2 INFLOW AND INFILTRATION

2.1 Introduction

Inflow and infiltration (I/I) in sewer systems can cause many problems, including:

- increased operational and capital costs in the sewer network and at treatment plants;
- reduced sewer and treatment capacity leading to increased operation of combined sewer overflows, flooding and pollution;
- reduced sewer and treatment capacity restricting future development;
- lowering of groundwater levels leading to detrimental effects on local water resources;
- loss of soil into sewers causing operational problems and structural damage.

These problems all ultimately result in increased costs. As mentioned in the first bullet point above, there is the direct cost of conveying and treating illegal flows. Accepting illegal flows results in additional costs in extending existing assets or building new facilities, or in being restricted in servicing future development. Passage of flows through faults in the fabric will shorten the operating life of the facilities with corresponding additional costs.

Sewer systems are required to operate to basic performance requirements (*European Standard EN 752-2: 1996, Drain and sewer systems outside buildings, Part 2 Performance Requirements*). Excessive inflow and infiltration can constitute a failure to meet certain of these requirements.

Worldwide, reduction of I/I is most commonly undertaken in order to reduce capital expenditure required by legislation. For example, in a new sewage transfer and treatment works scheme, it may be more cost effective to locate and remove excessive infiltration than to size transfer mains and treatment units to deal with existing levels. Alternatively, high levels of I/I may be identified and addressed during a drainage area study carried out as part of a general sewerage rehabilitation programme.

It is not always cost effective to reduce or eliminate infiltration. There is often uncertainty over the practicalities and, furthermore, little understanding of the relative costs of continuing to accept I/I versus the costs of I/I reduction. However, various strategies and procedures for addressing I/I problems on a systematic basis have been developed and implemented.

2.2 Definitions of Inflow and Infiltration

A typical hydrograph showing the components of flow in a foul/combined sewer system is given in Figure 2.1. The figure shows a period of 7 days with a rainfall event occurring on the fourth day.

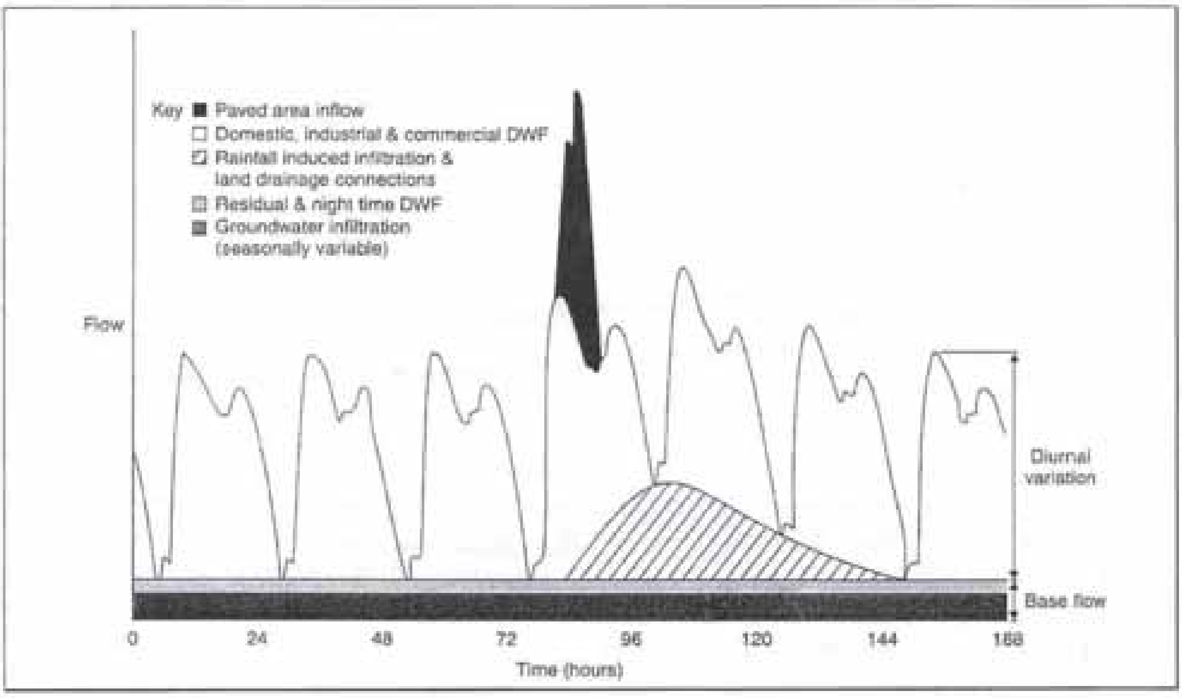

Figure 2.1 The Components of Flow in a Foul/Combined Sewer System

The term "infiltration" is used for water entering the sewer system from groundwater or from below ground level. The term "inflow" is used for water entering the sewer system directly. The expression "I/I" refers to the combined effects of inflow and infiltration.

Infiltration enters the sewer system through openings such as: displaced or open pipe joints; cracks, fractures and breaks in the fabric of the main sewer and lateral connections, and manhole chambers.

Inflow enters the sewer system via sources such as faulty manhole covers, cross-connections from surface water sewers/domestic drains and land drainage connections. In addition, in separate sewer systems, inflow includes the mis-connected direct runoff of surface water to the foul sewer system. In Ireland, the term "inflow" is not generally used for stormwater runoff entering sewers that were designed to operate as combined systems.

Table 2.1 shows the relationship between the various sources of inflow and infiltration that make up the total I/I influents in both dry and wet weather.

Source	Condition	Category
Groundwater infiltration *(may occur if the groundwater level is above the sewer invert level and may be seasonally influenced)*	**Background / base / dry weather infiltration**	**Infiltration** *(enters sewer system from the ground)*
Tidal infiltration *(infiltration of seawater from tidally saturated ground which the sewer crosses – will coincide with tidal cycles and will be most obvious during spring tides)*		
Leaking water mains		
Seepage of rainfall through subsoil of permeable areas *(may persist for days or weeks depending on the extent and permeability of the catchment subsoil)*	**Rainfall induced infiltration**	
Leaking storm sewers		
Domestic drain connections	**Dry weather inflow**	**Inflow** *(enters sewer system directly)*
Tidal inflow *(e.g. via combined sewer overflow outfall pipes)*		
Land drainage connections	**Rainfall induced inflow**	
Cross-connections from surface water sewers/domestic drains		
Mis-connected direct runoff of surface water to the foul sewer system *(in separate sewer systems)*		
River inflow via backflow in combined sewer overflows *(can exhibit similar properties to rainfall induced infiltration as the response time of the river is slower than that of the sewer)*		
Surface runoff and entry through manhole covers		

Table 2.1 Inflow and Infiltration Constituents

The maximum flow passed forward to a treatment works is often dominated by inflow, due to storm events. However, the background / base / dry weather infiltration is usually constant throughout the day and can therefore form a significant proportion of the total annual flow. Furthermore, reduction of dry weather infiltration will automatically reduce the overall quantity of wet weather infiltration.

2.3 Irish Experience of Inflow and Infiltration

There is limited literature available relating to infiltration studies or removal programmes in Ireland. Drainage area studies (undertaken as part of the design process for new sewage transfer/treatment schemes or to address deficiencies such as flooding) have often identified I/I as a problem and local authorities have followed up with works to locate sources and reduce flows.

The 2001 to 2004 Greater Dublin Strategic Drainage Study covered 18 foul/combined sewerage catchments with a combined population of 1.4 million (about 1/3 of the total state population). A major programme of flow measurement (480 flow monitors and 270 raingauges) and sewerage modelling in these catchments provided an opportunity for an initial assessment of infiltration, albeit on a 'snapshot' basis due to the short-term sewer flow surveys. Table 2.2 shows the existing approximate infiltration flows for the Ringsend WwTW catchments.

Catchment	Infiltration Flows in l/s
Grand Canal System	615
City Centre/ Docklands	558
Dun Laoghaire	338
Rathmines & Pembroke High Level	500
Total Infiltration Flow	2011 l/s

Table 2.2 Infiltration Flows into Ringsend WwTW

Appendix B provides a summary of the infiltration assessment for all catchments.

Data collection during the early stages of the GDSDS provided information on I/I from previous studies and investigations. The following examples give an impression of the situation in parts of the Greater Dublin Area.

- The presence and effects of infiltration have long been recognised in Dublin. The design report for the Grand Canal Drainage Scheme (1968) included assessments of the existing drainage networks draining to the Main Pumping Station.
  - In the 34,000 population Rathmines and Pembroke (low level) catchment "a considerable portion of the Pembroke area lies below the level of h.w.o.s.t. (high water of spring tide) and a large quantity of subsoil water finds its way into the sewers". Pumping records at the terminal station suggested that average infiltration was in the order of 80 l/s or 25% of total dry weather flow.
  - In the 341,000 population Centre City Main Drainage network, infiltration was estimated at 156 l/s or 12% of total dry weather flow.
  - Daily flow records at the Main Pumping Station serving the Centre City catchment were analysed. The report makes several references to infiltration:

    "The daily flows at this station show a wide variation… and even flows during long periods of dry weather are influenced to some degree by antecedent rainfall";

    "The development of the system during the past has been such that certain watercourses and streams which drained to the old city area were incorporated in the drainage system."

> "Infiltration from the tidewaters of the Liffey is also appreciable as the old city sewers which originally drained to the River are now equipped with tidal flap valves and operate as storm overflows."

- A sewer modelling study of Dublin Docklands in 2000 found that flows in the main city centre sewers showed a marked response to tide levels. Flows at the Main Lift Pumping Station were found to rise substantially with the tide. Tidal effects were also noted in other sewers further from the River Liffey.

- A short-term flow survey was undertaken in the Grand Canal Trunk Sewer (GCTS) catchment in the winter of 2001. On three selected 'dry' days, minimum nighttime flows at the downstream end of the GCTS ranged from 150 l/s to 500 l/s, with the corresponding range of infiltration estimated at 10% to 50% of total dry weather flow. This demonstrates the significant influence of preceding rainfall.

- Investigations for the Lower Liffey Valley Regional Sewerage Scheme found high rates of groundwater infiltration, particularly in the mid-autumn to mid-spring period. Increased pumping times were noted at pumping stations and infiltration was described as 'a serious problem'. It was also evident that some surface water pipes were connected to supposedly separate foul sewers. In Leixlip, Celbridge and Maynooth, infiltration typically ranged from 25% to 75% of total dry weather flow. In Kilcock, the minimum recorded infiltration was 45% of dry weather flow (flows from Kilcock are pumped twice before reaching the WwTW at Leixlip). The study proposed both sewer rehabilitation and some separation and diversion of surface water.

- A study to identify sewage disposal options for a major development in South Dublin (Adamstown Area Action Plan) reported infiltration of 70 l/s, or 30% of dry weather flow, in a catchment area of 2300ha. Inflow of surface water to the foul system was also found to be considerable with up to 20% contributing impermeable area in some subcatchments. Identification and removal of surface water connections was recommended prior to connection of foul flows from the new development.

