Factors influencing temporal exfiltration rates in sewer systems

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ABSTRACT

Sewer rig studies demonstrate a rapid exponential decline in exfiltration rates from gaps and joints to establish an ultimate steady-state equilibrium varying between $10^{-2} - 10^{-6}$ l s^{-1}, with minimum average daily rates per standardised leak area and sewer length varying between 0.02 – 9.0 l $d^{-1}cm^{-2}$ and 0.0002 – 2.0 l s^{-1} km^{-1} respectively. These loss rates are much larger than those derived from indirect monitoring/modelling studies which suggest losses between 1.4 x 10^{-5} – 0.179 l s^{-1} km^{-1}. The confusion regarding conflicting definitions of the colmation, transition, bridging and biofilm layers is addressed, and the significance of these clogging layers in terms of both impermeability and pressure head on the exfiltration loss is evaluated. The influence of variability and instability of flow and bed turbulence on determining critical leakage conditions following the onset of equilibrium steady-state is assessed. This challenges the generally held assumption that elevated head pressure condition is a necessary precursor for rupture of the clogging layers.

KEYWORDS

Exfiltration; sealing; colmation, bridging and clogging layers; equilibrium breakthrough.

INTRODUCTION

Exfiltration loss provides a direct measure of sewer performance in terms of the cost-effectiveness of sewer pipe hydraulics and as such offers a potential serviceability indicator for sewerage operators. The EU standard EN 752-2 recognises the potential problem of sewer leakage and demands the structural integrity of urban sewer systems including their water-tightness. Some level of exfiltration loss however, is regarded as being inevitable in sewer systems due to poor construction and materials, heavy traffic loadings as well as operational and service damage (Davies *et al*., 2001; Selvakumar *et al*., 2004). However past investment in the water industry has largely been driven by mandatory regulations and directives which have focussed principally on sewage treatment and combined sewer overflows (CSOs) and not on the sewer pipes which convey the wastewater effluent to treatment and discharge. It is only in the recent past that the industry has begun to address the historic neglect of the sewer network with for example, the UK water industry requesting £8.5 billion for sewer infrastructure rehabilitation under the most recent periodic review. Paralleling this increasing concern in operational sewer asset management, there have been a considerable number of direct and indirect studies on exfiltration losses and their potential effect on urban groundwater (Ellis and Bertrand-Krajewski, 2008). Whilst these studies have yielded largely contentious results, they nevertheless indicate that there is considerable potential for leakage during dry weather flows in old sewers as well as during extreme flow events.

The majority of direct sewer test rig studies have demonstrated a rapid exponential decline in exfiltration rates from open joints and other sewer leaks (Ellis *et al*., 2003; Vollertsen and Hvitved-Jacobsen, 2003; Blackwood *et al*., 2005a), and this pattern of decline has been confirmed from various direct field studies (Klinger *et al*., 2007). This decline has been noted to reach an ultimate or equilibrium steady-state exfiltration rate which varies between 10^{-2} to 10^{-6} l s^{-1} in the different studies, with minimum average daily rates per standardised leak area varying between 0.02 – 9.0 l d^{-1} cm^{-2}. These steady-state conditions are also typically reached within a period of hours to days. Figure 1 illustrates the typical decline trends observed for an

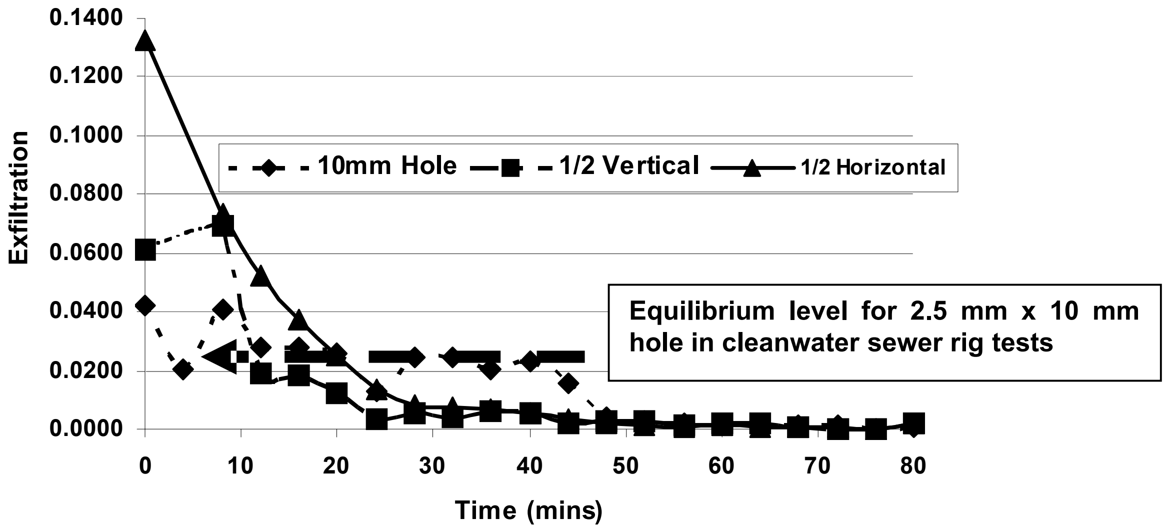

Figure 1. Temporal trends in exfiltration rates for varying 3 mm gap geometries and constant head (42 – 44 mm) in a live wastewater test rig. (After Blackwood *et al*, 2005b)

