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Water Regional Alliance Program

April 2018

Infrastructure Cliff? Queensland's Ageing Water and Sewerage Assets. 1. In-ground network asset lives.

QWRAP Research Report 5.1

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Executive Summary

In-ground network assets are the most expensive component of water utilities' infrastructure. Water (42,000 km) and sewer (33,500 km) pipes comprise the largest component of the $37 billion local government-owned water and sewerage infrastructure servicing over 4.3 million people across 370 communities. Queensland's networks saw rapid expansion in the decades following World War II creating a large cohort of assets that will come to the end of its useful life over a similarly short period in coming years. Continuing expenditure on network expansion along with the hidden nature of existing networks means that degradation of existing pipes is not obvious and ageing assets attract public and political attention only during major incidents.

In other jurisdictions a business-as-usual-approach to maintenance has resulted in an investment deficit when large numbers of ageing assets require repair or replacement at the same time. In many countries the need for increased asset investment has contributed to 'water reform' including corporatisation and privatisation in an attempt to increase efficiencies and avenues for investment. These experiences and anecdotal evidence of ageing Queensland assets led to the current research through the Queensland Water Regional Alliances Program (QWRAP) to better understand the age, quantity and types of in-ground assets across Queensland.

Data collected represented 70% of all Queensland public networks and represented service providers of all sizes. Initial examination revealed that a significant component (29%) of current water and sewerage networks are composed of asbestos cement (AC) pipes installed between the 1960s to the 1990s (Fig. A). The median expected life for all the AC pipes was 70 years meaning a large cohort of mains is likely to require renewal over a similarly period in coming years.

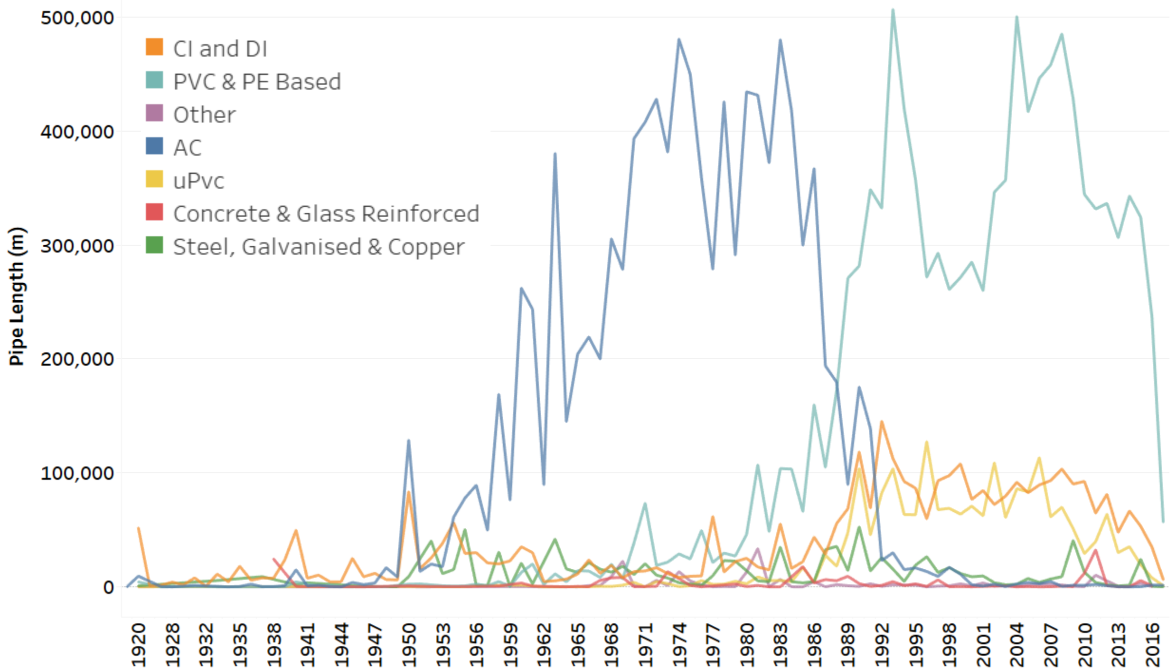

Figure A: Over 22,000 km of asbestos cement mains were installed between the 1960s and 90s leaving a cohort of pipes that will soon reach their expected life-time.

Three independent modelling approaches predicted that the cohort of AC mains would suffer increasing failure rates over the next two decades peaking by the 2040s. Similar results were projected for sewer networks, which although typically younger than corresponding water schemes, are predicted to suffer a more rapid degradation. One model (based on historical Queensland data) predicted annual breaks for the major size classes of AC water mains. The model predicted breaks that aligned with independent annual reports but increased rapidly over the next two decades and be four times higher by 2040 (Fig. B).

