APUSS

Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems

Contract number : EVK1-CT-2000-00072 APUSS
Project homepage : http://www.insa-lyon.fr/apuss

DELIVERABLE 2.4

EXFILTRATION RATES AND PATTERNS ON LIVE WASTEWATER FLOWS WITHIN AN EXPERIMENTAL SEWER RIG

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September 2004

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1. BACKGROUND TO THIS REPORT

1.1 Original Objectives

The original June 2000 APUSS Description of Work proposal envisaged that Deliverable 2.4 would involve the production of a general mathematical model for determining tracer adsorption and release rates together with an error analysis. This 36 month deliverable within Work Area 1 (Experimental Methods) was considered at this early planning stage as being a logical outcome of WP2 (Sediment-Tracer Interactions), given the known potential of certain chemical tracers for adsorption to organic sediments.

1.2 Progress Reports and Deliverables

Following a series of laboratory batch reactor tests to evaluate sediment adsorption and uptake rates for a range of selected non-reactive tracers under controlled dynamic conditions, an initial report (*Report No.2, November 2002*) describing methodological protocols was produced as a supporting document to the 12 month Deliverable D2.2. This reported on the use of lithium and Rhodamine WT batch testing techniques and derived adsorption curves for differing sewer sediment types. The work identified a long term Rhodamine WT adsorption of up to 10% of the tracer concentration but for the lithium tracer no evidence of adsorption over the test duration periods was observed.

The 24 month Deliverable D2.3 (*Report No.3, November 2003*) provided a full account of standard protocols for assessing real sediment effects on tracer behaviour under laboratory simulated flow conditions. Following discussions in Zurich with the EAWAG lead partners of Work Area 1 in November 2002 and subsequent further experimental testing, it was agreed that for Rhodamine WT and associated fluorescent dyes there were possible problems due to the perceived extent of adsorption and further investigations were initiated on bromide (APUSS 2003 Annual Management Report). Bromide behaves similarly to lithium in showing no evidence of chemisorption. The problems associated with Rhodamine WT as a tracer substance also removed the need for any detailed mathematical modelling of equilibrium adsorption characteristics within the context of the APUSS Work Area 1 objectives. However, some preliminary modelling has been completed which shows that over time periods in excess of 4 hours, Freundlich Isotherms offer better explanations than Langmuir Isotherms for the adsorption behaviour of Rhodamine WT in contact with sediments collected from a sedimentation chamber and from a combined sewer outfall.

1.3 Sewer Exfiltration Testing

As the APUSS project has progressed, there has been an increasing interest in the development and application of experimental rigs for the field testing of live wastewater exfiltration rates. This interest in pilot scale field tests within the APUSS project is reflected in the additional £20,000 financing given by a consortium of 5 UK water companies to establish a live wastewater test rig at the Riverside screening works in Dundee, Scotland (as noted in the half year summary report for the period January to July 2003). The results of the first 12 months work on the rig is summarised in the APUSS 2003 Management Report and two peer-reviewed publications have been produced covering these results. The significance of the test rig exfiltration work has thus assumed much greater importance within the context of the overall APUSS work objectives for WP2 and is providing a substantial market profile for the EU project to the UK water industry. It has also enabled the testing of the applicability of the different identified tracers under controlled field conditions where all relevant parameters can be fully monitored.

1.4 Revised Title for Deliverable D2.4

Given the re-orientation of work interests described above and which have arisen from the logical, but unforeseen, progression of work within WP1, the proposal has been put forward that Deliverable D2.4 be re-titled and given a new subject direction. The increased profile and potential significance of the test rig results in terms of the Articles within the EU Water Framework Directive covering diffuse pollution, suggests more value would be gained to the project by substituting a full report of the field exfiltration tests. This report will also discuss the tracer results obtained within the sewer rig which indicate that over short travel distances and therefore contact times, Rhodamine WT can be equally efficient as lithium and bromide for the determination of exfiltration.

2. SCOPE OF THE FIELD EXFILTRATION TESTS

The overall objective of the research described in this report was to provide further information on the self sealing effects of sewage on sewer defects. This was achieved using a field test rig into which sewage was extracted directly from a sewer and passed, at various rates and flow heads, through a pipe with test boxes containing pipe joints that enabled defects to be simulated with varying boundary conditions. The following range of experiments are discussed:

- measurement of exfiltration rates from a variety of defects, with a discharge to air, under varying flow levels and associated heads;
- measurement of exfiltration rates, for selected defects, with sewer pipe bedding effects being simulated by a gravel surround to the pipe and
- an assessment of the performance and efficiency of non-intrusive tracers for the evaluation of exfiltration losses

3. METHODOLOGY

3.1 Test rig description

The experimental rig was designed to simulate radial defects of varying geometries. The test rig was constructed on a concrete cover slab of an overflow chamber at a Scottish Water/United Utilities site at Riverside, Dundee (Figure 1). The rig consists of a 10m length of 150mm clear plastic pipes running through three, 2 m high boxes, with flanged joints between the plastic pipes inside each of the boxes (see Figures 2 and 3). Defects were simulated by placing inserts between the flanges of the joints with the inserts cut to different thickness and geometries. Three geometries were considered; a 10mm hole at invert level, a radial opening extending half way round the pipe from invert to soffit, (i.e. vertically in the pipe) and a radial opening extending half way round the pipe from the invert to the middle of the pipe wall on each side (i.e. horizontally in the pipe). The exfiltration rate for a particular gap size, geometry and flow head was determined by directly collecting and measuring the volume of exfiltrate over time, as it discharged from the pipe defect. Sewage was drawn by a submersible pump, which was placed in a live sewer 3.5m below the rig. Frequent removal of the pump was required to remove ragging and blockages. Two flow monitors measured the inflow and outflow rates to the rig and a V-notch weir was constructed at the outlet from the rig to enable accurate measurement of low flows. The V-notch assembly then discharged back into the sewer.

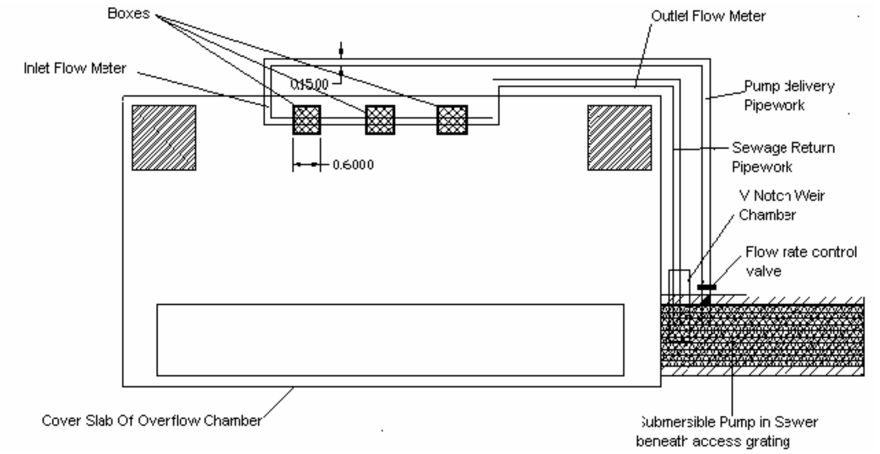

Figure 1. Schematic representation of the experimental sewer pipe rig.

Figure 1. Overall view of the test rig showing the pipe passing through the test boxes.

Figure 3. Internal construction of a test box showing the location of the pipe defect.

3.2. Initial flow calibration tests

Calibration of the flow monitors was undertaken following complete sealing of the sewer pipe within the rig so that no exfiltration was possible. Using the measured head before each of the test boxes, manually measured flows were compared to readings on the in and out flow monitors. Calibration of the inlet flow compared to each of the boxes in series was undertaken. This calibrated the changes in flow at each box. The results of the calibration show a good correlation between the inflow and outflow readings as shown in Figure 4.

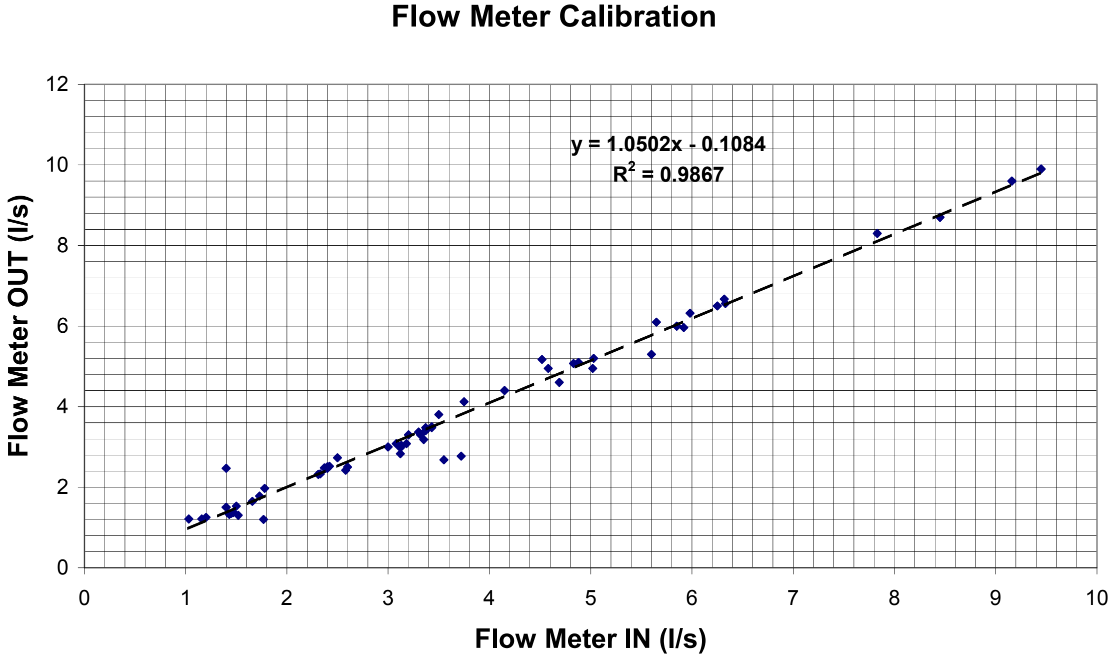

Figure 4. Calibration graph of inlet against outlet flow rates measured by the relevant flow meters.

Initial runs to establish minimum recordable flows and highest steady established that low flows, below 20mm head, could not be read from the flow meters and therefore a 90 degree V- notch weir was fitted at the outlet to the system.

3.3. Overview of experiments carried out.

Initially, it was envisaged that gaps of 2, 3, and 4mm would be investigated to replicate the previous laboratory studies, carried out as part of the APUSS project, in which granular sediments were mixed with clean water. However, almost complete sealing of the 2mm and 3mm gaps was observed and hence further tests with a 6mm and then a 10mm gap size were also programmed. Experiments were run initially for 30 - 40 minutes but this was extended to between 1 – 1.5 hours for the 3mm gaps and to 1 - 2.5 hrs for the 6mm and 10mm gaps to allow the leakage rates to tend towards an equilibrium value. The relatively short duration of the runs would not allow time for a build-up of biofilm and therefore the sealing effects observed in the experiment would be mainly due to mechanical blocking of the defects. It should also be noted that there were occasions when it was difficult to keep flow rates in the rig steady due to pump and sewer conditions, but it is believed that the surges and flow drops encountered may represent the situation in real sewers. However, runs were kept as steady as possible and the timings of surges and flow reductions were noted in each experiment. A full list of experiments is shown in Table 1.

All runs took place during normal working hours (09:00 hours to 18:00 hours) with experiments starting between 10:00 hours and 15:00 hours. A range of depths of flow in the pipe, between 25 mm and 120 mm, was created to represent a range of flow conditions in sewers.

Table 1. Descriptions of the completed exfiltration experiments.

