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Practical evaluation of key factors contributing to pipe failure by using a case study approach combined with statistical analysis

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Abstract: Water pipe failure can be disruptive to the water utility sector in terms of economic loss, cause public inconvenience and damage to the surrounding property. Within South Australia, there were no thorough investigations conducted to determine these failures. In this paper, an approach was proposed to focus only on several key factors, while the others remained the same, by adopting a case study after careful selection of two similar sites within a capital city. Then, a multivariable analysis was conducted to develop a relationship between the pipe properties (age, diameter and material) to the number of failures or failure rates. Through the analysis, it was found that age and material were linked, and older pipes made up of Cast Iron Concrete Lined (CICL) material are far more susceptible to failure. Pipes under the age of 30 years old, primarily composed of new-age PVC materials, are unlikely to experience failures, pipe age of 50 years old shows an increase in failure rates and pipe age of 80 years old was deemed critical. Pipe diameter has little impact on the number of pipe failures; however, when these failures do subsequently occur, they are likely to happen in smaller pipes of 100 mm and 150 mm diameter due to the significant portion of water main pipes. Therefore, the failure rate (number of failures per km of pipe length) is a better representation of the pipe failure. After a statistical analysis of all the factors, the pipe diameter and material exhibit good correlations with the failure rate per km, which are helpful in a further development of a prediction model for water main failure.

Key words: Water utilities; asset management; data and information; pipe failures; environmental factors.

1. INTRODUCTION

Water pipe failures can cause interruption of domestic and industrial water supply, as well as in some cases extremely high repairing costs for the damaged pipe and associated infrastructures (Javadinejad et al. 2019). Pipe failure has become a significant issue across Australia and most evidently in Adelaide, South Australia. SA Water, a water utility owned by the state government for providing water services, manages approximately 26,400 km of water mains across the state (Australian Water Association 2016). In the National Performance Report from the Australian Bureau of Meteorology, it was stated that the average duration of unplanned interruptions, which is the average time a customer is without water supply, due to an unforeseen interruption, requiring attention by the utility (BOM 2018). SA Water had an average duration of unplanned interruption of 195 minutes in 2016-2017, it was a 3% increase from 2015-2016.

There were 2046 reported failures in Adelaide alone in 2016, which is a six-year high. It has been recorded that, on average, a water pipe failure occurs in Adelaide once every 4 hours and 20 minutes. When a pipe becomes disturbed by its surroundings, it consequently becomes weak and beginning to take on the characteristics of a simple beam. Typically, pipes are designed to withstand significant loads and pressures internally from the flow of water. This subsequent exposure to external factors results in the pipe experiencing several longitudinal stresses, strains, and bending movements that it is not designed to undertake, thus failing. Three primary forms of break are considered as pipe failures, namely, circumferential breaks, longitudinal breaks, and cracks caused by corrosion (Mora-Rodríguez et al. 2014). These breakages are caused by three different types of mechanisms, and these are classified by Rajani and Kleiner (2001) as internal and external loads, material deterioration, and the general structural properties of the pipe. Temperature fluctuations can also contribute to pipe failures. For instance, water volume expansion and frost heave can affect the brittleness of the pipe (Majumder et al. 2018). Furthermore, extended durations and increased intensity of cold weather can significantly impact pipe failures by 60%, as shown for the UK water utility (Burn et al. 2010; Rezaei et al. 2015). Another factor like various kinds of stresses felt by pipes is often associated with ground movement and surrounding conditions. Boxall et al. (2007) specified that approximately 25% of the United Kingdom's mains network is positioned in highly aggressive and shrinkable soils. It was also assessed that 30% of mains fail due to suffering heavy corrosion that takes place in highly aggressive soil locations.

The above review reveals that many factors such as pipe materials, geometry, soil and climatic conditions are entangled to understand the role of each factor on pipe failures. It would be great to completely eradicate water main pipe failures with the full understanding of the factors that drive them to fail, however, in real situation, it would be impossible to include all these factors in one study. Therefore, this study adopted the approach of using a case study by a careful selection of two similar locations (concerning soil type) with different pipe failure rates (defined as number of failures per km of pipe) in order to focus only on the role of several key factors, such as age, material and size, on pipe failures, while other factors remained the same. This may add new findings to the existing knowledge on pipe failure patterns.

2. METHODOLOGY

2.1 Location selection criterion

It is a known fact that soil characteristics can have a large impact on failure rate (Rajani et al. 1996), but there are only limited research studies available for the influence of soil type on failure rate, particularly for the highly expansive soils in Adelaide which added additional complexities (Sheard and Bowman 1998; AS 1289.7.1.1 2003; Hekmati et al. 2020). Therefore, in this study, Adelaide metropolitan area was chosen with the addition of two other reasons: first, there was a higher concentration of pipes in a smaller area and this enabled for easier control of variables, and the second reason was due to the higher population density there is a lower chance that the minor water pipe failures could be a miss for longer periods, or missed completely, which affects the integrity of the data attained (the current system relies on people to report pipe failure). The next criterion was to determine two areas with different failure rates, but with the same soil types, which were attained by creating cluster maps and heat maps using the SA Water GIS system (SA Water 2018).

Two locations (suburban areas) with similar soil (sandy silty clays) were selected for this study and using real-life data attained from SA Water for the assessment. Both selected locations are approximately 1.5 km^2. The first location had a low failure rate. This area will be analysed and compared to a second location with a very high failure rate. The datasets used in this study are state-wide potable water pipe network data (e.g. age, material, diameter, etc.) and the data recorded (e.g. failure location, date, etc.) when a water pipe failure was reported and then repaired. These data sets were combined to perform an extensive data analysis.

2.2 GIS software

Geographic Information System (GIS) software is widely used and stores valuable information like South Australia's water pipe dataset (Alexandru Marian et al. 2012). This software depicts the accurate location and alignment of water pipes and their attributes, such as age, material, diameter, etc.

2.3 Data collection, pre-treatment, processing and analysis

Risk analysis is an important tool used in infrastructure asset management process (Mamo 2015). The data used in this study was collected from the Asset Management System, where SA Water's assets information was stored, and associated data were recorded. This system also used to generate work orders with the inclusion of pipe details and other information regarding the failure for the repair jobs. Other recorded data and information after the repair job included a description of the failure type (leak or any other types of failure), the failure mode - mechanisms of failure (longitudinal break or circumferential break), how the pipe was repaired and the exact location with GIS coordinates.

Once the exact location was recorded, the GIS ID of the pipe was added as part of the work order information. This complete dataset was used as a reporting record for SA Water's key performance indicators that were published as part of the national performance of urban water utilities. This combined dataset was then layered on top of the base maps in the GIS software packages such as ArcGIS. This data collection method was started in 2011 when the current Asset Management System was first introduced. The software was able to link to the GIS systems and can allow a holistic view of water pipe network and pipe properties, included the raw dataset of complete breakdown work orders on water pipes for South Australia over 7 years and the connected shapefile that contained the exact locations and the water pipe failure records. A total of 24,251 water pipe failures were reported, with 11,059 occurring in the metropolitan Adelaide water pipe network, with the remainder occurring in 311 different regional water pipe networks. A data pre-treatment procedure was used to develop the dataset with full associate data, any pipes with missing information were removed and not included in this study to increase the quality of the data.

