PIPE LEAKAGE – FUTURE CHALLENGES AND SOLUTIONS

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ABSTRACT

Pipe leakage in Australia is perceived to be a major problem by many water authorities, both from an environmental point of view, as well as the associated costs that are incurred due to overdesign of our sewerage systems (to cope with wet weather loads) and the treatment of additional potable water that is lost due to leakage. This paper discusses the state of our reticulation systems, design and environmental concepts to allow us to categorise the problem, methods of leakage detection, solution concepts to solve leakage and finally methods to allow planning to occur to prioritise asset management solutions.

Key words: Pipes, leakage, environmental, pressure control, rehabilitation, asset management.

INTRODUCTION

Major advances have been made in recent years in pipeline technology. However, typical sewerage and water distribution systems in many cities worldwide contain a large percentage of older pipes. For example, in many German systems over 54% of the pipes are older than 25 years and 24% are older than 50 years (Fuhrmann n.d.). In Australia, systems are generally newer, and a typical system has only 47% of pipes that exceed 25 years in age and 13% older than 50 years (D. Santamaria, South East Water, pers. com.). As pipes age, the problems of infiltration and exfiltration increase in sewer pipes causing potential environmental problems, although in many cases these problems have yet to be quantified (Fuhrmann n.d.). Also, in water reticulation pipes the failure levels increase with age (WSAA Facts 1998) and consequently the levels of unaccounted for water and the associated lost revenue from water reticulation mains can also increase due to these failures and the associated water leakage.

In many water distribution systems, a significant percentage of water is lost while in transit from treatment plants to consumers. According to an inquiry made in 1991 by the International Water Supply Association (IWSA), the amount of lost or “unaccounted for water” (UFW) is typically in the range of 20–30% of production (Cheong 1991). In the case of some systems, mostly older ones, the percentage of lost water could be as high as 50% (AWWA 1987). In Australia and Canada the problem is not quite as severe due to relatively newer systems. For example, water authorities in Australia report UFW levels varying between 8 and 28% with the average being 15% in 1997/98 (WSAA Facts 1998).

UFW is usually attributed to several causes including leakage, metering errors and theft. According to the IWSA survey, however, leakage is the major cause. Water leakage is a costly problem, not only in terms of wasting a precious natural resource but also in economic terms. The primary economic loss due to leakage is the cost of raw water, its treatment and transportation. Leakage inevitably also results in secondary economic loss in the form of damage to the pipe network itself, e.g. erosion of pipe bedding and major pipe breaks, and in the form of damage to foundations of roads and buildings. Diminution of supply security as a result of a reduction in water stored per capita may also represent a cost if such diminution requires augmentation of supply to maintain security. Besides the environmental and economic losses caused by leakage, leaky pipes create a public health risk, as every leak is a potential entry point for contaminants if a pressure drop occurs in the system.

In sewer systems, infiltration and exfiltration raises a number of problems such as increased cost and environmental impact. This is due to increased sewerage transportation and treatment costs associated with wet weather water ingress, or potential leaks and overflows and their associated environmental problems. In Australia wet weather flows are 3–8 times dry weather flows (D. Santamaria, South East Water, pers. com.). Whilst these increased flows cause additional operating costs due to increased volumes of sewerage being treated, they can also cause significant operating problems for sewerage treatment plants, especially in areas with significant salt water ingress. If the system is not designed to cope with these extra loads (peak day to peak system load factors in Australia vary from 0.4 to 1.9 (WSAA Facts 1998)), then overflows can occur, with their associated bad publicity, environmental impacts and health concerns.

CURRENT STATUS OF THE AUSTRALIAN INFRASTRUCTURE

Water Supply System

The supply system for a capital city in Australia typically consists of large supply lines, referred to as transfer mains, delivering water from a catchment or treatment plant to a network of distribution mains that deliver to reticulation mains. These mains are generally 900 mm (diameter) and above, although smaller mains of 300–825 mm pipelines make up the total system. Although these pipelines may have originally been in cast iron, in nearly all cities they have since been replaced with mild steel (enamel or cement lined) pipelines. From about 1925, installations were almost exclusively in lined mild steel. The transfer pipelines supplying Australian cities are in generally good condition with nearly 90% of the pipes with a residual life up to 50 years or more. Figures 1 and 2 show the typical pipe profiles in a 1000 km system and their projected residual life.

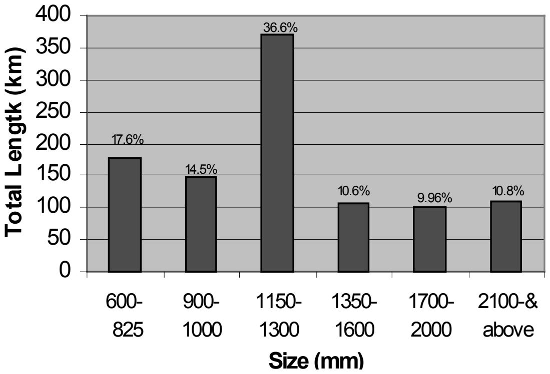


Figure 1. Profile of transmission pipe sizes in a typical system.

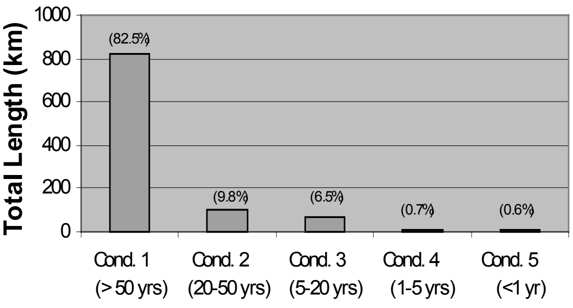


Figure 2. Projected residual life of pipes in a transmission pipe systems.

In contrast to the transfer mains, the distribution and reticulation systems typically reflect the full spectrum of pipeline types installed from the very early days, i.e. cast iron, galvanised wrought iron, asbestos cement, ductile iron, uPVC and polyethylene. High proportions of these pipelines are in the 100–300 mm size (approx. 80%). However, the size range extends from 50 to 825 mm. The smaller pipes (50–63 mm) are mainly in cul-de-sacs (courts) and sub-50 mm pipes are generally in supply lines to properties (commonly referred to as property connections). It is in these pipelines where small leaks are likely to go undetected, especially in sandy soils. Figure 3 shows the typical profile of the growth of distribution pipelines from the 1850s to 1997.

The failures encountered in distribution and maintenance pipes are typically described as "bursts" and not differentiated into joint or pipe failure. High proportions of these failures are in the older cast iron pipes (WSAA Facts 1998). However, asbestos cement pipes also have high failure rates, especially for pipes in acidic soils or subject to movement. Figure 4 shows the typical failure profile in a network.

