Sewer infiltration/exfiltration and interactions with sewer flows and 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 methods of quantifying I/I and I/E as well as their impact on wet weather sewer performance and on urban groundwater pollution. Whilst the impacts of sewer trench I/I upon peak sewer flow conditions can be severe, the impacts of I/E appear to be of less concern although some caution is advocated in respect of long term sewer sustainability.

KEYWORDS

Sewer inflow, infiltration and exfiltration; critical sewers; marker species; sewer trench flow; 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 1(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 (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.

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 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 leading to hydraulic overloading of the wastewater treatment plant. The amount of infiltration can range between 0.01 to 1.0 m^3/day/mm pipe diameter/km length according to Metcalf and Eddy (1991) and increases proportionally with the age of the sewer. 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)

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. Using the standard UK industry grading system as described in the *Sewer Rehabilitation Manual* (FWR, 1994), about 10% 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 of non-critical sewers in the poorest conditions.

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 (OFWAT, 2000). 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

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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. It will be politically interesting in the UK to see how water companies try to shift the burden of responsibility in AMP3 if sewer failures cause serious problems. 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 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/I and I/E

Most estimation methods for I/I make use of flow data recorded during dry weather by subtracting the base flow (often derived from population estimations) from the site-measured flow. However, such approaches can fail to take account of peaks in rainfall-induced infiltration occurring during prolonged wet periods. Graphical (Lutz, 1976) and time series modelling approaches (Newport, 1977; Males and Turton, 1979; Heywood, 1997) have been used whilst the SWMM model incorporates a procedure based on multiple linear regression. Smoke and dye tests can be used in the field to identify I/I sources draining into the combined system whilst CCTV surveys are widely used to monitor sewer condition.

General 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 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.

INFLOW/INFILTRATION

In a combined sewer system, the contribution from direct runoff (inflow) dwarfs any infiltration flows during large storm events. However, in separate surface water systems such infiltration flows can be the dominant contributor to peak flow. Direct stormwater inflows enter the sewer system from a variety of sources including:

- street/highway drains connected to the sewer system
- roof and yard downpipes/drains connected to the sewer system

- unsealed manhole covers
- sump pumps
- overflows from storm drains
- illegal misconnections into the combined system

Table 1. Marker Species for I/E and I/I

Marker Group	Species	Source Indicator and Usefulness	Limitations
Major cations/anions	Ca, Mg, K, Na, HCO_3, SO_4, Cl	Generally useful for broad rural/urban distinction	Only Cl and SO_4 are reasonably conservative
	Nitrogen species	NH_4 distinctive for sewage; quite useful if combined with ^{15}N isotope data	Rapidly oxidised to NO_3
Minor ions	B, PO_4, Br, CN	Typify trade/industrial effluents (from detergents, bleaches/dyes, pesticides) in urban sewers. Boron isotope ratios (Cl:Br) useful.	B and P constrained by pH and effects of solubility and sorption
Heavy metals	Fe, Mn etc	Only very general use	Difficult to isolate recharge source; rapid complexing and reactions
Organics	Chlorination by-products (THMs)	THMs useful mains water marker species (especially TCM)	Difficult to separate leakage from mains and sewer pipes
	Faecal steroids	Coprostanol Ammopropanone potentially very useful indeed	Highly hydrophobic tending to remain with gross solids Costly technique
	Synthetic oestrogens	17α-ethynylestradiol, mestranol and APEs; trade/industrial and domestic effluents	Difficult, costly analytical methodology
	Detergents	Optical brighteners, EDTA; d-limonene ($C_{10}H_{16}$); trade/industrial effluents	Occur only in trace quantities within sewage effluent
	Chlorinated solvents	General industrial/trade waste discharges	Difficult to separate spillage, landfill seepage from sewer I/E
	Bacteria and Pathogens: E Coli, FS, Enterovirus, Bacteriophage	Widely used sewage indicator species; coliphage virus easy to isolate and quantify and potentially bacteriophage excellent markers for sewer I/E. Aerobic soil bacteria (Thiobacillus, rhizobia species) potentially useful for sewer I/I	Coliform and enterovirus difficult to isolate and quantify; E Coli and FS do not survive very long; soil bacteria may die-off rapidly
	Colloids	Highly sorbing, so can be used to "seed" I/I trench and groundwater	Tedious, expensive methodology; little known on colloid-solute reactions
Stable isotopes	^{15}N	$\delta^{15}N > 10^{0}/_{00}$ distinctive and used as faecal indicator whereas soil lies between 1 - $7^{0}/_{00}$	Problems of isotope fractionation, denitrification and groundwater mixing
	^{18}O, ^{34}S, ^{2}H	Where mains and groundwater isotope signatures differ, potential for identification of sewer I/E	Problems of fractionation and overlapping recharge source signatures

