A COMPARISON OF PULSE TRACER DOSING AND CONTINUOUS TRACER DOSING FOR THE DETERMINATION OF SEWER EXFILTRATION

D Michael Revitt*, J Bryan Ellis and Nikoloas Paterakis
Urban Pollution Research Centre, School of Health and Social Sciences, Middlesex University, Queensway, Enfield, Middlesex, EN3 4SA, UK.
* e-mail: m.revitt@mdx.ac.uk; telephone: + 44 208 411 5308; fax: + 44 208 411 5440

Abstract

Two different experimental techniques involving the in-sewer responses of conservative tracers along designated indicator and reference reaches to determine exfiltration losses are reported. Rhodamine WT was used as the single tracer in a pulse dosing approach in which the indicator and reference peaks need to be well resolved and reproducible in order to provide realistic results. A more consistent technique involves the continuous introduction of two different tracers with the objective of producing simultaneous downstream peak tracer concentrations, which allows both peak and background concentrations to be more accurately determined. Rhodamine WT, Li and Br were used in different combinations and were found to demonstrate conservative behaviours with measured recoveries of 97.7-98.0%, 98.3-101.4% and 108.5-109.1%, respectively. Due to more pronounced analytical problems associated with the determination of Br, the preferred combination of tracers is Rhodamine WT as the indicator and Li as the reference and these are shown to be capable of estimating sewer losses to an accuracy of ±1.0% using the continuous dosing technique.

Introduction

Sewer systems are prone to the development of structural defects which allow wastewater leakage and subsequently contamination of the surrounding soil and eventually the underlying groundwater. The determination of such losses pose a difficult problem for sewage utilities given the requirement for costly preliminary pipe scale testing and groundwater monitoring as a necessary precursor for rehabilitation planning. At the same time, there is a considerable if contentious literature that leaky sewers present a potential diffuse source of contaminants to urban aquifers (Barrett *et al*., 1999; Reynolds and Barrett, 2003; Wolf *et al*., 2004). The EU Standard EN752-2 recognises this problem and demands the structural integrity of urban sewer systems, including their water-tightness. The traditional approaches for determining exfiltration have been based on rather inaccurate methods of flow measurement, pressure testing, analysis of diurnal flow and load variation, water balancing and expensive CCTV inspections (Rutsch *et al*, 2005). As part of the recently completed EU 5th Framework APUSS (Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems) project, two novel tracer methods identified as the QUEST (Quantification of Exfiltration from Sewers with artificial Tracers) and the QUEST-C techniques were developed. The former involves mass balance comparisons over an investigated sewer reach and a leak free reference section following the pulse injection of a single tracer (Rieckermann and Gujer, 2002). The QUEST-C method requires access to similar sewer stretches but because two different tracers are dosed continuously, in-line monitoring equipment possessing a low response time is not essential (Rieckermann, 2005).

The standard tracer for use in the QUEST technique is sodium chloride because of its proven inertness in the presence of sewage. Previous workers have used conductivity probes as the in-sewer detection technique for this tracer (Rieckermann and Gujer, 2002; Guillanelli *et al*, 2003) despite the fact that this mode of detection is not specific to sodium chloride and that high dosing concentrations are required to overcome the natural background salinity of sewage. Alternative ionic tracers, which can be utilised at lower dosing concentrations due to their negligible presence in natural waters and sewage, are lithium (usually as lithium chloride) and bromide (usually as sodium or potassium bromide). However, for these tracers there are currently no direct monitoring probes available, which can tolerate the hostile sewer environment, and therefore they are not appropriate for use in the pulse dosing method but can be utilised in the continuous dosing approach. A tracer, which because of its ease of detection at very low concentrations, can be used for both pulse and continuous dosing techniques is Rhodamine WT (RWT). This fluorescent dye has been widely used as a tracer in both surface waters and groundwaters (Flury and Wai, 2003). The continuous monitoring of Rhodamine WT can be achieved using a dedicated submersible fluorimeter probe but, prior to this research study, the use of such a probe had not been thoroughly tested in a sewer environment where interferences due to high turbidity are to be expected. The behaviour of Rhodamine WT in sewage could also be complicated by the existence of two isomers in the commercially available product. The *para*-isomer has been shown to demonstrate conservative behaviour under laboratory test conditions whereas the *meta*-isomer exhibited efficient sorption to mineral surfaces (Vasudevan *et al*, 2001).