2.4 Statistical analysis

The effect of influencing factors such as pipe material, age and diameter on the failure rate of water pipe can be derived from the coefficients of correlation between the failure rate (i.e. number of breaks per 1 km of the pipe length) and those factors. The mathematics of this relationship can be expressed from the following equations.

- Mean is the measure of central tendency of the random variable. Notation: $\bar{x}$.

  $$\bar{x} = \sum_{i=1}^{n} x_i / n \quad (1)$$

  where x_i is the i^{th} random variable and n is the total number of random variables.
- Standard deviation is the measure of the variability of the random variable. Notation: $\sigma(x)$.

  $$\sigma(x) = \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 / (n-1)} \quad (2)$$

- Covariance (cov) is the measure of joint variability of two variables. The sign of covariance shows the tendency of the relationship, whereas the magnitude of covariance shows the similarity of the relationship i.e. high magnitude means that the variables tend to show similar behaviour. Notation: $\mathrm{cov}(\dots,\dots)$.

  $$cov(y,x) = \sum_{i=1}^{n} (y_i - \bar{y})(x_i - \bar{x}) / (n-1) \quad (3)$$

- Correlation coefficient (corr) is the measure of statistical relationship of two variables. High magnitude of correlation coefficient shows strong correlation, whereas small magnitude of correlation coefficient shows weak correlation. Notation: $\mathrm{corr}(\dots,\dots)$.

$$corr(y, x) = \frac{cov(y,x)}{\sigma(y)\sigma(x)} \quad (4)$$

Note that the statistical analysis can be done in EXCEL by using the above formulations.

3. RESULTS AND DISCUSSION

Both the cluster map and heat map were generated for the case study areas; where the cluster map shows the number of failures in the selected areas and the heat map gave a visual representation of the clustering.

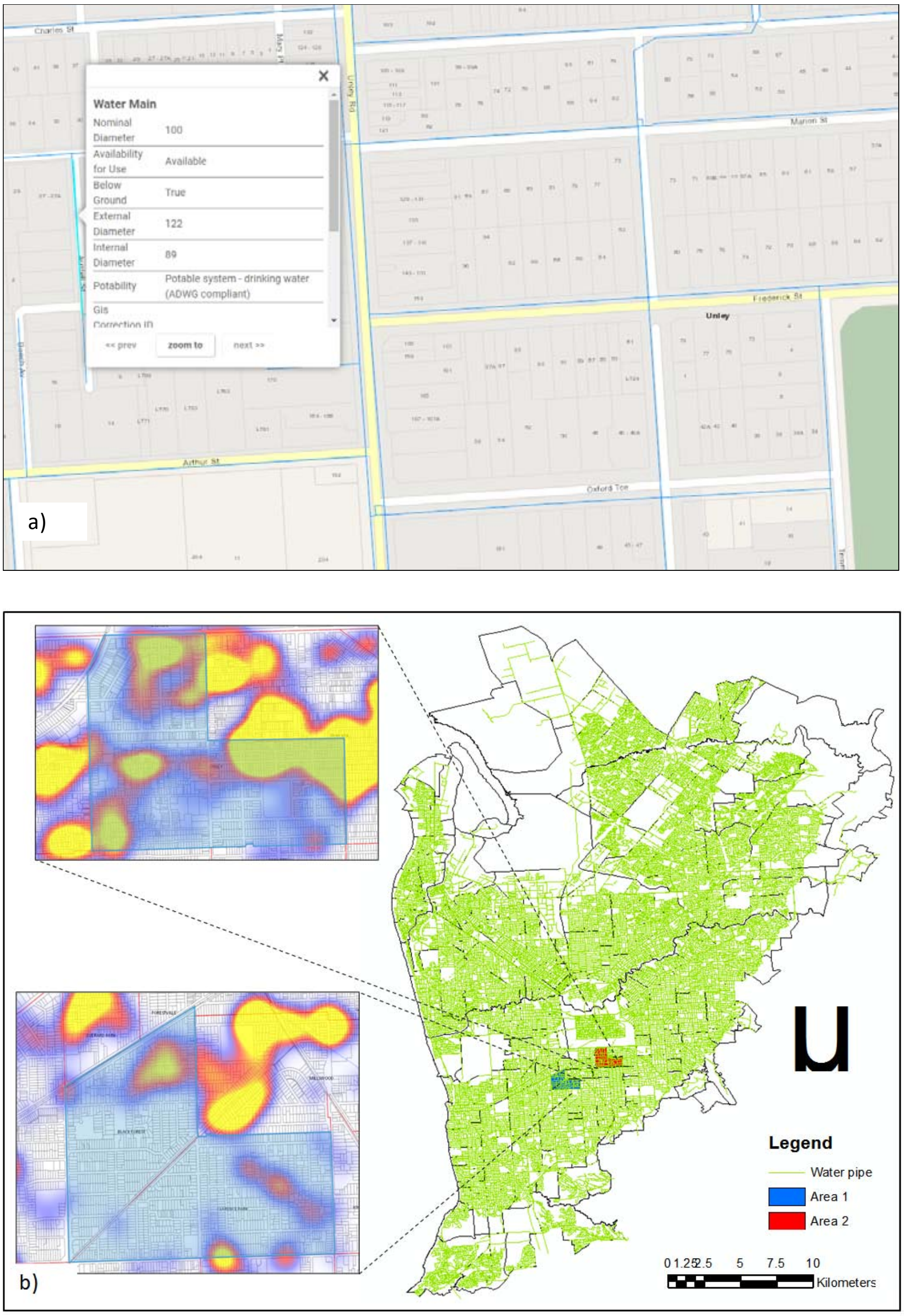

Figure 1. (a) Example of pipe information from GIS data; (b) Heat maps of Area 1 and Area 2 in Metropolitan Adelaide water pine network.

The two case study areas that are in relative proximity of each other were selected. These are located on the southern outskirts of the Adelaide CBD (South Australia). GIS data for South Australia's waterpipe network is available on the government website (http://location.sa.gov.au/viewer/). All attributes of the selected pipe can be obtained as the example shown in Figure 1a. The stored data for each pipe includes pipe construction material, construction year and pipe diameter among others. The GIS software has embedded features that allow for shapefiles to be imported and then layered onto the base pipe map.

Based on the available data, Area 1 displayed lower failure rate compared to Area 2, where the latter experienced 2.7 times higher failure rate per km^2 than the former in the last 7 years (see Figure 1b). As mentioned earlier, these failures occur due to numerous factors like surrounding soil and prominently by pipe network characteristics, like material, age and diameter.

