Sewer losses and interactions with groundwater quality

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Abstract Inflow/infiltration (I/I) and infiltration/exfiltration (I/E) are interactive processes which dynamically affect sewer and groundwater performance. The incidence and condition of “critical” sewers in the UK are identified together with chemical and bacterial methods of quantifying I/E and its potential impact on sewer performance and on urban groundwater pollution. Whilst the impacts of I/E do not appear to be substantial on the basis of existing evidence, some caution is advocated in respect of long term sewer sustainability.

Keywords Critical sewers; marker species; sewer exfiltration; urban groundwater pollution

Introduction

Sewer systems provide a very significant asset to the economy, health and well-being of urban communities. Their structural integrity and functional efficiency are key parameters to the continued guarantee of public and economic health in terms of the effective conveyance and treatment of domestic, trade and stormwater effluents. The EU Standard EN 752-2 identifies basic performance criteria applicable to any sewer system and emphasises that:

• receiving water quality should be protected against sewered discharges
• the structural integrity of urban sewer systems including their water-tightness, should be guaranteed.

The EU Wastewater Directive (91/271) also demands that large sewerage systems should comply with the requirements laid down in Annex I(A) covering “leakage” by the end of 2000. In addition, the sequence of drafts accompanying the Framework Directive reveal (Article 4, Document 9085/99 DG11) a strong emphasis on ensuring all avoidable sewer impacts on groundwater. The same document also demands an identification of both point and diffuse sources which contribute to groundwater pollution (Annex II, 2.1). Thus ensuring the integrity of sewer systems in terms of prevention of both inflow/infiltration (I/I) and infiltration/exfiltration (I/E) presents a very real challenge to the achievement of integrated and sustainable wastewater management and in closing the urban water cycle. I/I and I/E are processes which interact with and directly affect sewer and treatment plant performance as well as receiving water and groundwater quality, thus indirectly impacting upon overall catchment water use.

The objectives of continued structural sewer integrity are undermined by:

• the age of urban sewer pipes with some parts of major European cities having drainage systems over 100 years old
• poor and/or outdated construction quality and installation/maintenance criteria (poor quality of pipe/brick material, inefficient “laying” conditions, ignorance or under-estimation of the effects of unstable geotechnical or road traffic conditions, continued disturbance by infrastructure provision including communication and utility cabling etc.)
• lack of or insufficient maintenance
• lack of appropriate investment and rehabilitation strategies
• high costs of construction and rehabilitation
• continued extension of the sewer system with increasing pipe sizes, joints, manholes, inspection chambers etc., which collectively increase the chance of leakage into and out of the sewer.

In addition, some concern has been expressed as to whether the emergence of split asset ownership and operational management of UK sewer systems under recent privatisation arrangements, may be likely to further prejudice sewer sustainability.

**Sewer conditions**

Both inflow/infiltration (I/I) and infiltration/exfiltration (I/E) are issues of increasing concern within the European water industry. This is due to a growing awareness of the operational and capital costs associated with sewerage collection and treatment and their impact in terms of:

• increased pumping costs
• reduced hydraulic capacity leading to potential sewer surcharging and thus increasing the risks of surface flooding
• increased frequency of CSO overflow operation even during dry weather conditions if there are locally very high groundwater levels
• sewer damage and collapse
• interference with treatment plant performance
• increased surface sediment and soil inputs to the sewer system
• increased groundwater pollution.

It is estimated that I/I alone costs in the region of £1M/m$^3$/day for sewerage effluent in the UK and can dilute sewage flows by a factor of 1:1 to 1:3. In the UK, it has been customary to specify infiltration as being some 10% of Dry Weather Flow (DWF) but recent studies have indicated that this is far too low especially for sewer systems in high groundwater areas. Ainger et al., (1997) have suggested that infiltration levels as high as 120 l/head/day should be used. UK infiltration rates have been found to range between 15% to 50% of average dry weather flow (White et al., 1997) and figures of 10%–20% of total wet weather flows have also been quoted (Heywood and Lumbers, 1997). Leakage rates resulting from exfiltration (I/E) losses are not as well quantified with estimated rates varying between 1 to 10 m$^3$/km/year. I/E losses appear to bear no obvious relationships with Environment Agency (EA) groundwater vulnerability mapping, with most water utilities operating a “patch-repair” approach in high risk/critical performance locations.

In the UK some 23% (73,000 km) of sewers are classified as being in “critical” condition out of a total of 320,000 km length. A critical sewer is defined as being of strategic importance for the correct functioning of the sewerage system and has the highest economic consequences of failure. Using the standard UK industry grading system as described in the *Sewer Rehabilitation Manual* (FWR, 1994), about 10% of such critical sewers are considered to be in unsatisfactory condition of Grade 4 to 5. Grade 4 means there is some fabric (brick/cement) loss, badly made connections or loss of level. Grade 5 refers to either sewer collapse, sewer deformation or extensive loss of wall/invert fabric. These figures do not include the 20,000 km (80%) of non-critical (and usually small-diameter) sewers in the poorest conditions and for which reactive maintenance is the normal rehabilitation strategy (Fenner and Sweeting, 1999).

