Pressure:Bursts Relationships: Influence of Pipe Materials, Validation of Scheme Results, and Implications of Extended Asset Life

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Keywords: Pressure Management; Burst reduction; Extension of Asset Life

Abstract and Introduction

The proven benefits of pressure management in distribution systems have now moved beyond basic leakage control, as initially promoted in the UK and Japan thirty years ago. Pressure management is now recognised as having a wide range of benefits (Table 1, adapted from Lambert and Fantozzi, 2010; WSAA, 2011).

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 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

Six years ago, data showing significant reductions in mains and services bursts from 112 Pressure Management Zones (PMZs) in 12 countries (Thornton & Lambert, 2006; Thornton & Lambert 2007) helped to promote international recognition that burst frequencies on mains and services can be controlled by pressure management.

A conceptual explanation ('the straw that breaks the camel's back), coupled with calculation of simple separate Burst Frequency Indices (BFIs) for mains and services, can quickly identify distribution system zones where significant reductions in bursts, on mains and/or service connections, could be expected if surge and or excess operating pressures were reduced. The 2007 prediction equation developed from data in the 112 PMZs was:

% reduction in bursts (or burst frequency) = S x % reduction in Pmax.

where Pmax is the maximum pressure at the Average Zone Point, and S varied from 0 to around 3.0 in individual schemes, with an average of around 1.4. This equation, using S = 1.4, was recommended as an initial equation for predicting burst reduction in individual PMZs with a high Burst Frequency Index. This simple prediction method has since produced quite reliable predictions of average burst frequency reductions for groups of PMZs with high initial burst frequencies in Brazil (180 PMZs) and Australia (60 PMZs).

The prediction method in Figure 1 was used in conjunction with a conceptual approach (the 'Straw that breaks the camel's back', summarised in Figure 2) to explain why some PMZs showed large reductions in bursts on mains and/or services, but some PMZs showed no reduction.

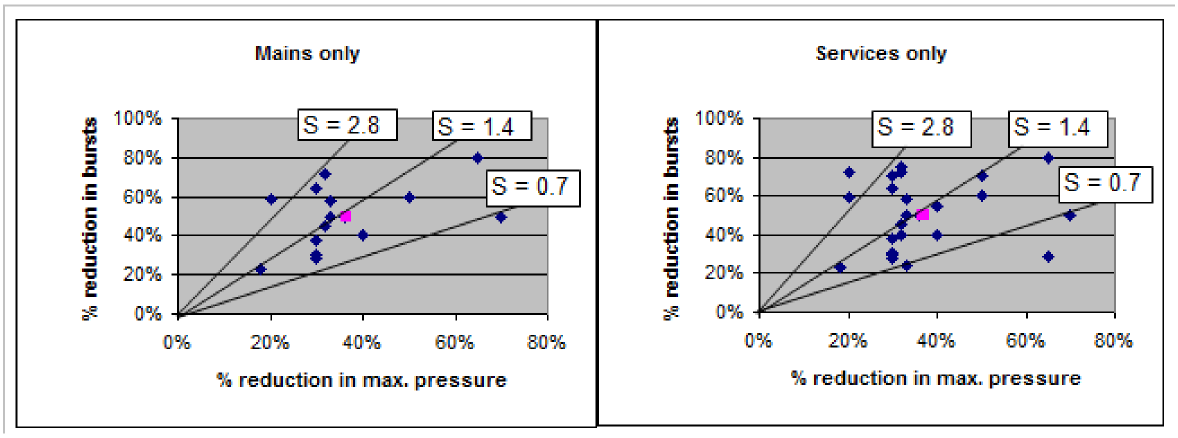


Figure 1: % burst reduction vs. % Pmax reduction, for 112 Pressure Management Zones in 12 countries