3.1 Pipe network properties

Before undertaking any analysis of the two selected locations, it was vital to establish some existing conditions, present factors and context for the areas in order to establish more accurately any possible relationships. The total pipe length in both areas, Area 1 and Area 2, are almost the same. However, it can be seen in Table 1 that the total pipe length in Area 1 is slightly longer, it contains 29 ± 1 km of pipe compared to 27 ± 1 km in Area 2.

As stated, the selection of the two locations with similar soil and environmental properties (same soil and climatic condition) formed the key design of this study, Area 1 displaying lower failure rate than Area 2, which can be seen in Table 1. It has been discovered that Area 2 has experienced 2.6 times more failures than Area 1 in the last 7 years, with 54 failures compared to a mere 21 failures, found in the same sized areas. The factors contributing to these numbers will be discussed by analysing the most prominent materials in each of the two areas, the common diameter pipes found and lastly the age of the pipes. Furthermore, it has been noted that the number of pipes in each of these areas may affect the results yielded, thus each of these factors will be normalised both in total numbers in addition to per kilometre of pipe factor. It is important that not only the number of failures used in each area for the analysis, but that the failure rates are used to develop an understanding of an all-round picture. As seen in Table 1, Area 2 experiences significantly more failures per kilometre than Area 1 at 2.03 occurrences compared to only 0.73 in Area 1, further highlighting a significant issue present.

Pipe material has been identified to be a key factor related to the failure of water pipes via literature search. Studies conducted by Wols and van Thienen (2013) and Li et al. (2015) in Baocheng district of China found that the most used pipe materials are galvanised steel, asbestos cement and cast-iron, which are the most vulnerable materials to corrode, especially in areas with heavy rainfall. The four common pipe materials found in both the case study areas are Asbestos Concrete (AC), Cast Iron Concrete Lined (CICL), Cast Iron Concrete in Situ (CICS) and PVC. Based on the similar installation periods depicted in both the case study areas, CICL is the prominently used pipe material at the time when cast iron was the primary material of choice. AC material is the second most common material used in each of the areas followed by CICS being the third most prominent and so on (Mahmoodian and Li 2016). Figure 2a presents the percentage failure rate per km and shows that the CICL material pipes are most susceptible to failure as well as for Asbestos concrete (AC) material pipes. It also shows that none of the alternative pipe materials or the newer PVC pipes are present in Figure 2a, indicating zero to very minimal failure rates. The failure rate in Figure 2b exhibits a similar trend as the percentage failure rate in Figure 2a. However, the failure rate of CICL is comparably higher than other pipe materials. AC pipe has the second-highest failure rate per km. The reason behind may be that most pipes in the water main networks are made of CICL and AC.

Pipe diameter is another important attribute for failure analysis as it provides an understanding of the types of water flow pressures present in the selected area (Sadiq et al. 2004; Xu et al. 2011). Some evidence suggests the larger the diameter, and thus the thicker the walls, can withstand higher circumferential loads (Rezaei et al. 2015). Additionally, due to their increased thickness, these pipes are more resistant to corrosion and degradation. In this study, the maximum size pipes include the greater than 500 mm category which can be sized up to 900 mm. Smaller diameter pipes are used in residential areas for water distributions due to the lower flow rates, so Area 1 and Area 2 that consists of 100 mm and 150 mm diameter mark, were susceptible to higher failure rate when compared to pipe diameters of 250 mm and beyond. Figure 3a shows the percentage of failure in different pipe diameters for both areas. As mentioned, the primary water main pipe sizes are either 100 mm or 150 mm, but some of these numbers cannot be disregarded. Both the areas display a primary failure rate when it comes to 100 mm pipes, as it depicts 4.4% for Area 1, which is slightly less compared to Area 2, at 5.5%. It can also be seen that the 150 mm pipes are failing at a slightly different rate across both areas depicting 2.7% and 3.6%, respectively. These similarities begin to dissipate when analysing the 200 mm pipes where the failure rates are not as similar, e.g. 4% are observed to have failed in Area 1 compared to only 0.6% in Area 2. Although the 100 mm pipes seem to be the most likely diameter of pipes to fail while being under stress or other factors, hence it is highly likely these significant numbers are purely due to the sheer volume of pipes this size. The notion that 100 mm pipes are more likely to fail due to their smaller size could arise from viewing these data. But these data can largely be discarded when analysing the percentage of 80 mm pipes that are also seen to be failing in these areas, where numbers are at 3.9% and 4.6%, respectively. Although the diameter may not carry a significant impact on the failure of water main pipes in Figure 3a, they are most likely to occur in 100 mm sized pipes.

Table 1. Summary of Area 1 and Area 2 with corresponding pipe characteristics and failures.

	Area 1	Area 2
Number of Failures	21	54
Total Pipe Length (km)	29 ± 1	27 ± 1
Failure Rate (failure per km)	0.73 ± 0.02	2.03 ± 0.09
Area (km^2)	1.5 ± 1	1.5 ± 1
Materials in length (km)		
Asbestos Concrete (AC)	8.5 (30%)	7.5 (28%)
Cast Iron Concrete Lined (CICL)	14.4 (50%)	13.7 (51%)
Cast Iron Concrete in Situ (CICS)	3.1 (11%)	2.3 (9%)
PVC + other	2.7 (9%)	3.1 (12%)
Number of failure by materials		
Asbestos Concrete (AC)	5 (23.8%)	13 (24.1%)
Cast Iron Concrete Lined (CICL)	14 (66.7%)	37 (68.5%)
Cast Iron Concrete in Situ (CICS)	2 (9.5%)	1 (1.9%)
PVC + other	0 (0%)	3 (5.6%)
Diameter of Pipe in length (km)		
80 mm	1.2 km (4.2%)	0.4 km (1.5%)
100 mm	14.2 km (49.3%)	14.5 km (54.5%)
150 mm	8.8 km (30.6%)	5.7 km (21.4%)
200 mm	2.4 km (8.3%)	2.9 km (10.9%)
350 mm	0.1 km (0.3%)	2.3 km (8.6%)
>500 mm	2.0 km (6.9%)	0.9 km (3.4%)
Number of failures by diameters		
80mm	1 (4.8%)	1 (1.9%)
100mm	13 (61.9%)	40 (74.1%)
150mm	5 (23.8%)	11 (20.4%)
200mm	2 (9.5%)	1 (1.9%)
250mm	0 (0%)	1 (1.9%)

However, Figure 3b shows the failure rate per km which exhibits a completely different trend to what was observed in Figure 3a. The failure rates in Area 1 are relatively close (around 0.6 to 0.9

failure per km) for different pipe diameters from 80 to 200 mm. The failure rates in Area 2 are also close (around 1.9 to 2.7 failure per km) for different pipe diameters from 80 to 150 mm. This relation shows that the pipe diameter may not be the most influencing factor for pipe break. Sometimes there are more recorded breaks because of more pipes in that diameter category.