- An eleven week winter flow survey in the Grand Canal Tunnel Sewer catchment showed marked differences between infiltration rates in the two main trunk sewer tributaries: the 9B (Clondalkin) Sewer and the 9C (Blanchardstown) Sewer. Flow plots for the full survey period are included in Appendix A. In the 9B Sewer, the base infiltration is low, at around 5 or 10% of total dry weather flow. In the 9C Sewer, it is significantly higher, at around 40 or 50% of dry weather flow. The effects of rainfall-induced infiltration are clearly shown in both systems, which are essentially separate foul sewers. The fast response to rainfall (peaks of up to 5 times average) indicates the presence of inflow.

2.4 International Experience of Inflow and Infiltration

The nature of the UK's sewerage system is similar to that of Ireland's (a mixture of older combined systems with newer separate areas) and an understanding of the UK's approach to I/I problems is beneficial. Literature from elsewhere in Europe indicates a similar level of understanding and experience to that in the UK.

In the USA, the great majority of sewer systems are intended to be fully separate and since the 1970s much effort has been expended in attempts to eliminate excessive I/I. There is a great deal of literature available describing I/I reduction programmes in American cities.

Sewerage systems in Australia and New Zealand are generally similar to those in the USA but major I/I reduction work has been more limited. Some major I/I studies have been undertaken in Hong Kong and Singapore in recent years.

2.4.1 United Kingdom Experience

In the UK, water services are provided by a number of private companies whose actions are regulated by the Office for Water Services (OFWAT). Since privatisation in 1989, investment has been delivered in five-year cycles known as Asset Management Plan (AMP) periods. Major improvements to sewage treatment, combined sewer overflows and property flooding have been achieved. However, the programme constraints imposed by the AMP process, combined with the scale of the workload, are such that the majority of capital works have been designed to deal with existing levels of inflow/infiltration.

The report, *Control of infiltration to sewers (CIRIA, 1996),* describes a questionnaire survey of infiltration problems in the UK. Of the 1,646 catchments included in the survey, 28% were reported to have greater than 25% infiltration and 9% to have more than 50% infiltration. The report describes a method for estimation of infiltration and a procedure for establishing the cost effectiveness of infiltration reduction.

A subsequent report, *Dry weather flow in sewers, (CIRIA, 1998),* presented an analysis of long term dry weather flow data from 95 sites in England and Wales. Infiltration ranged from 0% to 89% of total measured dry weather flow, with a mean of 45%. For purely domestic catchments, the 45% level is equivalent to 115 to 120 litres/capita/day. The report includes guidance on alternative methods of infiltration assessment depending on the available data.

Sewers for Adoption (Water UK/WRc, 5th edition 2001) is a design and construction guide for developers who want their new sewers to be 'adopted' (i.e. taken in charge) by the water company. The guide requires a design flow of 4000 litres/unit dwelling/day for gravity sewers serving new residential developments. The derivation of this figure effectively allows for 10% infiltration, which equates to 120 litres/capita/day.

Drains have been recognised as a potentially significant source of infiltration in many areas of the UK but no corrective action has been reported in this sector *(Control of infiltration to sewers, CIRIA, 1996*). A research project has recently been commissioned to investigate this issue further.

With the aim of improving water quality at EC identified bathing waters, spills from storm tanks at numerous sewage treatment works around the UK's coast have been required to be limited to an average of 3 per bathing season. Understanding the range of infiltration present during the summer months has been found to be an important factor in optimising design of the storm tanks to achieve the new standards. A design study for a 3 spills storm tank at a WwTW on the south coast of England *(Poole, WaPUG Spring Meeting, 2002)* analysed five years of flow and rainfall data. Infiltration was found to vary seasonally but was more strongly influenced by the preceding rainfall. The amount of infiltration was also found to be influenced by the amount of rain that fell as much as 3 months earlier.

The benefits of long-term flow monitoring data were also demonstrated by an investigation carried out prior to award of a Private Finance Initiative (PFI) contract for a WwTW at Edinburgh, Scotland *(Friend and Hill, WaPUG Spring Meeting, 2001).* On average, infiltration amounted to some 60% of the dry weather flow and seasonal variations were noted. The PFI payment system was based on flows receiving full treatment at the WwTW and for the total payment over the 25 years concession period, approximately half is infiltration based. Infiltration values on dry days over a twelve-month period were plotted against both the number of preceding dry days and the Antecedent Precipitation Index (API30) values (API30 is a factored total of the rainfall that fell during the 30 days prior to the dry day). The analysis found that the lowest infiltration did not necessarily occur after the largest number of dry days or when the API30 value was lowest.

The considerable investment in CSO improvements in the UK in recent years has highlighted the importance of understanding rainfall-induced infiltration and representing it correctly in sewerage models. Where storage is proposed as a solution for reducing CSO spill frequency, the required volume may be underestimated if the model does not adequately represent the 'recession' of flows after a rainfall event. The typical five to ten week flow survey carried out to verify a sewerage model has been found, in many cases, to be insufficient for understanding infiltration variation to the extent needed for design.

2.4.2 United States of America Experience

The *US Environmental Protection Agency (EPA) 1975 Guidelines* required cities to eliminate excessive I/I in order to qualify for grants to improve collection systems or build new wastewater treatment plants. The threshold infiltration rate was set at 1500 gpd/in-mile or approximately 140 litres/day per mm diameter – kilometre length and communities were required to remove any infiltration in excess of this (for comparison, the US EPA standard for new construction is 18.5 litres/day per mm-km). This requirement has led to considerable work being undertaken and as a result there is a great deal of literature from the USA regarding I/I. The vast majority of sewerage systems are separate so WwTWs are not designed to accommodate storm flows. Historically there has been a high emphasis on the removal of inflow from both public and private sources. More recently, the drive to reduce combined sewer overflow spills has also focused attention on reduction of inflow.

A number of case studies suggest that I/I programmes have, for various reasons, often been ineffective or not cost effective. However, more recent work (Merrill, Lukas, Swarner and Klusman, 2001) suggests that detailed and good quality flow monitoring (ADS monitoring for low flows), together with modelling of individual I/I components, is helping to target priorities and therefore lead to a more cost effective and successful removal programme.

Success rates of I/I reduction are highly variable. The City of Nashville reported in 1994 that I/I reduction in five pilot basins ranged from 49 to 86 percent. In Seattle, Washington, a complete sewer rehabilitation programme in a pilot project area of 4ha achieved a total I/I reduction rate of 60%. A review of USA practice (Wade, *Controlling Inflow and Infiltration in Wastewater Collection Systems*, *1999*) found that it was “rare that I/I reduction rates exceed 50%” but that “most cities can expect cost recovery within a 3 to 5 year period.”

One of the most difficult factors involved in removing significant quantities of I/I from sewer systems is the large percentage of sources that are located on private property. In Cincinnati, Ohio, a major programme to reduce rainfall induced I/I provided reimbursement of up to $3,000 to each participating private property owner for re-routing storm flows and eliminating their discharge to the foul sewer *(Niehaus, 1995).* Over 10,700 unauthorised storm connections were identified, with a total removal cost of $16m. Savings in capital and operating costs were estimated at over $300m. The two most common types of inflow sources removed were roof drain connections and driveway drains. A change in the law was required to permit the funding of sewer improvements on private properties but the resulting strategy was definitely found to be a “win-win” approach.

A similar programme in St Paul, Minnesota was described in a guidance note on *Inflow Reduction for CSOs (US EPA, 1999)*. An estimated 20% of CSO volume came from roof drains. As a result of a $40 rebate for voluntary redirection and other efforts, some 18,000 homes redirected their roof drains over a three-year period.

Introducing similar funding schemes to the Dublin Region should only be done after cost-benefit analysis has been done to demonstrate that they would be worthwhile. Such analysis would need to compare the levels of I/I measured and the likely reduction that could be achieved (the benefits), with the funding amounts offered and the likely take-up of the scheme (the costs). The first step in this process is implementation of the I/I/E Reduction Procedure recommended as a short-term measure in Section 4, to define the potential benefits.

In Indianapolis, Indiana, frequent basement flooding was experienced, generating over 1,000 residential complaints. Rapid development compounded the problem by further taxing the hydraulic capacity of the sewer system and a sewer moratorium was threatened. Flow monitoring in 400 sub-catchments found that only 27% of the system contributed 80% of the I/I. This allowed rehabilitation efforts to be focused on the high priority areas for the quickest results. Construction of a new relief sewer was avoided with savings of $21m.

2.4.3 Experience Elsewhere

An extensive programme of infiltration studies was carried out in eight catchments in Singapore during the 1990s to identify sewers most at risk of structural deterioration *(Sharpe and Turner, WaPUG Spring meeting, 1999).* The separate foul sewer networks were mainly constructed in the 1970s. Detailed hydraulic models were built in each catchment and a total of 178 flow monitors were used with an average sub-catchment size of 32.5ha. Model calibration was used to identify the separate I/I components of base infiltration, rainfall induced infiltration and storm inflow. Infiltration was ranked using a l/s per mm-km analysis. Dry weather infiltration contributed between 0% and 57% additional flow. Storm inflow contributions more than doubled the peak dry weather flow in a 1-year return period event in some catchments. In the worst two catchments, storm inflow increased peak dry weather flow by a factor of 10 in a five-year return period storm event.

A pilot study in Hong Kong *(Atkins China, 2001)* for Inflow and Infiltration reduction investigated a study area with a population of 1.34 million. The realisation that capacity taken up by infiltration could instead be reserved for future population growth was a key driver for the study. The study employed flow and rainfall monitoring, sewer modelling, CCTV surveys and cost models to identify the most cost effective levels of I/I reduction. Rehabilitation work to reduce I/I was found to be cost effective in all but one of the 34 catchment areas in the pilot study area.

The *New Zealand Infiltration and Inflow Control Manual (NZ Water and Wastes Association, 1996)* highlights “three major issues which have an important influence on successful I/I control.” These include “flow measurement (both before and after remedial works), the careful investigation of sub-catchments to locate the worst problem areas, and house lateral rehabilitation.”

2.4.4 Summary of International Experience

It is evident that I/I/E is a worldwide problem with DWF percentage flows similar to those being experienced in the Dublin region. Due to the difficulty in identifying exfiltration, most investigative work has been directed towards inflow and infiltration.

The most successful approach is to use detailed and good quality flow monitoring, together with modelling of individual I/I components. Priorities are thus targeted and therefore produce a more cost effective and successful reduction/removal programme. This approach is being recommended for I/I/E policy in the Dublin region.

Reduction/removal rates are very variable, and should not be applied to the Dublin region without some pilot study into local problems. However the 80:20 principle applies (80% of I/I contributed by 20% of the system), again emphasising the worth of the structured approach being proposed in the policy.

Faults in private drainage systems contribute greatly to the I/I/E problem, and therefore drainage policy should concentrate on policing private connections.