Sewer System

Vitreous clay was the principal pipe type for sewer systems until the late 1970s. uPVC pipes have penetrated the market since the 1970s and these pipes are now the principal pipe material used in sewer systems. Figure 5 shows the typical growth of sewer networks in Australian capital cities. The predominant problem with sewer systems is thought to be infiltration/exfiltration through joints, however, although most water authorities have a good idea of their wet weather versus dry weather flows, generally the relative contribution of the various components, including joints, in the sewer systems is not known.

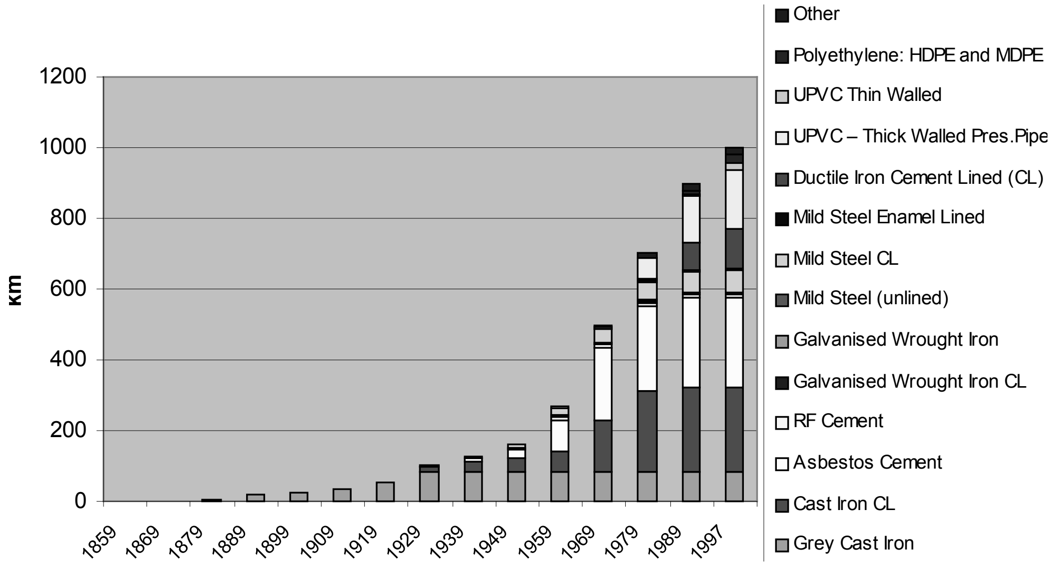


Figure 3. Profile of the growth of distribution pipelines in a 100 km distribution network.

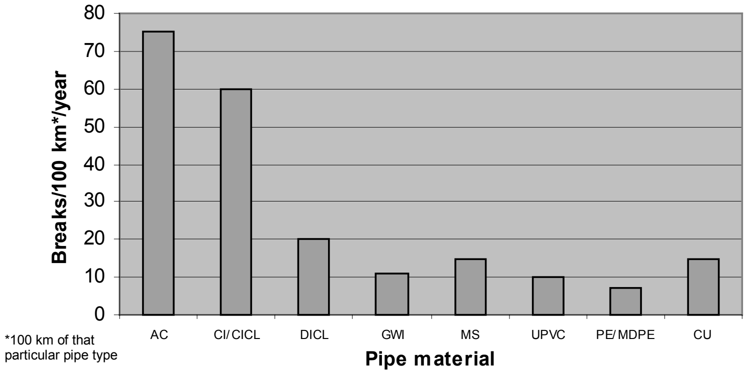


Figure 4. Typical failure frequency in pipe types.

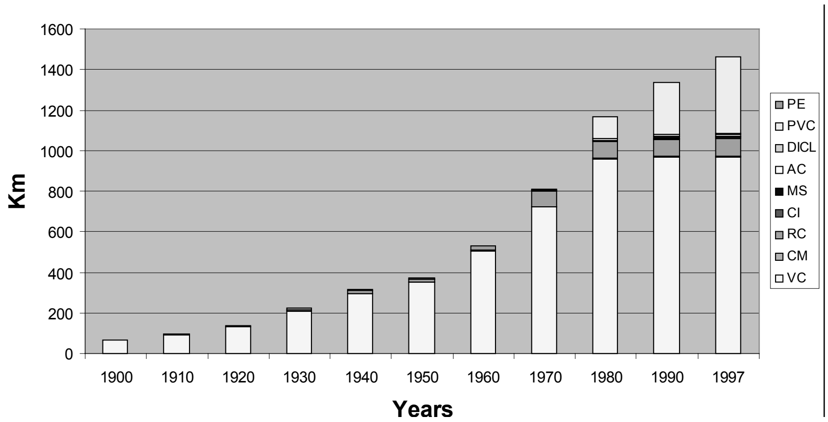


Figure 5. Profile of the growth of sewer pipelines to service 100,000 properties in 1997.

DESIGN AND ENVIRONMENTAL EFFECTS OF LEAKAGE

Little attention has been given to the environmental aspects of leakage from water mains and the main focus has been on damage to property and the infrastructure. In the area of environmental effects, most attention has been applied to sewerage pipes. Characterisation of sewerage system performance requires recognition of the impacts of leakage into and out of the pipe network. While overflows do cause environmental impacts, these vary in significance from location to location. Thus a balanced understanding is required. Of equal significance for sewer system managers and the customers they serve, may be the cost incurred in designing pipes to take into account leakage, particularly inflow during heavy weather. Once again, these costs vary according to circumstances.

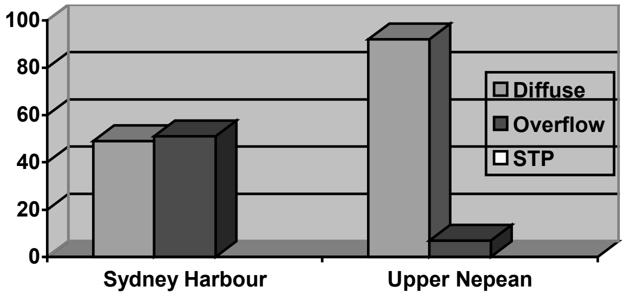
Leakage occurs at both designed overflow points and from joints and cracks in pipelines. The purpose of designed overflow structures is to relieve pressure in pipes at controlled locations, i.e. adjacent to stormwater drains, so that overflows do not occur at private residences or businesses or environmentally sensitive locations. They function when pipe capacity is exceeded due to infiltration or blockage during storms. Except in the most poorly designed systems, they do not function in dry weather when no blockage exists. Cracks, on the other hand, may function at any time, releasing sewerage into local waterways or soils (exfiltration) or allowing storm-flow to enter sewers (infiltration), leading to pressure build up and possible overflows during heavy weather.

