Including the effects of pressure management in calculations of Short-Run Economic Leakage Levels

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Abstract

During 2005 and 2006, research and publications by IWA Water Loss Task Force members have shown, beyond reasonable doubt, that management of surges and excess pressures can have a significant effect of the frequency of new leaks and bursts in water distribution systems. Reductions in new burst frequencies in the range 23% to 90% have recently been reported for 112 pressure management schemes in 10 Countries.

Existing UK methods of calculating Short Run Economic Leakage Levels (SRELLs) are usually based only on the principle of economic management of the run-time of current numbers of unreported numbers of leaks and breaks, assuming no change in pressure. Some of these approaches have also allowed for changes in pressure in relation to changes in the flow rates of leaks and bursts, but not to changes in the number of leaks and bursts, or for the effects of changes in annual repair costs. As changes in annual repair costs (following pressure management) may well be a dominant economic factor, the coming generation of SRELL calculations must surely include allowances for the influences of pressure management, if they are to be meaningful.

The paper proposes a practical way in which the effects of pressure management can be included in calculations of short-run economic leakage level, taking into account changes in leak flow rates, changes in numbers of leaks and repair costs, and changes in income from metered customers (for financial planning purposes).

Introduction

The paper consists of the following Sections and Sub-Sections:

- Achieving an Economic Level of Real Losses
    - Definition of Short Run Economic Leakage Level SRELL
- Steps in development of a practical international SRELL calculation method
- How does pressure management influence components of SRELL?
    - Predicting changes in leak flow rates
    - Predicting reductions in frequencies of leaks and bursts
    - Predicting changes in Economic Unreported Real Losses and associated parameters
    - Predicting changes in consumption
- SRELL calculations using BABE component analysis and FAVAD Concepts
- Other Calculations using Pressure:burst relationship predictions
- Summary and Conclusions

Achieving an Economic Level of Real Losses

Figure 1 is now widely used internationally to demonstrate the essential principles for effective economic management of Real Losses. For all but a very few Utility systems, the Current Annual Real Losses (CARL, represented by the largest box) exceed the Unavoidable Annual Real Losses (UARL, the smallest box), and there is an Economic Level of Leakage (ELL) somewhere between the two.

An economic level of real losses (ELL) for a particular system cannot be achieved, or calculated, unless the Utility commits to effectively applying all four methods of real losses management shown in Figure 1. The ELL can be broadly defined (CIWEM, 2003) as:

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> ***'the level of leakage at which any further reduction would incur costs in excess of the benefits derived from the savings'***

In the absence of a simplified method for calculating economic leakage levels, progressive Utilities such as Malta Water Services Corporation, and Halifax Regional Water Council (Canada) have previously adopted a 'step by step' approach. A series of 'best practice' initiatives within the 4 components that individually have high benefit: cost ratios, or short payback periods, are identified and implemented. When no further economically viable initiatives can be found, it can be reasonably assumed that an economic leakage level - based on the above definition of ELL - has probably been achieved, whilst recognising that the economic leakage level will change with time.