It is recognised worldwide that I/I/E is a difficult and expensive problem to address, and therefore the most cost-effective approach is to avoid it in the first place. Policy should therefore also concentrate on good quality construction and supervision to maximise the life of the drainage assets. This principle is being recommended in the Regional drainage policies, in particular that for New Development.

2.5 Causes of Inflow and Infiltration

Inflow and infiltration can be caused by a wide variety of sewer system faults and ground conditions. In essence, I/I can be considered as the presence of rainwater/groundwater/seawater coinciding with sewer system faults allowing entry of the water.

2.5.1 Causes of Infiltration

Infiltration can occur where existing sewers undergo material and joint degradation, which results in entry paths for water. This degradation can be progressive, so that repair of, for instance, all faulty joints, may be followed by further degradation of different, formerly sound joints and renewed infiltration requiring further repair. Infiltration can also occur in new sewers where these, or the connected laterals, are poorly designed or constructed.

Factors that influence the occurrence and extent of infiltration include:

- Ground movement – caused by mining activity, construction work, change in overlying ground use, ground loss from around the sewer due to infiltration through damaged pipes.
- Soil type – will affect the drainage of water and movement of the pipe. Silts, sands and gravels generally have a high permeability allowing rapid erosion of soil particles. Clays have much smaller pore spaces and a greater resistance to this process.
- Pipe type and quality of construction – traditional materials are durable but the joints and mortar can be more prone to attack.
- Chemical attack – can be caused by standing sewage turning septic or illegal/un-licensed discharge of trade effluents to sewer or to groundwater.
- Groundwater – location, movement and response to rainfall. The mechanism of soil erosion is accelerated by high groundwater levels.
- Hydraulic regime – erosion of soil is dependent on flows through the defect and hence cycles of infiltration or exfiltration caused by periods of surcharge within the sewer are important.
- Pipeline bedding – highly permeable bedding can affect the local natural drainage paths; the use of cut-offs within the bedding prevents rapid flows along the sewer trench, which can result in erosion of backfill.
- Type and extent of land development – use of sustainable drainage systems (SuDS) in new developments.
- Age of sewerage system – materials and methods of design and construction have changed over the years.
- Quality of sewer system maintenance – workmanship and materials used for sewer repairs, replacement or re-lining; sealing/isolation of abandoned lateral sewers.
- Ownership – drains that are intended to remain in private ownership are not subject to the same standards of construction or maintenance as publicly owned sewers.
- Leakage from water mains – foul sewers are usually laid at a greater depth than potable water mains, reduction in potable water leakage rates may reduce infiltration.

The *Sewerage Rehabilitation Manual (4th edition, WRc, 2001)* provides a detailed explanation of the factors that result in infiltration, exfiltration and eventually sewer collapse. The three stages of collapse are referred to as initial defect; followed by deterioration and finally collapse, brought about by a number of contributing factors.

A thorough description of the causes of infiltration is given in *Control of infiltration to sewers (CIRIA, 1996).* The report describes types of sewerage systems particularly at risk from infiltration:

- sewers laid in poor ground conditions
- sewers lying below the water table
- sewers situated in estuarine or marine environments
- lateral connections to private properties
- systems where poor workmanship was employed during construction
- foul sewers situated below leaking water mains and storm sewers.

Sewerage systems are most easily characterised by:

- the age of the system
- local ground conditions
- factors specific to the system usage.

Migration of infiltration has been found to be a problem in some infiltration reduction programmes. This can occur where sewer rehabilitation removed the previously existing infiltration flow paths, resulting in localised raising of the groundwater level and flows of groundwater to un-rehabilitated sections of sewer, which previously were not leaking.

2.5.2 Causes of Inflow

Causes of inflow are less complex because the water enters the sewer system directly. Factors that influence the occurrence and extent of inflow include:

- Topography;
- State of the stormwater system – e.g. missing or damaged manhole covers, faulty flap valves on CSO outfall pipes, cross connections from storm sewers, presence of land drainage connections;
- Capacity of the stormwater system in comparison with experienced flows;
- Illegal stormwater connections – on new developments if work is not checked before sewers are taken in charge; in existing areas where new house extensions, patios or driveways are drained to the foul sewer;
- Low or unsealed foul gully traps allowing surface water to enter foul system.

2.6 Estimation of Inflow and Infiltration

It has been said that “you can’t manage what you can’t measure” and this is certainly applicable to I/I in sewerage systems. However, measurement of infiltration has sometimes proved difficult in the past and results have been affected by poor quality or insufficient data or by a lack of understanding of I/I components.

Evidence from the USA *(Merrill et al, 2001; Swarner and Thompson, 1999; Keefe, 2000),* where considerable effort is invested in I/I reduction, suggests that recent I/I investigations have been more successful than those in the past. These recent studies have employed detailed flow and rainfall monitoring combined with hydraulic modelling to understand the relative contributions of individual I/I components in wet and dry weather. This has helped to target available funds to where they can have the biggest cost saving impact.

However, different methods are appropriate at different stages of an investigation and initial estimates must be based on whatever data is available. The aim of this section is to describe a range of methods that may be applied at different stages as appropriate. For the purposes of analysis, the methods are described under two categories: dry weather flow and rainfall induced flow.

2.6.1 Dry Weather Flow

Sources of infiltration and inflow in dry weather are listed in Table 2.1. Two CIRIA reports: *Control of infiltration to sewers (1996)* and *Dry weather flow in sewers (1998)* describe various methods for estimating the quantity of base, or dry weather, infiltration in a sewerage system and much of the following is based on the findings of these two research studies.

The basic definition of dry weather flow (DWF) is **all flow in a sewer except that caused directly by rainfall**. The average daily DWF is given by:

$$DWF = PG + I + E$$

where

DWF = dry weather flow (m3/day)
P = population served
G = average domestic wastewater contribution (m3/capita/day)

I = infiltration (m3/day)
E = industrial effluent discharged in 24 hours (m3/day)

This formula gives an average flow rate that in practice will vary through the day. E is sometimes deemed to include metered commercial discharges.

The following sections describe methods for estimating dry weather infiltration in a catchment. The methods increase in complexity along with the level of data that is available or collected.

2.6.1.1 No Data

In the absence of any other data for sewerage systems in areas with high groundwater levels, it is suggested that infiltration is assumed to be 45% of total DWF (including infiltration). In other words:

I = 45% of (PG+I+E)

Alternatively, if I is expressed in terms of (PG+E):

I = 80% of (PG+E)

The average value of 45% was identified in *Dry weather flow in sewers*, *(CIRIA, 1998),* following an analysis of long-term dry weather flow data from 95 sites in England and Wales. Conditions influencing infiltration are likely to be generally similar in Ireland and, in the absence of any similar research covering Irish catchments, the same value is considered appropriate. For purely domestic catchments, the 45% level is equivalent to 115 to 120 litres/capita/day.

In theory I should be expressed as 81.8% of (PG+E). However 80% is satisfactory for this estimation process.

2.6.1.2 Data from Local Catchments with Similar Conditions

Where data is available from local catchments with similar conditions (i.e. similar age, pipe materials, subsoil type etc), this gives a better estimate of long-term infiltration. Data is best analysed in terms of litres/day per mm diameter – km length.

> The 2001 to 2004 Greater Dublin Strategic Drainage Study covered 18 foul/combined sewerage catchments with a combined population of 1.4m (about 1/3 of the total state population). A major programme of flow measurement (480 flow monitors and 270 raingauges) and sewerage modelling in these catchments provided an opportunity for an initial assessment of infiltration, albeit on a ‘snapshot’ basis due to the short term sewer flow surveys. It should also be noted that monitoring was undertaken in both summer and winter conditions. The results contained in Appendix A, are of the initial Grand Canal Flow Survey, undertaken between December 2001 and February 2002.
>
> The infiltration information in Appendix B resulted from flow surveys undertaken between June and September 2002. Infiltration in each monitored subcatchment was expressed in terms of percentage of DWF and was also related to system extent in terms of litres/day per pipe surface area. The measured infiltration rates ranged from 0 to 104% of DWF, and from 0 to 16558 $l/d/m^2$. Appendix B lists the results for each flow monitor and catchment.

2.6.1.3 Flow Survey Data

Two methods of estimating infiltration are proposed in *Control of infiltration to sewers (CIRIA, 1996).*

Method 1 – Minimum Flow Calculation

The first method involves examination of dry weather flows during the early hours of the morning when the domestic sewage contribution is at its lowest. Flow survey data for a dry weather day will provide values of average dry weather flow and minimum nighttime flow. At the time of minimum flow, it is assumed that approximately 10% of wastewater production (or PG+E) is present.

Deducting minimum night time flow from average dry weather flow eliminates infiltration, I, and so:

PG + E = (Ave – Min) / F, where

Ave = Average flow over 24 hours (measured)
Min = Minimum night time flow (measured)
F = Factor (typically 0.9)

Infiltration, I is then given by:

I = Ave – (PG+E)

Estimation of infiltration by this method is sensitive to the value used for the factor F. In upstream parts of sewer catchments, F is thought to be approximately 0.9 but attenuation will decrease the value in the downstream reaches of larger systems. The effect of attenuation of the dry weather flow profile is shown in Figure 2.2.

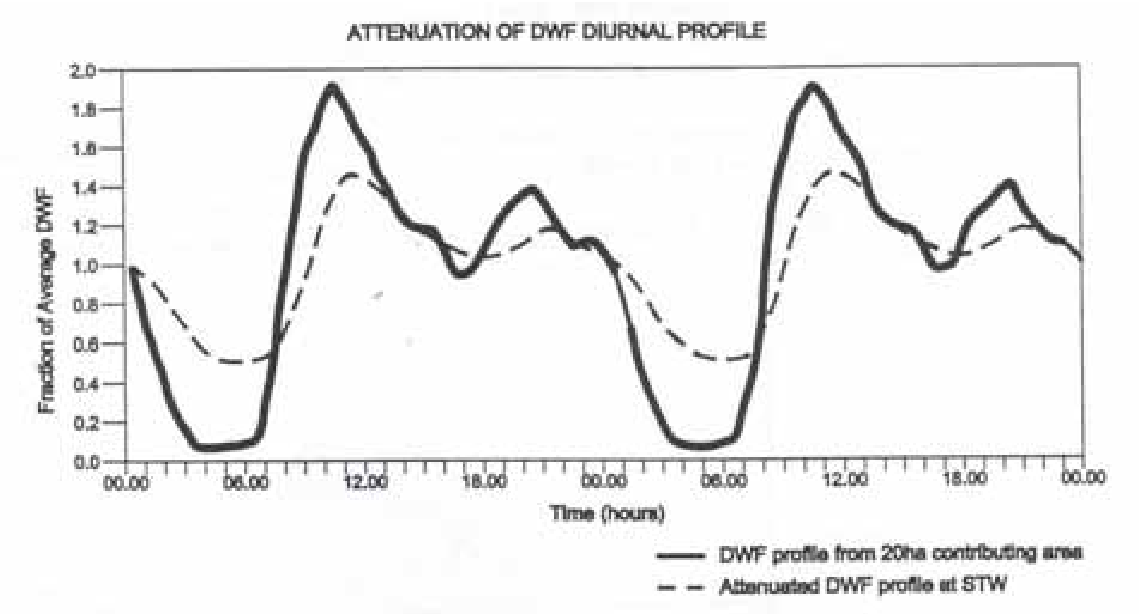

Figure 2.2 Attenuation of DWF diurnal profile *(Control of infiltration to sewers (CIRIA 1996))*

F should also take into account flows from industrial premises which may be working 24-hour days or discharging effluent overnight, e.g. from cleaning processes.

