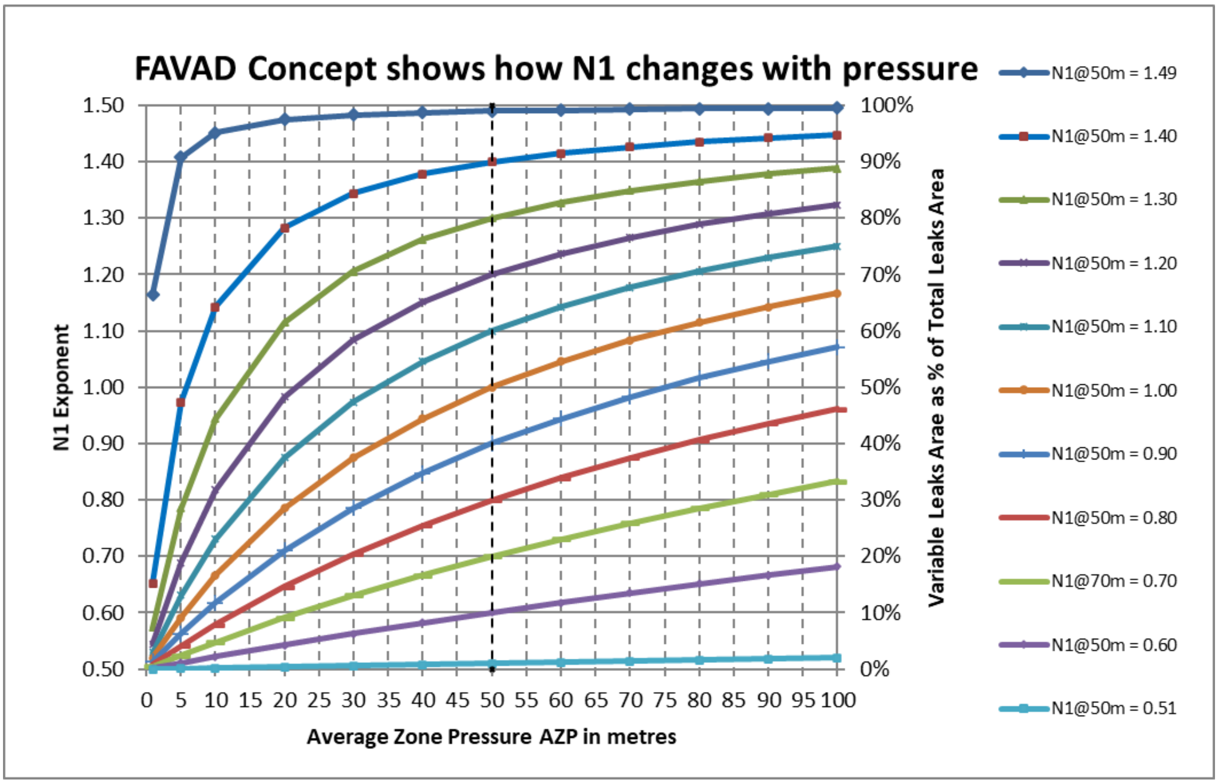
Practical approaches to modeling leakage and pressure management in distribution systems – progress since 2005

Historical Perspective comments on this paper (May 2021)

Improvements in understanding of modeling pressure:leakage and pressure:bursts relationships between 2006 and 2013 are summarized in this paper. Key points are as follows:

In Section 1: 'Reduced and more efficient use of energy' was added to the previous version of Table 1.

Section 2: The empirical relationship between N1, ICF and ILI shown in Equations 1 and 2, and in Figures 1a and 1b, would later be superseded as it did not account for the most important influence, average zone pressure. In 2017 Lambert, Fantozzi and Shepherd used a full FAVAD analysis, interpreted using the Leakage Number vs N1 relationship mentioned in Section 2.1 and equation 5 of this paper, to demonstrate how N1 varies with Average Zone Pressure, and that there are in fact a family of N1 vs AZP curves.



This chart shows that if the range of AZP in a Zone is only a few metres, the assumption of a fixed N1 value at mid-range pressures is not unreasonable. However, if the range of AZPs is large, the fact that N1 reduces with pressure should be recognized. If you assume, for example, that N1 is 1.1 at 50 metres pressure, the dark green curve shows that N1 would reduce to 0.97 at 30 metres AZP and 0.72 at 10 metres AZP.

So it is ALWAYS good practice when quoting an N1 test result, or an assumed N1 value for pressure:leak flow rate calculations, to associate the N1 with an AZP pressure, e.g, N1 = 1.05 at 40 metres AZP.

Allan Lambert 14th May 2021

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Abstract

In 2005 a Plenary Invited Lecture on this topic, at the 2005 Exeter CCWI by Lambert (2005), outlined the initial progress that had been achieved by the IWA Water Loss Task Force (now the Water Loss Specialist Group), by its Pressure Management Team formed in 2003. Since then, the practical approaches developed by the PM Team have been used in many countries to achieve demonstrable sustained reductions in Real (Physical) losses.

