DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

# Modelling the Impact of Pressure Management on Pipe Burst Rates

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## Reference

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*This work was completed to address information gaps identified during the development of the New Zealand Pressure Pipe Inspection Manual, established at the bequest of the Water Services Managers Group. The Building Innovation Partnership has provided funding and commissions for this research.*

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# Executive Summary

**Background and Objective:**

This study investigates the relationship between pressure and burst rates in water distribution systems. The study aims to understand how pressure affects burst rates under both steady-state and pressure-managed conditions, analyze existing and new predictive models, and provide insights from real-world case studies.

**Key Findings:**

- ***Pipes fail*** when the load on a pipe exceeds the weakest point in the pipe wall. Wall stresses are mainly the result of pressure, although external forces also contribute. The main strength deterioration mechanisms are corrosion, fatigue fracture, soil scouring and construction damage.
- The ***leakage flow rate*** is the main factor making leaks discoverable. Pressure drives the leakage flow rate by influencing both the leak area and velocity.
- Several international studies and new data analyses show a positive, approximately ***linear relationship*** between burst rate and maximum daily pressure.
- Evidence is presented that ***pipe burst rates respond to pressure management in two stages*** - a substantial immediate reduction, followed by an increase to a more moderate reduction after a few years.
- Two pressure management prediction models are presented:
    - **Lambert's Model** predicts a reduction in burst rates with a cubic relationship to pressure reduction for pressure-dependent bursts. The model predictions are shown to be reasonably accurate.
    - **Vega's Model** predicts an initial significant drop in burst rates, followed by an increase to a higher burst rate in line with the steady-state pressure and burst rate relationship after a few years.
- Case Studies:
    - ***Drenthe, Netherlands:*** Demonstrated a sharp initial decline in burst rates after pressure reduction, which later increased, aligning with Vega's model predictions.
    - ***Barwon Water, Australia:*** Showed consistent reductions in burst rates for AC and CI pipes after implementing pressure management in line with Lambert's prediction, but with evidence of a two-phase response.

**Conclusions:**

- Pressure management is effective in reducing pipe bursts, with benefits including lower water loss, extended pipe life, and reduced repair costs.
- The impact of pressure management seems to involve two stages: an immediate significant reduction in bursts followed by a moderate increase over time as pipes age, indicating that the initial benefits might not be sustained indefinitely.

**Recommendations:**

- Water utilities should consider long-term strategies for pressure management, including periodic reassessment of the effect of pressure management on pipe failure rates.
- Further research should focus on refining models to better predict burst rate changes under diverse operational pressures and network conditions, gathering more data from the field to support further work.

# 1 Introduction

## 1.1 Background

The second edition of the National Water Loss Guidelines (Water NZ, 2023) makes a strong case for reducing losses in water supply systems: water is considered a taonga (treasure), and water losses represent a waste of this precious resource. The drivers for reducing water losses include giving effect to Te Mana o te Wai, reporting requirements of Taumata Arowai, improving resilience to better deal with water scarcity and climate change, reducing greenhouse gas emissions and demonstrating stewardship of the environment.

The guidelines list four strategies for reducing real losses: good asset management practices, speed and quality of repairs, active leak detection and pressure management. In pressure management, District Metered Areas (DMAs) are supplied through pressure-reducing valves (PRVs) that reduce excess pressure. These DMAs are called Pressure Managed Areas (PMAs).

Pressure management is widely used worldwide and is growing in popularity in New Zealand. The benefits of pressure management include reductions in leakage and pipe burst rates, lower water demands and longer pipe service lives (Water NZ, 2023).

International field studies have reported that pressure management substantially reduces pipe burst rates, thus reducing the associated damage, disruptions and repair costs. Therefore, the cost savings resulting from reduced pipe bursts have become a key driver for pressure management.

However, the mechanisms through which pressure management reduces pipe burst rates and the preservation of the reduction over time are not yet well understood. For instance, while it may be expected that the reduced burst rate after pressure management will correspond with the steady-state burst rate of similar pipes at the lower pressure, pressure management has been shown to result in significantly lower burst rates.

There are indications that pipe burst rates respond to pressure management in two stages - a substantial immediate reduction, followed by an increase to a more moderate reduction after a few years (Vega, 2023). However, more work is required to understand the relationship between pressure and burst rates and how these relationships change over time under both pressure management and steady-state conditions.

## 1.2 Project Objectives

The aim of this project was to investigate the impact of pressure on pipe burst rates under steady-state and pressure management conditions through a review of available literature and the analysis of field data. The project objectives were as follows:

- Conduct a literature review on pressure and pipe burst rates, including published data from field studies.
- Collect and analyse data on pressure and burst rate data from water utilities.
- Evaluate existing and newly developed models to predict the effect of pressure management on pipe burst rates.

## 1.3 Scope

Pressure affects burst rates in both mains and service pipes, but little research results and data are available for the latter. Thus, this report focuses on mains while including results of service pipes where available.

Transient pressures may occur in distribution systems due to sudden valve closures or pumps stopping or starting. These transient pressures may be significantly larger than regular system pressures and thus need to be addressed when they occur. However, since transients are network-specific and mostly not a problem in gravity systems, this report only considers regular diurnal pressure fluctuations and daily maximum (static) pressure in pipes.

## 1.4 Layout of this Report

This report starts by discussing how leaks in pipes develop and the role that pressure plays in this process in ***Chapter 2***. Loads on pipes and pipe strength are discussed, including the deterioration mechanisms that reduce pipe strength. The influence of pressure on the leakage flow rate is then discussed, considering how pressure affects both the leak area and flow velocity.

***Chapter 3*** discusses the relationship between pressure and pipe burst rates under steady-state conditions, i.e. where pipes in the same system are subjected to different pressures. Pressure variations and characterisation are reviewed, followed by discussions of how the daily maximum pressure and pressure fluctuations affect burst rates. These discussions include analyses of New Zealand data.

***Chapter 4*** discusses pressure management and how it affects pipe burst rates. The existing and new models for predicting burst rates are presented and compared with data from several case studies.

Finally, ***Chapter 5*** summarises the findings of this study and makes key recommendations.

# 2 Development of Pipe Failures

## 2.1 Introduction

Like all infrastructure systems, water supply networks are subject to deterioration and failure. However, monitoring and maintenance of pipes and fittings is hindered by the fact that they are buried and thus invisible unless excavated. In practice, pipe bursts are the primary way to estimate pipe condition, and many studies have analysed the relationship between pipe bursts and factors such as pipe material age, diameter, and material.

A ***leak*** is defined as "a failure of the water supply network such that there is an unplanned loss of water from the water supply network" (Pearson, 2019). Leaks can be further classified as background leaks, which have "flow rates too low to be detected by an active leakage control campaign" and bursts. Bursts can be either reported or unreported. Historic pipe burst rates are based on repair records and thus, by definition, exclude unreported leaks. Thus, in this report, the term 'burst' refers to leaks that have been discovered.

Bursts can occur instantaneously, but generally, they develop over many days, weeks or even years. It is important to understand the causes and development of leaks over time and how pressure can play a role in this process. The development path of a leak is summarised in Figure 1.

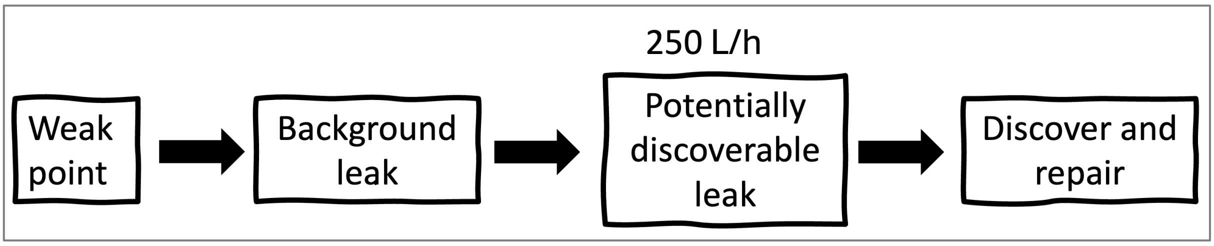


*Figure 1 Development path of a pipe leak*

A structure, such as a pipe wall, will fail when subjected to loads that exceed its strength. Pipe loads can be internal due to pressure or external due to surface loads, soil movement or construction activities. All points on a pipe wall do not have the same strength, and some points may be significantly weaker, for instance, due to manufacturing defects or construction damage. Since a pipe will fail at its ***weakest point***, its strength is determined by its weakest point, not its average wall strength.

Pipe walls are subjected to various deterioration mechanisms that will weaken the pipe over time. After some time, the strength of the weakest point on a pipe will deteriorate to such an extent that the load exceeds its strength, resulting in a breach of the pipe wall and initiation of a leak.

Initially, the leak may be tiny, but it will grow over time due to the deterioration mechanisms. Leaks are discovered when they have a measurable impact, such as water appearing above the ground or a drop in system pressure, or through active leak detection. The primary determinant of discoverability is the leakage flow rate. Tiny leaks don't show themselves and cannot be discovered with regular leak detection equipment. They are called ***background leaks,*** and very little is known about their prevalence and properties in water networks.

Once a leak reaches a flow rate of approximately 250 L/h, it becomes big enough to be detected and is called a ***potentially discoverable (PD) leak***. However, most PD leaks don't become visible at this point and will continue to grow until they are discovered. Once a leak is discovered, it is called a ***burst,*** which can be repaired.

Pressure plays a vital role in the leak development process as the primary load on pipe walls, a contributing factor in some deterioration mechanisms, and the main driver of the leakage flow rate. Pipe leaks are orifices, and thus, the leakage velocity will increase with the square root of pressure. However, pressure may also affect the area of leaks and thus have a bigger impact on the leakage flow rate.

This chapter discusses the factors influencing the development and behaviour of pipe leaks, with a particular emphasis on the role of pressure. Loads on pipes, pipe strength and deterioration, leakage flow rate, and the strength index (a way to plot pipe strength on the same scale as pressure) are discussed in this section. More information on the development of leaks can be found in Vega et al. (2024).

## 2.2 Loads on Pipes

Pipes are subjected to internal and external loads. Internal loads are caused by pressure, which is counteracted by internal pipe wall stresses. The relationship between pressure and wall stresses can be determined by considering sections through a closed cylinder, as shown in Figure 2.

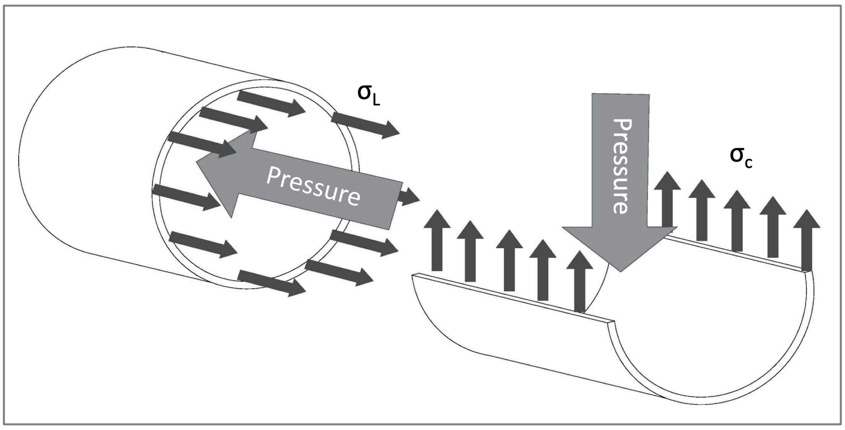


*Figure 2 Pressure and wall stresses in a closed cylinder*

Applying the principle of equilibrium leads to the following equations for circumferential ($\sigma_c$) and longitudinal ($\sigma_L$) wall stresses:

$$\sigma_c = \frac{pD}{2t} \tag{1}$$

$$\sigma_L = \frac{\mathrm{pD}}{4\mathrm{t}} \tag{2}$$

Where *p* is pressure, *D* internal pipe diameter, and *t* wall thickness. The equations show that internal wall stresses are proportional to pressure, and that the circumferential stresses are double the longitudinal stresses. The impact of longitudinal stresses is further diminished by external pipe supports such as thrust blocks, brackets and soil friction. Unlike the unsupported closed cylinder in Figure 2, longitudinal pressure forces will be counteracted by pipe supports and thus have a small or no impact on longitudinal stresses.

Pipe pressures vary diurnally due to water demand fluctuations in a network and reach a maximum during the early morning hours when demands are at a minimum, known as the ***minimum night flow (MNF)*** period. Besides the normal diurnal pressure fluctuations, pipes may also be subjected to pressure transients caused by pump switches, sudden valve closures or firefighting demands, resulting in short-term spikes in pipe wall stresses.

Finally, pipes are subjected to external loads such as soil and surface loads, swelling clays, soil movement, and thermal expansion. The maximum stress in a pipe wall will likely result from a combination of internal and external forces.

## 2.3 Pipe Strength

Pipes are designed to handle the loads they are subjected to under normal operational conditions. However, not all points on the pipe wall have the same strength, and weak points may be present due to manufacturing defects or damage.

Pipes are subjected to various deterioration mechanisms that reduce their strength over time. Weak points and discontinuities (such as small leaks) are more susceptible to deterioration mechanisms than the rest of the pipe wall. The main pipe deterioration mechanisms are corrosion, fatigue, soil scouring and construction damage, which are discussed in more detail in this section.

### 2.3.1 Corrosion

Material loss from the pipe wall is called corrosion and can occur through chemical, electrochemical and biological processes.