Spacer Size	**Geometry**	**Number of runs**
Free Draining		
2mm	10mm hole	2
	Half Vertical	7
	Half Horizontal	5
	In series	
3mm	10mm hole	1
	Half Vertical	1
	Half Horizontal	1
	In series	4
4mm	10mm hole	9
	Half Vertical	3
	Half Horizontal	3
	In series	
6mm	10mm hole	4
	Half Vertical	3
	Half Horizontal	2
	In series	4
10mm	10mm hole	2
	Half Vertical	2
	Half Horizontal	2
	In series	
Gravel Surround		
6mm	10mm hole	2
	Half Vertical	2
	Half Horizontal	2
	In series	
10mm	10mm hole	3
	Half Vertical	2
	Half Horizontal	2
	In series	
		68 total

4. EXPERIMENTAL RESULTS

Exfiltration rates, sewage head in the pipe (depth of flow), flow logger readings at the inlet and outlet positions of the pipe of the test rig, and the head over the weir (for lower flows only) were recorded at four minute intervals and entered into a spreadsheet for presentation and analysis as shown in the example in Tables 2 and 3. The flow loggers recorded the cumulative flow and this was averaged over each four minute interval and across the duration of the run using the first and last flow readings.

Table 2. Typical data analysis approach for lower flows in the test rig.

Gap (mm)	Depth of flow (mm)	Weir (cm)	Time (minutes)	Exfiltration rate (l/s)
3 mm series	20.5	20.5	0	0.0088
	205	20.5	4	0.0115
	20.5	20.5	8	0.0095
	19	20.5	12	0.0190
	19.5	20.5	16	0.0012
		20.4	20	0.0011
	19	20.4	24	0.0011
	19	20.4	28	0.0011
	19	20.4	32	0.0010
	25	20.5	36	0.0010
	20	20.5	40	0.0008
	20		44	0.0007
	24	20.7	48	0.0006
	25	20.7	52	0.0007
	24	20.8	56	0.0007
	24	20.8	60	0.0007
	24	20.8	64	0.0007
	24		68	0.0006
	24		72	0.0006
	24		76	0.0007
	24		80	0.0005
	25		84	0.0006
	Depth	206		
	Correction	190		
Weir readings				
	Difference	16		
	Flow	0.12 l/s		

Table 3. Typical data analysis approach for higher flows in the test rig.

Gap (mm)	**Depth of flow (mm)**	**Time (minutes)**	**Cumulative flow in (m^3/min)**	**Cumulative flow out (m^3/min)**	**Flow in (l/s)**	**Flow out (l/s)**	**Exfiltration rate (l/s)**
10; ½	57	0	9.047	8.961			0.430
vertical	57	4	9.589	9.418	2.258	1.904	0.420
	57	8	10.272	9.943	2.846	2.188	0.424
	57	12	10.878	10.451	2.525	2.117	0.420
	57	16	11.812	11.249	3.892	3.325	0.420
	57	20	12.533	11.841	3.004	2.467	0.422
	57	24	13.232	12.457	2.913	2.567	0.438
	57	28	13.864	12.983	2.633	2.192	0.424
	57	32	14.671	13.660	3.362	2.821	0.402
	57	36	15.301	14.192	2.625	2.217	0.430
	57	40	15.908	14.814	2.529	2.592	0.402
	57	44	15.492	14.316	-1.733	-2.075	0.420
	57	48	16.117	15.006	2.604	2.875	0.410
	57	52	16.672	15.719	2.313	2.971	0.414
	57	56	17.221	16.410	2.288	2.879	0.400
	57	60	17.770	17.126	2.288	2.983	0.400
				Average	2.423	2.268	

The head in the pipe in the rig was found to be variable during runs (generally ±10% of the average value) although on infrequent occasions larger surges and flow drops occurred for short periods due to the performance of the pump. Consequently, calculated flow rates in Table 3 represent an average over four minutes, determined from the cumulative volumetric flows indicated by the loggers. A good linear correlation was noted between the inlet and outlet flow loggers although at flow rates greater than 2 l/s, the outlet flow meter read consistently higher than the inlet flow meter. Where possible, the depth over the V-notch weir was noted for further verification of the average flow rates.

The average head (depth of flow) during each run was also determined and Figure 5 plots average flow against average head in the 3mm to 10mm gap size runs. A reasonable pattern emerges, and this figure provides a useful contextualisation, in terms of flow rate, of the data presented in other sections of this report where the focus is on the head in the pipe. It should be noted that the range of flow rates associated with some head values is large and therefore this figure is recommended only for a qualitative evaluation of the relative flow rates.

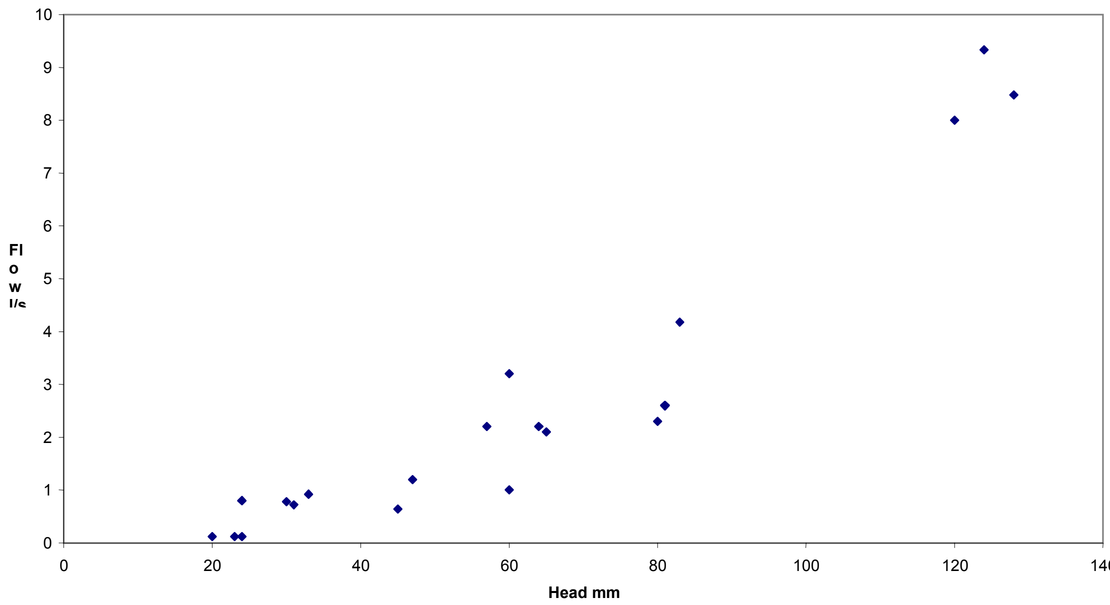

Figure 5. Average flow against average depth for experimental runs with different gap sizes

The graphical representations of the full range of exfiltration experiments indicate that, in virtually every case, exfiltration rates dropped rapidly during the initial fifteen minute period and then tended towards an equilibrium rate. In addition, several other interesting general features are evident.

There is clearly a variation in the time taken to the initial rapid drop in exfiltration rate as can be seen by comparing Figures 6 and 7. This is probably due to randomness in the arrival time of material in the sewage that was suitable for gap sealing. The sealing material was observed to be a mixture of paper and small pieces of rag, mixed with a clear grey slime. In general, the time to initial drop was higher under lower heads probably due to the reduced pressure available to force sedimentation of material in the defects.

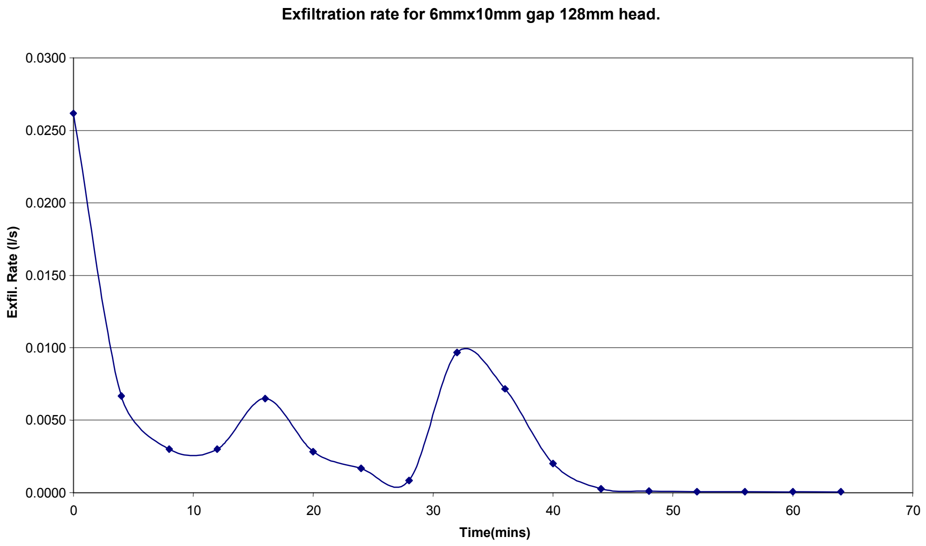

Figure 6. Experimental results showing an immediate initial drop in exfiltration rate.

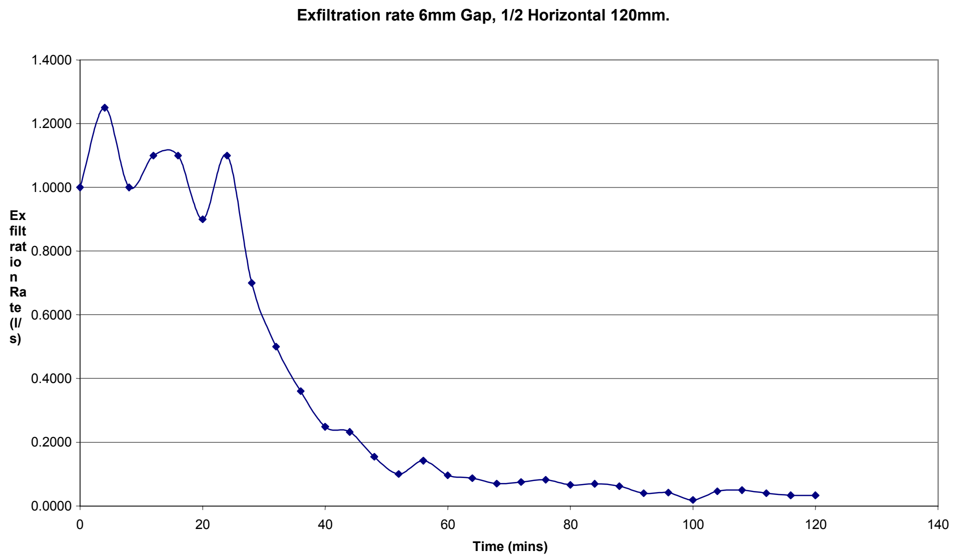

Figure 7. Experimental results showing a delayed initial drop in exfiltration rate.

Figure 7 shows a substantial time delay before the available sealing material is able to plug the pipe defect. This period may also represent a situation in which rapid removal of any blocking material occurs preserving a high exfiltration rate until the sealing process predominates and the exfiltration rate follows the characteristic downward trend. There is also evidence that partial scouring of the gap can occur at later stages within the overall exfiltration process (Figure 6) although in all cases the impact of temporary re-suspension does not greatly influence the final exfiltration rates. Evidence for the existence of a temporary release of sealing material at the start of the experimental runs was frequently observed to occur as illustrated in Figure 8. Further work is necessary to investigate the prevalence and the timing of the removal/resealing phenomenon as this may occur more during summer storms where full bore flow can be preceded by a long dry period with associated low flows.