Note, the data for pipe diameter more than 200 mm is insignificant to infer any relation.

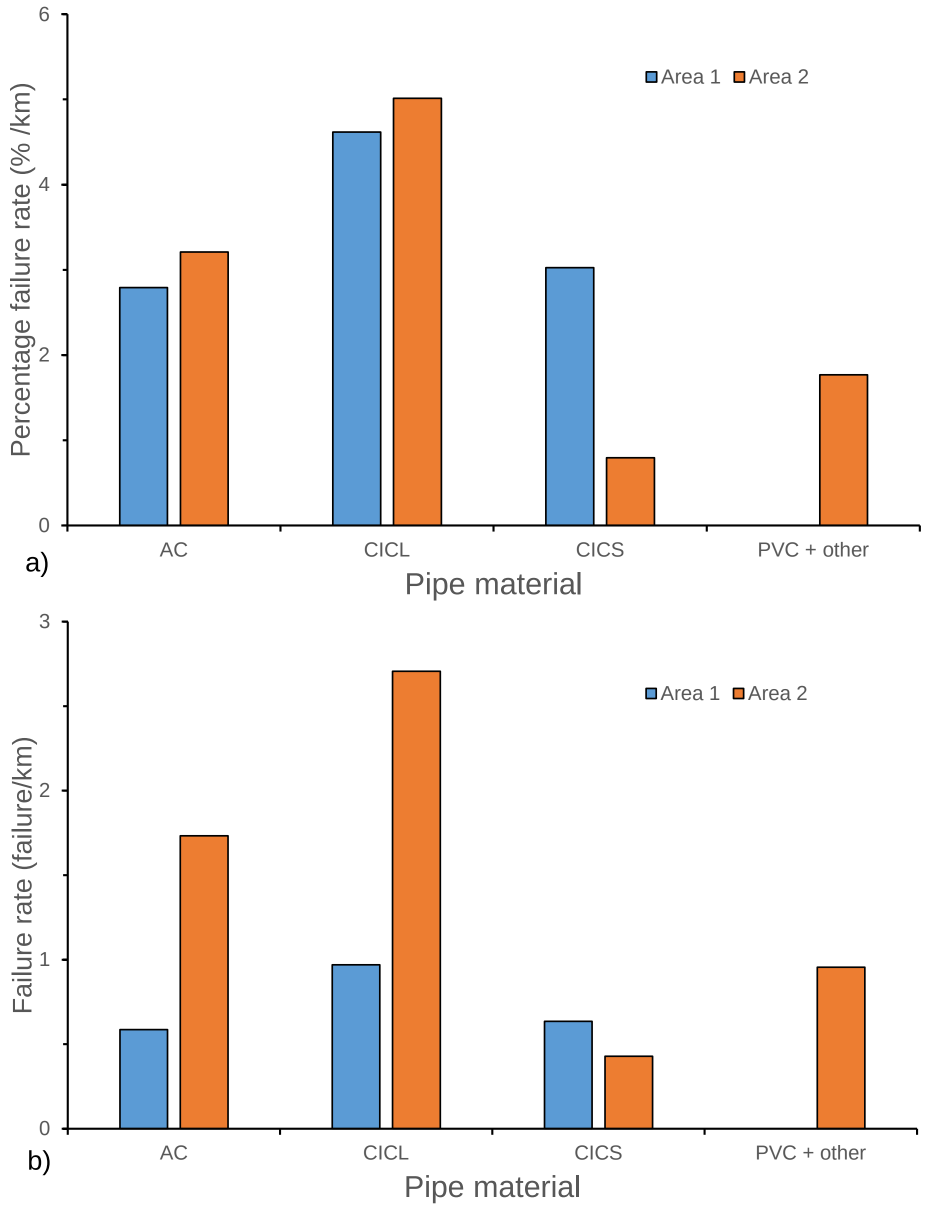

Figure 2. Comparison of (a) percentage failure rate and (b) failure rate for different pipe materials.

Pipe age plays a vital role in the existing conditions of pipe infrastructure, as it has a significant bearing on both pipe material and size, simply due to advancements in technology as time progressed (Large et al. 2015). Pipe age ranging from less than 10 years old to more than 120 years old were analysed for both the study areas selected. Figure 4 shows less, or no failure is depicted for age pipes under 40 years old. Pipes aged between 80 and 50 years old depict interesting results. Pipe age of 80 years old shows higher failure rates in Area 2 when compared to Area 1. The same goes for the pipe age of 50 years old. The two-pipe ages displayed interesting differences and diverse sets of results; hence a further analysis was undertaken to breakdown the reasons for water main pipe failures and possibly highlight any relationships between the two areas or other prominent factors.