This paper describes a series of field experiments which have been devised to test the behaviour of Rhodamine WT during sewer transport and hence assess its applicability for use as a tracer in the determination of exfiltration. The performance of Rhodamine WT in both pulse dosing and continuous dosing experiments has been investigated and compared to that of Li and Br ion tracers in the latter methodology. The results obtained enable the two approaches to be compared in terms of their feasibility and efficiency for the determination of exfiltration rates and hence provide further evidence of the suitability of tracer studies for this purpose.

Site Details and Tracer Methodologies

Potters Bar is a large commuter suburb lying to the north of Greater London and a section of sewer within the catchment was selected for testing of the tracer exfiltration methodology. The overall length of the combined sewer pipe run used for the test was 660 m with a gradient of 0.00173 m/m. The pipe run consists of a 510 m length of circular 450 mm concrete pipe which passes into a 150 m length of 600 mm steel piping. This last section runs above ground on a sewer ‘bridge’ and could be observed to be watertight and, therefore, represented an ideal reference section against which to measure exfiltration in the up-sewer stretches using different tracer methodologies. The test sewer section is also free from sedimentation which might cause inhibition of tracer recovery due to potential absorption in dead zones.

Access to the sewer for dosing and monitoring purposes was by means of existing manholes. Two up-sewer manholes (identified as C1 and C2) were used for the introduction of the indicator tracer and were separated from the down-sewer monitoring manhole (identified as manhole A) by distances of 660 m and 480 m, respectively. Manhole B, located 150 m up-sewer of manhole A was consistently used for the introduction of the reference tracer. A submersible fluorimeter (Turner Designs SCUFA III) was positioned at manhole A to obtain direct in-sewer readings of the Rhodamine WT concentrations. In addition, this monitoring point also included equipment for depth measurement (pre-calibrated STS Model 8370 pressure transducer) and 30 second time-averaged flow velocity measurement (Ott Nautilus C200 ultrasonic probe) to facilitate the calculation of sewer flow rates.

Results and Discussion

Pulse dosing experiments

The pulse dosing experiments (PulDos) involved the introduction of discrete volumes of tracer at the separate indicator and reference dosing points. A constant ratio between indicator and tracer of 2.5 to 1 was maintained for all pulse dosing experiments. However, two different strategies (identified as 1 and 2) were employed.

Strategy 1 Pulse Dosing Experiments

In this strategy, a single pulse dose of the tracer solution (Rhodamine WT; 20 g/L) was introduced at either manhole C1 or C2 accompanied by two earlier or later pulse doses of the fluorescent dye at manhole B. The timings of these tracer additions were carefully adjusted with the objective of achieving full peak separation at the monitoring point (i.e. manhole A). The dosing arrangements employed for Strategy 1 are shown in Table 1.

Table 1. Dosing arrangements for the Strategy 1 pulse dosing experiments.

Reference code	Upstream indicator dosing point	Indicator dosing volume (20 g/L RWT)	Reference dosing volume (20 g/l RWT)
PulDos 1a	C1	50 mL	20 mL
PulDos 1b	C1	25 mL	10 mL
PulDos 1c	C1	100 mL	40 mL
PulDos 1d	C2	50 mL	20 mL
PulDos 1e	C2	25 mL	10 mL

The results obtained for the Strategy 1 experiments are represented in Figure 1 by the temporal variation in the recorded Rhodamine WT concentrations (readings taken at 1 second intervals) at the monitoring man-hole A following the introduction of tracer pulses at dosing points B and C1. The first two peaks are reference peaks (dosing at B) followed by the indicator peak (dosed at C1) and two more reference peaks. The objective in carrying out this dosing strategy was to achieve peak separation but also to ensure that the reference peaks immediately before and after the indicator peak were as close as possible to ensure that the tracer was exposed to the same sewer flow and sewage quality conditions during its passage through the sewer. This particular situation can be difficult to obtain and in Figure 1 it can be seen that the post-indicator reference peak is too close preventing complete resolution whereas in the case of the pre-indicator peak, there is too much separation.