experimental wastewater rig in Dundee, Scotland under test runs for varying 3 mm gap geometries (10 mm hole, half-horizontal and vertical joint openings) and at near constant head under free-draining conditions i.e discharging to air. Thus there were no physical constraints on the material accumulating over the gap, so that any blockage could be fully attributed to the growth of a colmation layer plus any other additional sediment or biofilm layers i.e there was no scope for the development of a transition zone. The rapid exponential decline from initial high exfiltration rates is clearly illustrated with ultimate equilibrium rates for all gap geometries being just under 0.002 l s^{-1} and for the 30 mm^2 hole being 0.001 l s^{-1}. The reduction in final equilibrium level from 0.023 l s^{-1} in cleanwater test runs, to 0.002 l s^{-1} in the equivalent wastewater rig tests illustrates the effect of sediment on the loss rates. A similar but lower reduction in exfiltration rate from 0.045 l s^{-1} to 0.001 l s^{-1} was observed for a 10 mm long hole. Similar patterns of rapid reduction in leakage losses have been demonstrated in both test rig and field investigations where the pipe is trenched in a compacted gravel backfill (Vollersten and Hvitved-Jacobsen, 2003; Klinger *et al*., 2007; Ellis and Revitt, 2008).

However, the universal validity of the results derived from these direct sewer rig and field studies is not in line with a number of indirect modelling studies, which would suggest much lower levels of exfiltration losses (Yang *et al*., 1999; Chisala and Lerner, 2008). How robust therefore are the loss rates quantified from experimental sewer studies and are equilibrium exfiltration loss rates maintained over extended time periods? The principal cause of the rapid decline in exfiltration to limiting loss levels in the region of 10^{-1} – 10^{-3} l s^{-1} per km sewer length has been explained by sediment sealing of sewer pipe gaps and joints; an assertion which has been widely accepted. In most direct rig studies, periods of total sealing have also been recorded with zero ultimate exfiltration losses reported (Ab-Wahab *et al*., 2004; Blackwood *et al*., 2005a), although the sampling and reporting times are frequently less than 30 to 60 minutes and thus insufficient time may have elapsed before true equilibrium condition had become established. With very short sampling times (sometimes less than 2 - 4 minutes), detectable exfiltration flows cannot really be expected under ultimate steady-state conditions. In addition, the throttling of exfiltration could at least be partly due to increased saturation and impermeability of the underlying bedding layers over the test run periods. However, whilst the results allow an understanding of rates and patterns of initial sealing, the short term testing (< 24 to 36 hours) and sampling times cannot be representative of exfiltration losses that will occur over extended time periods of up to 10 years and beyond.

Despite this, there is a belief that even in deteriorating sewer systems having frequent joint gaps and cracks, the sealing or colmation process can become sufficiently efficient to prevent further exfiltration losses of any real magnitude once the ultimate equilibrium level is established. However, it is highly unlikely that such sealing will be permanent and the prevailing hypothesis would argue that the onset of elevated pressure conditions provides the appropriate criteria and threshold conditions for the "rupture" of sealed joints and cracks. Such failure could then result in the catastrophic and sudden leakage of any "pooled" pollutants, e.g. in sewer invert slack sections, releasing contaminants to the sub-surface system and onward transmission to groundwater. This paper will challenge this hypothesis and re-examine the nature and definitions of the sealing layer(s) associated with the blockage of sewer pipe gaps and joints.

EXFILTRATION RATES

Table 1 provides a summary of published estimates of exfiltration rates reported from various European studies with minimum average daily rates per standardised leak area varying between 0.02 – 9.0 l d^{-1} cm^{-2} for seepage (dry weather flow; DWF) conditions. The German and UK sewer networks have been noted to be similar in size, age and structural condition, with an estimated 22% of the length of German sewers being quoted as sufficiently defective to allow exfiltration (Decker and Risse, 1993). This figure compares well with the 23% of UK sewers believed to have defects which might similarly allow leakage (Reynolds and Barrett, 2003). It is clear that the exfiltration estimates quoted in Table 1 cover a wide range of values with the highest losses coming from laboratory sewer test rigs.

