Recent developments in Pressure Management

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Historical Perspective comments on this paper

This paper was presented by Marco Fantozzi at the IWA Specialised Conference 'Water Loss 2010',Sao Paolo, Brazil, June 2010

It describes 'state of the art' at the time in rapidly improving understanding of the wide range of benefits of pressure management, and how to model them in practical ways using logical principles, being assembled by members of the Pressure Management Group of the IWA Water Loss Task Force.

In this 2021 update, the section on 'Predicting Reductions in Consumption from pressure management' has been reviewed for greater clarity. A typo error in Equation 3 (identified thanks to Suvi Virta from Finland) had been corrected in 2015, and an extra Table 2a has now been added to compare the prediction method based on FAVAD concepts (with separate components for inside and outside consumption) and a simplification of that method.

The period from 2005 to 2010 produced irrefutable evidence that burst frequencies on mains and on services could be reduced significantly by reducing excess static pressures in zones with higher burst frequencies. The 'straw that breaks the camel's back' concept, for rapidly identifying and prioritizing zones in which reduction of excess pressure would lead to significant reductions in bursts, enabled pressure management schemes to be targeted for burst reduction and extension of infrastructure life, changing the economics of pressure management from the previously perceived single benefit on reducing flow rates of existing leaks.

Allan Lambert 15th May 2021

Recent Developments in Pressure Management

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Abstract
Pressure management of potable water distribution systems is now undergoing an international renaissance, as Utilities begin to realise the many benefits that it can bring. Thirty years ago, research in Japan and the United Kingdom identified that the average relationship between pressure and flow rates of leaks in distribution systems was approximately linear, rather than a square root relationship.

During the last five years, the effects of pressure management on burst frequencies of mains and service connections have become more widely recognised; initially through the published work of the Pressure Management Team of the IWA Water Loss Task Force, and more recently from Utilities reporting their own success stories.

Other benefits include deferment of pipe renewals and increase of infrastructure life, reduced costs of active leakage control, reductions of some components of consumption, and improved service to customers from fewer interruptions to supply. Pressure management is now being used not only for leakage control, but also for demand management, water conservation and asset management.

Utilities wishing to implement pressure management need to make predictions of these benefits, which vary from one situation to another. Reliable concepts and practical methods are needed to make a sound financial case for such investment, and for prioritising individual pressure management schemes. This paper attempts to summarise the 'state of the art' of these concepts and methods, and to promote further international co-operation for improving them where necessary.

Introduction
Thirty years ago, Japan and the United Kingdom identified that reduction of excess pressure could significantly reduce flow rates of existing leaks and bursts, and they began to practice and promote active pressure management. Some countries and Utilities followed this lead, but even ten years ago many others had not; perhaps because of concerns of possible loss of income from metered customers, or uncertainly about predicting benefits that might not justify the investment costs,.

However, during the last five years, the effect of pressure management on burst frequencies of mains and service connections has also become more widely known. Moving from intermittent supply to continuous supply at a lower pressure – the 24/7 policy approach in India – is one example. In systems with continuous supply, rapid reductions in bursts and repair costs are now changing the economics of pressure management and the perception that leaks and bursts can only be managed by repairs or pipe replacement.

Utilities that have recently implemented pressure management schemes are now realising that reduced leak flow rates and burst repair costs are not the only benefits. Pressure management is not only a tool for leakage control, but also for demand management, water conservation and asset management. Other benefits including:

- deferment of pipe renewals and increase of infrastructure life
- reduced costs of active leakage control
- reductions of some components of consumption
- improved service to customers through fewer interruptions

are summarised in Table 1.

PRESSURE MANAGEMENT: REDUCTION OF EXCESS AVERAGE AND MAXIMUM PRESSURES						
CONSERVATION BENEFITS		WATER UTILITY BENEFITS			CUSTOMER BENEFITS	
REDUCED FLOW RATES		REDUCED FREQUENCY OF BURSTS AND LEAKS				
REDUCED CONSUMPTION	REDUCED FLOW RATES OF LEAKS AND BURSTS	REDUCED REPAIR COSTS, MAINS & SERVICES	DEFERRED RENEWALS AND EXTENDED ASSET LIFE	REDUCED COST OF ACTIVE LEAKAGE CONTROL	FEWER CUSTOMER COMPLAINTS	FEWER PROBLEMS ON CUSTOMER PLUMBING & APPLIANCES

Table 1: overview of range of benefits of pressure management

Utilities need to be able make reasonably reliable predictions of all of these benefits – which vary from case to case - so as to make a sound financial case for investment in pressure management, and to be able to prioritise individual pressure management schemes. This paper attempts to summarise the present 'state of the art' of concepts and methods used for:

- predictions of benefits from proposed pressure management schemes
- data analysis from completed schemes to assess actual benefits and improve existing prediction methods where necessary

How does pressure reduction influence leakage and Real Losses volume?