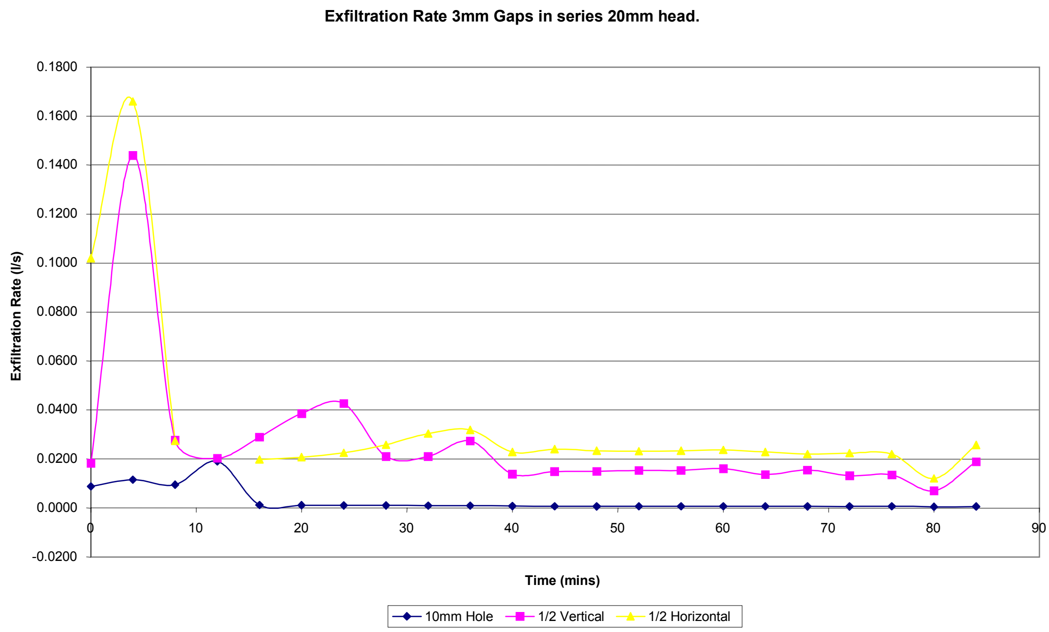

Figure 8. Experimental results showing initial temporary increases in exfiltration rate due to the release of sealing material

It was not feasible to prolong the experimental runs to identify final or ultimate equilibrium exfiltration rates. This was due to time restrictions within the overall programme and, infrequently, to flow reductions caused by pump ragging which required experiments to be terminated before equilibrium rates were reached. Runs were terminated when it was believed that the pattern of change in exfiltration rate was stable and at this point the lowest recorded exfiltration rate was determined. This concept is used in the further evaluation of the data contained in this report. It should be noted that two phenomena were accepted as indicating a stable pattern in the data:

- the exfiltration rate appeared to reach an equilibrium value with no strong evidence of further reduction; and
- the exfiltration rate had not yet reached an equilibrium value but the rate of change of the exfiltration rate was near zero or very low.

The former is illustrated in Figure 8 and Figure 7 shows the latter. It is not believed that the different phenomena will affect the robustness of the lowest recorded value across the 1 – 2.5 hour durations of the experiments but the possibility of further reductions in exfiltration rates over a much longer timescale in both cases should be noted. Further research is required to investigate and determine long-term trends and ultimate exfiltration rates over extended periods of time particularly under minimum dry weather flow conditions.

4.1. Discharge to air experiments.

This section contains a selection of graphical interpretations of the free draining experiments enabling comparisons to be made of exfiltration rate trends for the different heads, geometries and gap sizes. Figure 9 shows an example of the temporal pattern of exfiltration for the three defect geometries under a similar head. In most cases complete or virtually complete sealing of the smallest defect (10mm hole) was observed with the half horizontal and half vertical radial defects tending towards a similar value.

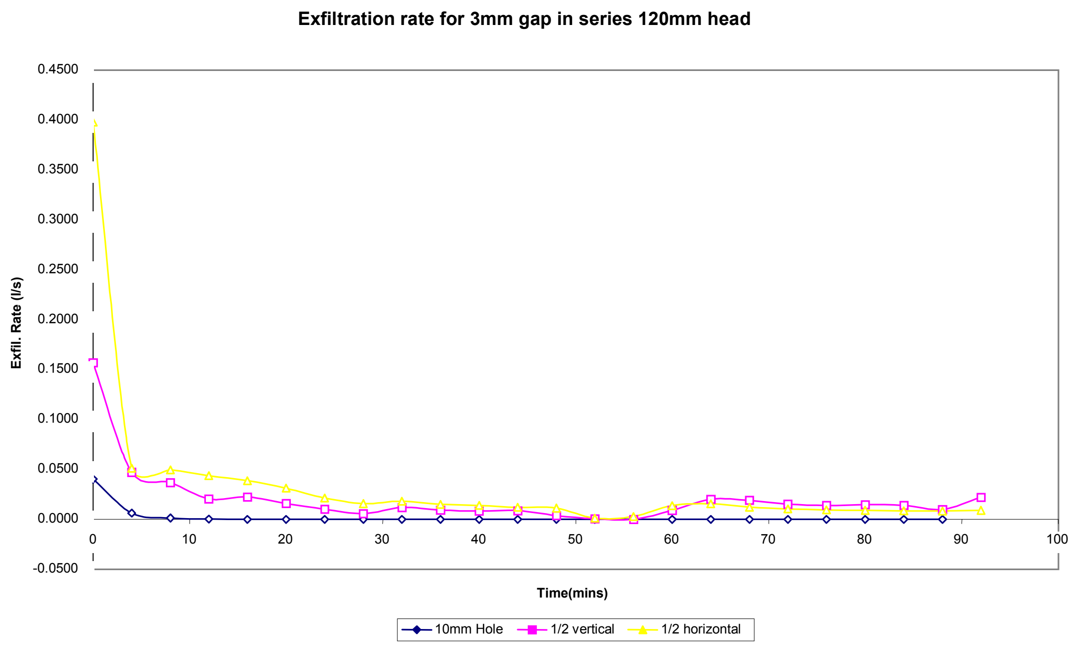

Figure 9. Comparison of exfiltration rates from the three defects (3mm gap) at a single head (120mm).

Figure 10 shows an example of the pattern of exfiltration over time for one defect (10mm hole) over a range of heads. Again total sealing was observed for this, the smallest defect, even at a 6mm gap, with the exception of run 1, which had the lowest head (23mm), where no sealing was observed. This phenomenon of less effective sealing at the lower heads was also observed in a number of other runs, which suggests that a critical head may be required to ensure sealing. However, the configuration of the apparatus and the short durations of the runs may not have allowed sufficient sealing material to reach the defects in these cases. This concept merits further evaluation as it would be important in terms of potential sewer losses under low heads during extended dry weather flow periods.

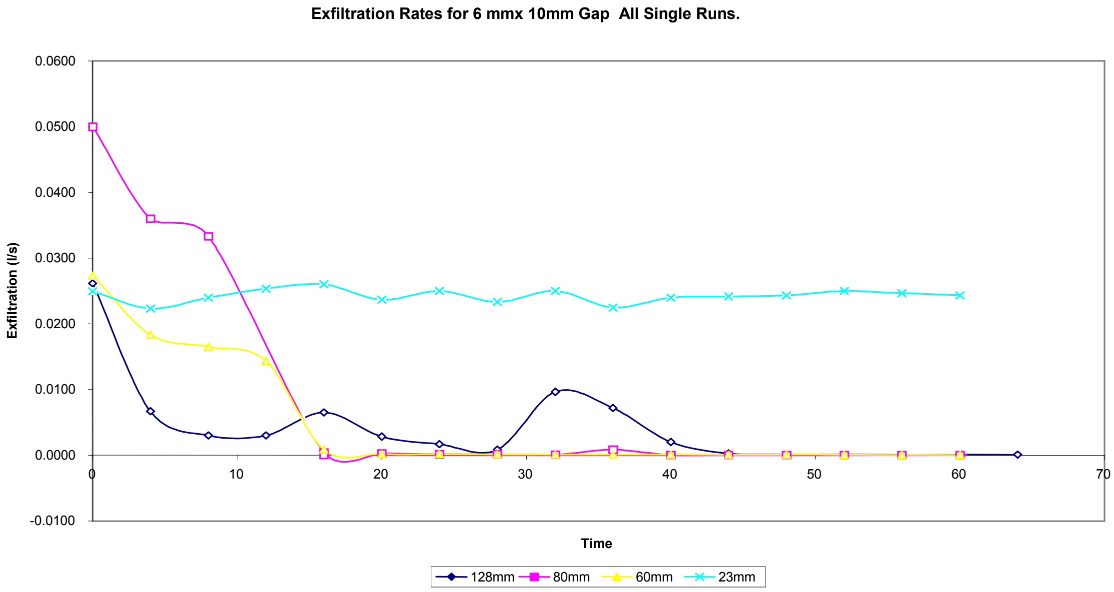

Figure 10. Comparison of exfiltration rates from a 6mm x 10mm hole under a range of heads.

Figure 11 shows an example of the pattern of exfiltration over time for one defect, the half vertical radial configuration, with varying gap widths under similar heads. As might have been anticipated, the rate of sealing and the degree of sealing are clearly influenced by the gap width, with virtually no sealing being observed for the 10mm wide gap whereas the 2mm and 3mm gaps show a decrease within 30 minutes from a low initial exfiltration rate to effectively complete sealing. The 6mm gap represents an intermediate case with evidence that efficient sealing is starting to occur after 60 minutes of exposure to sewage at a head of 47mm.

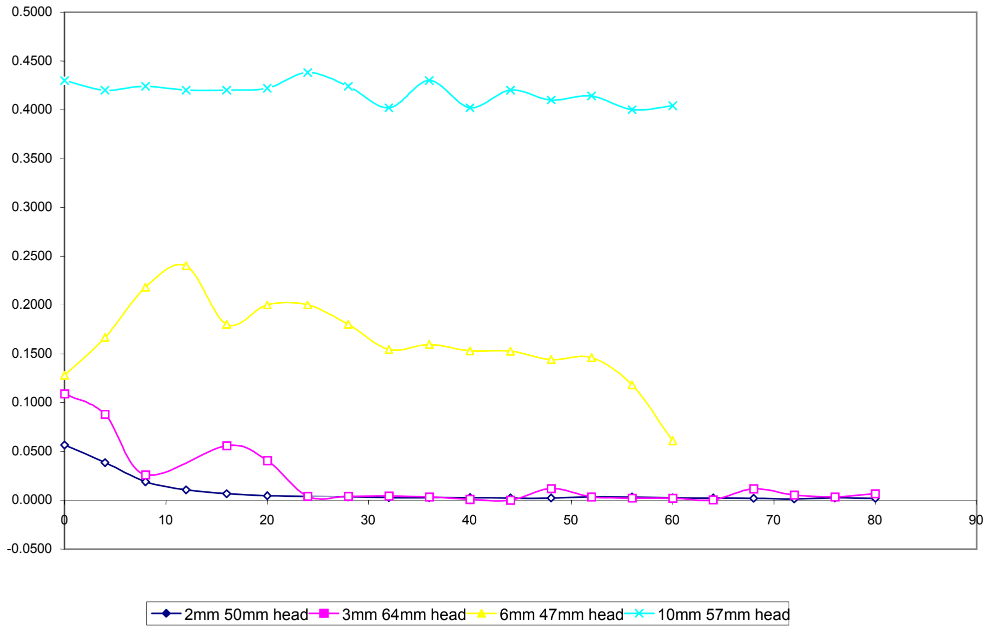

Figure 11. Comparison of exfiltration rates from a defect with a range of gap widths under a single head.

4.1.1. Analysis of free discharge data

The results obtained from the free to air discharge experiments are summarised in Tables 4 to 6. As would be expected, the initial exfiltration rates (t = 0) generally increase with increasing head, gap size and the area of the defect in contact with the flow. However, as discussed earlier there are some instances, even in large defects, where the initial exfiltration rate was lower than might have been expected due to the random early arrival, in the sewage flow, of appropriate sealing material.

Another two phenomena noted earlier in this report can also be observed in the data after 4 minutes. Firstly, an increase from the initial exfiltration rate can also be observed in a number of cases due to the removal by the flow, or by the exfiltrate, of the sealing material that had arrived early. Secondly, where reductions were observed they were generally more rapid under higher heads.

Significant reductions in the exfiltration rate can be seen for almost every run after 12 minutes, with the reductions typically ranging between 20% and 100% of the starting values. Again, more effective sealing at higher heads can be observed. In a few cases, however, little or no reduction was evident between 4 and 12 minutes, again demonstrating randomness in the time of arrival of sealing material in the flow.

After 32 minutes, further reductions can be observed in almost every run with exfiltration rates ranging between 40 and 100% of the starting values. At this point complete sealing of the 10mm wide hole can be seen for a number of gap sizes. More effective sealing of defects under higher heads is still apparent.