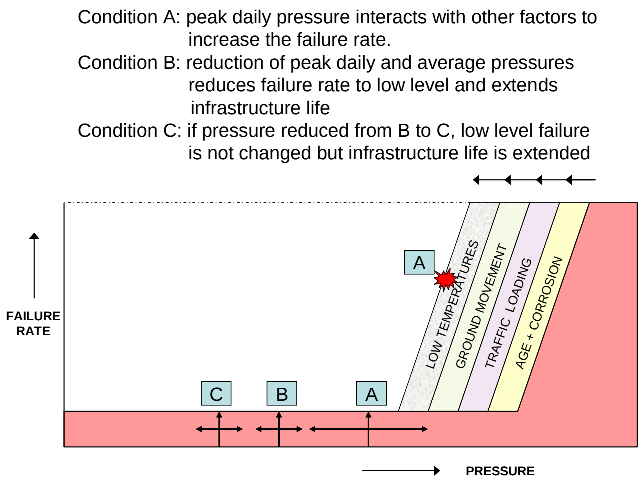


Figure 2: Conceptual Approach to Pressure: Break Frequency Relationships

Since 2006, the authors have been seeking a deeper understanding of pressure:bursts relationships, and the associated question of extension of infrastructure life. It became clear that progress is only likely to be achieved by analysis of good quality data from individual PMZs, using reliable approaches to process the data, and appropriate concepts that take into account factors such as pipe materials, residual life etc. This paper describes the authors' 'state of the art' of practical methods for selecting Zones and data for analysis, and some of the latest conceptual approaches used to interpret the data.

Section 1 of the paper outlines practical approaches to 3 issues relating to selection of PMZs and PMZ data for analysis, to improve understanding, prediction and validation:

- an initial overview of burst frequencies in the distribution system
- selecting Zones for Pilot studies or analysis of pressure: burst frequency relationships
- investigating the extent of interaction of pressure with failures attributed to ground movement, for different pipe materials and types of failure

Section 2 of the paper outlines some recent developments in conceptual issues related to pressure:bursts relationships:

- equations for predicting reductions in bursts after pressure management
- ongoing validation of predicted reductions in bursts after pressure management
- assessing and valuing extension of residual asset life following pressure management

1. Practical approaches to pressure:bursts data analysis issues

1.1 An Initial overview of burst frequencies in the Distribution System

Burst frequency can vary seasonally and from year to year, even when system pressure is unchanged. These changes generally occur alongside climatic influences (low or high air or water temperatures, or soil moisture changes causing ground movement). Recorded repair frequencies are influenced by repair backlogs due to weather, vacation periods, administrative repair contract holds ups, and active leakage control interventions.

The first step is to look at the variations in monthly bursts and burst frequencies for the Utility as a whole; for meaningful interpretation these ***must*** be presented separately as burst frequencies for mains per 100 km/year (Figure 3) and burst frequency for service connections (main to property line) per 1000 service connections/year (Figure 4). The more specific the repairs information, the better, but as a minimum:

- repairs on mains and at mains joints should be shown separately from repairs on mains fittings (hydrants and valves)
- service burst frequencies should include repairs at the main tap and Utility pipe, but stop tap and meter repairs, and private pipe repairs, should be shown separately.

Using the ‘reference’ burst frequencies BFuarl from the IWA Unavoidable Annual Real Losses (UARL) equation (13 per 100 km/year for mains; 3 per 1000 service connections/ year, main to property line), Burst Frequency Index BFI (= Burst Frequency/BFuarl) can be calculated, see right hand Y axes in Figs. 3 and 4. This gives an immediate overview measure of the relative propensity for bursts, with separate BFIs for mains and services.

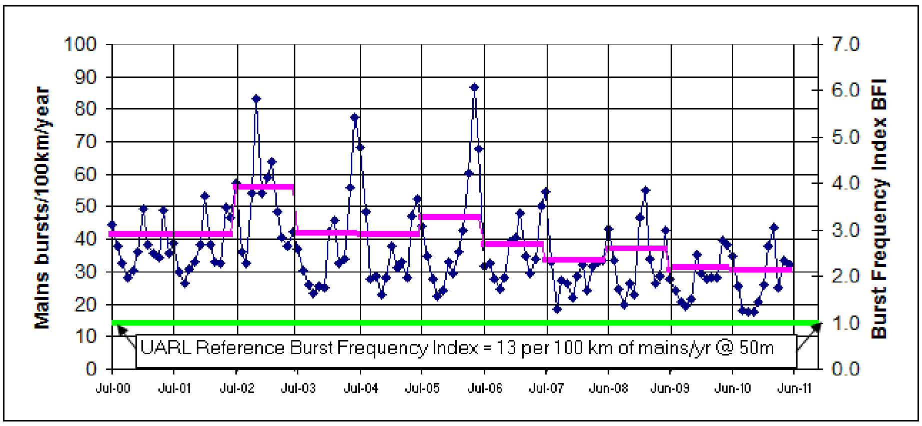


Figure 3: Variation of monthly mains burst frequency for a large Australian Utility

