

What Do We Know About Real Losses On Transmission Mains?

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Abstract

Transmission mains have long been a challenging component to address effectively in water network audits and modelling of real losses. The lack of reliable methods for assessing this component of real water loss has forced the use of educated guesses and assumptions. Over the last 15 years, technical developments for identifying unreported leaks in transmission mains have resulted in a substantial library of data on prevalence and flow rates of thousands of such leaks in over 25 countries. This library can now be used to develop more robust analysis and modelling of real losses in transmission mains.

The authors have used this data to gain a better understanding of the probability distribution of leak flow rates in transmission mains, and to consider whether the BABE (Bursts and Background Estimates) concepts of components of Real Losses, developed for distribution systems, should be modified or re-calibrated when applied to transmission mains. Pipe age data, where available, is used to obtain initial estimates of the rate of rise of unreported leakage in transmission mains over time. Estimates of rate of rise can be used to assess estimated economic intervention frequencies, for different costs of intervention and valuations of real losses. The implications for calculation of an economic component for unreported leaks in transmission mains are discussed.

For the purposes of this paper, the terms 'Leak', 'Burst' and 'Break' are used interchangeably, and transmission mains are defined as larger diameter pipelines with few service connections per km of main, and insufficient numbers of accessible fittings for effective use of historically available external leak detection technologies, such as acoustic listening devices and conventional leak noise correlators. There is no strict cut-off by pipe diameter, however a reasonable assumption would be 300 mm and larger for plastic or concrete mains, and 600 mm and larger for metallic mains.

The methods, costs, and benefits of addressing transmission main leakage are different enough from distribution networks to warrant separate consideration. The cost of detection, location, and repair of transmission main leaks is significantly greater on a per-km basis than on distribution mains, often by an order of magnitude or more; this often leads utilities to simply exclude transmission mains from leak detection programs. The authors consider whether, and under what conditions, the benefits are commensurately great, through the use of the Economic Intervention Frequency concept.

Review of Leak Detection Methods on Transmission Mains

Leak detection has historically relied upon acoustic methods to detect and locate leaks, based on the sound emitted by the water escaping from the pipeline. Such devices rely on the sound travelling to a point where it can be detected from above ground, either travelling through the ground to the surface directly above the leak site, or travelling along the pipeline to appurtenances where sensors can be attached. Transmission mains present problems to both of these approaches. They tend to be buried more deeply, and in less accessible locations than distribution lines, often making it impractical to detect

sound rising to the surface. They also tend to have few appurtenances, and do not transmit broad bands of sound for long distances in the way that many distribution mains do. This makes historical approaches to leak detection on transmission mains ineffective.

Two fundamental approaches have been taken to allow acoustic leak detection methods to work in transmission mains: detecting the sound of leaks at greater distances in transmission mains (transmission main correlators), or finding a way to bring the acoustic sensor to the sound (inline methods). Both are primarily offered as commercial services, as they require a great deal of specific expertise to employ successfully.

Inline methods involve inserting a sensor into the pipeline, which traverses a run of the pipeline, collecting acoustic data as it travels. This can be done using either tethered systems (where the sensor is connected to the surface through umbilical cables) or free-swimming systems (which are deployed into the line and retrieved from a different point downstream). Bringing the sensor very close to the source of sound avoids the problem of leak sounds not transmitting as well along the pipeline. It also presents unique challenges, such as eliminating other noise sources (acoustic noise inside the pipe and electrical noise in the cable), and the costs and risks involved in deploying and retrieving the sensors in this challenging environment. The first inline approach to be broadly employed was a tethered leak location system developed in the UK in the 1990's (Bond et al, 2001). Inline techniques are now proven and commercially available in both tethered and free-swimming forms throughout the world.

Transmission main correlators have become practical in recent years thanks to the National Research Council of Canada's research indicating that while most sounds attenuate very quickly in large diameter pipelines, certain acoustic signals travel extremely long distances before dissipating. Custom engineered sensors, acoustic filters, and signal processing algorithms taking advantage of these findings have brought new correlators to the market in the past decade specifically for large diameter transmission mains. This technology has since been improved, and is now capable of consistently finding most transmission main leaks at extremely long sensor spacings (generally 1 to 2 km).