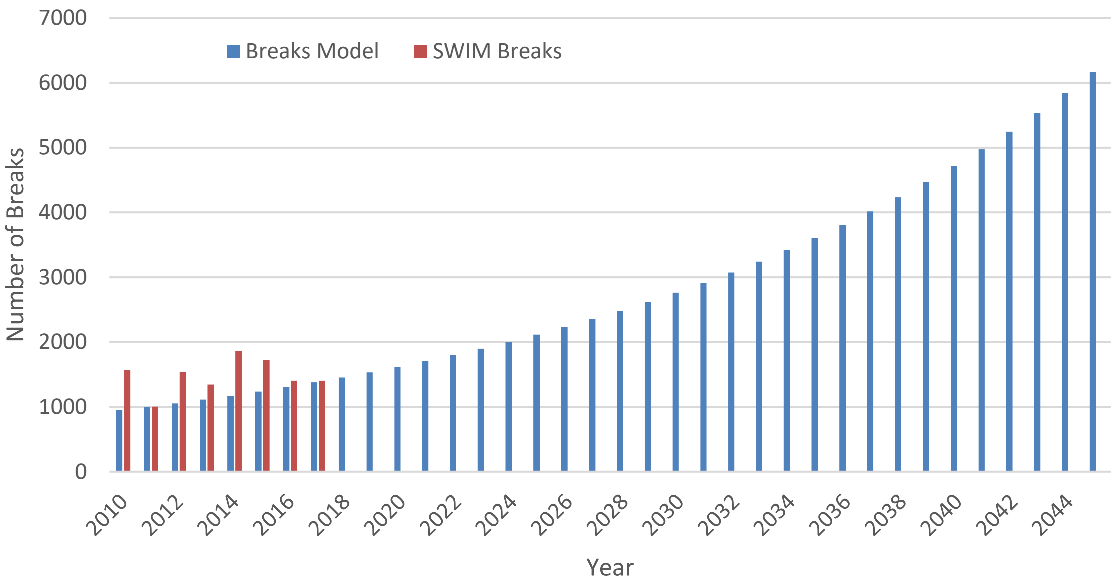

Figure B: Reported (SWIM) breaks aligned well with predicted breaks for asbestos cement water mains which were predicted to accelerate from the 2020s.

Demand from increased rates of failure will be in addition to current background renewal rates. At a conservatively estimated current rate averaging 0.3% per annum, the ageing AC cohort alone would take over 170 years to replace. Other pipe cohorts, notably old cast iron and ductile iron water mains, and other cement-based sewers, will concurrently suffer increased failure rates meaning current management will not suffice to maintain networks. The current low rate of replacement along with the length of pipe at risk means the emerging acceleration in network failures represents a potential infrastructure cliff that requires a significant shift in the way in-ground assets are managed across the entire State.

Optimal renewal of in-ground assets prioritises methods and timing for repair, relining and replacement based on maintaining agreed levels of service at the lowest cost. All methods seek to balance the need to maintain services and optimise the trade-off between repair and replacement. This is a nuanced trade-off that varies from town-to-town and even from pipe-to-pipe and must be based on appropriate data. This report is the first in a series that collates asset ageing information and solutions for optimising future investment for Queensland. The second report examines the costs associated with the deficit in investment in in-ground assets and examines trade-offs between repair and replacement.

1 Background

Infrastructure investment often emphasises growth driven by new standards, technologies or population increases, but a greater focus on asset replacement is becoming increasingly important for three reasons:

1. International studies show an infrastructure cliff is likely when large cohorts of assets reach the end of their life concurrently following years of business-as-usual maintenance.
2. Historical patterns of infrastructure investment in Queensland saw numerous assets installed in the 1960s-80s meaning many will reach the end of their useful lives over a similarly short period (Fig. 1).
3. Underinvestment and the (real or perceived) need for greater capital spending are the most common triggers of water sector reform in Australia and overseas.

In the face of multiple assets coming of age, business-as-usual repair and replacement will not suffice as failures increase beyond historical levels. An early, considered response can reduce the impact of ageing assets as well as mitigate reputational risks for the water and sewerage sector.

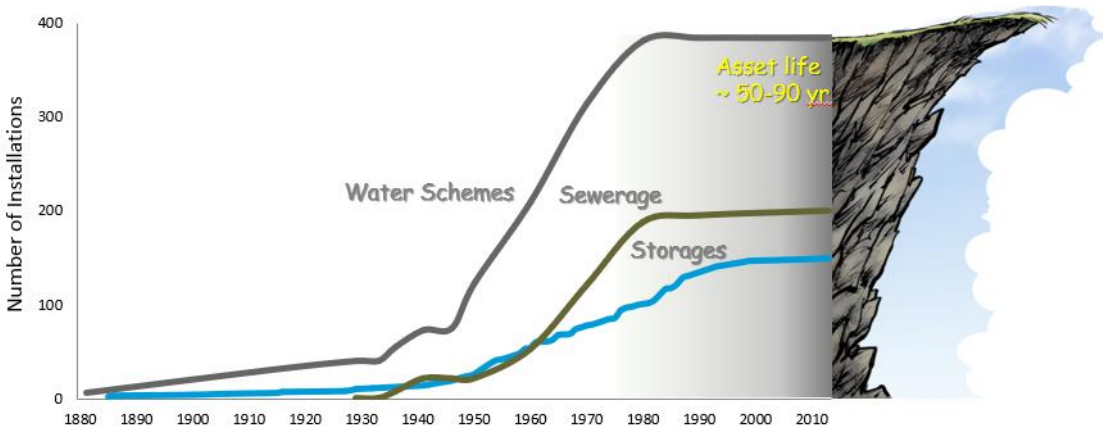

Fig. 1: Installation of water and sewerage infrastructure increased rapidly in the second half of last century with many assets having a 50 to 90 year expected working life.

The Queensland Water Regional Alliance Program (QWRAP) was created to assist regional groups of councils to collaborate on strategic management of water and sewerage services. The program is a collaboration among the Queensland Government, Local Government Association of Queensland, Queensland Water Directorate and participating councils in regional Queensland and is funded by the Department of Natural Resources, Mines and Energy). Although regional economies of scale can be difficult to achieve across the many small and distant Queensland communities, QWRAP has demonstrated that regional collaboration can produce financial savings for both small and large service providers (QWRAP, 2016, 2017). However, regional infrastructure planning and investment is uncommon among water and sewerage service providers in Queensland and requires further investigation.

Ageing mains will be reflected in increasing rates of breaks and failures necessitating increased repair, relining or replacement each with different costs, risks and benefits. Investment decisions must balance these factors and require good information on rates of failure and relative costs of different solutions. This research aims to initiate further discussion on these issues by:

1. collating and analysing existing asset information to estimate the scale and timing of future demand, and
2. identifying and recommending mechanisms by which infrastructure planning could reduce future cost-to-serve and optimise investment.

