Exfiltration from sewers – Is it a serious problem?

D. J. Blackwood[1] *, D. J. Gilmour[1], J. B. Ellis[2], D. M. Revitt[2] and A. Staines[1]

[1]Urban Water Technology Centre, University of Abertay Dundee, Bell Street, Dundee, DD1 1HG
[2]Urban Pollution Research Centre, Middlesex University, Queensway, Enfield, London. EN3 4SA
**Corresponding author, e-mail d.blackwood@abertay.ac.uk*

ABSTRACT
This paper contends that estimates of exfiltration leakage from sewers, and the problems arising from it may be too high due to an underestimation of the "self-repairing" action of sewage and sewage sediments in raw sewage. Two aspects of a continuing programme of research are reported; (i) the measurement of exfiltration rates from a range of defects in a sewer pipe with pipe bedding effects simulated by a dry gravel trench surround to the pipe, and (ii) an assessment of the persistence of pathogens in the gravel and soil beneath the test rig pipe, using coliforms as a biological indicator. The results show that the introduction of a gravel surround resulted in more rapid and effective sealing across the entire range of defects tested compared to previously performed experiments with the defects discharging to air. Complete sealing eventually occurred on every run for a 10 mm x 10 mm defect situated at the invert of the sewer and the lowest recorded levels in each experiment for a 10 mm wide radial defect were of the order 10^{-3} to 10^{-4} l s^{-1}. These results have been scaled-up to estimate leakage rates in lengths of sewers and sub-catchments and levels significantly lower than previously estimated are indicated. Additionally, the pilot experiment to investigate the fate of biological contaminants in the exfiltrate suggests rapid reduction in microorganisms levels beneath the sewer pipe.

KEYWORDS
Exfiltration; Groundwater; Leakage rates; Pathogens; Sewer Defects

INTRODUCTION
A major study by Blackwood *et al* (2001) found little evidence of widespread environmental damage or major risks to public health arising from exfiltration in the UK. The study did note a possible problem of long term groundwater pollution and potential challenges to water companies arising from the requirements of the EU Water Framework Directive. There is however, a growing body of research which asserts that exfiltration from sewers can be a major contributor to groundwater pollution. Most recently, Reynolds and Barrett (2003) reporting on research, which was primarily targeted at the Birmingham and Nottingham conurbations of England, have suggested that there is "*conclusive evidence of sewage contamination of shallow and deep groundwater resources*". These authors, and others, develop their conclusions mainly from an assumption that the extent of known defects in sewer systems will inevitably lead to high rates of sewer exfiltration and that leakage modelling, based on theoretical assumptions and observed laboratory data, has provided confirming evidence of high leakage rates. However, there is a contrary view held within the UK water industry that exfiltration is unlikely to constitute a real problem because defects in

sewer systems are self-sealing due to the nature and constituents of the sewage effluent and that much of the noted urban groundwater contamination may be historical in nature e.g seepage from septic tanks etc.

Test rig studies by the authors and others (Blackwood *et al*., 2004; Ellis *et al*., 2003; Vollertsen and Hvitved-Jacobsen, 2003; Rauch and Stegner, 1994) have demonstrated a capacity for defects in sewer systems to be self-sealing due to sewer sediments and associated solids, wall slimes and biofilm growth which suggests that exfiltration rates in most sewers are likely to be much less than have been previously estimated. Further research has now been undertaken to investigate the impact of granular pipe bedding material on exfiltration rates and the survival rates of pathogens in soil beneath the sewer to enable a more robust and defendable quantification of the true extent and impact of exfiltration from sewers to be made. This work will inform the contentious debate on the impact of exfiltration from sewers.

Details of the test rig

The types and frequencies of defects which can lead to exfiltration in sewers have been reported to include defects at lateral connections (5%), leaking joints (48)%, and cracks and fractures (45%) (Decker, 1994). Consequently, the experimental rig was designed to simulate radial defects of varying geometries. The rig consists of a 10 m length of 150 mm clear plastic pipes running through three 2 m high boxes with flanged joints between the plastic pipes inside each of the boxes (Figure 1). Defects were simulated by placing plastic inserts of different thicknesses and geometries between the flanges of the joints (Figure 2). Three geometries were tested; a 10 mm 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 box was then filled with 10 mm gravel to simulate sewer pipe bedding effects. Exfiltration rates were measured for a range of gap sizes, geometries and flow heads. Sewage was drawn by a submersible pump from a live sewer at a depth of 3.5 m below the rig. Two flow monitors measured the inflow and outflow of 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 to the sewer. Further details of the equipment are given in Blackwood *et al* (2004).