It can also be difficult to make a sufficiently accurate estimate of minimum flow at sites where flows are low and flow rates are only available in litre/second increments. ADS or equivalent-type flow monitors can provide better measurement of low flows. Alternatively, a temporary flume with ultrasonic depth measurement could be used.

Method 2 – DWF Calculation

An alternative approach is to calculate the values of PG and E and deduct from a measured value of dry weather flow (PG+I+E) over a 24-hour period.

There is a link between water consumption and wastewater generation – it has been estimated that about 95% of water used is returned to the sewer network. A value for G can therefore be obtained from water consumption figures. In the absence of local data, a value for G of 140 - 150 litres per capita per day could be assumed. Factors that may affect future trends in per capita water consumption include household size, water metering, and population age structure and climate change.

The accuracy of the calculation of E will depend on the level of data available for discharges by industries into sewers. Discharge licences usually state a maximum discharge rate, which may not be produced in practice. If possible, metering records should be obtained in order to calculate the amount discharged during a 24-hour period.

In addition to domestic and metered industrial sources, dry weather flow is also generated by a whole range of commercial establishments such as shops, offices, schools and pubs. Some town or city centre catchments may include a significant proportion of commercial flows and it is important to be clear about how these are accounted for in the above calculation. One option is to use water consumption records to derive a higher 'equivalent' G figure that includes for commercial flows. Alternatively, commercial flows could be included in the E figure by estimating volumes of wastewater production for individual sources (typical annual volumes for various sources are given in *Dry weather flow in* sewers *(CIRIA, 1998)*. The size of the catchment will determine which method is appropriate.

Records of incoming flow at a sewage treatment works are a commonly available source of data for obtaining a value of DWF. A period with no rain of at least seven days is usually considered sufficient to ensure that the effects of rainfall-induced flows are eliminated. However, this period may vary with catchment type and antecedent wetness. Figure 2.3 shows a typical pattern of flow recession after rain – the last rain occurred about 09:00 on day 1 of the plot. The indirect rainfall effects continue for a week until a constant diurnal pattern is achieved.

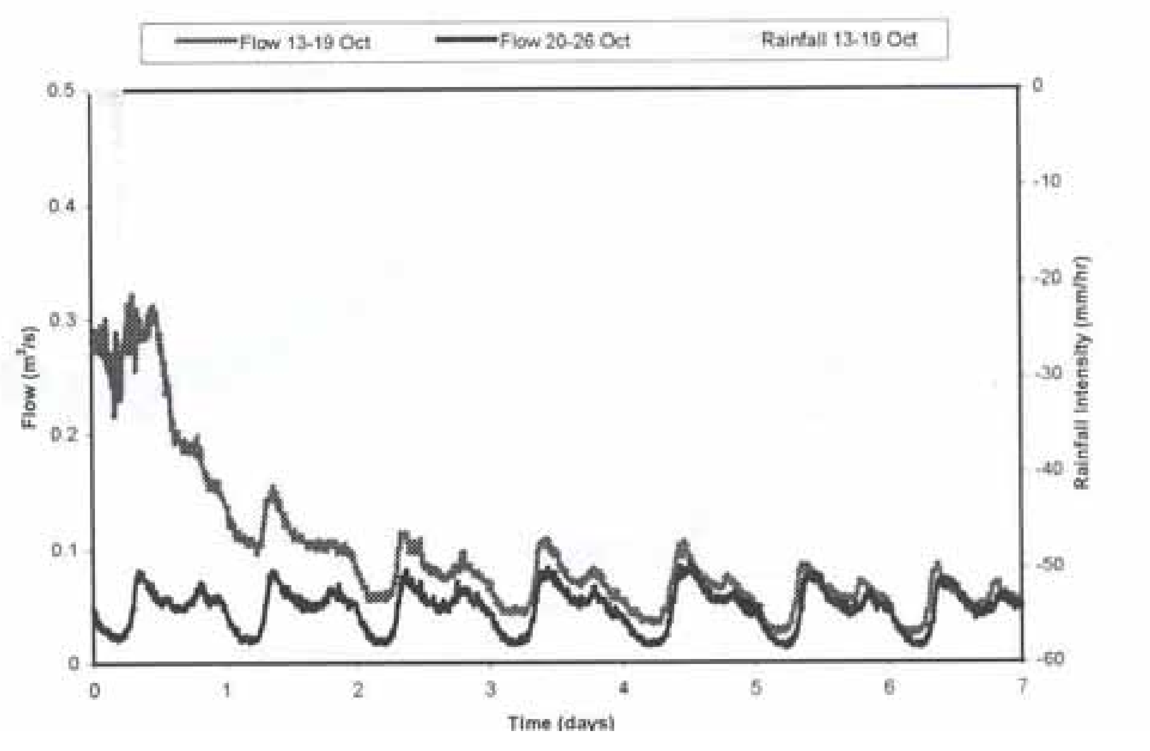

Figure 2.3 Flow Recession after Rain *(Dry weather flow in sewers (CIRIA 1998))*

The UK Institute of Water Pollution Control *(IWPC, 1975)* defined dry weather flow as

The average daily flow to the treatment works during seven consecutive days without rain following seven days during which the rainfall did not exceed 0.25mm on any one day.

Where there is a significant industrial component, the flow on five working days should be used. To overcome the problem of seasonal variation (see next section), the UK National Water Council *(NWC, 1979)* defined DWF as:

The median flow in dry weather, i.e. the median value over 24hrs of all days when rain did not exceed 1mm (in four quarters of the year).

In practice, the length and accuracy of the available flow and rainfall data will determine how much confidence can be placed in the estimate of dry weather infiltration. The benefits of long-term data are discussed in the following section.

2.6.1.4 Long Term Flow and Rainfall Data

For both methods described above, it is important to appreciate the potential for long-term variation due to antecedent rainfall. Studies have found that the flow at any given moment can reflect about 6 months of prior rainfall *(Merrill et al, 2001).* Seasonal variations in base infiltration are common in certain catchments due to seasonal variation in groundwater levels. Figure 2.4 shows diurnal profiles for two dry weather days for the same site in January and October. After removal of the infiltration component, Figure 2.5 shows that the two diurnal profiles are almost identical.

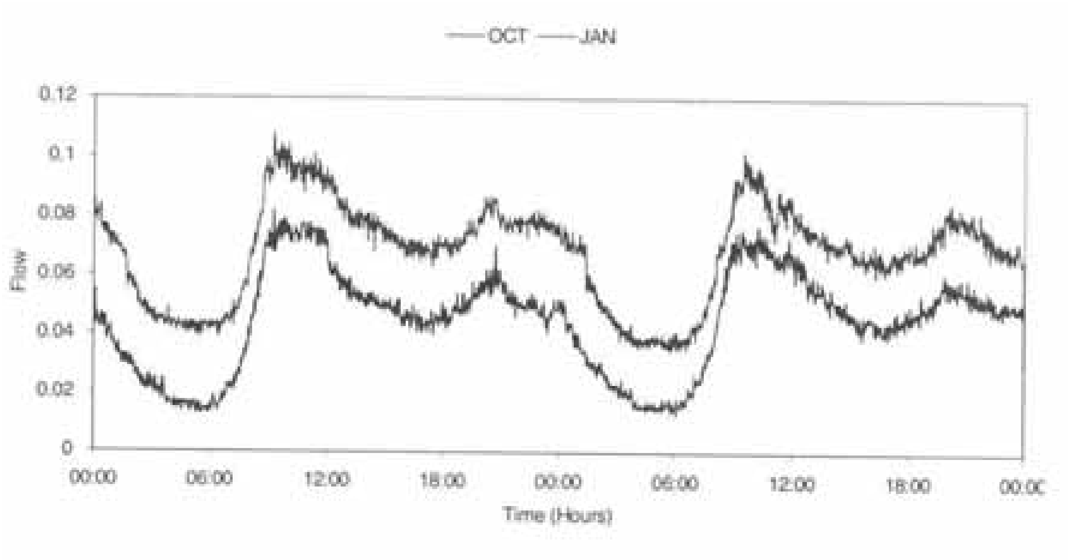

Figure 2.4 Seasonal Variation in Infiltration *(Dry weather flow in sewers (CIRIA 1998))*

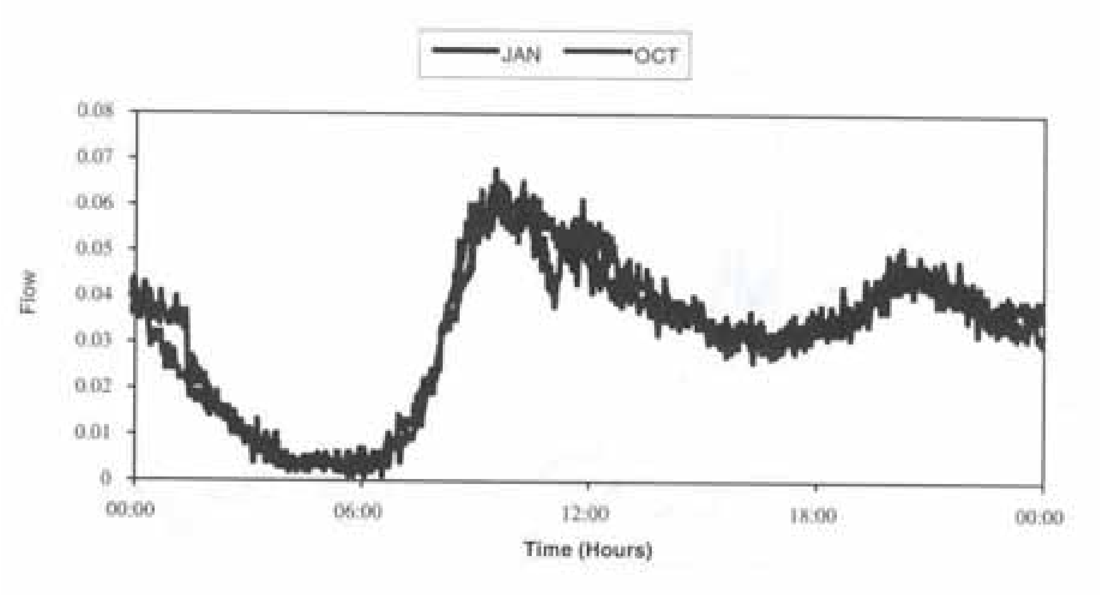

Figure 2.5 Diurnal Profiles after Removal of Infiltration *(Dry weather flow in sewers (CIRIA 1998))*

In assessing infiltration, the benefits of long term flow and rainfall data cannot be over-emphasised and the longest possible record should be obtained. A simple spreadsheet-type model of dry weather infiltration based on antecedent rainfall *(Poole, WaPUG Spring Meeting, 2002)* may be beneficial in cases where infiltration is known to vary significantly and its level affects the design of new infrastructure. At worst, a long term record will reveal a range of values within which base infiltration is known to lie – a useful aid to decision making and of much greater benefit than an estimate based on a single short term (e.g. 5 to 10 weeks) flow survey.