The environmental impacts of leakage include impacts on ecosystems, aesthetic impacts and human health risk. These impacts, however, need to be considered in context. The Sydney Water Corporation has recently completed a series of Environmental Impact Statements (EISs) looking, in part, at the environmental effect of overflows and sewer system leakage (Sydney Water Corporation 1998). These documents listed the potential environmental effects of overflows as being:

- Eutrophication as a result of nutrient-rich sewage reaching receiving waters.
- Toxicant impacts (especially chlorpyrifos and dieldren (respectively, organophosphate and organochlorine pesticides) copper and ammonia).
- Faecal coliforms; oxygen reduction in receiving waters (which may lead to fish kills and other impacts).
- Increased turbidity and increased sediment loads (and litter).

Each of these has potentially serious impacts. Their actual environmental effect depends, however, on the volume and concentration discharged and the receiving water environment. So too must the general environmental conditions at the time of discharge be considered (i.e. rain or dry weather).

The wealth of data included in the Sydney Water EISs cannot be reproduced here, but by way of illustration, Figures 6 and 7 show the relative contribution of faecal coliforms and nutrients of overflows from Sydney Water's systems at different locations.



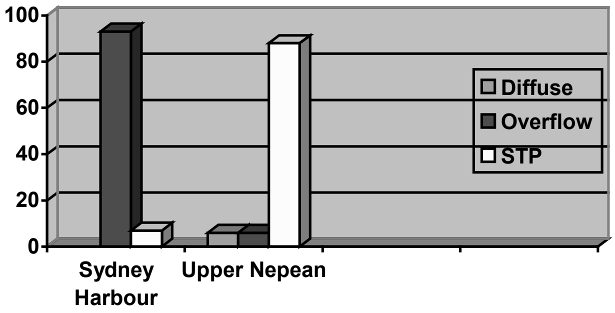


Figure 6. Relative distriubtions of phosphorus.

Figure 7. Relative contributions of facecal coliforms.

As will be appreciated, the effect of the various overflow-derived impacts will depend upon the response of the receiving environment to those pressures, the frequency of the overflow and the degree of flushing that occurs as a result of storms (which often coincide with overflows). The key point to stress, however, is that quantification of leakage impacts and, by extension, the degree of remedial action required will depend on the circumstances and the degree of risk we judge acceptable. That leakage causes environmental impacts on receiving waters, land (e.g. waterlogging and nutrient enrichment), recreational amenity, flora and fauna, and air quality is, however, undeniable.

Sewerage systems are designed to cater for wet weather ingress. International best practice allows for sewer overdesign to cater for such flows. Sewerage systems may be designed to cater for up to 10 times average dry weather flow. It stands to reason, that such overdesign increases the cost of sewerage systems. Viewed over time, however, it might be suggested that this overdesign represents underutilisation of an expensive asset (as peak capacity may be utilised only a small percentage of the time). Such underutilisation is counter to the principles of modern business practice which seeks to drive assets as hard as possible. Without going into significant detail, it should be noted that pipe costs rise exponentially with size. CSIRO's Urban Water Program has gathered extensive data on pipe and laying costs in different environments. As a generalisation, this shows that 1 m of installed pipe costs 30% more than a pipe of half the capacity (85% more for pipe only), as shown in Table 1

A reduction in peak pipe flow therefore has the capacity to reduce costs and increase asset utilisation. Concepts that might lead to such a reduction would include improved pipe materials, characterisation of the performance of pipes in different laying environments (enabling targeting of materials and techniques at specific circumstances) and transport of sewage from a common holding pit under pressure.

As well as environmental impacts and construction/operation costs caused by pipe leakage, an additional category of costs – "those accruing to third parties" – exists, however, these are generally not accounted for. These costs arise where there is a cost to a third party, in this case arising from sewerage system leakage, that is borne by that party rather than by the operator or user of the sewerage system. Such costs may include diminution of recreational opportunities, loss of income from, say, oyster farming or fishing, and potentially increased health costs. These costs too must be considered in the characterisation of sewerage system performance.

Table 1. Class 16 PVC pipe cost and installed cost

ND	Approx. internal cross-sectional area (m^2)	Pipe cost ($) (nominal)	Installed cost ($) (nominal)
100	0.0078	3.77	75.00
140	0.015	7.00	90.00
200	0.031	13.75	113.00
275	0.059	25.00	145.00
375	0.110	45.00	195.00
500	0.196	76.00	265.00

LEAKAGE DETECTION

Economic pressure, concern over public health risk, the need to conserve water and the increased treatment costs associated with infiltration (White *et al*. 1997) motivate water system operators to implement leakage control programs. Leakage control can forewarn asset managers of potential problems, including the impending collapse of a pipeline, which usually damages adjacent utilities such as gas and telephone, or damages nearby assets including roadways and buildings. Significant efforts were made in the past to develop such programs, and as a result procedures for systematic water loss control programs are now well established and widely used. There are two major steps in any systematic leakage control program:

- Water audits.
- Leak detection surveys.

Water audits involve detailed accounting of water flow into and out of the distribution system or parts of it. The American Water Works Association manual *Water Audits and Leak Detection* provides detailed procedures for water audits (AWWA 1990). The audits help to identify parts of the distribution system that have excessive leakage and hence they are an important part of any effective leakage control program. However, they do not provide information about the exact location of leaks requiring attention. In order to locate leaks in areas that have been identified by water audits as suffering from leakage, leak detection surveys must be undertaken. Water system operators now have several new techniques to help them find and control water losses. In today's world of ever-increasing costs of treatment and distribution and tight capital, efficiency in detecting water leakage is critical to maintain the efficiency of our urban water systems (Keeling 1999).

Leak Detection in Water Distribution Systems

Monitoring of water flows
Over the past few years several new non-instrumental techniques have been developed to provide better and more cost-effective leakage detection and control programs. A very useful tool in determining the most effective leakage control program for a particular system is to monitor minimum night flows. Since leaks flow 24 hours a day, the night flows minus any flows from legitimate usage, such as commercial cleaning or 24-hour process loads, give a true volume of water lost to leakage. If night flows minus any legitimate usage flows are close to zero, leakage is also close to zero and an intensive leakage survey to pinpoint leaks is not warranted. On the other hand, if night flows minus the legitimate usage flows are high, then a major leakage detection survey may be warranted. When such leakage surveys are undertaken, the volume of lost water can serve as a benchmark against which subsequent surveys can be gauged and can provide a sound basis for cost/benefit studies. Once the survey has been completed and the located leaks are repaired, monitoring of night flows can be repeated to determine the volume of water saved.