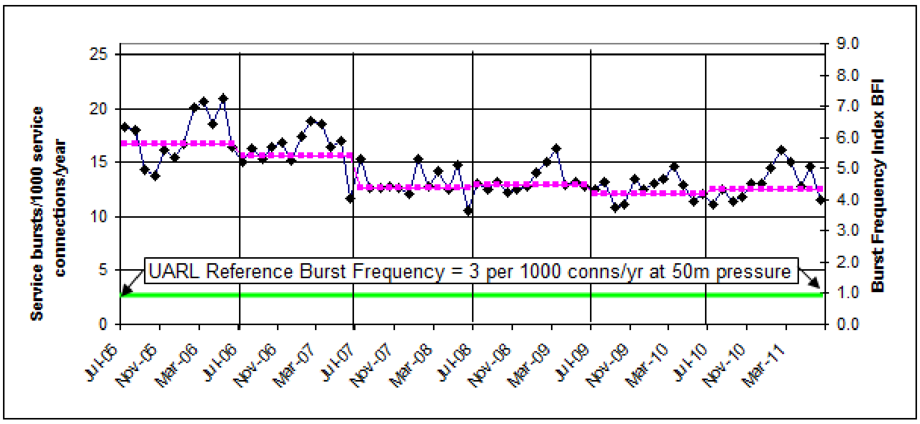


Figure 4: Variation of monthly service burst frequency for a large Australian Utility

1.2 Selecting Zones for Pilot studies or analysis of pressure: burst frequency relationships

When selecting Pilot Zones to ***investigate*** the influence of pressure management on burst reduction, it is ***essential*** to select Zones with significant numbers of bursts before pressure management. If there are only 5 mains bursts/year before pressure management, then it will not be possible to be sure if reductions after pressure management (to, say, 3 or 4 mains bursts per year) were due to the pressure management or to natural year on year variations; also, extrapolation or analysis of the results will be unreliable.

Suggested guideline values for Zone selection for 'before' and 'after' data analysis (WSAA, 2011 and other sources) are:

- more than 20 mains bursts/year and more than 20 mains bursts/100 km/year
- more than 20 service bursts/year and 10 or more service bursts/1000 service conns/year
- significant reductions (> 20%) in maximum pressure at the Average Zone Point (AZP) and continuous pressure measurements at the AZP Point
- try to select Zones with one predominant pipe material for mains and one for services, as different pipe materials are likely to respond differently to changes in pressure
- a minimum of 3 to 4 years reliable monthly repairs data before pressure management, separated into mains and services repairs, to establish pre-PM average burst frequencies

By identifying the month in which the PMZ was established, Figures 3 and 4 can be used to assess if the average burst frequency calculated for the periods before and after Pressure Management in a large 'Control' group may have been unusually high or low.

1.3 Investigating the extent of interaction of pressure with failures attributed to ground movement, for different pipe materials and types of failure

In distribution systems where burst frequencies fluctuate significantly on a seasonal and annual basis, even when pressure is effectively constant, some practitioners and asset management analysts consider that types of pipe failures typically associated with seasonal increases in burst frequency are not pressure-dependent, and will not be influenced by pressure management.

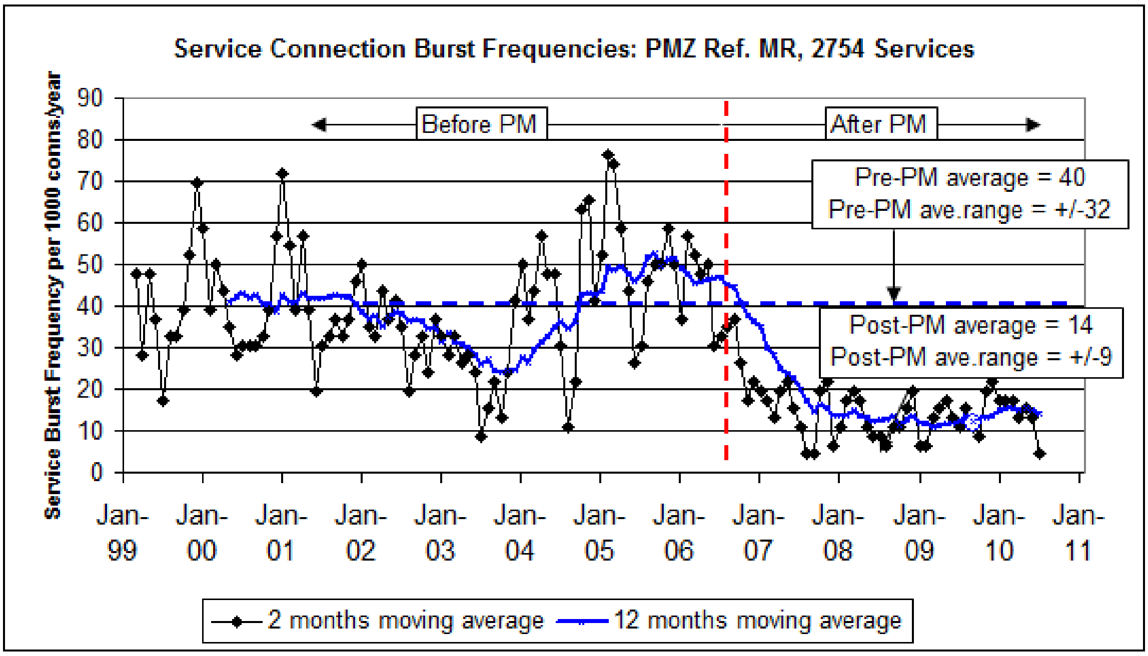
Ring cracks (broken backs) in small diameter cast iron and AC mains, which often experience increased frequency at times of ground movement, are perhaps the most frequently quoted example; theoretical considerations of stresses may appear to support this view, but for other pipe materials and failure modes (e.g. longitudinal splits), maximum pressure and effective pipe wall thickness are recognised as key parameters.