2.6.1.5 Ammonia Data

Dry weather flow in sewers (CIRIA, 1998) describes how an additional check on infiltration can be made if quality monitoring, usually at a WwTW inlet works, has included measurement of ammonia concentration. The research found that ammonia loads per capita for domestic wastewater appeared to be relatively constant across different catchments - an average concentration of 47 mg/l is suggested. Infiltration can be estimated by finding the flow rate necessary to adjust the measured ammonia concentration to this expected average value. This method should, however, only be used as a check and with caution as significant anomalies have been found in some catchments.

2.6.1.6 Sewerage Modelling

A hydraulic model of the sewerage system allows many of the limitations of the methods described above to be overcome. The advantages for estimation of dry weather infiltration include the following:

- the attenuation of domestic dry weather flow can be found at any point in the system by applying a standard diurnal profile to relatively small sub-catchment areas (1 – 5 ha) – this overcomes the uncertainty over the choice of value for F in Method 1 described above;
- model construction commonly requires collection of population data, household numbers, household size, water consumption, trade effluent licences, trade effluent monitoring records, tide levels, pump run times – all of which are relevant for understanding dry weather flow and for the calculation of PG+E in Method 2 described above;
- models are usually verified using flow measurements taken at various points within the catchment, allowing infiltration to be assessed at each flow monitor location.

However, care is needed when using existing models to assess infiltration:

- older models often contain only a single dry weather flow value at each node or conduit, i.e. the components of DWF are not separately identified;
- verification of dry weather flows may not have been considered important by a modeller primarily concerned with assessing flooding in a combined system;
- the quality of the dry weather flow verification is dependent on the modeller’s understanding of dry weather flow in sewers, the extent and quality of the data collected and the validity of any assumptions made;
- assumed values for G are commonly too high (perhaps due to misleading guidance in modelling specifications or design manuals), leading to an underestimate of infiltration;
- models are usually verified on the basis of a single short term (5 – 10 weeks) flow survey
  - a period long enough to eliminate the effects of rainfall induced flows may not have occurred during the survey
  - base infiltration may have been influenced by rainfall occurring before the measurement period started
  - selected dry weather days may have been influenced by tourist numbers, industrial shutdown periods, tidal effects or public holidays.

- older models may be unrepresentative due to large-scale development, new industry or structural deterioration of sewers.

Based on the above, there are clearly advantages in constructing a new hydraulic model to assess infiltration but this should be justified on a cost-benefit basis by means of an initial estimate using one of the simpler methods described in the preceding sections.

For diurnal variation of purely domestic dry weather flow, dimensionless profiles for modelled areas of 2 to 5 ha are given in *Dry weather flow in sewers (CIRIA, 1998).* Guidance on modelling dry weather flow was given in *WaPUG User Note No.33 (1996)* but recent improvements in modelling software have increased the ways in which dry weather infiltration can be modelled. For example, a time varying profile can be applied to groundwater infiltration flows and tidal variations in infiltration can be simulated.

2.6.2 Rainfall Induced Flow

Sources of rainfall-induced infiltration and inflow are given in Table 2.1. Due to the variety of sources and entry mechanisms, the measurement of volumes of these flows can be a complicated process. In a sewer system designed or required to be fully separate, such as many of those in the USA, all storm response would be considered as I/I and the total I/I could be assessed by means of flow measurements.

However, a typical urban catchment in Ireland may contain some combined and partially separate sewer systems in older areas with fully separate systems elsewhere. In separate areas, the system may contain mis-connections of storm to foul and vice-versa. In these circumstances, the complexities are such that a hydraulic model, verified with flow survey data, offers the only practical means of determining contributing areas.

Recent advances in modelling techniques, combined with good quality flow survey data, allow the separate identification and representation of dry weather infiltration, rainfall induced infiltration and rainfall induced inflow. System performance under different conditions can be tested using design storms or long-term historical rainfall records. Whatever the reason for wanting to reduce I/I, understanding the relative contribution of the different components allows reduction efforts to be targeted effectively.

The modelling of rainfall-induced infiltration is complex and there is little guidance currently available other than that provided with modelling software. The process should realistically be considered as one of calibration rather than verification but it has been reported *(Allitt, 2002)* that “with sufficient storms and sufficiently long periods of reliable data it is possible to achieve a very high degree of confidence in the way in which this (rainfall induced infiltration) is modelled. This then gives confidence in the way in which the flows might be extrapolated with higher return period storms.”

2.7 Costs of Inflow and Infiltration

An assessment of flow records at a WwTW may have identified that base infiltration is 50% of total dry weather flow – is this a problem? Is it worth spending any money to investigate further? Is it worth spending money on an I/I study? Is it worth spending money on reducing infiltration or inflow? How much infiltration should be removed? Authorities responsible for sewerage systems will be faced with having to make decisions concerning I/I and such decisions invariably have to be justified in terms of cost.

It is important to be able to demonstrate the cost benefits of an I/I programme from the earliest stage of the investigation through to the end. A staged approach to the I/I investigation allows a cost appraisal to be undertaken at each stage and thus determine whether further work is necessary.

In order to make rational decisions regarding expenditure on measuring, locating and removing I/I from a sewerage system, it is necessary to establish:

- the net present value (NPV) cost of the system if existing levels are accepted;
- the net present value (NPV) cost of the system with reduced I/I;

- the cost of reducing I/I.

In most cases, there will be a level of I/I at which the combined whole life costs of: (a) reducing the I/I to that level; and, (b) accepting the remaining I/I are at a minimum. A scheme that succeeds in reducing I/I to this level is therefore the optimum cost solution. Determination of the most economic level of I/I reduction depends on accurate estimation of both the quantity of inflow and infiltration (Section 2.6) and its associated costs.

2.7.1 Cost of Accepting Inflow and Infiltration

2.7.1.1 Operating Costs

A typical combined sewer system deals with storm flows by spilling at CSOs and by utilising storm tanks at the WwTW. In such a system, base infiltration may have the most significant impact due to increased operating costs at pumping stations and treatment works. These costs are incurred continuously, irrespective of weather conditions, and are therefore important when calculated on a whole life basis.

Pumping costs – power costs can be estimated from knowledge of the flow rate and pumping head at pumping stations on the network and at the WwTW. In calculating annual costs, account should be taken of any known seasonal variation in the base infiltration level. *Control of infiltration to sewers (CIRIA, 1996)* describes an approach for calculating annual pumping power costs.

Treatment costs – many of the operational costs at WwTWs will not be greatly affected by the additional flow from infiltration. The main costs arise from aeration, pumping and chemical addition. In practice, it can be difficult to calculate the true extra cost of dealing with infiltration at a WwTW and each WwTW has to be assessed on an individual basis. The most straightforward cost to calculate is that of pumping – costs associated with infiltration can be significant if there are multiple stages of pumping at the WwTW. In principle the aeration cost is determined by the BOD load, which should not be changed by the presence of infiltration. Chemical addition is affected by many catchment specific factors and costs will have to be assessed on an individual basis. Ingress of seawater can create corrosion and odour problems from generation of hydrogen sulphide and sulphuric acid.

2.7.1.2 Maintenance Costs

Infiltration can cause fine material from around the outside of sewers to enter the pipes. This can lead to: structural failure; accumulation of fines in sewers, wet wells and WwTWs, and pump wear from abrasion. Unfortunately, although elimination of infiltration could be considered as prolonging the effective life of existing pipes, estimating the cost associated with these impacts is not practical.

2.7.1.3 Capital Costs

Reduction of I/I may eliminate the need for capital works or reduce the capital costs due to smaller pipe sizes, storm tanks or treatment process units. Capital costs associated with infiltration need to be assessed on a case-by-case basis. As stated in the previous section, it is important to understand the relative contributions of the different components of total I/I. The type of capital scheme under consideration will then determine which component should be targeted for maximum cost impact.

- A sewage transfer scheme may be designed to transfer flow to a new WwTW. Flow to Full Treatment (FFT) may be set at 3PG+I+3E so all infiltration is passed forward through the system to the WwTW. Reducing the base infiltration sufficiently to allow a smaller pipe size to be used could have a significant effect over a long transfer distance. There would also be reduced pumping and treatment costs.
- Storm storage tanks are commonly provided to reduce the frequency of CSO spills. Rainfall induced infiltration can affect the volume of storage required to meet spill frequency requirements, e.g. where the CSO is impacting on a bathing water. Reduction of rainfall-induced infiltration could lead to reduced storage tank costs.

- In a separate sewer system, where flooding or CSO spills in storm conditions should not occur, reduction of inflow from sewer mis-connections may be sufficient to avoid the need for sewer upsizing to pass forward the higher-than-designed-for flows.

At WwTWs, the unit processes most sensitive to hydraulic loading are preliminary and primary although some secondary and tertiary processes will also be flow sensitive.

Cost estimates for capital works should be derived using current civil engineering cost databases or manuals. Basic graphs of ‘cost per l/s’ versus ‘flow in l/s’ can be derived for treatment works. For pumping stations, a series of curves can be plotted for different pumping heads. For pipework costs, curves can be generated for gravity mains and rising mains and for a range of depths. These graphs give a useful visual impression of the cost impact of changes in flow rate.

2.7.1.4 Other Costs

The problems caused by I/I, as described in the Introduction, may also have environmental and social costs. Where an improvement scheme is required to alleviate these problems, the capital cost of the scheme can be taken as the cost of accepting I/I. If improvements are not carried out, the environmental and social costs should be evaluated.

Control of infiltration to sewers (CIRIA, 1996) refers to various economic techniques available for valuing these issues. However, even if such costs are not formally evaluated, an appreciation of their existence may be sufficient to swing the balance in favour of I/I reduction.

2.7.2 Costs of Reducing Inflow and Infiltration

In some cases, a single major point source of infiltration, such as a damaged sewer at a river crossing, may be known. In these circumstances, the cost of reducing the infiltration will be relatively low, being primarily that of sewer repair or replacement. However, in many catchments, the distribution of I/I will be throughout the system and measurement and source location will also be required. A planned, structured investigation will ensure the cost effectiveness of any I/I reduction work carried out.