1.1 Initial Focus on In-ground Assets

In-ground assets (bulk transfer pipes, mains, reticulation and collection systems) provide the backbone of the water and sewerage industry. Despite being the principal asset class in Queensland's $37 billion water and sewerage infrastructure (SWIM, 2016) these assets are 'out-of-sight and out-of-mind' and not an obvious investment priority for either the public or politicians responsible for water and sewerage services. It is common for public water authorities to have chronic underinvestment interspersed with periods of panicked expenditure when public support is awakened during a crisis. Signs and symptoms of underinvestment in ageing pipe fleets include increasing leaks, stormwater infiltration, bursts, elevated maintenance costs and customer complaints.

In-ground assets are expensive to maintain but costs are inflated if the assets are neglected. As an example, while the cost to reline or repair ageing pipes can be high, deferring maintenance until pipes collapse completely typically requires more expensive replacement techniques. Along with costs, other risks also increase with ageing of water and sewerage networks, including threats to:

- public health (through impacts on water quality),
- environmental and public health from sewage leaks,
- safety (e.g. if flows for fighting fires are reduced),
- collateral damage (flooding, pressure damage and sinkholes),
- disruption to residents and businesses (through shut-downs and road closures),
- sewage treatment and discharge (because of infiltration to sewer pipes),
- water security (due to leaks and bursts),
- financial sustainability (through increased cost for repair and replacement), and
- reputation (perceptions of quality, interruptions and real and perceived risk).

Although such risks are routinely managed by water and sewerage utilities, an 'infrastructure cliff' would represent a rapidly increasing occurrence and severity of these threats. This is particularly problematic for utilities accustomed to a predictable, low background rate of asset degradation due to the bulk of assets being installed relatively recently. A large, up-front investment can be followed by decades of low-cost maintenance with little need for immediate repair or planning for asset replacement. These factors have all contributed to emerging infrastructure cliffs for extensive in-ground asset fleets (see Table 1) overseas (e.g. the United States (AWWA, 2013), United Kingdom (UKWIR, 2017) and Thailand (Punurai & Davis, 2017).

In the USA a $152 billion gap (total) in necessary expenditure has been predicted by 2040 if current 'business as usual' spending continues (ASCE, 2016). For water mains alone, it has been estimated that replacement costs will total between $13 billion and $30 billion per year by 2040 requiring an investment of $526 billion over 25 years (AWWA, 2001; AWWA, 2013). These reports did not examine sewerage assets but acknowledged they posed a similar problem and that costs for both types of mains would be impacted by tightening expectations and regulatory standards.

Table 1: Comparison of in-ground asset size from various jurisdictions.

Jurisdiction	Water Mains (km)	Sewer Mains (km)	Source
USA	~1,600,000	~1,600,000	EPA (2002); Folkman (2012)
UK	350,000	635,000	UKWIR (2017)
Australia	187,150	141,800	NPR (2017)
Queensland	42,000	33,500	SWIM (2017)

For the United Kingdom, UKWIR (2017, p.1) have noted that although analysis of pipe assets had improved markedly in the previous decade, investment "remained low at 0.6% [water mains] and 0.2% [sewers] per annum". This implies asset renewal at a rate of 170 years for water and 500 years for sewerage. The report concluded investment would need to increase between 2-6 times if current service levels were to be maintained.

Fewer studies have been undertaken in Australia. Replacement and relining rates specifically for pipes made of asbestos cement in large Australian utilities have been estimated to be around 0.04% for sewer mains, 0.27% for rising mains and 0.3% for water mains on average per year (WSAA, 2013). This was a conservative estimate as replacement was primarily focussed on "older and smaller diameter pipes" which are generally less expensive to rehabilitate (p. 21-22). The report concluded that the investment required to renew ageing pipes "is expected to be above current annual budget levels" (p. 40).

The costs and risks associated with in-ground asset ageing along with evidence in other jurisdictions facing an infrastructure cliff, led to prioritising this initial research on Queensland asset ageing on water and sewerage networks. There is little information on replacement rates and pipe ages in Queensland though some service providers have active research programs in this area. A small proportion of large Queensland utilities were included in the national WSAA study discussed above and one South East Queensland service provider has independently reported a replacement rate of 0.26% for water mains. In contrast, some small service providers have aggressive replacement programs driven by availability of internal or grant funding, a perverse incentive to replace pipes (potentially) prematurely.

Anecdotal information from a broad range of Queensland utilities provides a mixed view of the potential need for increased investment. While some have increased monitoring and renewal programs, others believe that current life expectancies may be over or under-estimated. There are numerous anecdotes of old pipes being exposed and looking 'good-as-new' while others report prematurely degraded and even collapsing mains. These diverse experiences are likely driven by the diversity of pipe ages, size and materials and the variables responsible for degradation. The following section examines the major failure modes for pipes and reviews models that estimate rates of degradation allowing for this variation.

2 Pipe Degradation

WSAA (2013) noted that causes of pipe failures are wide-ranging including internal wall corrosion, which is often the key cause, closely followed by poor construction, third party damage, external loading, internal loading and external corrosion. The impact of each of these factors is influenced by pipe size. Small pipes are less robust (thinner walls) than larger pipes and are more difficult to renew using techniques such as relining, although technologies are being developed to further make relining more efficient. Regardless of size, failure mode is influenced strongly by the soil type, bedding material and how carefully pipes were laid.

Corrosion is a constant risk for many pipe materials and in the absence of other factors, will eventually cause failure of many pipes. However, other failure modes generally dominate in environments with less aggressive internal or external conditions, and also in larger pipes which have relatively thick walls and thus take a long time to corrode. Exposure to aggressive liquids and pressures (internal or external) combine to be key causes of degradation which is why smaller (thinner) pipes are more prone to decay. As examples, sewer mains are prone to internal corrosion in areas where hydrogen sulphide gas (and thus sulphuric acid) build up is common. Similarly, concrete-based water mains transporting 'soft water' decay faster than those in areas with 'hard water' because the water constantly erodes the inner surface of the pipes.