In general terms, these two approaches represent a trade-off between sensitivity and location accuracy on the one hand, versus cost and ease of use on the other. Inline technologies have shown the capacity for finding even tiny leaks, down to 0.02 litres/minute. The sensitivity of transmission main correlators depends on the particular device used, with the top performing devices sensitive to leaks as small as about 2 litres per minute at typical sensor spacings. Inline technologies tend to be more expensive, and also to require significant preparatory work (adding and modifying taps), as well as much more support during the surveys (modulating flows and closing side outlets to ensure the devices travel the desired path). These are generally appropriate for use when reduction of transmission main leakage by the greatest possible extent is justified. Transmission main correlator services are less expensive, and can often be employed with no preparatory work and minimal support during the surveys. They are generally appropriate as part of non-revenue water reduction programs aiming to reduce water loss at minimal cost, or where inline technologies are not feasible due to the complexity of piping or risk involved.

Transmission Mains Unreported Leak Data

Component Analysis Concepts applied to Unreported Leak Data

The establishment of inline transmission main leak location techniques has produced a wealth of data, which offers a unique opportunity for improving the industry's understanding of transmission main leakage. The fact that inline techniques can detect even miniscule leaks in large diameter mains means that these provide an accurate

picture of all significant leaks actually present in the mains. A repository of data containing over 3,000 km of transmission main leak detection inspections has now been accumulated and made available to the authors, allowing for the creation of a baseline understanding of actual leakage rates in transmission mains, which can be compared with previous assumptions based on component analysis of real losses.

The Bursts and Background Estimates (BABE) Concept was developed for component analysis of Real Losses on distribution systems (Lambert, 1994; Lambert and Morrison, 1995). It classifies leakage events into three different categories – undetectable background leakage, unreported bursts and reported bursts – each with different characteristics in terms of typical frequencies, flow rates and run-times. If all reported bursts are promptly repaired, leak detection exercises on transmission mains should identify only the ‘unreported bursts’ component of transmission mains leakage.

The three components for distribution mains in the Unavoidable Annual Real Losses (UARL) formula are shown in Table 1. The unreported component is 0.65 bursts per 100 km per year (based on a nominal 5% of 13 bursts per 100 km/year), each running at 6 m³/hr at 50m pressure, for 50 days on average, producing an estimate of 0.13 m³/km/day, out of a total of 0.90 m³/km/day. Reported burst frequencies on transmission mains of around 5 per 100 km/year (Laven, 2010) are lower than on distribution mains, but the Table 1 values have sometimes also been applied to transmission mains when no other data existed.

Table 1: Parameters used to calculate Distribution Mains Component of UARL at 50 metres pressure

Infrastructure Component	Unavoidable Background Leakage	Detectable Reported Bursts	Detectable Unreported Bursts	Total
On Distribution Mains	20 litres/km/hr	95% of 13 bursts/100 km/year at 12 m ³ /hr for 3 days* = 864 m ³ /burst	5% of 13 bursts /100 km/year at 6 m ³ /hr for 50 days = 7200 m ³ /burst	
	0.48 m ³ /km/day	0.29 m ³ /km/day	0.13 m ³ /km/day	0.90 m³/km/day

* or 36 m³/hour for 1 day, 6 m³/hr for 6 days, 3 m³/hr for 12 days, etc.

The 50 day run time of unreported bursts that was considered ‘unavoidable’ assumes surveying a network for leakage every 100 days. It has been noted, however, that if unreported bursts are not being located and repaired, a backlog will develop. (Lambert & Morrison, 1996). Given the historical absence of effective tools for locating leaks on transmission mains, it is a hypothesis worth testing that most pipelines have been accumulating a backlog of unreported bursts since their construction.