After 60 minutes, exfiltration rates had in most cases dropped by more than 85% of their starting values. The rates from the 10mm hole are approaching a 100% reduction, as are the rates for the higher heads for the 6mm gap for the radial defects. The 10mm wide gaps show an unusual pattern with more effective sealing at the lower head than for the higher head. This may be feature of larger defects, but may again be a result of the random arrival of sealing material as observed in other runs and further experiments would be required to determine whether this is a characteristic feature of larger defect sizes. This could be an important issue as larger gap sizes would be expected to generate higher loss rates, but if such increased surface area effects do lead to enhanced localised sedimentation rates and thus greater sealing potential, this is an important finding of practical significance to sewerage system operators.

Table 4. Variations in exfiltration rate over time for 10mm hole geometries; defects discharging to air

Defect Geometry and Gap Width 10mm Hole	Head	Exfiltration rate (l/s) t = 0	Exfiltration rate (l/s) t = 4 minutes	% Reduction in exfiltration rate t = 4 minutes	Exfiltration rate (l/s) t = 12 minutes	% Reduction in exfiltration rate t = 12 minutes	Exfiltration rate (l/s) t = 32 minutes	% Reduction in exfiltration rate t = 32 minutes	Exfiltration rate (l/s) t = 60 minutes	% Reduction in exfiltration rate t = 60 minutes
3mm	20mm	0.0088	0.1150	N/A	0.0190	N/A	0.0100	N/A	0.0007	92
	45mm	0.0420	0.0207	51	0.0280	33	0.0247	41	0.0017	96
	64mm	0.0200	0.0070	65	0.0044	78	0.0028	86	0.0041	80
	120mm	0.0402	0.0062	85	0.0002	100	0.0000	100	0.0000	100
6mm	23mm	0.0249	0.0223	10	0.0253	N/A	0.0250	0	0.0243	2
	24mm	0.0207	0.0183	12	0.0150	28	0.0210	N/A	0.0223	N/A
	60mm	0.0273	0.0183	33	0.0143	48	0.0001	100	0.0001	100
	65mm	0.0323	0.0400	N/A	0.0012	96	0.0000	100	0.0000	100
	80mm	0.0500	0.0360	28	0.0004	99	0.0008	98	0.0000	100
	81mm	0.0270	0.0258	4	0.0133	51	0.0000	100	0.0000	100
	124mm	0.0960	0.0427	56	0.0413	57	0.0037	96	0.0000	100
	128mm	0.0262	0.0067	74	0.0030	89	0.0097	63	0.0001	100
10mm	33mm	0.0467	0.0633	N/A	0.0480	N/A	0.0567	N/A	0.0567	N/A
	60mm	0.0358	0.0331	8	0.0320	11	0.0125	65	0.0000	100

Table 5. Variations in exfiltration rate over time for ½ vertical geometries; defects discharging to air.

Defect geometry and gap width **½ vertical**	**Head**	**Exfiltration rate (l/s) t = 0 minutes**	**Exfiltration rate (l/s) t=4 minutes**	**% Reduction t = 4 minutes**	**Exfiltration rate (l/s) t = 12 minutes**	**% Reduction t= 12 minutes**	**Exfiltration rate (l/s) t = 32 minutes**	**% Reduction t = 32 minutes**	**Exfiltration rate (l/s) t=60 minutes**	**% Reduction t = 60 minutes**
3mm	20mm	0.0183	0.1440	N/A	0.0202	N/A	0.0210	N/A	0.0160	13
	45mm	0.0613	0.0635	N/A	0.0193	69	0.0042	93	0.0023	96
	64mm	0.1090	0.0880	19	0.0560	49	0.0043	96	0.0023	98
	120mm	0.1567	0.0471	70	0.0203	87	0.0117	93	0.0090	94
6mm	24mm	0.1020	0.1000	2	0.0840	18	0.0580	43	0.0580	43
	24mm	0.1020	0.1093	N/A	0.1213	N/A	0.1200	N/A	0.1067	N/A
	47mm	0.1280	0.1667	N/A	0.2400	N/A	0.1545	N/A	0.0610	52
	65mm	0.3300	0.3900	N/A	0.1720	48	0.0580	82	0.0527	84
	81mm	0.1120	0.0790	29	0.0333	70	0.0183	84	0.0055	95
	83mm	0.4675	0.4625	1	0.3060	35	0.1840	61	0.0565	88
	124mm	0.0320	0.3380	N/A	0.2320	N/A	0.1000	N/A	0.0070	78
10mm	31mm	0.3240	0.4020	N/A	0.4020	N/A	0.1520	53	0.1300	60
	57mm	0.4300	0.4200	2	0.4200	2	0.4020	7	0.4040	6

Table 6. Variations in exfiltration rate over time for ½ horizontal geometries; defects discharging to air.

Defect geometry and gap width ½ horizontal	Head	Exfiltration rate (l/s) t = 0 minutes	Exfiltration rate (l/s) t = 4 minutes	% Reduction t = 4 minutes	Exfiltration rate (l/s) t = 12 minutes	% Reduction t= 12 minutes	Exfiltration rate (l/s) t = 32 minutes	% Reduction t = 32 minutes	Exfiltration rate (l/s) t = 60 minutes	% Reduction t = 60 minutes
3mm	20mm	0.1020	0.1660	N/A	0.0274	73	0.0303	70	0.0237	77
	45mm	0.1327	0.1033	22	0.0520	61	0.0073	94	0.0015	99
	64mm	0.1840	0.0927	50	0.0767	58	0.0097	95	0.0042	98
	120mm	0.3980	0.0510	87	0.0436	89	0.0180	95	0.0137	97
	60mm	0.0358	0.0331	8	0.0320	11	0.0125	65	0	100
6mm	24mm	0.1120	0.0980	13	0.0640	43	0.0710	37	0.058	48
	30mm	0.3440	0.3640	N/A	0.3800	N/A	0.4400	N/A	0.328	5
	65mm	0.4200	0.4400	N/A	0.3520	16	0.1420	66	0.024	94
	81mm	0.2120	0.1450	N/A	0.0560	74	0.0170	92	0.009	96
	120mm	1.0000	1.2500	N/A	1.1000	N/A	0.5000	50	0.096	90
10mm	30mm	0.5200	0.5200	0	0.3000	42	0.2840	45	0.236	55
	60mm	0.6250	0.6250	0	0.6250	0	0.6250	0	0.625	0

Tables 7–9 show information on the lowest recorded exfiltration level for each experimental run.

Table 7. Changes in exfiltration rate for the 10mm hole; defect discharging to air

Defect geometry and gap width **10mm hole**	**Head**	**Flow in pipe (l/s)**	**Exfiltration rate (l/s) t = 0**	**Lowest recorded exfiltration rate (l/s)**	**Time (minutes) for lowest exfiltration rate**	**Lowest recorded exfiltration rate as a % of flow in pipe**
3mm	20mm	0.12	0.0088	0.0006	80	0.50
	45mm	0.64	0.042	0.0003	76	0.05
	64mm	2.2	0.02	0	80	0.00
	120mm	8	0.0402	0	16	0.00
6mm	23mm	0.12	0.0249	0.0223	4	18.58
	24mm	0.8	0.0207	0.015	92	1.88
	60mm	1	0.0273	0.0001	28	0.01
	65mm	2.1	0.0323	0	16	0.00
	80mm	2.3	0.05	0	40	0.00
	81mm	2.6	0.027	0	16	0.00
	124mm	9.33	0.096	0	60	0.00
	128mm	8.48	0.0262	0.0001	48	0.00
10mm	33mm	0.92	0.0467	0.048	12	5.22
	60mm	3.2	0.0358	0	56	0.00

Table 7 shows the lowest recorded exfiltration levels observed in each experiment for the 10mm hole, which are of the order of 10^{-2} to 10^{-4} l s^{-1} with complete sealing occurring for 50% of the experimental runs. As already noted, the more effective sealing is associated with higher heads, except in the case of the 10mm wide gap. There is considerable variation in the time taken to reach a complete seal and this is probably due to randomness in the time of arrival of suitable sealing material in the sewer flow.

Tables 8 and 9 show the lowest recorded levels in each experiment for the radial defects, and for the 3mm and 6mm gap size these are again of the order of 10^{-2} to 10^{-4} l s^{-1}, with more effective sealing occurring at higher heads. However, much higher rates of the order of 10^{-1} l s^{-1} were recorded for the 10mm gap widths. The experimental test durations recorded for these lowest levels were generally the times at which the experiments were terminated, normally because the exfiltration rate had reached an apparent equilibrium or in a few cases due to a sudden drop in the pipe flow rate due to the pump being blocked by ragging. Generally, the exfiltration rates tended towards an equilibrium value after between 60 and 120 minutes. The rates of exfiltration, as a percentage of the flow in the pipe were, in most cases, between 0.1 to 1%. However, values of around 5% of flow for lower heads and between 15% and 30% for the largest gaps were found.

Table 8. Changes in exfiltration rate for the ½ vertical radial defect discharging to air.

Defect geometry and gap width **½ vertical**	**Head**	**Flow in pipe (l/s)**	**Exfiltration rate (l/s) t = 0**	**Exfiltration lowest recorded rate (l/s)**	**Time (minutes) for lowest exfiltration rate**	**Lowest recorded exfiltration rate as a % of flow in pipe**
3mm	20mm	0.12	0.0183	0.007	80	5.83
	45mm	0.64	0.0613	0.0003	76	0.05
	64mm	2.2	0.109	0.0034	76	0.15
	120mm	8	0.1567	0.009	60	0.11
6mm	24mm	0.8	0.102	0.048	52	6.00
	24mm	0.12	0.102	0.078	24	65.00
	47mm	1.2	0.128	0.061	60	5.08
	65mm	2.1	0.33	0.0267	120	1.27
	81mm	2.6	0.112	0.0052	64	0.20
	83mm	4.19	0.4675	0.0367	48	0.88
	124mm	9.33	0.032	0.007	60	0.08
10mm	31mm	0.72	0.324	0.094	92	13.06
	57mm	2.2	0.43	0.4	56	18.18

Table 9. Changes in exfiltration rate for the ½ horizontal radial defect discharging to air.

Defect geometry and gap width ½ horizontal	Head	Flow in Pipe (l/s)	Exfiltration rate (l/s) t = 0	Exfiltration lowest recorded rate (l/s)	Time (minutes) for lowest exfiltration rate	Lowest recorded exfiltration rate as a % of flow in pipe
3mm	20mm	0.12	0.102	0.012	80	10.00
	45mm	0.64	0.1327	0.0003	76	0.05
	64mm	2.2	0.184	0.0005	80	0.02
	120mm	8	0.398	0.0011	32	0.01
6mm	24mm	0.8	0.112	0.048	88	6.00
	30mm	0.78	0.344	0.098	120	12.56
	65mm	2.1	0.42	0.01	112	0.48
	81mm	2.6	0.212	0.0077	64	0.30
	120mm	8	1	0.0183	100	0.23
	124mm	9.3	0.5	0.0042	60	0.05
10mm	30mm	0.7	0.52	0.204	80	29.14
	60mm	2	0.625	0.625	60	31.25

4.1.2 Estimation of the ultimate equilibrium exfiltration levels.

The experimental design and the nature of the sewage did not allow extended runs over many hours to be undertaken, which would have allowed a fuller assessment of the concept of an ultimate equilibrium rate of exfiltration for the various defects and gap sizes. A data set of similar heads on a selected defect geometry was assembled to enable a preliminary assessment to be made of the consistency of the exfiltration rates between runs for a particular gap, defect and head and to assess the feasibility of extrapolating the results over a longer timescale. The most useful data set for this purpose was for a vertical radial defect with a 6mm gap, discharging to air, with a range of heads between 25 – 65mm having been monitored.

The first 20 minutes of data were omitted for each subset to remove the influence of the early fluctuations in sealing and resealing phenomenon observed earlier in this report. The data were analysed using Minitab and a function was fitted to the data as shown in Figure 12.