Failure history can be a predictor of the probability of future failure. Martins (2011, p. 17) found "there is a clear relationship between the occurrence of previous failures and the occurrence of future failures, […] the higher the past individual failure rate is, the higher is the tendency to fail in the future." Anecdotal evidence from Queensland service providers confirmed this finding with the consensus being once a break occurs in a length of pipe there is a higher probability that another break will occur in the same length of pipe.

Queensland is a vast and diverse state with multiple factors influencing the failure modes of buried infrastructure. A major cause for failure in one area may only be a minor concern elsewhere depending on soil types, rainfall, pipe age, construction method and network pressure and maintenance. Pin pointing the most critical failure point becomes an immense task at a regional or even scheme-wide scale and must be done on a case by case basis.

Managing and predicting different types of pipe degradation is of increasing interest and modelling of failures of water mains and sewerage networks is an emerging area of research. A major review of work on pipe failure models prior to the year 2000 was undertaken by Kleiner and Rajani (2001), while Wilson, *et al.* (2017) reviewed models post 2001. Most modelling studies recognised multiple factors that are involved for failure of water and sewerage mains, predominately corrosion, pipe pressure loads and material composition (see e.g. Rajeev *et al*., 2016; Kleiner and Rajani, 2001; Wilson *et al.*, 2017).

There are two main categories of models used for these purposes. Physical models focus on corrosion of various pipe materials while statistical models use analysis of historical data on pipe breaks. Both types have various advantages and disadvantages. A key difference is that physical models do not require large amounts of historical data. If large amounts of historical data are available, a statistical model may prove easier to use (Wilson *et al.,* 2017). Some of the features of the two categories of models are analysed below in order to guide model selection for the current research.

2.1 Physical Models

Extensive research into physical processes of pipe failure and corrosion has occurred (Wilson *et al.,* 2017). The advantage of a physical model is the limited amount of historical pipe degradation data required, although conversely, this can be a hindrance to physical models due to the difficulty in verifying parameters with such limited data (Kleiner and Rajani, 2001; Wilson *et al.,* 2017). Liu and Kleiner (2013) suggested that the current challenge of physical models is the lack of mature inspection techniques to verify data and modelling results. Physical models work on the logic that degradation (e.g. corrosion) over time will lead to the weakness and failure of pipe infrastructure.

Several physical models seeking to accurately predict the failure of cast iron (CI) mains have been created with varying degrees of success (Rajani *et al*., 2000; Tesfamariam *et al*., 2006; Moglia *et al*., 2008; and ACAPFP, 2014). Rajani *et al*. (2000) provided the simplest model to apply to CI mains failure as the model was designed to work out the maximum corrosion pit depth that can be used to calculate the length of time before a 'failure' occurs. The defining problem of the models is the difficulty in verifying the data when applied to the entire supply network (Sadiq *et al*., 2004). Sadiq *et al*. (2004) tried to include a probabilistic framework to provide higher accuracy with limited success.

Physical models for other pipe materials are not as numerous as those for CI. This is due to cast iron having been in use for a significantly longer period than poly-vinyl chloride (PVC) and asbestos cement (AC). Research into PVC deterioration is currently not well documented due to the material being relatively young and also long-lived (Kleiner and Rajani, 2001). Davis *et al*. (2007) developed a model for predicting PVC pipe failure which provides a starting point for future PVC pipe modelling research although it is currently limited to calculating the impacts of loading.

Research into AC pipes has seen more activity than for PVC in the attempt to find the optimal time for replacement, due to its older age[1] (Wilson *et al.,* 2017). Davis *et al*. (2008) modelled the effect of loading failures over time but did not examine corrosion. The New Zealand Water and Waste Association has undertaken research since 2001 to understand the corrosion of asbestos cement pipes and released recent results in 2017. The research suggested that corrosion was the main factor in AC pipe degradation and that it can be modelled over time with an average annual corrosion rate (NZWWA, 2017).

[1] AC pipes were used commonly between 1926 to the 1980s whereas PVC became commonplace in the 1970s.

2.2 Statistical Models

Statistical models are based upon the observation and analysis of large amounts of historical data on Local pipe degradation and differ from physical models in not considering the physical mechanisms that lead to failure (Wilson *et al*., 2017). Many different types of statistical models have been created but due to their reliance on long term observations, application to new assets lacking historical data is fraught with difficulties (St. Clair and Sinha, 2012). Wilson, *et al*. (2017) suggested that it is possible to reduce the amount of data required but the cost is that the mathematical calculations become much more complex. The key issue with statistical models is that their results are heavily dependent on the underpinning historical data.

General statistical models do not require significant amounts of data and provide an approximation of degradation rates which is well suited for large macro level assessments, as undertaken in this report. An example is the use of the Weibull distribution, a statistical approach widely used in reliability engineering to model failure distributions. The benefit of a Weibull distribution model is that the expected life can be used as one of two parameters to define the distribution allowing for a simple sensitivity analysis based on the different expected life projections.

An example of a more specific model was analysed within this report; exponential functions were developed by a large Queensland water and sewerage service provider based on historical break data of its own water networks. This ‘exponential model’ examines the number of breaks for the most common sizes and materials of pipes in a Queensland context. The stochastic data used to create the exponential model represents a substantial break-history relevant to Queensland. Although the diversity of Queensland means that this model will not be accurate for all areas, it is the most relevant data set that has been developed to date.

3 Data Collection and Collation

3.1 Data Survey and Template

To gather data for the current research, a survey was distributed among Queensland councils and the two SEQ distributor-retailers. Data requests were sent to technical officers at each service provider and also to CEOs of each council. The request was followed with phone calls to check how councils were progressing with the data survey. Each of the survey’s fields were developed to mirror the content of a ‘typical’ asset register.

The following information was requested from each organisation, split into primary and secondary fields based on the importance of the data and the likelihood it could be successfully collected.

