Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships

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Abstract

Substantial advances have been made in the last decade in the development of practical methods for understanding and predicting how leakage rates and burst frequencies in distribution systems, and some elements of consumption, are influenced by pressure. Members of the Pressure Management Team of the Water Losses Task Force continue to try to improve the practical methods available for analysis and prediction. The combination of existing and new material is presented under four principal topic headings:

- ◆ Predicting pressure: leakage rate relationships using Power Law exponents

- ◆ Extending the range of operating pressures for the UARL formula

- ◆ New information on pressure: consumption relationships

- ◆ Pressure: new burst frequency relationships

The paper concludes with a brief listing of some practical research topics that could usefully be pursued, and explains that, by using software specifically designed for pressure management, practical predictions can usually be made rapidly without the need for network analysis models.

Introduction

### *Pressure Management – the foundation for effective leakage management*

In Japan, the UK and several other countries it has been widely recognised for at least 25 years that pressure has a fundamental influence on average leakage rates in distribution systems and this influence is usually significantly greater than the theoretical relationship between pressure P and discharge rate Q through an orifice (P varies with $Q^{0.5}$). But in many other countries and Utilities, pressure management is still unfortunately considered as only marginally relevant - or not relevant at all - to leakage management.

However, an ever-increasing number of countries and Utilities are now recognising that good pressure management is the fundamental foundation of good leakage and infrastructure management. The weight of evidence now available, and the ever-improving reliability with which technical and economic predictions can be made, are such that progressive Utilities can no longer afford to ignore investigating possibilities of pressure management in their systems. Pressure management for leakage control, in its widest sense, can be defined as

"The practice of managing system pressures to the optimum levels of service ensuring sufficient and efficient supply to legitimate uses and consumers, while reducing unnecessary or excess pressures, eliminating transients and faulty level controls all of which cause the distribution system to leak unnecessarily"

The Water Losses Task Force promotes the use of a '4-Component' diagram for managing Real Losses; Figure 1 shows that Pressure Management also has a major influence on the other components, as reduction of excess pressures and surges usually reduce the numbers of new leaks - sometimes to a major degree – resulting in:

- ⬥ Fewer reported bursts, lower repair costs, shorter run-times, reduced repair backlogs

- ⬥ Fewer unreported bursts, lower rates of rise of unreported leakage, less frequent interventions, lower economic volume of unreported leakage, lower annual intervention and repair costs

- ⬥ Reduced investments in mains and services replacement programs, if criteria are based on replacement in 'X' number of bursts occur in 'Y' km of pipes in 'Z' years.
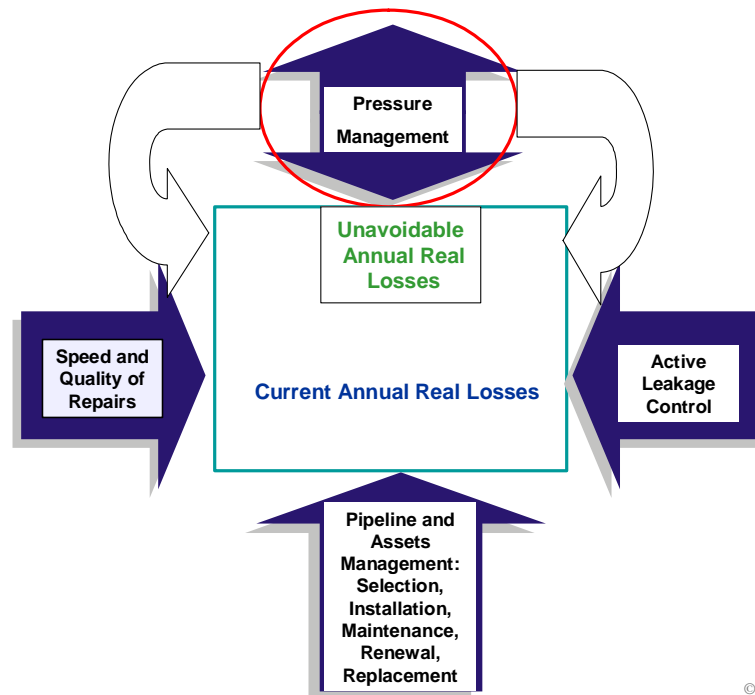
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Figure 1: The four components diagram, with secondary influences of pressure management