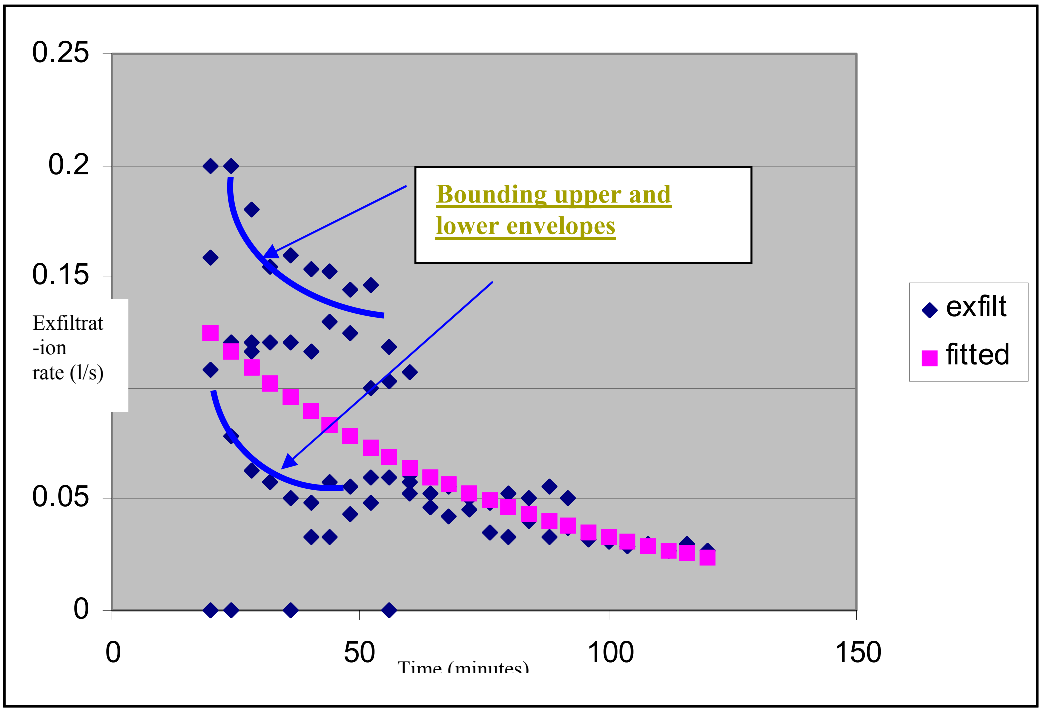

Figure 12. Estimation of an exfiltration rate function for the ½ vertical geometry and 6mm gap.

The best fit function was confirmed (Box-Cox method) as logarithmic, defined by

$$\text{Exfiltration} = \exp(-1.76 - 0.0166 \times \text{time}) \quad (r^2 = 56\%)$$

Whilst it is clear from the data scatter that this fit is not ideal, it nevertheless enables an extrapolation to predict an ultimate exfiltration rate and to assess the robustness of the prediction. It could be argued from the data that the bounding envelope curves support the extrapolation to the lower tail of the fitted curve, particularly if the four near zero values were to be omitted. Table 10 shows the result of this extrapolation.

Table 10. Range of extrapolated exfiltration rates, expressed as 95 percentiles.

Time (minutes)	Lower 95 percentile predictions for exfiltration rates (l/s)	Upper 95 percentile predictions for exfiltration rates (l/s)
240	0.0011233	0.009245
480	0.0000101	0.0003562
960	0.0000000	0.0000007

Whilst the range of prediction is wide, the extrapolation suggests that exfiltration rates could reduce from those observed in the experiment by an order of magnitude to 10^{-4} - 10^{-5} l s^{-1} over an 8 hour period and approach zero after around 16 hours. This is in keeping with previous work with discharges to sand where rates in the order of 10^{-6} l s^{-1} were observed within a few hours (Vollerstsen and Hvitved-Jacobsen, 2003). The limited nature of the data set and the poor fit of the function prevents any clear conclusions from being drawn, but the temporal trend of extended reduction rates should be investigated particularly for the largest gap sizes having the highest potential for losses.

4.2. Exfiltration to a gravel surround

This section describes a series of experiments in which a 150mm surround of 10mm pea gravel was added to the test box to simulate the ground conditions in the immediate vicinity of a sewer pipe. Exfiltration rates, flow logger readings at the inlet and outlet positions of the pipe of the test rig, and the head over the weir (for lower flows only), were recorded at four minute intervals as previously described for the free discharge experiments. Representative graphical interpretations of the results are shown in Figures 13 and 14.

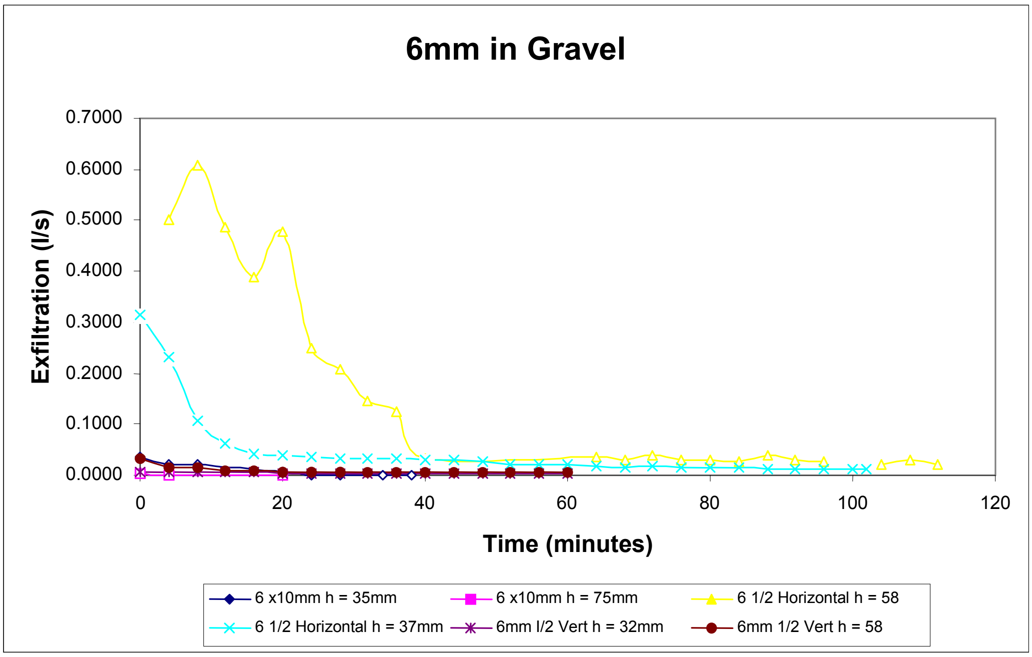

Figure 13. Temporal variations in exfiltration rates for 6mm gap defects exposed to gravel.

Figure 13 shows the results from a series of runs with a 6mm gap. Rapid and effective sealing can be seen at both the monitored heads for the 10mm hole and the vertical radial defect. The horizontal radial defect under a low head achieves efficient sealing from an initial higher exfiltration rate but at a moderate head the same defect geometry takes 40 minutes to reach a low constant exfiltration rate.

Figure 14 shows the corresponding runs for a 10mm gap and in this case rapid and effective sealing was eventually observed for all defects. A comparison of Figures 13 and 14 with Figures 10 and 11 suggests that the presence of gravel leads to more uniform and effective sealing. It can also be seen that gravel has a more pronounced effect under lower heads and with larger defects where less effective sealing had been observed for the free discharge runs.

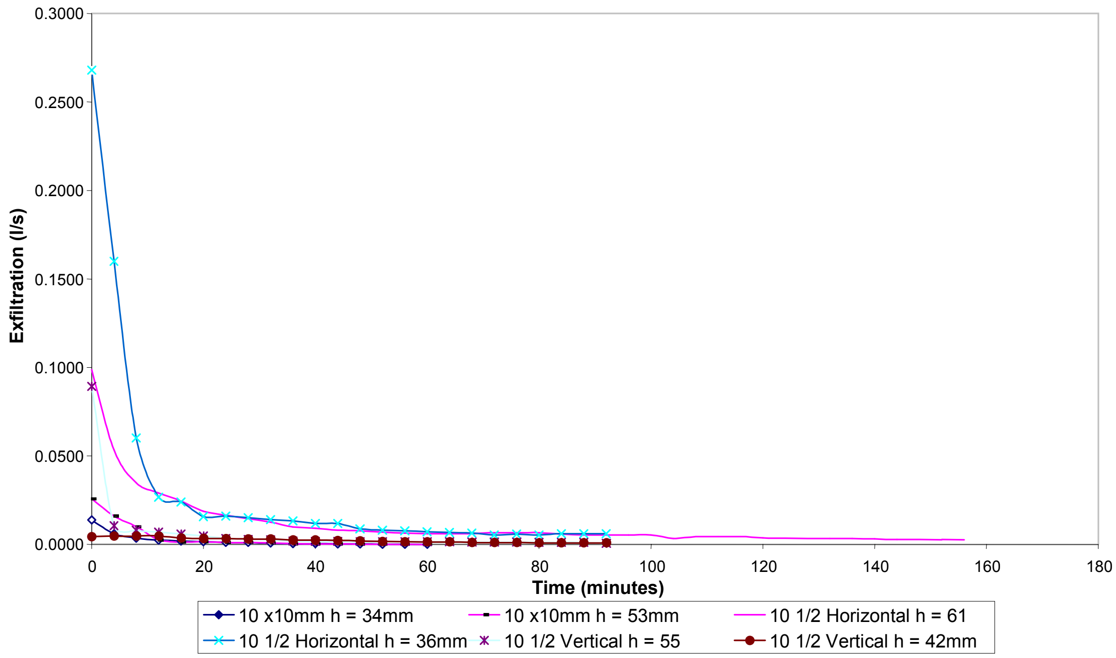

Figure 14. Temporal variations in exfiltration rates for 10mm gap defects exposed to gravel.

The influence of the gravel on exfiltration rates is illustrated more clearly in Figures 15 to 18 below. Figure 15 shows the impact on the smallest defect, the 10mm hole, with a 6mm gap under a moderate head of approximately 67mm. More rapid initial sealing can be observed in the presence of gravel, although essentially complete sealing was observed in both cases.

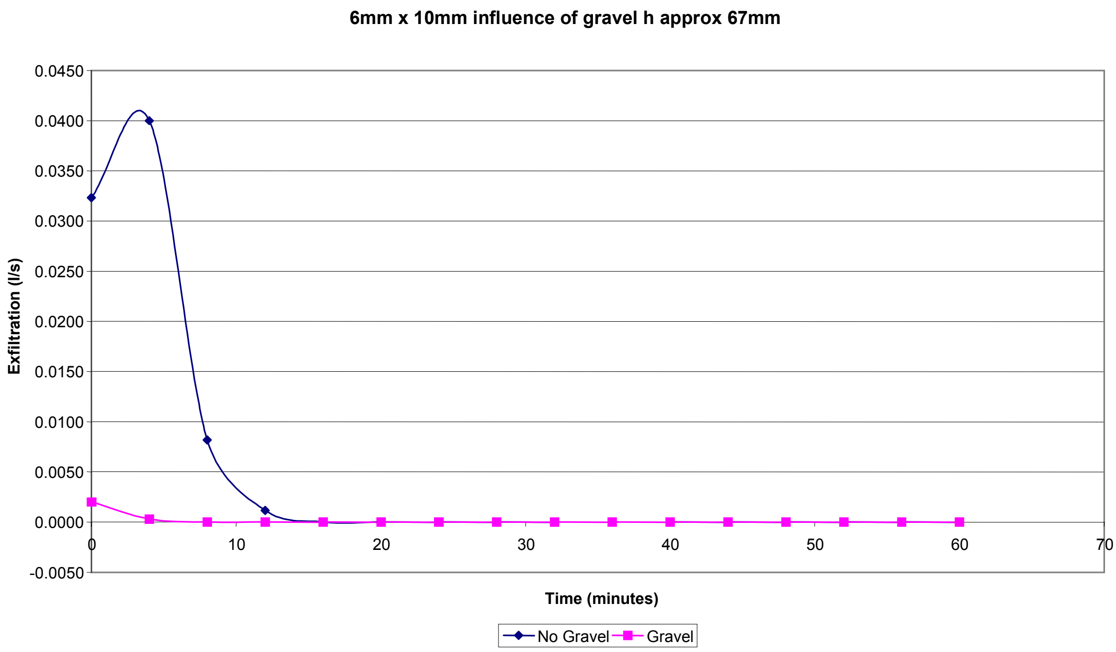

Figure 15. Comparison of exfiltration rates in the presence and absence of gravel for a 6mm x 10mm defect at a single head.