To best test this hypothesis, an adjustment should be made for the higher pressures at which transmission mains operate, with 80 meters being somewhat typical. As the relationships between pressure and both flow rate of bursts and their rate of formation have been well studied in recent years, this adjustment can be made using conservative assumptions - a linear relationship between burst frequency and pressure, and a square root relationship between flow rate and pressure for fixed area leaks on rigid pipes (FAVAD N2 = 0.5). Tables 2, 3 and 4 show the results, and highlight the importance of pressure when estimating rate of rise of unreported leaks.

Table 2: Predicted unreported leak frequency, average flow rate and rate of rise of unreported leakage at 50 metres and 80 metres pressure, based on unreported distribution mains burst assumptions in UARL formula

Average Pressure metres	Unreported Leak Frequency No per 100 km/yr	Average flow rate, per leak m ³ /hour	Rate of Rise of Unreported Leakage	
			m ³ /km/hour, per yr	m ³ /km/day, per yr
50	0.65	6.0	0.039	0.94
80	1.04	7.6	0.079	1.90

Table 3: Predicted accumulated number of unreported leaks at 50 metres and 80 metres pressure, based on unreported distribution mains burst assumptions in UARL formula

Pressure metres	Unreported leak frequency per 100 km/yr	Accumulated # of unreported leaks/100 km after				
		20 years	40 years	60 years	80 years	100 years
50	0.65	13	26	39	52	65
80	1.04	21	42	62	83	104

Table 4: Predicted accumulated leakage in m³/hour at 50 metres and 80 metres pressure, based on unreported distribution mains burst assumptions in UARL formula

Pressure metres	Rate of Rise m ³ /hour/km/yr	Accumulated unreported leakage in m ³ /hour/km mains after				
		20 years	40 years	60 years	80 years	100 years
50	0.039	0.8	1.6	2.3	3.1	3.9
80	0.079	1.6	3.2	4.7	6.3	7.9

The figures in Table 4 are clearly orders of magnitude greater than the 0.13 m³/km/hour figure used in the UARL formula (Table 1), which assumes active leakage control interventions every 100 days on average. But how do Tables 2, 3 and 4 predictions compare with the field results from 3000 km of trunk mains?

Unreported Leak Frequency Variations by Geographic Region

The transmission main leak detection data analyzed by the authors indicate an average frequency of 92 unreported leaks/100 km in 3,221 kilometres of large diameter pipelines surveyed. The breakdown of the unreported burst rates by geographical region, shown in Table 5, reveals variations between 22 and 128 leaks/100 km, which is not dissimilar to the range in Table 2, but perhaps higher.

Table 5: Measured frequencies of unreported bursts on transmission mains in different geographic regions.

Region	Dist (km)	Leaks	Leaks/100 km
Worldwide	3,221	2966	92
North America	711	496	70
Latin America	186	40	22
Europe	1,583	2023	128
Africa	383	244	64
Asia & South Pacific	298	150	50
Middle East	60	13	22

Unreported Leak Frequency Variations by Pipe Material and Pipe Diameter

Pipe material records, available for over 2,500 kilometres (78%) of the data, are shown in Table 6. These reveal a fairly wide variation of unreported leak frequencies by material; Cast Iron has by far the highest leak frequency, steel and concrete much lower.

Table 6: Measured frequencies of unreported bursts on transmission mains in different pipe materials.

Material	Dist (km)	Leaks	Leaks / 100 km
Cast Iron	1,127	1871	166
Ductile Iron	199	142	71
Steel	296	87	29
Concrete	961	417	43

A breakdown of unreported leak frequencies by pipe diameter in Table 7 (based on a smaller sample of 1116 km) shows a trend of larger diameter transmission mains having a smaller frequency of unreported leaks. This agrees with information available on reported bursts, where pipe diameter is known to be a good predictor, with smaller diameters experiencing higher burst frequencies (Stone et al, 2001), (Sundahl, 1996).

Table 7: Measured frequencies of unreported bursts on transmission mains of different diameters.