Pressure management programs often have positive impacts on apparent loss reduction and revenue recovery, especially in relation to theft and authorised unbilled consumption. Where customers have roof tanks, pressure management often improves effectiveness of ball valve closure, and improves metering accuracy by reducing the duration of extremely low flows ('ball valve tails') which some meters cannot record.

There are certain key steps to be undertaken to establish if, and to what extent, pressure management is appropriate for individual systems and sub-systems; there are also concerns to be addressed, such as flows for fire fighting, customer expectations etc (Thornton, 2002), but limitations of space preclude their inclusion in this paper. However, if pressure management is to become fully accepted as an essential tool in the leakage management tool-kit, it is also necessary to have the technical ability to predict the costs,

benefits and paybacks of different options and individual schemes, in order to justify investments and rank priorities.

This paper seeks to inform the reader of the practical methods used for predictions, and advances in the exponents and coefficients used in these tools. So what are the sources of information, and the 'State of the Art' in this respect, in September 2005?

Sources of Information

The diversity of membership of the Pressure Management Team of the Water Losses Task Force, in terms of both countries and occupation of the members (academics, researchers, modellers, consultants, practitioners etc) has had a notable influence on the speed with which good quality data is being identified, constructively discussed, and compared. The three principal sources of information, indicated by the interlocking circles, are shown in Figure 2. Each source overlaps with the others, which improves the reliability of the methods used for analyses and predictions.
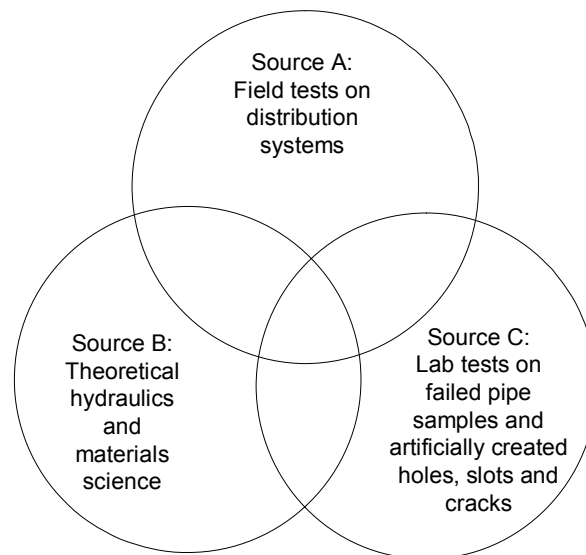

Figure 2: Sources of data for the study of pressure/leakage relationships in distribution systems

Pressure: leak flow relationships using Power Law relationships

Data from field tests on distribution systems (Source A)

The practice of reducing excess pressures to reduce leakage from distribution systems and plumbing fittings is not new (Parry J, 1881). Some 25 years ago, two major sources of field test data became available:

- ⬥ Short tests of pressure: leakage relationships on 20 small sectors of all-metal Japanese distribution systems (Ogura, 1979), analysed and presented in the form of a simple Power Law (Leakage L varies with Pressure P^n).

- ⬥ Pressure: net night flow relationships from longer duration tests on 18 district metered areas in the UK where all detectable leaks had been located and repaired (Goodwin, 1980), presented in the form of a graph

In 1994, May introduced the concept of Fixed and Variable Area Discharges (FAVAD) to explain the diversity of pressure: leakage rate relationships, in its simplest form this is also a power law. Empirical quadratic and exponential relationships were also used (or

rather, misused) in the UK and elsewhere from 1994 to 2003 to analyse test data and predict the effects of pressure management.