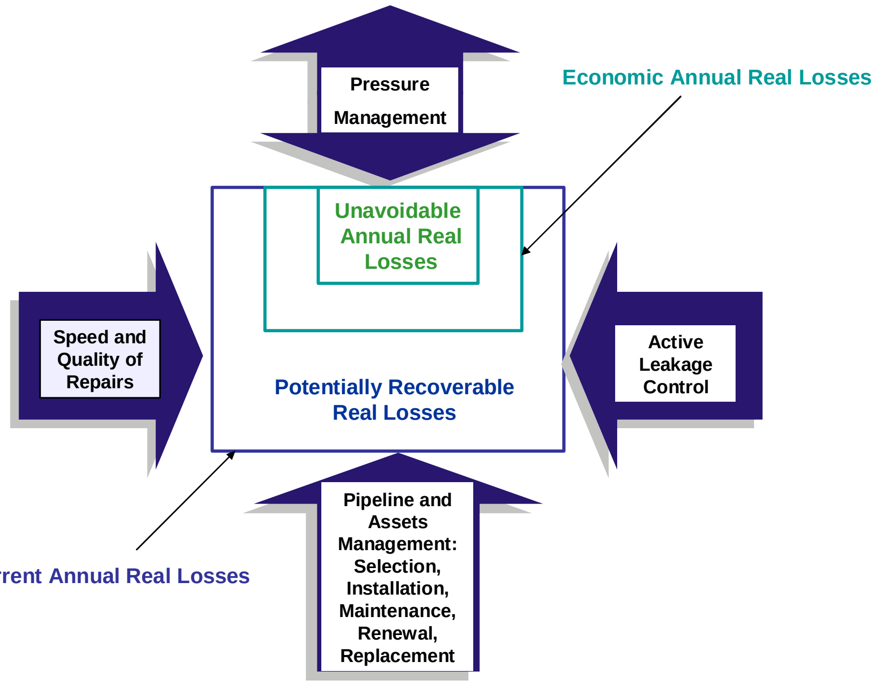

Figure 1: The Four Components Approach to Management of Real Losses

The ratio of the CARL to the UARL is known as the Infrastructure Leakage Index (ILI). If the ILI for a system in a developed country is greater than 4 (i.e. in Bands C or D of the World Bank Institute Banding System) there is little point in attempting to calculate or predict an Economic Leakage Level, as there are likely to be one or more fundamental activities which are not being effectively carried out. On more than one occasion, this has been found to be failure to ensure prompt repairs (or any repairs!) of leaks on customers' private pipes upstream of the customer meters used in the water balance calculation.

When a Utility commences to apply the ‘Four Component Approach’ to management of Real Losses in its system(s), activities of ‘Pipeline and Assets Management’ almost always (in the experience of the authors) have considerably longer payback periods than the other three activities ‘Speed and Quality of Repairs’ , ‘Pressure Management’ and ‘Active Leakage Control’. So, by concentrating on these three activities, for the first few years at least, Utilities with initial high leakage levels (expressed in volume/day) can usually achieve substantial reductions in Real Losses with short payback periods.

Definition of Short Run Economic Leakage Level SRELL

While there are varying degrees of sophistication of pressure control and active leakage control, the initial objective should be to ‘get started’ with each of the simple basic activities. In this paper, the term ‘**Short Run Economic Leakage Level (SRELL)’** is defined as that which should be achievable by the ‘West’, ‘North’ and ‘South’ arrows on Figure 1, i.e. by

- ensuring all detected leaks and bursts are repaired promptly and to a high standard
- introducing basic pressure management, to reduce excess pressures and surges
- active leakage control by regular survey, at an economic intervention frequency

Steps in development of a practical international SRELL calculation method

This paper can be considered as one of a series by Water Loss Task Force members which have sought to develop and refine practical international methods for predicting Short Run Economic Leakage Levels (SRELLs) for water distribution systems.

One of the more intractable problems – that of quickly assessing the SRELL component relating to unreported leaks – was substantially solved (for a policy of regular survey) by the development of basic equations (Fantozzi and Lambert, 2005), using three local parameters:

- CI: Cost of an Intervention – excluding repair costs (local currency)
- CV: Variable cost of water (in local currency/m^3)
- Rate of Rise of Unreported Leakage – m^3 per day, in a year

to calculate:

- EIF: Economic Intervention Frequency EIF (in months)
- EP%: Economic % of System to be surveyed each year
- ABI: Annual Budget for Intervention – excluding repair costs (local currency)
- EURL: Economic Unreported Real Losses (m^3/year)

In a second paper ((Lambert & Lalonde, 2005) the presentation of the equations used for calculating EIF and associated parameters was improved, and an example given of how to calculate SRELL for an Australian system at the current average operating pressure. The paper then briefly highlighted the necessity to incorporate pressure management options into calculation of SRELLs, but without going into detail as to how this could be accomplished.