Ongoing research reported by Thornton and Lambert (2006, 2011) and Lambert et al (2012) has helped to stimulate an international renaissance in pressure management, not only for the traditional purpose of reducing leak flow rates, but also for reducing burst frequencies on mains and service connections, extending residual asset life, energy conservation, management of consumption and improved Utility: customer relationships. The paper reviews the development, testing and 'state of the art' of some of these practical analyses and prediction concepts, and includes example from a number of international pressure management Case Studies. Topics covered in this paper are limited (by space) to improvements in prediction methods for changes in:

- leak flow rates (practical and theoretical aspects)
- frequency and numbers of leaks and bursts, with separate calculations for mains and services

Examples of practical techniques for validating predicted reductions in bursts following pressure management are shown, and ongoing practical research for predicting the benefits of extended asset life, and more efficient use of energy with pressure management, are briefly discussed.

Keywords: Pressure management; leakage management; bursts management; energy management; residual infrastructure life;

1. Introduction

The proven benefits of pressure management in distribution systems have now moved beyond basic control of leak flow rates, as initially researched in the UK and Japan thirty years ago. Pressure management is now seen as having an increasingly wide range of benefits; Table 1 is the latest version of a format first used in WSAA (2011) and recently with an 'energy' component added (Fantozzi et al, 2013).

Table 1: Multiple benefits of pressure management

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 EXCESS OR UNWANTED CONSUMPTION	REDUCED FLOW RATES OF LEAKS AND BURSTS	REDUCED AND MORE EFFICIENT USE OF ENERGY	REDUCED REPAIR AND REINSTATEMENT COSTS, MAINS & SERVICES	REDUCED LIABILITY COSTS AND REDUCED BAD PUBLICITY	DEFERRED RENEWALS AND EXTENDED ASSET LIFE	REDUCED COST OF ACTIVE LEAKAGE CONTROL	FEWER CUSTOMER COMPLAINTS	FEWER PROBLEMS ON CUSTOMER PLUMBING & APPLIANCES

The CCWI Plenary Invited Lecture by Lambert (2005) ‘Practical Approaches to Modeling Leakage and Pressure Management in Distribution Systems’ outlined:

- the IWA Best Practice Water Balance, Terminology and Performance Indicators introduced in 1999/2000
- component analysis of leakage, based on bursts and background estimates (BABE) concepts, and
- Fixed and Variable Area Discharges (FAVAD) concepts, to model different pressure:leak flow rate relationships from different typed of leaks: leak flow rate L varies with pressure P to the power N1
- Initial results of large reductions in burst frequency from 50 pressure management schemes, analysed using the initial assumption that burst frequency varies with maximum pressure (Pmax) to the power N2.
- Co-operation opportunities between leakage modeling, Network Analysis, Energy Management modeling.

The following Sections provide a brief overview of developments, since 2005, in the IWA practical predictions methods of beneficial influences of pressure management on leak flow rates and burst frequency..

2. Pressure and Leak Flow Rates

2.1 *IWA Practical Prediction Methods*

The IWA practical prediction methods developed by 2005 were that N1 exponents for distribution systems were mostly in the range 0.5 (fixed area leaks) to 1.5 (variable area leaks). N1 exponents could be assessed from field tests (which have many pitfalls for the unwary), or predicted reasonably well if relative proportions of fixed and variable leaks could be assessed, together with the overall level of leakage. Thornton and Lambert (2005) recommended an empirical predictive equation for N1 in individual Zones and systems with low background (undetectable) leaks as:

$$N1 = 1.5 - (1 - 0.65/ILI) \times p\% \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where ILI is the Infrastructure Leakage Index, and p is the % of detectable leaks on rigid pipes. As ILI increases above 1.0 (the value for Unavoidable Annual Real Losses, based on an IWA formula incorporating mains length, number of service connections, meter location and average pressure), and the predicted N1 will increase. In 2008, Lambert modified Equation (1) to cater for systems with poorer infrastructure and higher background leakage. The revised predictive equation, published in this paper for the first time, is:

$$N1 = 1.5 - (1 - 0.667 \times ICF/ILI) \times p\% \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where ICF is the Infrastructure Condition Factor, the ratio of actual to unavoidable background leakage. As ICF increases above 1.0 (the value for Unavoidable Background Leakage), the predicted N1 will increase. Equations (1) and (2) are shown as graphs in Figures 1a and 1b.

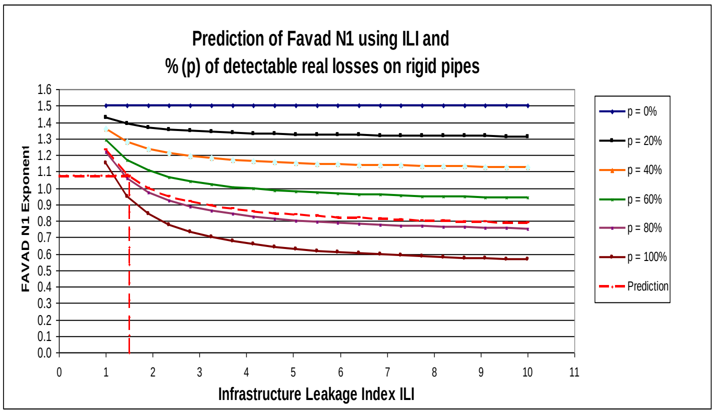


Figure 1a: Prediction of N1 using ILI and p%, for infrastructure in good condition, with low background leakage (ICF close to 1.0)

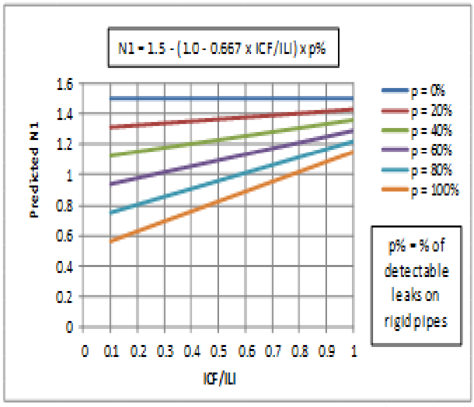


Figure 1b: Prediction of N1 from ICF/ILI and p% for infrastructure with higher background leakage

Notte: Equations (1) and (2), and Figures 1.a and 1b, were superseded after 2017 for a methodology which includes the influence of average pressure, see ‘Historical Perspective’ page which precedes this paper.