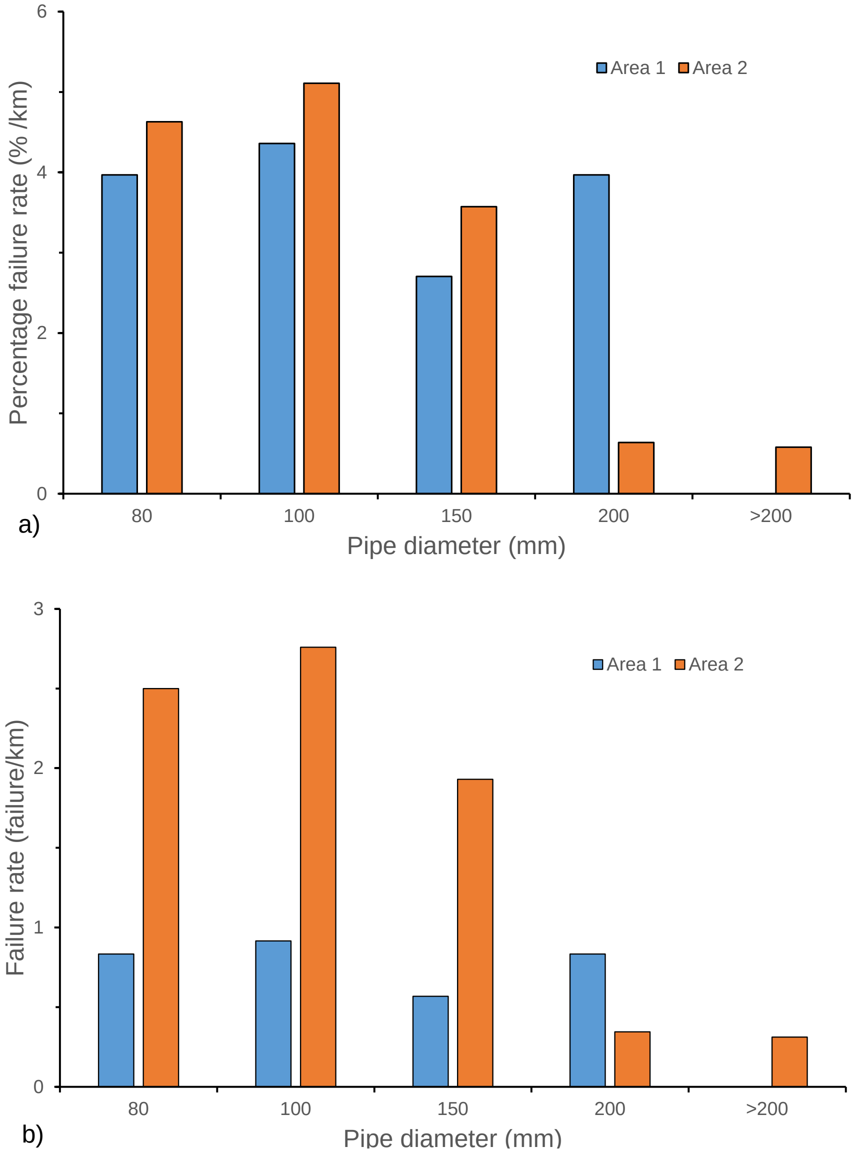

Figure 3. Comparison of (a) percentage failure rate and (b) failure rate for different pipe diameters.

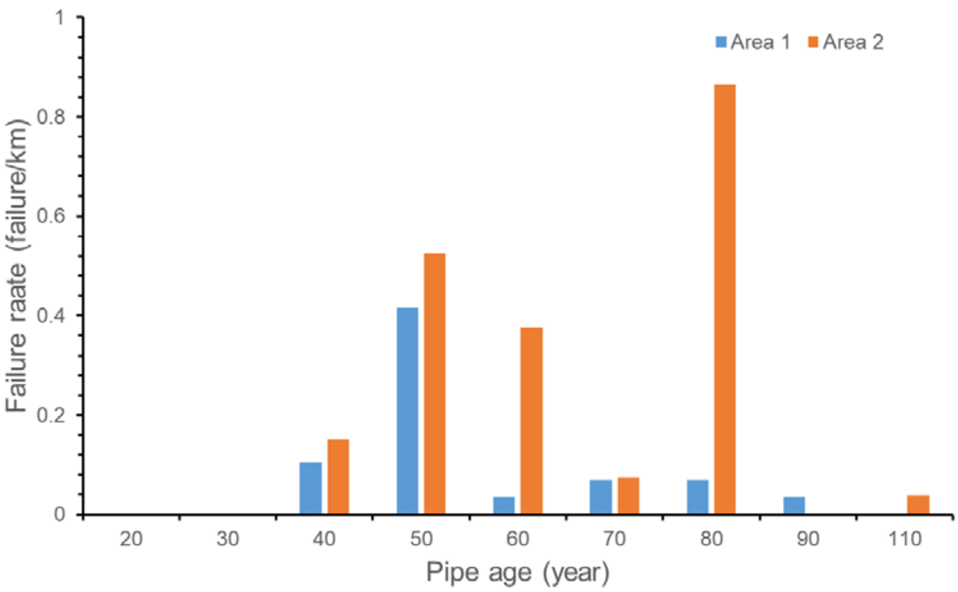

Figure 4. Comparison of failure rate based on pipe age.

3.2 Comparative analysis of pipe age: 80-year-old vs. 50-year-old

The 80-year old pipe category was selected due to such a substantial number of failures in Area 2 compared to lower numbers seen for Area 1. Based on the data provided, it was previously established that the CICL is most commonly used material for water pipes and the result yielded as although there are not many 80-year old pipes in Area 1, the failure rate per kilometre is still almost double the rate compared to the rest of the area and, as seen in Figure 5a, these pipes are also made up of a variety of Cast Iron Concrete, highlighting as a significant issue.

The other pipe attributes, such as pipe diameter, failing in the 80-year-old pipe age brackets for both areas, form an unclear relationship, if the diameter does result in the pipes to fail. However, in Figure 5b, Area 2 exhibits many 100 mm pipe failures, like the overall results seen for the entire research study. Further differences are then observed when analysing the Area 1 diameters, which displays an almost 50/50 split between 100 mm and 150 mm pipe diameters, however little to no failures are observed for all diameters, further clouding any judgments on the role of pipe diameter resulting in water main pipe failures.

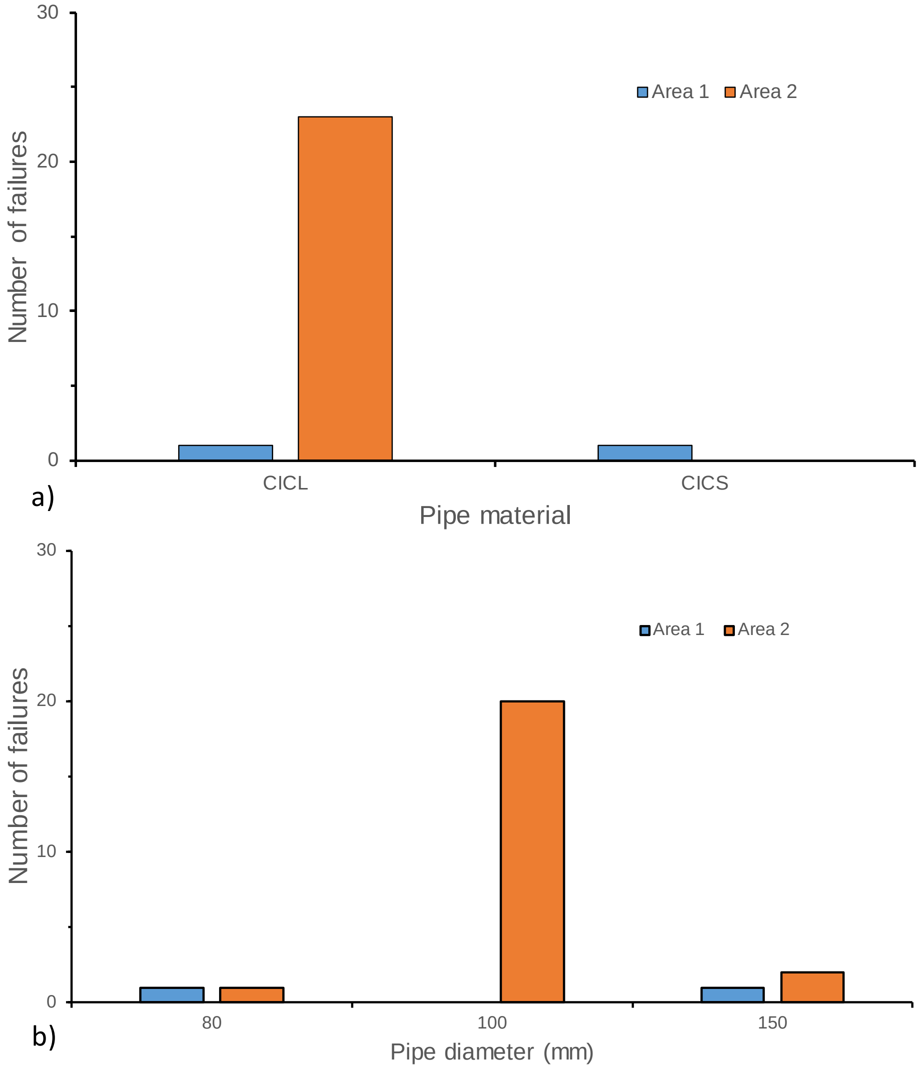

Figure 5. Comparison of 80-year-old pipe a) failure against built material and b) failure against diameter.