The third paper in the sequence (Thornton and Lambert, 2005) summarised methods for analysis and prediction of pressure:leak flow rate and pressure:consumption relationships using the FAVAD (Fixed and Variable Area Discharges) concept, using the exponent N1 for components of leakage, and N3 for components of consumption. That paper also attempted to analyse a limited number of early sets of pressure:burst data using a FAVAD type of relationship (exponent N2) but following discussions between WLTF members after Leakage 2005, it quickly became clear that the N2 exponent approach was definitely not appropriate for pressure:bursts relationships.

Following further collection of many more sets of pressure:burst data, an alternative concept for analysis and prediction of pressure:bursts relationships was circulated amongst WLTF members during 2006, with a brief summary appeared in Water 21 (Thornton and Lambert, 2006). Further research since then is being reported more fully in the fifth key paper (Thornton and Lambert, 2007), to the Water Loss 2007 Conference in Bucharest.

This research has now reached the stage where predictions of likely % reductions in the frequencies of leaks and bursts can be attempted separately for mains and services. Whilst further testing, refinement and improvement of the prediction method is continuing, this remainder of this paper explains, with an example, how predictions of changes in leak flow rates and frequency of leaks and bursts, following pressure management, can be included in the calculation of SRELL.

How does pressure management influence components of SRELL?

Component Analysis models based on BABE (Background and Bursts Estimates) concepts can be used to estimate, for each relevant part of the infrastructure (mains, service connections etc) the following components of annual real losses volume, using appropriate average flow rates and average run-times:

- ***'Reported'*** leaks and bursts (typically with high flow rates, but short run times)
- ***'Background'*** leakage (small non-visible, inaudible leaks, running continuously)
- ***'Unreported'*** leaks (moderate flow rates, run times depend on Utility policies)

A visual example of the effect of pressure management on components of SRELL is shown in a simplified format in Figures 2 and 3. Figure 2 illustrates the three BABE components of SRELL as a simplified time series, at some specified average pressure, before pressure management is introduced to reduce excess pressures and surges.

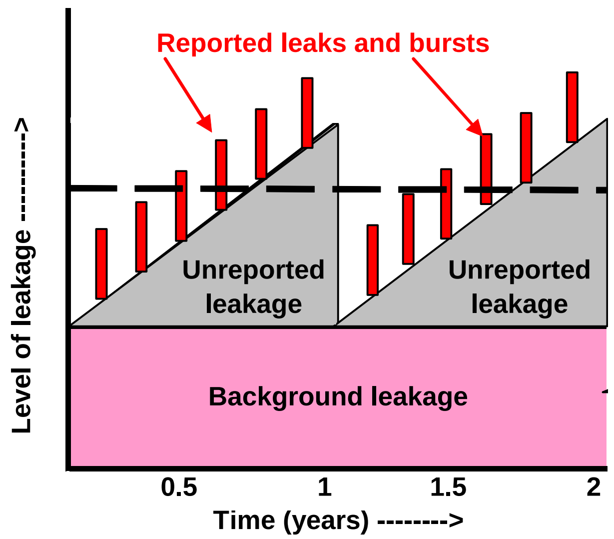

Figure 2: Simplified BABE components of SRELL, varying with time, assuming regular survey

Background (undetectable) small leaks run continuously. Unreported leakage gradually accumulates, at an average rate of rise RR, and economic intervention occurs when the accumulated value of the 'triangle' of unreported leakage equals the cost of the intervention - once per year, in this example - and the process then repeats itself. Reported leaks and bursts (generally high flow rates but short duration) are superimposed on the other two components. The SRELL (shown as a dashed line) is the annual average of all three components.