The Background and Bursts Estimates (BABE) concept of Component Analysis of Real Losses splits leaks into 3 categories for purposes of analysis:

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

Figure 1 illustrates these three components within a Zone of a distribution system as a simplified time series, before and after the introduction of pressure management to reduce excess average pressures and pressure transients.

Background leakage runs continuously. Unreported leaks gradually accumulate, 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; the process then repeats itself. Reported leaks and bursts are superimposed on the other two components. The annual average of all 3 components, representing the annual real losses volume, is shown as a dashed line.

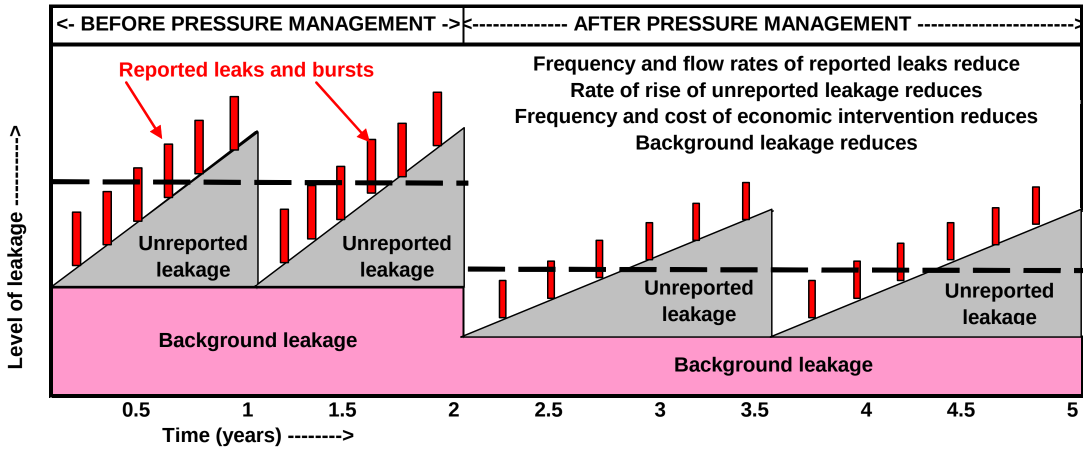

Figure 1: Influence of pressure management on BABE components of Real Losses
Source: Fantozzi & Lambert (2007)

Predicting Reductions in Leak Flow Rates

The Pressure Management Team of the IWA Water Loss Task Force (WLTF) recommends use of the FAVAD (Fixed and Variable Area Discharges) Concept, proposed by May (1994) for these types of predictions.

Japanese research (Ogura, 1979) showed that leak flow rate L in individual sectors of a distribution system varies with pressure P^{N1}, where the exponent N1 averaged 1.15 but could vary from 0.5 to more than 2.0. The FAVAD concept attributes this variability to some types of leaks having fixed areas (N1 = 0.5) and others having areas that vary with pressure, resulting in N1 values of 1.5 or more.

The basic FAVAD equation for analysing and predicting changes in leak flow rate (L_0 to L_1) as average pressure changes from P_0 to P_1 is

$$L_1/L_0 = (P_1/P_0)^{N1} \qquad \ldots\ldots\ldots\ldots..(1)$$

It is the ***ratio of average pressures*** and ***assumed N1 exponent*** that influence the reliability of the predictions. Tests in different countries have shown that:

- N1 is usually close to 1.5 for background leaks, and splits in flexible pipes that increase in area as pressure increases
- N1 is close to 0.5 for detectable leaks from cracks and holes in rigid pipes
- N1 is often close to 1.0 for large systems with mixed pipe materials, i.e. a 10% change in average pressure produces a 10% change in leak flow rates

N1 values can be assessed from tests at night when average pressure is reduced and changes in night leakage are measured; or using an empirical prediction equation (Thornton & Lambert, 2005) based on Infrastructure Leakage Index (ILI) and % of rigid pipes (p%) :

$$N1 = 1.5 - (1 - 0.65 / ILI) \times p/100 \qquad \ldots\ldots\ldots\ldots.(2)$$

Further explanation of night tests and the use of equation (2) will be provided in the WLTF Pressure Management Team Guidelines scheduled for publication in 2011.