The 50-year-old pipe was selected due to a slightly high number of failures in Area 2 compared to Area 1. Based on the data provided, CICL and AC are the most common pipe materials found across the two study areas and these materials are evidently at the forefront of the pipe failures across the 50-year-old pipes age bracket. Figure 6a shows both the AC and CICL materials are heavily contributing to water main pipe failures, particularly CICL.

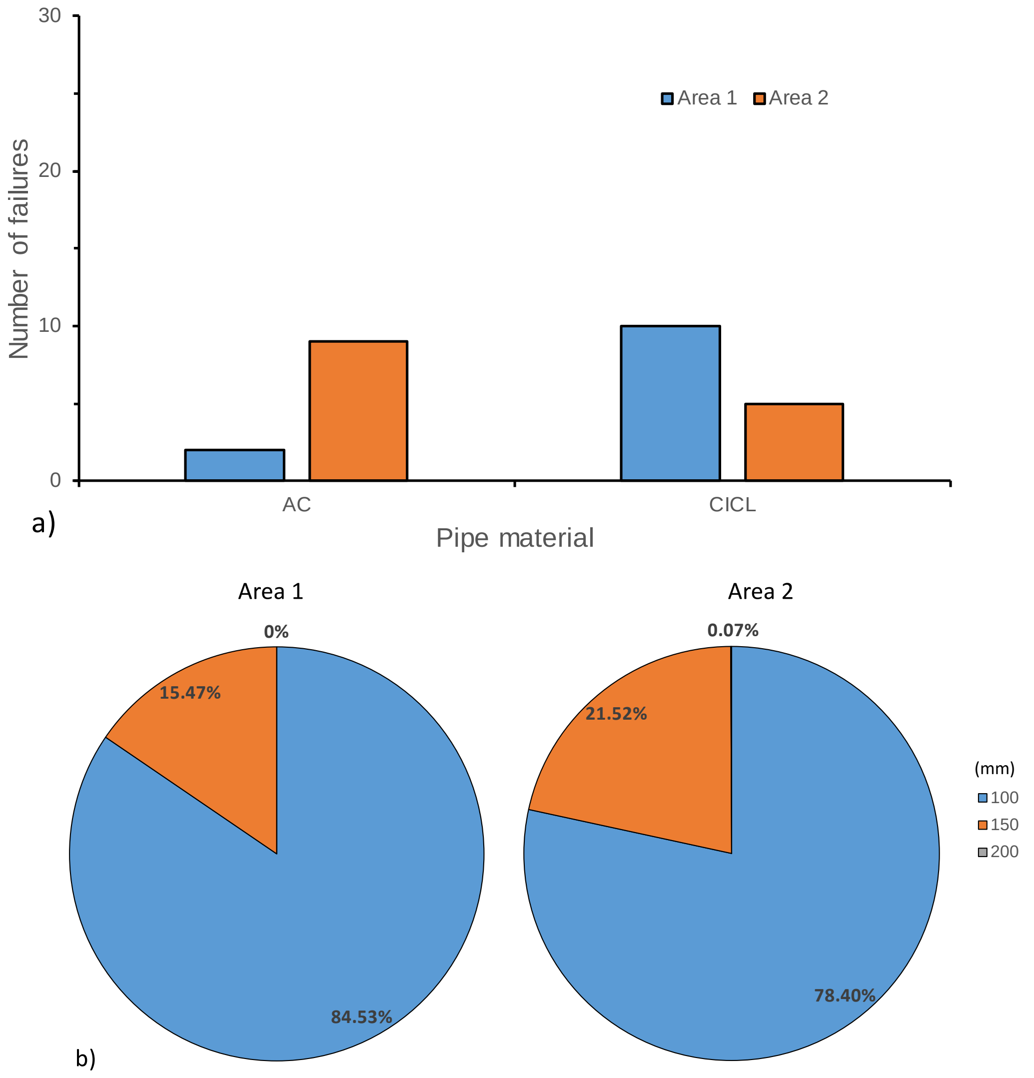

Figure 6. Comparison of 50-year-old pipe a) failure against material and b) failure against diameter.

As previously stated, the pipe diameter has little effect on water main pipes failure, however, 100 mm pipes are the most likely to be involved in failures. As seen in Figure 6b, 100 mm is once again the primary pipe size present, so some correlation can be established between this pipe size and water main pipe failure. Hence, more substantial information and research are required to make any significant statements indicating 100 mm pipes being the primary reason for the failure of water pipes.

From the analysis conducted on the two study areas based on relevant pipe attributes, it can be deemed that both pipe age and material have a significant effect on the failure rates of water main pipes and these are linked to one another. There are no failures of any water pipes that have been recorded under the age of 30 years. Similarly, zero failures were recorded under the PVC material, thus, a large portion of these pipes under the age of 30 are PVC materials or other new type materials such as DICL. These pipes are new, having been installed in new developments and as part of pipe reinstallation packages by the state government and thus newer pipe material technologies have been implemented. Thus, based on the research conducted between the two case studies, it can be concluded that water main pipes under the age of 30 are at little to no risk of failing, especially if they are made from any form of PVC material. However, as discussed, the specifics of such pipe replacement programs are difficult to find and certainly unclear for the most part, in addition to these sorts of data collection only taking place in the last decade. These factors have led to struggles in forming concrete conclusions and correlations surrounding age and materials due to lack of evidence. Furthermore, the data collection process and methods accessed throughout this research study did not provide details surrounding re-furbished pipes. Having access to the replaced pipes and the subsequent data would have further built an even stronger foundation for this high failure area leading to stronger correlations being formed between pipe age, material, and failure rates. As seen in the results, it was found that Area 2 had approximately 10 years extra in average pipe age, even though it also had a larger portion of younger pipes, primarily of the PVC material; indicating there were certainly much older pipes present in certain areas, thus further skewing the results and harming accuracy.