Infiltration into a sewer pipe occurs from two principal sources. The first and most significant may be leakage from the trench (sand/gravel) backfill in which the pipe is laid and via loose/broken joints and deteriorating pipework. Some estimates suggest that house lateral connections may contribute as much as 30% - 40% of the total infiltration to sewer via these sources which if correct would present a strong argument for the introduction of plot-site source control for roof and house yard runoff. The second source mechanism is by hydraulic leakage into the sewer pipe from elevated groundwater levels particularly following wet weather conditions. The decay rate in sewer flow (due to inflow) is much faster than the decay rate in the surrounding water table and in the sewer backfill trench and slow leakage occurs into the sewer long after the storm event has ceased.

Modelling and field monitoring using smoke and dye testing in Seattle (US) has shown that base infiltration (primarily from backfill trenches) is the largest I/I contributor to peak flows in the sewer system. Trench flow follows on after early direct (impermeable surface) inflows and is itself followed by rainfall-dependent groundwater infiltration which contributes much of the sewer flow on the recessional limb of the storm hydrograph (Swarner and Thompson, 1995). Figure 1 shows the relative contribution of these source components during a monitored storm event in a separate stormwater sewer with trench backfill comprising some 30% - 40% of the observed sewer flow at peak conditions and groundwater leakage supporting the recessional tail. The early first-flush flow is dominated by direct impervious surface inflow which rapidly decays to be replaced by trench infiltration.