Diameter	Dist (km)	Leaks	Leaks / 100 km
< 600 mm	47	31	66
600 to 900	302	267	88
1050 to 1500	399	141	35
> 1500 mm	368	52	14

Unreported Leak Frequency Related to Age of Mains

If the concept of unreported bursts accumulating over periods of years in Table 3 is valid, leak detection frequencies found during occasional interventions on newer transmission mains should be lower than for older materials. Several of the groupings of pipe are homogenous enough that a typical age can be estimated. Figure 1 shows a plot of leakage rate versus age for the roughly 1,500 km of pipe data where age could be estimated. The black line shows the linear trend of accumulated unreported leak frequencies growing over time, at an average rate of 1.56 leaks / 100 km / year of age, with an R^2 value of 0.80, indicating a very strong correlation between age and the accumulation of unreported leaks.

Predictions based on the parameters used for unreported mains bursts in the UARL formula, from Table 2, are also shown as blue and red lines, and represent the predicted backlogs based on the UARL formula at pressures of 80 meters (blue) and 50 meters (green). At 0.65 and 1.04 per 100 km per year of age, they lie at the lower bound of the field data. However, it is also necessary to consider the flow rates of the unreported leaks.

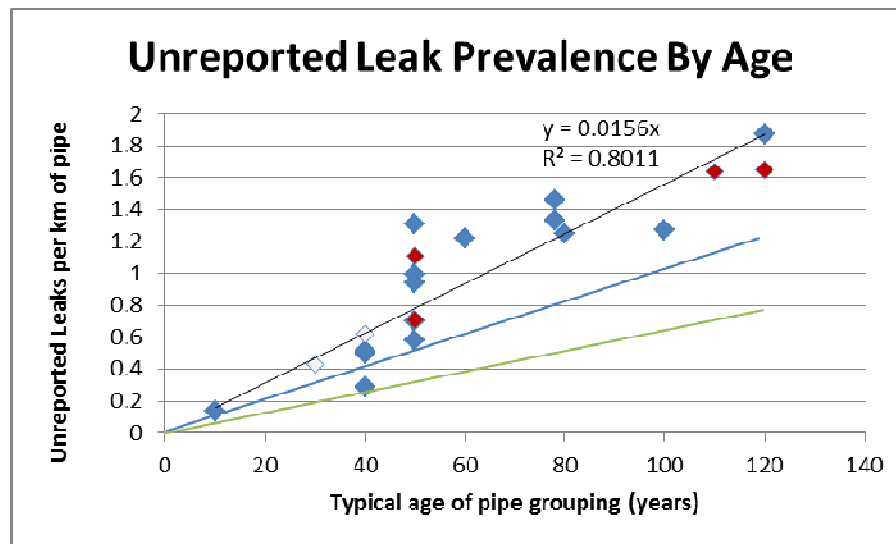


Figure 1: Measured frequency of unreported leaks compared to approximate pipe age.

Variations in Leak Flow Rates

A relatively consistent methodology for classifying leak flow rates from the use of in-pipe ‘Sahara’ surveys has been employed in most of the surveys. Leaks are grouped in five qualitative size bands, generally described as “Very Small” through “Very Large”. A UK study (Bond et al, 2007) was undertaken to excavate and measure roughly 400 of these leaks, and confirm the approximate minimum and maximum flow rates for each grouping such that approximately 90% of the leaks would fall into these bands. Table 8 presents the results of this study, and provides a method for converting raw leak numbers into estimated leak flow rates. However, it should be noted that different median flow rates are

sometimes used for these Size classifications, and that when applied to survey data they are **estimates**, not actual measurements.

Table 8: Qualitative Size Classifications for Leak Flow Rates: UK.

	Size 1	Size 2	Size 3	Size 4	Size 5
	m ³ /hr	m ³ /hr	m ³ /hr	m ³ /hr	m ³ /hr
Min	0.23	1.6	6.7	11.8	16.9
Median	0.93	4.2	9.3	14.4	25.5
Max	1.6	6.7	11.8	16.9	34.0

Distributions of the leak frequencies classified using the Table 8 criteria are available for several major projects and data groupings. Figure 2 indicates that the majority of the leak numbers found fall into the smaller Size 1 and Size 2 ranges.