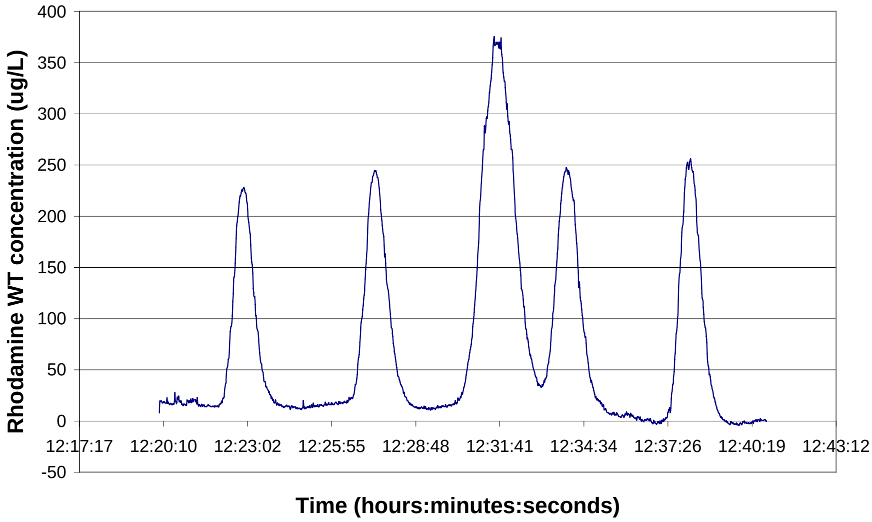

Figure 1. Separation of Rhodamine WT peak concentrations during PulDos 1a experiment.

Good peak separation is essential to enable accurate estimation of the peak areas which are required for the calculation of the amount of tracer passing the monitoring point. The adopted peak fitting process involved separate baseline adjustments for each of the tracer peaks followed by an area estimation. The crude results for each of the five experiments are shown in Table 2 with the ratios representing the indicator: reference peak area values. There is clearly substantial variability around the expected value of 2.5 assuming the absence of any exfiltration in the indicator stretch (C1 to B) of the sewer. This variability is evident within single experimental runs as well as between the different experiments and the range of predicted exfiltration rates (-6.0% to 13.2%; Table 2) clearly question the viability of this measuring approach. Possible errors in the technique include failure to introduce consistent tracer doses and the problems associated with the time lapse between many of the indicator and reference doses. These problems were addressed by carrying out another series of pulse dosing experiments (Strategy 2) which are described below.

Table 2. Estimated peak area ratios for Strategy 1 pulse dosing experiments.

	Peak area ratios				**Average peak area ratio**	**Average equivalent exfiltration**
	Peak 3: Peak 1	Peak 3: Peak 2	Peak 3: Peak 4	Peak 3: Peak 5		
PulDos 1a	2.65	2.33	2.31	2.06	2.34±0.21	6.4%
PulDos 1b	2.99	2.59	2.37	-	2.06±0.26	-6.0%
PulDos 1c	1.86	1.95	2.55	2.32	2.17±0.28	13.2%
PulDos 1d	1.97	2.24	2.93	-	2.38±0.40	4.8%
PulDos 1e	2.05	2.10	2.65	1.98	2.20±0.27	12.0%

3 = indicator peak; 1, 2, 4, and 5 = reference peaks

Strategy 2 Pulse Dosing Experiments

For PulDos 2, a major change in the experimental procedure was that alternate indicator and reference doses were introduced continuously at dosing points C1 and B, respectively over time periods of at least 1 hour. The objective was to obtain a series of situations in which a reference peak could be clearly identified as being associated with an indicator peak. The results of one experimental run are shown in Figure 2 together with the flow rates which were monitored at 30 second intervals within the sewer at man-hole A. Additional care was taken during the dosing procedure to ensure that the exact amount of Rhodamine WT solution added on each occasion was known.