Next, consider what happens after pressure management, if excess pressures and surges are reduced. The flow rates of existing and new leaks are reduced, and (in most cases) the number of new leaks and bursts is also reduced. As shown in Figure 3:

- the background leakage (which is very sensitive to pressure, N1 = 1.5) reduces
- the frequency and flow rates of reported leaks and bursts are reduced
- the rate of rise of unreported leakage also reduces
- the SRELL reduces to the lower dashed line

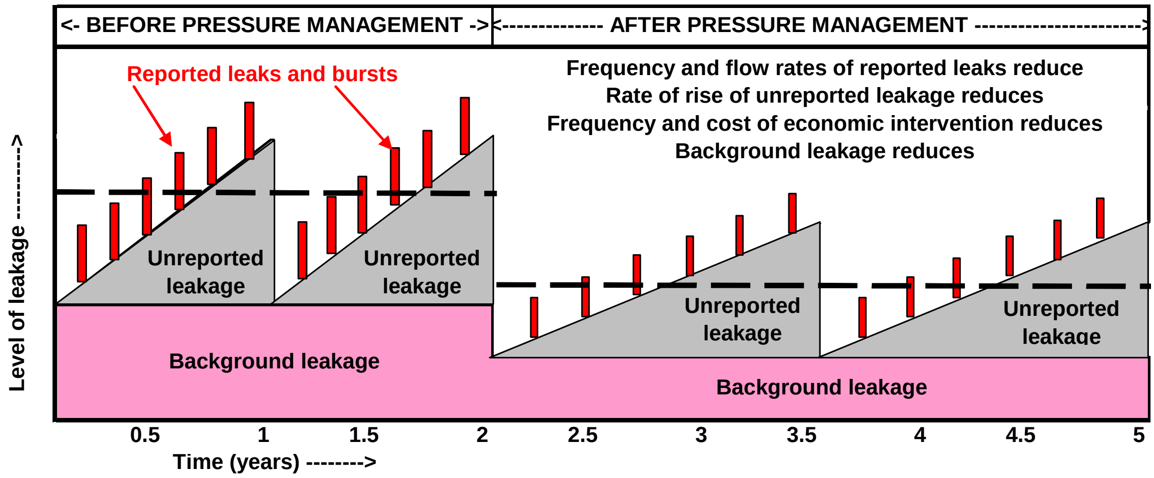

Figure 3: Influence of pressure management on simplifies BABE components of SRELL

The predicted reduction in annual expenditure 'before' and 'after' pressure management will consist of 3 elements:

- the reduction in SRELL volume multiplied by the assumed variable cost of water
- the reduction in annual cost of economic interventions, as fewer will be needed
- the reduction in annual cost of repairs due to fewer leaks and bursts occurring

The estimated cost of implementing different methods of pressure management can then be compared against the predicted reductions in annual expenditure, and 'payback periods' calculated, to identify which pressure management option is likely to be most economic.

Predicting changes in leak flow rates

The most physically meaningful 'Best Practice' form of equation for pressure: leak flow rate relationships is the FAVAD (Fixed and Variable Area Discharges) equation:

$$L \text{ varies with } P^{N1} \qquad \text{and} \qquad L_1/L_0 = (P_1/P_0)^{N1}$$

If the average pressure is reduced from P_0 to P_1, flow rates through existing leaks change from L_0 to L_1, and the extent of the change depends on the ratio of average pressures and the exponent N1.

Tests on systems where all detectable leaks have been repaired or temporarily shut off, leaving only background (undetectable) leakage, tend to produce high N1 exponents close to 1.5. Detectable leaks and bursts on rigid pipes usually have an N1 value in the range 0.5 to 1.0, whilst splits on flexible pipes can have N1 values of 1.5 or even higher. However, not all detectable leaks on flexible pipes necessarily have high N1 values; leaks associated with poor quality connections at the main can have N1 values as low as 0.5

A practical approach for pressure management SRELL predictions as follows:

- for background leakage, assume N1 = 1.5

- for detectable leaks and bursts (reported and unreported),
    - o assume N1 = 1.0 if pipe materials are not known
    - o assume 1.0 < N1 < 1.5 if splits in flexible pipes are predominant
    - o assume 0.5 < N1 < 1.0 if leaks from rigid pipes, or leaks from flexible pipes at the mains connection point, predominate

Predicting reductions in frequencies of leaks and bursts.