2.2 *Theoretical Prediction Methods*

The principal theoretical advance in understanding of pressure - leak flow rate relationships since 2005 has been the development by the University of Johannesburg and the Cape Town University group of the concept of Leakage Numbers to explain variations in the FAVAD N1 exponent for different types of cracks in pipe materials which experience linear elastic (but not plastic) deformation (Van Zyl and Cassa, under review). If A_0 is the initial area of a leak, m is the pressure-area slope relationship, and h is the pressure head (metres) then

Area of crack $= A_0 + mh$ …………………….. .(3)

Leakage Number $L_N = mh/A_0$ …………..…….. (4)

and $N1 = (1.5 \times L_N + 0.5)/(L_N + 1)$ ………………….(5)

Equation 5 allows N1 to be predicted from the leakage number for any leak, and vice versa. It was found that N1 is equal to 1 when L_N is equal to 1, practically 0.5 when L_N is less than 0.01 and 1.5 when L_N is greater than 100. From Equation 4 it can be seen that a large leakage number (and thus high N1) may be obtained from a leak in a very flexible material (high m) or by a very small initial Ao, such as a crack that only opens under pressure. This means that laboratory tests of machined 'cracks' in pipes will produce lower leakage exponents than similar length, but narrower cracks found in real systems.

Using Finite Element Analysis to predict 'm' for longitudinal, spiral and circumferential cracks, with pressure head, Young's modulus, Poisson's ratio, longitudinal stress, wall thickness, internal diameter, length of crack and width of crack as parameters, Cassa and van Zyl (2013) developed predictive equations which showed that, for all three crack types, crack length had the dominant effect on the pressure:area slope 'm', followed by wall thickness, Young's modulus and internal diameter. Generally good correlations were obtained from using the predictions to retrospectively analyse published test data of individual laboratory tests on cracked pipes. (Van Zyl & Cassa, under review) where plastic deformation was not reported to occur.

Schwaller and van Zyl (2013) then investigated the collective influence of multiple cracks in small distribution zones (District Metered Areas). This paper tends to confirm the average N1 exponents observed and used for practical predictions in Zones (0.5 to 1.5, with an average close to 1), and concludes that the most important parameters influencing the N1 leakage exponent are the mean system pressure, condition of the system (expressed by the total initial area of leaks in the system) and the range of static pressures in the system. It was also found that it was important to use a reliable estimate of average pressure, and that even a small fraction of high Leakage Number leaks (leaks in flexible materials such as rubber seals, or leaks closing under zero pressure conditions) will result in a substantial increase in the background leakage N1, and is a likely cause of leakage exponents around 1.5 often found in field studies of background leakage. Efforts to apply the leakage number approach to systems with a large number of leaks, and to further reconcile the practical and theoretical prediction methods, continue.

3. Pressure and Burst Frequency

3.1 UK Studies 1994 to 2003

UK studies in DMAs by May (1994) and Welsh Water regions (Lambert and Morrison (1995)) had suggested that mains burst frequency might vary with P^{N2}, where P is the average system pressure and N2 is an exponent with a value of around 3.0. Studies of pressure:bursts data for grouped DMAs data in three UK Utilities some 8 years later (UKWIR 2003), concluded that 'long-term mains repair vs pressure results do not show a convincing relationship between pressure and mains repair frequency'. Figure 2 shows the Welsh Water and May data plotted to the same scale as the 2003 UKWIR data.

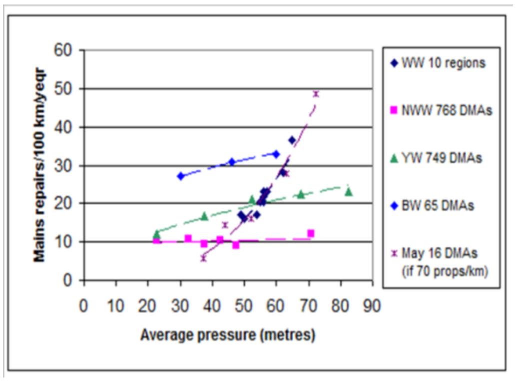


Figure 2: UK Pressure: Bursts relationships for Regions, Grouped DMAs and DMAs, 1995-2003

The UK water industry seemed to lose interest in further research into pressure:bursts relationships after 2003. However, the newly formed WLTF Pressure Management team had identified a number of international case studies of pressure management schemes where mains and service burst frequency had been substantially reduced following pressure management. Some of these case studies were shown at the CCWI in 2005, including remarkable results from Turin (Italy) and the Australian Gold Coast (Figure3).