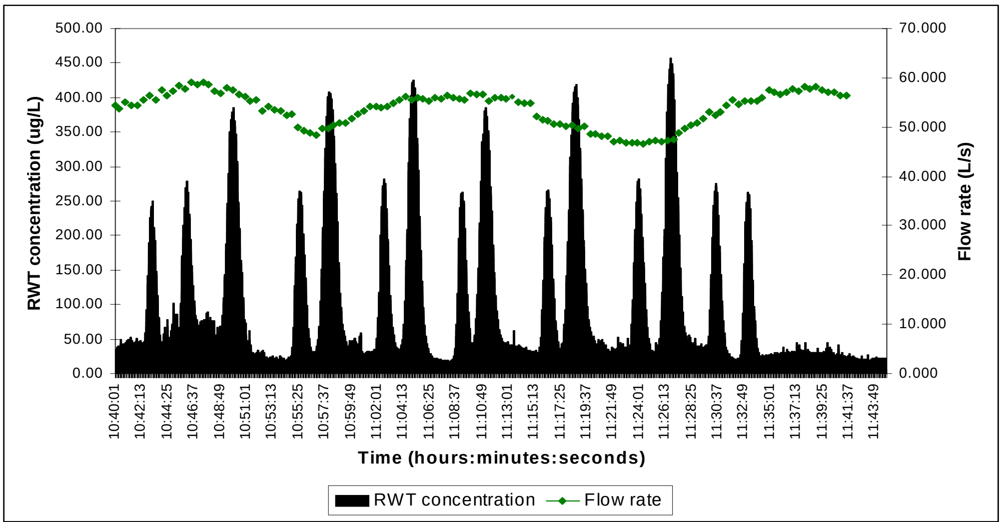

Figure 2. Separation of Rhodamine WT peak concentrations and variation of flow rates during a PulDos 2 experiment.

The smaller reference peaks associated with each indicator peak can easily be identified in Figure 2. Two reference doses were introduced at the beginning and end of the experiment. Applying the same peak fitting approach as described previously, the ratios of indicator to reference peaks were calculated to vary between 2.21 and 2.71. This is a similar range to that derived for the average values for the Strategy 1 pulse dosing experiments and again is not sufficiently reliable to support this technique as a practical method for the determination of exfiltration rates.

It is evident that the observed signal intensities will be influenced by fluctuations in the background turbidity. Every attempt was made to counteract this by calibrating the fluorimeter using sewage samples collected immediately before the exfiltration experiments commenced. One possible error identified in the Strategy 1 experiments was that variations in sewer flow rates could influence the monitored concentrations. Inspection of the trends in Figure 2 show some evidence that tracer concentrations do increase at lower flow rates and vice versa but this is not a consistent trend. To allow for variations in flow, Rhodamine WT loadings were calculated and the temporal trends plotted. The ratios of indicator to reference peak areas based on tracer loadings (2.32 – 2.51) are less extreme than those calculated using concentrations but are still too variable to have full confidence in the reliability of a technique based on pulse dosing. In spite of improvements in the experimental technique and allowances for environmental variables, a major problem with the overall approach is the accuracy with which the peak areas, which represent the pulse dose, can be determined. More sophisticated peak fitting procedures have been developed (Rieckermann *et al*, 2005) and although their use may lead to over-interpretation of the measured data, an estimation of the uncertainty involved can be obtained. The measurement of a pulse dose is made more difficult by the possible occurrence of intermittent tracer interferences which may be magnified during the short time duration of the pulse. A way to overcome this problem is to replace pulse dosing by continuous dosing (over time periods of up to 10 minutes) as this then allows an average signal due to the tracer to be derived and which can then be used to calculate the exfiltration rate.