Reduction of I/I may include the following elements:

- Study
  - management of investigation
  - initial data collection and assessment
  - estimation of I/I
  - hydraulic modelling
  - scheme development
  - cost calculations
  - reporting
- Site measurement of I/I
  - flow and rainfall monitoring
  - local flow gauging
  - river/tide/groundwater level gauging
- Source detection
  - CCTV survey
  - manhole inspection
  - isolation testing
  - dilution gauging / salinity testing
  - dye and smoke testing
  - jetting

- Reduction of inflow
  - re-direction of inflow sources to separate surface water system, soakaway or outfall
  - repair/maintenance of flap-valves on CSO outfalls
  - Sealing of manhole covers
- Reduction of infiltration
  - renovation (pointing/chemical grouting or lining/repairs)
  - replacement (open-cut or trenchless techniques).

Each of these elements has an associated cost and the realistic estimation of these costs is important to ensure that the correct (i.e. most economic) level of I/I reduction can be identified. Flow and CCTV work may involve additional preliminary costs for sewer jetting or arranging safe access to manholes.

Reference to published cost databases will provide some of the cost information required (e.g. sewer renovation and replacement) but the remainder is more likely to come from analysis of recent survey contract costs (e.g. flow and CCTV surveys) or a build-up of labour and material costs for minor works. Sections 2.6 and 2.7 describe techniques for site measurement, source detection and reduction of I/I.

There are a small number of catchments in which I/I removal could cause detrimental effects. For example, the presence of I/I can:

- ensure that sewer self cleansing velocities are achieved in periods of low flow;
- reduce the risk of septicity in pumping station wet wells and detention tanks during periods of low flow;
- help to improve sewage treatment works processes by diluting strong flows upstream of the works.

Where these operational risks occur, a cost should be estimated and included in the analysis.

2.7.3 Optimum Cost Solution

A strategy for dealing with I/I should aim to identify the most economic level of I/I by seeking the point at which total costs (accepting and reducing) are a minimum – the optimum cost solution. This can be expressed in terms of either an absolute level of infiltration (or inflow for a particular return period) or as a percentage of infiltration removed. Figures 2.6 and 2.7 give examples of both options.

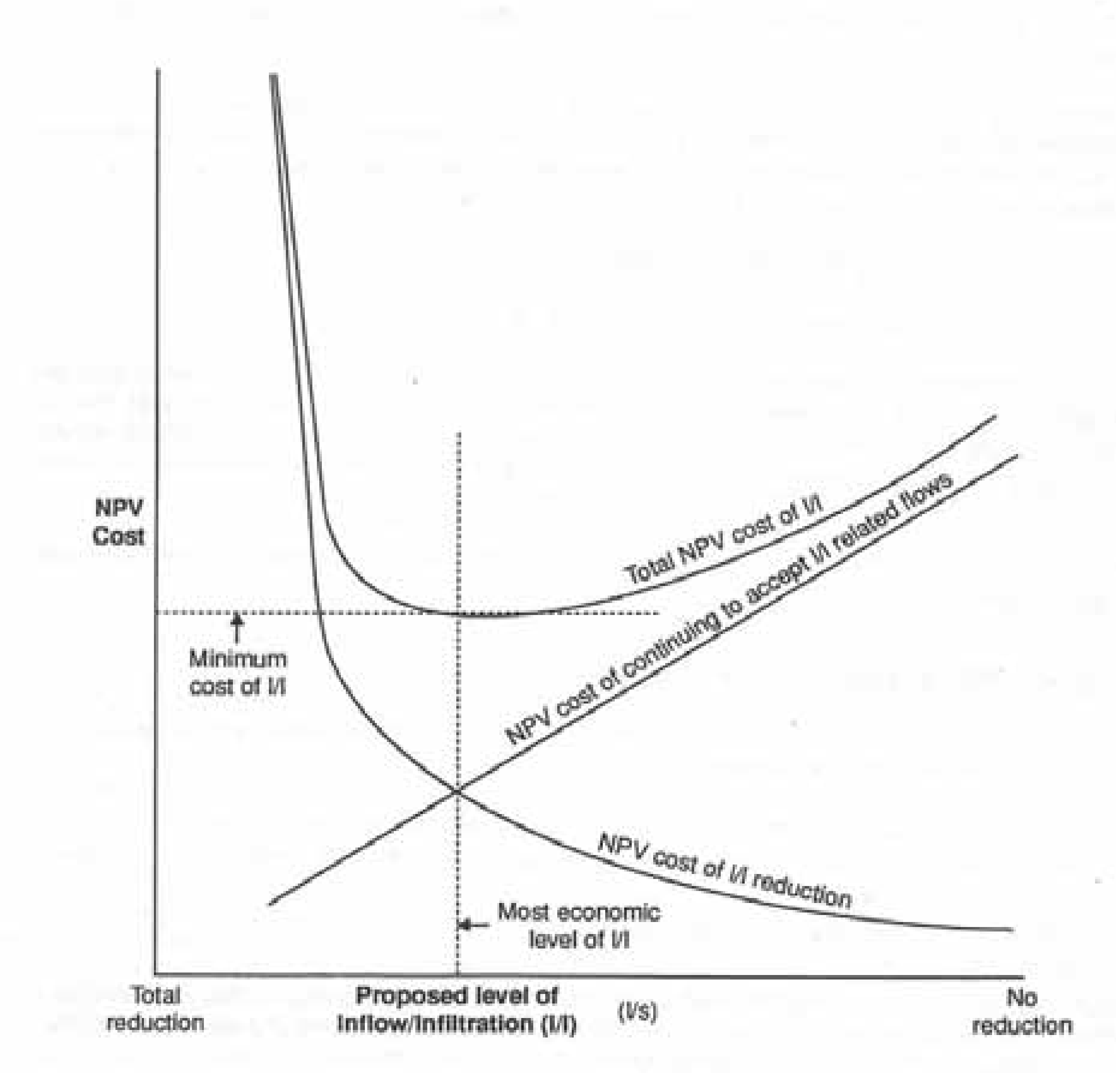

Figure 2.6 – The Most Economic Level of I/I Reduction

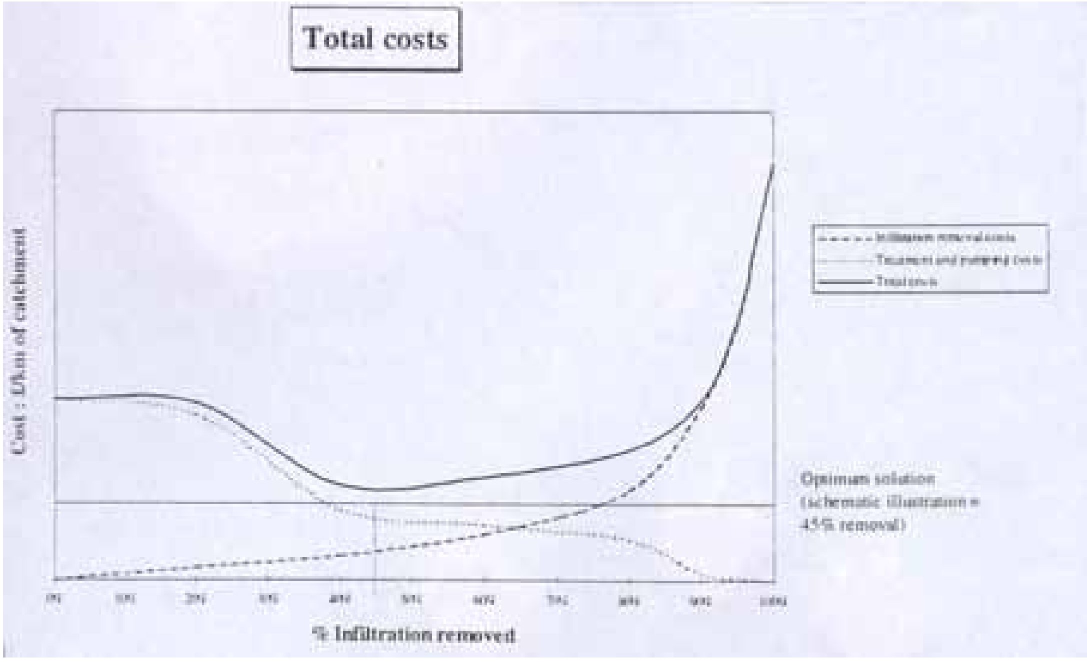

Figure 2.7 Optimum Cost Solution *(Control of infiltration to sewers (CIRIA 1997))*

In the early stages in the investigation, the distribution of I/I within the catchment is unlikely to be known and it is therefore difficult to estimate reduction costs. However, studies have shown that in many cases the distribution of infiltration has been shown to follow the Pareto principle. This states that for an 80/20 distribution, 80% of the problem will originate from 20% of the area. *Control of infiltration to sewers (CIRIA 1996)* refers to studies of catchments surveyed with CCTV, which have shown the Pareto principle to apply in the majority of cases with a range of 70/30 to 90/10. The principle is illustrated in Figure 2.8.

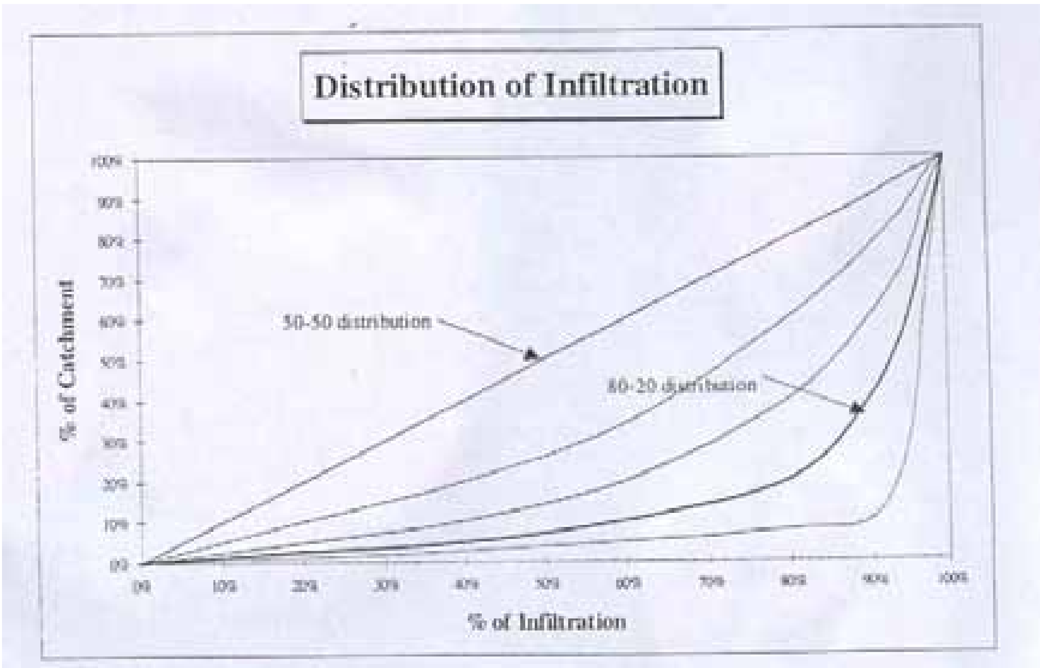

Figure 2.8 Distribution of Infiltration *(Control of infiltration to sewers (CIRIA 1997))*

On this basis, an 80/20 distribution could be assumed for an initial cost estimate to assess the need for progressing an I/I study into a second phase.