Some £230M/year is spent on sewer maintenance in the UK of which £150M represents expenditure on infrastructure renewal. Even given such levels of expenditure, less than 1700 km of critical sewers (only 2%) were renovated or replaced between 1990 and 1998. If work continues at this rate, critical sewers in the UK can be expected to last an average of 350 years and for some water companies this figure is over 1000 years. It will take at least 35 years to repair or replace the 7350 km of critical sewers in Grades 4 and 5. The UK water
industry regulator (OFWAT) budget for sewer maintenance in England and Wales for the AMP3 period (2000–2005) is set at £890M with an additional £1.7B targeted for combined sewer overflow (CSO) improvements. Although the total sum represents an increase on the previous AMP2 quinquennial expenditure, water companies claim that OFWAT’s water pricing cuts this year will prevent them meeting the targets set by the previous outgoing OFWAT regulator. They claim that there is at least a 30% difference between what they believe should be spent on capital and operational maintenance and the figure OFWAT has set for AMP3. In France for example, water agencies consider that 2 Euros must be spent for sewer system rehabilitation and upgrading for each Euro given over to process plant expenditure. In contrast, process plant expenditure by the UK sewerage industry shot up to £887M in 1997; a nominal growth increase of 69%, equivalent to 25% of the total capacity in the year. Whilst there was a decline in overall expenditure (about 3% in real terms) between 1998 and 2000, operational and maintenance expenditure still lags a long way behind process plant expenditure.

There would seem to be clear evidence for considerable increases in operational and capital expenditure in order to deal with the poor condition of the ageing sewer network. However, pro-active rather than reactive approaches to sewerage investment are difficult to achieve given that 5 year planning horizons are moulded into the UK OFWAT periodic asset review process. This makes it difficult to monitor and identify changes in sewer status over such short term time periods and thus prejudices the development of an effective long term strategy.

Identifying and quantifying I/E

Inspection of the structural integrity of critical sewers is normally made using CCTV surveys but given the large critical sewer lengths and average survey costs of £1000 per km, this pre-emptive approach is clearly not cost-effective, especially given that only 5–10% of such surveys reveal sewers in need of urgent repair or rehabilitation. Approaches which enable identification of clusters of sewer failures offer the most economic strategy with analysis of sewer blockage and utility maintenance records comprising one possible cost-effective methodology (Fenner and Sweeting, 1999). A risk-based approach being considered by Thames Water uses a combination of data sources including CCTV, soil (fracture capability) maps, traffic information, sewer collapse and mains water burst data, borehole logs, property age and local authority street work records (Davies et al., 2001). The most significant risk factors being identified include shallow depth, small diameter, pipe section lengths less than 1m, urban main roads and high flows of heavy vehicles. Brownfield sites having highly aggressive soils and which lead to corrosion of pipe jointing were additionally identified as high risk I/I and I/E locations. This Thames Water research has identified a large number of complex factors and interactions as being important in influencing sewer condition and potential I/E flows. There is clearly further scope for more comprehensive analysis as well as improvements in water utility data and data management.

Conventional approaches to identify and quantify exfiltration (I/E) have utilised standard ion chemistry to fingerprint solute recharge sources to groundwater. Such approaches are far from ideal as the “marker” species are normally present in all sources of recharge water and the ionic ratios can change due to ion exchange and other reaction processes. Table 1 outlines some of the principal marker species that can be used to identify potential sewer exfiltration (and I/I in some cases) and indicates their relative limitations. Whilst marker species such as bacteriophages and stable isotopes offer the best opportunities for tracing sewer leakage, it is inevitable that such methods will still leave room for interpretation of actual exfiltration rates. It might therefore be better to quantify I/E loss by adding...
conventional, non-reactive tracers in exactly controlled time-dependent amounts at different locations within the sewer network.