Iron pipes are susceptible to corrosion, such as pitting or graphitic corrosion. Pitting corrosion acts on the pipe wall, reducing its thickness, while graphitic corrosion leaches iron from the metal matrix, reducing pipe wall strength (Ruchti, 2017). Soil properties have a significant impact on the corrosion rates of buried metal pipes and soils with high moisture content, low resistivity, high dissolved oxygen, and high microbial activity increase corrosion rates.

Corrosion of asbestos cement (AC) pipes is caused by soft water, acids, and sulphates (Campopiano et al., 2009). Soft water leaches the free lime from the pipe wall matrix, releasing asbestos fibres. Acidic sulphatic soils may react with the cement in the pipe wall, creating expansive byproducts that weaken the pipe (NZWWA 2001; Punurai and Davis 2017).

Corrosion in pipes is modelled with several approaches, including a constant rate, linear or power growth, and two-phase modelling, which has a rapid initial corrosion rate that slow down over time.

Pressure does not affect corrosion directly, although it may play a minor role inside the pipe by lessening the protective effect of corrosion byproducts.

### 2.3.2 Fatigue fracture

Material fatigue is caused by force or pressure cycles and contributes significantly to the development and growth of pipe cracks. Crack initiation due to fatigue happens at a microscopic level and is influenced by the pressure load, number of loading cycles, and microstructure of the material (Bardet et al. 2010; Rajani and Kleiner 2012; Richard and Sander 2016).

Crack propagation occurs through a cumulative fracture process in which the crack grows incrementally due to fluctuating load cycles. Once the crack reaches a critical length, residual fracture occurs, causing rapid catastrophic failure of the pipe.

Crack propagation due to pressure fatigue is modelled using the Paris law, which is based on fracture mechanics principles:

$$\frac{da}{dN} = C_1\,\Delta K^{C_2} \tag{1}$$

Where *a* is half the crack length (m), *N* the number of cycles, $\Delta K$ the stress intensity factor in (MPa $\sqrt{m}$), and $C_1$ (in $\frac{m/cycle}{(MPa\,\sqrt{m})^{m}}$) and $C_2$ (-) are material-dependent constants. The stress intensity factor is given by the equation:

$$\Delta K = \Delta P \frac{D}{2t} Y\sqrt{\pi a} \tag{2}$$

Where $\Delta P$ is the size of the pressure fluctuation (MPa), $D$ is pipe diameter (m), and $t$ wall thickness (m). $Y$ is a geometric factor based on the crack length, pipe diameter and wall thickness.

It should be noted that fatigue fracture isn't affected by the maximum load but by the size of load fluctuations, the number of load cycles, and the current crack length. Pipes are subjected to several pressure fluctuations, including diurnal, background transient noise and large transients, all of which may contribute to crack growth.

Iron pipes are susceptible to fatigue, and crack growth rates are affected by the quantity and shape of graphite in the pipe wall. The spherical graphite particles in ductile iron are less susceptible to crack growth than the graphite flakes in cast iron pipes (Hosdez et al. 2017).

Asbestos cement is a brittle material that is susceptible to cracking, particularly circumferential cracks, as a result of shrinking or swelling clays, soil movements, temperature changes, and frost loads (Ellison and Spencer, 2016; Mordak and Wheeler, 1988). Thus, a seasonal pattern is usually observable in AC failure rates. Longitudinal cracks also occur in AC pipes due to pressure fluctuations (Punurai and Davis 2017).

Plastic pipes are flexible but can deteriorate and become more brittle, for instance, due to UV light exposure, cold temperatures, disinfectants, hydrocarbons, and solvents (Barton et al., 2019; Brandt et al., 2017). Crack growth rates in PVC are significantly affected by the additives used in the manufacturing process (Farrow et al. 2017).

Polyethylene (PE) pipes are resistant to UV light and are designed to resist crack growth under normal operating conditions. However, slow crack growth does occur. In some cases, high water chlorine content has been found to weaken PE pipes, leading to early failure (Colin et al., 2011). Most PE failures occur at joints (Barton et al. 2019) made using a welding process. Joint strength is susceptible to impurities and the correct welding temperature and force, which are difficult to achieve in the field.

### 2.3.3 Soil scouring

Once a leak initiates, local fluidisation of the soil outside the leak may cause scouring of the pipe wall surface, reducing the wall thickness and accelerating leak growth. Figure 3 (Bailey, 2015) shows local fluidisation occurring in a uniform granular medium caused by an upward leakage jet. The water jet picks up sand particles at the leak opening and deposits them at the top of the fluidised zone. The sand particles then slowly move down in the mobile bed zone until they reach the leak opening, and the process repeats. The pipe wall is scoured by the rough sand particles moving across it.

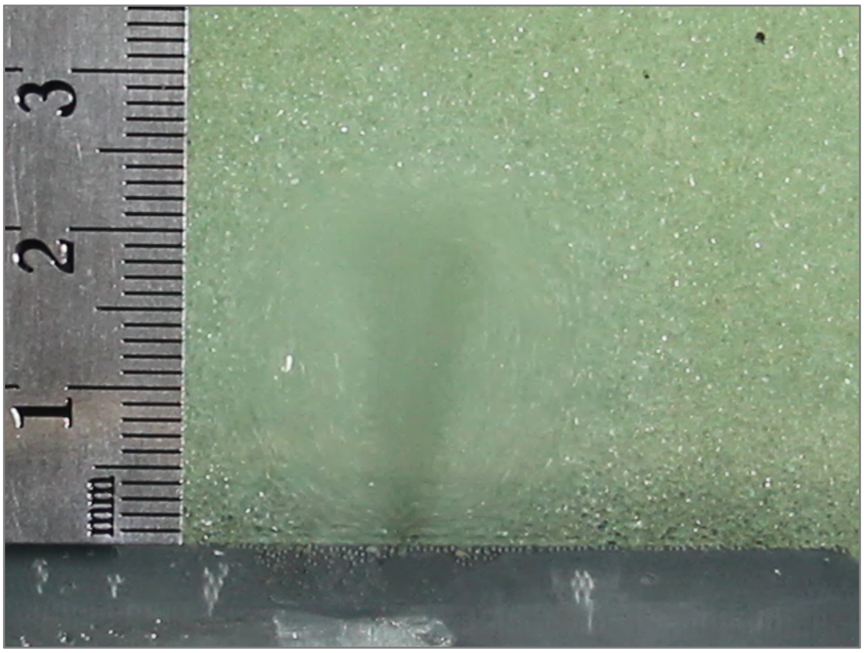


*Figure 3 Local fluidisation in a uniform granular medium caused by a simulated leak through the bottom of the tank (Bailey, 2015)*

The scouring process may enlarge the existing leak or create a new leak. For instance, Figure 4 shows failures made by a leaking collar moving sand particles across the surface of the pipe. Figure 4(a) shows an example taken from the field, and Figure 4(b) shows the result of an experimental study by Pike et al. (2018).

(a) (b)

*Figure 4 a) A failed 180 mm diameter PE pipe caused by soil erosion driven by a water jet from a leaking collar and b) a similar failure from a laboratory study (Pike, 2018)*

The study found that leak flow moving across the pipe surface (as shown in Figure 4) resulted in much greater scouring rates than other leak orientations. Besides the leak orientation, the leakage flow rate was the most critical factor influencing the scouring rate. A linear relationship was observed between the scouring and leakage flow rates.

Since the leakage flow rate is primarily driven by pressure, it can be concluded that pressure will significantly impact the scouring rate of leaks in water pipes.

### 2.3.4 Construction damage

Pipes can be damaged when the surrounding soil is excavated during construction, and the pipe is damaged by soil movement or construction equipment. The pipe pressure does not affect construction damage.

## 2.4 Leakage Flow Rate

Leaks are hydraulic orifices and thus adhere to the orifice equation, which is derived from the conservation of energy principle. The orifice equation for the flow rate $Q$ through an orifice or leak is given by:

$$Q = C_d A \sqrt{2gh} \tag{3}$$

Where $C_d$ is the discharge coefficient, $A$ leak area, $g$ gravitational acceleration, and $h$ pressure head.

It has been shown that the area of leak openings is not fixed but varies linearly with pressure (Cassa and van Zyl 2013; Van Zyl and Malde 2017). Thus, the leak area can be described by:

$$A = A_0 + mh \tag{4}$$

Where $A_0$ is the initial leak area (under zero pressure conditions), and $m$ the head-area slope. Replacing this equation into the orifice equation results in the modified orifice or FAVAD (Fixed and Variable Area Discharges) equation:

$$Q = C_d\sqrt{2g}(A_0 h^{0.5} + m\,h^{1.5}) \tag{5}$$

The modified orifice equation consists of two terms that vary with pressure to the power 0.5 and 1.5, respectively. Van Zyl et al. (2017) discuss the modified orifice equation and its implications for leakage behaviour.

The head-area slope $m$ is determined by the leak type (e.g. round hole, longitudinal crack or circumferential crack), leak dimensions, and pipe material, diameter and wall thickness. The following head-area slopes are recommended for different leak types based on experimental and modelling analyses (Niebuhr et al. 2020):

- Any leak type in small diameter metal pipes: head-area slopes are very small (-0.02 mm$^2$/m to 0.02 mm$^2$/m), and orifice flow may be assumed.
- Round holes in any pipe material: head-area slopes are very small (-0.02 mm$^2$/m to 0.02 mm$^2$/m), and orifice flow may be assumed.
- Circumferential cracks: head-area slopes are small and mostly negative (-0.5 mm$^2$/m to 0.5 mm$^2$/m). It is reasonable to assume orifice flow in most cases.
- Longitudinal cracks: Large head-area slopes (> 0.3 mm$^2$/m). Cassa and van Zyl (2013) proposed the following equation to predict the head-area slope of longitudinal cracks:

$$m_{longitudinal} = \frac{2.93157\ D^{0.3379}\ L_C^{4.8} 10^{0.5997(log L_c)^2} \rho\ g}{E\ t^{1.746}} \tag{6}$$

Where $D$ is the pipe diameter (m), $L_c$ crack length (m), $E$ elasticity modulus (Pa), $t$ wall thickness (m), and $\rho$ water density (kg/m$^3$).

## 2.5 Strength Index

It is useful to plot pipe strength on the same scale as the pressure since this allows the relationship between pressure and burst rate to be shown visually. To do this, the ***strength index*** of a pipe is defined as the pressure at which its weakest point will become a discoverable leak. The strength index concept is described in this section and applied later when discussing pressure management.

To demonstrate this concept's application, a pipe's strength index is plotted as a grey line in Figure 5. The strength index reduces with time as various deterioration processes weaken the pipe wall strength. The dashed line at point 1 represents a weak point that is not yet leaking. It will not be discoverable if the pipe pressure is at $Pb$ or $Pc$. However, if the pipe pressure is raised to $Pa,$ the weak point will fracture, creating a discoverable leak.

The solid line starting at point 2 represents a leak that continues to grow with time. When the leak reaches point 3, it will still be a background leak (i.e. too small to discover) if the pressure is at $Pc$. However, if the pressure is raised to $Pb$, the flow rate will increase enough for the leak to become discoverable.

Finally, if the pressure remains at $Pc$, the leak, and thus its flow rate, will continue to grow with time until it becomes discoverable at point 4. As the strength index line shows, the leak isn't necessarily discovered at this point but may continue to grow until it is eventually discovered and repaired.

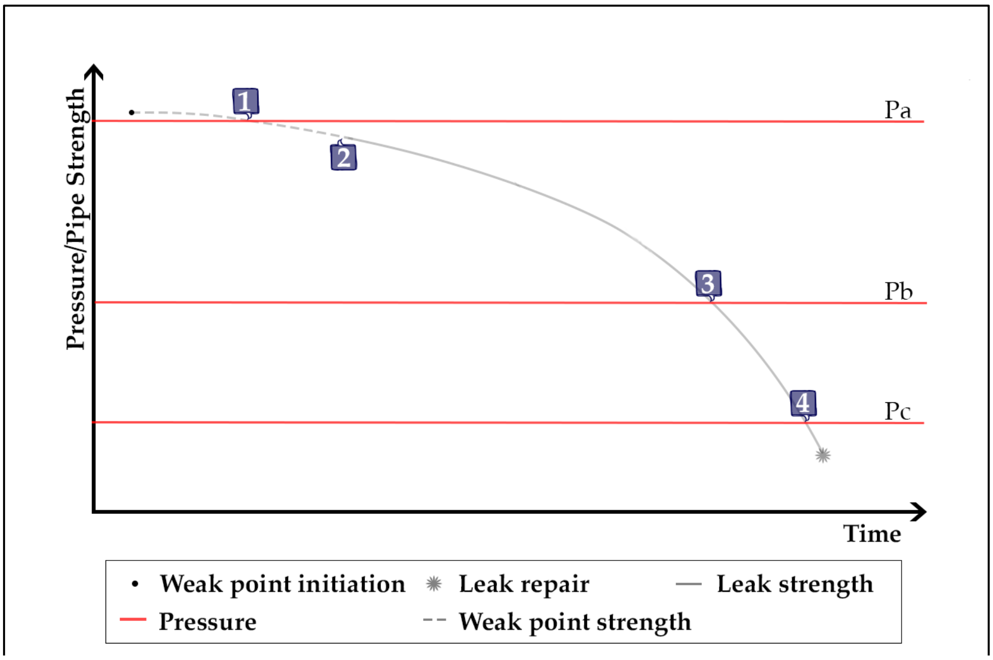


*Figure 5 The development of the strength index (grey line) of a pipe with time. The red lines represent different pressures (Vega, 2023)*

In summary, a leak becomes discoverable when its strength index falls below the pressure in the pipe. When the strength index is above the pressure, the leak is too small to be discovered and is thus a background leak.