2.8 Survey Techniques for Inflow and Infiltration

Inflow and infiltration can occur anywhere in a sewer network, including private lateral sewers. However, as discussed in the previous section, I/I does not normally occur uniformly throughout the sewerage system. Location surveys need not, therefore, involve full, in-depth coverage of the whole network. A rational, structured survey approach is needed, firstly to identify the areas where the worst problems occur, and secondly to locate specific sources within those areas. The survey process may prove to be iterative, depending on the available resources and the size of the area under investigation.

2.8.1 Flow Surveys

Flow surveys are the most effective method of gaining an initial understanding of the distribution of I/I problems within a catchment. Data from any long term or permanent flow measurement sites (e.g. at WwTWs, pumping stations or where trunk sewers cross local authority boundaries) should be used as a starting point. Long term data, assuming it is reliable, has the advantage of providing information on seasonal / long term variation in infiltration. Such data is generally rarely available, or is only at one or two sites within a catchment.

Flow surveys undertaken for verification of sewer models (e.g. built for drainage area planning) usually have a good coverage of flow monitors through a catchment but are normally 'short term', i.e. a minimum of 5 weeks. These surveys, the primary aim of which is to record storm responses, may be extended to say, 15 or 20 weeks if there are insufficient rainfall events in the initial period. For assessment of inflow, short-term survey periods are acceptable. For assessment of infiltration, a long dry spell (at least a week) is useful to eliminate the short-term effects of rainfall. Beyond that, the longer the survey period the better.

Whilst maximum use should therefore be made of any existing flow survey data, a new, planned flow survey, specifically designed to identify I/I, has considerable advantages. *Control of infiltration to sewers (CIRIA 1996)* gives two methodologies for carrying out flow surveys for locating infiltration:

- Single Stage Survey
- Multi Stage Survey.

2.8.1.1 Single Stage Approach

A single stage survey covers a whole catchment in detail in one step. Direct comparison is possible between sub-catchments. The number of flow monitors required to cover the whole catchment in detail, together with the time required to record sufficient data, means that this can be an expensive approach.

Ideally, for a single stage survey to be effective, it needs to be undertaken in worst-case conditions (e.g. when groundwater levels and infiltration levels are at their highest). In some catchments, these conditions are more a function of antecedent rainfall than they are of season so it can be difficult to plan the best time for a survey.

Owing to the relative ease of locating direct inflows, a single stage survey should be sufficient to locate areas of high inflows, and to prioritise areas for further detailed location.

2.8.1.2 Multi-Stage Approach

The multi-stage approach takes longer, but uses fewer monitors than the single stage method. It identifies areas of high I/I by a series of surveys, each progressively concentrating on smaller catchment areas. A disadvantage of this type of flow survey is that conditions (i.e. groundwater, tides, rainfall) change between surveys so it is not possible to directly compare the relative contributions from specific areas.

2.8.1.3 Long Term Flow Monitoring

Establishment of long term flow monitoring for the duration of the investigations, e.g. at a number of key strategic points in the system, enables long term variations to be measured and provides a means of comparing relative contributions from sub-catchments. A period of one full year is commonly used for this type of monitoring.

On-going long term monitoring of sewer flows throughout the network is desirable to monitor the effectiveness of any I/I reduction works, any deterioration in the network condition and the impact of new development.

2.8.1.4 Recommended I/I Flow Survey Procedure

The recommended procedure for flow surveys to locate I/I is:

1) Establish a framework of long term flow monitors and raingauges to measure long-term trends. These monitors will remain in place throughout the investigations (at least a year) and preferably after implementation of I/I reduction. It is clearly important that good sites are selected for monitoring, i.e. good hydraulic conditions, no ragging and no silt. Results from the first week or two should be studied carefully and monitors re-located if necessary. Existing measurement sites, e.g. at a WwTW, should be checked for accuracy.

2) Carry out a short-term flow survey with monitor coverage that is sufficient to verify a hydraulic model of the sewer system, e.g. to drainage area planning standard. Ideally, this flow survey will be undertaken at a time when 'worst case' conditions for infiltration are likely to be present. This survey should record at least three suitable rainfall events and allow an initial assessment of inflow at each monitoring site. An initial assessment of infiltration at each monitoring site should be made by interpreting a flow and rainfall plot of the full flow survey period (examples are contained in Appendix A from a survey of the Blanchardstown and Clondalkin trunk sewers).

3) Based on the levels of I/I measured in 1) and 2), carry out an economic appraisal as described in Section 2.7. If this justifies reduction of I/I, proceed with further stages of flow survey, focusing on areas where the worst problems have been identified (typically 20 to 30% of the network). In this way, the target areas are progressively narrowed down until they are small enough for other source detection techniques to become more cost effective.

Recorded values of inflow and infiltration should be shown on separate thematic maps of the sewerage catchment. Infiltration should be expressed in absolute terms (l/s), as a % of wastewater flow (PG+E) and in l/s per mm-diameter km length. Peak observed inflow can be expressed as a multiplier of wastewater flow (PG+E). (If expressed as a multiplier of dry weather flow (PG+I+E), the factor will vary depending on the level taken for infiltration, I.) Alternatively, the hydraulic model can be used to predict peak flows in a design storm, say 1 or 5 year return period, and this can be expressed as a multiplier of wastewater flow (PG+E).

2.8.2 Source Detection

2.8.2.1 Inflow Source Detection

As inflow enters the sewer system directly, e.g. via mis-connected surface water drains, sources are generally easier to detect than those of infiltration. By using a hydraulic model, in conjunction with flow survey data, the approximate impermeable area connected in a sub-catchment can be estimated.

An Impermeable Area Survey (IAS) will form the basis of inflow location. Four basic techniques are used to detect direct inflows:

- Dye Testing
- Smoke Testing
- Visual Inspections
- Jetting

Dye Testing

Dye testing involves flushing non-toxic dyes down known surface water drains and observing nearby foul/combined sewer manholes for traces of the dye entering the foul system. Possible sources such as roof downpipes, yard or road gullies are targeted.

Dye testing is a labour intensive process, as it requires every possible course to be tested individually. Many of the possible sources (such as roof down pipes, yard or basement drainage) will be located on private property with associated difficulties of access and liaison with the public. An area-wide public relations exercise to inform residents of the work and its purpose is beneficial in this respect. A good level of public awareness will also assist if it is decided that it is cost effective to remove the inflow source.

It is also possible to isolate and flood either foul or storm sewers with dye to identify cross connections. Visual inspection of adjacent sewers or watercourses being tested will be required to further identify possible sources.

Having identified sources, CCTV inspections may be required to confirm the actual point of connection into the sewer.

Smoke Testing

Smoke testing involves pumping non-toxic, non-staining coloured smoke into a sewer and observing any points where the smoke reaches the surface. A typical smoke test between manholes takes between 10-30 minutes (after establishment) and is regarded as a quicker means of locating direct connections than dye testing if conditions are right. However, smoke testing can be affected by climate conditions such as wind and rain. It is important that properties are properly inspected (including backyards) for signs of smoke.

As with dye testing, smoke testing is good for locating inflow sources but further techniques are necessary to locate the actual connection points to the sewer.

CCTV Inspection

The development of Close Circuit Television (CCTV) inspections over the last fifteen years has greatly improved the success rate of inflow location. CCTV inspections are used in conjunction with dye testing or jetting to positively identify connection points and prove cross connections.

CCTV inspections also have the added benefits for structural assessment and for locating potential additional inflow points not detected by other means. Depending on the condition of the sewer, additional works (with associated cost) may be required to carry out the CCTV inspection. These include, but are not limited to:

Cleaning	Sediment and grease deposits can hinder the movement of the CCTV camera through the sewer. Removal of these deposits will also make hydraulic improvements to the sewer.
Removal of Obstructions	Obstructions such as intruding tree roots, lateral connections and foreign objects such as sewer rods, traffic cones, etc can prevent movement of the CCTV camera through the sewer. Removal of these obstructions will require more significant works, e.g. use of specialist trenchless equipment.
Diversion of Flows	Large diameter, or steep sewers may require diversion of flows to allow the CCTV camera access. This can be particularly time consuming and expensive when large flows are involved.

Wet Weather Spot Flow Measurement and Property Inspections

Location of inflows or rainfall-induced infiltration may be quickly narrowed down to a small area by systematically spot-measuring flows during or immediately after rainfall using hand held flow measurement probes. This does, however, require resources to be available on stand-by so that they can be mobilised when wet weather occurs.

Inflow can occur during wet weather due to localised flooding, e.g. flooding in a yard area to a level higher than that of foul gully traps on the outside of buildings. Knowledge or records of regular flooding locations are needed to identify potential problem areas. Analysis of river and tide levels should be undertaken to assess the likelihood of inflow via CSO outfalls.

Jetting

Cleaning or jetting a storm sewer and observing nearby foul sewers can be a cheap and effective means of locating cross-connections to small diameter sewers or sewers with low baseflows. This work will also have the added hydraulic benefits of cleaning the sewer in question.

A summary of inflow source detection methods is provided in Table 2.3.

Method	Advantages	Disadvantages
Smoke Testing	Quick and simple Minimises time spent on private properties	Can depend on climatic conditions Does not locate point of connection
Dye Testing	Simple	Does not locate point of connection Time spent on private properties
Jetting	Simple Additional maintenance	Requires low flows in receiving sewer to make noticeable difference Does not locate point of connection
Visual Inspection (CCTV)	Also useful for structural assessment location of infiltration Locates point of connection	Does not locate source of inflow Flow diversion, cleaning, root cutting may be required
Wet Weather Inspections & Flow Monitoring	Locates sources that cannot be found in dry weather conditions Quick and relatively simple	Requires staff on stand-by

Table 2.3 Summary of Inflow Source Detection Methods

2.8.2.2 Infiltration Source Detection

Infiltration detection needs to be as comprehensive as possible and should include both public and private sewers. Location and repair of only selected sources or defects can cause localised changes to groundwater levels and 'migration' of infiltration, e.g. to un-repaired private lateral drains.

Access is not always straightforward when investigating private drains and lateral connections. It is also seldom possible to accurately quantify the amount of infiltration arising from a particular source. The increased difficulty in detection of infiltration (compared to inflow) is such that smaller investigation areas, i.e. as defined by monitor density in the preceding flow surveys, are likely to be required.

Methods commonly used to locate infiltration sources include:

- Smoke and Dye testing
- Visual Inspection
- Isolation testing
- Dilution Gauging.

Smoke and Dye Testing

Smoke testing has only very limited value in locating sources of infiltration as it should not be carried out in wet ground or when sewers are below the groundwater table (the smoke can be trapped in the ground). Damaged sewers in shallow, dry ground have been known to be successfully detected by smoke testing.