Based on the extrapolated upper limit of 2.0 l s^{-1} km^{-1}derived from a UK study by Blackwood *et al* (2005a), a recharge from sewers alone of 1400 mm yr^{-1} would be expected for the 756 km of sewers in the 34 km^2 Nottingham urban area. This is much higher than the public water supply (650 mm yr^{-1}) for the city and the total recharge of 211 mm yr^{-1} for the aquifer (Yang *et al*., 1999). The average estimated sewer recharge to the unconfined aquifer of urban Nottingham is quoted as 6 - 13 mm yr^{-1} by Yang *et al* (1999), corresponding to an average value of 10 mm yr^{-1}. This would yield an exfiltration rate of 0.014 l s^{-1} km^{-1} for the 756 km length of sewers in the urban area. It therefore seems reasonable to discount the upper range exfiltration rates recorded in the direct laboratory and field test studies. Based on an examination of the data in Table 1, the remainder of exfiltration loss rates lie in the range of 0.005 – 0.7 l s^{-1} km^{-1}. Most of the data at the upper range of direct exfiltration rates shown in

Table 1. Estimates of sewer exfiltration rates from various European studies

Study	Exfiltration Rate	Method
Direct Test Rig Studies		
Rauch & Stegner (1994)	0.87 – 52 l/d/cm^2	Flowing wastewater through a leaky pipe
Vollertsen & Hvitved-Jacobsen (2003)	0.02 – 0.06 l/d/cm^2	Recirculated wastewater through a leaky pipe
Blackwood *et al* (2005a)	9 – 86 l/d/cm^2 (0.1 – 2.0 l/s/km)	Flowing live wastewater through a leaky pipe
Rutsch *et al* (2008)	2 – 167 l/d/cm^2	Mass balance of artificial tracer loads
Dohmann *et al* (1999)	0.07 – 109 l/d/cm^2	Pressure testing of field sewer pipe
Klinger *et al* (2007)	7 – 56 l/d/cm^2 (0.0002 l/s/km)	Collector tank below live sewer pipe
Ab-Wahab *et al* (2004)	0.0001 – 304 l d/cm^2	Recirculated wastewater through a leaky pipe
Indirect Modelling Studies		
Karpf & Krebs (2005)	0.0014 l/s/km (2.8% DWF)	Balancing time series on catchment scale
Eisworth & Hotzl (1997)	0.000014 l/s/km	Groundwater monitoring/water balance studies
Harig (1991)	~1.7 x 10^{-9} l/s/km	Groundwater flow modelling and solute balance
CIRIA (1993)	0.062 – 0.179 l/s/km	Leakage estimates (441 – 904 Ml/year)
Yang *et a*l (1999)	0.014 l/s/km	Groundwater flow modelling and solute balance
Morris *et al* (2006)	0.03 – 0.075 l/s/km	Water balance estimate
Trauth *et al* (1995)	<7.5 x 10^{-9} l/s/km	Balancing time series

Table 1 might be reasonably discounted as giving improbably high recharge rates, as serious groundwater contamination problems might be expected if such rates were continuously active. The higher recorded values might well be related to specific test and flow conditions experienced in the individual sewer rig and field studies such as the unrestrained draining conditions in the Dundee rig tests (Blackwood *et al*., 2005a).

The published European exfiltration estimates based on direct laboratory/field studies, which vary between 0.011 – 2.0 l s^{-1} km^{-1} as shown in Table 1, are on the high side compared to the indirect measurements based primarily on water balance and groundwater monitoring studies, and which indicate much lower losses varying between 1.4 x 10^{-5} – 0.179 l s^{-1} km^{-1}. It can therefore be argued that the former direct investigations tend to yield over-estimates as a result of extrapolation up to full scale field coverage. On the other hand, the lowest indirect exfiltration modelling estimates represent virtually watertight systems. With these considerations in mind, it is more likely that real sewer exfiltration rates might reasonably be expected to be in the region of 0.01 – 0.2 l s^{-1} km^{-1} or less. All the experimental work however, strongly suggests that sewers carrying high sediment loads are likely to seal gaps and cracks in the sewer invert and side walls over relatively short periods of time, and thus even the reduced exfiltration values might be over-estimates.

GAP SEALING AND THE EXFILTRATION PROCESS

The conventional view of joint and gap sealing in sewers has followed the baseline work of Rauch and Stegner (1994) which identifies a saturated colmation layer plugging an opening, with an underlying transition zone forming immediately below the pipe in the surrounding bedding layer (Figure 2). In the case of an open joint, the colmation layer extends into the open joint where the joint fill or sealing material has been lost or destroyed, and thus the colmation zone is represented by the transition zone in the backfill and its extension into the spiggot joint. Initially, exfiltration will be governed by the permeability of the surrounding bedding material (the backfill material). Within a time span of minutes to hours, particles contained in the exfiltrating liquid will cover the surface of this coarser backfill material (Vollertsen, 2007). With time, particles from the sewer migrate into the pores, forming a permanent colmation and growth of bacteria and algae in the underlying soil pores of this transition zone will further reinforce this colmation layer. There can also also be a variable biofilm and/or basal sediment layer overlying the colmation zone. However, it has been argued by Velickovic (2005) that the most important part of the colmation structure is the external colmation which comprises the transition zone within the underlying bedding zone to the joint or gap opening, rather than the infill in the joint/gap opening itself.