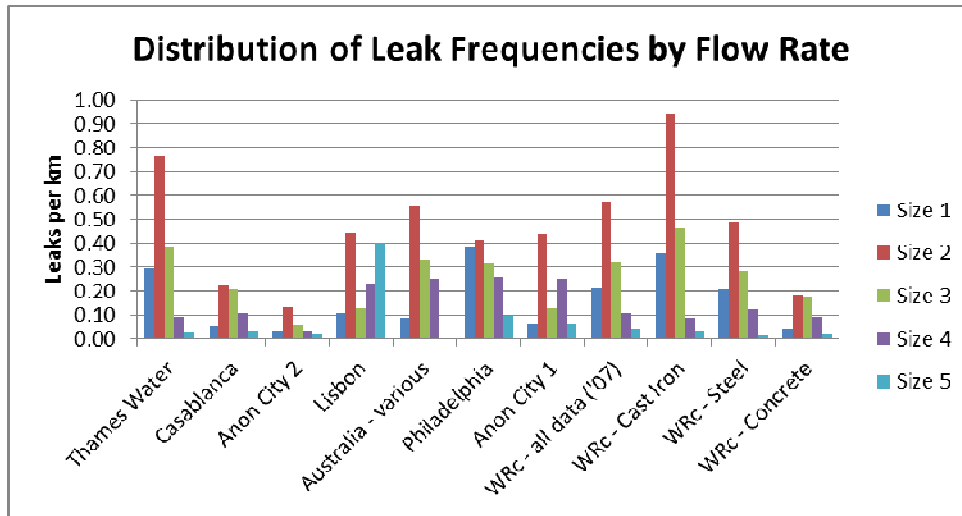


Figure 2: Distribution of number of leaks among the five flow rate classifications

Figure 3, which displays the same case study groupings with leakage shown in m³/hr/km, indicates that while the majority of the leak numbers are in Sizes 1 and 2, the bulk of the water volume loss usually comes in the moderate Size 3 and Size 4 ranges.

The Size 1 leaks offer a very small contribution to the total, with the remainder each offering sizable contributions. Lisbon is a clear outlier, having a disproportionate number of Size 5 leaks, which contributed the majority of the water loss.

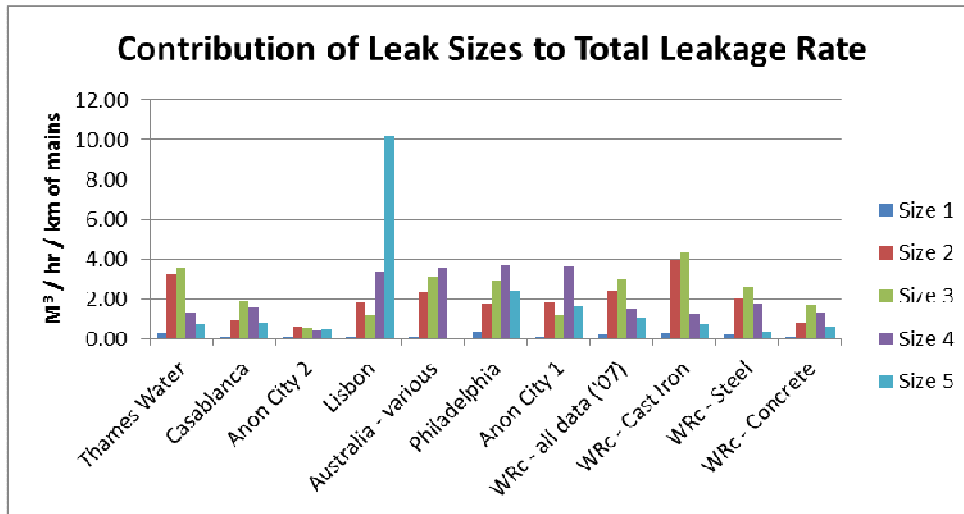


Figure 3: The contribution to the total leakage rate of each of the five size

Figure 4 shows leakage rates by age for those data points where it is available. The black line represents the linear trend in the data, whereas the blue and red lines represent the predicted backlogs based on the UARL formula at pressures of 80 meters (blue) and 50 meters (green).