Figure 16 compares the temporal trend in exfiltration rates for the same defect and head but for a larger gap size of 10mm. More rapid sealing was observed in the gravel run and again both tests demonstrated the attainment of the same minimal exfiltration rates.

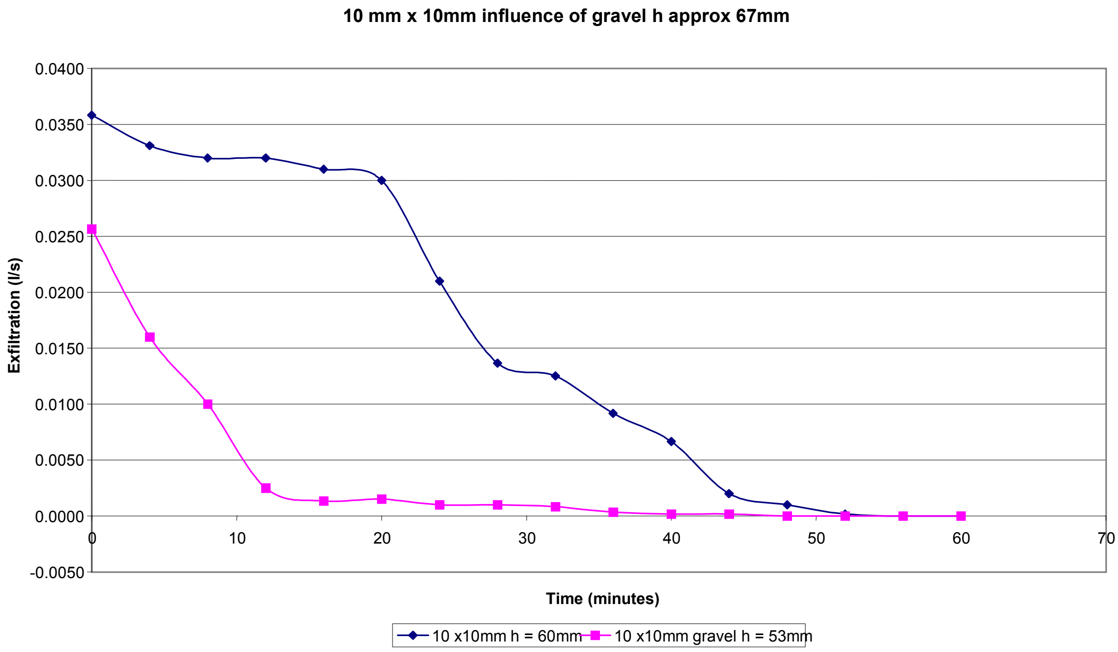

Figure 16. Comparison of exfiltration rates in the presence and absence of gravel for a 10mm x 10mm defect at a single head.

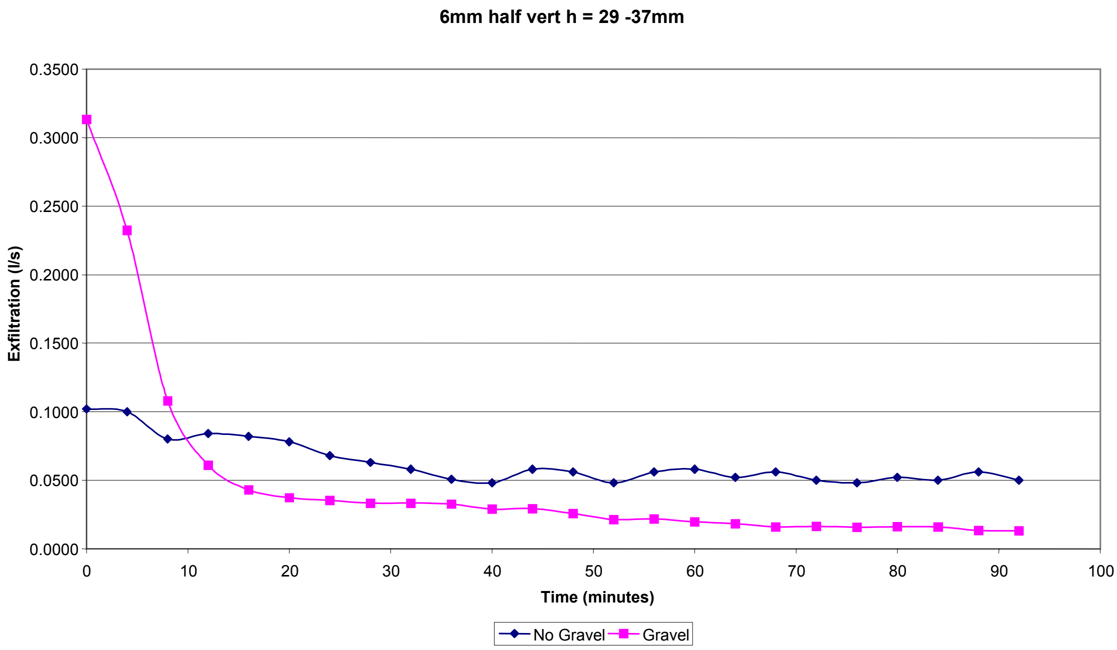

Figure 17. Comparison of exfiltration rates in the presence and absence of gravel for a 6mm ½ vertical defect at a single head

Figure 17 shows the impact produced by a larger radial defect (1/2 vertical radial) with a 6mm gap under a low head. Although the gravel run had a particularly high starting exfiltration rate, there is clear evidence of rapid sealing which was considerably greater than that previously seen for this configuration in the non-gravel runs. The consequences are progressively lower exfiltration rates from the defect surrounded by gravel after 10 minutes of exposure to sewage.

Figure 18 shows the dramatic effect of gravel for the larger defect (10mm gap; vertical radial defect) under a moderate head. Rapid initial sealing was observed with the gravel surround and the lowest recorded level was also very much lower than the non-gravel run where very limited sealing was observed. This could be due to the larger defect allowing more sealing material in the sewage to reach the gravel, resulting in more effective sealing of the gravel voids and ultimately leading to more effective sealing than had been observed in some runs for the smaller defects in gravel.

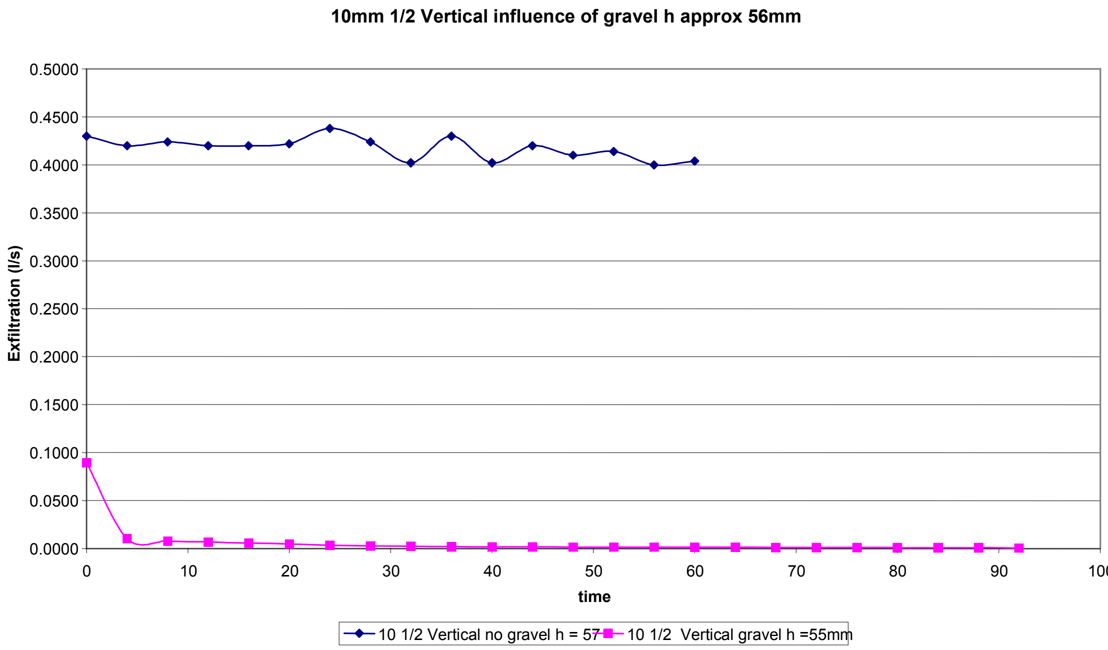

Figure 18. Comparison of exfiltration rates in the presence and absence of gravel for a 10mm ½ vertical defect at a single head.

The graphical presentation of the data suggest that the introduction of gravel has resulted in more rapid and more effective sealing across the range of defects compared to the results observed for the non-gravel runs.

4.2.1. Analysis of data obtained for discharge to gravel.

The key points arising from the analysis of the data obtained from the experiments involving exfiltration to gravel are shown in Tables 14 to 16 and these allow more detailed evaluation of the results.

Table 14. Variations in exfiltration rate over time for 10mm hole geometries; defects discharging to gravel.

Defect geometry and gap width **10mm Hole**	**Head**	**Exfiltration rate (l/s)** **t = 0 minutes**	**Exfiltration rate (l/s)** **t = 4 minutes**	**% reduction in exfiltration rate** **t = 4 minutes**	**Exfiltration rate (l/s)** **t = 12 minutes**	**% reduction in exfiltration rate** **t = 12 minutes**	**Exfiltration rate(l/s)** **t = 32 minutes**	**% reduction in exfiltration rate** **t = 32 minutes**	**Exfiltration rate (l/s)** **t = 60 minutes**	**% reduction in exfiltration rate** **t = 60 minutes**
6mm	35mm	0.0367	0.0219	40.33	0.0056	84.74	0.0008	97.82	0	100.00
		0.002	0.0003	85.00	0	100.00	0	100.00	0	100.00
10mm	32mm	0.0137	0.006	56.20	0.0023	83.21	0.0007	94.89	0	100.00
	53mm	0.0257	0.16	N/A	0.0025	90.27	0.0008	96.89	0	100.00

Table 15. Variations in exfiltration rate over time for ½ vertical geometries; defects discharging to gravel.

Defect geometry and gap width **½ Vertical**	**Head**	**Exfiltration rate (l/s)** **t = 0 minutes**	**Exfiltration rate (l/s)** **t = 4 minutes**	**% reduction in exfiltration rate** **t = 4 minutes**	**Exfiltration rate (l/s)** **t = 12 minutes**	**% reduction in exfiltration rate** **t = 12 minutes**	**Exfiltration rate (l/s)** **t = 32 minutes**	**% reduction in exfiltration rate** **t = 32 minutes**	**Exfiltration rate (l/s)** **t = 60 minutes**	**% reduction in exfiltration rate** **t = 60 minutes**
6mm	32mm	0.0063	0.0057	9.52	0.0053	15.87	0.0032	49.21	0.0027	57.14
	58mm	0.0323	0.014	56.66	0.0057	82.35	0.006	81.42	0.006	81.42
10mm	42mm	0.0043	0.0047	N/A	0.0047	N/A	0.003	30.23	0.0013	69.77
	55mm	0.0893	0.0105	88.24	0.0068	92.39	0.0025	97.20	0.0014	98.43

Table 16. Variations in exfiltration rate over time for ½ horizontal geometries; defects discharging to gravel.