Continuous dosing experiments

The continuous dosing (ConDos) experiments involve the prolonged introductions of two different tracers at constant rates (using a peristaltic pump set to a nominal delivery rate of 1 L/s) at dosing points C1 and B with subsequent monitoring at the downstream man-hole A. In addition to the continued use of Rhodamine WT, lithium (as lithium chloride) and bromide (as potassium bromide) were also employed and their sewer concentrations determined by collecting timed grab samples and returning these to the laboratory for analysis by flame emission spectrophotometry (Li) and ion chromatography (Br). An important advantage of these multi-tracer experiments over the pulse dosing technique is that they are less susceptible to short term variations in sewage characteristics (eg flow rate) which may influence the tracer signal. The existence of small variations in the measured tracer concentration can be compensated for by calculating an overall average value for the peak tracer concentration. The errors associated with accurately estimating peak areas and relying on this as an accurate measure of pollutant load are thus eliminated in the continuous dosing technique.

Details of the dosing strategies used to test the ConDos technique are provided in Table 3. The ConDos 1 and ConDos 4 experiments were designed to assess the behaviours of the different tracers either along the full length of the monitored sewer (C1 to A) or the reference section (B to A), respectively. The comparison of two experiments involving continuous dosing with Rhodamine WT over the indicator section of the sewer (ConDos 2) and continuous dosing with Li over the reference section of the sewer (ConDos 3) enables an estimation of the exfiltration rate in the upstream indicator stretch of the sewer to be made. However, these were not performed simultaneously and therefore complete overlap of the tracer signals at the downstream monitoring site was not achieved. ConDos 5 and ConDos 6 experiments were carried out to achieve this requirement and hence eliminate any variability in the results due to changes in sewer conditions. Similarly, the ConDos 7 experiment achieved this situation but with the tracers reversed relative to the indicator and reference doses. Flow rates within the sewer were monitored at the outlet manhole site A for all the ConDos experiments.

Table 3. Dosing arrangements for the Condos experiments.

Reference code	Indicator dosing details at C1	Reference dosing details at B
ConDos 1	Mixed tracer containing Rhodamine WT (1 g/L), Li (1 g/L) and Br (2.5 g/L) at 1 L/minute for 9 minutes	-
ConDos 2	Rhodamine WT tracer (1 g/L) at 1 L/minute for 9 minutes	-
ConDos 3	-	Li tracer (1 g/L) at 1 L/minute for 9 minutes
ConDos 4	-	Mixed tracer containing Rhodamine WT (1 g/L), Li (1 g/L) and Br (2.5 g/L) at 1 L/minute for 9 minutes
ConDos 5	Rhodamine WT tracer (1 g/L) at 1 L/minute for 5-6 minutes	Mixed tracer containing Li (1 g/L) and Br (2.5 g/L) at 1 L/minute for 5-6 minutes
ConDos 6	Rhodamine WT tracer (1 g/L) at 1 L/minute for 5-6 minutes	Mixed tracer containing Li (1 g/L) and Br (2.5 g/L) at 1 L/minute for 5-6 minutes
ConDos 7	Mixed tracer containing Li (1 g/L) and Br (2.5 g/L) at 1 L/minute for 5-6 minutes	Rhodamine WT tracer (1 g/L) at 1 L/minute for 5-6 minutes

ConDos 1 and 4 experiments

Monitoring of the Rhodamine WT and lithium concentrations at the downstream manhole A during these experiments resulted in concentration profiles for both tracers which mirrored each other exactly, indicating that they behaved consistently within the sewer environment regardless of whether they were introduced at dosing locations C1 (ConDos1) or B (ConDos2). The peak concentrations achieved in ConDos 1 showed evidence of slight decreases for both tracers due to gradually increasing flow rates within the sewer. The reverse of this pattern was observed during ConDos 4, with the peak concentrations increasing slightly as the flow decreased during the duration of the experiment.