However, it is now recommended by the Water Losses Task Force (Thornton 2003) and in the UK (UKWIR, 2003), that the most physically meaningful and 'Best Practice' form of equation for representing pressure: leakage rate relationships is a simple Power Law. There is no international convention for characters used for the exponent, and the Water Losses Task Force uses the alpha-numeric 'N1', resulting in the equations:

$$L \text{ varies with } P^{N1} \qquad \text{…………… ……………….. (1)}$$

$$\text{And} \qquad L_1/L_0 = (P_1/P_0)^{N1} \qquad \text{….………………… ……….. (2)}$$

So, if pressure is reduced from P0 to P1, flow rates through existing leaks change from L0 to L1, and the extent of the change depends on the exponent N1. The general relationship of equation (2) is shown in Figure 3.
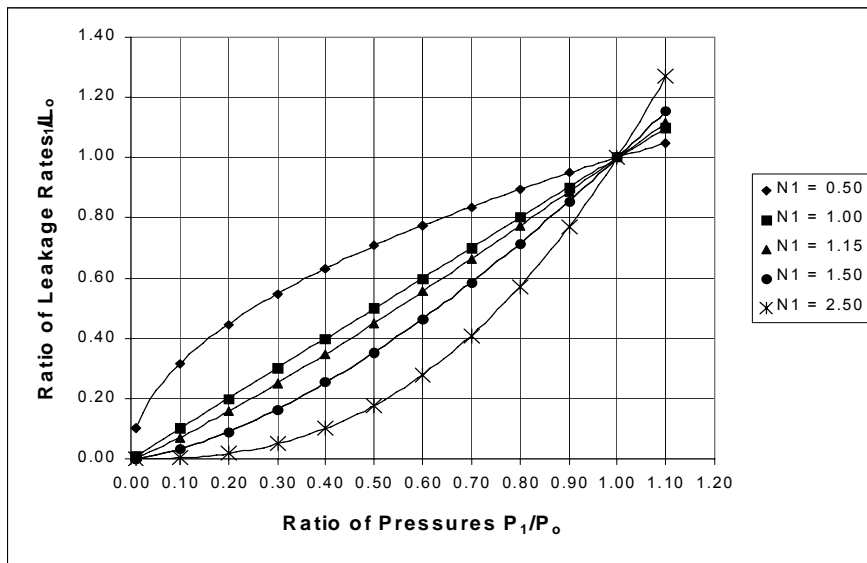

Figure 3: General relationship between pressure and leakage rate based on the power law equation

Analyses of over 100 field tests on sections of distribution systems in Japan and district metered areas in Australia, Brazil, Canada, Malaysia, New Zealand, U.K. and the U.S.A have confirmed that the N1 exponent typically lies between 0.5 and 1.5, but may occasionally reach as high as 2.5. The Japanese use a weighted average exponent value of 1.15 (Ogura, 1979). The weighted average of substantial numbers of tests from the UK is also close to 1.0 (linear). 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. The most recent research in the UK (UKWIR 2003) recommends using a power law relationship with:

♦   linear pressure: leakage relationship in large zones and undertaking-wide assessment, or where no other evidence exists and high precision of results is not a priority

♦   different powers at different leakage levels, for smaller zones, or where more precision is required

♦   individual measurements of the pressure-flow relationship should be made where the precise relationship is critical

Drawing on a broader test data sets than would be available to any individual country, the Pressure Management Team has been developing and testing a method of predicting N1 which uses ILI as a measure of system leakage level, and the percentage of

detectable real losses occurring on rigid pipe materials (mains and services) as a secondary parameter. This prediction method is shown in Figure 4.

