189,000	301,000	Average
N for flow = 300 m^3/day	—	—	—	4	10	1	—
Average–low flow	—	—	—	230	230	220	227
High–low flow	—	—	—	720	760	640	707
N for flow = 340 m^3/day	—	—	—	8	29	6	—
Average–low flow	—	—	—	270	270	270	270
High–low flow	—	—	—	680	760	790	743
N for flow = 420 m^3/day	—	—	7	62	36	15	—
Average–low flow	—	—	270	300	300	300	293
High–low flow	—	—	870	830	910	790	850
N for flow = 530 m^3/day	—	—	37	32	36	48	—
Average–low flow	—	—	340	340	340	340	340
High–low flow	—	—	950	910	910	870	910
N for flow = 680 m^3/day	—	—	3	5	14	25	—
Average–low flow	—	—	420	380	380	380	390
High–low flow	—	—	1,060	980	910	950	975
N for flow = 870 m^3/day	26	35	—	—	1	20	—
Average–low flow	450	450	—	—	380	300	395
High–low flow	1,170	1,170	—	—	950	790	1,020
N for flow = 1,100 m^3/day	21	7	—	—	—	1	—
Average–low flow	490	610	—	—	—	380	493
High–low flow	1,290	1,440	—	—	—	870	1,200
N for flow = 1,360 m^3/day	14	7	—	—	—	6	—
Average–low flow	570	640	—	—	—	300	503
High–low flow	1,480	1,970	—	—	—	790	1,410
N for flow = 1,590–1,740 m^3/day	—	—	—	—	—	8	—
Average–low flow	—	—	—	—	—	570	570
High–low flow	—	—	—	—	—	1,480	1,480

Note: Average flow is batched into nine categories ranging from 300 to 1,590–1,740 m^3/day as shown on Fig. 8. All units are m^3/day except where noted.

Table 2. Evaluation of infiltration and inflow in the Hillcrest Outfall Line line from 2010 to 2015

Parameter	2010	2011	2012	2013	2014	2015	Average
Total wastewater flow (m^3/year)	345,000	313,000	251,000	175,000	189,000	301,000	262,000
Low monthly flow (m^3/month)	21,000	24,000	16,000	12,000	10,000	13,000	—
Low flow month	February	January	August	July	February	January	—
Low daily flow (m^3/day)	760	720	420	300	300	300	—
Number of low flow days	42	21	7	4	10	1	—
Range of low flow days	January 27–December 21	January 26–May 10	August 8–14	April 1–5	January 18–April 1	January 17	—
Absolute low flow (m^3/day)	260	190	150	40	40	80	—
Number of absolute low days	7	7	21	1	12	17	—
Range of absolute low days	November 3–9	May 4–10	July 4–December 22	April 7	January 9–March 4	January 18–February 8	—
Percent RDII							
Relative to driest month each year (%)	21	10	25	19	31	49	26
Relative to driest day each year (%)	20	16	39	39	42	64	36
Relative to driest day all years (%)	68	65	56	37	42	64	55
As above less absolute low (%)	72	69	62	45	49	68	61

curves were estimated by linear regression although the curves may be second degree equations. The slopes indicate that the average minus low flow measurement increases about 25% as fast as the average flow increases, and that the high minus low flow measurement increases about 50% as fast as the average flow increases. The reason for these increases as average flow increases is not apparent but will result in some increasing overestimation of sanitary flow, and therefore decreasing estimation of RDII as average flow increases.

In the Hillcrest Outfall Line the lowest average daily wastewater flow of 3.5 L/s (0.08 mgd) is 6.2% of the 57 L/s (1.3 mgd) capacity of the outfall line. However, the risk of a surcharge and home damage varies with the high daily flow. The lowest high daily wastewater flow is 8.8 L/s (0.20 mgd) or 15.4% of the maximum