Recent data from 112 systems in 10 countries (Thornton & Lambert 2007), has clearly demonstrated that the frequency of new leaks and bursts can be significantly decreased by pressure management. A simple plot of the data relationship is shown in Figure 4; in these calculations it is more appropriate to use the % reduction in the <u>maximum</u> pressure at the average Zone Point.

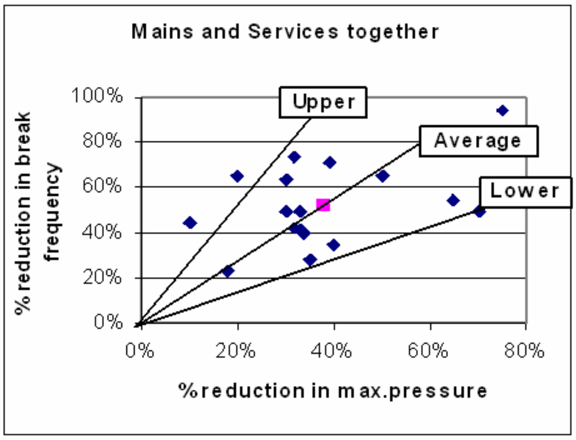

Figure 4: Simple basis for predicting % reduction in breaks from % reduction in maximum pressure

The average relationship in Figure 4 suggests that a permanent reduction of X% in maximum pressure will reduce new break frequency by 1.4 x X%; the upper and lower limits are respectively 2.8 x X% (subject to a maximum reduction of 90%), and 0.7 x X%. However, it was noted that in some cases there were:

- significant reductions in mains burst frequency, but not in service pipe bursts
- significant reductions in service pipe burst frequency, but not in mains bursts

Using and testing a conceptual approach to explain why these differences may occur, Thornton & Lambert (2007) consider that an important parameter for practical predictions of reductions in burst frequency may be the initial (pre-pressure management) burst frequency. Initial burst frequency Fbo can be expressed as a multiple of the frequency (Fbu) used in the Unavoidable Annual Real Losses formula (Lambert et al, 1999) for well maintained pipes in good condition, which are:

- Mains and private length of service connection: 13 repairs per 100 km per year
- Services (main to property line): 3 repairs per 1000 service connections/year

Initial comparisons in Thornton & Lambert (2007) suggest that if the multiple Fbo/Fbu is high the % reduction in burst frequency will also tend to be high – near the upper line in Figure 4 – indicated by movement from the red circle towards the blue circle in Fig 5.. If Fbo/Fbu is closer to 1 (indicating pipes in good condition before pressure management, blue circle) the % reduction in burst frequency will tend to be smaller (lower range in Figure 4), or even absent. This practical approach is in fact assuming that burst frequencies on pipes that already have high burst frequencies will be more strongly influenced by pressure management than burst frequencies on pipes that already have low burst frequencies.

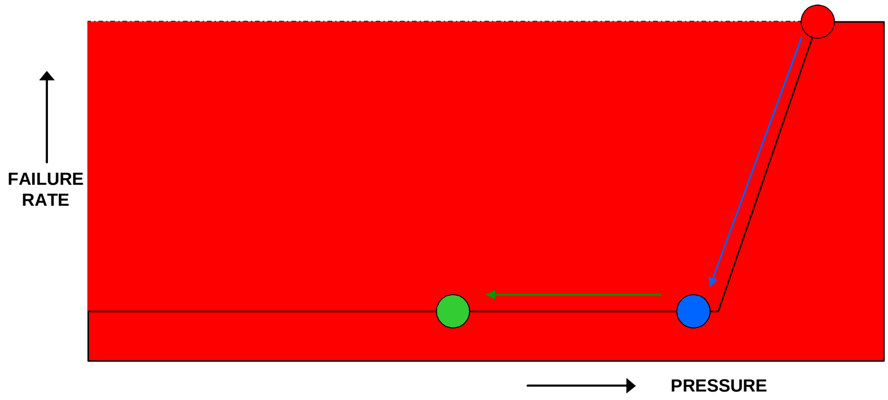

Figure 5: % reductions in burst frequency influenced by initial burst frequency.