If Lisbon is considered to be an outlier (for reasons explained above), Figure 4 suggests that leakage rates do indeed increase at a relatively consistent pace, but that at somewhere around 80 years, the rate of increase of leakage may drop off significantly.

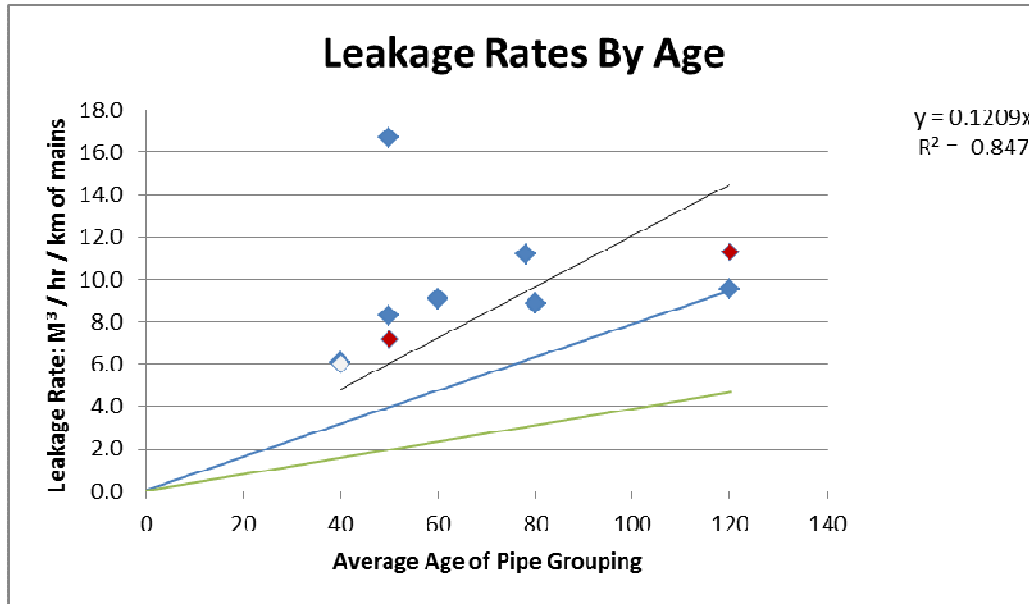


Figure 4: Leakage rates as compared to pipe age, for cities in which both factors were available.

The best fit line to the field data in Figure 4 has a slope of 0.12, indicating an average Rate of Rise (RR) of 0.12 m³/hour per year, per km of mains. This represents the average Rate of Rise (RR) of leakage on the pipelines within this data set, between their installation date and the date of survey. This can be compared to the theoretically expected rates of rise shown in Table 4, based on the parameters used for unreported distribution mains bursts in the UARL formula, of 0.04 (at 50 m pressure) and 0.08 m³/hour per year per km of mains (at 80 metres pressure).

As a note of caution, it should not be assumed that all pipelines and all networks will experience the same rate of rise. The rate of rise for any given utility is likely to depend on many factors, including materials, diameter, pressure, and the general performance of the utility in effectively managing leakage, as indicated by the Infrastructure Leakage Index. As evidence to this variation, the lowest average rate of rise found by the authors to date is 0.013 m³/hour per year per km of mains, as obtained from re-analysis of data from a seven year 'direct measurement' study on 113 sections of relatively small diameter transmission mains (150 to 1050 mm) in the UK totalling 400 km (Goodwin, 1980). The best method for a utility to predict their future rate of rise would be through careful analysis of active leakage interventions on transmission mains in individual Utilities, taking into account age, materials, diameter, pressure and other local factors such as propensity of leaks to surface based on local ground conditions.

That said, if the relationship between leakage rate per kilometer and age of the main can be assumed to be approximately linear in some situations, this offers the possibility of employing the Economic Intervention methodology first established for distribution networks (Lambert & Lalonde, 2005) on large diameter transmission mains. Further consideration of this approach is provided in Section 3 of this paper.