The simplest possible basis for roughly estimating N1 is as follows:

- if you know nothing about the pipe materials or type of leaks in your system or zone, assume N1 = 1.0 (linear) with confidence limits of +/- 0.5
- for systems with rigid pipes, N1 falls from 1 to 0.5 as leakage increases; but if background leakage is very high N1 values could still be close to 1.0
- for systems with flexible pipes with many splits, assume N1 is close to 1.5

Predicting Reductions in Frequency of New Bursts

During the 1990's, a few Utilities and individuals in a few countries started to collect data on the number of leaks and bursts before and after pressure management in individual Zones. Many of the results were impressive – in Torino, a 6 metre (9%) reduction in maximum piezometric pressure, in a system with pumping at night, resulted in a 46% reduction in leaks, that has been maintained for at least 6 years

Attempts (mainly in the UK) to derive correlations between average pressure and mains burst frequency for large sets of grouped data were generally inconclusive. However, in 2004, following another impressive example in a Zone in Gold Coast, Australia (a 75% reduction in bursts on both mains and services), the IWA WLTF members provided 'before' and 'after' data from 50 individual pressure management schemes in Australia, Brazil, Italy and the UK; many of these data sets showed substantial reductions in frequency of new leaks. Pearson et al (2005) found that a basic FAVAD equation (burst numbers vary with P^{N2}) was not appropriate to analyse this data, but the concept of failure envelopes and duty points in this paper was fundamental in developing a conceptual approach to pressure:bursts relationships.

A data set of 112 example from 10 countries was then collected by the WLTF Pressure Management Team (Thornton & Lambert, 2006), for mains and/or service connections. The summarised data were simply presented as graphs of % reduction in pressure against % reduction in new burst frequency. Although the separate graphs for mains and service connections were similar (Figure 2), this does not mean that in an individual Zone, both respond by the same % to pressure management.

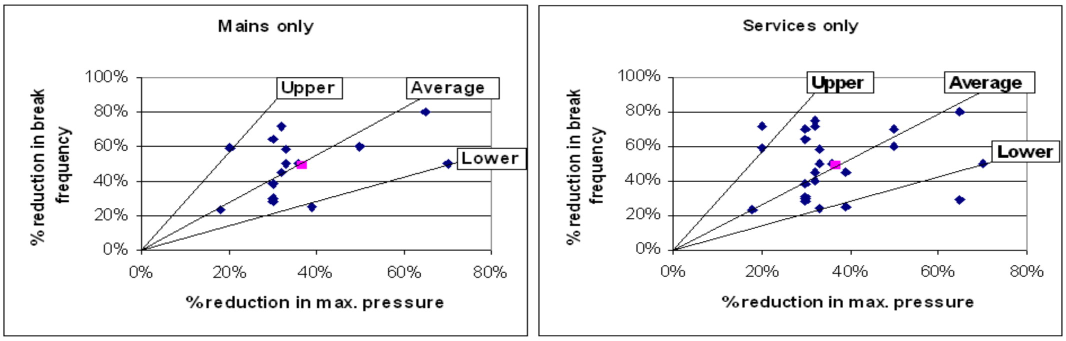

Figure 2: Influence of pressure management on break frequency of mains and services

In both graphs, the overall average % reduction in burst frequency was 1.4 times the % reduction in maximum pressure; but the multiplier could occasionally be higher (up to 2.8 times, 'Upper' line) or lower (0.7 times or less). On rare occasions, the break frequency increased after pressure management. Further collection of this type of data has produced similar scatter plots. However, ongoing research shows that some of the variability in the data is probably caused by quite large changes in the overall break frequencies within a Utility from year to year due to natural variations in seasonal weather conditions.

For post-implementation analysis of break frequency in individual Zones after pressure management, and for research to improve prediction methods, it is necessary to adjust the 'before' and 'after' break data using break numbers from a larger 'control' group in which the pressure was not modified. The objective is to compare the recorded break frequency after pressure management, with what it would have been if pressure management had not been applied in the Zone.