Yet in practice, significant reductions in bursts usually occur after pressure management in ***all*** systems with a relatively high initial Burst Frequency Index, irrespective of the pipe materials. We cannot yet explain why, except to say that the 'straw that breaks the camel's back' concept assumes that high pressure is usually a ***contributory*** factor to failure, rather than the prime factor.

Further insights into pressure-bursts relationships for individual pipe materials are being gained by analysis of large PMZs with initial high burst numbers and burst frequencies, with predominant types of pipe material (Lambert and Thornton, 2011).

In the PMZ in Figure 5, pressure management reduced both ***average*** burst frequency and ***seasonal range.*** In this example, the seasonal increases in burst frequency initially attributed to ground movement are clearly strongly pressure-dependent for this pipe material and predominant type of failure (lateral split).

Figure 5: Average burst frequency & seasonal range before and after PMZ

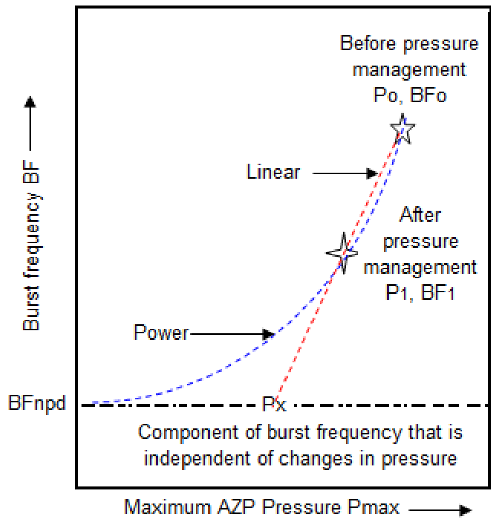


2. Recent developments in pressure: bursts conceptual issues

2.1 Equations for predicting reductions in bursts after pressure management

When considering appropriate forms of equation for these predictions, it is essential to remember that we are ***not*** trying to derive a general relationship between pressure and burst frequency for a distribution system as a whole. The objective is to identify a general form of equation that will give reasonable practical predictions of how different parts of a distribution system (i.e. potential PMZs, each with its own particular characteristics) will respond to a permanent reduction of excess maximum pressure (including transients).

In Figure 6a, the initial average burst frequency BFo at a maximum AZP pressure Po is known; this point could be located almost anywhere on the graph, for different international situations and groups of Zones. We wish to select an equation (linear or power) to interpret how the burst frequency changes if the maximum AZP pressure is reduced from Po to P_1, as for example in the group of PMZs in Figure 6b.



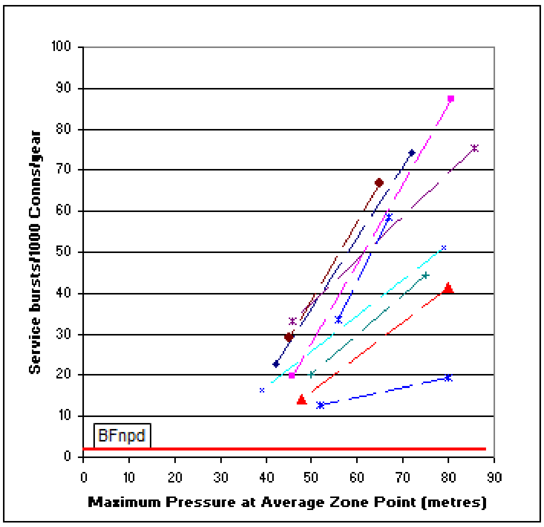


Figure 6a: Options for Pressure:burst frequency relationships **Figure 6b::** Data from a group of 9 PMZs