Figure 4 suggests that (at 100 years age) the average leakage rate is around 12 m³/km/hour, while Figure 1 indicates that transmission mains accumulate unreported leaks at an average rate of around 0.0156 per km/year. These two figures imply that the overall average unreported burst flow rate is 12/(0.0156 x 100 = 7.7 m³/hour. This agrees with results from several utilities that have excavated and verified the sizes of their leaks (Bond et al, 2007), (Laven, 2010); and also with the 7.6 m³/hour in Table 2 at 80 metres pressure.

Economic Intervention Policy applied to Transmission Mains

The Economic Intervention Frequency EIF (Lambert and Lalonde, 2005) occurs when the Cost of Intervention CI (excluding repair costs) equals the value of water lost since the last intervention (the area of the red triangle in Figure 5).

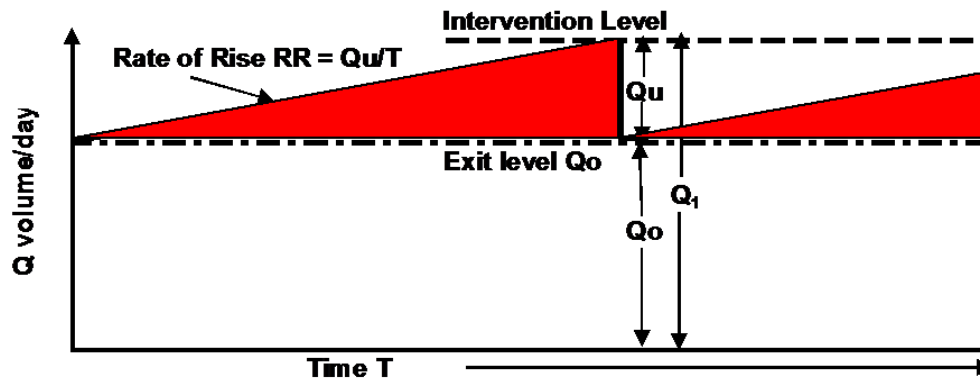


Figure 5: Concept of Economic Intervention to locate Unreported Bursts

- If
- RR = Rate of Rise in m³/km of mains/day in a year
 - Q₀ = Level of real losses after an intervention (background leakage)
 - Q₁ = Level of real losses at which an intervention is triggered
 - Q_u = Level of unreported real losses when an intervention is triggered
 - T = Time between active leak detection interventions (years)
 - CI = Cost of an Intervention (\$/km) excluding repair costs
 - CV = Variable Cost of Water (\$/m³)
 - EIF = Economic Intervention Frequency (years)

The value of the water lost between interventions (the area of the red triangle in Figure 5) can be expressed as:

$$\text{Value of Water Lost Between Interventions} = 0.5 \times RR \times T^2 \times CV \quad (1)$$

Setting this as equal to the cost of an intervention yields the equation:

$$CI = 0.5 \times RR \times T^2 \times CV \quad (2)$$

The economic intervention frequency parameters can be calculated by making T (in Equation 2) equal to EIF, and rearranging Equation 2 to obtain the following:

$$\text{EIF (years)} = 0.074 \times \sqrt{(CI/(CV \times RR))} \quad (3)$$

$$Q_u \text{ (m}^3\text{/km/hr)} = \text{EIF} \times RR \quad (4)$$

$$Q_u \text{ (m}^3\text{/km/hr)} = 0.074 \times \sqrt{(RR \times CI/CV)} \quad (5)$$

$$\text{Avg. unreported real loss between economic interventions} = 0.037 \times \sqrt{(RR \times CI/CV)} \quad (6)$$

Further details and explanations for calculation of Economic Intervention Frequencies can be found in Lambert and Lalonde, 2005. Table 9 shows example calculations for transmission mains using the typical rate of rise shown in the data presented in this paper.