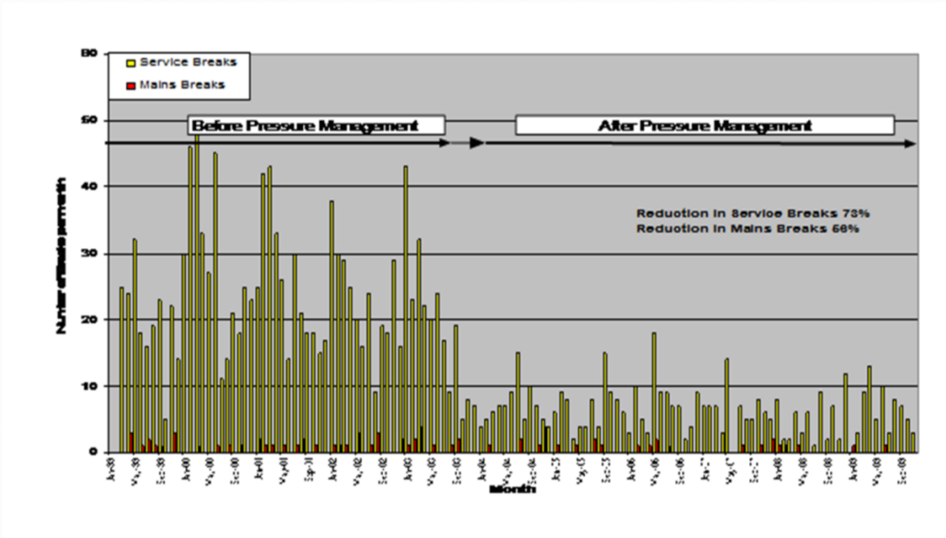


Figure 3: Gold Coast, Burleigh Heads Pilot Scheme: Gravity System, 3300 services. Inlet pressure reduced by 30% (72 to 50 metres) in 2003. Break reductions: 68% on mains, 73% on services, sustained for 10 years to date

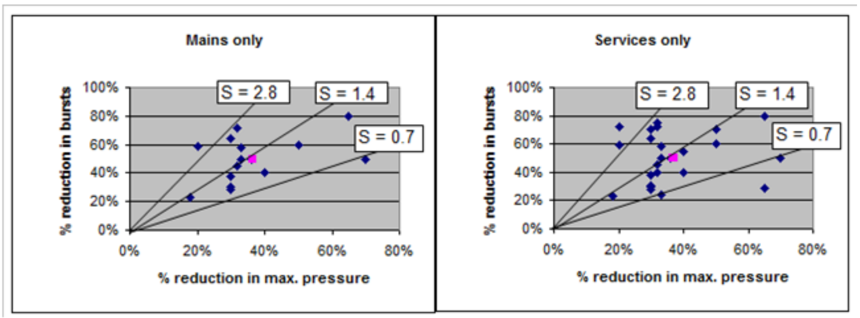
3.2 IWA Water Loss Task Force Studies 2004 to 2010

WLTF members Pearson et al (2005) presented 50 sets of data from Case Studies in Australia, Brazil, Italy, and mainly the UK, which showed that pressure management had produced significant reductions in the mains and service repair frequencies of many DMAs. Their attempts to model the relationship using the equation

$$\text{Burst Frequency varies with Pressure}^{N2}$$

produced a wide range of N2 exponents (from 0.2 to 12), but the discussion of the concept of failure envelopes and duty points in their paper provided the inspiration for the next practical conceptual breakthrough.

Thornton and Lambert (2006, 2007) concentrated on demonstrating beyond reasonable doubt that reduction of excess pressure could have a substantial influence on reducing bursts, by publishing a summary of data from 112 case studies in 11 countries, in which (on average) the % reduction in burst frequency was 1.4 times the % reduction in average pressure for mains, and also for service (Figures 4a and 4b), with a maximum close to 3.



Figures 4a and 4b: % reduction in burst frequency vs % reduction in max. pressure, for mains, and for services

A simplified concept (the straw that breaks the camel's back) was used to provide an approximate visual explanation of the variability of results between different Zones, and between reductions in mains and services repairs frequency in the same zone. This was coupled with the calculation of a simple Burst Frequency Index BFI. In Figure 5, suppose that a zone within a distribution system has a relatively low failure rate until some particular pressure is exceeded, when failure rate increases rapidly for small increases in pressure. Over a period of years, and also seasonally, the interface can move to the left, both, due to other influences (age and corrosion, ground movement, low temperatures, traffic movement etc).

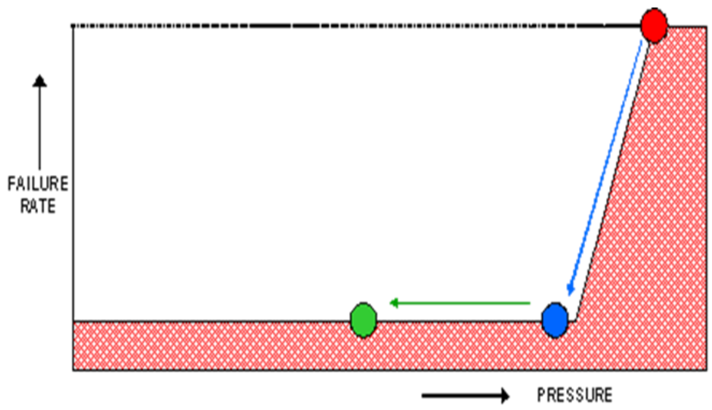


Figure 5: Qualitative categorisation of burst reduction opportunities, using Burst Frequency Index

Suppose that the low failure rate (horizontal part of the graph) can be represented by the 'Unavoidable' burst frequency used in the IWA formula for Unavoidable Annual Real Losses, which (at 50 metres pressure) is 13 per 100 km/year for mains, 3 per 1000 conns/year for service connections from the main to the property line, and 13 per 100 km/year for private pipes after the property line. The Burst Frequency Index (BFI) is then the ratio of the actual burst frequency in the Zone to the UARL burst frequency.