# 3 Pressure and burst rate

## 3.1 Introduction

Pipe failures are affected by many different factors, such as pipe material, age, diameter, traffic, surface loads, climate and soil properties. Lopez et al. (2024) found the most critical factors influencing burst rates in Auckland are 1) age, 2) pipe material, 3) diameter and 4) pressure. Of these factors, only pressure can be influenced in an existing system without major construction work. Thus, this section will focus on pressure and how it influences pipe failures.

Only steady-state conditions will be considered in this chapter. The effects of pressure changes with time, such as pressure management, are discussed in the next chapter.

This chapter first describes the behaviour and estimation of pressure in PMAs (Pressure Managed Areas, followed by a review of research and data analyses of pressure-independent pipe bursts and the impact of the daily maximum pressure and pressure fluctuations on burst rates, respectively.

## 3.2 Pressure Variations

### 3.2.1 Pipe networks

Pressure varies spatially and temporally across different points in the pipe network as conditions change over space and time. These variations are due to pipe elevation, user demand, supply point pressure and distance from the supply point.

Pipe elevation varies across a DMA due to the local topography. The terrain may slope towards or away from the supply point or consist of hilly terrain with high and low points distributed across the zone. Under static conditions, pipe pressure will be determined by the height difference between the supply water surface and pipe. Thus, lower points will be subjected to higher pressures, and higher points lower pressures.

Under high user demand conditions, friction losses will occur in the zone, causing the hydraulic grade line to slope away from the supply point and pipe pressures to drop accordingly. Each pipe will experience a maximum pressure under MNF (Minimum Night Flow) conditions and a minimum pressure during peak demand conditions.

In most DMAs, the diurnal pressure variation is lowest near the supply point and greatest far from the supply point. However, PMAs or pumped systems controlled by the critical point, diurnal pressure variation may be greatest near the supply point and lowest far from the supply point (at the critical point). Finally, variations in the supply point pressure will also affect pressures in the DMA.

### 3.2.2 Pipes

As described in the previous section, a given pipe will be subjected to a pressure influenced by its position in the PMA. It is helpful to consider the pressure load on a pipe over its lifetime, as shown in Figure 6.

A newly installed pipe is first subjected to a test pressure substantially higher than its operational pressure. Then, after commissioning, it is subjected to an operational pressure (point 1) that varies diurnally (point 2), as well as background transient noise (point 3) caused by valves and taps opening and closing. Large transients (point 4) may occur at times, and finally, the pressure in the pipe will go to zero (point 5) when it is isolated for maintenance.

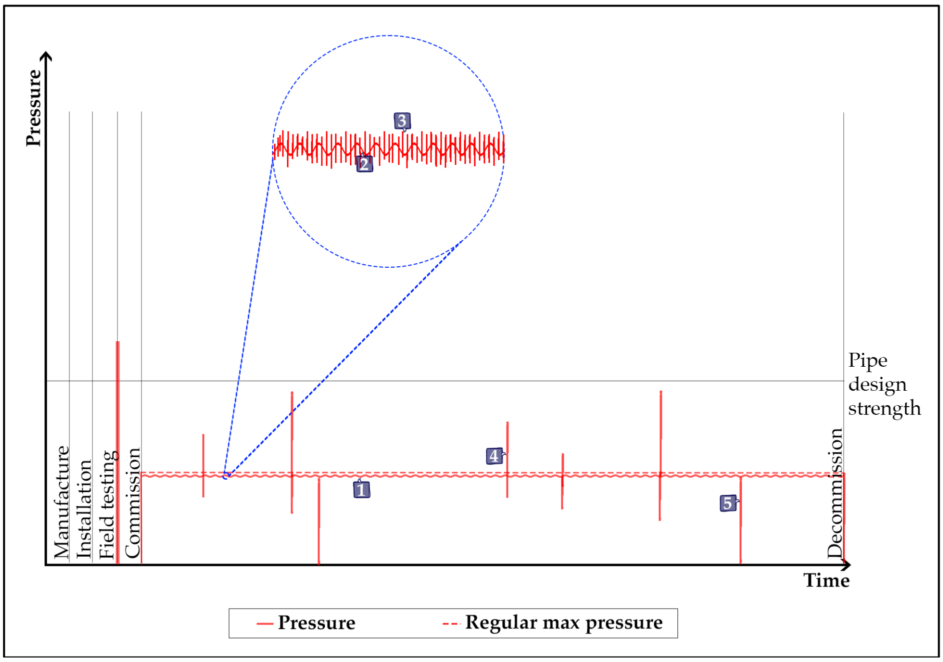


*Figure 6 Pressure load during the lifetime of a pipe (Vega, 2023).*

The two most important aspects of pressure for burst rate studies are the daily maximum pressure and pressure fluctuation. Transient pressures are also important but are system-specific and thus not considered in this report.

The daily maximum pressure is important as this represents the largest load on a pipe and, thus, the most likely time for a failure to occur. It is also when the highest leakage flow rate will occur and, thus, when a leak will be easiest to discover.

Pressure fluctuations are important as the main driver for fatigue fracture (see Section 2.3.2).

## 3.3 Past Studies

This section provides a brief overview of past studies that investigated the relationship between pressure and burst rate.

An early example of the link between pressure and burst rate is given in Figure 7, which shows the average mains burst rate against pressure for large water supply systems in Wales (Lambert, 2000). A strong, roughly linear correlation between burst rate and pressure is evident.

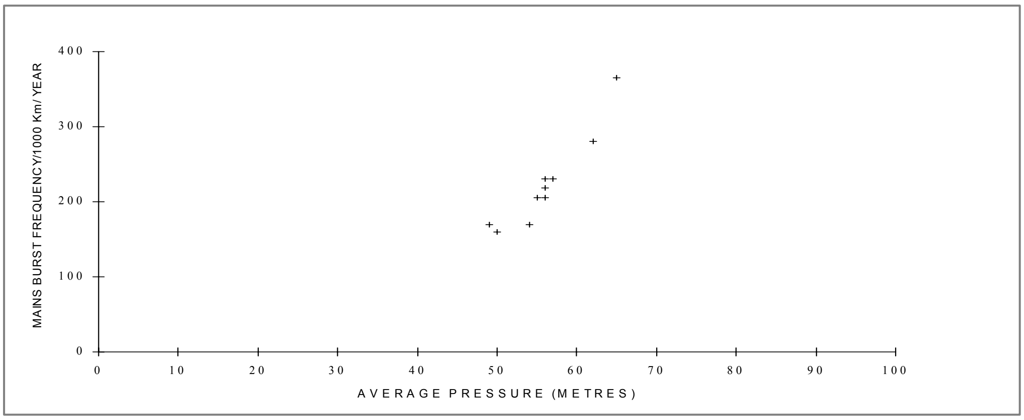


*Figure 7 Mains burst rates as a function of pressure for large water supply systems in Wales (Lambert, 2000)*

The UK Water Industry Research (UKWIR, 2003) investigated the relationship between burst rates and average zonal night pressure (AZNP) for 276 Bristol Water DMAs, 749 Yorkshire Water DMAs, and 769 Northwest Water DMAs, as shown in Figure 8. DMAs were grouped by AZNP, and the total number of failures and pipe length in each group were used to calculate the pipe failure rate. For Bristol Water, staff further selected 65 DMAs with the best data quality, and this group was analysed separately. The Yorkshire Water, North West Water and selected Bristol Water data show a positive relationship between pressure and failure rate, although only the Yorkshire data relationship was found to be significant at a 5 % level.

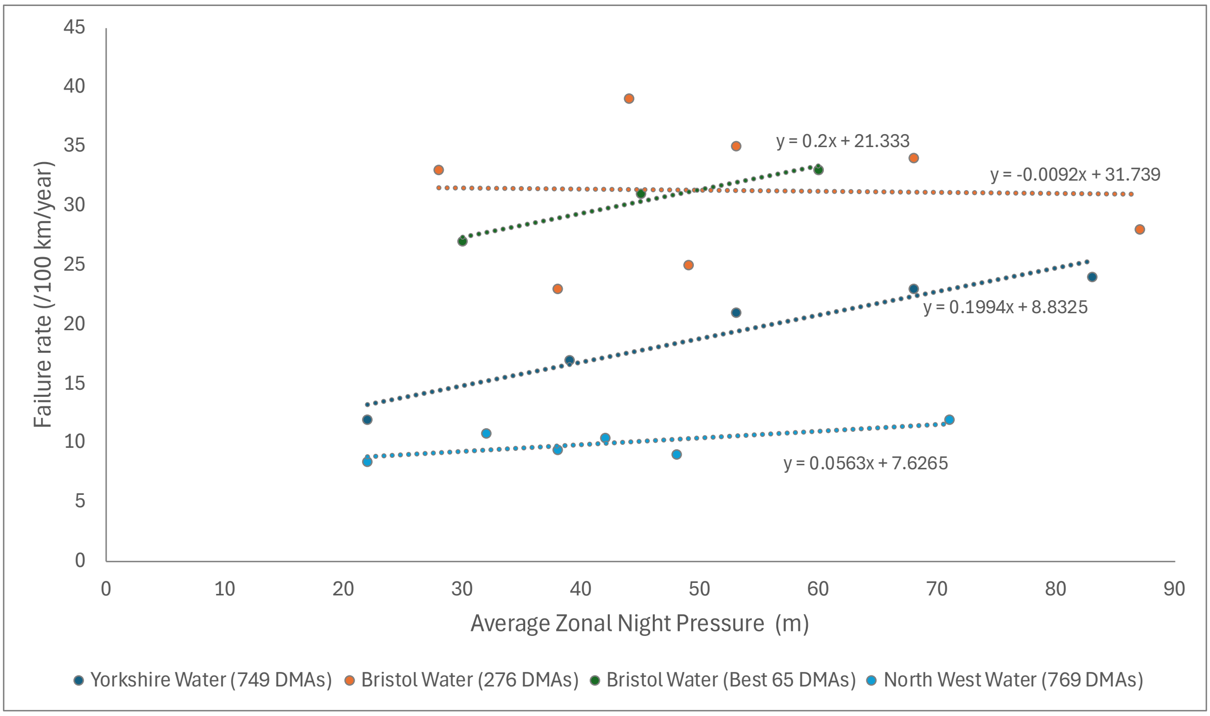


*Figure 8 Failure rate as a function of AZNP for DMAs in the UK (Source: UKWIR, 2003)*

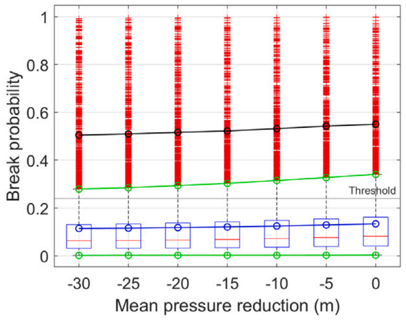
Thornton and Lambert (2006) suggested that there is a threshold pressure at which pipe failures will begin to occur. As the pipe ages, this threshold pressure decreases due to various factors, including corrosion, ground movement, and environmental and operational stresses.

Martínez-Codina et al. (2015) showed that pipe materials respond differently to pressure variations. The study examines how materials like fibre cement, ductile iron, and polyethene react under varying pressure conditions, highlighting that some materials are more prone to pressure-induced failures.

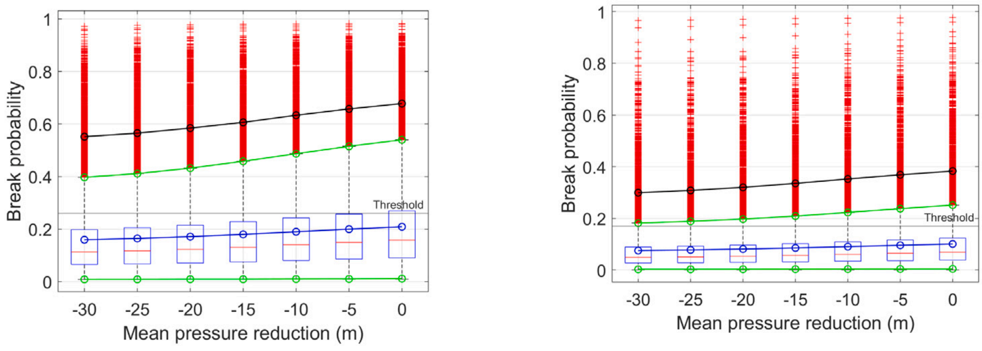
Martínez-Codina et al. (2016) developed a statistical technique to investigate the correlation between pipe bursts and the pressure parameters: maximum, minimum, average, range, variability, and variation rate. They applied the technique to six zones in Madrid and found the pressure variation range to be the strongest predictor of pipe bursts. Other indicators related to pressure variation were also found to affect burst rates, supporting the idea of limiting pressure variations in distribution systems to reduce burst rates. The maximum daily pressure was not found to correlate strongly with burst rates.

Martínez et al. (2020) analysed the correlation between pressure and main burst rates in five California networks, finding that areas with consistently high pressure have higher failure rates.