Figures 6a and 6b allow for a Non Pressure Dependent Burst Frequency (BFnpd) component that is not influenced by pressure. However, it is not known if the pressure-dependent part of the relationship is linear (reaching BFnpd at a maximum AZP of Px), or a power law relationship. A form of general equation that covers both situations is:

$$BF = BFnpd + A \times (P - Px)^{N2} \quad \text{...}(1)$$

where 'A' is a coefficient influencing the slope of pressure-dependent part of the relationship. The possible options for equations become:

Linear (N2 = 1.0): $BF = BFnpd + A \times (P - Px)$..................(2)

or Power with BFnpd = 0: $BF = A \times (P- Px)^{N2}$ …….. ….(3)

or Power with Px = 0: $BF = BFnpd + A \times P^{N2}$ ……..…. (4)

or Power with Px = 0, BFnpd = 0: $BF = A \times P^{N2}$ ……… .(5)

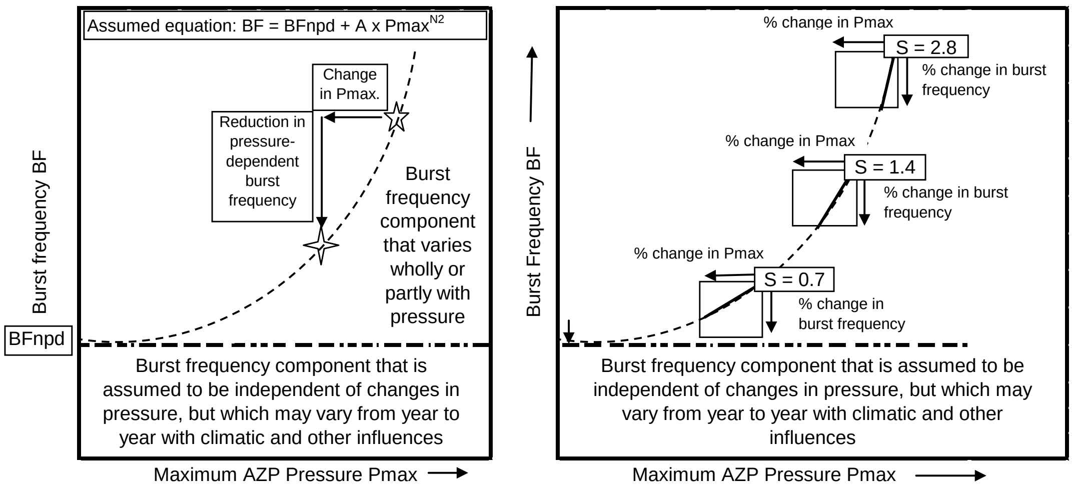
Using equation (5) to analyse 50 data sets, Pearson et al (2005) obtained N2 values ranging from 0.2 to 8.5 (median 2.5) and 0.2 to 12 (median 2.4) for services; they also showed that the N2 range and median values could be reduced by using equation (3). with Px = 10 or 20 metres. However, in all three cases (Px = 0, 10 and 20 metres) it was clearly seen that N2 reduced for larger reductions in pressure; and that as Px increased, N2 reduced. No conclusions were reached regarding how to explain the variations, or to predict N2, but the paper went on to show highly relevant concepts relating to failure envelopes, which were later used in the 'Straw that breaks the camel's back' concept.

Equation (4), which recognises that some bursts may not be pressure-dependent, has now been further investigated, and tested with good quality data sets from 22 PMZs and also the 110 international data sets. Limitations of space preclude showing all the data, theory and equations in the following brief summary:

- from Equation (4), the maximum possible slope S is equal to N2, when BFnpd/BF is zero, and the % reduction in maximum pressure $(1 – P_1/Po)$ is small
- in Figure 1, maximum values of S are close to 3 for small % reductions in pressure.

Use of Equation (4), with an N2 exponent close to 3.0, reconciles the Figure 1 data for Slope S with a modified 'straw that breaks the camel's back' concept (Figure 7a), as shown in Figure 7b. The Slope S can be calculated from Equation (6).

$$\text{Slope } S = (1 – BFnpd/BFo) \times (1 - (P_1/Po)^{N2}) / (1 – P_1/Po) \quad \text{…………}(6)$$



Figures 7a and 7b Linking Slope (S) in Figure 1 to the N2 exponent in Equation 4 .