If the BFI before pressure management is low, the initial failure rate is close to the 'low' failure rate, and the % reduction in bursts will be small or zero (blue circle to green circle); however, the residual infrastructure life will be extended. But if the BFI and initial failure rate are 'high' (red circle), a large % reduction in burst frequency may be achieved for quite a small reduction in maximum pressure (red circle to blue circle).

By calculating a Burst Frequency Index for mains, and a separate Burst Frequency Index for Utility-owned service connections, it is possible to quickly identify *qualitatively* if pressure management in any individual Zone would be likely to significantly reduce mains burst frequencies (or not) and service burst frequencies (or not). Then, by targeting Zones with high initial Burst Frequency Index, the average '1.4 multiplier' relationship between % reduction in burst frequency and % reduction in pressure can be used to *quantitatively* predict the average reductions in numbers of mains and service bursts. The financial benefits of these predicted reductions could then be included in the economic evaluation of pressure management payback periods, Net Present Value and Benefit:Cost calculations.

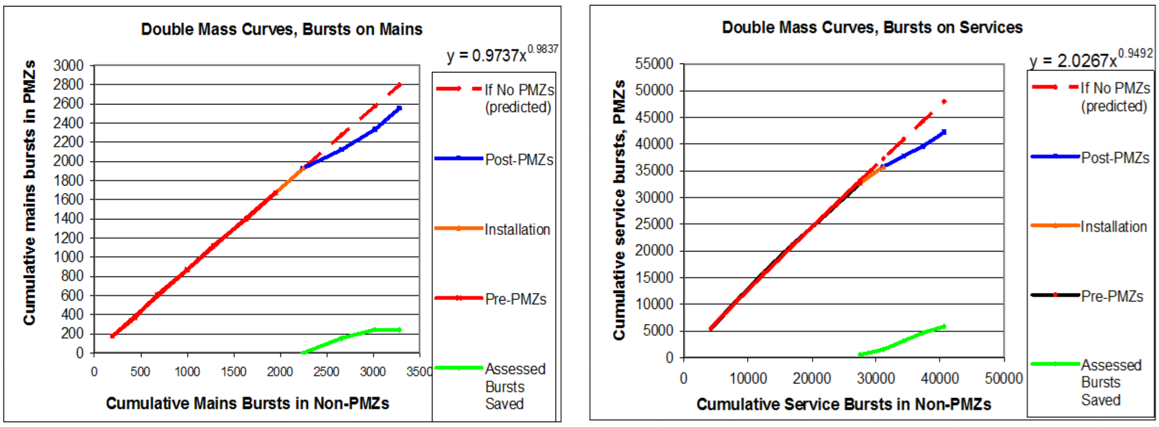
Many hundreds of pressure management schemes have been implemented internationally since 2006, with a strong (and long overdue) focus on monitoring the effect on burst frequency, as well as the more traditional expected reductions in leak flow rates. The benefits have been clearly seen, both in high income countries with generally good infrastructure (e.g. Australia) and also in LAMIC (Low and Middle Income Countries) such as Brazil and Malaysia, with less robust infrastructure.

In Australia, the severe constraints imposed by the multi-year millennium drought meant that by 2007 many Utilities had already almost reached the limits of reductions in real losses that could be achieved by leak detection and rapid repairs, with ILI values close to 1.0. The inclusion of predicted reductions in bursts meant that many hundreds of new pressure management schemes could be economically justified, with a focus on asset management rather than leak flow reduction. In a major 3-year project by WSAA (2008 – 2011), the simple IWA pressure-bursts targeting and prediction methods developed in 2006 proved to be relatively robust, and were complemented by techniques for monitoring achievements (Figures 5a and 5b), estimates of extension of asset life, predicting reductions in consumption, and other benefits as in the fore-runners of Table 1.

3.2 IWA Water Loss Task Force Studies 2011 to 2013

Although the simple qualitative and quantitative predictions developed by Thornton and Lambert (2006) proved to be effective for rapidly targeting zones for pressure management using high BFI values, and predicting burst frequency reductions using the 1.4 times approach, the authors recognized that there were inherent contradictions in the simplified assumptions used. The excellent quality and quantity of data from some of the Australian pressure reduction schemes, before and after pressure management was implemented, provided Lambert with the opportunity to undertake further research to try to improve the predictive equations for Zones with low to medium Burst Frequency Index.