This should then enable an accurate quantification of tracer loss through monitoring changes in relative concentration across defined sewer sections. Such an approach would necessitate substantial initial investment in automatic, real-time flow measurements and complex systems analysis (identification of transfer-functions). It also assumes that little (or predictable) attenuation of the dissolved tracer will occur during the conveyance period as a result of biochemical reactions and/or sediment uptake. Exfiltration from house lateral connections can be quantified as a pressure drop in time following blockage of the connection at the downstream end and then filling-up the connection pipe with water. Infiltration into the connection can be volumetrically measured following exclusion of normal water

<table>
<thead>
<tr>
<th>Marker group</th>
<th>Species</th>
<th>Source indicator and usefulness</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major cations/anions</td>
<td>Ca, Mg, K, Na, HCO₃, SO₄, Cl</td>
<td>Generally useful for broad rural/urban distinction; NH₄ distinctive for sewage; quite useful if combined with ¹⁵N isotope data</td>
<td>Only Cl and SO₄ are reasonably conservative. Rapidly oxidised to NO₃</td>
</tr>
<tr>
<td>Nitrogen species</td>
<td>B, PO₄, Br, CN</td>
<td>Tryptophan/trade/industrial effluents (from detergents, bleaches/dyes, pesticides) in urban sewers. Boron isotope ratios (Cl:Br) useful.</td>
<td>B and P constrained by pH and effects of solubility and sorption</td>
</tr>
<tr>
<td>Heavy metals</td>
<td>Fe, Mn etc</td>
<td>Only very general use</td>
<td>Difficult to isolate recharge source; rapid complexing and reactions</td>
</tr>
<tr>
<td>Organics</td>
<td>Chlorination by-products (THMs)</td>
<td>THMs useful mains water marker species (especially TCM)</td>
<td>Difficult to separate leakage from mains and sewer pipes</td>
</tr>
<tr>
<td>Faecal steroids</td>
<td>Coprostanol</td>
<td>Ammonopropionate potentially very useful indeed</td>
<td>Highly hydrophobic tending to remain with gross solids</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Costly technique</td>
</tr>
<tr>
<td>Synthetic oestrogens</td>
<td>17-α-ethynylestradiol, mestranol and APEs; trade/industrial and domestic effluents</td>
<td></td>
<td>Difficult, costly analytical methodology.</td>
</tr>
<tr>
<td>Microorganisms</td>
<td></td>
<td></td>
<td>Occur only in trace quantities within sewage effluent</td>
</tr>
<tr>
<td>Colloids</td>
<td></td>
<td>Highly sorbing, so can be used to “seed” I/I trench and groundwater</td>
<td>Tedious, expensive methodology; little known on colloid-solute reactions</td>
</tr>
<tr>
<td>Stable isotopes</td>
<td>¹⁵N</td>
<td>(¹⁵N &gt; 10% distinctive and used as faecal indicator whereas soil lies between 1 – 7%)</td>
<td>Problems of isotope fractionation, denitrification and groundwater mixing</td>
</tr>
<tr>
<td></td>
<td>¹⁸O, ³⁴S, ²H</td>
<td>Where mains and groundwater isotope signatures differ, potential for identification of sewer I/E</td>
<td>Problems of fractionation and overlapping recharge source signatures</td>
</tr>
</tbody>
</table>
usage. Varying urban land use types could be tested to build-up a picture of typical I/I and I/E rates for residential/commercial lateral connections as a basis for catchment-scale modelling. This approach is being adopted within the context of a current EU 5th Framework project coordinated by the Lyon National Institute of Applied Sciences (INSA) in a eight nation consortium.

Exfiltration losses
As indicated above, there are no proven methods of accurately identifying or quantifying sewer exfiltration (I/E) as most potential biochemical markers are present naturally in groundwater and also occur in other sources of urban pollution. Evidence for groundwater contamination as a result of sewer leakage on a city-wide scale within the UK comes from a number of studies using standard ion chemistry, boron and isotopic ratios (Nazari et al., 1993; Lerner et al., 1994; Anderson et al., 1996). In the Greater London region estimates suggest a 5% loss; equivalent to a recharge rate of some 20–25 mm/year (Bishop et al., 1998) although rates of only 9–10 mm/year have been recorded in the Nottingham urban region (Yang et al., 2001). The potential dangers of sewer exfiltration have led the UK Environment Agency to oppose the construction of new sewer systems within its most vulnerable Groundwater Source Protection Zone I regions where travel times are less than 50 days.

Studies using stable nitrogen isotopes in the Chalk groundwaters of the Colne valley in NW Hertfordshire revealed $^{15}$N values varying between 4–12‰ (with a mean value of 8.5‰). The enriched nitrogen species (<10‰) surrounding the Watford and Harpenden/Luton urban areas have been attributed to storm and foul sewer leakages and similar conclusions were made by Rivers et al. (1996) from their studies of the Nottingham urban area. The urban groundwater of the Luton/Dunstable area has been shown to possess widespread low-level organics, solvent and aromatic compound (BTEX) contamination with localised “hotspots” being related to exfiltration from surface water sewers serving industrial/commercial premises as well as from highway drains (Ellis, 2000). The chemical contamination of surface water sewers from urban industrial estates is now widely recognised and has been estimated, for example, to be the primary cause of organic pollution in some 150 km of Scottish watercourses as well as a major source of groundwater contamination (D’Arcy et al., 2000). Work in German cities (Hannover and Plittersdorf), although detecting exfiltration rates varying between 1.2 l/day.km to 17,300 l/day.km sewer length, similarly found groundwater deterioration was only relatively minor in nature, being severest in a narrow zone either side of the sewer trench line (Eiswirth and Hotzl, 1997).