Predicting changes in Economic Unreported Real Losses

Calculation of the Economic Unreported Real Losses (EURL) and other economic intervention parameters is easily done using a set of equations (Lambert and Lalonde, 2005) based on Cost of Intervention CI, Variable Cost of Water CV, and Rate of Rise of Unreported Leakage RR:

- Economic Intervention Frequency EIF = $\sqrt{}$(0.789 x CI/(CV x RR))
- Economic % of system to be surveyed annually EP (%) = 100 x 12/EIF
- Annual Budget for Intervention (excluding repair costs) ABI = EP% x CI
- Economic Unreported Real Losses EURL (volume/year) = ABI/CV

Predicting changes in consumption

For a full financial analysis of pressure management options, Utilities may wish to take into account the effect of pressure management on income from metered consumption. The most physically meaningful and 'Best Practice' form of equation for representing relationships between average pressure and certain components of consumption is the FAVAD (Fixed and Variable Area Discharges) equation:

$$C \text{ varies with } P^{N3} \quad \text{and} \quad C_1/C = (P_1/P_0)^{N3}$$

For external consumption (garden watering etc), an N3 of 0.5 is usually appropriate. For internal residential consumption, an N3 of around 0.1 can be used, unless this is supplied through a customer's private storage tank, in which case N3 would be zero.

SRELL Calculations using BABE component analysis and FAVAD concepts

To demonstrate the effect of introducing pressure management options to SRELL calculations, the example in Lambert and Lalonde (of SRELL for an Australian System at an initial average pressure of 65 metres) has been taken as the starting point (Table 1).

Table 1: Summary of SRELL components for an Australian System at initial pressure of 65 metres

System	Anytown		Current average pressure =			65	metres
Assumed FAVAD N1 for Reported Bursts =		1.0					
Assumed FAVAD N1 for Background Leakage =		1.5	Assumed Infrastructure Condition Factor ICF =				1.1
Infrastructure Component	Length or number	Real Losses from Reported bursts	Background leakage		Economic Unreported Real Losses	Short -Run Economic Leakage Level SRELL	
			Unavoidable	Additional			
		Ml/year	Ml/year	Ml/year	Ml/year	Ml/year	lit/conn/day
Mains (km)	603	92	157	16	200	883	151
Services, main to property line	16000	133	260	26			
Services, prop. line to meter (km)	0	0	0	0			
Totals		225	416	42			

Other data for this system are as follows:

- 82 reported mains bursts/year, costing $3500 each to repair
- 533 service pipe bursts per year (333 reported, 200 unreported) at $500 per repair
- Rate of Rise RR = 0.020 m^3/conn/day/year or 320 m^3/day/year
- Cost of an Intervention CI = $5.0/service conn. ($80,000)
- Variable Cost of Water CV = $0.12/$m^3$.

Calculations of Economic Intervention parameters for regular survey are as follows:
EIF (months) = $\sqrt{(0.789 \times CI/ (CV \times RR))} = \sqrt{(0.789 \times 80000/(0.12 \times 320))}$ = **40 months**
Economic % of system to be surveyed annually EP (%) = 100 x 12/EIF = **30 %**
Annual Budget for Intervention (excluding repair costs) ABI ($) = EP% x CI = **$24,000**
Economic Unreported Real Losses EURL = ABI/CV = 200,000 m^3/year = **200 Ml/year**

Using the prediction methods now available, consider the effect of reducing the average pressure by around 20%, to 52 metres, through a combination of sectorisation and pressure reducing valves. The **background leakage** at the new average pressure (52 metres) can be calculated using the FAVAD equation with an exponent of 1.5

$$L_1/L_0 = (P_1/P_0)^{N1} \quad \text{or} \quad L_1 = L_0 \times (P_1/P_0)^{1.5} = L_0 \times (52/65)^{1.5} = 0.715 \times L_0$$

and the figures of 157, 16, 260, 26, 416 and 42 in Table 1 become, respectively: 112, 11, 186, 19, 297 and 30; total, background leakage is predicted to decrease by **131 Ml/year**.