Jara-Arriagada and Stoianov (2021) studied the influence of mean pressure and pressure range on pipe burst rates using a large dataset with over 20 years of historic pipe break records from a medium-sized water supply utility in the UK. Their findings reveal that reducing mean pressure by 20 meters can lead to an 18% to 32% decrease in pipe breaks. Different pipe materials, such as cast iron, asbestos cement, and plastics, exhibit varying sensitivities to pressure conditions, particularly in older pipes. The study found that cast iron pipes are more prone to failure under large pressure fluctuations than large mean pressures. While the paper didn’t directly report on the relationship between average pressure and burst rate, they give the results of a break probability analysis for a reduction in pressure, shown in Figure 9. Note that, while the results are linked to a reduction in pressure, it reflects the data for steady-state conditions, not the effects of pressure management. The results show a roughly linear relationship between burst rate and average pressure for AC and CI.



(a)



(b)

(c)

*Figure 9 Failure probability as a function of pressure for a medium-size utility in the UK for a) AC, b) CI in winter, and c) CI in summer (Martínez et al., 2020).*

Wang et al. (2022) found that steady-state pressure contributes significantly to pipe failures, particularly through structural reliability analysis and material degradation. They also considered pressure variations, particularly transient events, on pipe bursts. The study highlights the significance of understanding pressure variations to improve burst prediction and prevention strategies.

Research by Ravanbakhsh et al. (2024) considered the correlation between burst rates and various parameters, finding that average pressure correlated significantly with failure rates in PE and AC pipes.

Rjaibi and Duchesne (2024) investigated the impact of pressure on pipe bursts, specifically focusing on how pressure covariates, such as maximum and mean pressures, contribute to burst rates. The study evaluated the impact of these pressure covariates on the likelihood of pipe breaks, providing insights into pressure management strategies. The findings suggest that maximum and mean pressures significantly influence pipe break occurrences, particularly in older pipes.

## 3.4 Pressure-independent Burst Rate

Some failures in water distribution systems are pressure-independent, such as failures due to soil movement or construction activity. It is necessary to understand the causes and rates of pressure-independent bursts to allow them to be separated from pressure-dependent bursts.

To be pressure-independent, the failure discovery time should not be significantly affected by the pressure in the pipe. Since pressure affects the leakage flow rate and, thus, the time at which a gradually developing leak will be discovered, pressure-independent leaks are likely to occur suddenly and quickly become discoverable.

Failures that occur due to the weakening of the pipe wall, such as fatigue fracture or corrosion, will be pressure-dependent since pressure will affect pipe wall stresses (and thus the failure time) and flow rate (and thus the discovery time).

Thus, causes of pressure-independent leaks include construction activity and unbalanced external loads due to swelling or shrinking soils, soil movement, bridging and thermal contractions.

Longitudinal pipe wall stresses are unlikely to be much affected by pressure (see Section 2.2). Thus, the proportion of circumferential breaks may be related to the pressure-independent burst rate. Construction-related bursts usually are well-documented and, therefore, should be easy to estimate.

An interesting reference point is the ‘unavoidable’ burst rates that were assumed in the formulation of the IWA UARL (Unavoidable Annual Real Losses) formula of 13 bursts/100 km/year for mains, 3 bursts/1000 conns/year for service connections up to the property line, and 13 bursts/100 km/year inside the property boundary (Lambert, 2000).

Lambert et al. (2013) proposed a method to estimate the pressure-independent burst rate by plotting the failure rate of several DMAs with at least 10 failures per year against their AZNPs (Average Zonal Night Pressures) and using the lower boundary as an initial estimate. An example is shown in Figure 10 for mains and service pipes, respectively. A disadvantage of this approach is that it doesn’t take into account how DMAs may be affected differently by influencing factors and thus have different pressure-independent failure rates.

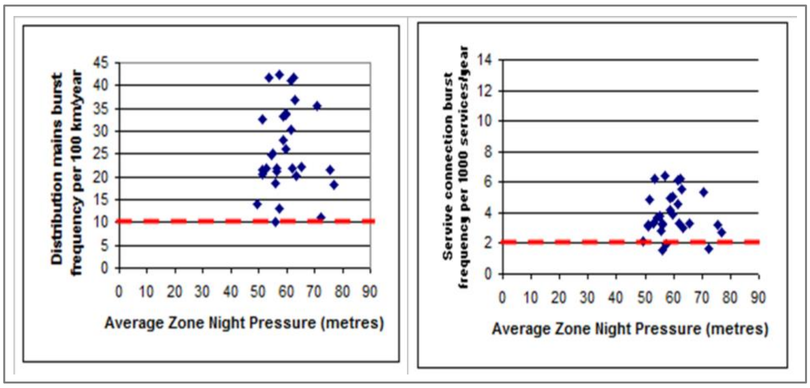


*Figure 10 Estimating pressure-independent burst rate for mains and service pipes based on the lowest DMA value (Lambert et al., 2013)*

## 3.5 Daily Maximum Pressure and Burst Rate

### 3.5.1 Auckland

Vega et al. (2023) analysed 13 107 main failures in Auckland between 2014 and 2019. Information on the pipe properties was obtained from the Watercare GIS database, as well as maximum daily pressure and pressure fluctuation values from the hydraulic models of the system.

Figure 11 shows the relationship between burst rate and maximum daily pressure for AC, iron, PVC and PE. The figure shows a strong correlation between failure rate and pressure for all materials. AC has the greatest failure rates, followed by PVC, iron and PE. The relationships mostly seem linear, although PVC and PE show a more rapid increase in failure rates for the higher pressure ranges.

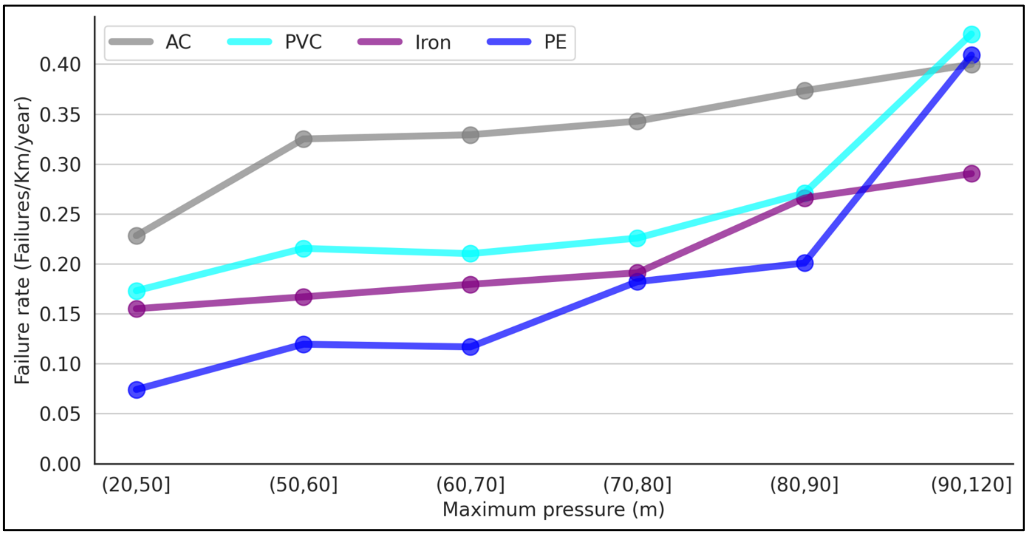
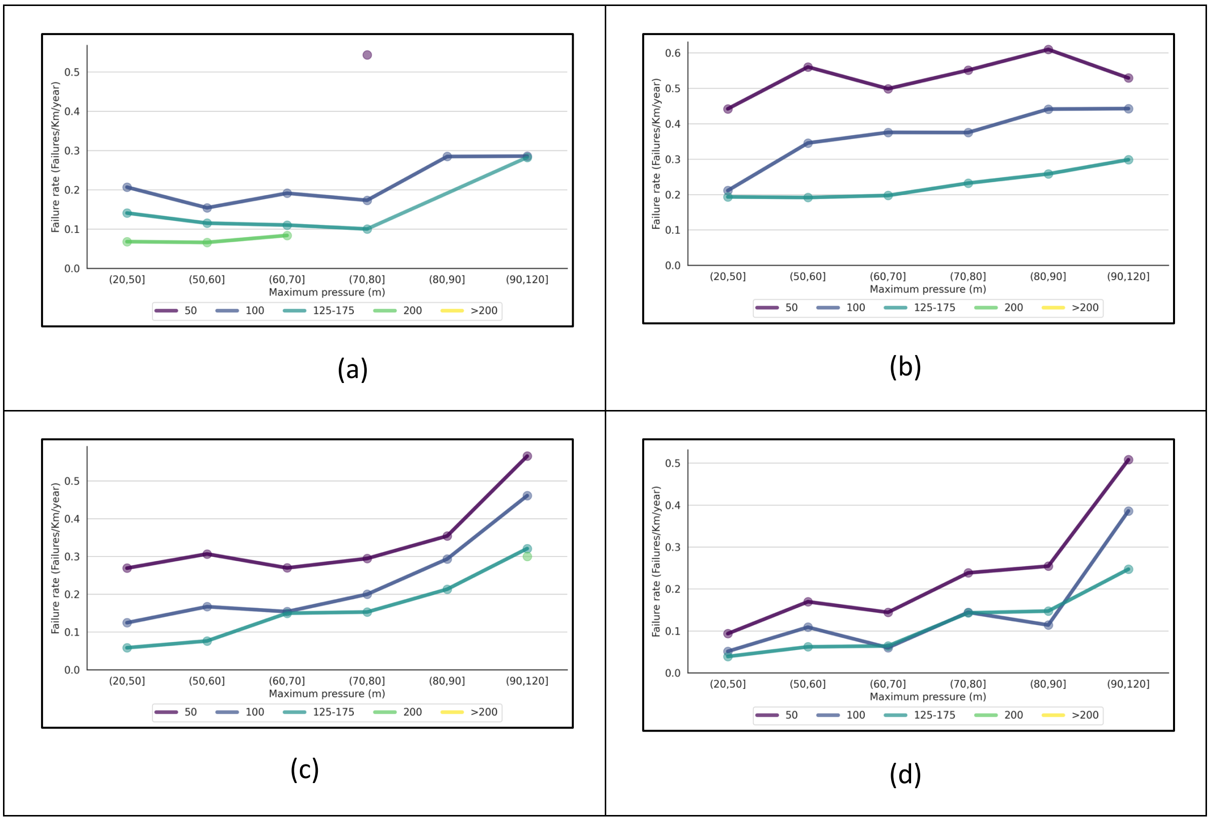


*Figure 11. Failure rate against maximum daily pressure for different pipe materials in Auckland (Vega, 2023)*

Vega (2023) investigated the pressure and burst rate relationship more deeply by grouping the data by pipe diameter, as shown in Figure 12. Only data points representing more than 2 % of each material's total pipe length were included in the graphs to ensure consistency of the graphs.



(a)

(b)

(c)

(d)

*Figure 12. Failure rate against maximum daily pressure for different diameter ranges in Auckland for a) iron, b) AC, c) PVC and d) PE pipes (Vega, 2023).*

The figure shows the correlation between burst rate and maximum daily pressure holds for different diameter ranges in all materials. The relationship remains approximately linear for the rigid iron and AC pipes and increases more rapidly with pressure for the plastic PVC and PE pipes. Larger pipe diameters display larger failure rates. The only case where this trend isn't clear is the similar lines observed for the 100 mm and 125 – 175 mm diameter ranges in PE.

Vega (2023) also investigated the relationship between failure rate and pressure for different age ranges in AC pipes, as shown in Figure 13. Again, similar trends are observed for the various age ranges. As expected, older pipes have higher failure rates than younger pipes.

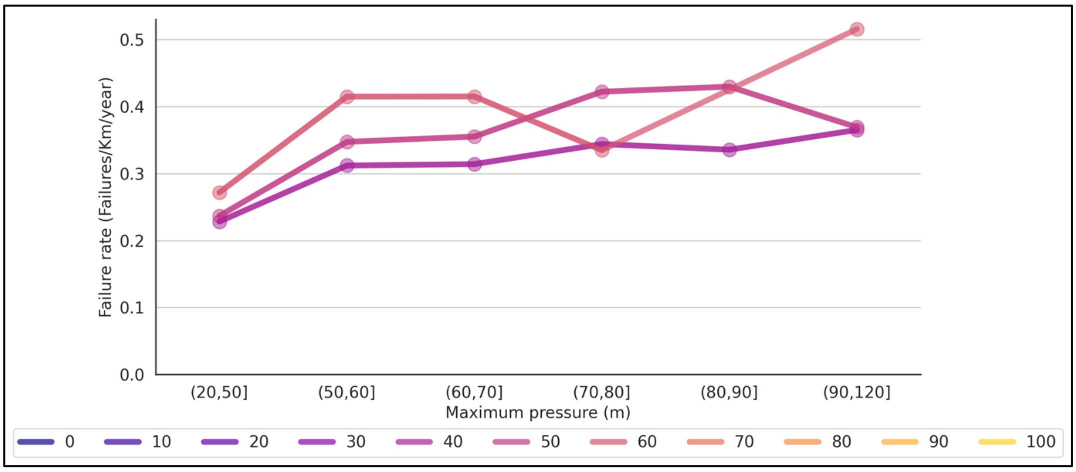


*Figure 13. Failure rate against maximum daily pressure for different age ranges in Auckland AC pipes (Vega, 2023)*

### 3.5.2 Wellington

Stantec analysed pipe leak repair data for Wellington, Porirua, Upper Hutt and Lower Hutt to identify key drivers of pipe failures (Caldwell and Papion, 2024). The data spanned 3.5 years, consisting of approximately 3,000 failures on mains and rider mains and 10,000 on service pipes. However, these numbers exclude approximately 30 % of recorded failures that could not be linked to specific assets. These failures were allocated to different pipe materials in proportion to the number of observed failures on each material.