The monitoring of flows can be taken one step further for an even more effective survey. Instead of monitoring the entire system, individual zones can be monitored. The resulting information can then be used to plan the most effective leakage detection program where zones of high night flows (and hence high leakage) are surveyed first. Decisions can be made before surveying each zone as to whether or not there is sufficient leakage to justify the survey and repair costs. This technique can again be taken one step further. Zones (ideally of 1000–3000 properties) that can be supplied by one or two pipes are monitored individually. The technique involves successively closing valves within the zone to isolate sections of pipe and then recording the corresponding reduction in the water flow. A large reduction in the flow indicates the existence of a leak between the boundaries of the last two isolated sections. As a result of this procedure, leak locations can be narrowed down to a very small area and the leak(s) can then be pinpointed easily using traditional acoustic methods.

Flow monitoring techniques can also be used for ongoing leakage control. For instance, by monitoring night water flows continuously, unusual changes in water volumes can be detected.

Based on experience with the water system, the system operator can then determine if the volume and flow increase is due to new leaks or not. If new leaks are the cause, they can be bracketed by step testing and then quickly pinpointed by acoustic methods as described below.

Detection of leak sounds

The water distribution system can be systematically checked for leaks by using acoustic equipment, which detects the sound or vibration, induced by water as it escapes from pipes under pressure. The water passing through the orifice or leak causes a sound in the pipe, normally in the 500–800 Hz range. The leaking water impacting on the soil in the leak area causes a different sound, normally in the 20–300 Hz range. A third sound, also normally in the 20–300 Hz range, is caused by the leaking water circulating in the water remaining in the cavity in the soil adjacent to the leak. The first sound can be transmitted along the pipe wall for significant distances depending on the type of pipe, so it is important that initial rough surveys be carried out. The other two sounds are generally limited to the immediate area of the leak and therefore they are useful for pinpointing the leak. Leak sounds transmitted through the soil or the pipe can be detected by means of commonly used listening devices placed on the soil or road surface directly above the pipe or placed in direct contact with a pipe or its accessories, e.g. fire hydrants.

Listening devices utilise sensitive mechanisms or materials, e.g. piezo-electric elements, for sensing leak-induced sound and vibration. They could be either of the mechanical or electronic type. Modern electronic devices may include signal amplifiers and noise filters, which could be very helpful in adverse environments. The use of listening devices is usually straightforward but their effectiveness depends on the experience of the user. Leak noise correlators, on the other hand, are state-of-the-art portable computer-based devices, which can locate leaks automatically. They work by measuring vibration or sound signals at two points that bracket the location of a suspected leak. Vibration sensors (normally accelerometers) are attached to fire hydrants, valves or any other contact points with water pipes. Alternatively, hydrophones (or underwater microphones) can be used. These are inserted into fire hydrants through modified hydrant caps. Vibration or sound signals are usually transmitted from the sensors to the correlator via wireless radio transmitters. In order to pinpoint a suspected leak, noise correlators first determine the time lag between the measured leak signals by calculating the cross-correlation function. The location of the leak relative to one of the measurement points is then easily calculated by the correlator based on a simple algebraic relationship between the time lag, distance between the measurement points, and sound propagation velocity in the pipe. Normally, leak noise correlators are more efficient and yield more accurate results compared to listening devices. Since the introduction of these devices in the early 1980s, they have significantly improved the "*art*" of pinpointing leaks.

The effectiveness of existing acoustic methods and equipment has been demonstrated successfully for metallic pipes (Fantozzi *et al.* 1993; Fuchs & Riehle 1991; Liston & Liston 1992). Until recently, however, the effectiveness of acoustic methods for locating leaks in plastic pipes was not well understood or established. Existing acoustic equipment was developed mainly with metallic pipes in mind, but the acoustical characteristics of leak signals in plastic and metallic pipes differ significantly – plastic pipes are "quieter" and do not transmit sound or vibration as efficiently as metallic ones (Hunaidi & Chu 1999). A recently completed study of leak detection methods for plastic pipes (Hunaidi *et al.* 1999) demonstrated that leaks in plastic pipes can be located using acoustic equipment and established the necessary procedures and guidelines. This study also identified several modifications to field procedures and equipment that will improve their effectiveness.

Alternative methods

Leaks can also be detected using several alternative methods or equipment developed by other industries. These non-acoustic techniques, such as the tracer gas methods, infrared photography (or thermography) and ground-penetrating radar (Hunaidi *et al.* 1999), have been used in a limited way, however, their effectiveness is not well established.

The tracer gas method – This involves the introduction of non-toxic, water-insoluble and lighter-than-air gases into the water distribution system. Commonly used gases are helium and hydrogen. Tracer gases injected into pipes escape at leak locations and then, being lighter than air, they permeate through the soil and pavement. Highly sensitive gas detectors are employed to locate escaping gas directly above the pipe. The tracer gas method has been used extensively in the past by the telecommunication industry for leak testing of pressurised telephone cables.

Thermography – The principle behind the use of thermography for leak detection is that water leaking from an underground pipe changes the thermal characteristics of adjacent soil and in turn makes it a more effective heat sink relative to the surrounding dry soil. Infra-red scanners are used to detect thermal anomalies above pipes, which may be taken as an indication of water leaks. Available scanners can be either hand-held or vehicle-mounted.

Ground-penetrating radar – In this method a short pulse of electromagnetic waves is transmitted into the ground using a radar-transmitting antenna. When a radar pulse encounters an interface between two materials, it is partially reflected to the surface where it is sensed by a radar-receiving antenna. Partial reflection of electromagnetic waves at an interface between two materials, or any anomaly, is due to a contrast in dielectric properties. The time lag between transmitted and reflected electromagnetic waves is then used to determine the depth of the reflecting surface. By transmitting radar pulses at regular surface positions, i.e. performing a scan, the size and depth of buried objects could be determined. Ground-penetrating radar may be used to detect water leaks in two ways: (a) identifying soil cavities created by the turbulent flow of leaking water; and (b) identifying pipe segments which appear deeper than expected because of the increase of the dielectric constant of adjacent soil saturated by leaking water (Hunaidi & Giamou 1998).

Sewer Leakage Detection

The current inspection technology available on the market is dominated by closed circuit television (CCTV)-based systems. These are remotely controlled vehicles, which travel through the sewer pipes carrying TV cameras. A range of other new techniques has, however, also been established and is becoming commonly used worldwide. These include techniques which involve flow measurement and statistical techniques.