Figure 8 shows how calculated values of Slope S for the 110 PMZs and recent data lie reasonably within the limits of 2% < BFnpd/BFo < 80% if N2 = 3.0. Whilst the simple average of S = 1.4 in Figure 1 is close to the average S of all the data, higher values of S can be expected for relatively small % reductions in Pmax; outliers in Figure 8 suggest that N2 in equations (4) and (6) might be as high as 4 or 5, but N2 = 3 gives better overall predictions of reductions in numbers of bursts for the recent data. Slope S for N2 = 3 can be predicted using Figure 9a. Figure 9b replaces Figure 1 for advanced analysis.

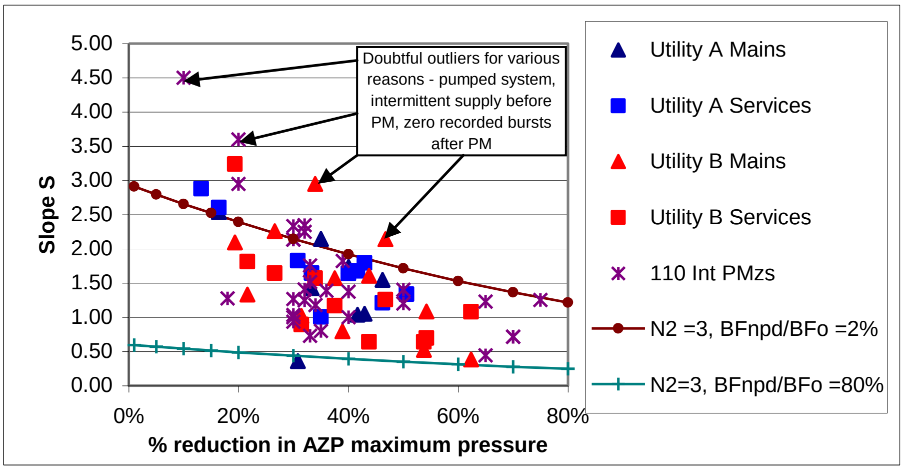
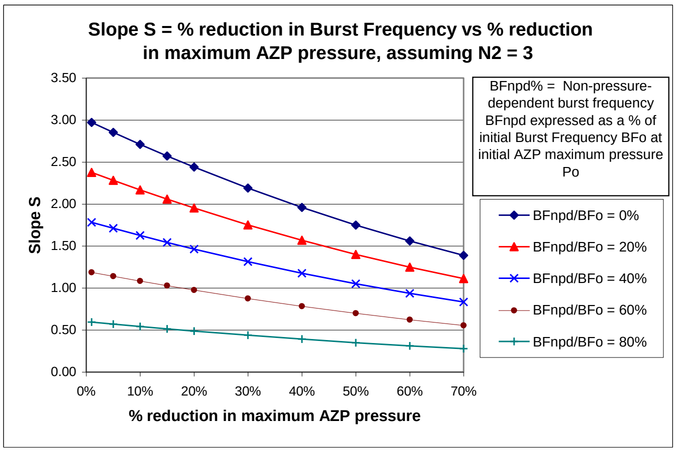


Figure 8: Comparison of Slopes (S) from PMZ data with Equation 6, N2 = 3.0



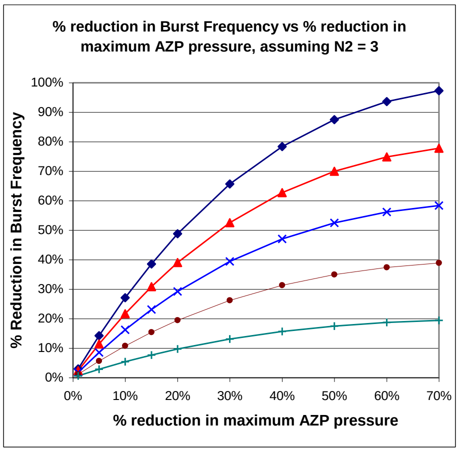


Figure 9a: Predicting S, if N2= 3.0.

Figure 9b: Predicting % Reduction in Burst Frequency

Values of BFnpd may be expected to vary quite widely for different pipe materials in different Utilities. Research to date into appropriate values of BFnpd has so far been limited to AC, uPVC and Cast Iron mains, and copper and polyethylene service connections, in a developed country. Research continues for other pipe materials.