The upper line in Figure 4 for 100% flexible pipe materials (p = 0%) is assumed to be constant at 1.5, whatever the ILI. The lower line for 100% rigid pipe materials was calculated assuming N1 = 1.5 for unavoidable background leakage for infrastructure in good condition, and N1 = 0.5 for detectable leaks in rigid pipes. Intermediate lines are based on the empirical equation:

$$N1 = 1.5 - (1 - 0.65/ILI) \times p/100 \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\text{ (3)}$$

So if ILI = 1.3 and p = 43%, the predicted N1 is around 1.3.
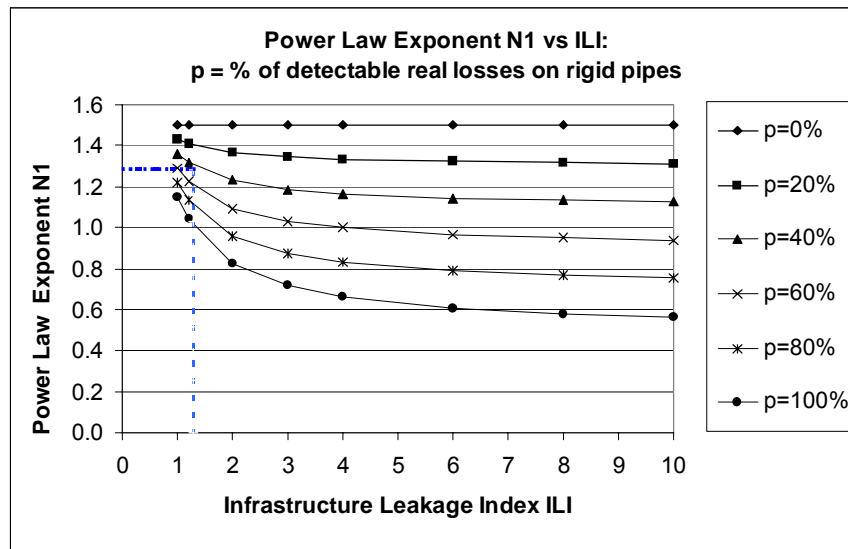

Figure 4: Predicting the power law exponent using ILI and % of detectable real losses on rigid pipes

Comparison of some predicted and actual N1 values from tests in Australia and USA are shown in Table 1. The relationship shown in Figure 4 is considered to be the most reliable practical method currently available for predicting the N1 exponent in individual distribution systems or sub-systems, in the absence of specific test data. Further information on N1 predictions and N1 tests can be found in the PresCalc software.

Table 1 Comparison of predicted power law exponents with test data, using equation (3)

Country	ILI	p%	Power Law N1	
			Predicted	From Test
Australia	1.3	43%	1.29	1.33
U.S.A	3.0	27%	1.29	1.33
U.S.A	5.5	99%	0.63	0.67
U.S.A	12.0	100%	0.55	0.60

Data from theoretical hydraulics and laboratory tests (Sources B and C)

The equation for 'turbulent' flow (Q) through a fixed orifice of area A at pressure P is:

$$Q = Cd \times A \times (2gP)^{0.5} \qquad \dots\dots\dots\dots\dots\text{(4)}$$

However, the exponent in equations (1), (2) and (4) will appear to exceed 0.5 if the area of the hole or holes, and the coefficient of discharge Cd, also change with pressure

Over the last 10 years, results from an ever-increasing number of laboratory tests have been published for leaking pipe samples from both mains and services, and on artificially created holes, slots and cracks in pipes of different materials. In laboratory tests, the researcher can measure or assess the size and shape of the orifice or crack

being tested, calculate the non-dimensional Reynolds Number (Re), and characterize the flow as 'turbulent', 'transitional' or 'laminar'. Calculation of Re is based on velocity, hydraulic diameter and kinematic viscosity (which varies with temperature). Data that have been analysed to date using the Power law equation (notably from South-West Water (UK), University of Johannesburg, C.I.A.C.U.A. in Colombia, and John May) show some consistent conclusions, briefly summarized below:

- ⬥ Circular holes:

  - ▪ N1 near 0.5 for metal & pVC pipes for Reynolds Number Re > 4000

  - ▪ N1 likely to be near 0.5 for polyethylene and AC, and Re > 4000

  - ▪ but N1 can be in range 0.5 to 1.0 for small leaks (see Figure 6)

  - ▪ and N1 for corrosion hole clusters may be even higher

- ⬥ Longitudinal splits: Length/Width ratio (L/W) is an important parameter

  - ▪ pVC pipes: N1 = 0.5 at low L/W, rising to 2.0 at L/W = 500

  - ▪ AC pipes: N1 = 0.8 to 1.0 (some opening of crack occurs)

For Re less than 4000, the flow characteristic through a fixed area circular orifice changes from 'turbulent' to 'transitional', and the exponent can rise to between 0.5 and 1.0. This effect is seen in Figure 5, for tests on 1.1mm diameter hole in a copper pipe.
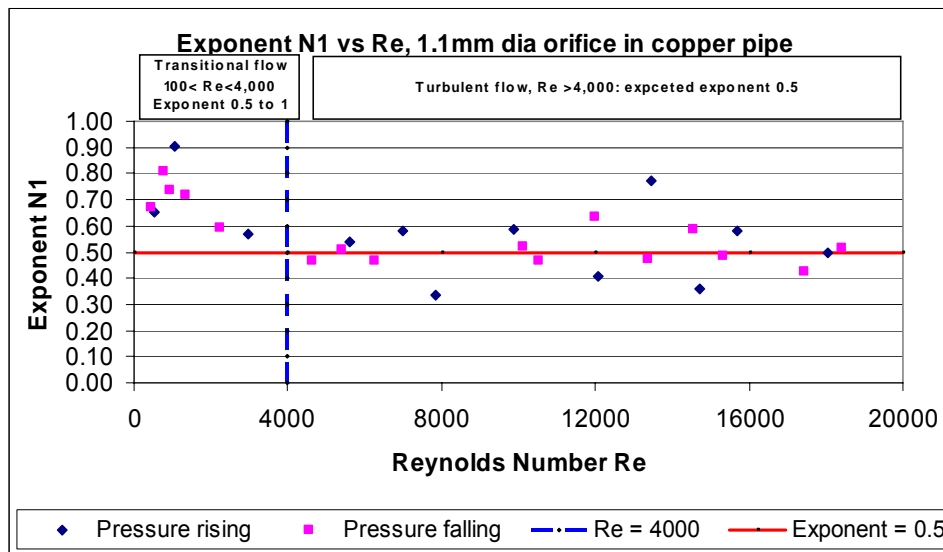
Figure 5 Reynolds Number Re vs. Exponent N1 Source of data: John May

However, information from laboratory tests presented in terms of Re and discharge coefficient Cd is not particularly 'user-friendly' for leakage engineers, who must try to interpret the behaviour of various leakage paths of different shapes and sizes in terms of flow rates and pressures. If the boundary value of Re = 4000 applies to any size or shape of orifice, then the flow at which the change from transitional to turbulent flow occurs (Q') is a function of the wetted perimeter (p) of the orifice and the water temperature T

Q' (litres/hour) = 3.6 x Ct x p ………………………………………….…………….. (5)

where; Ct = 1 – 0.023 x (20-T);   T is in $^\circ$ Centigrade; and p is in mm.