Primary fields:	*Secondary Fields:*
Scheme/Location: Location of pipe asset Pipe Length (m): Length of pipe in metres	Planned Replacement Date: Expected replacement date

Pipe Diameter (mm): Diameter of pipe in millimetres Pipe Material: Material of pipe Pipe Year of Install/ Build Date: Year of install of pipe asset Pipe Useful Life: Expected useful life of pipe asset Pipe Remaining Useful Life: Remaining useful life of pipe	Pipe Condition: Condition of pipe as of last inspection Depth (m): Depth for pipe asset Soil Type: Soil type in which the pipe was buried Joining/ Connection: Joining or connection used for pipe asset Importance/ Criticality: Importance and criticality of pipe asset to network

3.2 Collation and Initial Analysis

The survey response provided data on 70% of the State's water and sewer networks from a range of small, medium and large service providers. The data is representative of all but the largest and oldest city's infrastructure (Brisbane). Anecdotal information and semi-structured interviews with service providers during the survey provided some ground-truthing and first-hand accounts of inground asset management across a range of circumstances.

An unexpected finding was the range of detail and scope of available data across different entities. The data was often extracted directly from council asset management systems and thus represents the most accurate information available. However, a number of respondents suggested that while the information was the best at hand, it suffered from inaccuracies (e.g. install-years of some pipes are missing, material of pipes was sometimes unknown and relining of pipes was seldom recorded in the asset information). These gaps affected approximately 10% of the data. In general, asset management systems, data management and data quality have improved over time.

A summary of the data coverage is provided in Table 1. The total mains length for Queensland in 2017 was 42,000 km (water) and 33,500 km (sewers) (SWIM, 2017). A response rate of 41 of 72 service providers (57%) provided a broad cross-section of the total possible dataset (Figure 2) including around 70% of total mains. Collation of data was undertaken with Tableau™ software to combine several inputs and rapidly produce multiple ways to visualise the data.

Table 2: Summary of extent of data collected in context of State-wide totals from SWIM (2017).

	Queensland	**Survey Data**	**%**
Number of entities	72	41	57%
Water main length	42,000 km	29,750 km	71%
Sewerage length	33,500 km	22,600 km	67%

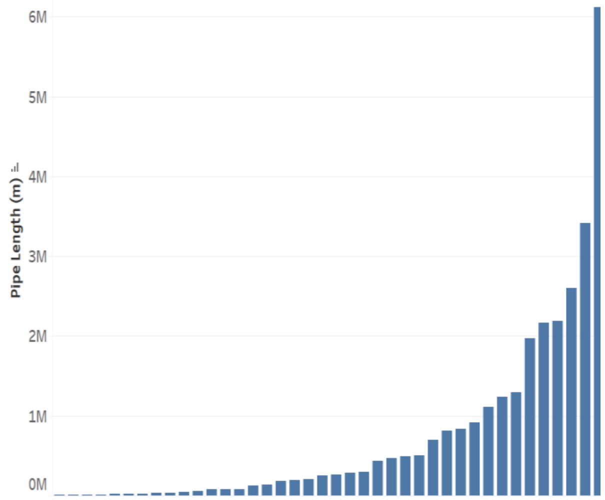

Figure 2a: Length of water mains across 41 entities that provided data (Length in millions of metres).

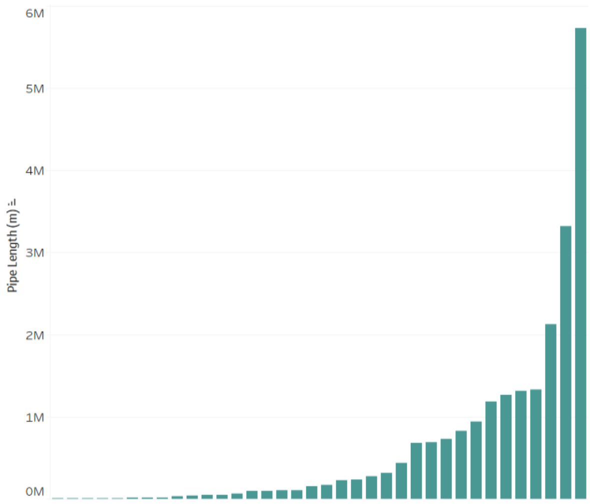

Figure 2b: Length of sewers across 41 entities that provided data (Length in millions of metres).

The following analysis provides a summary of the lengths, ages and types (materials) of pipes represented in the data collected.

3.3 Water Mains

Water mains currently in service are constructed from a broad range of materials which were grouped into the seven categories summarised in Figure 3. The two largest categories were AC (38.1%) and PVC and PE-based materials (37.7%). However, there was a distinct difference in the installation profile of these two broad categories of mains.