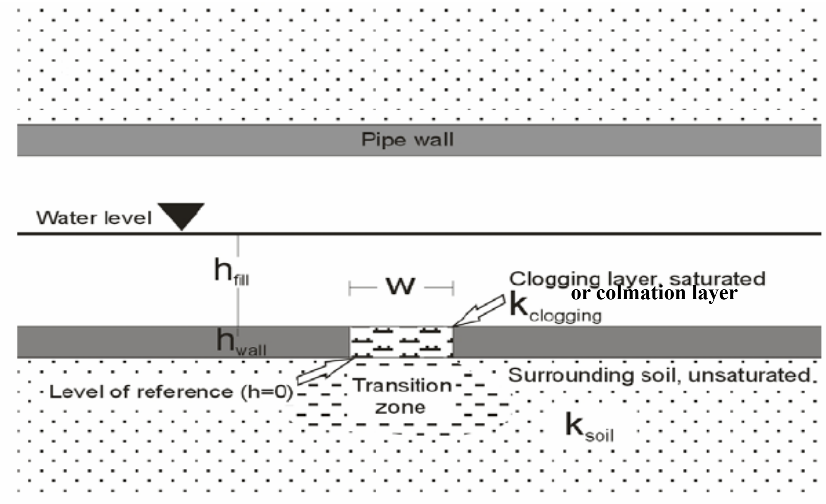

Figure 2. Schematic representation of a blocked leak.

Current state-of-the-art approaches for modelling leakage (Q_{ex}) are based on Darcy's Law, wherein a linear dependency between hydraulic gradient, cross-sectional leakage area (A_{leak}) and discharge is assumed: $Q_{ex} = A_{leak} \cdot k_{colmation} \cdot (h_{fill}/h_{colmation})$, where $k_{colmation}$ (noted as k_f in Figure 3) is the permeability coefficient of the soil column below the leak, $h_{colmation}$ is the thickness of the colmation layer and h_{fill} is the effluent level in the sewer pipe. The leakage factor (L) is therefore defined as: $L = \frac{k_{colmation}}{h_{colmation}} = \frac{Q_{ex}}{A_{Leak} \cdot h_{fill}}$

The application of Darcy's Law assumes that exfiltration and leakage rate will be a function of the sewer fill depth i.e head pressure, as well as the leakage area and colmation properties. The above equations provide a deterministic basis for the assumption that the flow depth in the sewer will have a direct influence on the exfiltration rate, since the pressure differential between the hydraulic head in the sewer and that of the underlying groundwater will force effluent out of the sewer openings into the surrounding bedding/soil material. The strength and direction of the hydraulic gradient has been stated as being the "*key factor*" influencing the occurrence of exfiltration (Amick and Burgess, 2000), and this assumption forms the basis for the US national "depth-to-groundwater" distributional mapping of exfiltration rates. However, the underlying soil properties will change due to percolation of wastewater and subsequent processes such as colmation, surface clogging, biofilm growth and biological degradation. Darcy's Law as a mechanistic approach may be considered to be appropriate to model leakage of clear water, but dynamic changes in wastewater composition, processes in the underlying soil and changing soil/groundwater properties might require additional input factors. Nevertheless, Darcy's Law has been used in various studies of sewage exfiltration and in the prediction of indicative amounts of sewage exfiltration. Irrespective of this, and for practical reasons, it can be questioned whether the necessary information on leakage area, soil properties, and water level are available in sufficient accuracy to reliably and robustly apply the Darcian approach for a real sewer situation.

Leaks from sewers typically form a colmation layer that is relatively enriched (by up to 25%) in organic matter. This colmation layer (or "schmutzdecker" as it would be termed by conventional wastewater treatment operators) serves to limit the volume of leakage. The layer is assumed to be thin and varying between 0.01 to 0.05 m according to various workers and possessing a relatively low permeability. The Darcian conditions described above, would restrict the thickness of the colmation layer to the pipe wall thickness (h_{wall}), plus the thickness of any biofilm layer forming over the leakage area on the pipe invert. Such an assumption would derive a colmation layer in the order of 0.01 to 0.02 m. However some workers also include within the colmation layer the transition zone occurring immediately below the leak (Figures 2 and 3). Inclusion of this transition zone within the definition of the