Existing technologies

Statistical methods cover the full range from dry weather flow to modern stochastic computer models. For sewer leakage work, such methods can only give a very broad-brush picture, and thus should only be used for a general view of the system. The main disadvantages are cost and time, as most systems use deterministic models that require many flow and sewer surveys to be undertaken before they are useful. They are, however, the best starting point for identifying problem areas. The very latest computer programs, based on stochastic methods, do however show great promise. Accuracy of within 10% has been obtained from a very limited database (e.g. flows at key points of a catchment).

Flow monitors (or meters) are only useful as part of a statistical modelling exercise, as their accuracy is insufficient to gauge minor variance between manholes. Data on water use, and hence discharge to sewers, is at present mostly statistical and thus not accurate enough for micro studies. A few strategically placed monitors, however, can quickly include or exclude parts of a system from a study. When combined with network modelling, a very accurate overall picture of a catchment can be obtained at a reasonable cost. Development of more accurate meters may improve the effectiveness of this technique further.

Dye dilution is a method that relies on injecting a dye into the system at a known dilution and measuring the dilution rate downstream. Obviously this can act as a form of monitoring where infiltration is suspected, but by adding a flow monitor at the point of sampling, exfiltration can be possibly gauged.

CCTV is a very useful micro tool for infiltration. Its use is very limited in exfiltration as it relies totally on a visual record. Whilst visually it is easy to identify defects which may leak, defective joints are almost impossible to spot. It is also almost impossible to survey the parts of the sewer under the flow, unless the effluent is very clear. CCTV has also been combined with a sonar unit on partially surcharged sewers to give a complete picture of the sewer both above and under the sewage flows.

Infra-red thermography as for water mains detection can be carried out using an aeroplane overflying the area or by using specially equipped vans. Although good results have been obtained, the technique is susceptible to environmental conditions (particularly rain) and is prohibitively expensive for general use.

Dye and smoke testing is a technique much used in Australia and America where records of sewers are reasonably accurate. It is of less use in European sewers as all connections must be known prior to tests.

Air pressure tests are the standard test for new sewers. Until very recently, they were of little use on older sewers as it was almost impossible to seal laterals etc. against air leakage. New robotic techniques have enabled the insertion of stoppers in sewers. This has made air testing of older sewers feasible and cost effective, the limitation being that only the main sewer is tested but none of the laterals or manholes.

Water tests are the only testing systems which give 100% accurate results for both infiltration and exfiltration. They are unfortunately very labour intensive and disruptive. It is therefore important to target the lengths for testing by other methods.

Manual surveys simply involve opening manholes in a progressive manner at periods of low flows (night) and noting any inexplicable clear flows (interim stoppers may be needed). Probably the most cost-effective method of tracing infiltration, its use in exfiltration studies is very limited.

New techniques

Sonar can give a fairly accurate picture of the profile of the pipe wall and surrounding soil. The results, however, are very much open to interpretation, and a very skilled operator is vital. It can, however, show flow regimes under water, so it can be used to spot infiltration into surcharged pipes.

Ground probing radar until recently was of little use as each type of soil and depth of pipe required a different frequency of radar, hence selection of the correct frequency was critical. A new system, developed initially to trace plastic land mines, uses multifrequency radar and hence works in a variety of ground conditions. At present, however, this system has had very few trials on sewers and its effectiveness is difficult to gauge.

Current sonde is a very new system, developed in Germany. The sonde emits a current perpendicular to itself (and the pipe) which increases in strength when the sonde passes a leak point. The main disadvantages are that the computer read-out is difficult to interpret, and that there is no difference on the screen between a leak and a connection. New developments of a German R&D project on this method will possibly solve this problem (Eiswirth & Hötzl 1998).

Optical triangulation is a technique used for the optical 3D measurement of a sewer pipe. A new system has been developed and integrated in Germany (KARO) as well as in Australia (PIRAT) which permits automatic measurement of the tube shape (diameter and deviations from the circular shape) during the robot motion. Since the 3D sensor used in these systems looks straightforward into the direction of robot motion, the sensor scope is comparably large; however, the resolution and corresponding accuracy remains low. Cracks less then 1 mm cannot be detected (Kuntze *et al.* 1995; Campbell *et al.* 1995).

Microwave signals can be used to inspect the state behind sewerage pipes. Commercial microwave sensors are on the one hand too big for inspecting small pipes and on the other too expensive for many standard missions. In the KARO project, a smaller and cheaper microwave backscattering sensor has been developed in Germany which is able to explore anomalies in a medium range behind the outer pipe surface (Kuntze *et al*. 1995). During the last year, a wall scanning microwave sensor has been developed which is carried by a vehicle and can be rotated around the pipe axis. Thus, the complete wall surface can be scanned with optimal resolution (Eiswirth & Hötzl 1998).

Hydrochemical sensors used in preliminary tests in Germany with mobile probes within sewers indicate the applicability of this method for the detection of ground water infiltration with high accuracy. Since electrochemical sensors are sensitive to only a few chemical compounds and they have a comparable low resolution, they must be tuned to the wastewater composition. The detection of ground water infiltration has been shown to be possible; however, sewage exfiltration detection remains nearly impossible. Detailed investigations concerning the improvement of resolution and accuracy of these sensors have been done in laboratory experiments as well as in field experiments (Eiswirth & Hötzl 1998).

Neutron and gamma ray probes have been used in geophysical boreholes for the detection of cracks as well as in ground water observation wells for the investigation of soil density, soil moisture content, etc. Tests with radioactive sensors within sewers indicate the applicability of this methods to the detection of active sewer leaks (significant changes in soil moisture) and holes behind the sewer pipes (different density). Since radioactive sensors are affected by different physical underground parameters, their sensitivity and resolution was low until now. Detailed investigations with radioactive sensors are planned in laboratory experiments, as well as in test beds under different situations in Germany.

Air ultrasonic sensors have been adapted and integrated into the German KARO multisensor system (Kuntze *et al*. 1995) for the detection and quantification of cracks and wall thickness. Air ultrasonic sensors used in the KARO system have a large inspection area, however, the resolution and corresponding accuracy is rather small. Fine fissures, their depth and extent, are difficult to detect.

Acoustic systems are based on detecting vibrations and other phenomena caused by the spreading of mechanical waves, and are suitable for detecting cracks as well as for determining the state of connections and the bedding. Vibrations in the low frequency range (100–10,000 Hz) are excited through hammer taps (Klingmoller 1995). Until now the resolution and corresponding accuracy of this method has not been suitable for detecting leaks in sewers.