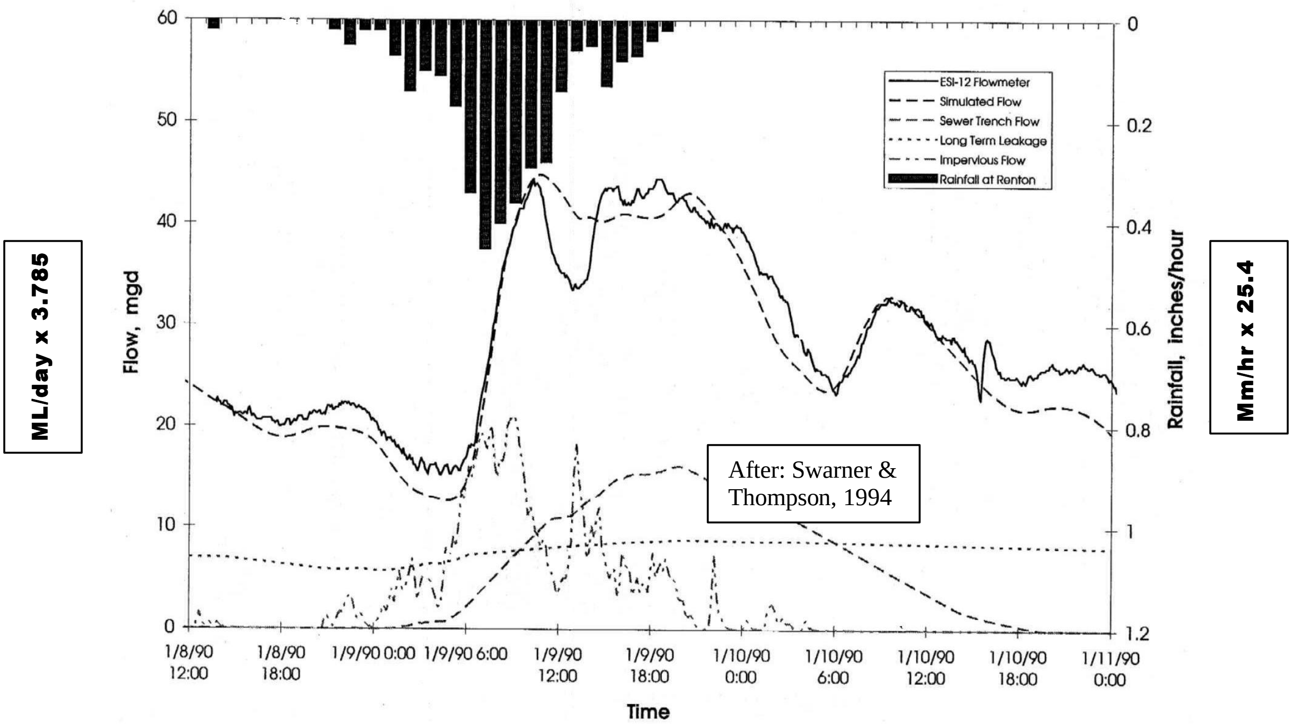

Figure 1. Infiltration Components in a Separate Surface Water Sewer

However, the tail of the recessional limb is attenuated by long term leakage associated with groundwater infiltration and which may take many days to decay following a storm event. Such chronic groundwater infiltration into the sewer pipe between storms can have a significant effect on the available capacity in the collection system when subsequent storm flow commences as well as on sediment accumulation in the sewer.

Swarner and Klusman (1995) estimate that benefit/cost ratios from I/I rehabilitation programmes can range from 1.7 to 4.4 with perhaps only a 15% reduction achieved in peak flow and infiltration. Even these modest levels would accrue benefits of up to $100M although as indicated by Martin *et al* (1982) under a worst case scenario, local authorities could be paying twice; first for the remaining inefficient I/I control and again for expansion of treatment and conveyance capacity. Irrespective of such reservations, the Seattle urban drainage authorities have installed over 800 flowmeters into their sewer system covering the entire 623 km^2 service area of King County. By the end of 2001, they expect to have a much better understanding on which parts of the system are particularly "leaky" and which sections need to be tackled most urgently.

Heywood (1997) developed a time series approach to separate domestic/industrial, direct rainfall-runoff and infiltration components and derived long term infiltration volume-frequency relationships for catchments subject to high infiltration rates. The model application suggests that I/I can contribute between 15% - 55% of total sewer flow and clearly such levels could prejudice urban drainage sustainability principles. For highly populated areas, effective I/I abatement programmes to combat such high infiltration rates could imply capital costs of some £100 - £150M (Anderson *et al*., 1996) which provides a strong argument for including I/I as a sewer service efficiency indicator. Given such high baseline costs, I/I should not be considered in isolation and a holistic, integrated approach to managing on-site (source) infiltration with catchment-wide strategies for wastewater collection/treatment is needed.

EXFILTRATION

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*., 2000). 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.

Recent investigations (Barrett *et al*., 1999) in Nottingham, using shallow (2 - 5m) borehole data, showed elevated levels of faecal coliforms and faecal streptococci below and adjacent to 30 year old housing developments (Table 2).

Table 2. Sewage Marker Species in Shallow Urban Groundwaters of the Nottingham Urban Area

	Total Coliforms (MPN/100ml)	**E.Coli** (MPN/100ml)	**F Streptococci** (MPN/100ml)	**Coliphage** (PFU/ml)	**d^{15}N** ($^0/_{00}$)	**Organic Colloids** (mg/l)
Range	1 - 910	1 - 160	2 - 180	0 - 1	7 - 24	10 - 50
Average	176	29	80	-	12	-

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

The frequent presence of coliphages and the <$10^0/_{00}$ δ^{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).

Studies using stable nitrogen isotopes in the Chalk groundwaters of the Colne valley in NW Hertfordshire revealed δ^{15}N values varying between 4 - 12 $^0/_{00}$ (with a mean value of 8.5 $^0/_{00}$). The enriched nitrogen species (<10 $^0/_{00}$) 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).

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 $10^0/_{00}$ δ^{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 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 regulator, conservation interests, urban developers and the public.

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