The extent to which the tracers exhibited conservative behaviour during the experiments was assessed by comparing the amount of tracer detected passing the downstream monitoring point compared to the introduced dosing load. The percentage recoveries for each of the three tracers are plotted in Figure 3, and for Rhodamine WT and lithium are between 97.7% and 101.4% indicating that both tracers were relatively inert during sewer transport over periods of up to 20 minutes. The best agreement between the two tracers was for the ConDos 4 experiment where the sewer run was shortest (150 m). The recovery rates for bromide were less reliable with the elevated values of above 100% being related to the greater analytical problems associated with the determination of bromide as previous studies (Hess et al, 2002) have reported that bromide demonstrates conservative behaviour as a tracer when exposed to raw sewage. In this study bromide was determined in the laboratory using an ion chromatographic technique with an analytical precision of ±3.1% in the measured concentration range. This was considerably less precise than the corresponding techniques used for the determination of Rhodamine WT (*in situ* fluorimetry; ±0.6%) and lithium (flame emission spectrophotometry; ±0.7%) resulting in less reliable results for the bromide tracer.

ConDos 2 and ConDos 3 experiments

The combined tracer curves for these experiments together with the relevant flow rate changes are shown in Figure 4. Rhodamine WT represents the indicator tracer having been introduced at dosing point C1 and lithium is the reference tracer. Because the relative timings for the introductions of the two tracers were not correctly judged, the prolonged tracer peaks do not directly overlap. The slopes associated with both the Rhodamine WT and Li peak concentrations (Figure 4) identify the dangers with taking non-coincident average peak values, particularly where influencing changes (such as flow rate increases and decreases) occur within the sewer. An exfiltration value of -0.53% has been calculated using the average tracer concentrations and associated flow rates, from the short plateaux regions identified in Figure 4. Although this is consistent with the water company expectations of the tested sewer, greater confidence in the derived result would be obtained if the experimental conditions were amended in order to achieve maximum overlap of the tracer curves. The ConDos 5, ConDos 6 and ConDos 7 experiments were carried out to satisfy this requirement as well as further testing the versatility of the three different tracers.

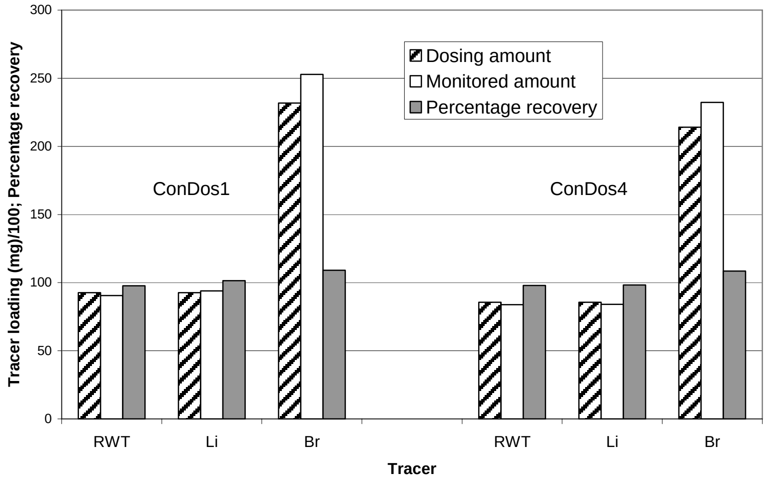

Figure 3. Representation of the percentage recoveries of the different tracers during ConDos 1 and ConDos 4.