Table 9: Example calculations of Economic Intervention calculations for transmission mains

Intervention Method	Variable Cost CV	Rate of Rise RR	Intervention Cost CI	Econ. Int. Frequency EIF	Unreported Real Loss	
					At time of intervention	Average between interventions
	\$/m ³	m ³ /km/day/yr	\$/km	years	m ³ /km/day	m ³ /km/day
In-line	1.0	2.9	25000	6.9	20	10
Transmission Main Correlator	1.0	2.9	10000	4.3	12.6	6.3

Because the EIF is calculated using the square root of CI, CV and RR, the confidence limits for the calculation are not greatly influenced by moderate errors in estimating Rate of Rise (or Cost of Intervention, or Variable Cost of Water). However, whilst Cost of Intervention CI and Variable Cost of Water CV are not too difficult to assess, Rate of Rise for individual lengths of transmission mains can be expected to vary widely.

This is particularly the case for relatively short sections of main, due to the low average frequency of unreported leaks (0.0156 per km per year of age, see Fig 1), so an 'economic' survey every 7 years on 10 km of transmission mains would only expect to identify $0.0156 \times 10 \times 7 = 1$ unreported leak. Figure 2 indicates this is most likely to be a Size 2 leak (4.2 m³/hr) rather than a leak with the weighted average flow rate (from large samples) of 7.7 m³/hour.

Clearly, there is further work to be done on an appropriate statistical approach to applying economic intervention concepts to actual and projected interventions on relatively small lengths of transmission mains. However, it's clear that whenever an intervention has been carried out, Rate of Rise should be calculated, based on numbers and estimated flow rates of leaks found, and age of mains (or years since last intervention). Average pressure for each length of main surveyed, is also likely to provide valuable data for future research, to improve predictions based on the economics of leak detection interventions on transmission mains.

Conclusions

The large data samples available for this initial brief study show substantial variations in the frequency of unreported leaks on transmission mains:

- by geographic region (22 to 128 per 100 km/year, from Table 5)
- by pipe material (29 to 166 per 100 km/year, from Table 6)
- by pipe diameter (14 to 88 per 100 km/year, from Table 7)

However, when unreported leak frequency is plotted against age of mains up to 120 years (Figure 1), much of this variability appears to be accounted for, indicating that (in the absence of active leakage control interventions) unreported leaks may be accumulating with time, rather than maturing into reported leaks and reaching a 'steady state' frequency. The average unreported leak frequency of 1.56 per 100 km per year is higher than the unreported leak frequency for distribution mains of 0.65 per 100 km/year at 50m pressure assumed in the UARL formula, and also higher than the 1.04 per 100 km/year at 80m pressure, which is perhaps more typical of transmission mains pressures.

When leaks found are categorised by estimated flow rates (Table 8, Figures 2 and 3), so that estimated leakage rate can be plotted against age (Figure 4), the average rate of rise of unreported leakage is calculated as 0.12 m³/hr per km per year (2.9 m³/day per km per year) up to around 80 years of age, but then possibly flattens out. This may be because unreported leakage of 230 m³/km/day (2.9 x 80 years) is likely to be high enough to be identified by other means (e.g. transmission mains mass balance) and acted upon.

As a note of caution, it would be unwise to conclude that there is a 'universally applicable' average rate of rise. It may also depend on factors such as the general performance of the Utility in effectively managing leakage, as indicated by the Infrastructure Leakage Index. The most reliable predictions of rate of rise are likely to come from careful analysis of active leakage interventions on transmission mains in individual Utilities, taking into account age, materials, diameter, pressure, and other local factors such as the propensity for leaks to surface based on local ground conditions.

There is reasonable agreement between weighted average flow rates of around 7.5 m³/hour from field data, the UARL formula (at 80 m pressure) and other sources.

The analysis in this paper shows that, whenever an active leakage control is carried out on transmission mains, Rate of Rise of unreported leakage should be calculated, based on numbers and estimated flow rates of leaks found, and age of mains (or years since last intervention). Average pressure, for each length of main surveyed, is also likely to provide valuable data for future research, to improve predictions based on the economics of leak detection interventions on transmission mains.

The title of this paper is 'What do we know about transmission mains losses?'. Perhaps a little more than previously, but there is still much more to be learned, and the authors hope this paper will stimulate others to support their ongoing efforts in this previously neglected field of research, now being opened up by recent developments in new technology.

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