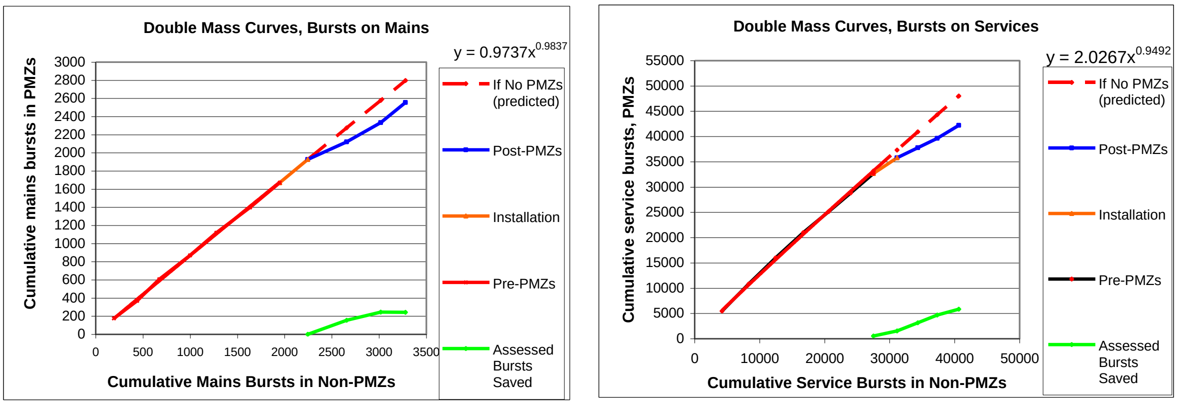
2.2 Ongoing validation of predicted reductions in bursts after pressure management

Assessments of reductions in bursts following pressure management can be difficult in individual PMZs with relatively small burst numbers. So, for a scheme with multiple PMZs, burst reduction needs to be monitored collectively. The first step is to split the distribution system into 'PMZs' and 'Non-PMZs', and attribute monthly bursts to each group.

Double mass curves can then be used to provide an overview assessment of the numbers of bursts saved as the years pass after implementation of a group of pressure management schemes. The basis of the approach is as follows:

- assemble month by month data on cumulative bursts for PMZs and Non-PMZs groups separately, for at least 3 to 4 years before implementation of pressure management
- create a graph with cumulative Non-PMZs bursts on the x-axis, and cumulative PMZ bursts on the y-axis, up to the time of implementation of pressure management
    - identify an equation of the form $y = ax^N$ between the two sets of data
- use the equation to predict the ongoing cumulative bursts in the PMZs if no PMZs had been established
    - compare with the actual ongoing cumulative bursts in the PMZs after their establishment and identify the ongoing reduction in cumulative burst numbers.

Examples in Figures 10a and 10b (from WSAA, 2011) show how double mass curves can be used to obtain a rapid but effective overview of reductions in bursts after establishment of a group of PMZs. The orange line represents the actual cumulative relationship while the PMZs were being installed; the blue line is the cumulative relationship when all the PMZs were operating.



Figures 10a & 10b: Analysis of Burst Reductions on Mains and Services after Installation of a Group of PMZs

The green line represents the difference between the dashed red line and the blue line, which is the assessed number of bursts that have been saved by the installation of the PMZs. If the green line continues to grow with time, bursts continue to be saved, year on year. If the green line flattens out or falls, no further bursts have been saved. Decreases in slope of the green line need to be investigated, as they could be due to increases in pressure arising from sub-optimal operation of the PMZs; a flag that it is time for PMZ maintenance, checking boundary valves and possibly Active Leakage Control.

The choice of mathematical function for the line of best fit influences the assessment of reductions in burst frequency. Whilst research on this topic by the authors continues, they currently prefer to use Power Laws based on both burst numbers and burst frequency, to allow for changes in relative growth rate in the PMZ and Non-PMZ group.

2.3 Assessing Extension of Asset Life following Pressure Management

Data in Table 2 relating average life of AC pipes to maximum pressure from New Zealand (Black J, 2010) have recently been used (LAPMET, 2011) to develop a method for assessing the financial benefit (in terms of Net Present Value) of extending asset life by pressure management in individual PMZs. This particular analysis assumes that it is the increased frequency of longitudinal splits and blow-outs (rather than ring cracks/broken backs, which can be fixed by repair clamps or compression-type couplers) that generally determines when AC mains are replaced. Any reduction in maximum pressure can be converted to a number of years (EP) that the renewal of a section of main can be deferred, e.g. a 20 metre reduction in Pmax should extend the life of 100 mm AC pipe by 3 years.

Table 2: Average Years to Failure vs. Maximum Pressure, New Zealand 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

The Financial Benefit of deferring replacement of a section of AC mains by EP years, when the assumed Residual Life is RL years, for discount rate r% and interest rate i%, can be calculated in terms of Net Present Value (NPV) from the equation:

$$NPV = RCo \times K^{RL} \times (1 - K^{EP}), \quad \text{where } K = (1 + i\%)/(1 + r\%) \quad \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

where RCo is the cost/metre of replacing AC mains. Figure 11 shows this relationship for an interest rate of 3% and a discount rate of 9%.