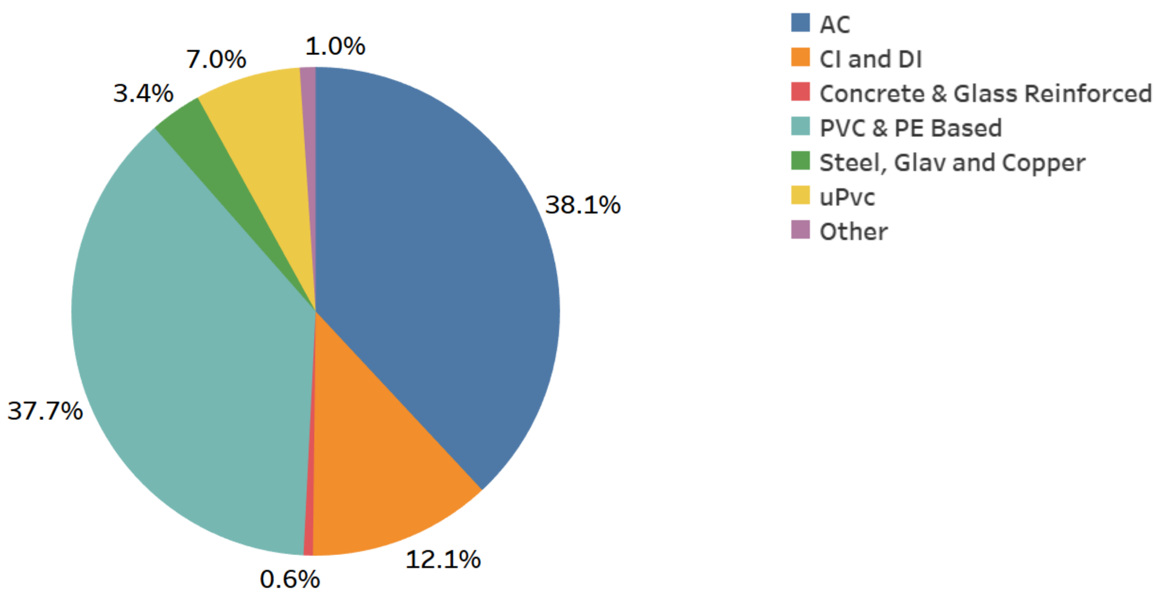

Figure 3: Percentage breakdown of water mains in the survey dataset categorised by pipe material.

A rapid increase in infrastructure installation following World War II saw significant use of AC materials in early growth of water schemes which was replaced in the 1980s and 90s with PVC and PE products (Figure 4). AC mains have an average life expectancy of 70 years leaving a significant cohort of pipes that are soon to reach the end of their useful life. This legacy is complicated by the risks associated AC materials. Although AC does not pose a health risk when in used in water mains, exposing and disposing of the pipes raises workplace health and safety risks that must be well managed (WHO, 1996; WSAA, 2013; qldwater, 2014). These historical patterns in installation mean that the driver of any imminent 'infrastructure cliff' will be the predominant AC pipe used for Queensland's older installations and further analysis and modelling in this research focussed on this cohort.

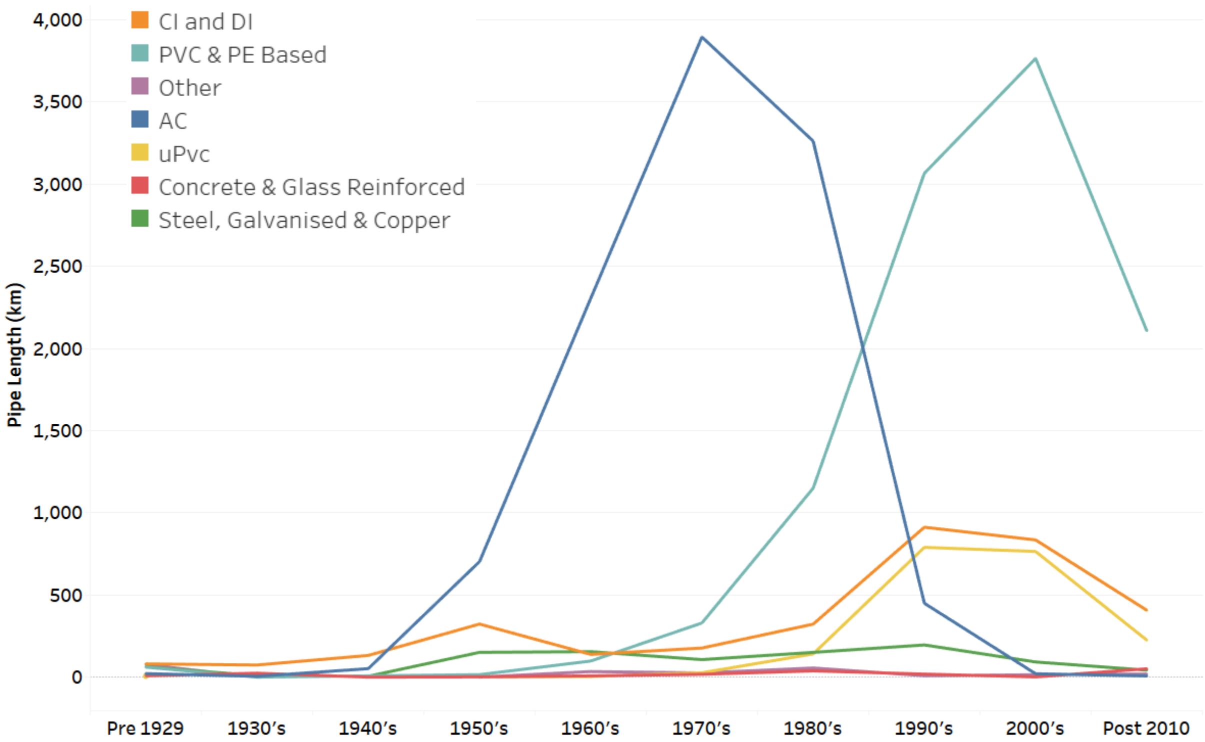

Figure 4: Length of water mains installed and still in service in the survey dataset categorised by pipe material.

The size of the AC mains used across Queensland varies from 16 mm to 1650mm (Appendix 1). For ease of analysis, the data were grouped into five categories; 100mm, 150mm, 225mm, 300mm and greater than 300mm. Based on the predominant pipes sizes used across the State (Figure 5), pipes of 100 and 150 mm diameter are the most common in Queensland water networks.