Application of methods

The most suitable method(s) applied for identification of sewer leakage will depend on the size of the sewer, location (under structure, in road, class of road, urban/rural etc.), flow, defect(s), nature of sewage and percentage of sewer capacity already used. Therefore, most detection techniques need to be combined with others to give the best results. Most water companies have implemented drainage area studies (DASs) and drainage area plans (DAPs). A DAS is a combination of a desk study, gathering all records of the system and collating, ground surveys, such as manhole and flow surveys, and CCTV. In a DAP, the data from the DAS is analysed and the system graded. After further surveys (CCTV, etc.) recommendations can be made based on the survey reports and computer modelling. A common strategy, much used throughout the world, would be (Jones 1998):

1. Use existing records to identify critical position in the catchment (node points such as major branch connections, etc.).
2. Monitor at these positions.
3. Model the system on stochastic computer models.
4. Separate inflow and infiltration (using rainfall data).

5. Prioritise the catchments.
6. Identify the dominant defect class in the priority catchments (by random survey).
7. Conduct the appropriate physical inspection for the defect.
8. Determine optimal system investment by evaluating the cost of rehabilitation versus the cost of replacement required for sufficient hydraulic capacity.
9. Carry out a cost/benefit analysis for each section or catchment.
10. Develop a sustainable capital investment program that addresses both replacement and rehabilitation projects.
11. Secure appropriate financing to bring the system into acceptable operating conditions.

Exfiltration, whilst as easy to cure as infiltration, is far harder to identify. It is possible to first identify potential problem areas by statistical methods, and then to monitor down to progressively smaller catchments. This is despite reservations about the accuracy of monitoring. To identify actual lengths that are leaking, the best method seems to be water tests, although the current sonde system and other new techniques are showing promise. At present, however, exfiltration work is generally ruled out on cost/benefit grounds, and seems likely to remain this way unless legislation, or public pressure, forces changes on the industry.

LEAKAGE SOLUTIONS AND CONTROL

Pressure Control

Pressure management has been around for many years in its basic form as a means of hydraulic system control and more recently has been very successfully introduced in many countries to combat leakage. Pressure management, as a means of combating leakage, can be used in most systems whether they are pumped or gravity fed, although the design of the scheme will change dramatically due to different hydraulic patterns. Often the reduction of pressure from one level to another can be a controversial subject, and one which sometimes utility managers prefer to ignore as there is a potential for customer dissatisfaction.

Pressure management may not be the answer for all utility systems, but it may prove to be very successful for others. Systems with a large percentage of uPVC pipes, systems with high service densities and systems in dense urban areas, would probably be among the best candidates to benefit from an advanced pressure management scheme.

Recent studies have proven that the relationship between leakage and pressure is not merely related to the square root of the pressure, but rather an expanding power law. This is because PVC leaks, and many other types of leaks and joints in particular, are subject to a change in area as pressure changes, and consequently the typical laws relating pressure and leakage do not apply. This means that potential benefit in pressure reduction, based on the volume of these leaks, has a much greater impact as not only the velocity of leak flow changes, but also the leak area.

Some of the potential benefits of a pressure management scheme are:
- Leakage reduction.
- Water conservation.
- Efficient distribution of water.
- Reduced hydraulic impact.
- Reduced customer complaints.

Some utilities are not comfortable with pressure management as a means of loss control for the following reasons:
- Fire flow concerns.
- Potential loss of revenue.
- Reservoirs not filling at night.

Where fire flows are a concern, sectors can have multiple feeds, controlled by pressure-reducing valves (PRVs) with flow-modulating capability. Therefore, if there is a fire, the system has sufficient hydraulic capacity to maintain pressures and flows for firefighting, as required for example in the USA in the NFPA regulations. The valves will automatically regulate pressure as determined by the demand requirement plus the minimum safe operating limit at residual conditions. Obviously when setting up potential pressure-controlled sectors, these limits along with insurance regulations for the type of property, should be taken into account.

As far as the loss of revenue is concerned, systems with high leakage will almost always see a positive benefit from pressure management, even when stacked against a potential loss of revenue, due to reduction of pressure in the residence or industry. This is especially true for systems with high water production or purchase costs, where the associated reduction in water losses can make significant savings. In situations where a loss of revenue cannot be tolerated, pressure management can be limited to night hours, when legitimate consumption is at its lowest and system pressures are at their highest. It should be remembered also that many systems are enforcing water-conservation programs where pressure-reduction programs can play an important role.

When considering pressure management for a sector, the per capita use must be considered. If it is excessive, then pressure management will become a natural part of a conservation program. If it is not, the components of consumption within the sector (residential, commercial, industrial), the volumetric consumption and the consumption directly tied to pressure must be decided. Then, the potential benefits of loss reduction over reduction in revenue can be analysed.

Many pressure management programs concentrate on the smaller mains, therefore allowing reduction of losses in selected areas while allowing normal system pressure in the larger trunk or transmission lines. Reservoirs are usually connected with the larger pipes, so there should not, in many cases, be a problem. Most utilities find that non-visible leakage tends to be on the smaller pipes and service connections, so the effectiveness of a potential pressure management program should not be reduced significantly, by the exclusion of larger pipes in the control area.

Pressure control can be characterised into a number of different types as follows.

Sectorisation

This is one of the most basic forms of pressure management and is still very effective. Subsectors are divided either naturally or by physical valving. The sectors are usually quite large and often have multiple feeds, therefore they do not usually develop localised hydraulic problems because of valve closures. Systems with gravity feeds are usually sectorised by ground level and systems with pumped feeds are usually sectorised depending on the level of elevated tanks or storage.

Pump control

Many utilities use pump control as a method of controlling system pressure. Pumps will be activated or de-activated depending upon system demand. This method is effective if the reduced level of pumping (usually at night) can still maintain reservoir levels. With recent energy conservation concerns, this methodology should be carefully reviewed as to the efficiency of energy use if the pump is operating outside of the normal profile.

Throttled system valves

Many system operators recognise the need for reducing system pressure and partially close a gate or butterfly valve to create a headloss and reduce pressure. This method is the least effective, as the headloss created will change as system demand changes. At night when a distribution system needs the least pressure, the pressure will be higher, and during the day when the distribution system needs the most pressure to supply demand, the pressure will be lower.

Fixed outlet hydraulic control

This is the traditional method of control and uses a basic hydraulically operated control valve. This method is effective for areas with low headlosses, demands which do not vary greatly due to seasonal changes, and areas with uniform supply characteristics.

Time-based modulation of a hydraulic valve (Ecowat)

This can be effected by using a controller with an internal timer. Control is effected in time-bands in accordance with demand profiles. This methodology is very effective for areas with stable demand profiles and headlosses and is usually used where cost is an issue, but advanced pressure management is desired. Time-based modulation controllers can be supplied with or without data loggers and/or remote links. Some manufacturers connect the controller to the pilot valve and alter the set point of the pilot valve by introducing a force against the existing force of the pilot spring. Other manufacturers use a timer and a solenoid valve to re-route control through preset pilots.