Adapting ideas from Pearson et al (2005), the WLTF Pressure Management Team (Thornton & Lambert, 2007) produced a conceptual presentation showing in simple terms how:

- combinations of factors, acting together with pressure, could result in temporary variations in burst frequency
- small reductions in pressure transients or average pressure could result in large reductions in break frequency in some cases, but no change in burst frequencies in other cases.

This is known as the 'straw that breaks the camel's back' concept (Figure 3).

Research to link the Figure 3 concept to the Figure 2 data (adjusted using control Zone data) continues. Initial research suggests that the sloping lines in Figure 3 are likely to curve upwards, rather than being straight; the more the pressure increases, the greater the % increase in break frequency.

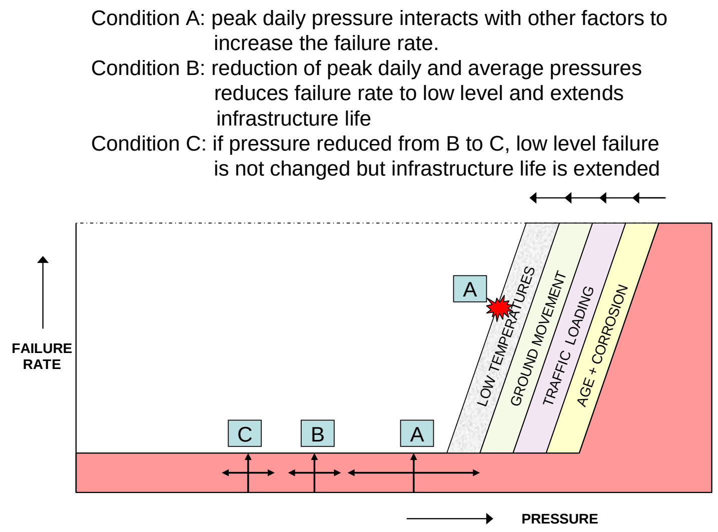

Figure 3: Influence of pressure management on break frequency of mains and services

Present guidance for Utilities considering pressure management for burst reduction is to systematically identify zones with high repair frequencies on mains and service connections, as that is where the greatest reductions are likely to be achieved.

- ensure that mains repairs and service connection repairs are analysed separately
- assume that the 'low level' of failure rate in Figure 3 is consistent with frequencies used in calculations of the Infrastructure Leakage Index ILI, namely:
  - mains repairs: 13 per 100 km of mains/year
  - services, main to property line: 3 per 1000 service connections/year (exclude small leaks at meters and stop taps from this calculation)
  - underground services after the property line: 13 per 100 km per year
- check if pressure transients are present; if so, take action to reduce them
- check for continuous excessive pressures at the highest properties, and identify the % reduction in maximum pressure that could be made
- for Zones where current repair frequencies are several times higher that the ILI reference frequencies shown above, assume the % reduction in burst frequency will (on average) be 1.0 times the % reduction in maximum pressure

Predicting Reductions in Rate of Rise of Unreported Leakage

For an economic active leakage control policy of regular survey, if the Rate of Rise of unreported leakage is RR (see Figure 1):

- the economic intervention frequency (EIF) varies with $(1/RR)^{0.5}$
- the annual cost (AC) of economic intervention varies with $RR^{0.5}$

After pressure management, the Rate of Rise should decrease if there are fewer leaks running at lower flow rates; so EIF should be increased (longer periods between interventions) and annual cost of interventions should be reduced.

If the % reduction in unreported leaks is the same as the % reduction in maximum pressure, and the % reduction in flow rates of unreported leaks is the same as the % reduction in average pressure, then a 10% reduction in pressure should theoretically result in a 20% reduction in Rate of Rise, EIFs that are 10% longer, and a 10% reduction in annual cost of economic active leakage control interventions.

Any Utility with reliable data on the effect of pressure management on rate of rise of unreported leakage is invited to provide the authors with data to confirm (or otherwise) the above theoretical calculation.

However it is most important to emphasise that reduced numbers of leaks and bursts after pressure management does not mean that active leakage control interventions are no longer required. Several utilities have already made this basic mistake.

Deferred Renewals and Extended Asset Life

Where Utilities have policies to replace their mains and services based on defined criteria such as ‘X bursts in Y km in Z years’, the short-term financial benefits of pressure management may be calculated as the savings in costs from not replacing mains and services that would otherwise have been replaced.

Another possible approach is to try to assess, in Figure 3, how quickly the sloping interface representing higher burst frequencies is moving, and how many years of extra infrastructure life are being gained by reduction of excess pressures.