Zones with relatively large numbers of bursts (say, more than 10 per year on mains, and more than 10 on services) are needed for this type of research, as the statistical 'noise' of natural year-on-year variability of lower burst numbers can easily mask any reductions that were due to the pressure management. Zones for such research must also have clear separation of monthly mains bursts and service bursts repairs, for several years before and after the pressure management is implemented. It is also essential to establish an 'average zone point' (AZP) to provide a measured assessment of the changes in maximum pressure at the AZP point (AZPmax). Furthermore, it is preferable that such research should be done on groups of Zones with similar pipe materials of similar age (e,g. mostly cast iron mains, or mostly polyethylene services), as different pipe materials may respond differently to changes in maximum pressure. These criteria mean that the data from many of smaller pressure-managed zones cannot be used for fundamental research, but it can still be used for mass testing of overall predictions for aggregated numbers of pressure management schemes, such as the 'double mass curve' approach which was recommended to simply monitor ongoing burst reductions, month by month, in one of the Australian Utilities with numerous pressure managed zones (Figures 6a and 6b)



Figures 6a and 6b: Double Mass Curves to monitor ongoing overall burst reductions in multiple pressure management Zones

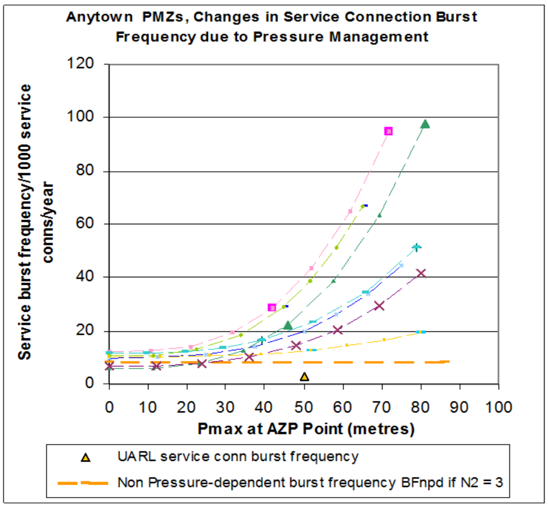
3.3 IWA Water Loss Task Force Studies 2011 to 2013

Using the selection criteria outlined above, for PMZs with consistently uniform pipe materials and large number of bursts, a reasonable number of 'before' and 'after' burst frequencies can be plotted against the 'before' and 'after' values of AZPmax in their individual Zones.

Figure 7a, which shows values for polyethylene service connections in 7 Zones in an Australian Utility, exhibits no sudden transition of failure rate with pressure (as in the simple 2006 assumptions of Figure 5). After testing various curve-fitting equations with several sets of good quality data from 22 PMZs and also the 110 international data sets, the currently recommended form of general equation, shown in Figure 7b, is

$$\text{Burst Frequency BF} = \text{BFnpd} + \text{BFpd} = \text{BFnpd} + A \times \text{AZPmax}^{N2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

BFnpd is a component of Burst Frequency which is not pressure-dependent. The pressure-dependent component (BFpd) is a function of AZPmax to the power N2, where N2 seems to be close to 3.0 (a cubic relationship), and. 'A' is a coefficient influencing the slope of pressure-dependent part of the relationship



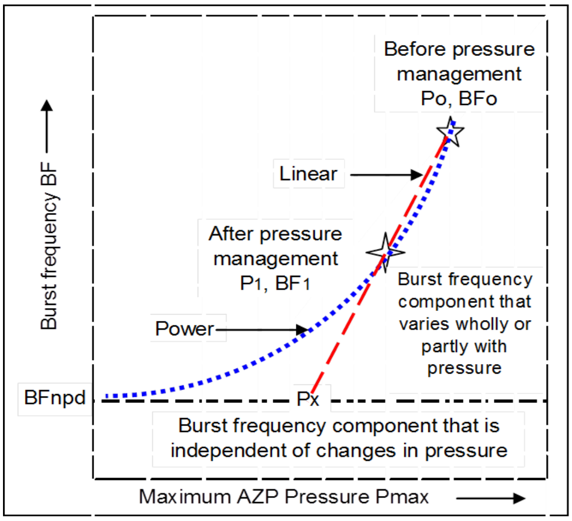


Figure 7a: Polyethylene services in PMZs in an Australian Utility's Pressure Managed Zones

Figure 7b: General relationship between Burst Frequency and Maximum Pressure at Average Zone Point

The general relationship between % reduction in Burst Frequency, and % reduction in AZP max, can be derived from equation (6) and is shown as Equation (7) and in Figure (8), which can be compared with (and supercedes) Figures 5a and 5b, which were based on the 2006 simplified approach.

$$\%\text{ reduction in Burst Frequency} = (1 - \text{BFnpd}/\text{BFo}) \times (1 - (P_1/Po)^3) \quad \ldots\ldots\ldots\ldots\ldots(7)$$

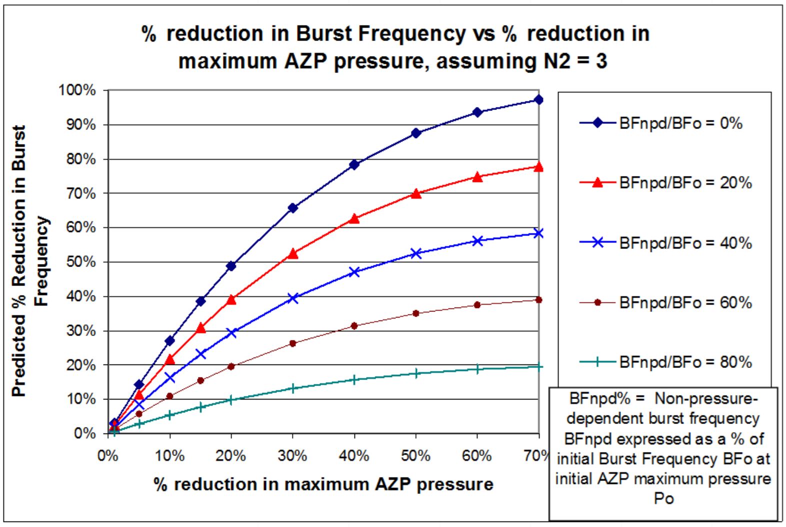
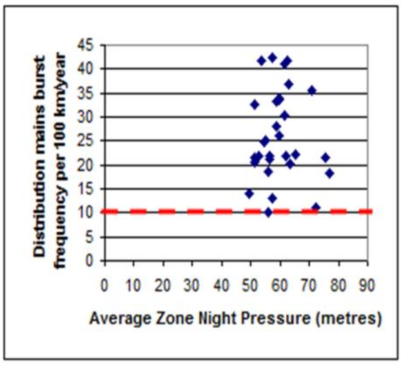