Flow-based dynamic modulation of a hydraulic valve (Autowat)

This is the best type of control for areas with changing conditions, headloss, fire flow requirements and the need for advanced control. This type of control is affected by controlling outlet pressure in relation to demand by connecting the controller to a metered signal output. Modulation of outlet pressure is achieved by altering the force against the pilot spring. The controller is normally supplied with a local data logger and optional remote communications. Control can be effected with a preset profile which shows the changing relationship of demand and headloss in the sector. Alternatively a direct communications link can be made between the controller and the critical point. Obviously the second option involves communications and therefore higher costs, which are not always necessary or cost effective. In general, installation costs are higher for this type of control, however, additional savings and guaranteed fire flows due to more intelligent control usually make this type of control more desirable.

Pressure Control – Water Savings

Pressure control can offer significant savings in water loss, as shown in Table 2, for sites in the metropolitan area of Sao Paulo, Brazil, utilising demand-based dynamic control methods, time-based methods and fixed traditional control. It should be noted that these water savings are not just a function of the reduced pressure, but also of the size of the zone in kilometres, service density and number of connections, and also the amount of pressure controlled and for how many hours per day.

Figure 8 shows how pressure control can significantly flatten the pressure profile across a system, even though the actual pressure reductions are very small, being in the order of only 10 m.

Table 2. Water savings achieved utilising pressure control

Site location	Pressure before (m)	Pressure after (m)	Pipe length (km)	ϕ pipe/ PRV (mm)	Savings (L/s)	Control
Rua do Curtume x Av. Hermano Marchetti (Lapa)	45–63	20–50	5.2	150/150	12.10	Autowat
Rua Francisco da Cunha Menezes	28–72	20–40	11.6	300/150	11.50	Autowat
Rua Antônio Portugal (Guaraú)	86–130	60	7.9	200/150	9.40	Fixed
Rua José Arnoni (Guaraú)	77–105	20	4.25	200/75	6.20	Fixed
Rua Pilões (Sacomã)	42–87	20–47	30.5	400/200	49.00	Autowat
Avenida Paulo de Queiroz (Sapopemba)	54–67	25	6.7	400/100	4.89	Fixed
Rua S. Francisco Magiano (Itaquera)	20–42	20–33	41.3	300/200	10.80	Ecowat
Av Cantidio Sampaio X Rubens Raul (Jaraguá)	60–97	20–40	3.7	150/100	2.00	Autowat
Rua Alvarenga (Butantã)	43–63	32	10.5	200/150	4.98	Fixed
Rua Xavier de Moraes (Caieiras)	110	70	3	200/75	1.00	Fixed
Rua Tomás Xavier de Almeida (Perús)	63–72	26	15.2	300/200	13.20	Fixed
Av. Santo Amaro x R. Mal. Deodoro (Sto. Amaro)	41–69	20–44	10.4	200/100	3.80	Ecowat
Rua Ambrosina do Carmo (Caieiras)	21–53	17–30	30	200/200	33.30	Autowat
Rua Lacerda Franco (Vila Deodoro)	45–54	22–42	20.1	350/250	16.70	Autowat
Total					**178.87**	

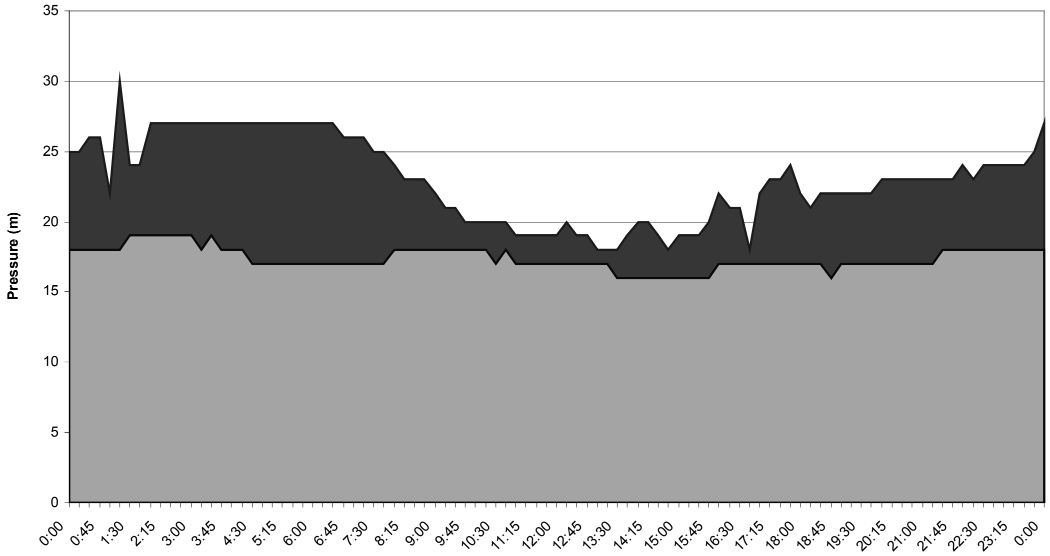


Figure 8. Pressure before and after control.

Even though the amount of pressure reduction was small, the savings in water loss were very significant, as can be seen in Figure 9. We should also note that the pressure after control shown by the bottom area in Figure 8 is much more stable than the top area, which is uncontrolled and subject to wide variation. This smoothing of the pressure cycle also reduces new bursts within the system.

REHABILITATION, REPAIR OR REPLACEMENT

Once a defect has been identified in a pipeline, a decision has to be made to undertake a specific type of rehabilitation.

Maintenance involves the cleaning and repair of the pipeline, to optimise hydraulic capacity by the removal of foreign or dislodged materials such as tree roots, encrustations and bricks, and it is fairly easy to make a decision on the correct procedures to apply.

Repair involves fixing local damage to the pipeline and may involve such techniques as part lining repair of pipelines using small areas of epoxy linings etc., grout injection to stabilise backfill soil or to stop areas where water infiltration/exfiltration occur, or brick repointing.