As for **Real Losses from Reported Bursts**, assuming (for simplicity in this example) an N1 of 1.0, the leak flow rates will fall to $(52/65)^{1.0}$ or 0.8 times their original value, and the numbers may also reduce. Initial mains burst frequency is 82 from 603 km, or 13.6/100 km/year; this is almost equal to the UARL mains burst frequency of 13 per 100 km/year, so no significant reduction in mains burst frequency can be expected. So real losses from reported mains bursts are predicted to reduce only in terms of flow rates, from 92 Ml/year to 92 x 0.8 = 74 Ml/year, a reduction of **18 Ml/year**.

In contrast, service pipe burst frequency is 533 from 16,000 service connections, or 33 per 1000 service connections/year; this is **11 times** the UARL service pipe burst frequency. If reduction in average pressure is 20%, % reduction in maximum pressure will be less – say 16% - and the 'Upper' line in Figure 4 indicates an expected 45% reduction in reported service connection bursts, from 333 per year to 183 per year, or 55% of their former number. So real losses from reported service connection bursts are predicted to reduce from 145 Ml/year to 145 x 0.8 (for flow rates) x 0.55 (for bursts) = **64 Ml/year**, and annual repair costs for reported service pipe bursts by (333–183) x $500 **= $75,000/year**

As for **Unreported Real Losses**, these included repairs to 200 service pipes per year. Using the same approach as for Real Losses from reported bursts (a 20% reduction in flow rates and a 45% reduction in numbers of service pipe bursts), the Rate of Rise may be expected to fall from 320 m^3/day/year to 320 x 0.8 x 0.55 = 141 m^3/day/year, giving the following revised parameters for economic intervention:

EIF (months) = $\sqrt{(0.789 \times CI/ (CV \times RR))} = \sqrt{(0.789 \times 80000/(0.12 \times 141))}$ = **60 months**
Economic % of system to be surveyed annually EP (%) = 100 x 12/EIF = **20 %**
Annual Budget for Intervention (excluding repair costs) ABI ($) = EP% x CI = **$16,000**
Economic Unreported Real Losses EURL = ABI/CV = 133,333 m^3/year = **133 Ml/year**

The estimated reduction is **$8,000** and **67 Ml/year** in Economic Intervention parameters, and a saving of 90 x $500 = **$45,000/year** in repair costs of unreported service pipe leaks.

Table 2 summarises the predicted effects on SRELL of reducing the average system pressure by 20%; a 36% reduction in SRELL from 881 Ml/year, 151 litres/service connection/day, to 599 Ml/year, 103 litres/connection/day. The predicted saving in production and distribution costs is (881-599) Ml/year x $0.12/m^3 = $34 k per year. Annual cost of service connection repairs is predicted to fall by $120k, and annual cost of economic intervention by $8k per year. So the cost of implementing the sectorisation and pressure management program can be offset by predicted savings of $162k per year.