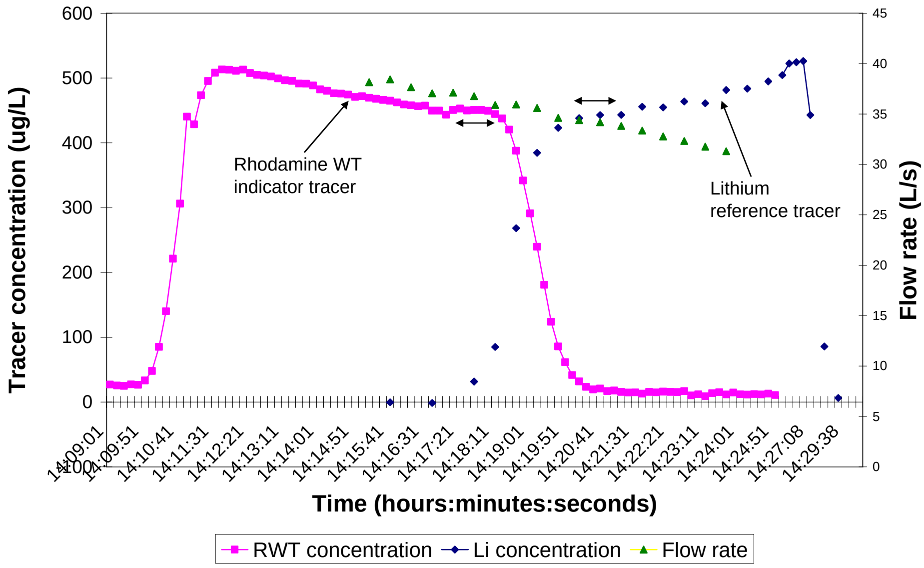

Figure 4. Tracer curves and flow rates for ConDos 2 and ConDos 3 experiments.

ConDos 5, ConDos 6 and ConDos 7 experiments

In the ConDos 5 and ConDos 6 experiments, Rhodamine WT was used for the indicator tracer with a mixed tracer of lithium and bromide being used as the reference. These tracer identities were reversed for the ConDos 7 experiment. The results obtained for each experiment in terms of the average peak concentrations and their variability in the region of overlap are shown in Table 4 together with the calculated percentage exfiltration in the indicator stretch of the monitored sewer. The greater variability in the bromide signal is indicative of the lower reliability of this anion as a tracer compared to Rhodamine WT and lithium. The dosing concentration for bromide was 2.5 g/L compared to 1.0 g/L for lithium and the monitored ratio of the average peak concentrations is 2.50 ± 0.4 which provides confirmation that bromide exhibits an in-sewer conservative behaviour consistent with the other tracers, particularly Li.

Table 4. Peak tracer concentrations and predicted exfiltration rates using different combinations of tracers for the overlapping indicator and reference signals.

	Tracer combination and peak concentration (µg/l)		Predicted percentage exfiltration
	Indicator	Reference	
ConDos 5	RWT; 234.4 ± 3.0	Li; 228.5 ± 1.6	- 0.381 ± 0.002
	RWT; 234.4 ± 3.0	Br; 573.0 ± 10.2	- 0.685 ± 0.005
ConDos 6	RWT; 243.5 ± 7.2	Li; 254.2 ± 8.9	+ 1.078 ± 0.009
	RWT; 243.5 ± 7.2	Br; 659.3 ± 5.6	- 2.571 ± 0.021
ConDos 7	Li; 212.3 ± 8.0	RWT; 213.8 ± 1.2	- 0.697 ± 0.023
	Br; 529.9 ± 15.5	RWT; 213.8 ± 1.2	- 0.860 ±0.059

The exfiltration results obtained from the ConDos 5 and 7 experiments are in good agreement and predict an overall loss due to exfiltration of between 0.38% and 0.86%. The conformity of these results would suggest that all three tested tracers are interchangeable in terms of their use as either the indicator or reference tracer. However, this is clearly not the case for ConDos 6 where the Rhodamine WT/Li tracer combination predicts a positive exfiltration value (+1.08%) and the Rhodamine WT/ Br tracer combination suggests a sewer loss of -2.57%. The latter result is clearly an outlier compared to the other results and can be partly explained by the previously discussed difficulties associated with accurately analyzing Br in the collected sewage samples. The positive exfiltration value of +1.08% is also unlikely as it suggests that the indicator tracer was entering the sewer during the experiment. The most reliable values in Table 4 are for the Rhodamine WT/Li tracer combination and optimistically predict that the use of the ConDos technique is capable of determining the percentage exfiltration within a sewer system, not exceeding 1 km in length, to within ±1.0%.