Another approach is to use data from asset management studies that relate average working life of pipes to pressure. Table 1 contains unpublished data which suggests that the working life of small to medium diameter AC pipe increases as maximum pressure reduces. Similar information presumably exists for other pipe materials

Table 1: Influence of maximum pressure on average life of AC pipes.

AC Pipe DN/Class	Maximum Pressure (metres)			
	40	50	60	70
100/CD	55	54	52	51
150/C	60	58	55	53
200/C	72	69	66	63
250/C	82	78	75	71
300/C	95	91	86	82

Source: Black J, Opus Consultants, New Zealand, personal communication

Whatever the current uncertainties about how to assess the financial benefits of deferred renewals and extension of infrastructure life, it is already evident from initial approximate calculations that these benefits are likely to be large in comparison to the benefits for reduction of leakage and reduction of repair costs.

Predicting Reductions in Consumption

Reductions in consumption by customers (C) can also be predicted using the FAVAD concept, assuming C varies with average pressure P^{N3}. However, it is necessary to split the consumption into ‘in-house’ and ‘outside’ components, as the exponent N3i for ‘inside’ consumption is much smaller than the N3o for ‘outside’ consumption.

For direct pressure systems without customer storage tanks, some components of ‘in-house’ residential consumption (for example, toilet flushing, some types of toilet cistern leaks, use of showers) can be influenced by system pressure. Limited data from Australia suggests the typical overall exponent N3i is around 0.04. Where there are roof storage tanks, N3i is zero if all ‘in-house’ consumption comes from the tank.

Tests in Australia of ‘outside’ residential consumption subject to mains pressure have shown that N3o = 0.5 for sprinklers and hosepipes, and N3o = 0.75 for flexible seepage hoses with multiple small holes. Allowing for the presence of swimming pools (N3o = 0), and for adjustments in sprinklers when pressure is changed, a reasonable practical estimate for overall N3o is likely to be close to 0.45.

For any pair of assumed values of N3i and N3o, the % reduction in consumption can be predicted by estimating the % of outside consumption (OC%), and then using equation (3); a spreadsheet look-up table can then be created as shown in Table 2

$$\% \text{ reduction in consumption} = 1 – OC\% \times (P_1/P_0)^{N3o} – (1 - OC\%) \times (P_1/P_0)^{N3i} \quad ……(3)$$

Table 2: Predicting reduction in consumption using FAVAD N3i and N3o approach

	Prediction of % Reductions in Consumption assuming							**N3i =**	**0.040**	**N3o =**	**0.450**
	Percentage of Consumption outside property OC%										
P_1/P_0	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
1.00	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
0.90	**0.4%**	**0.8%**	**1.3%**	**1.7%**	**2.1%**	**2.5%**	**2.9%**	**3.4%**	**3.8%**	**4.2%**	**4.6%**
0.80	**0.9%**	**1.8%**	**2.6%**	**3.5%**	**4.4%**	**5.2%**	**6.1%**	**7.0%**	**7.8%**	**8.7%**	**9.6%**
0.70	**1.4%**	**2.8%**	**4.1%**	**5.4%**	**6.8%**	**8.1%**	**9.5%**	**10.8%**	**12.1%**	**13.5%**	**14.8%**
0.60	**2.0%**	**3.9%**	**5.7%**	**7.6%**	**9.4%**	**11.3%**	**13.1%**	**15.0%**	**16.8%**	**18.7%**	**20.5%**
0.50	**2.7%**	**5.1%**	**7.5%**	**10.0%**	**12.4%**	**14.8%**	**17.2%**	**19.6%**	**22.0%**	**24.4%**	**26.8%**
0.40	**3.6%**	**6.6%**	**9.6%**	**12.7%**	**15.7%**	**18.7%**	**21.7%**	**24.7%**	**27.8%**	**30.8%**	**33.8%**
0.30	**4.7%**	**8.4%**	**12.1%**	**15.8%**	**19.6%**	**23.3%**	**27.0%**	**30.7%**	**34.4%**	**38.1%**	**41.8%**

The simplest possible approximate basis for estimating the weighted N3 exponent is to use equation (4) below

$$\text{Weighted } N3w = N3i + (N3o – N3i) \times OC\% \quad ....(4)$$

Equation (4) is shown as a graph in Figure 1. For any value of OC% (e.g. OC% = 25%), read the corresponding weighted value for N3 (0.14) from the left side Y axis.