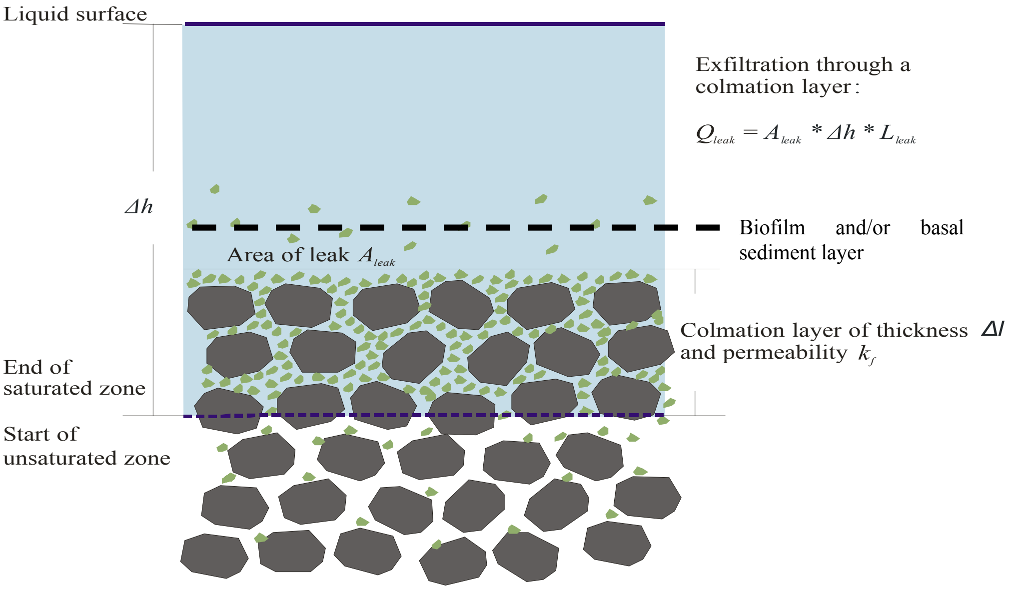

Figure 3. Representation of the structure and growth of the colmation layer [After Vollersten, 2007)

colmation layer would increase its total depth to as much as 0.05 m and is also likely to increase its permeability value.

Biofilm can be formed on almost any surface exposed to sewage effluent and frequently in sewer situations, a fibrous organic matrix several millimetres thick can develop between the bacterial cell layer and the pipe wall or colmation surface (Rocher *et al*., 2002). The biofilm and associated bacterial growth is therefore developed on top of the colmation layer, being embedded or rooted in the interstices and pores of the colmation matrix. The nature and structure of the biofilm is such that it will not significantly affect in any way the rate of exfiltration through a leak and thus could be regarded as forming an "integrated" component of the layer itself. If sediments are in continuous movement along the sewer invert (as a moving or tractive bed), biofilm will not develop. In addition to these organic compounds, the joint may also be covered by sewage solids and shredded toilet tissue temporarily deposited from the wastewater. Such materials can form a bridging layer lying over and straddling the colmation layer. This bridging layer can be further cemented by fat, oil and grease (FOGs) to form a cohesive congealed matrix. These coatings become frequently adultered through contact with detergents and cleaning solutions. In such situations, the bridging layer not only protects the underlying colmation layer but also increases the impermeability and yield strength of the combined material. The bridging layer effect caused by deposition of materials from the sewage effluent has been remarked upon by other workers (Ellis *et al*., 2003; Blackwood *et al*., 2005b) and has been termed a "cream" layer in French exfiltration studies (Oms *et al*., 2002). This terminology reflects the inclusion of degraded shredded toilet paper embedded in glutinous organic and fatty slimes.

There is therefore considerable laxity in the literature on the definition of the colmation layer which strictly should be confined to that part of the infill material which fills the joint or gap opening and the immediate transition zone down to the saturated basal level as illustrated in Figure 3 (for sewer pipes lying above the groundwater level). Any overlying biofilm and/or sediment layer should be referred to as a bridging layer and not included in the definition (or quantification) of the colmation layer *senso stricto*. Where all of these various layers are being

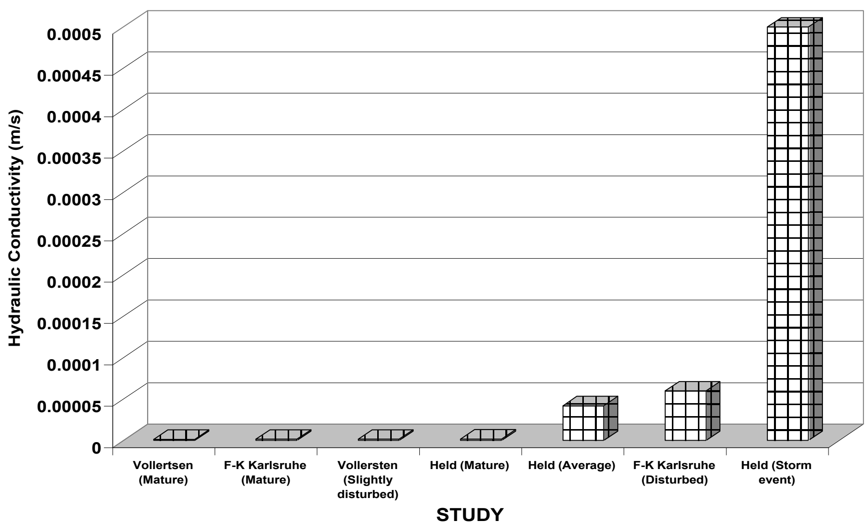

Figure 4. Results reported for exfiltration permeability measurements.