Defect geometry and gap width **½ Horizontal**	**Head**	**Exfiltration rate (l/s) t = 0 minutes**	**Exfiltration rate (l/s) t = 4 minutes**	**% reduction in exfiltration rate t = 4 minutes**	**Exfiltration rate (l/s) t = 12 minutes**	**% reduction in exfiltration rate t = 12 minutes**	**Exfiltration rate (l/s) t = 32 minutes**	**% reduction in exfiltration rate t = 32 minutes**	**Exfiltration rate (l/s) t = 60 minutes**	**% reduction in exfiltration rate t = 60 minutes**
6mm	37	0.3133	0.2325	25.79	0.061	80.53	0.0333	89.37	0.0167	94.67
	58	0.5	0.5	0.00	0.486	2.80	0.144	71.20	0.037	92.60
10mm	36mm	0.268	0.16	40.30	0.0267	90.04	0.014	94.78	0.007	97.39
	61mm	0.0987	0.0533	46.00	0.029	70.62	0.0125	87.34	0.006	93.92

The initial exfiltration rates (t = 0) are very low in a number of cases, which suggests very rapid initial blinding of the gravel surface during the stabilisation period of the runs. Examples of low initial rates were also observed in the non- gravel runs, but this phenomenon is more frequent for the gravel runs. In contrast to the non-gravel runs, improved sealing occurred in almost every case after 4 minutes, represented by values between 10% and 90% in the reduction of the initial exfiltration rates. After 12 minutes, exfiltration had reduced by more than 70% of initial levels for nine of the twelve runs with the most effective sealing, in most cases, being associated with the higher heads. Further reductions in the exfiltration rate can be observed after 12 minutes in every run with reductions in excess of 95% for the 10mm hole and between 40 and 97% for the radial defects.

After 60minutes, exfiltration rates in nine of the twelve 12 runs had dropped by more than 92% of their starting values, with complete sealing of the 10mm holes. The other three results are associated with the vertical radial defects with reductions ranging between 57 and 81% of the initial exfiltration values. It is thought that this is a result of randomness in the arrival of sealing material, as there are no obvious reasons why sealing of the vertical radial defect should be less effective than that of the equivalent horizontal configuration.

Tables 14 to 16 confirm the earlier conclusion from the graphs that the gravel surround leads to more rapid sealing for the full range of defects compared to the effects observed during the non gravel runs.

Tables 17 to 19 present a further analysis of the exfiltration results for each experimental gravel run with a particular emphasis on the lowest recorded values.

Table 17. Changes in exfiltration rate for the 10mm hole; defect discharging to gravel.

Defect geometry and gap width **10mm hole**	**Head**	**Flow in pipe (l/s)**	**Exfiltration rate (l/s)** **t = 0 minutes**	**Lowest recorded exfiltration rate (l/s)**	**Time (minutes) for lowest exfiltration rate**	**Lowest recorded exfiltration rate as a % of flow rate**
6mm	35mm	0.5	0.0367	0	36	0.00
			0.002	0	12	0.00
10mm	32mm	0.48	0.0137	0	52	0.00
	53mm	1.15	0.0257	0	48	0.00

Table 18. Changes in exfiltration rate for the ½ vertical radial defect; discharging to gravel.

Defect geometry and gap width ½ vertical	Head	Flow in pipe (l/s)	Exfiltration rate (l/s) t = 0 minutes	Lowest recorded exfiltration rate (l/s)	Time (minutes) for lowest exfiltration rate	Lowest recorded exfiltration rate as a % of flow rate
6mm	32mm	0.6	0.0063	0.0025	56	0.42
	58mm	2.01	0.0323	0.0055	24	0.27
10mm	42mm	1	0.0043	0.0008	80	0.08
	55mm	1.63	0.0893	0.0005	92	0.03

Table 19. Changes in exfiltration rate for the ½ horizontal radial defect; discharging to gravel.

Defect geometry and gap width ½ horizontal	Head	Flow in pipe (l/s)	Exfiltration rate (l/s) t = 0 minutes	Lowest recorded exfiltration rate (l/s)	Time (minutes) for lowest exfiltration rate	Lowest recorded exfiltration rate as a % of flow rate
6mm	37mm	0.4	0.3133	0.012	96	3.00
	58mm	2.01	0.5000	0.021	104	1.04
10mm	36mm	0.32	0.268	0.0053	72	1.66
	61mm	1.9	0.0987	0.0027	144	0.14

Table 17 shows the lowest recorded levels in each experiment for the 10mm hole with complete sealing occurring on every run including the 10mm gap. It should be noted that only partial sealing had occurred in the non-gravel runs for the wider gaps.

Tables 18 and 19 show the lowest recorded levels in each experiment for the radial defects which are in the order of 10^{-3} to 10^{-4} l s^{-1}, for all cases, and are significantly less than the 10^{-1} l s^{-1} which was recorded for the 10mm gap width in the non-gravel runs. The time recorded against these lowest levels is generally the time at which the experiment was terminated, normally because the exfiltration rate had reached zero or an apparent equilibrium. The exfiltration rates were tending toward equilibrium between 12 and 144 minutes, which is shorter than for the non-gravel runs.

The rates of exfiltration as a percentage of flow in the pipe are shown in the final columns of each of the above three Tables. These were in most cases, between 0.1 to 1% of the flow, but rates as high as 1 - 3% were observed for the radial defects. Hence, Tables 17 to 19 confirm the earlier conclusion from the graphs that the gravel surround leads to more effective sealing of the full range of defects than had been observed in the non-gravel runs.

5. TRACER EXPERIMENTS USING THE TEST RIG.

As described previously, an advantage of the experimental rig is that it allows the direct measurement of exfiltration rates through the collection of a measured exfiltration volume within a specified time. However, this technique is clearly not feasible within an operational sewer system where direct access to the exfiltration site is not possible. An alternative method to determine exfiltration is to use conservative tracers which are able to follow the different flow paths within the system. This approach has been advocated as part of the APUSS project through the use of sodium chloride as the tracer with in-sewer detection using conductivity probes (Rieckermann and Gujer, 2002). A major disadvantage of the use of this tracer is that very high dosing concentrations are required to overcome the natural background salinity of sewage.

Tracers which can be utilised at lower dosing concentrations due to their negligible presence in natural waters and sewage are lithium and bromide. However, direct monitoring probes are not readily available for these ions and therefore measurement techniques have to be based on continuous injection of the tracer with downstream measurement of tracer concentrations within collected grab samples. Synthetic dyestuffs are extremely sensitive tracers because of their ease of detection at very low concentrations. This is particularly true for fluorescent dyes such as Rhodamine WT which has been widely used as both a surface water (Upstill-Goddard *et al*, 2001) and groundwater (Sutton *et al*, 2000) tracer. Efficient detection of this tracer is possible using a purposely designed fluorimeter probe which is able to measure either instantaneous plug doses or continuous doses of the tracer. A reported disadvantage of Rhodamine WT is its tendency to be removed from solution by adsorption to suspended solids (Vasudevan *et al*, 2001). This could obviously lead to serious problems within sewage where the high turbidities can also enhance the fluorescent signal. Ellis *et al* (2003) have developed a way of overcoming the latter effect but studies of the interactions between Rhodamine WT and sewage solids have proved inconclusive.

The experimental rig provides an ideal opportunity to investigate the performances of different tracers as monitoring tools for sewer exfiltration. The pathways taken by different tracers can be relatively easily assessed and the results of exfiltration rates can be compared with those obtained by direct exfiltration volume measurement under identical conditions. In this section of the report we concentrate on a series of experimental runs using Rhodamine WT as the tracer and also compare the use of lithium in the form of lithium chloride.

5.1 Tracer Methodology

The tracer solution was introduced into the pipe on the outside of the connecting bend leading to the 10m stretch of horizontal pipe (see Figure 22). A constant dosing rate of 20ml/minute (0.3333ml/s) was achieved using a Masterflex peristaltic pump.

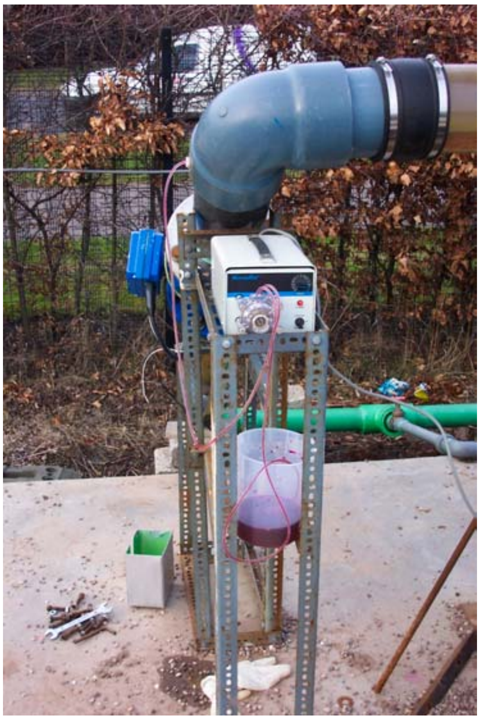

Figure 18. Introduction of tracer during dosing experiments in the experimental rig

This flow rate was chosen to ensure that efficient mixing occurred with the sewage flows which typically varied between 1 and 5 l/s. To facilitate this mixing process, all exfiltration experiments were performed at the final exfiltration box with the other pipe defect positions being completely sealed.

Prior to commencing the experiments it was essential to calculate the optimum required tracer dosing concentration in order assist the mixing process and also to achieve a readily detectable tracer concentration at the downstream measurement point following the dilution process. For the Rhodamine WT tracer, the objective was to produce a downstream concentration in the range 0 to 200ppb. If the sewage flow rate was 1l/s, the identified tracer dosing rate would give an overall dilution of 3000 times. Therefore, an ideal dosing concentration for Rhodamine WT would be 500mg/l, producing a predicted downstream concentration of 166.7ppb. A similar relationship between dosing concentration and downstream detectable concentration was feasible for lithium in the form of lithium chloride.

Following the commencement of the introduction of tracer at the dosing point, exfiltration samples were collected at 4 minute intervals. The fluorescent signal in the collected exfiltration sample was measured directly using a Turner Designs SCUFA probe, which had previously been calibrated between 'zero' (using raw sewage) and 200ppb Rhodamine WT (using a solution prepared in raw sewage). Hence, simultaneous measurements were obtained for the exfiltration volume and the Rhodamine WT concentration in the collected exfiltrate.

In the case of the lithium tracer, it was not possible to measure the concentrations directly in the field. Therefore, samples of the collected exfiltration were returned to the laboratory for lithium analysis by flame emission spectrophotometry. The instrument was calibrated using standards containing 0mg Li/l, 0.25mg Li/l and 0.5mg Li/l made up in raw sewage. This was necessary to compensate for the interference which occurs to the lithium signal due to the high background concentrations of sodium within sewage.

5.2. Tracer Results

The calculation of percentage exfiltration using tracers is based on comparing the tracer loading at the point of exfiltration with that introduced at the dosing point. The latter is known from a combination of the dosing concentration and the dosing rate. The loading of the tracer in the exfiltration can be calculated from the measured concentration of the tracer within a known volume of exfiltration. In the sewer rig experiments, a measured volume of tracer was obtained over a specific time to allow a direct calculation of the exfiltration rate. This was then compared with the value derived from the tracer studies.

The initial tracer experiments were conducted with the 6mm spacer in the ½ vertical configuration fitted into the pipe at the exfiltration point. Rhodamine WT (500mg/l) was introduce at a dosing rate of 0.3333ml/s (loading rate of 166.7µg/s) into a sewage flow rate of 1.221 to 1.242l/s (head within the pipe = 39 mm). This experiment was repeated using lithium as the tracer (loading rate of 166.7µg/s) into a sewage flow of 1.071 to 1.092l/s (head within the pipe = 36 mm). The aim was to achieve identical conditions in both these experiments but the flows in the second experiment were slightly reduced compared to the first one and hence the results from the two experiments cannot be compared directly. The results obtained, in terms of percentage exfiltration relative to the sewage inflow, are shown in Figure 19. The overall trends in both experiments clearly demonstrate the previously identified decreasing exfiltration over time as effective sealing of the gap occurs.