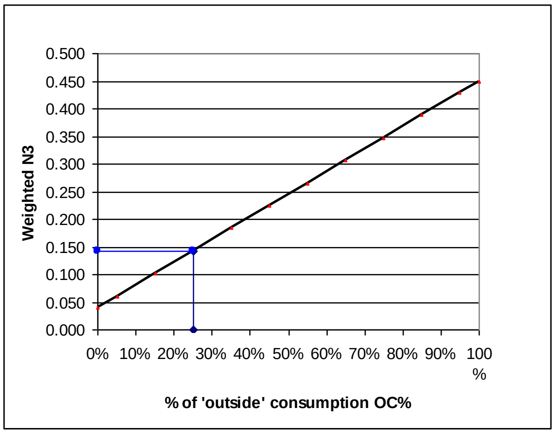

Figure 4: simple graphical predicted method for weighted N3 exponent for consumption

Additional Material added in May 2021. Table 2a below uses equation (4) to calculate an approximate N3w by simply averaging the N3i and N3o exponents. Comparison with the more mathematically accurate equation 3 used for Table 2 shows that the differences are not large for moderate reductions in pressure, as both N3i and N3o exponents are quite low (less than 0.5).

Table 2a

Prediction of % Reductions in Consumption using Weighted N3w = N3i + (N3o-N3i) x OC% = 0.040 + 0.41 x OC%												
Percentage of Consumption Outside Property = OC%												
OC%		0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Weighted N3w		0.040	0.081	0.122	0.163	0.204	0.245	0.286	0.327	0.368	0.409	0.450
P_1/P_0 =	100%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
P_1/P_0 =	90%	0.4%	0.8%	1.3%	1.7%	2.1%	2.5%	3.0%	3.4%	3.8%	4.2%	4.6%
P_1/P_0 =	80%	0.9%	1.8%	2.7%	3.6%	4.5%	5.3%	6.2%	7.0%	7.9%	8.7%	9.6%
P_1/P_0 =	70%	1.4%	2.8%	4.3%	5.6%	7.0%	8.4%	9.7%	11.0%	12.3%	13.6%	14.8%
P_1/P_0 =	60%	2.0%	4.1%	6.0%	8.0%	9.9%	11.8%	13.6%	15.4%	17.1%	18.9%	20.5%
P_1/P_0 =	50%	2.7%	5.5%	8.1%	10.7%	13.2%	15.6%	18.0%	20.3%	22.5%	24.7%	26.8%
P_1/P_0 =	40%	3.6%	7.2%	10.6%	13.9%	17.0%	20.1%	23.1%	25.9%	28.6%	31.3%	33.8%
P_1/P_0 =	30%	4.7%	9.3%	13.7%	17.8%	21.8%	25.5%	29.1%	32.5%	35.8%	38.9%	41.8%

Improved service to customers

Bristol Water (UK) has monitored changes in customer complaints for supply interruptions and low pressure following pressure management; some recent Case Studies show a significant reduction in complaints following pressure management.

Australian plumbing standards now require maximum 50 metres pressure to avoid reducing the life of customers' appliances (taps and fittings) and excessive noise.

Conclusions

- the general influence of pressure on leak flow rates has been known for 30 years
- relationships between average pressure and leak flow rates based on the FAVAD N1 concept are now quite reliably predictable
- methods of predicting reductions in metered consumption, based on % split between in-house and outside use, based on FAVAD N3, are also now available
- further additional benefits for water conservation, asset management and customer service are now beginning to be appreciated; consequently, pressure management is undergoing a renaissance internationally
- the effectiveness of pressure management in reducing burst frequencies on mains and services is now also known to an increasing international audience
- Utilities need practical concepts and methods to predict benefits, justify pressure management investments, and identify and prioritise cost-effective schemes; the paper describes the 'state of the art' for analysis and prediction methods
- conceptual understanding of pressure:bursts relationships has improved; current prediction methods are based on knowing burst frequencies for mains and services (separately) and % reduction in maximum pressure; research continues.
- a model for predicting changes in economic intervention frequency and active leakage control costs exists, and needs checking with reliable data
- methods of assessing the value of deferred renewals and extension of asset life are in early stages of research; these are likely to be the largest financial benefits
- significant reductions in customer complaints have been observed but more examples are needed to develop a basic prediction method

Requests for Data, Information and Comments

Any reader of this paper with data, information or comments that could assist in testing or improving any of the prediction methods outlined in this paper, please contact the authors.

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