For a circular orifice of diameter D mm, the wetted perimeter p = $\prod$ x D, so
Q' (litres/hour) = 11.3 x Ct x D   ……………   …… (5a)

For a circular orifice, a relationship can also be derived between Q', pressure P (in metres) and water temperature T (in $^\circ$ Centigrade), see Figure 6. If flow is less than Q' it

will be transitional, with N1 greater than 0.5. This shows why small leaks that contribute to background leakage can have N1 values greater than 0.5, even if their area is fixed.
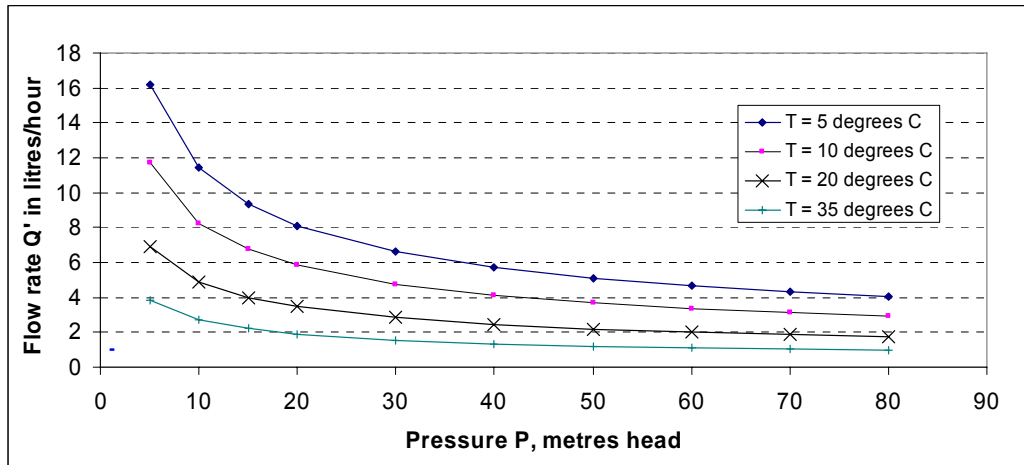

Figure 6 Pressure: flow relationship for circular orifice at transitional: turbulent boundary, Re = 4000

For artificially created rectangular slots in pipes, of length L and width W, the equation for Q' is $\quad$ Q' (litres/hour) = 7.2 x Ct x (L + W) $\qquad$ ………………………. (5b)

Comparison of equations 5a and 5b demonstrates that the boundary flow Q' between transitional and turbulent flow for slots, splits and cracks in rigid pipes can be far greater than that for a circular orifice; and transitional flow has an N1 exponent greater than 0.5. In addition, for flexible pipe materials, the N1 exponent will be further increased if the area of the crack changes with pressure, either in terms of the average width of the crack (influenced by the L/W ratio), and/or the length of the crack.

Extending the range of operating pressures for the Unavoidable Annual Real Losses (UARL) formula

The equation used for calculating Unavoidable Annual Real Losses (UARL) (Lambert et al 1999), is based on components of Real Losses originally calculated at 50 metres pressure, then corrected for pressure, assuming a linear pressure: leakage rate relationship for large systems with mixed pipe materials. The equation for UARL is

$\quad$ UARL (litres/day) = (18 x Lm + 0.8 x Nc + 25 x Lp) x P $\quad$ ………. (6)

Where L is mains length (km), Nc is number of service connections (main to property line or curb-stop), Lp is total length (km) of private pipes (property line or curb-stop to customer meter) and P is average pressure in metres.

Practical limitations placed on applying the UARL formula were, originally, that systems should not have less than 5000 service connections, not less than 20 connections/km of mains, and not less than 25 metres of pressure. Following recent research, the lower limits for number of service connections is now 3000, and the lower limit on density of connections has been removed (Liemberger, 2005).