Figure 8: % reduction in burst frequency vs % reduction in max. pressure, for mains, and for services

To use the latest prediction method, it is necessary to be able to make an estimate of BFnpd, which can be checked and refined if necessary two or three years after pressure management has started.. A simple approach to making quick estimates of BFnpd has been developed and tested (Figures 9a and 9b):

- Assemble mains repairs data (exclude hydrant/valve repairs) from Zones with more than 10 mains repairs per year to minimize 'noise' from Zones with few repairs (aggregate data from smaller Zones if necessary)
- Plot burst frequency against average zone night pressure for each zone
- Estimate lower boundary to the data points, this can be used as initial estimate of BFnpd for mains
- Repeat the procedure for service repairs (exclude small leaks at the stop tap and customer meter)



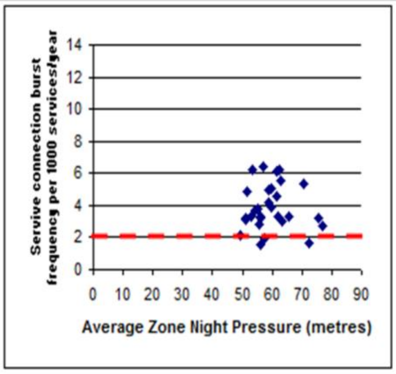
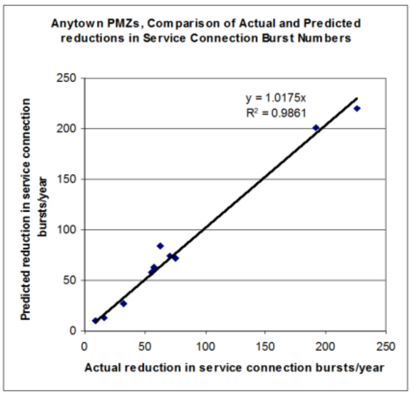


Figure 9a: An initial BFnpd estimate for mains   Figure 9b: An initial BFnpd estimate for service connections

Values for BFnpd vary between Zones. The values in Figures 9a and 9b, for infrastructure in reasonably good condition in a High Income country, are consistent with (being slightly lower than) the UARL burst frequencies at 50m pressure for mains (13 per 100 km/year) and services (3 per 1000 service connections/year).

3.4 Testing the 2012 prediction method in different countries and circumstances

Using values of BFnpd established from numerous PMZs, predicted and actual reductions in annual numbers of burst repairs were compared in large Zones with high initial burst frequency, for two Australian Utilities. The correlation for polyethylene services (Figure 10a) was excellent. For Cast-Iron mains (Figure 10b), the 2012 prediction method also had a high correlation, and gave better predictions than the simpler 2006 method.



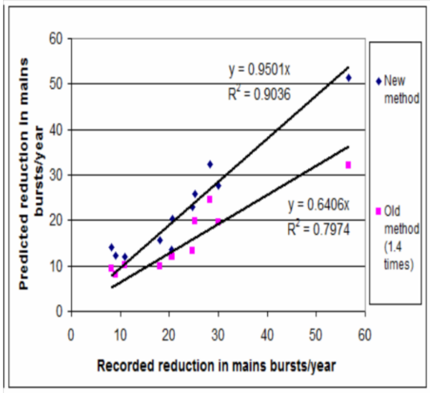
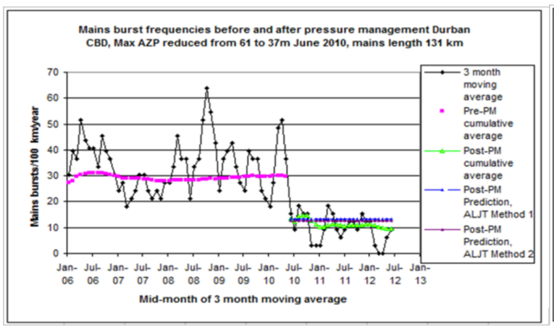


Figure 10a: Actual vs predicted burst reductions, PMZs with polyethylene services

Figure 10b: Actual vs predicted burst reductions, PMZs with cast iron mains

Predicted changes in repair frequency in Durban Central Business District, using both prediction methods, are shown in Fig. 11a for mixed mains materials (AC, plastic, steel, Cast Iron) and 11b (polyethylene services).