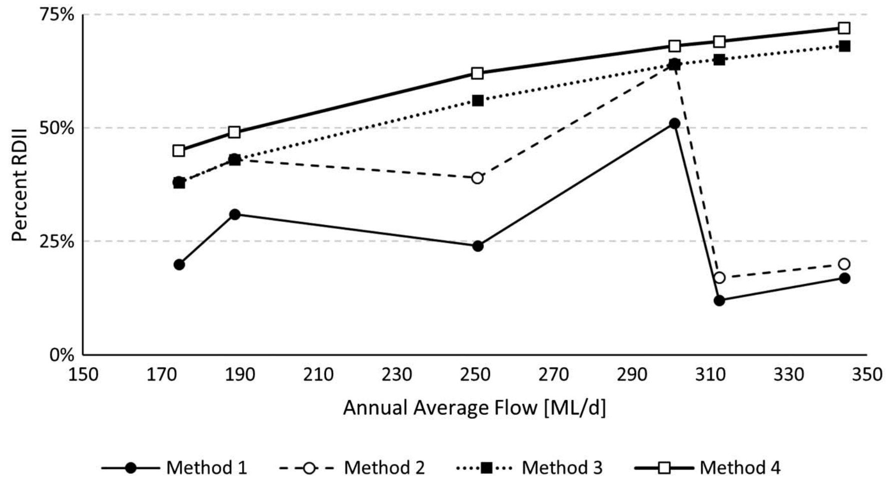

Fig. 7. Estimated percent RDII in the Hillcrest Outfall Line using four different methods for estimating sanitary flow across a dataset of 6 years.

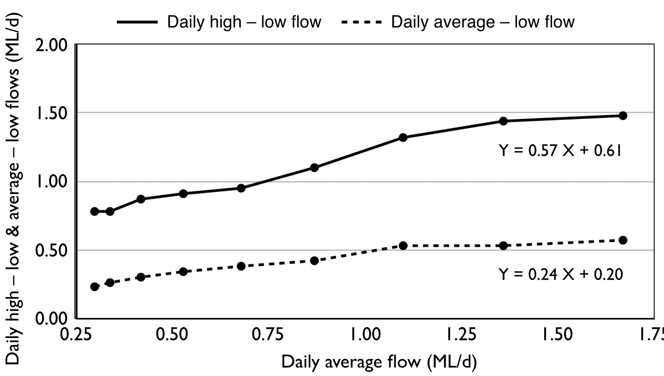

Fig. 8. Average daily flow minus low daily flow, and high daily flow minus low daily flow as a function of increasing daily average flow.

capacity of the outfall line, which represents a safety margin of 6.5-fold under dry conditions.

Presence of Inflow and Trends

Figs. 3–5 all show sharp rises in sanitation system flow over a period of several hours that are more likely inflow, e.g., improperly connected sump pumps that discharge into the sanitary sewer, than an unusually high rate of infiltration. Fig. 4 shows flows significantly above the peak sanitary flow, with two spikes corresponding to unusually severe rainstorms on May 10, 2015, and June 12, 2015. As indicated by the vertical black line on the right of Fig. 4, the surcharge on June 12, 2015, could have been caused by activation of approximately 15 improperly connected sump pumps with each sump pump discharging approximately 2.63 L/s (0.06 mgd). Fig. 5 shows high, average, and low daily flow curves over 11 years from 2005 to 2015. During this time period the high, average, and low flows remained relatively constant without an overall trend. However, it can be seen that every 2–3 years there is a new record high (peak) flow in the form of a sharp increase and fall consistent with improperly connected sump pumps. Importantly, if these multiyear curves had been evaluated annually, the trend of an increasing magnitude of inflow consistent with activation of improperly connected sump pumps might have been detected and acted on prior to June 12, 2015, and the surcharge and home damage might have been prevented.

Sanitation District Practices at Time of Surcharge

At the time of the June 2015 surcharge it was estimated that approximately 80% of Denver metropolitan region sanitation districts had flowmeters at the connection point of their outfall line to their regional wastewater collection and treatment system. Despite the prevalence of flowmeters, no waste treatment facility in the Denver metropolitan region is known to have provided data equivalent to that shown in Figs. 2–5 so that sanitation districts could have evaluated their sanitation systems for the parameters described previously: (1) percent RDII, (2) presence of spikes in daily flow suggestive of inflow from improperly connected sump pumps, and (3) any trend of increasing magnitude of flow spikes over time indicating an increasing risk of surcharge and consequent risk to public health and property damage.

Discussion

High-quality, reliable public utilities are a hallmark of advanced modern societies. The public depends on the board of directors and their consulting engineers to ensure the proper function of the utilities that people rely on every day. Failure of any public utility is an unpleasant experience for homeowners, but flooding of the lower level of homes with sewage is particularly intrusive and distressing. In addition, raw sewage carries significant public health risks.

This paper has emphasized a potentially overlooked resource for individuals responsible for sanitation districts: the information content of flowmeter data from sanitary sewer outfall lines. The components of flow in a typical sanitary sewer—sanitary flows and RDII—have fairly characteristic patterns. Sanitary flow generation varies markedly during the day but varies little from day to day throughout the year. Conversely, RDII varies relatively little during the day, barring the onset of a heavy rainstorm, but does vary significantly from season to season with changes in precipitation.