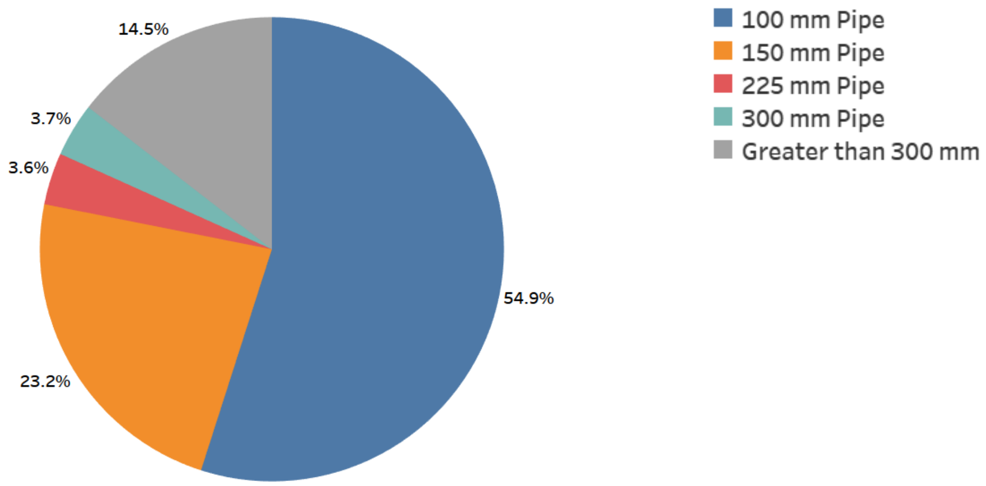

Figure 5: Length of water mains in the survey dataset grouped by diameter

3.4 Sewerage Mains

The length of the Queensland sewerage network is roughly 80% of the water network and sewers were typically installed later than corresponding water supplies. Sewer installation grew dramatically the 60s and 70s, an approximate 10-year delay compared with the expansion in water networks (Fig. 6).

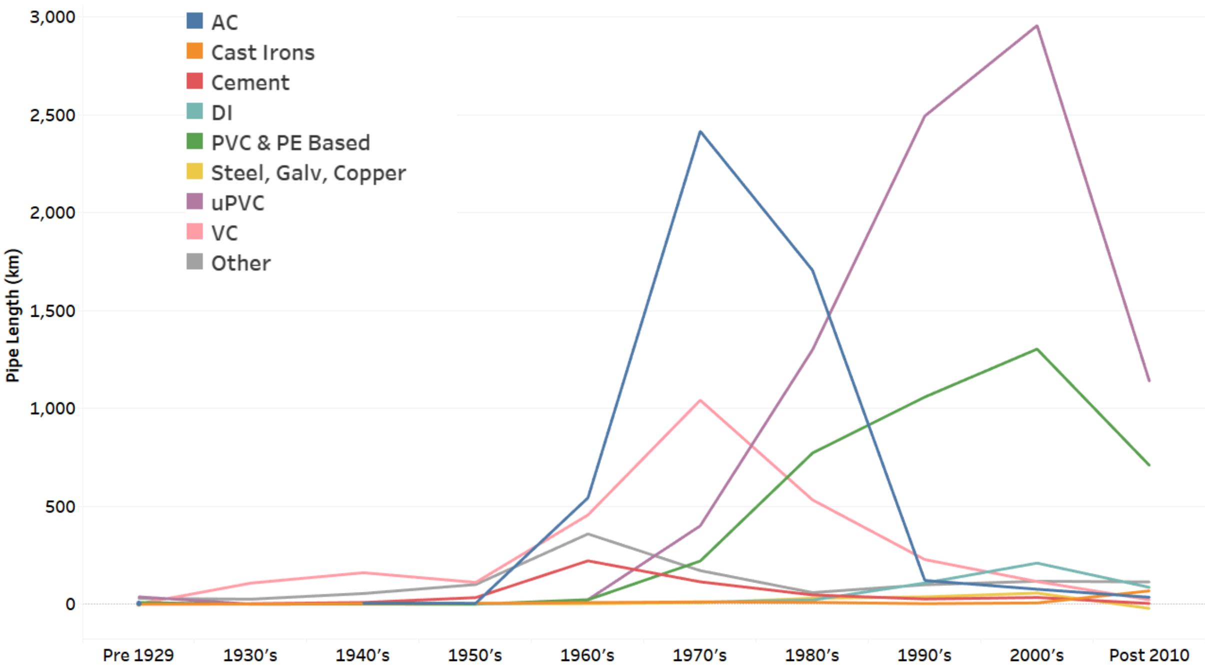

Figure 6: Length of sewers in service in the survey dataset categorised by pipe material.

AC pipe was used predominantly for sewers throughout Queensland until the 1980s but unlike the water mains, contemporary alternatives, primarily vitrified clay (VC) pipes, were also significant. Of the 22,600 km of sewer pipes 5,000 km (22%) was of AC composition (Figure 7). PVC and PE-based materials and unplasticised PVC (uPVC) replaced these initial pipe materials rapidly from the 1980s. All of these materials have expected life-spans of 70-80 years (Appendix 5). AC sewer pipes were selected for further analysis in this research because of their predominance in the cohort of pipes soon to reach the end of their working lives.