After the comparative analysis and based on the data it seems that when pipes turn approximately 50 years of age, they are expected to see a significant increase in failure rates. Primarily, these pipes are largely composed of CICL and AC materials, which have the most significant failure rates, however, seem to be still deemed too young to be replaced. It has further been found that 80 years of age is the critical age for water main pipes to fail as they are almost exclusively CICL, the most problematic material found in water main pipes. It is these pipes that have been replaced as part of these programs with the new line PVC and other new materials. These timeframes have been identified through the data and are an approximate guide to pipe age failure nature as when analysing the pipe age data, it is clear that there are little failures shown between 60 to 70-year age brackets, due to simple peaks in installation periods in the past, thus yielding such significant failure results at 50 and 80 years of age in particular. When further analysing these data and the most prominent ages of pipe failures, it further points to significant pipe replacements, especially at this 80-year old period, hinting that this critical age number may have already been discovered previously and thus acted upon, most evidently in Area 2, where there is a significant lack of pipes over this age. The results surrounding the effect of the diameter on water main pipe failures, unfortunately, have not brought about as strong correlations as the other mentioned pipe properties. Although the effect of diameter on failures has been somewhat clouded across the results yielded and there is a pattern that was evident depicted throughout the study. Firstly, 100 mm water main pipes are significantly the most common, followed by 150 mm sized pipes in both the study areas and, these both, are also the most common size pipes to fail. Throughout the research, this trend has been visible, most notably in the 50-year-old and 80-year-old pipe studies that were assessed. Although it seems that smaller pipes are at more risk of failing and metropolitan pipes are very much exclusively underground and carrying relatively smaller flows of water, thus limiting the data available for analysis when the data consists of only larger-sized pipes.

3.3 Relationship between the influencing factors and failure rate

As shown in the previous analysis, the number of failures in each area were classified in different categories, including pipe type, age and diameter. Using the above formulations, the correlation between the failure rate per km with these influencing factors were determined in Table 2 and Figure 7. It can be clearly seen that the pipe type and diameter showed strong correlation with the failure rate, which is consistent with the finding from Gould et al. (2011) and Duchesne et al. (2013).

However, the pipe age factor did not show any obvious relationship with the failure rate, as the coefficients of correlation in the two areas were much closer to 0. The reason was that the pipe age around 80 years were more prone to fail, i.e. having higher failure rate than other age groups. Although there is no strong statistical relationship between pipe age and failure rate, the pipe age of 80 years was reportedly a critical age for pipe failure. Therefore, for the prediction model for pipe failure, the age factor can be only used to categorize the failure rate into different groups, but it would not show any direct correlation with the failure rate.

Table 2. Coefficient of correlation between different factors and the failure rate (no. of failures per km)

		No. of failures		Length (km)		Failure per km		Coeff. of correlation	
		Area 1	Area 2	Area 1	Area 2	Area 1	Area 2	Area 1	Area 2
Pipe type	1 (AC)	5	13	8.530	7.501	0.586	1.733	-0.671	-0.601
	2 (CICL)	14	37	14.441	13.670	0.969	2.707		
	3 (CICS)	2	1	3.148	2.331	0.635	0.429		
	4 (Other)	0	3	2.669	3.141	0.000	0.955		
Diameter (mm)	80	1	1	1.200	0.400	0.833	2.500	-0.771	-0.947
	100	13	40	14.200	14.500	0.915	2.759		
	150	5	11	8.800	5.700	0.568	1.930		
	200	2	1	2.400	2.900	0.833	0.345		
	250	0	1	2.100	3.200	0.000	0.313		
Pipe age (year)	40	3	4	8.156	3.373	0.368	1.186	-0.372	0.042
	50	12	14	7.725	9.014	1.553	1.553		
	60	1	10	3.090	6.005	0.324	1.665		
	70	2	2	4.018	0.794	0.498	2.520		
	80	2	23	1.445	5.127	1.384	4.486		
	90	1	0	3.374	1.720	0.296	0.000		
	110	0	1	0.980	0.611	0.000	1.638		

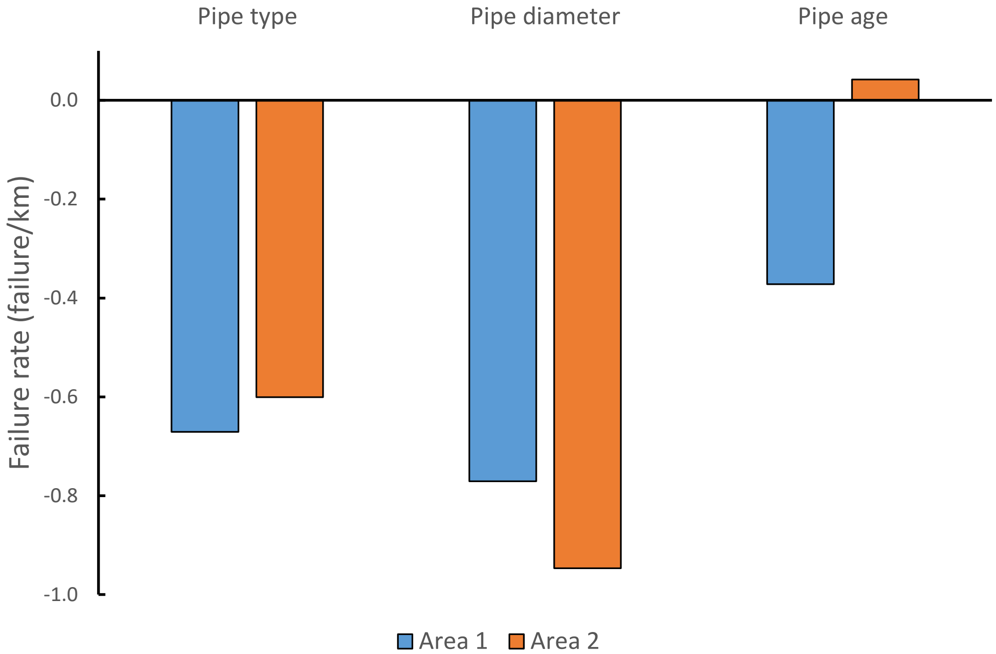

Figure 7. Coefficient of correlation between the failure rate and other influencing factors.

4. CONCLUSIONS

There has already been significant research into failure prediction modelling. However, there are still many unknowns in such models due to the vast number of potential variables that can be responsible for pipe failures. Hence, our approach was based on chosen two areas that consisted of similar soil properties to control this unknown variable of soil and focus more on statistical information available surrounding pipe properties. Ultimately, the development of such a failure prediction model will have major economic benefits to the water utility with the ability to identify and potentially replace water pipes prior to failure. Additional benefits would also arise surrounding the maintenance and replacement of such critical pipes identified (preventative maintenance), though having the ability to predict these pipe failures (Gao et al. 2021), maintenance can be scheduled accordingly in off-peak periods such as overnight. Implementation of such methods will drastically minimise traffic interruptions and delays as opposed to the current problematic situations brought about from the unplanned failure of water mains. It could also save huge amounts of money due to the emergency work and in case any businesses or households are affected by the interruptions. Ideally, a failure prediction model will factor in as many variables as possible to predict (in units of time) when a pipe is close to failing.