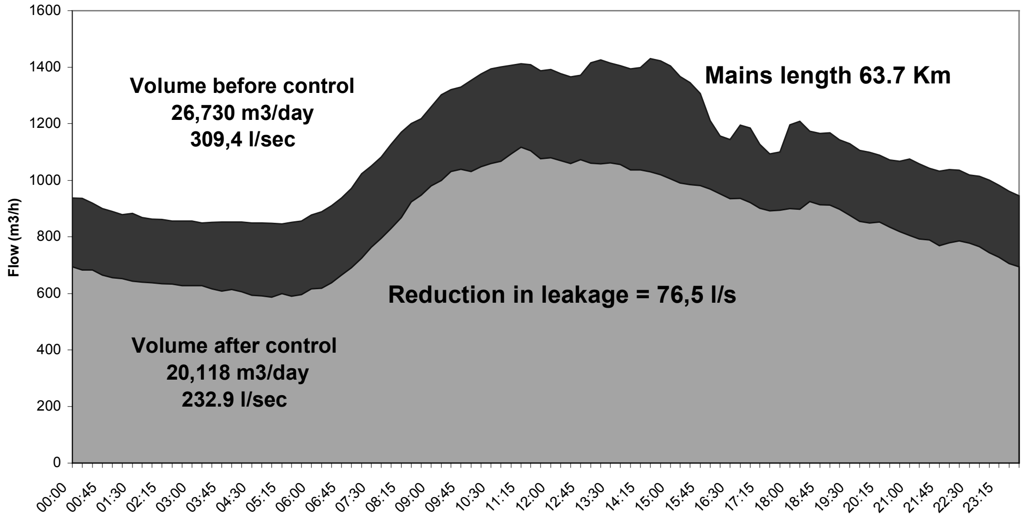


Figure 9. Volumes and flow before and after control.

Renovation is where the original pipeline is maintained and the structural condition of the whole pipeline is improved. This may involve lining the pipeline with a lining using pipe or sprayed materials and may involve a reduction of hydraulic performance. Alternatives include soft lining, folded lining, reduced diameter lining, spiral lining, manual lining, unmodified slip lining, spray-on lining, grouting and brick repointing.

Replacement is where the pipeline is replaced by either laying a new pipeline alongside the existing pipeline using techniques such as pipe bursting, back reaming, microtunneling, jetting, conventional tunnelling, trenching or off-line replacement techniques such as trenchless steerable, guided drilling, directional drilling, microtunneling, conventional tunnelling or trenching.

Rehabilitation Selection Criteria

A large range of procedures is available for pipeline rehabilitation, however, the selection of a suitable rehabilitation technique can be a difficult decision. This choice requires decisions to be made concerning:

- The required lifetime to be obtained.
- The structural integrity of the existing pipeline and the structural integrity needed.
- The hydraulic capacity needed.
- Whether disruption to service can occur.
- The ability to divert sewer or potable water flows.
- The extent and location of surface works.
- Soil and ground conditions.
- The number and method of reconnecting laterals.
- The chemical, corrosion and abrasion resistance needed.
- The degree of cleaning needed to undertake the recommended renovation technique.

Systems to allow rational selection of a pipeline rehabilitation technique based upon the above points are not readily available. Decision support systems to evaluate replacement or preventive maintenance priorities have been suggested or implemented by several groups (Kulkarni & Reid 1991; Madiec *et al*. 1996; Fenner & Sweeting 1999). These do not necessarily address the issue of selection of the repair/replacement technology. Kleiner *et al*. (1998) discuss the choice of an optimal rehabilitation strategy. Their proposal is based on dynamic programming and (sometimes) implicit enumeration of schemes to select, for each pipe in an existing network, the rehabilitation alternative and the time of its implementation so as to minimise the cost of the rehabilitation. However, none of these systems look at a full lifecycle costing methodology taking into account the expected life of the repair or maintenance, the costs associated with all aspects of the rehabilitation and the costs borne by third parties (externalities).

Also important will be quantification of the benefit gained for the expenditure committed. As indicated earlier, environmental impacts of, for example, sewer overflows are not consistent across all receiving environments. The level of rehabilitation required to achieve the desired goal and its cost should be taken into account in prioritising rehabilitation programs. This is not to suggest that the environment should be compromised, but that a rational decision-making framework is required to ensure that money available for environmental rehabilitation programs is directed to those rehabilitation programs that will produce the greatest effect.

Recent major failures in Australian urban water infrastructure highlight the problems that can occur if a consistent approach is not taken to the development of a rational asset management system to deal with pipe leakage. Development of an asset management system incorporating the components of leakage detection, pressure management and rehabilitation selection has not occurred in an Australian water authority, although some aspects are currently under development. For this process to occur, a decision-support system to allow selection of rehabilitation techniques incorporating lifecycle costing methodologies, to assess the viability of each selection decision, needs to be developed. The AWWA has recently commissioned a project in this area and as these tools are developed the implementation of a rational asset management system in this area becomes possible.

CONCLUSIONS

It is recognised that leakage of sewer and water reticulation pipes is a problem worldwide. Although the problem in Australia is not as great as countries with older systems such as Germany, as our infrastructure continues to age the problems will increase. This is compounded by recent changes to the way water authorities operate, where capital expenditure needs to be justified as being cost effective before any replacement or maintenance of pipes occurs.

Leakage in both water and sewerage pipelines can have significant ecological and design effects, with overdesign of sewerage systems and the associated pipework being a major cost factor in providing a service to customers. If overdesign does not occur, as is the case for some water authorities in Australia, then sewer overflows are a real possibility, with their associated health risks and bad publicity. Whilst most attention has been focussed on sewer overflows, sewer leakage has also been highlighted as a potential source of environmental problems, although one that is currently receiving little attention.

To solve leakage in both sewer and water reticulation systems, sophisticated leak detection techniques are required. The best method of leakage detection and control is very dependent on the type of system and customer base in the utility. Whilst new systems may appear, the most likely developments will be in the combining of current systems. A combination of CCTV, current sonde, microwave sensor, neutron and gamma ray probe, and hydrochemical sensors would be a powerful tool, provided it was not prohibitively expensive. The most significant factor requiring water authorities to undertake such exercises, however, will be the public perception of sewer leakage. This is already happening in Germany where leaking sewers are becoming of environmental concern to the public (Misstear *et al.* 1996). The focus of the media up to now has largely been on water pipe leakage, but the future focus will be on sewers.

A number of procedures can be undertaken to reduce leakage in both sewers and water supply systems. In sewers, the only existing technology is rehabilitation or replacement. For water reticulation pipelines, either rehabilitation can be undertaken or pressure management techniques instigated. Pressure management can be a very cost-effective means of reducing losses or controlling demand, for many utilities, with a wide diversity of conditions. As with any potential investment, in loss control or demand management it is important to carefully model or calculate the effects and benefits of the control prior to implementation to ensure ongoing system requirements while cutting out unnecessary losses and system inefficiencies.

The choice of which rehabilitation technique or whether rehabilitation needs to be undertaken at all is currently difficult, as little information is available to aid selection of the appropriate technology. Asset management systems need to be developed to allow technology selection, taking into account lifecycle costing methodologies as well as externalities, such as customer disruption and health risks.

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