The study found that failures on mains and rider mains are correlated to pipe material, historic failure rate, age, diameter, and pressure. The relationships between failure rate and maximum daily pressure are shown in Figure 14 for different pipe materials. A significant linear relationship was observed for most materials.

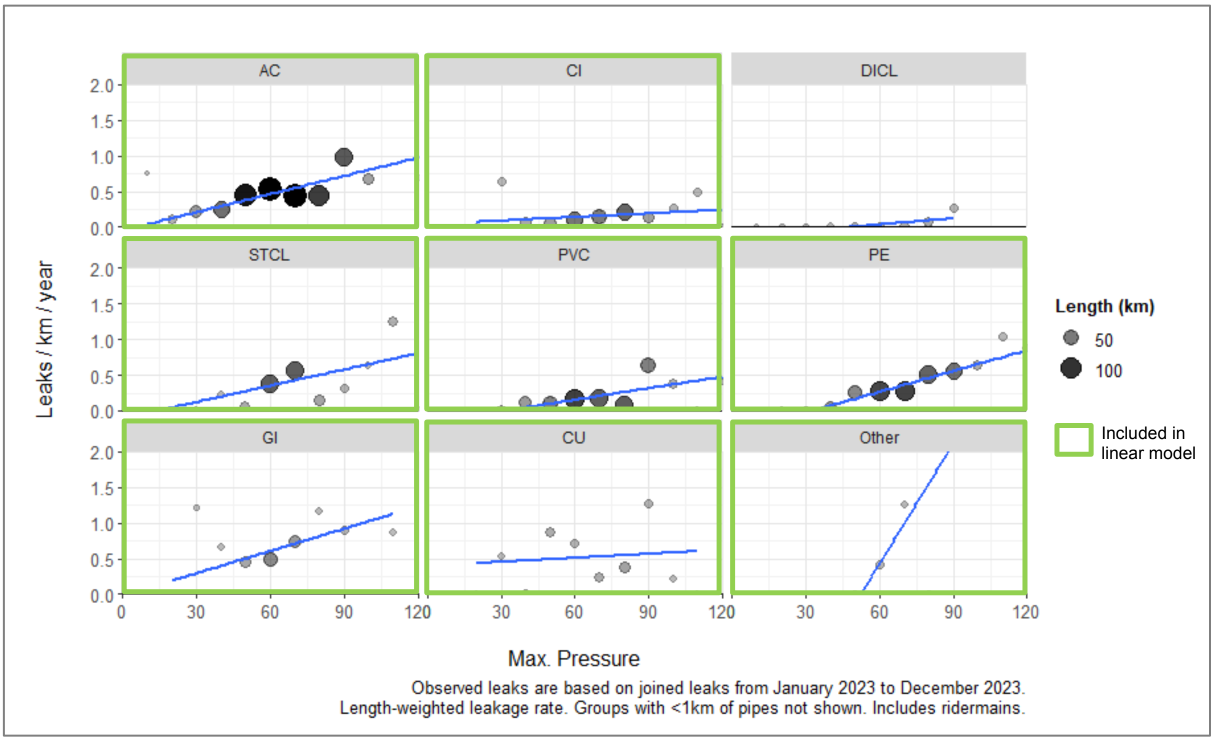


*Figure 14 Mains and rider mains failure rate against maximum daily pressure for different pipe materials in Wellington. Only the relationships with a green border were considered strong enough to be included in a failure prediction model (Caldwell and Papion, 2024).*

Failures on service pipes were found to correlate with historic failure rate, age, pressure and council. The relationship between failure rate and maximum daily pressure, and failure rate and pressure range are shown in the bottom line of Figure 15. Failure rates varied linearly with maximum daily pressure, and no significant relationship was observed between failure rate and pressure range.

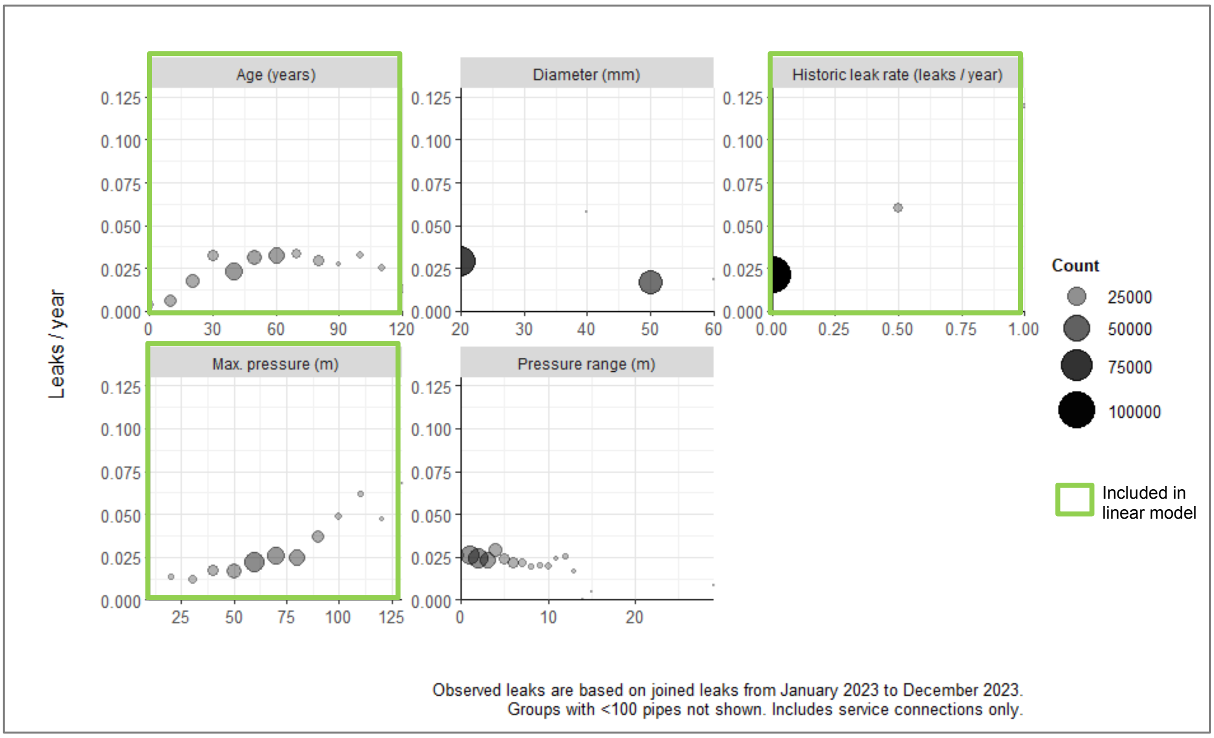


*Figure 15 Service pipe failure rates in Wellington. The bottom two graphs show the service pipe failure rate as a function of maximum daily pressure and pressure range, respectively. Only the relationships with a green border were considered strong enough to be included in a failure prediction model (Caldwell and Papion, 2024).*

### 3.5.3 Tauranga

Tauranga City Council provided pipe failure and GIS data, from which 997 mains failures over five years were selected for analysis. Most of the failures (84 %) were on AC, PVC, and PE pipes, and the other materials did not have enough data to conduct a reliable analysis.

The data and linear trend lines are shown in Figure 16. There is significantly more uncertainty in the data due to the lower number of failure data compared to the Auckland analysis. However, as in Auckland, AC showed the highest burst rates, followed by PVC and PE. AC and PE show a positive correlation between burst rate and pressure, but the slope for PVC isn’t statistically significant.

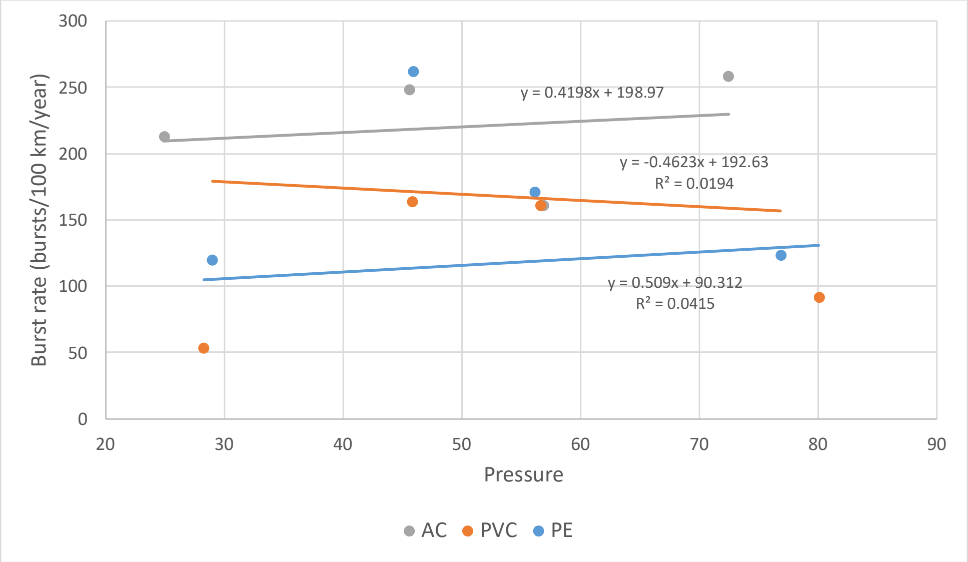


*Figure 16 Failure rate against maximum daily pressure for different pipe materials in Tauranga*

## 3.6 Pressure Fluctuation and Burst Rate

Pressure fluctuation studies and data are more challenging to obtain than for maximum daily pressure. Vega (2023) analysed the correlation between burst rate and diurnal pressure fluctuation, as shown in Figure 17.

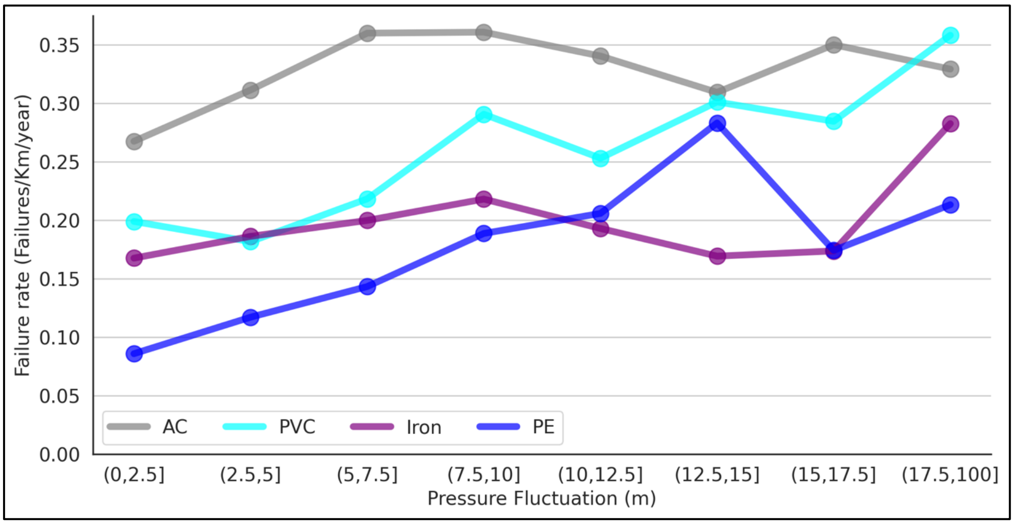
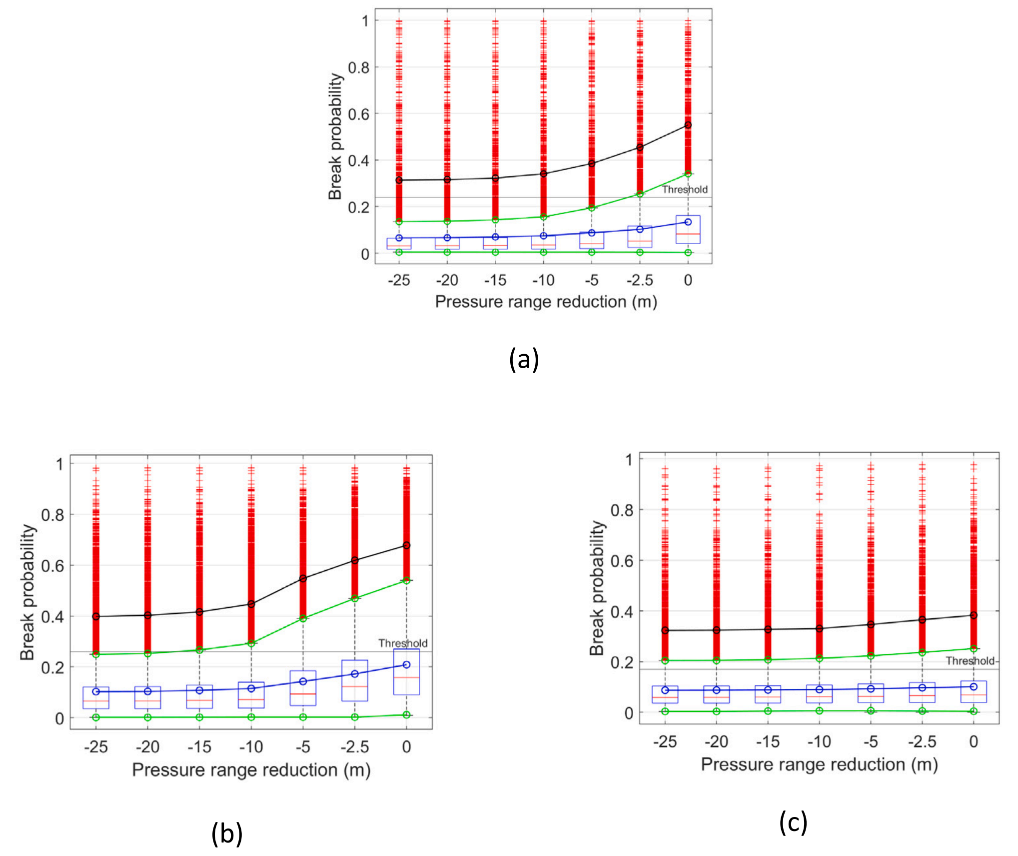


*Figure 17. Failure rate against diurnal pressure fluctuation for different pipe materials in Auckland (Vega, 2023)*

As with the relationship between burst rate and maximum daily pressure, rigid and plastic pipes both displayed similar patterns. Iron and AC show increases in failure rate with pressure fluctuations for lower values, but overall, they don't show a clear trend. The statical p-test showed that the overall trend for these two materials isn't significant at a level of 5 %. However, a significant positive relationship between burst rate and pressure fluctuation is evident for PVC and PE. The results are consistent with those of Wols et al. (2019) in the Netherlands.