included in the definition, it is best to refer to a general clogging layer rather than a colmation layer. The separate terms of colmation layer, bridging layer and clogging layer are frequently used in an interchangeable manner in the literature but this misuse ignores the independent exfiltration processes which underlie their formation and growth. It is the confusion of colmation infill/transition zone, bridging layer (biofilm/sediment) and clogging layer which can help to explain the differences in hydraulic conductivities of the various clogging layers reported by test studies which have used medium sand as bedding material (Figure 4). The differences may also of course, be partly related to differing "ages" of the undisturbed clogging colmation layer. It is also the case that application of the Rauch and Stegner model gives rise to a broad band of uncertainty in defining the hydraulic conductivity (or permeability) for the overall clogging layer comprising the colmation/transition layer and any other overlying bridging layer.

EQUILIBRIUM BREAKTHROUGH

There is a general implicit assumption in the defining of an equilibrium steady-state exfiltration condition that such lower limiting losses will be maintained over extended periods of time. Such an assumption is often accompanied by an unquestioned acceptance that when equilibrium steady-state is represented by zero detectable losses, that this provides evidence of total and extended sealing. However, such assumptions are normally based on evidence of short term testing and sampling times and there is little evidence of semi-permanent sealing for DWF and low flow conditions. On the contrary, both laboratory and field tests provide considerable evidence for persistent variability and breakthrough of exfiltration following the establishment of steady-state condition. Such leakage has been reported from many studies including those of Vollertsen and Hvitved-Jacobsen (2003), Blackwood *et al*., (2005b), Held *et al*., (2005) and Wolf *et al*., (2007). Leakage losses of up to 2 orders of magnitude above the equilibrium level can occur even under normal dry weather flow (DWF) operational conditions.

It is considered that such breakthrough leakage is in part the result of instability in the growth conditions and ageing process of the colmation and bridging layers. However, a major influence on such long term leakage losses is the effect of small scale, diurnal kinematic wave pulses which generate temporary local increases in bed shear stress which in turn cause scour and mobilisation of the clogging layers. Such pulses are exacerbated in small diameter sewers due to the shunting or "sliding dam" nature of the sediment material moving along the sewer bed (Littlewood and Butler, 2003) and the inclusion of cementitous toilet tissue exacerbates the dam building tendency (Memon *et al*., 2007). Flow restriction following such in-sewer accumulation locally increases velocity, turbulence and bed shear and the increasing hydrostatic head following back-up and partial blockage, will increase flow rates as defined by Darcy's Law, through the accumulated layer. The shear rate through interstices in the retaining sediment subsequently increases, and can dislodge material allowing more flow to pass and increased scouring to occur on the sewer invert (Guzman *et al*., 2007)..

Exfiltration losses in a Rastatt sewer in SW Germany showed that stabilised exfiltration conditions were disturbed by short term increases in leakage which varied over 2 orders of magnitude above the equilibrium steady-state level (Wolf *et al*., 2007). Similar leakage pulses have been observed by Blackwood *et al*., (2005a) and by Vollertsen and Hvitved-Jacobsen (2003). In the former live wastewater rig studies in Dundee, Scotland, these pulses were noted to occur at quite low pressure heads in tests with a 6 mm half-vertical opening under 22 – 25 mm flow levels in the 150 mm diameter pipe with a gravel trench backfill (Blackwood *et al*., 2005a). The short term pulses were believed to be due to temporary local increases in bed turbulence which were sufficiently strong to lift out the colmation fill material from the joint. In the Rastatt studies, the colmation layer appeared to be very vulnerable to changes in flow velocity both during peak diurnal flows as well as during storm events (Klinger *et al*., 2007). During rig tests on live wastewater in the Dundee, Scotland experiments, flow depths at $Q_{70/75}$ in a 150 mm pipe were sufficient to generate velocities of 7 – 8 l s^{-1} and generate bed shear stress in excess of 2.5 N m^{-2}; the frequently quoted critical yield strength for cohesive sewer bed sediment. Some workers have suggested that even lower bed shear stresses in the order of 1.1 – 1.4 N m^{-2} are sufficient to prevent biofilm growth as well as to scour the colmation layer (Guzman *et al*., 2007). There is also considerable evidence of disturbance and removal of clogging layers during sewer pressure testing even at fairly low flushing pressures (~90 psi). Vollersten *et al* (2002) have reported increased exfiltration rates by a factor of 4 to 5 times from steady-state levels following low pressure jetting. Some workers have also described "wash-out" cavities located beneath holes and gaps in sewer pipes attributed to the scouring effect of exfiltrating effluent (Vollertsen, 2007). Such cavities would also dislocate any transition zone such that subsequent blockage would only be comprised of the colmation layer.