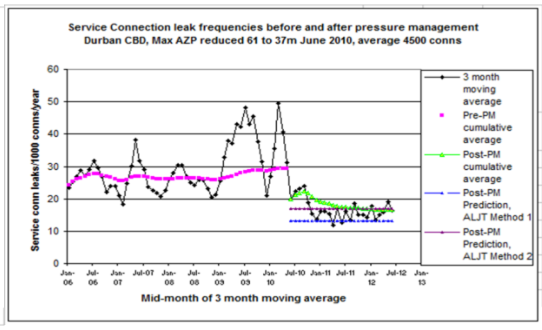


Figure 11a: Mains repair frequencies pre- and post- pressure management, Durban Central Business District

Figure 11b: Service repair frequencies, pre- and post- pressure management, Durban Central Business District

The IWA 2012 prediction method has now also been tested in two UK Utilities, to revisit bursts data in their District metered areas and pressure management zones, to try to identify Zones where further pressure management could be targeted to reduce burst frequency and extend infrastructure life.

36 sets of Bristol Water data used in the Pearson et al (2005) study were re-examined, with predictions of reductions in bursts being based only on the data available before pressure management was implemented. The 2012 IWA prediction method was compared with a recent prediction method (UKWIR, 2012) based only on UK DMA data. The UKWIR 2012 method identified 4 Zones in which 6 bursts per year would be saved (the actual reduction was 14 per year), with pressure management being predicted as 'not measurably beneficial' in any of the other Zones. The IWA 2012 method predicted 16 fewer bursts/year in 4 Zones (actual reduction 16/year) and a further 7 DMAs in which more than 1 burst/year (18 in all) might be saved (actual also 18/year). The IWA 2012 method had clearly identified the DMAs which experienced the highest burst reductions.

The form of Equation (7) implies that a logical first step in targeting Zones for burst reduction is to identify Zones with the largest numbers of pressure-dependent bursts (on mains, and also separately on services). As quite moderate % reductions in maximum pressure can produce large reductions in burst numbers in such Zones, more detailed investigation of the scope for reducing maximum pressure can then be concentrated on those Zones first. This approach was used in another UK Utility, to rapidly analyse mains and service repair data from several thousand DMAs and PMZs of varying sizes. When the much smaller number of Zones with largest numbers of pressure-dependent bursts had been identified, more detailed and time-consuming investigations into potential for further pressure management could then be concentrated on them, and benefits in terms of reduced annual repair costs and leakage reduction quantified. The results are expected to be published later in 2014.

4. Ongoing Practical Research

4.1 Influence of pressure management on seasonal burst frequency

It is clearly evident in Figures 11a and 11b that seasonal variations in burst frequency can be significantly reduced by reduction of excess pressure, as such failures result from the interaction of pressure and other causes (ground movement, temperature, traffic loading etc); other good examples of this are available. Research continues into different types of pipe materials and failure modes, but the new form of pressure:bursts equation (Figure 12) provides a simple plausible overview of why this might be expected to happen.

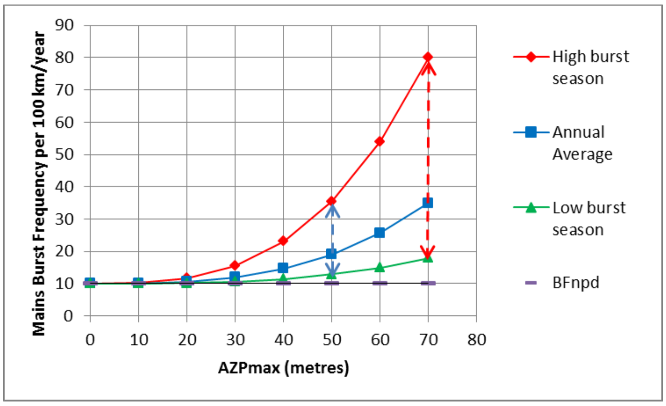


Figure 12: Influence of reduction of pressure on seasonal burst frequency

At 70m pressure, each of the uppermost (top right-hand) mains burst frequencies could be considered as the annual averages for 3 different zones, each with varying propensity for bursts to occur. If AZPmax is reduced to 50 metres, each Zone will follow its own individual curve downwards. However, if they are all considered to represent the same Zone at different times of year - 80 in the 'high' burst season, 35 annual average and 17 in the 'low' burst season – then if pressure is reduced to 50 metres, the 'high' season bursts will fall to 36, the 'low season to 13, and the annual average to 20. .

4.2 Influence of reduced burst frequency on emergency repairs and residual infrastructure life

As well as reduction of repair costs, the reduction of bursts can realize major cost savings in emergency mains renewals, and extended infrastructure life (Lambert et al, 2012). A Melbourne distribution Utility implementing pressure management found that 215 fewer mains bursts saved $0.37 million in repair costs but $2.75 million in deferred renewals (Beaton, personal communication, 2012). Further examples and case studies are being sought.

4.3 Influence of reduced pressure and burst frequency on energy management

The various ways in which improved pressure management, and the consequent reductions in bursts and leakage rates, can influence energy management are receiving increased attention, particularly from pump manufacturers. Papers on this topic can be expected in Water Loss Conferences in 2014 onwards.

5. Summary

The paper has summarized some of the progress made by the Pressure Management Team, and other members of the IWA Water Loss Specialist Group, in developing better understanding and practical predictions of the benefits of pressure management in public water distribution systems, with particular emphasis on pressure:burst frequency relationships and their consequences. The latest suggested equation relating pressure and burst frequency is now being used to make practical predictions of changes in burst frequency in an increasingly wide variety of countries and situations. The project continues.

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