Table 2: Summary of predicted SRELL components, Australian System, at new pressure of 65 metres

System	Anytown		New average pressure =			52	metres
Assumed FAVAD N1 for Reported Bursts =		1.0					
Assumed FAVAD N1 for Background Leakage =		1.5	Assumed Infrastructure Condition Factor ICF =				1.1
Infrastructure Component	Length or number	Real Losses from Reported Bursts	Background leakage		Economic Unreported Real Losses	Short -Run Economic Leakage Level SRELL	
			Unavoidable	Additional			
		Ml/year	Ml/year	Ml/year	Ml/year	Ml/year	lit/conn/day
Mains (km)	603	74	112	11	133	599	103
Services, main to property line	16000	64	186	19			
Services, prop. line to meter (km)	0	0	0	0			
Totals		138	298	30			

Table 1 data in the above example are based on an actual 'pre-pressure management' situation as it was in 2001, and the predictions in Table 2 can be compared with actual achievements 5 years later, in 2006. The system has grown rapidly to almost 20,000 service connections, while the average pressure has been reduced from 65 to 53 metres (rather than 52 as assumed in Table 2). Real Losses calculated from annual water balances have been reduced to 105 litres/service connection/day, as compared to the 103 litres/service conn/day predicted in Table 2 above. The mains burst frequency has not changed to any obvious extent, but service pipe burst frequencies have reduced by 73% (substantially more than the 45% predicted); however there has been some replacement of older service connections, and also substantial increases in new service connections.

Other Calculations using Pressure: Burst Relationship Predictions

The ability to be able to make reasonably meaningful predictions of changes in frequencies of leaks and bursts on mains and service connections separately, following pressure management, is likely to have significant impact upon the payback periods for pressure management schemes in individual zones. Previously, payback period was usually based only upon the predicted saving in the value of the volume of water saved through reduction in leak flow rates. However, bringing reductions in annual repair costs into the calculations is likely to significantly reduce payback periods in many situations, and make it economic to proceed with schemes that are at present being deferred.

LEAKSSuite softwares Checkcalcs, PressCalcs, PreMoCalcs and ELLCalcs have been updated to include the latest prediction methods for pressure:leak flows and pressure:burst frequency; and also for pressure:consumption relationships (as some Utilities will wish to include predictions of changes in income from metered customers in their calculations).

As an example, Table 3 below, from the Pressure Management Options software PreMoCalcs, predicts the various components of volume and cost savings for options of Fixed Outlet, Time Modulation and Flow Modulation, based on a 24-hour Zone test in a Brazilian system in which inflows are measured at the Inlet point, and pressures are measured at the Inlet, Average Zone Point and Critical Point.

Table 3: Various payback periods for Pressure management options in a Zone in Brazil (PreMoCalcs)

CALCULATION OF PAYBACK PERIODS			Fixed Outlet	Time Modulation	Flow Modulation
Predicted Changes	Leakage	Euro/yr	21572	45830	71397
	Repairs	Euro/yr	2790	4680	6240
	Income	Euro/yr	-2331	-2419	-5866
Implementation Cost		Euro	20000	30000	40000
Predicted Payback Periods, allowing for:	Leakage only	Months	11.1	7.9	6.7
	Leakage + Repairs	Months	9.9	7.1	6.2
	Leakage - Net Loss of Income	Months	12.5	8.3	7.3
	Leakage - Net Loss of Income + Repairs	Months	10.9	7.5	6.7

Summary and Conclusions

- Most methods of assessing Short Run Economic Leakage Levels, developed in the UK in the 1990's, do not allow for any influences of changes in pressure
- Those methods that do allow for changes in pressure take account of changes in leak flow rates, but not changes in frequencies of leaks and breaks, changes in repair costs, changes in frequency and cost of economic intervention, or changes in income from metered customers
- The paper shows how concepts developed collaboratively by Water Loss Task Force Members - the latest being a method to predict changes in new break frequency following pressure management - can be used to incorporate these additional concepts for more comprehensive and meaningful SRELL calculations
- The example shown in the paper demonstrates that attempts to calculate SRELL without taking pressure management options into account cannot be considered as being meaningful – the many influences of pressure on all components of leakage, and on costs of repairs and economic active leakage control, are simply too substantial to be ignored.
- Research continues into testing and refining the prediction methods, and the longer term economic effects of pressure management on mains and services replacement policies and costs.

Acknowledgements

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