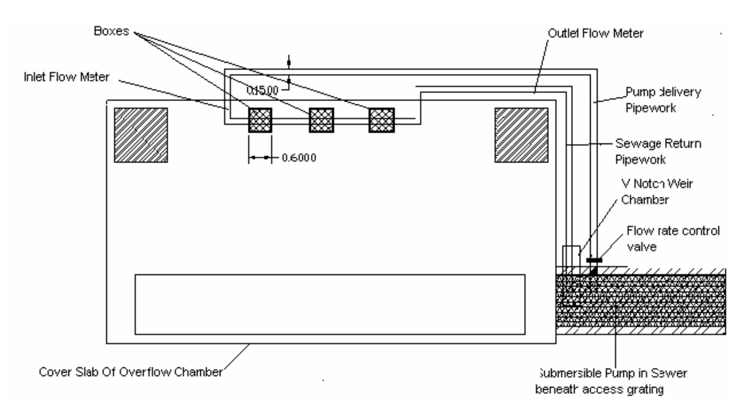

Figure 1. Schematic diagram of the experimental rig

Figure 2. View of interior of test box before addition of gravel showing pipe joining structure

PROGRAMME OF EXPERIMENTS

The object of the experiments was to provide further information on the self sealing effects of sewage with respect to a variety of sewer defects and with sewer pipe bedding effects being simulated by a gravel surround to the pipe. The range of experiments undertaken are shown in Table 1. A preliminary assessment of the persistence of pathogens in the exfiltrate in the gravel and soil beneath the test rig pipe was also undertaken.

Table 1. Details of the defect geometries and widths for the gravel experiments.

Defect	Runs
6mm x 10mm hole	2
6mm wide radial defect from pipe soffit to pipe crown on one side (Half Vertical)	2
6 mm wide radial defect from pipe invert to mid-way up the pipe on each side (Half Horizontal)	2
10mm x 10mm hole	3
10mm Half Vertical	2
10mm Half Horizontal	2

EXFILTRATION RATE RESULTS

Previous experiments have provided an understanding of the patterns and rates of exfiltration through defects discharging freely to air (Blackwood *et al*, 2004). Complete sealing was observed in 50% of the experiments for a 10 mm hole and the other defects resulted in minimum recorded exfiltration rates of between 10^{-2} and 10^{-4} l s^{-1}.

The gravel experiments demonstrated the impact of the trench backfill on exfiltration rates. Overall, the gravel surround leads to more effective sealing of the full range of defects compared to that observed for the non-gravel runs. The influence of the gravel on exfiltration rates is illustrated clearly in Figures 3 and 4 below. Figure 3 shows a comparison between leakage rates with a gravel surround and with a free discharge to air for a 10 mm x 10 mm defect under similar heads. More rapid sealing was observed in the gravel run although both experimental set-ups reached the same minimal exfiltration rates. Figure 4 shows the dramatic effect of gravel for the defect with the largest surface area in contact with the flow (10 mm gap; horizontal 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 defects 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. Overall, it was noted that the introduction of gravel resulted in more rapid and more effective sealing across the entire range of tested defects compared to the non-gravel runs, with complete sealing occurring on every run for the 10 mm defects and the lowest recorded levels in each experiment for the radial defects being between 10^{-3} and 10^{-4} l s^{-1}. In addition, the exfiltration rates tend towards equilibrium values over shorter run times than for the non-gravel runs. The rates of exfiltration, expressed as a percentage of total 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.