To summarise the findings of this study, two databases were used; the state-wide potable water pipe network data and the water pipe failure data that also consists of repairs for the last 7 years in South Australia. The two study areas selected within the metropolitan area contained a broad range of pipes bearing distinct attributes. After the analytical study based on the obtained data, it was found that both pipe age and material have a significant effect on the failure rates of water mains, and these are correlated to one another. To highlight the main findings:

- The older pipes being primarily made up of CICL material are susceptible to failure but CICL pipes are replaced after 50 years just before they start to degrade thus eliminating an increase in failure rates.
- Although there is not a strong statistical relationship between the pipe age and failure rate per km, it was found that a certain pipe age was more prone to fail than others. Pipes under the age of 30, primarily composed of new-age PVC materials, are extremely unlikely to experience failures and show a greater potential by providing a longer service life and fewer failure rates, pipes aged 50 years begin to experience an increase in failure rates and 80 years of age are critical.
- The diameter has very little impact on the failure rates of water mains, but diameters cannot be ruled out as a factor leading to water pipe failures solely due to the limited diameter range and relevant data attained for the study. However, it was found that when these failures did occur, it was more likely to occur in smaller pipes of 100 mm and 150 mm diameter.
- The pipe diameter and material had high coefficients of correlation with the failure rate, whereas the age factor did not show any direct relationship with the failure rate. Note, that the coefficients of correlation did not reflect the impact of the influencing factors on the failure rate. But these coefficients could be used to predict the chance of failure of the water main. Higher coefficients could provide a better prediction. Having said that, in a future prediction model, the pipe age can be used as a factor to categorize the data of water main failure.

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REFERENCES

Alexandru Marian R., Haidu I., Crăciun A., Ionuţ, Văduva B., 2012. GIS Utility For Hydrological Impact Evaluation Caused By Damages Of Water Supply Network In Rural Areas. Applications In Baia Mare Depression. Geographia Napocensis, VI(2).

AS 1289.7.1.1, 2003. Method 7.1.1: Soil Reactivity Tests – Determination of the Shrinkage Index of a Soil – Shrink-Swell Index, Methods of testing soils for engineering purposes. The Council of Standards Australia.

Australian Water Association, 2016. Water Main Failures. http://www.awa.asn.au/AWA_MBRR/Branches/SA/Recent_events/Water_main_failures.aspx (accessed by 8 August 2017)

BOM, 2018. National performance report 2016–17: urban water utilities, part A. Bureau of Meteorology, Melbourne, Australia.

Boxall J. B., O'Hagan A., Pooladsaz S., Saul A. J., Unwin D. M., 2007. Estimation of burst rates in water distribution mains. Proceedings of the Institution of Civil Engineers - Water Management, 160(2): 73-82.

Burn, S., Marlow, D., Tran, D., 2010. Modelling asset lifetimes and their role in asset management. Journal of Water Supply: Research and Technology - AQUA 59(6-7): 362-377.

Duchesne S., Chahid N., Bouzida N., Toumbou B., 2013. Probabilistic modeling of cast iron water distribution pipe corrosion. Journal of Water Supply: Research and Technology-AQUA, 62(5): 279-287.

Gao J, Rameez R, C.W.K Chow, Gorjian N., 2011. Preventative maintenance strategy for pipe burst by integrating monitoring data: A case study in South Australia. Water Utility Journal, 27: 37-43.

Gould S. J. F., Boulaire F. A., Burn S., Zhao X. L., Kodikara J. K., 2011. Seasonal factors influencing the failure of buried water reticulation pipes. Water Science and Technology, 63(11): 2692-2699.

Hekmati N., Rahman M. M., Gorjian N., Rameezdeen R., Chow C. W. K., 2020. Relationship between environmental factors and water pipe failure: an open access data study. SN Applied Sciences, 2(11): 1806-1817.

Javadinejad, S., Ostad-Ali-Askari, K., Singh, V.P., 2019. Reliable, resilient, and sustainable water management in different water use sectors. Water Conserv Sci Eng 4: 133–148.

Large A., Le Gat Y., Elachachi S.M., Renaud, E., Breysse D., 2015. Improve modelling of 'long term' future performance of drinking water pipes. Journal of Water Supply: Research and Technology - AQUA, 64 (4): 404-414.

Li S., Wang R., Wu W., Sun J., Jing Y., 2015, Non-hydraulic factors analysis of pipe failure in water distribution systems. Procedia Engineering, 119: 53-62.

Mahmoodian, M., Li, C.Q., 2016. Serviceability assessment and sensitivity analysis of cast iron water pipes under time-dependent deterioration using stochastic approaches. Journal of Water Supply : Research and Technology - AQUA, 65(7): 530-540.

Majumder, P., Majumder, M. & Saha, A.K., 2018. Climate change and urbanization impact on hydropower plant by neural network-based decision-making methods: Identification of the most significant parameter. Water Conserv Sci Eng., 3: 169–179.

Mamo, T.G., 2015/ Risk-based approach to manage aging urban water main infrastructure. Journal of Water Supply: Research and Technology - AQUA, 64 (3): 260-269.

Mora-Rodríguez J., Delgado-Galván X., Ramos H. M., López-Jiménez P. A., 2014. An overview of leaks and intrusion for different pipe materials and failures. Urban Water Journal, 11(1): 1-10.

Rajani B., Kleiner Y., 2001. Comprehensive review of structural deterioration of water mains: physically based models. Urban Water, 3(3): 151-164.

Rajani B., Zhan C., Kuraoka S., 1996. Pipe–soil interaction analysis of jointed water mains. Can Geotech J, 33(3): 393-404.

Rezaei H., Ryan B., Stoianov I., 2015. Pipe failure analysis and impact of dynamic hydraulic conditions in water supply networks. Procedia Engineering, 119: 253-262.

SA Water, 2018. SA Water Geographical Information System (GIS) maps. http://sawater.maps.arcgis.com (accessed by 15 July 2018)

Sadiq, R., Kleiner, Y., Rajani, B., 2004. Aggregative risk analysis for water quality failure in distribution networks. Journal of Water Supply: Research and Technology-AQUA, 53(4): 241-261.

Sheard M.J., Bowman G.M., 1998. Soils, stratigraphy and engineering geology of near surface materials of the Adelaide Plains. Primary Industries and Resources, South Australia (PIRSA) and CSIRO, Adelaide, 492.

Wols B.A., van Thienen P., 2013. Impact of weather conditions on pipe failure: a statistical analysis. Journal of Water Supply: Research and Technology-AQUA, 63(3): 212-223.

Xu Q., Chen Q., Li W., 2011. Application of genetic programming to modeling pipe failures in water distribution systems. Journal of Hydroinformatics 13(3): 419-428.