Jara-Arriagada and Stoianov (2021) studied the influence of pressure fluctuation on pipe burst rates using a large dataset with over 20 years of historic pipe break records from a medium-sized water utility in the UK. The study found that cast iron pipes are more prone to failure due to pressure fluctuations than mean pressures. While the paper didn't directly report on the relationship between burst rate and pressure fluctuation, they give the results of a break probability analysis for a reduction in pressure fluctuation, as shown in Figure 18. Note that, while the graphs are linked to a reduction in pressure fluctuation, they reflect the results for steady-state conditions, not pressure management. Interestingly, the results show greater increases in burst rate with higher pressure fluctuations for both AC and CI.



(a)

(b)

(c)

*Figure 18 Failure probability as a function of pressure fluctuation for a medium-size utility in the UK for a) AC, b) CI in winter, and c) CI in summer (Martínez et al., 2020). Note that while the graphs are linked to a reduction in pressure fluctuation, they reflect data for steady-state conditions, not for pressure management.*

The Wellington pipe failure study (see Section 3.5.2) also investigated the relationship between failure rate and pressure range for different materials, as shown in Fig. 19. The only significant relationship observed was for AC pipes, although it was noted that this has a high variance and is relatively flat. Thus, the study didn't include pressure range in its failure model.

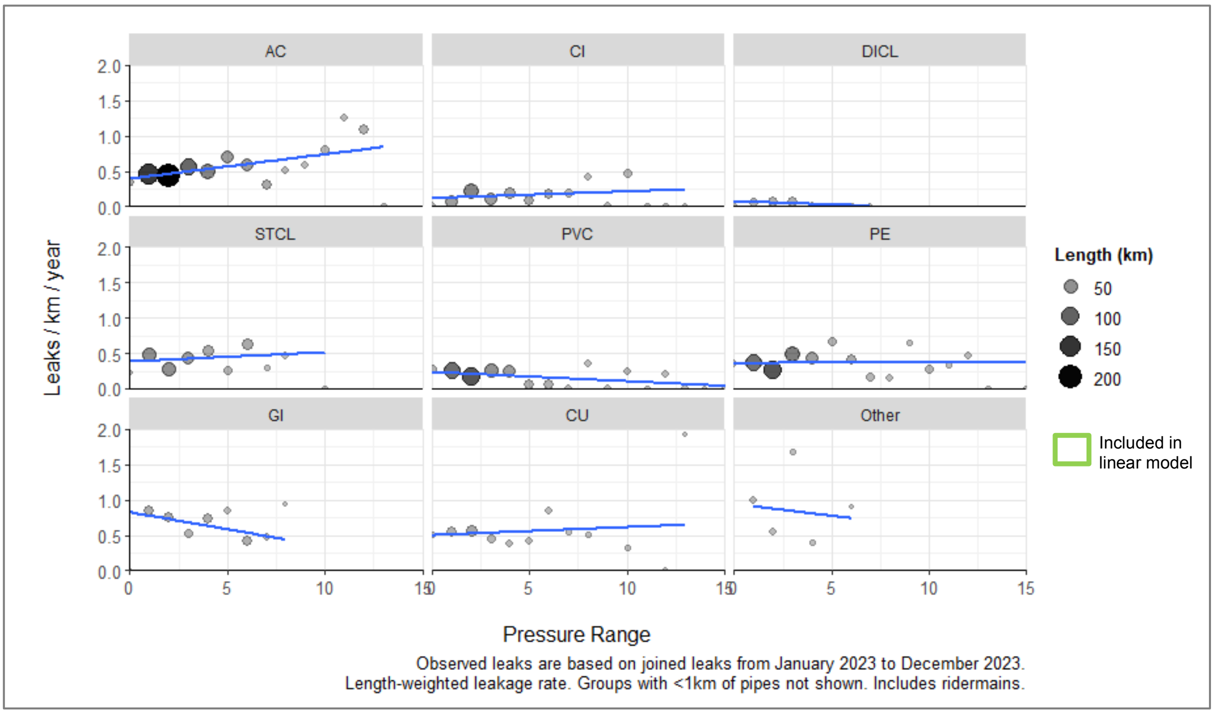


*Figure 19 Mains and rider mains failure rate against pressure range for different pipe materials in Wellington (Caldwell and Papion, 2024).*

# 4 Pressure Management and Burst Rate

## 4.1 Introduction

Pressure management is an important water loss strategy in water distribution systems worldwide. While pressure management hasn't been widely used in New Zealand, it is gaining popularity, with Wellington, Auckland and Christchurch currently implementing it.

The main benefits of pressure management are reduced leak flow and pipe burst rates, which can extend infrastructure life (European Commission, 2015). There are also other benefits, such as reduced consumption and energy savings, as shown in Table 1.

*Table 1 Benefits of pressure management (European Commission, 2015).*

| Pressure management: reduction of excess average and maximum pressures | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Conservation benefits | | Water Utility benefits | | | | | Customer benefits | |
| Reduced flow rates | | Reduced frequency of leaks and bursts | | | | | | |
| 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 and services | Reduced liability costs and reduced bad publicity | Deferred renewals and extended asset life | Reduced costs of active leakage control | Fewer customer complaints | Fewer problems on customer plumbing and appliances |

Several international field studies have shown that pressure management often substantially reduces burst rates. In fact, the model recommended by the Water Loss Taskforce of the International Water Association (IWA) predicts the decrease of pressure-dependent burst rates as a function of the pressure reduction cubed (Lambert et al., 2013). An often-quoted case study is of a system owned by Gold Coast Water in Australia, where a decrease of 80 % was observed in water main breaks over the first 8 months after implementing pressure management (Girard and Stewart, 2007).

The reduction in burst rates observed in pressure management studies seems significantly larger than for steady-state pressure and burst rate studies (see Chapter 3). One possible explanation for this difference is that the impact of pressure management on burst rates will not be sustained indefinitely but will change with time to match the steady-state relationship eventually.

This possibility was raised in 2005 by Pearson et al., who stated that pressure management may result in the burst rate dropping to zero for a period before increasing after a period in which the pipes have deteriorated to such an extent that they begin to fail again. Pearson's view has not been adopted in practice, and the consensus view is that the reduction in burst rates after pressure management will continue indefinitely.

In this chapter, results and models dealing with the effect of pressure management on burst rates are discussed and then compared to the results of recent field studies.

## 4.2 Pressure Management Models

This section discusses the development and application of two models for predicting the effect of pressure management on pipe burst rates. The first model was developed by Lambert (2013) and is recommended by the International Water Association. Vega (2023) recently developed the second model as part of her PhD research at the University of Auckland.

### 4.2.1 Lambert model

The Water Loss Task Force of the International Water Association initially proposed a single power equation to model the relationship between pressure and burst rate:

$$B = ah_{AZP}^{N2}$$

Where *B* is the burst rate (/100 km/year), $h_{AZP}$ the average zonal pressure head, *N2* the burst rate exponent and *a* a coefficient. Pearson et al. (2005) fitted this model to 50 pressure management case studies in Australia, Brazil, Italy, and the UK, finding N2 values between 0.2 and 12 (Lambert et al., 2013).

Thornton and Lambert (2006, 2007) applied a linear model to 112 case studies from 11 countries, finding that the average reduction in burst rate was 1.4 times the reduction in average pressure for mains and service pipes, with a maximum ratio close to 3.

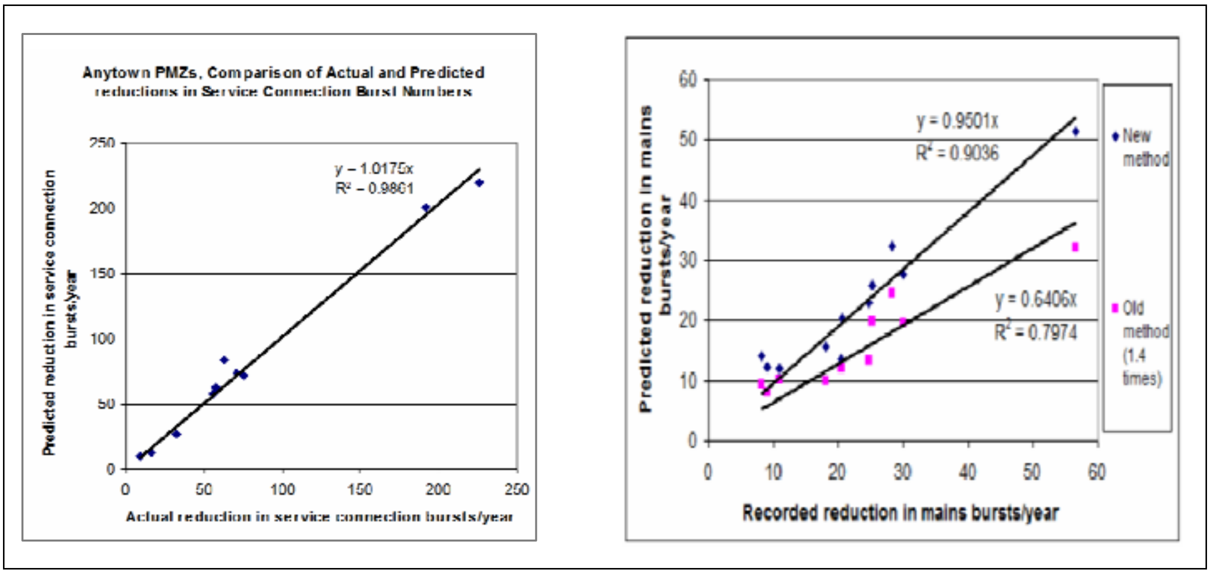
Lambert et al. (2013) realised that some pipe failures would be pressure-independent and that the N2 exponent should only apply to pressure-dependent bursts. He subsequently proposed a modified form of the power equation:

$$B = B_{pi} + B_{pd}$$

Where $B_{pi}$ is the pressure-independent and $B_{pd}$ the pressure-dependent burst rate. The pressure-dependent burst rate is expressed as a power equation to obtain:

$$B = B_{pi} + ah_{AZP}^{N2}$$

Lambert found that the value of N2 is approximately 3. Figure 20 shows the prediction accuracy of Lambert's model for PE service pipes CI mains for data from two Australian Utilities (Lambert et al., 2013).



| (a) | (b) |
|---|---|

*Figure 20 Accuracy of Lambert's method for predicting the effect of pressure management on the burst rate of a) PE service pipes and b) CI mains for two utilities in Australia (Lambert et al, 2013). The 'old method' in (b) refers to a past linear model.*

### 4.2.2 Vega model

Vega et al. (2023) proposed a conceptual framework for leak development over time. This model was calibrated using Auckland data for the relationships between pressure, age and burst rate for different pipe materials, and then used to predict how pressure management will affect pipe burst rates.

The first step in the model development was to plot the relationship of burst rate against age for different pressure ranges, as shown for PVC in Figure 21. Linear functions were fitted to each pressure category, and it was observed that, generally, the failure rate against age lines increases in value and slope as the pressure increases.

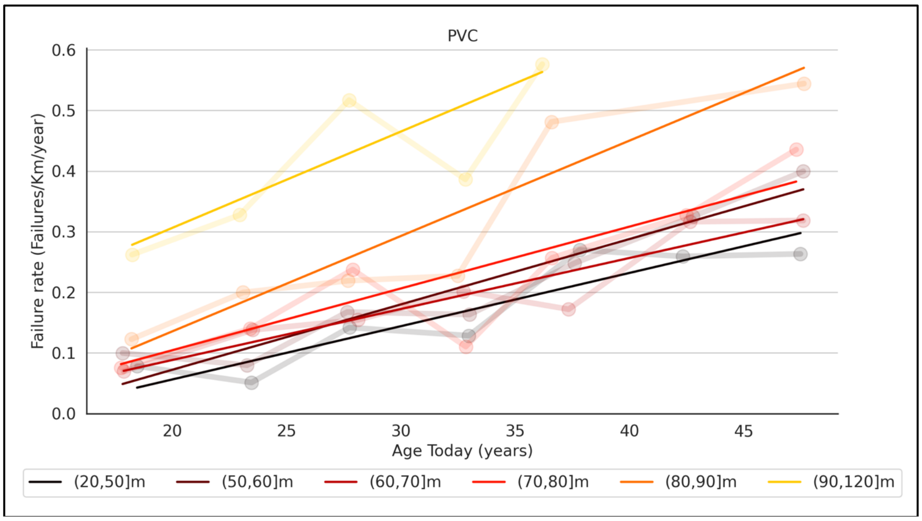


*Figure 21 Steady-state failure rate as a function of pressure and age for PVC pipes in Auckland (Vega, 2023).*

A typical size PMA consisting of 40 km of single pipe material was assumed, and the observed relationships between pressure, age, and burst rate were used to predict pipe failures at two different pressures. Figure 22 shows the predicted pipe bursts at 85 m and 55 m for AC using pink dots. The X-axis starts at 53 years, the average age of AC pipes.