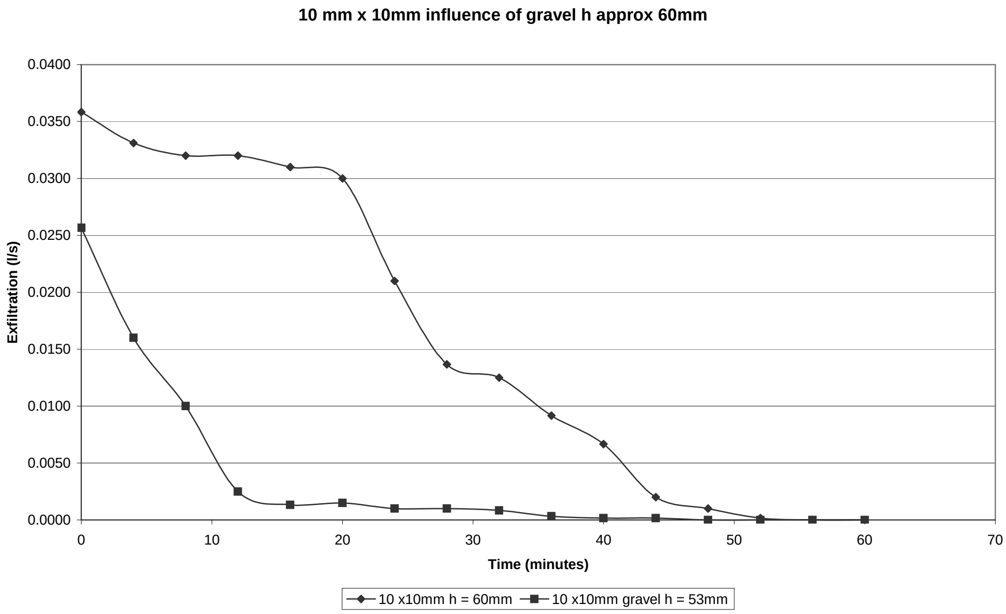

Figure 3. Comparison of exfiltration rates in the presence and absence of gravel for a 10 mm x 10 mm defect at a single head

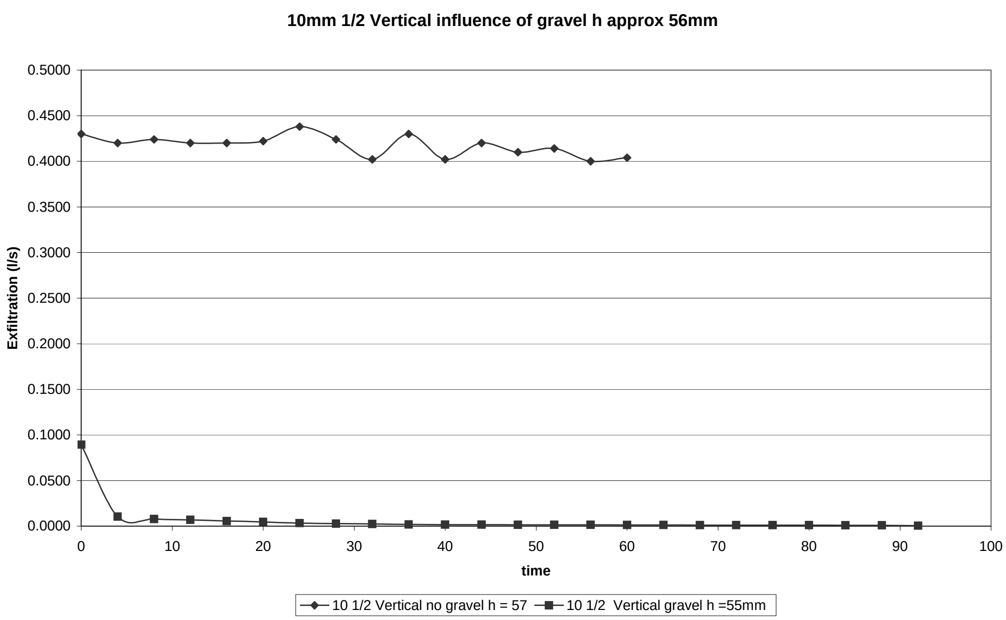

Figure 4. Comparison of exfiltration rates in the presence and absence of gravel for a 10 mm ½ vertical defect at a single head