The lower limit of 25 metres for pressure sought to avoid significant errors from extrapolating the assumption of a linear pressure: leakage relationship to systems with 100% flexible pipes at low pressures, where the N1 exponent would be close to 1.5 (see Figure 3). However, in many systems where the operating pressure is less than 25 metres, Utilities or their consultants wish to calculate a realistic UARL. Having considered various options, the authors recommend the most effective approach to achieve this objective is to introduce a coefficient Cp to the UARL equation, where Cp can be assessed for different %s of rigid and flexible pipes, over a wider range of pressures; this

is a similar principle to using different values of Cd for flow through orifices at low Reynolds numbers. A slightly more detailed equation for UARL would therefore become:

$$\text{UARL (litres/day)} = (18 \times Lm + 0.8 \times Nc + 25 \times Lp) \times P \times Cp \quad \ldots\ldots\ldots (7)$$

The authors' provisional calculations of the relationship between Cp and pressure, for systems with different proportions of Real Losses on rigid and flexible pipes, are shown in Figure 7. These are based on the assumption that the N1 exponent for background leakage and bursts on flexible pipes is 1.5, and for bursts on rigid pipes N1 is 0.5.
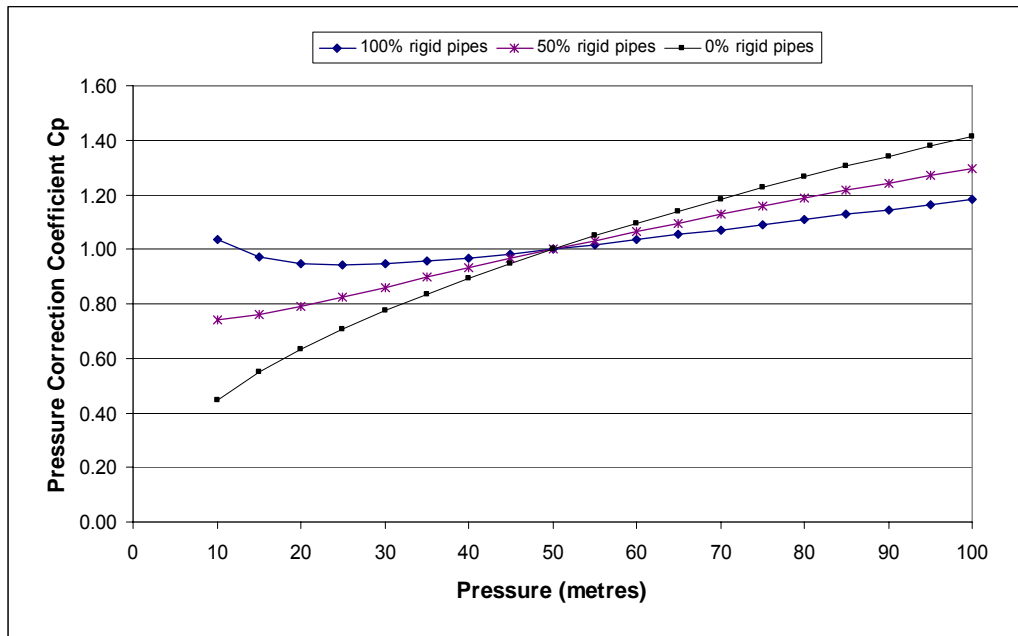

Figure 7: Provisional relationship between pressure and Cp, for systems with different % of rigid pipes

New Information on Pressure: Consumption Relationships

The Fixed and Variable Area Discharge (FAVAD) concept introduced by May (1994) is versatile, in that the simple power law can be applied not only to flows from leaks and bursts, but also to elements of consumption. For example, when toilet cisterns subject to mains pressure are flushed, water flows in under mains pressure as the cistern is emptying. N1 exponents of between 0.07 and 0.25 have been derived by comparing the volumes discharged against the inlet pressure, for various types of UK toilet cisterns. Bartlett (2004) reports a pressure: consumption exponent of 0.2 for indoor water consumption at student accommodation on the campus at Johannesburg.