Conclusion

The two described traced techniques (PulDos) and (ConDos) are shown to represent feasible practical methods for the determination of exfiltration in sewer systems although with different degrees of reliability. The PulDos technique is, in principle, easier to use but there can be major problems with the determination of the amount of tracer passing the monitoring point due to baseline variability and the impact of interferences on the measured peak area. The methodological approach adopted in the ConDos experiments largely eliminates any errors due to flow variations and the background tracer concentrations can be more accurately subtracted from the average measured peak concentrations. A disadvantage is that the analytical problems associated with the determination of two different tracers have to be overcome but Rhodamine WT and lithium are shown to be an appropriate tracer combination. The preferred ConDos application uses Rhodamine WT (as indicator) and Li (as reference) and is capable of estimating the occurrence of exfiltration over a sewer length of less than 1 km to ±1%. However the method provides no direct information on the actual volume of wastewater lost due to the variable flow dynamics over the monitoring period. It is also the case that the method is best suited for main and trunk sewer lines where there is corroborative evidence of potential leakage to groundwater.

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References

Barrett, M.H., Hiscock, K.M., Pedley, S., Lerner, D.N., Tellam, T. H and French, M.J. 1999. Marker species for identifying urban groundwater recharge sources: a review and case study. Water Research, **33**, 3083 – 3097.

Flury, M., Wai, N. N. Dyes as tracers for vadose zone hydrology. 2003. *Review of Geophysics*, **41**(1), Art. No. 1002.

Giulianelli, M., Mazza, M., Prigiobbe, V., Russo, F. 2003. Assessing exfiltration in an urban sewer by slug dosing of a chemical tracer. *Proceedings of NATO Workshop on Urban Runoff*, Marsalek, J. Ed., Rome, Italy, 5-8 November, 2003, 1-12.

Hess, K. M., Davis, J. A., Kent, D. B., Coston, J. A. 2002. Multispecies reactive tracer test in an aquifer with spatially variable chemical conditions, Cape Cod, Massachusetts: Dispersive transport of bromide and nickel. *Water Resour. Res.*, **38**(8), Art. No. 1161.

Rieckermann, J., Gujer, W. 2002. Quantifying exfiltration from leaky sewers with artificial tracers. *Proceedings of the International Conference "SOM 2002 Sewer Operation and Maintenance"*, Bradford, UK, 26-28 November, 2002, pp 8.

Rieckermann, J. Quantification of exfiltration from sewers with tracers. 2005. *Unpublished PhD thesis,* Swiss Federal Institute of Technology, Zurich, 2005.

Rieckermann, J., Borsuk, M., Reichert, P., Gujer, W. 2005. A novel tracer method for quantifying sewer exfiltration. *Water Resour. Res.*, **41**(5), Art. No. W05013.

Rutsch, M., Rieckermann, J., Krebs, P. 2005. Quantification of sewer leakage – a review. In *Proceedings of 10th International Conference on Urban Drainage*, Eriksson, E., Genc-Fuhrman, H., Vollertsen, J., Ledin, A., Hvitved-Jacobsen, T., Steen Mikkelsen, P. Eds., Copenhagen, Denmark, 21-26 August 2005, pp 9.

Vasudevan, D., Fimmen, R. L., Francisco, A. B. 2001. Tracer-grade rhodamine WT: Structure of constituent isomers and their sorption behaviour. *Environ. Sci. Technol.*, **35**(20), 4089-4096.

Wolf, L., Held, I., Eisworth, M and Hotzl, H. 2004. Impact of leaky sewers on groundwater quality. Acta Hydrochim.Hydrobiol., **32** (4), 1 – 13.