Scaling up of results

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 2.5 m 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 130 – 1300 m^3 km^{-1} $year^{-1}$. If this is scaled-up, using a worst case assumption of 25% Grade 5 and 4 sewers for a sample catchment with 64,374 km network, this would yield losses due to exfiltration of between 2.1M and 21M m^3 $year^{-1}$. Even this worst case scenario produces an estimate that is significantly less than the reported values for a similarly sized UK catchment of 3% exfiltration and 109.5M m^3 $year^{-1}$ (CIRIA, 1996), but nevertheless may be a concern for areas with abstractive groundwater beneath cities in the light of the requirements of the Water Framework Directive. It must be remembered when considering even the estimated annual loss rates derived from the rig studies, that such leakage volumes assume initial starting conditions having a full potential for joint loss and are based on run times rarely exceeding a few hours. Even over such short time periods, it was observed that the pipe walls developed slime and algal growths and it is clear that longer term sedimentation would stimulate full biofilm and slime growth within the pipe. This would inevitably reduce exfiltration losses to a much greater extent than recorded for the short experimental runs. An extrapolation of a composite data set previously obtained from non-gravel runs in the test rig (Blackwood et al. 2004) suggests that levels would reduce to at least 10^{-6} to 10^{-8} l s^{-1} after 48 hours. However, there is also the counter possibility that high groundwater levels might reduce the hydraulic pore volume and colmation process at the sewer openings and joints, thus facilitating renewed leakage for short time periods. Such possibilities need to be investigated further.

SOIL EXPERIMENT

An empirical assessment of the potential risk that an exfiltrate might present to the below-ground environment is required and therefore a pilot experiment was devised to ascertain the spread of microorganisms in the gravel and soil immediately beneath a pipe. This approach used standard microbiological methods. Microbiological wastewater detection methods are well established and are used extensively in water legislation, such as the European Bathing Water Directive (EEC, 1976) and Quality of Surface Water for Drinking Directive (EEC, 1975), but have not commonly been used in detection of pollution to land. The methods employed are ideal for aquatic and marine systems due to the lack of *in-situ* micro-organisms.

In soil, however, there is a vast panoply of microorganisms, such as fungi competing for survival that are well adapted to utilise the nutrients present in wastewater, and which may out-compete the organisms that are naturally present in wastewater. The competitors in soil can also have a detrimental effect on the detection of faecal organisms and may produce negative results in laboratory analyses, which would have otherwise been positive. To address this issue, the analyses can be carried out to give preferential growth to faecal organisms and thus provide a simple **“**present/absent**”** test for faecal organisms in soil. The soil already contains many organisms that influence physical soil behaviour. A change in the bacterial make-up of the soil by the introduction of sewage, may affect the stability of the soil and its future functioning. There is therefore, a potential impact to the soil structure as well as to the pollutant capabilities of the sewage entering groundwater.

Methods
Enteric bacteria were selected as the prime biological indicator and samples were taken during a run on a selected head, joint opening and pipe surround with 40cm of sandy-clay-loam soil in the test box below the gravel surround. Samples for microbiological analysis were taken both from the gravel surround and at depths of 100 mm, 200 mm and 300 mm in the soil below the surround. The samples were analysed in the microbiology laboratory at the University of Abertay Dundee.

The soil was packed in the test box ensuring that the density was representative of normal soil conditions. The soil was 410 mm deep with a density of 1700 kg m^3. The soil moisture content was 6.06 %. Sample access holes in the test box were sealed with stoppers during the 2-hour exfiltration run and once the experimental run was finished the stoppers were removed and 400 mm lengths of metal tubing were used to recover core samples from the soil. The coring tubes were inserted to a depth of 200 mm i.e. to the centre of the box.

Laboratory analyses
The samples were grown in lauryl tryptose broth, which has been used extensively to select against fungi, a prominent competitor in the laboratory culture of soil microorganisms (Rosa *et al*, 1995; Somashekar *et al*, 2002). The samples were incubated at 37°C (optimum growth conditions for faecal organisms) for 48 hours. Following incubation, the cultures were grown up on agar plates to look for the presence of colony formations that would confirm the presence or absence of faecal organisms. The agar used was Eosin methylene blue agar (modified), which is an isolation medium used for the differentiation of enterobacteriaceae, a large family of organisms that is present in the gastrointestinal tract of mammals and therefore found in typical domestic wastewater. To make sure that fungi were reduced further, two fungicides (cyclohexamide and nystatin) were added to the agar in quantities sufficient to inhibit growth (Ley *et al*, 2002).

The agar plates were set up using 2 plates for each depth of soil core and were further divided into a dilution series from 10^0 to 10^{-2} of the original broth. Replicate plates were grown without fungicide present to assess the effects that fungi may have on the results These plates were also grown up for 48 hours, to generate final data on the presence/absence of faecal organism at the various depths described.