None of the cited exfiltration investigations refer to any specific rupture pressure head values and there is little supporting evidence to underpin the legitimacy of elevated pressure conditions as a necessary or only precursor to the disturbance and mobilisation of the colmation layer, or indeed to disprove that flow levels and associated shear velocities below full hydraulic capacity are incapable of achieving the same "critical" flow conditions to initiate such disturbance. The colmation layer can be easily damaged by effluent flows which generate turbulent bed conditions particularly when it is at an immature growth stage. Thus the commonly held view that it is only sudden precipitous sewer backups and associated elevated pressure heads which severely disrupt the hydraulic regime, and consequently initiate exfiltration breakthrough, is not a fully justifiable assertion. What is generally not disputed is that sewer leakages never seal completely and that all sewer systems will be subject to leakage loss over extended time periods although severe sewer blockage will induce local pressurised conditions to an extent that catastrophic colmation rupture can also occur.

CONCLUSIONS

The average reported exfiltration rates resulting from direct laboratory and field test investigations frequently over-estimate leakage rates in comparison to indirect monitoring/modelling studies. Examination of the exfiltration process would suggest that there are detectable formative and structural differences between the colmation, transition, biofilm and bridging layers which can collectively cause joint and gap clogging. Stricter definition and quantification of these various clogging layers would assist a better understanding and prediction of sewer leakage. Substantial increases in leakage rate can occur within otherwise minimal steady-state sewer flow conditions and long term investigations provide firm evidence of continued instability in leakage rates even after prolonged equilibrium periods. This reinforces the confounding relationship that exists between flow depth, head pressure and leakage rate. Other factors such as the composition, strength, age and cohesion of the colmation and bridging layers are likely to be prime drivers for the initiation of critical leakage conditions as well as sewer blocking and the occurrence of small-scale, diurnal kinematic wave pulses generating local bed turbulence. Increases in hydrostatic pressure, even by a factor of 20 to 30 without increasing velocities or leakage area, whilst resulting in an increase in the leakage factor, do not necessarily lead to a rupture of the colmation layer.

REFERENCES

Ab-Wahab, M.A., Abdul-Talib, S., Baharom, B and Marwi, M.S. (2004). Exfiltration from pipes: Effects of flow rates, different leakage areas and soil beddings. In: Bertrand-Krajewski, J-L., Almeida, M., Matos, J and Abdul-Talib, S. (eds): *Proc. 18th European & 1st Asian Junior Scientists Workshop; Sewer Networks & Processes Within Urban Systems*. 138-146. IWA Publishing, London. UK

Amick, R.S and Burgess, E.H. (2000). *Exfiltration in Sewer Systems*. Report EPA/600/R-01/034, US Environmental Protection Agency, National Risk Management Research Laboratory. Cincinnati, Ohio, US

Blackwood, D.J., Ellis, J.B., Revitt, D.M., Gilmour, D.J and Stainer, A. (2005a). Factors influencing exfiltration processes in sewers. *Wat.Science & Tech*., 51(2), 147-154.

Blackwood, D J, Ellis, J B, Revitt, D M., Gilmour. D J and Stainer, A. (2005b). Exfiltration from sewers: Is it a serious problem? In: *Proceedings IWA 10th International Conference on Urban Drainage*, Copenhagen, Denmark.

Chisala, B and Lerner, D.N. (2008). Distribution of sewer exfiltration to urban groundwater. In: *Proc. Inst.Civil Eng; Water Management, Special Issue: Groundwater*, 161 (4), (In Press).

Davies, J.P., Clarke, B.A., Whiter, J.T and Cunningham, R.J. (2001). Factors influencing the structural deterioration and collapse of rigid sewer pipes. *Urban Water*, 3, 73-89.

Decker, J and Risse, A. (1993). Investigations about quantitative and qualitative pollution load of subsoil, ground and surface water by leaking sewers. In Marsalek, J and Torno, H. (eds): *Proc. 6th Int. Conf. Urban Storm Drainage*. 1591 – 1596. Seapoint Publishing, British Columbia, Canada.

Eiswirth, M and Hotzl, H. 1997. The impact of leaking sewers on urban groundwater. 399 – 404 in Chilton, J. (Edit): *Groundwater in the Urban Environment: Problems, Processes and Management*. AA Balkema, Rotterdam. ISBN 9054109238.

Ellis, J.B and Revitt, D.M. (2008). Effects of sediments and sediment tracer interactions. In: Ellis, J.B and Bertrand-Krajewski, J-L. (eds): *Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems*. IWA Publishing. London. Chapter 3. ISBN 9781843391444. (In Press)

Ellis, J.B and Bertrand-Krajewski, J-L. 2008. *Assessing Infiltration and Exfiltration in the Performance of Urban Sewer Systems*. IWA Publishing, London. UK. ISBN 9781843391444 (In Press).