For external irrigation consumption, a pressure: leakage exponent of around 0.5 may be expected for turbulent discharges through fixed area orifices. Cullen (2004) tested the pressure: discharge characteristics of four different types of rigid irrigation equipment, and two types of flexible soaker (or seepage) hose. Tests on a Pop-Up Irrigation System, a Spray Riser Network, an Oscillating Sprinkler, and a Tri-Arm Sled Sprinkler, all produced exponents close to 0.5. However, both of the tests on the 15m long seepage/soaker hoses, with hundreds of tiny orifices, yielded N1 values close to 0.75; but a discontinuity and reduction in exponent N1 occurred at around 40 metres pressure, which may be due to a change from transitional to turbulent flow through the individual tiny orifices.

Another reliable study of the effect of pressure on external residential irrigation is provided (Bamezai & Lessick, 2003) by data from two test groups and two control groups of neighbourhoods in California. The results from the larger of the two test groups support the assumption of an N1 of 0.5 for external irrigation. The results from the smaller test group were statistically inconclusive.

Pressure: new burst frequency relationships, and implications for calculating economic benefits of pressure management

Publication and dissemination of limited data on pressure: burst frequency relationships reported in Lambert (2002) has begun to stimulate increasing interest in this topic, which has previously received little or no attention internationally. The Pressure Management Team is seeking good quality data of recorded burst frequencies 'before' and 'after' pressure management, using the provisional equation:

Burst frequency (or repairs cost) varies with Pressure N2:

The exponent N2 can be calculated using freely available software (N2Calc). This approach gives more reliable results than attempts to derive relationships by statistical analysis of pressure and mains break frequency from large numbers of District Metered Areas in the UK (UKWIR, 2003).

Test data from Australia, UK and Italy analysed to date, summarized in Table 2, shows that the N2 exponent appears to vary between a minimum of 0.5 and a maximum of 6.5. These exponents represent significant (and often spectacular) reductions in new burst frequency and annual repair costs, with additional beneficial effects on average run times of bursts, backlog of repairs, active leakage control intervention frequency, and infrastructure replacement budgets. This topic is expected to become a major aspect of the future research of the Pressure Management Team, as Utilities realize the major economic savings and operational advantages which can be achieved by reduction of excess pressures and surges.

Table 2: Summary of N2 exponents recommended or calculated from tests

Country	System	N2
UK	UKWIR recommendation	> 0.5
Australia	Brisbane Pilot Area	0.5
	Yarra Valley Pilot Area D	0.64
	Yarra Valley Pilot Area B	0.68
	Yarra Valley Pilot Area C	0.91
	Yarra Valley Pilot Area A	1.55
UK	Welsh Water, Mains	3.0
Australia	Gold Coast pilot, Services	4.9
	Gold Coast pilot, Mains	6.3
Italy	Turin	6.5

Suggestions for practical research topics

The following are some of the research topics that can help the Pressure Management Team of the Water Losses Task Force to improve the current practical methods of analysing and predicting the effect of pressure management on leak flow rates, frequency of new bursts, and consumption:

- ⬥ Lab. tests on circular holes drilled in AC & Polyethylene pipes (check N1= 0.5)
- ⬥ Field tests on ring cracks and joint failures to establish N1 exponents
- ⬥ Lab tests on slots in rigid pipes (to check if turbulent flow occurs at Re > 4000)
- ⬥ Lab tests on individual corrosion holes (check influence of pipe wall thickness)
- ⬥ Lab tests on corrosion hole clusters (check influence of pipe wall thickness)
- ⬥ Field tests on systems with low background leakage (to check N1 = 1.5)

◆ More case studies on N2 exponents for pressure: new burst frequency

Specialist Software for Pressure Management Predictions

The development of the practical approaches explained in this paper has been accompanied, over the last ten years, by specialist customised software for analysis of carefully specified field test data, and prediction of technical and economic effects of pressure management. It needs to be emphasised that these are not Network Analysis Models, and that (except in some very complex systems) Network Analysis Models are not required for effective decision-making. For example, in Sao Paolo (Brazil), hundreds of pressure management systems have been successfully specified and installed on the basis of specifically designed 24-hour tests, and have achieved their forecast benefits and payback periods.

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