SOIL EXPERIMENT RESULTS

The results are represented using a basic 3+ point system in which 1+ is used to represent little growth and 3+ indicates abundant growth. A negative result (-) indicates the absence of faecal organisms or where they have been out-competed by another organism such as fungi. The results for the samples taken at the end of the run are presented in Table 2.

The results in Table 2a show that faecal organisms are totally out-competed when fungicides were not used in the agar plates. In the presence of fungicides (nystatin and cyclohexamide) abundant growth between depths of 0 and 100 mm is indicated (Table 2b). It can be concluded that the negative results at a depth of 300 mm (Table 2b) were due to an absence of organisms in the soil, and not over competition by fungi in the analysis.

Table 2. Results of the microbiological tests to detect faecal organisms in the soil below pipe defects.

a). Agar plates with soil and no fungicide

	Dilution Factor					
	10^{0}		10^{-1}		10^{-2}	
Depth from soil surface (mm)	Plate 1	Plate 2	Plate 1	Plate 2	Plate 1	Plate 2
0	-	-	-	-	-	-
100	-	-	-	-	-	-
200	-	-	-	-	-	-
300	-	-	-	-	-	-

b).Agar plates with soil and fungicide

	Dilution Factor					
	10^{0}		10^{-1}		10^{-2}	
Depth from soil surface (mm)	Plate 1	Plate 2	Plate 1	Plate 2	Plate 1	Plate 2
0	+++	+++	++	+++	+	+
100	+++	+++	+	-	-	-
200	+	+	-	-	-	-
300	-	-	-	-	-	-

There was abundant growth of faecal organisms at the surface of the soil, which is demonstrated by the abundance in the 10^{-1} dilution plates and further growth in the 10^{-2} dilution plates, which was not seen at any other depth. At a soil depth of 100 mm, there was still abundance in the undiluted sample with some growth at further dilutions. At 200 mm, there was little growth in the undiluted samples, with no further growth occurring below this depth. The absence of faecal organisms at a depth below 200 mm could be due to many factors including out competition over a short space of time, soil type/composition, natural filtration that occurs through soil and also the pattern of flow that the exfiltrate may take through the soil. A visual inspection of the soil on its removal from the test box confirmed that it had been well compacted and that good adhesion had been achieved between the soil and the sides of the box. There is no evidence to suggest that the flow of exfiltrate was directed to the sides of the test box and therefore the reduction in faecal organisms can be attributed to the natural processes in the soil.

Overall, the experiment suggests a rapid reduction in micro-organisms in the soil beneath the sewer pipe. This seems to support earlier work by Hagendorf *et al*, (1995) who noted a biologically active soil layer of 10 cm thickness around a defective sewer pipe within which the concentration of contaminants decreased from 90 to 10% of their levels in the sewer. However, given the many factors that may influence the noted results, further *in-situ* and *in-vitro* studies of exfiltration to soil need to be developed to fully understand the possible influence that a sewage exfiltrate can have on surrounding fauna and flora. Nevertheless, the experiment does demonstrate the feasibility and potential value of further work. The current microbiological tests were conducted on a loamy soil having a relatively high degree of cohesiveness dominated by Darcian matrix flow and showing little evidence of macro-fissuring. The softening and widening of such fissures within the unsaturated zone underlying sewer trenches could enhance exfiltration diffusion and associated sub-soil contamination but further work is necessary if the effects of such soil fissuring are to be defined and quantified.

CONCLUSIONS

The reported results above, support the view in the water industry that exfiltration rates are less than have been previously estimated due to the self sealing nature of defects in sewers and associated biofilm growth and that the impacts of exfiltration may have been overestimated. Consequently the risks to the water companies of exfiltration from sewers are likely to be low, but concern must remain over potential impact of persistent low-level losses in relation to the Water Framework Directive and the need to retain or restore all water bodies, including groundwater under major cities, to a good chemical and ecological status.

This may require water services providers to re-evaluate the extent to which sewer exfiltration contributes to groundwater pollution. Low levels of exfiltration have been recorded in the current experiments but the possibility of significantly lower levels occurring over a longer time period remains. However, the work suggests that pathogenic micro-organisms may be effectively removed in the soil and gravel around exfiltrating sewers.

However, further research is needed, to ensure that a robust and defendable quantification of the extent of exfiltration from sewers can be made and more extensive research should be undertaken on the survival of pathogens and other pollutants in the underlying unsaturated zone adjacent to sewers.

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