Based on the Auckland data, there are 16 failures at 85 m and 14 failures at 55 m in the first year plotted. The burst rates at both pressures increase with time, and at some point, the burst rate at the lower pressure equals the first year's burst rate at the highest pressure. The identical failure rates were assumed to be for the same failures, i.e. the leaks that would be discovered at the highest pressure in the first year would have to deteriorate for some time before they would be discoverable at the lower pressure.

Strength index lines were then drawn to connect the same failure rates at different pressures, as shown with the pink lines in Figure 22. The strength index lines represent the time and pressure at which a specific leak in the PMA becomes discoverable. (see Section 2.5 for an explanation of the strength index). For example, a strength index line may represent a small crack in the pipe wall that is slowly growing over time, meaning that the crack becomes discoverable at lower pressures as the pipe ages.

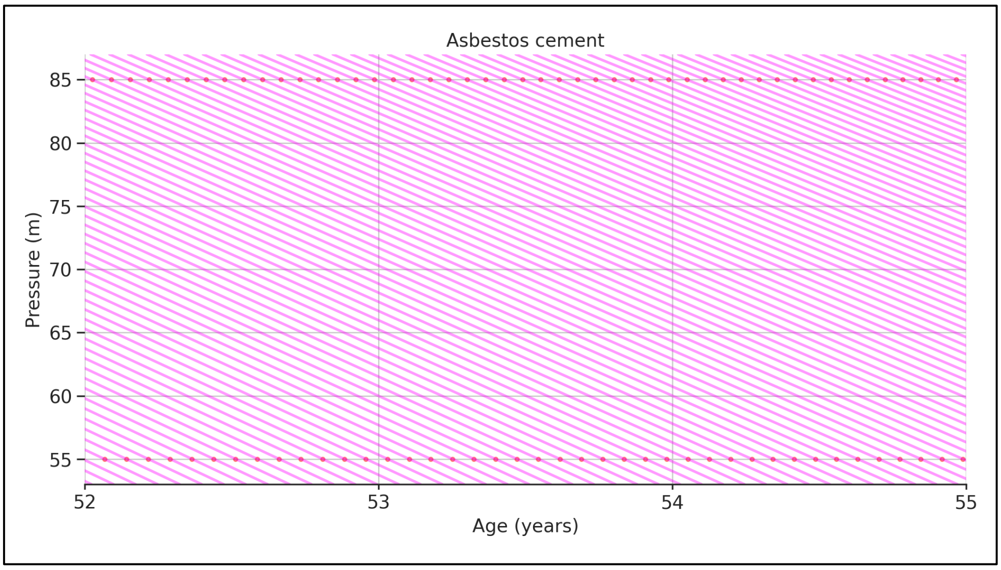


*Figure 22 Strength index lines for a typical PMA consisting of AC pipes calibrated using Auckland data (Vega, 2023).*

The strength index diagram allows the failure rate at any pressure or variation in pressure in the PMA to be investigated. For instance, the red line in Figure 23 represents the network at a pressure of 70 m. When a strength index line intercepts the pressure line, the leak becomes discoverable and is repaired, as is indicated by the colour change from pink to grey.

The strength index line can now be used to investigate the burst rate if pressure management is implemented by reducing the pressure from 70 m to 55 m at the start of year 54 as is shown in Figure 23. Directly after pressure reduction, the failure rate drops dramatically since all the leaks that would have been discovered at a pressure of 55 m are now grey lines, meaning they have already been discovered and repaired at the higher pressure. However, once this ‘shadow period’ passes, leaks become discoverable again and the burst rate increases.

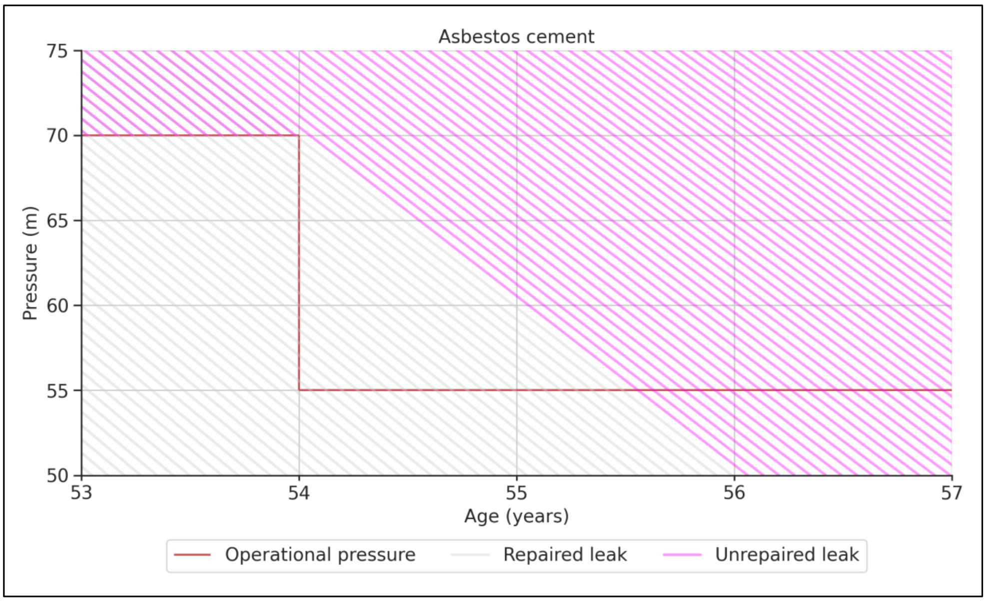


*Figure 23. Strength index lines for AC pipes with pressure management implemented at the beginning of year 54.*

Figure 24 summarises the failure rate over time for a typical PMA consisting of AC, iron, PVC or PE pipes. The year that pressure management is implemented is zero on the X-axis, and the dotted lines show what the progression of the burst rate would have been without pressure management.

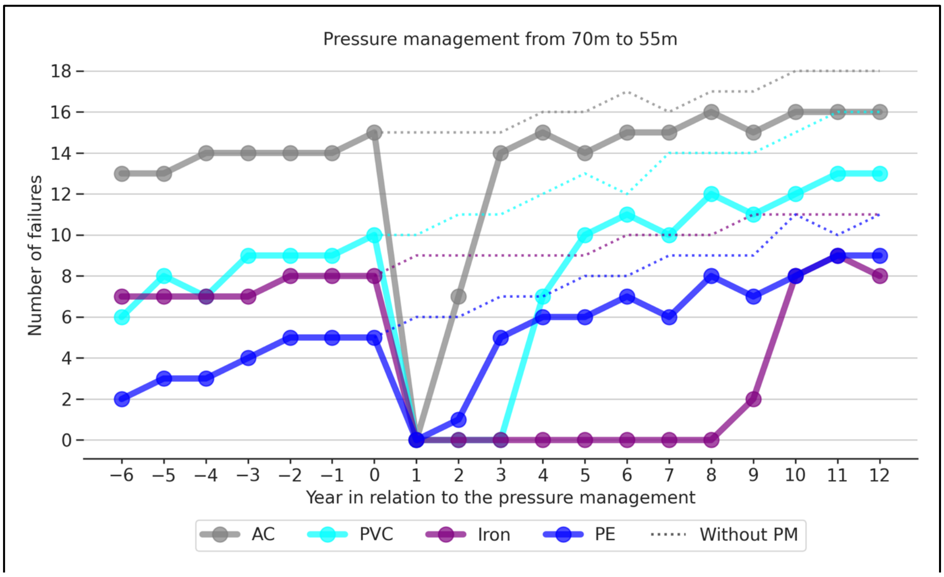


*Figure 24 Predicted burst rate as a function of time for different materials (Vega, 2023)*

It can be seen from Figure 24 that Vega's model predicts a large drop in burst rate immediately after the implementation of pressure management. The failure rate then stays at the reduced level for 1 year for AC and PE, 3 years for PVC and 8 years for iron, before increasing over a few years to a lower level parallel to the burst rate it would have had at 70 m. The example assumes that all failures are pressure-dependent, which is not true in real systems. Thus, it would be necessary to consider pressure-independent failures for real systems and apply the model to the pressure-dependent component only.

The proposed model includes several assumptions, such as treating all leaks as identical and assuming linear relationships between failure rate, pressure and age. However, it provides a mechanistic description of how pressure management impacts burst rates and may provide useful information on the condition of PMAs after implementing pressure management.

The model has significant potential practical implications for water asset management. It will allow water utilities to better understand the potential benefits of pressure management over an extended period. A more accurate burst rate reduction prediction after the pressure management implementation and the duration of the reduced burst rate will support better investment decisions and intervention planning. In addition, field observations of burst response to pressure management will provide information on the state of pipes in the network, including the frequency of failures and the rate of failure development. Further work is required to verify and test the model, some of which are presented in the next section.

## 4.3 Case Studies

### 4.3.1 Drenthe, Netherlands

The province of Drenthe in the Netherlands has an extensive supply zone consisting of 226,000 connections and 5,700 km of pipes. The water utility reduced the average pressure from 37.5 m to 35 m at the end of 2013 and monitored the effect on burst rates. The annual number of bursts of the 800 km of AC pipe in the zone is shown in Figure 25. The figure shows a marked reduction in burst rates after implementing pressure management. However, the burst rate subsequently increased in 2018 to follow a pattern similar to that predicted by Vega's model.

*Figure 25. Annual burst over time for 800 km of AC pipe in Drenthe, Netherlands. The average network pressure was reduced from 37.5 m to 35 m at the beginning of 2014.*

The data was analysed by separating pressure-dependent from pressure-independent bursts and then calibrating Vega's model to the measured failure behaviour at 37.5 and 35 m. The resulting model could reproduce the observed failure rate pattern well, as shown in Figure 26.

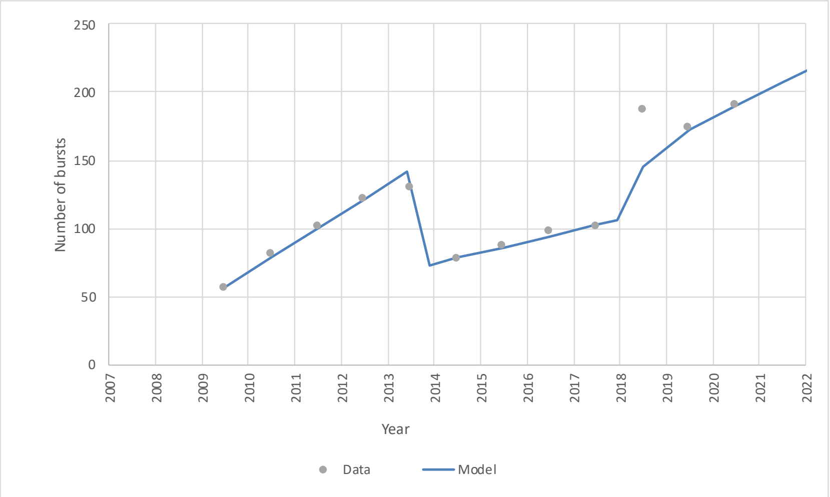


*Figure 26. Model prediction against measured failure annual burst rates for 800 km AC pipe in the network of Drenthe, Netherlands.*

While the good model fit does not represent verification of the model, it does give some confidence in the ability of the conceptual model to predict pipe failure rates accurately.

The model was then used to predict what would happen to the failure rate should the pressure be taken back up to 37.5 m at the beginning of 2024. As shown in Figure 27, a large spike in the burst rate is predicted for 2024, after which the burst rate returns to the pre-pressure management line. The spike can be understood by observing the number of strength index lines intercepted if the pressure in Figure 23 is increased from 55 m back to 70 m at the beginning of year 56.

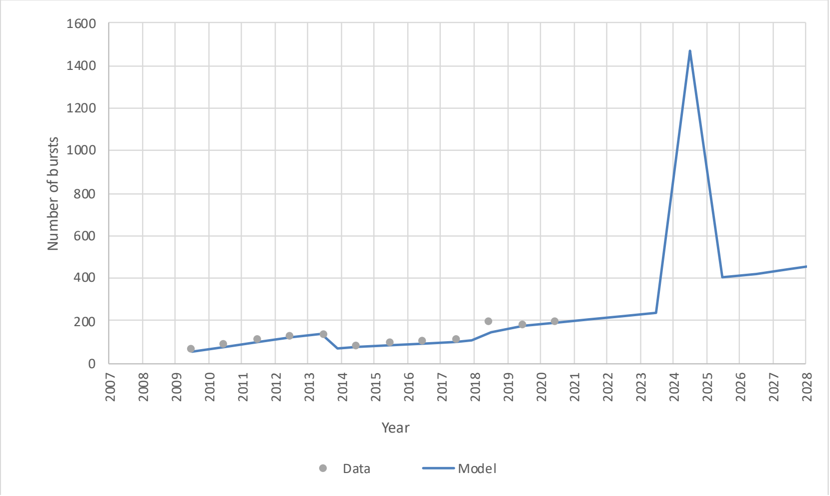


*Figure 27. Predicted annual burst rate rates for 800 km AC pipe in Drenthe if the network pressure is increased from 35 m to 37.5 m at the beginning of 2024.*

### 4.3.2 Barwon Water, Australia

Barwon Water is an urban water utility based in Victoria, Australia. Barwon Water implemented several pressure management schemes in the past, and they made their burst rate data available for analysis.