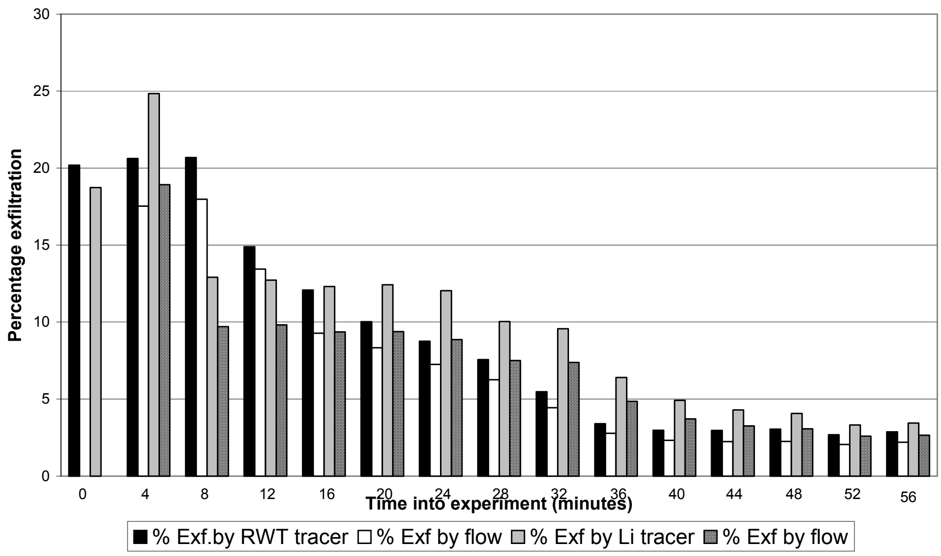

Figure 19. Comparison of percentage exfiltration by tracer and flow measurements through a 6mm x ½ vertical gap configuration.

For both tracers, the estimated percentage exfiltration predicted from tracer loadings is consistently higher than that determined by measurement of exfiltration volume. This is the opposite to what would have been expected if adsorption of the tracer was occurring. Lithium has been shown to be a conservative tracer in the presence of sewage and therefore the results of these experiments indicate a similar behaviour for Rhodamine WT under the conditions existing within the sewer rig.

The consistent deviation between the tracer and flow predictions for exfiltration may be due to the initial experimental design which involves collecting the exfiltrate in a holding reservoir (capacity ~10l) before it reaches the measuring apparatus. The effect of this 'mixing volume' will be to average out the changes in exfiltrate tracer concentration which occur relative to the pipe flow rates and the variable exfiltration rates thus preventing a rapid and completely realistic response in tracer concentration in relation to other changes within the system.

A more practical design for monitoring the tracer loading in the exfiltrate would be to keep the overall exfiltration flow rate constant by topping up with sewage as required, and allowing the tracer concentration to be the only variable. Such an approach would be particularly appropriate when using Rhodamine WT because continuous monitoring of the tracer concentration can be efficiently recorded using the fluorimeter probe and data logger. The determination of such a continuous exfiltration response avoids the requirement for any physical flow measurements and eliminates the need to average results over a set time period (eg 4 minutes). Further work is necessary in order to perfect this procedure.

A second series of tracer experiments has been conducted with the exfiltration gap set at 3mm in the ½ horizontal configuration but using only Rhodamine WT as the tracer,. Three sets of experiments were completed at sewage heads within the pipe of 60mm, 45mm and 41mm, respectively. The results are shown in Figure 20.

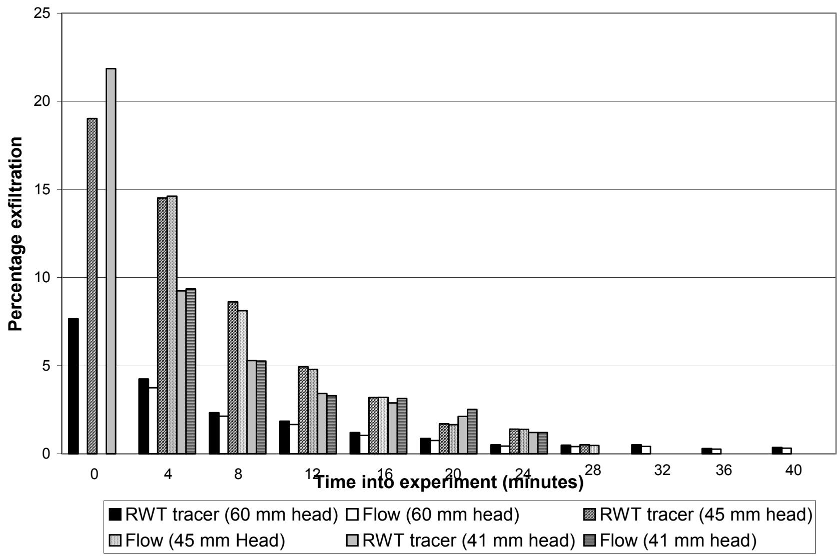

Figure 20. Comparison of percentage exfiltration determined by tracer and flow measurements for a 3mm x ½ horizontal gap configuration.

The percentage exfiltrations measured for the smaller gap size are generally lower than those observed for the 6mm gap and, as a consequence, there appears to be much better agreement between the results based on flow and those based on tracer measurements. This may be because tracer concentrations in the exfiltrate are less influenced by the 'mixing volume', prior to collection of the exfiltration sample, than was the case in the previous series of experiments. The lower percentage exfiltration values observed for the 60mm head experiment are partly a consequence of the higher average flow rates (3.21l/s) compared to the 45mm head (1.269 l/s) and 41mm head (1.167l/s) runs. However, the initial exfiltration flow rates were slightly lower for the higher flow rate experiment supporting the results discussed previously in this report. All three experiments demonstrated a temporal decrease in percentage exfiltration as progressive sealing of the 3mm gap occurred.

The final tracer experiment, using Rhodamine WT, was carried out using a 3mm gap in the ½ vertical configuration. The results obtained by the tracer and flow techniques are shown in Figure 21. There is a consistent pattern demonstrated by both techniques with the small discrepancies consistently suggesting slightly higher values from the direct flow measurements. The temporal trends for percentage exfiltration are very similar to those observed for the 3mm gap in the ½ horizontal configuration at an equivalent head (Figure 20; 41mm head) although there is evidence of a slight re-sealing of the gap between 16 and 24 minutes.

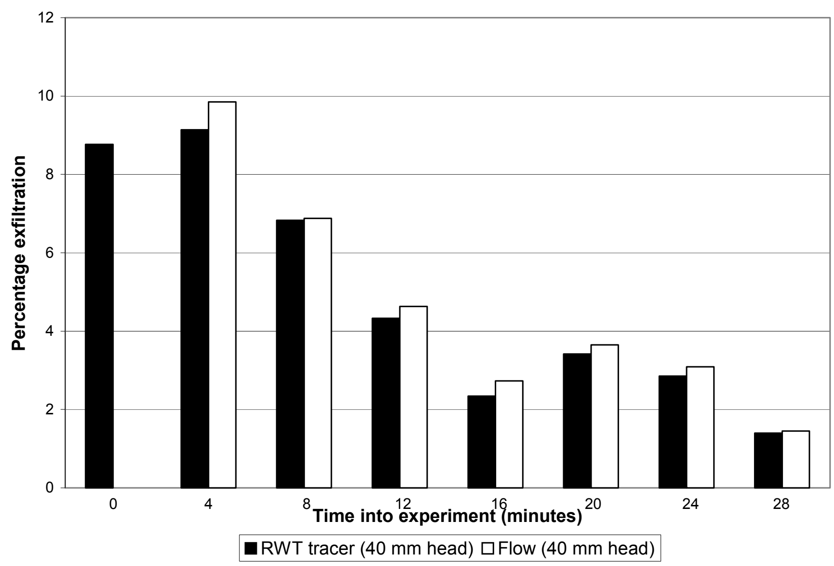

Figure 21. Comparison of percentage exfiltration determined by tracer and flow measurement for a 3mm x ½ vertical gap configuration.

6. CONCLUSIONS

Previously published research provides a wide range of estimates of exfiltration rates, derived through a variety of approaches. Exfiltration rates for individual defects have been determined in a number of experiments using water, synthetic sewage and sewage discharging to air, gravel and sand. The reported results have generally quoted exfiltration rates ranging between 10^{-2} -10^{-3} l s^{-1} with an estimate as low 10^{-6} l s^{-1} in one experiment on defects discharging sewage to sand.

The experiments described in this report have been designed to provide, for the first time, more detailed understanding of the exfiltration rates which may arise from a range of defects in a real sewerage system. The first series of experiments have provided an understanding of the patterns and rates of exfiltration through defects freely discharging to air. Complete sealing was eventually observed in 50% of the experiments for a 10mm hole and the other runs produced lowest recorded exfiltration rates of between 10^{-2} and 10^{-4} l s^{-1}. More effective sealing was associated with higher heads, except in the case of the widest gap (10mm). There was a considerable variation in the time taken to reach the lowest recorded exfiltration rates and this is probably due to randomness in the time of arrival of suitable sealing material in the sewer flow. The lowest recorded levels in each experiment for radial defects with 3mm and 6mm gap sizes were also in the order of 10^{-2} to 10^{-4} l s^{-1}, with more effective sealing occurring at higher heads. However, much higher exfiltration rates, of the order of 10^{-1} l s^{-1}, were recorded for the 10mm gap width. Generally, the exfiltration rates were tending toward equilibrium values after between 60 and 120 minutes. The rates of exfiltration as a percentage of flow in the pipe were also calculated and, in most cases, were between. 0.1 and 1%. However, values of around 5% for lower heads and between 15% and 30% for the largest gaps were found.

Components of the data set have been analysed by a grouping process to provide a prediction of exfiltration rates after 4, 8 and 16 hours. Whilst the predicted range was wide, the extrapolation suggests that exfiltration rates could reduce from those observed above by an order of magnitude to 10^{-4} - 10^{-5} l s^{-1} over an 8 hour period and approach zero after around 16 hours. This is in keeping with previous work with discharges to sand where rates of 10^{-6} l s^{-1} were observed within a few hours (Vollerstsen and Hvitved-Jacobsen, 2003). However it should be noted that the limited nature of the data set and the degree of fit of the selected function prevents any clear conclusions from being drawn.

The second group of experiments have provided an understanding of the impact of the gravel surround on exfiltration rates. Complete sealing eventually occurred on every run for the 10mm defect and the lowest recorded levels in each experiment for the radial defects were in the order 10^{-3} to 10^{-4} l s^{-1}. The exfiltration rates were tend toward equilibrium values over shorter run times than for the non-gravel runs with this condition typically being achieved between 12 and 144 minutes., The rates of exfiltration, expressed as a percentage of flow in the pipe, were, in most cases, between 0.1 to 1% of the flow, but rates of around 1 - 3% were observed for the radial defects. Overall, the gravel surround leads to more effective sealing of the full range of defects compared to those observed for the non-gravel runs.

The results of the test experiments can be scaled up to estimate leakage rates in lengths of sewers and in associated sub-catchments. As an initial estimation, assuming that sewer joints occur at intervals of 2.5m and that 10% of joints are defective in a 1 km sewer length, the wastewater rig outcomes for 10 mm wide defects in pipes in dry gravel surrounds would imply ultimate overall loss rates of between approximately 130 – 1300 m^3 km^{-1} $year^{-1}$. If this is scaled-up to the 25% Grade 5 and 4 sewers of the total 64,374 km network of Thames Water, this would yield losses due to exfiltration of between 2.1M and 21M m^3 $year^{-1}$. This is significantly less than the 1996 CIRIA reported value of 3% exfiltration and 109.5M m^3 $year^{-1}$, but is nevertheless still a concern for areas with abstractive groundwater beneath cities in the light of the requirements of the Water Framework Directive.

The required dosing conditions (flow rates and concentrations) have been optimised for the use of Rhodamine WT and lithium tracers to determine exfiltration rates within the experimental sewer rig. The performances of both tracers were successfully compared with direct volume measurements for the determination of percentage exfiltration values. The good agreement between the two approaches appears to be improved for smaller gap sizes but proposals have been put forward for overcoming these discrepancies through modifications to the experimental design. No evidence was found for adsorption of Rhodamine WT on to sewage solids during the pathways existing within the sewer rig and initial investigations suggest that the ease of detection of this tracer makes it ideal for further pilot scale experiments and eventually for use in real sewer experiments.

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