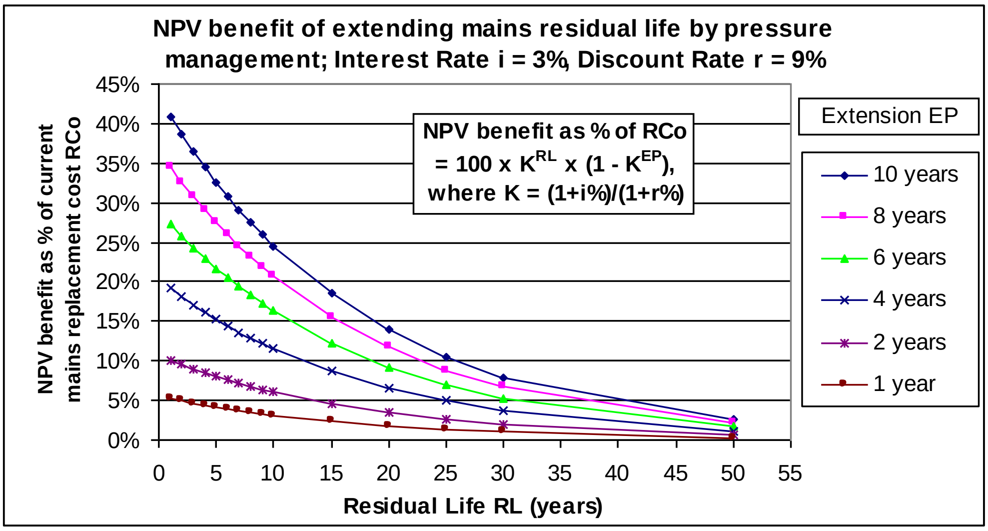


Figure 11: NPV benefit of extending mains residual life by pressure management

NPV benefits are greatest when Residual Life is low, and when large reductions in pressure produce longer life extension EP in years. Example calculations indicate that calculated NPV benefits can be substantial. Table 3 shows an example where sections of AC mains in an Australian PMZ have different residual lives, and a 3-year extension arising from a 20 metre reduction in pressure would produce predicted NPV benefits of \$157k over 10 years and \$256k over 28 years.

This approach is now being developed in software to rapidly identify potential PMZs with the highest NPV benefits from infrastructure replacement. The use of advanced in-situ testing methods to confirm estimates of residual life of AC pipes is also being explored. Relationships similar to Table 2 for pipe materials other than AC (notably Cast Iron) need to be developed for wider application of the method.

Table 3: Example calculation of NPV Benefits of extended Asset Life for AC mains

Year	Residual Life RL	100 mm AC	Extension EP	Current Renewal Cost RCo		NPV benefit from Table		Cumulative NPV benefit	
	Years	metres	Years	$/metre	$k	%	$k	$k	Years from now
2011									
2014	3	5580	3	200	1116	13.2%	147	147	6
2018	7	474	3	200	95	10.5%	10	157	10
2021	10	1107	3	200	221	8.9%	20	176	13
2026	15	1397	3	200	279	6.7%	19	194	18
2029	18	824	3	200	165	5.6%	9	204	21
2031	20	1348	3	200	270	5.0%	14	217	23
2036	25	5085	3	200	1017	3.8%	39	256	28

Summary

- The paper outlines several practical methods for analysis of good quality pressure:bursts data from Pressure Management Zones, to help improve predictions.
- A modified N2 power relationship (Eqn. 4) with a 'non-pressure dependent' burst frequency component BFnpd is recommended for pressure:burst relationships
- use Equation 6 and Fig. 9a to predict Slope S, with N2 = 3.0; research into BFnpd values for different pipe materials continues.
- A conceptual methodology for calculating Net Present Value of deferred AC mains replacement due to pressure management has been presented, and could usefully be extended to other mains materials if possible
- Readers with good quality PMZ data, or who are interested in the data analysis and conceptual models, are invited to contact the authors

Acknowledgements

To Water Services Association of Australia for permission to use material from the WSAA Asset Management Project PPS-3, Review of Leakage Reporting and Management Practices, and to Australian Utilities - Allconnex Water (previously Gold Coast Water), Sydney Water, Wide Bay Water Corporation - that permitted their data to be used in this paper. To David Pearson and other members of the Water Loss Specialist Group for significant contributions to the ongoing research into pressure management benefits.

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