Data was provided for PMAs in three primary network zones: Highton, LovelyBanks, and Montpellier. Failure rate data by pipe material was provided for three PMAs in Highton, four in Lovely Banks, and three in Montpellier. Additional data supplied included pipe age, rehabilitation records, pressure readings, and pressure management implementation year. Burst rates for some DMAs without pressure management were also provided.

After a preliminary analysis, some PMAs were excluded as they didn't have enough data to allow a reliable analysis, leaving six PMAs included in the study. Water mains renewal was found to be limited in these PMAs and was not expected to influence the results.

Annual failure rate data from 2006 to 2023 was included in the analysis. The yearly burst rate data displayed significant fluctuations between years, possibly due to multi-year climate variations. Scaling factors were calculated for non-PMA zones and applied to the PMA data to reduce the fluctuations.

After normalisation, the average pipe burst rates before and after pressure management were determined for each PMA, as shown in Figure 28 for AC pipes and Figure 29 for CI pipes in a typical PMA. No long-term trend could be detected in the burst rate data, and thus, constant burst rates before and after pressure management were assumed, as shown in the blue and orange lines in the figures.

Lambert's model was applied to each zone to predict the burst rate after pressure management, and his predictions are shown in a dashed red line in the figures. Lambert's method performed well on these two PMAs, slightly overestimating the burst rate reduction for AC and underestimating it for CI. The accuracy of Lambert's model for all PMAs and pipe materials is shown in Figure 30, indicating that his model provided a reasonable estimate of the behaviour.

A summary of the results for all materials and PMAs is provided in Table 2.

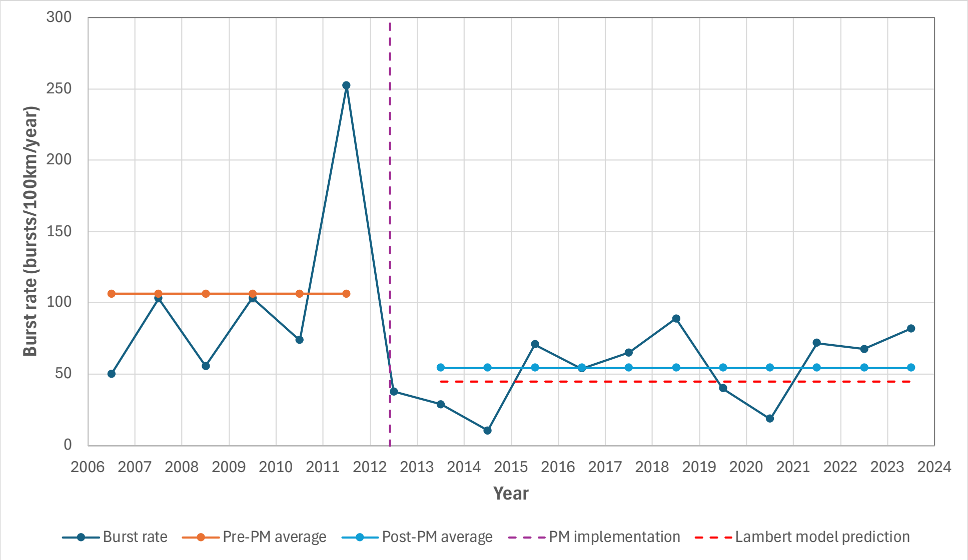


*Figure 28 Effect of pressure management on AC burst rate for a typical Barwon Water PMA*

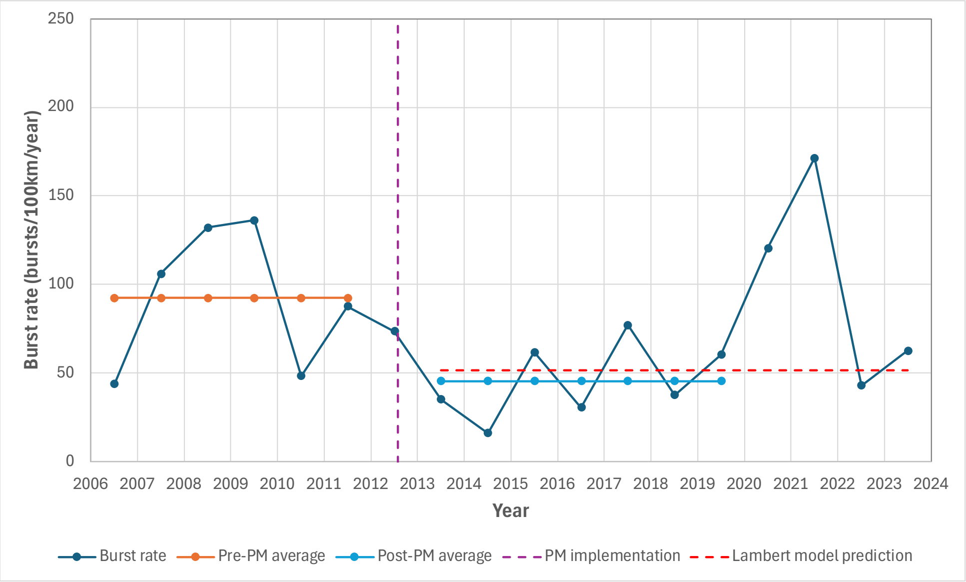


*Figure 29 Effect of pressure management on CI burst rate for a typical Barwon Water PMA*

*Table 2 Burst rates of AC and CI pipes before and after pressure management in a number of Barwon Water PMAs.*

| **Pipe material** | | **AC** | | | | | | **CI** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **PMA** | | **H2** | **H3** | **H4** | **LB2** | **M1** | **M2** | **H2** | **M1** | **M2** |
| Regular Maximum Pressure (m) | Before PM | 65.8 | 66.5 | 79 | 69.5 | 65.8 | 64.3 | 64.3 | 76 | 76 |
| | After PM | 52 | 47.6 | 55 | 48.4 | 52 | 45 | 45 | 54.1 | 54.1 |
| Pipe Break Rate (#/100km/year) | Before PM | 93.8 | 80.4 | 116.9 | 72.4 | 134.6 | 108.0 | 72.3 | 98.0 | 84.3 |
| | Shadow period | 22.5 | 35.7 | 53.1 | 51.0 | 89.5 | 34.0 | 29.6 | 35.5 | 53.8 |
| | After PM | 42.9 | 49.6 | 80.8 | 38.4 | 131.0 | 58.4 | 97.8 | 81.7 | 83.3 |
| | Reduction shadow | | | | | | | | | |
| | Reduction post PM | 60% | 41% | 43% | 41% | 59% | 29% | 51% | 49% | 15% |
| Lambert’s Model Break Rate Prediction (#/100km/year) | | 56.2 | 39.6 | 52.7 | 38.8 | 95.8 | 44.8 | 45 | 51.4 | 53.4 |

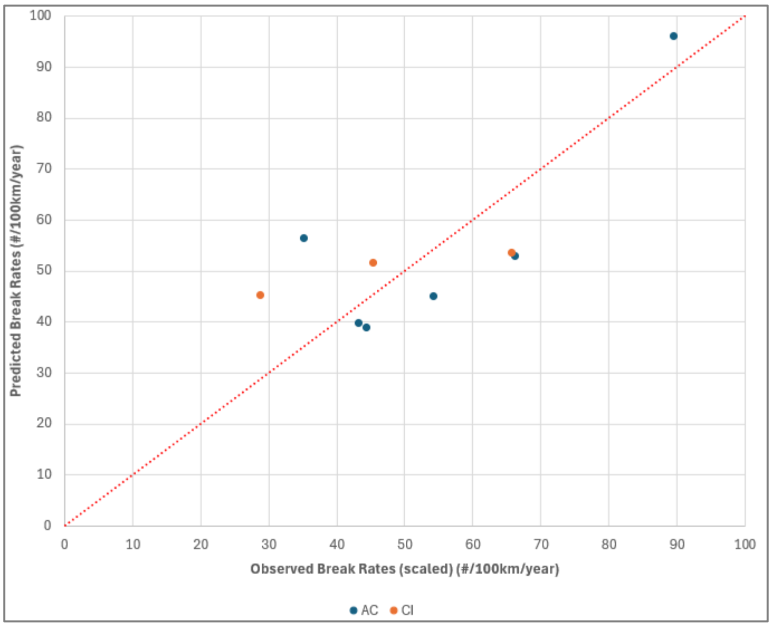


*Figure 30 Performance of Lambert's model in predicting the average burst rate after pressure management.*

Although a drop in burst rates directly after pressure management was observed for all PMAs, the fluctuations in the data made it hard to identify a clear pattern. The burst rate behaviour became clearer when plotting the cumulative burst rate data, as shown in Figures 31 and 32. The cumulative lines show a reduced burst rate (the slope of the cumulative line) directly after pressure management, followed by an increased burst rate, although still lower than the pre-pressure management value.

Pipe break rates of six PMAs managed by Barwon Water were analysed to identify the impact of pressure management. The results showed that pressure management consistently reduced the pipe burst rates of both AC and CI pipes, ranging from 15% to 60%. Lambert's model provided a reasonable estimate of the observed burst rate reductions, confirming its ability to predict the performance of pressure management. The results also show a two-phase trend, with pipe break rates reduced after pressure management but increasing somewhat after a few years.

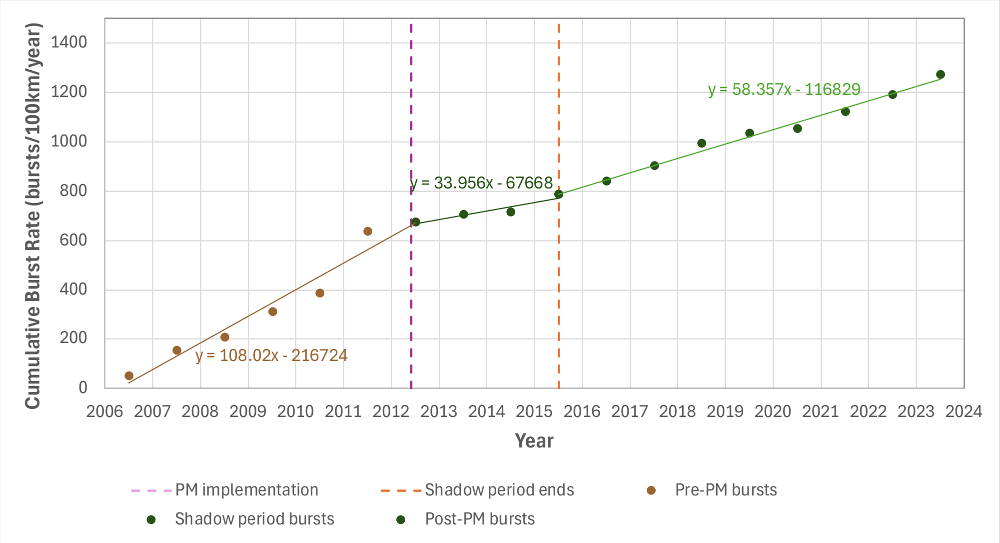


*Figure 31 Effect of pressure management on cumulative AC burst rate for a typical Barwon Water PMA*

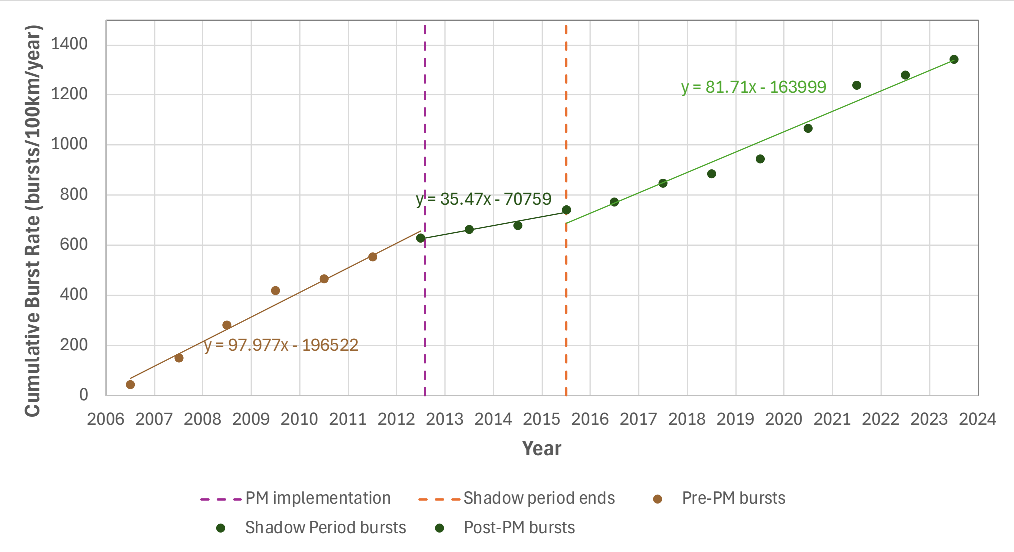


*Figure 32 Effect of pressure management on cumulative CI burst rate for a typical Barwon Water PMA*

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