The use of dye testing is similarly limited but shallow sewers in dry, rapidly draining soils have been successfully investigated using this method.

Visual Inspection Techniques

Visual inspection techniques, e.g. CCTV or manhole inspection surveys, are the most useful means of locating infiltration-causing defects. The best time to carry out a visual survey is when conditions for infiltration are worst, i.e. when groundwater levels or (in coastal areas) tide levels are high. In any event, signs of infiltration such as pipe encrustation at pipe or manhole joints and open or displaced joints should also be considered as possible infiltration sources even if they are not actually running at the time of the survey.

Whilst the advancement of CCTV technologies over the last fifteen years has greatly improved the ability to inspect inaccessible mains, it is rarely possible to inspect the complete network, i.e. including all private lateral drains and sewers.

The main two visual inspection techniques are manhole and CCTV inspections. Neither method is quantitative, but both are useful for identifying possible infiltration sources. Infiltration noted from manhole inspections needs to be seen in context, as manholes make up only a small proportion of the sewer network.

The analysis of CCTV data for infiltration location differs from that for structural and service defects as outlined in the Sewer Rehabilitation Manual. Whilst many infiltration-causing defects are also structural defects, all possible infiltration sources need to be considered. These include:

- observed infiltration (referred to as ''runners'' or ''gushers'');
- open pipe joints;
- displaced pipe joints;
- encrustation at pipe joints; and,
- other structural defects.

The 'Examiner' CCTV software is commonly used to record these defects.

Isolation Testing

Isolation testing involves isolating a section of sewer and either observing flows or testing the sewer with either air or water pressure. In practice, however, there are numerous problems associated with testing of existing sewers, including:

- the need to divert flows while the test is carried out;
- the difficulty of isolating lateral connections;

- the effect of groundwater levels at the time of testing.

This method of source detection will quantify levels of infiltration (and exfiltration), but additional visual inspection is required to locate the point of entry and, overall, it is considered more suitable for testing of new sewers.

Dilution Gauging

This method of source location can be used to quantify saline infiltration in coastal areas by comparing chloride concentrations in the groundwater and that in the sewage. A similar technique using ammonia concentrations in the sewage is described in Section 2.6. However, this procedure is limited by the time and cost required to carry out analysis.

A summary of infiltration detection methods is provided in Table 2.4.

Method	Advantages	Disadvantages / Limitations
Smoke Testing	Quick and simple Minimal time spent on private properties	Limited by climatic conditions Does not locate point of connection to sewer Success dependent on depth, soil type and water table level
Dye Testing	Simple	Does not locate point of connection to sewer High level of work carried out on private properties Relatively time consuming Success dependent on depth, soil type and water table level
Visual Inspection (CCTV)	Also provides structural condition Locates point of connection	Flow diversion, cleaning, root cutting may be required
Isolation	Quantifies infiltration / exfiltration	Requires isolation of section of sewer to be tested (i.e. over pumping etc.)
Dilution Gauging	Quantifies infiltration	Requires specialist analysis

Table 2.4 Summary of Infiltration Detection Methods

2.8.3 Lateral Drains

Lateral drains on private property can be a significant source of inflow and infiltration problems for the following reasons:

- lateral drains are often laid at shallow depths and are susceptible to damage from surface activities such as building works;
- the routing of lateral drains is often adjacent to trees - there are no controls on planting of vegetation over private drains;
- changing land use can leave abandoned lateral drains left un-sealed;
- damaged or un-capped inspection points often remain undetected; and,

- there is less construction control of lateral drains and often lower construction standards.

Legal arrangements for access to private properties may hinder the ability of a Local Authority to repair or enforce repair of an identified I/I source. Whilst existing systems may be difficult to inspect, measures may be undertaken to ensure new systems are easier to protect, e.g. installation of inspection chambers at all property boundaries. This would enable convenient access to carry out post-construction inspections and maintenance in both directions along the lateral (i.e. towards the sewer main and towards the property).

The occurrence of defects in lateral drains causing a significant number of pollution incidents is noted in *CIRIA Report No.44 'Reliability of Sewers in Environmentally Vulnerable Areas'.* Two possible strategies are identified that could also help in reducing I/I problems.

1. All private drains connected to a building or structure should be, as part of a condition of sale, be surveyed and tested, and any defects detected rectified prior to the sale proceeding. This strategy has been successfully implemented in Australia.

2. Disused sewers should be properly sealed (at the main) upon change of land use or demolition of a building.

2.9 Inflow and Infiltration Removal

2.9.1 Removal of Inflow Sources

Once an inflow source is located and its connection point to the foul system has been identified, provision can be made to redirect the flow to a surface water sewer or receiving water. In many cases, this will be a straightforward gravity connection but there can be situations where the foul drainage system has been used because there is insufficient fall available to reach the local surface water sewer. This can occur, for example, in low-lying areas where the foul system is pumped. Access arrangements for undertaking the necessary construction work will be more straightforward in local authority owned areas than on private properties.

While separation of surface flows from foul sewer systems has obvious benefits, the additional regular discharges of urban surface water runoff to local watercourses will create new adverse environmental effects. Therefore, in line with the recommendations in the Environmental Management Policy, SuDS techniques should be implemented where possible when upgrading an existing surface water sewer network or retrofitting a new surface water system. Retrofitting source controls can be difficult in established urban areas but it may be possible to provide some measures prior to discharge to the watercourse.

In addition to roof downpipes, road gullies, yard and driveway drains, other inflow sources that can be removed include:

Missing, Damaged or Jammed Flap Valves

Flap valves are commonly installed on CSO outfalls, particularly in tidally affected areas. These can become jammed open by debris or damaged by the action of river or seawater. Reverse flow via CSO outfalls can lead to large amounts of unnecessary flow in the sewer system and saline problems at WwTWs.

Each outfall needs to be assessed, and where flap valves are required, they need to be incorporated into the maintenance regime with regular inspections to ensure that they work correctly.

Faulty Manhole Covers

Where manholes are located in floodable areas (e.g. in floodplains adjacent to watercourses), it is important that their covers properly seal. Replacement of cover, frame or both may be required to achieve this. It is also important in certain areas to routinely check that manhole covers are actually present – it is not unheard of for covers to be stolen or tampered with.

Low-lying Foul Gully Traps

Inflow from low-lying foul gully traps on buildings can be eliminated by raising the lip well above the surrounding area.

2.9.2 Removal of Infiltration Sources

The method selected to remove infiltration sources largely depends on the degree of infiltration to the sewer and the nature of the defects causing the infiltration. The presence of groundwater can be a major factor in the selection of the rehabilitation method. Techniques for repair, renovation and replacement of sewers and drains are contained in Appendix C.

2.9.2.1 Repair

Owing to the migratory nature of infiltration, repair of infiltration-causing defects is not generally recommended as a stand-alone solution to infiltration problems. However, it is applicable for sewers that are generally in a sound material condition with isolated major structural defects. Such sewers are likely to be relatively young (less than fifty years old) and will not exhibit extensive minor defects (such as cracking or fractures). The defects present are most likely to be due to poor construction.

The use of robotic units with CCTV allows individual defects to be sealed and tested without rehabilitating the whole section of sewer. Some robotic systems with CCTV also allow access up lateral connections to repair defects away from the main.

The techniques available for infiltration repair include:

Joint Sealing

Leaking pipe joints or minor defects may be sealed by pumping grout or silicate gel from inside the pipe through the defective joint. This will fill any voids that have formed on the outside of the pipe. Following injection the pipe joint can be pressure tested to prove the repair.

Testing of non-structural defects such as open and encrusted joints is carried out prior to sealing. If the pipe joint has already started to deteriorate, a structural repair method will be needed. In this case, stabilisation of the ground behind the joint may be required to fill any voids.

The presence of infiltration at the time of repair can be a major factor in determining the suitability of sealing method as flows can wash out the sealant materials. Silicate gels have proved to be particularly effective in this regard - leaking joints are sealed by expansion on the outside of the pipe, filling any voids.

Trenchless Repairs

Most trenchless sewer lining systems have developed point repair methods to repair individual structural defects without rehabilitating the whole section of sewer. This will minimise the hydraulic restrictions caused by the rehabilitation and is particularly useful for rehabilitating sewers that are of limited hydraulic capacity without using a disruptive open-cut repair method.

Some systems rely on a resin anchor injected into the defect to hold the patch in place. This can be an effective repair if the defect is large enough and infiltration present at the time of repair does not prevent the resin anchor setting. This can be a particular problem of resin-based lining and repair systems.

In the past, various repair patch systems have proved to be unsuitable for controlling infiltration. It is important to consider the following aspects when selecting a trenchless repair method to rehabilitate a leaking defect:

- how the repair patch is sealed at the ends of the repair to prevent infiltration migrating between the repair material and original sewer;
- how the repair patch is anchored to prevent longitudinal movement of the repair along the sewer between the patch and the linings;
- how the edges of the patch are finished off to prevent solids catching in the interface with the original sewer.

The bond between the sewer and the patch is particularly important to consider. Systems that rely on adhesion between the patch and the original sewer have not been particularly successful. The difficulty of these systems is the ability to obtain clean or dry enough surfaces (especially) to obtain a good bond between the patch and the original material.

Open Cut Repairs

In cases of severely deformed or damaged sewers, or those that are severely restricted hydraulically, the only way to repair the sewer will be to excavate the damaged section and replace with a new section of sewer. Although usually more expensive and disruptive, open cut repairs remove the defective section of sewer from the system. The key component of an open cut repair is the integrity of the joints made with the original sewer material.

2.9.2.2 Renovation

In the case of extensively damaged sewers, complete renovation of the whole sewer is the preferred option to ensure that infiltration does not migrate towards minor or non-structural defects and make them worse. Particular attention to the sealing of lateral connections is required for controlling infiltration entering at lateral junctions - flows can migrate along the sewer between the lining and parent pipe. This particularly applies to slip lining and folded or wound in liners where excavation and reconnection, or grouting and sealing, of lateral connections is required after they have been cut out. Some cured in place lining manufacturers do not guarantee a leak proof seal at lateral junctions without grouting.

Renovation techniques do reduce the cross-sectional area of the sewer, so it is important to be confident that there will be sufficient hydraulic capacity following renovation. If in doubt, an alternative method may be required. Lining is also unsuitable for excessively deformed or damaged sewers.

A summary of renovation techniques (from *Control of Infiltration to Sewers, CIRIA 1996*) is contained in Appendix C.

2.9.2.3 Replacement

Replacement is the most expensive and disruptive rehabilitation method but is the only option where hydraulic improvements are also required or the existing sewer is too damaged to permit renovation techniques. Control of groundwater is a particular problem with open cut sewer replacement construction, as the fact that infiltration is a problem means that the sewer is below the groundwater level (or at least can be at certain times).

Various forms of ‘trenchless’ sewer replacement techniques are available. However, these do require proper re-connection of lateral connections to ensure effective infiltration control. This can limit the benefits of ‘trenchless’ sewer replacement techniques.