Ellis, J.B., Revitt, D.M., Lister, P., Willgress, C and Buckley, A. (2003). Experimental studies of sewer exfiltration. *Wat.Science & Tech*., 47(4), 61-67.

Guzman, K., La Motta, E.J., McCorquodale, J.A., Roiss, S and Ermogenous, M. 2007. Effect of biofilm formation on roughness coefficient and solids deposition in small-diameter PVC sewer pipes. *ASCE, Journ Envir.Eng*., 133(4), 364 – 371.

Held, I., Klinger, J., Wolf, L and Hotzl, H. (2005). Direct measurements of exfiltration at a sewer site under operating conditions. In: Howard, K.W.F. (Edit); *Proc. Mathias Eiswirth Memorial Volume*. Balkema, Rotterdam, The Netherlands.

Karpf, C and Krebs, P. 2005. Application of a leakage model to assess exfiltration from sewers. *Water Sciencei & Tech*., 52(5), 225 – 231.

Klinger, J., Turkovic, R., Wolf, L and Hotzl, H. (2007). Long term investigations of the colmation processes at a real sewer defect. *Geophysical Research Abstracts*, 9, 1-3.

Littlewood, K and Butler, D. (2003). Movement mechanisms of gross solids in intermittent flow. *Water Science & Tech.*, 47(4), 45 – 50.

Memon, F.A., Fidav, A., Littlewood, K., Butler, D., makropoulus, C and Liu, S. (2007). A performance investigation of small-bore sewers. *Wat.Science & Tech*., 55(4), 85 – 91.

Morris, B.L., Darling, W.G., Cronin, A.A., Rueedi, J., Whitehead, E.J and Gooddy, D.C. 2006. Assessing the impact of modern recharge on a sandstone aquifer beneath a suburb of Doncaster, UK. *Hydrogeol..Journ*., 14(6), 979 – 997.

Oms, C, Gromaire-Mertz, M C and Chebbo, G. (2002). In-situ observations of the water-sediment interface in combined sewers using endoscopy. 5-12 in: *Proceedings 3rd Int.Conf. Sewer Processes and Networks.* April 2002. GRAIE, Villeurbanne Cedex, Lyon, France.

Orange County Sanitation District. (2005). *Status Report on the Development of a Reporting Methodology for Subsurface Discharges of Sewage*. September 2005. Brown & Caldwell, 400 Exchange, Suite 100, Irvine, California, US.

Rauch, W and Stegner, T. (1994). The colmation of leaks in sewer systems during dry weather flow. *Water Science & Tech*., 30(1), 205 – 210.

Reynolds, J.H and Barrett, H.M. (2003). A review of the effects of sewer leakage on groundwater quality. *Journ.Chart.Inst.Water & Environ.Mangt*., 17(1), 34 – 39.

Rocher, V., Azimi, S., Moilleroi, R and Chebbo, G. (2002). Biofilm in combined sewers: Wet weather pollution sources and/or dry weather pollutant indicator. In: *Proceedings 3rd Int. Conf. on Sewer Processes & Networks*, April 2002. CEREVE, Ecole Nationale Pontes et Chaussees. Paris, France.

Rutsch, M., Rieckermann, J., Cullmann, J., Ellis, J.B., Vollertsen, J and Krebs, P. 2008. Towards a better understanding of sewer exfiltration. *Water Research*, 42(11). In Press. DoI:10.1016/j.

Selvakumar, A., Field, R., Burgess, E.H and Amick, R.S. (2004). Exfiltration in sanitary sewer systems in the United States. *Urban Water Journ*., 1(3), 227-234.

Velickovic, B. (2005). Colmation as one of the processes in interactions between groundwater and surface water. *Facta Universitates, Series Architecture & Civil Engineering*, 3(2), 165 – 172.

Vollersten, J., Vorkamp, K., Hvitved-Jacobsen, T and Jensen, M.A. (2002). *Udsiuning af spildevand fra aflohssystemer. (Exfiltration of wastewater from Sewers)*. Miljoproject No.685. Danish Environmental Protection Agency, Danish Ministry of Envrionment, Copenhagen, Denmark.

Vollertsen, J. (2007). *The Phenomenon of Sewerage Leakage*. Unpublished Report. School of Environmental Engineering, Aalborg University, Denmark.

Vollertsen, J and Hvitved-Jacobsen, T. (2003). Exfiltration from gravity sewers; A pilot scale study. *Wat.Science & Tech*., 47(4), 69-76.

Wolf, L., Morris, B and Burn, S. (Edits). (2007). *Urban Water Resources Toolbox: Integrating Groundwater into Urban Water Management*. IWA Publishing, London. UK. ISBN 1843391384.

Yang, Y., Lerner, D.N., Barrett, M.H and Tellam, J.H. (1999). Quantification of groundwater recharge in the city of Nottingham. *Envir.Geology*, 38(3).