Recent investigations (Barrett et al., 1999) in Nottingham, using shallow (2–5 m) bore-hole data, showed elevated levels of faecal coliforms and faecal streptococci below and adjacent to 30 year old housing developments (Table 2). The frequent presence of coliphages and the <10‰ $^{15}$N values provide clear evidence for sewage loading to the local groundwater. This conclusion is confirmed by the presence of degraded detergent products (d-limonene) and organic colloids. Very similar data was yielded from studies in the Liverpool urban area (Whitehead et al., 1999). Estimates of current average nitrogen loading to groundwater for the city of Nottingham are around 21 kg/ha/year of which some 13% is attributed to leaking sewers (Lerner et al., 1999). Figure 1 shows the incidence (MPN/100ml) of bacterial indicators recorded in shallow boreholes across the urbanised flood plain of the Lower Lee Valley in NE London. The occurrence of a wide suite of both coliform and pathogenic strains would imply quite an extensive, if low-level groundwater contamination. The occurrence of E.coli (EC) and Faecal Streptococci (FS) at locations A, C and D as well as the relatively high EC/FS ratios at location D, suggest “fresh” sewage pollution from leaking sewers although the clearest evidence for I/E appears to be
associated with losses immediately adjacent to the trunk sewer line at location D. The elevated level of FS at location A coincides with pre-war housing confirming the Thames Water analysis which placed 1925–1949 housing as being of particular risk in terms of critical sewer conditions. The use of coliphage (Cph) as a cost-effective exfiltration tracer is being further investigated.

**Conclusion**

The overwhelming evidence is that sewage leakage is presently occurring and is not just an historical problem as suggested elsewhere (Anderson et al., 1996). However, the brief data review given here would suggest that the overall impact of urban sewer exfiltration on groundwater quality does not appear to be that severe. Nevertheless, some caution must be expressed on the use of a threshold 10‰ $^{15}$N criterion as a distinguishing sewage marker. The heavier enriched isotopic nitrogen found in urban groundwaters results from the partial volatilisation of ammonia depleted in $^{15}$N during decomposition of urea in the sewage. The potential for such isotopic fractionation will therefore depend on whether exfiltration

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**Table 2** Sewage marker species in shallow urban groundwaters of the Nottingham urban area

<table>
<thead>
<tr>
<th>Marker Species</th>
<th>Total Coliforms (MPN/100 ml)</th>
<th>E. coli (MPN/100 ml)</th>
<th>F. Streptococci (MPN/100 ml)</th>
<th>Coliphage (PFU/ml)</th>
<th>$^{15}$N (‰)</th>
<th>Organic colloids (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>1–910</td>
<td>1–160</td>
<td>2–180</td>
<td>0–1</td>
<td>7–24</td>
<td>10–50</td>
</tr>
<tr>
<td>Average</td>
<td>176</td>
<td>29</td>
<td>80</td>
<td>–</td>
<td>12</td>
<td>–</td>
</tr>
</tbody>
</table>

Sources: Rivers et al., 1996; Barrett et al., 1999; Stagg et al., 1997

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**Figure 1** Bacterial indicators (MPN/100 ml) of sewer exfiltration
occurs directly to groundwater or is in contact with a sufficiently large vapour phase above the water table to enable volatile loss of ammonia. Thus not all sewer exfiltration will necessarily possess an isotopically heavy signature and the problem may be more severe than the results to date imply. In addition, it may be that “residuals” and “pools” of sewage-derived pollutants including DNAPLs (dense non-aqueous phase liquids) and other weakly attenuating substances, are still only slowly dissolving and may serve as semi-infinite sources of shallow groundwater contamination within urban areas. Much further work is needed to verify the nature and magnitude of long term sewer exfiltration before it can be safely discounted as a potential diffuse source of urban groundwater pollution. Inflow-Infiltration (I/I) on the other hand, presents a very evident problem and one which is already attracting the world-wide attention and resources of urban drainage authorities.

A strategic holistic approach to urban drainage planning is urgently required which encourages waste minimisation, good housekeeping practice by industry and effective on-site source controls together with the provision of sustainable best practice drainage systems (such as open grassed conveyance channels) to deal with unavoidable levels of background contamination. A catchment management approach can bring major benefits if it involves the cooperative action of key stakeholders including planning authorities, drainage agencies, pollution regulators, conservation interests, urban developers and the public.

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