In the case of inflow, a potentially overlooked cause is improperly connected sump pumps that discharge directly into the sanitary sewer. Sump pumps discharge no fluid when inactive, but discharge very large amounts of fluid when activated, and go from one state to the other in a matter of seconds.

Following the surcharge event of June 12, 2015, the Mansfield board of directors mandated an in-home inspection for improperly connected sump pumps, which are prohibited by Mansfield's connector contract with Metro, and a video inspection of the service line for all homes in the Mansfield district. Eight improperly connected sump pumps were identified; follow-up inspections confirmed that all eight sump pumps had been rerouted to daylight. Thus, approximately 5% of the 162 homes had sump pumps that discharged into the sanitation system. Video inspections of service lines revealed no evidence of other sources of inflow. Mansfield has met with the other four districts that discharge into the Hillcrest Outfall Line and all have concurred with the assessment of the data, but only one of those four other districts has completed their own inspection and correction programs for improperly connected sump pumps. Inspection of this second district identified an additional 12 improperly connected sump pumps. If the prevalence of improperly connected sump pumps throughout the other four sanitation districts is similar to Mansfield (i.e., 5%) there would be approximately 37 improperly connected sump pumps among the 757 total homes. If at least 40% of these 37 sump pumps were activated during the surcharge of June 2015, that would account for the estimated 15 sump pumps necessary to have caused the surcharge. These estimates appear to be plausible, considering that in-home inspections in two of the five districts have identified 20 improperly connected sump pumps. There appears to be no reason to expect a significantly different rate of improperly connected sump pumps in the three districts that have yet to be inspected.

This study has demonstrated relatively simple methods for determining several important parameters in sanitation system flowmeter data: (1) the percentage of flow attributable to rainwater, (2) the presence of inflow (most likely improperly connected sump pumps), and (3) any trend in the magnitude of flow spikes. This information is critical to the optimal operation of sanitation systems. The percentage of flow attributable to rainwater is an indicator of the integrity of a sanitation system and directly affects the fees a sanitation system pays for sewage treatment. The presence of flow spikes consistent with improperly connected sump pumps is a risk factor for surcharges and home damage, and also increases sewage treatment fees. Additionally, a trend of increasing magnitude of flow spikes warrants prompt action to identify the cause and correct the problem before a surcharge occurs.

The methods used here to calculate the percentage of RDII in wastewater flow have several advantages in comparison to standard methods: being independent of rainfall estimates; measuring sanitary flow directly; using the low daily flow rather than the low monthly flow; using a constant estimate of sanitary flows (in this case the lowest average daily flow over multiple years); incorporating high-temporal resolution lowest daily flow to better define a constrained range of sanitary flow; and not requiring computer software. Conversely, the EPA-standard software SSOAP (Vallabhaneni et al. 2007; Lai 2008; Vallabhaneni 2012) has the disadvantages of being oriented toward integrating rainfall data that are often not available, not including some of the analytical refinements discussed previously, being more complex, and being computer based.

We also evaluated the reliability of Method 4, average daily flow minus low daily flow, as well as high daily flow minus low daily flow as a function of average daily flow to determine if they were potentially useful in perpetually wet climates. Both the average minus low flow difference and to a greater extent the high minus low flow difference increased with increasing average daily flow. The reason for this finding is unknown and the cause deserves further study.

Prior to the June 2015 surcharge, the Mansfield board of directors did not examine the flow data. If the Mansfield board had been aware of the trend of increasing flow spikes over the 10 years prior to the surcharge of June 2015, it might have taken corrective action in the form of home inspections and mandated corrections. However, since the surcharge Mansfield has instituted a practice of analyzing the flowmeter data from their outfall line on an annual basis, or more frequently if needed, through a request to Metro. Ideally, every regional wastewater collection and treatment system would routinely record and distribute these data to connecting sanitation districts on an annual basis.

Conclusion

Relatively simple methods have been presented for estimating percent RDII, detecting flow spikes consistent with improperly connected sump pumps, and identifying any trend of increasing magnitude of flow spikes that may predict a surcharge. Limited anecdotal information suggests that most sanitation districts in the Denver metropolitan region have flowmeters, but few if any analyze the flowmeter data on a routine annual basis. The hope is that this case study will encourage regional wastewater collection and treatment systems with access to flow data to adopt a policy of annually generating and distributing data, in both tabular and graphical formats, that allow their connecting sanitation districts to evaluate these important operational parameters. This study demonstrates how and why the information content of these data should be applied for maximum benefit to public health, safety, and welfare.

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