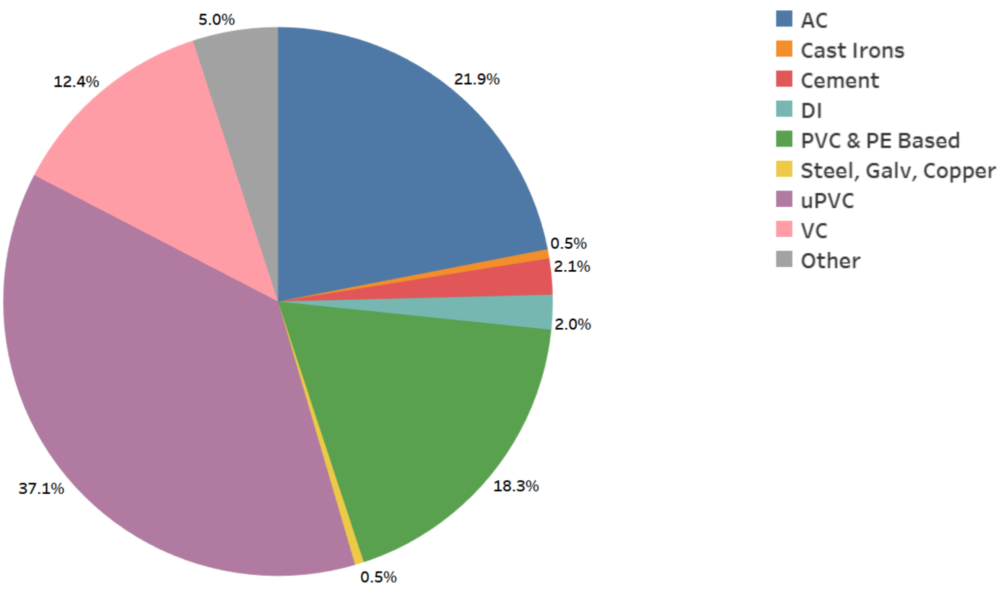

Figure 7: Percentage breakdown of sewer mains categorised by pipe material.

Sewer pipes ranged in size from 20 to 3250 mm but 150 mm dominated significantly (Appendix 2) and five size classes were used to group the pipes based on the most common diameters used across the State (Fig. 8).

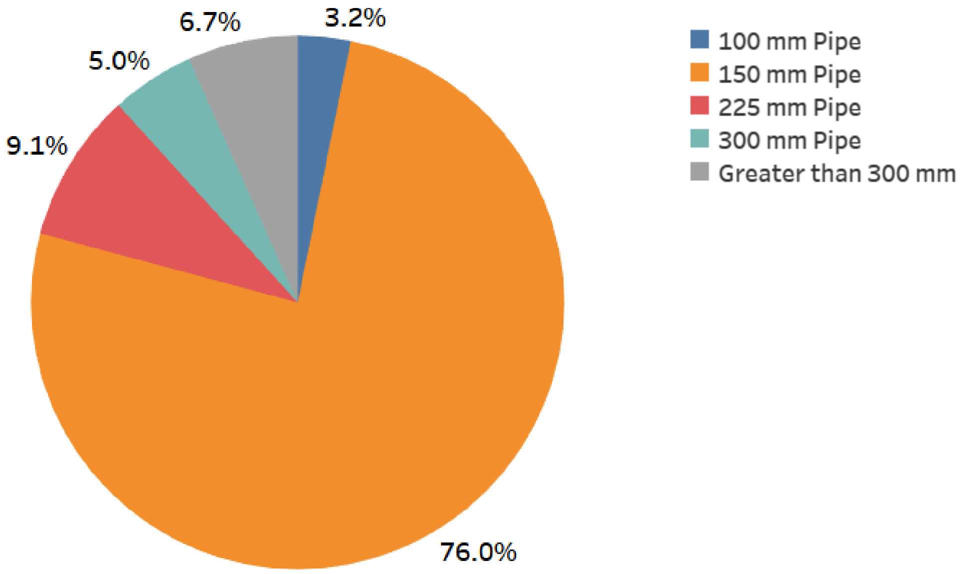

Figure 8: Percentage of AC sewers currently in service in the survey dataset categorised by pipe diameter.

4 Predicting degradation of AC water and sewer pipes

The expected life of AC mains varies depending on pipe diameter and other conditions (see Section 2). Councils use a range of expected lives ranging from 50 to 100 years for AC pipe with the average being around 70 years to cover the range of pipe sizes and external factors (see Appendix 4). A further complication is in defining a 'failure', which can range from a break at a single point to a failure along the length of a pipe. Some failures can be repaired at a single point while others require replacement or significant relining. For the sake of this report a failure/break is defined as an event where a pipe may leak water or sewage into the environment and so indicates where repair is required but does not necessarily result in a total failure of service.

Three models were chosen to explore the likely degradation rates of the current fleet of AC water and sewerage pipes across Queensland, a physical model and two statistical models. Initially, a physical model was trialled which estimates degradation rates of AC pipes based on significant research into internal and external corrosion rates in New Zealand (NZWWA, 2017). The model therefore considers only one (albeit a critical) failure mode for AC pipes. Moreover, the model was developed specifically for pressure pipes under New Zealand conditions and hasn't been modified in any way to represent the broad range of Queensland conditions. The model is based on the wall thickness of pipes which were estimated based on pipe diameter using the dimension and classes of AC pipe *Australian Standard 1711-1975* which focused on Hardie's Fibrolite AC Pressure Pipe. Using the wall thickness of pipes and the corrosion rates from the NZWWA (2017) study the model predicts when the wall of the pipe has been completely corroded.

A Weibull functional analysis was also trialled to provide a stochastic estimate of ageing of the AC network. The Weibull distribution has been used previously for prediction of AC pipe failures by Punurai *et al.*, (2014). The model predicts the length of pipe that will fail each year based on the age and length of existing pipes and their assumed life expectancy.

The final model trialled was the exponential (statistical) functions model developed by a Queensland service provider based on significant historical data. This model has the potential to be more accurate than the physical model as it is based on more regionally-relevant data and encompasses a broader range of failure modes (i.e. beyond only corrosion). Rather than failure of pipes by length, the model estimates the number of breaks per annum in a given length of pipe (of defined size and material).

4.1 Degradation models of water mains

All of the models showed a rapid increase in AC pipe degradation in the next three decades although there was some variability in the expected onset and rate of failures depending particularly on pipe size. The models cannot be used to predict the expected life of any specific length of pipe but rather, model an average rate of failure of pipes on a state-wide basis over time.

Considering only failures arising from corrosion, the degradation curve shown in Figure 9 shows the average failures of 100 mm AC pipes in Queensland increasing rapidly over coming decades. The corrosion modelling predicts that half of existing pipes will suffer corrosion by the 2020s and most will have experienced a failure by the 2040s. The model predicts that an increase in corrosion failure has already commenced (in older AC pipes) but is still at relatively low levels.

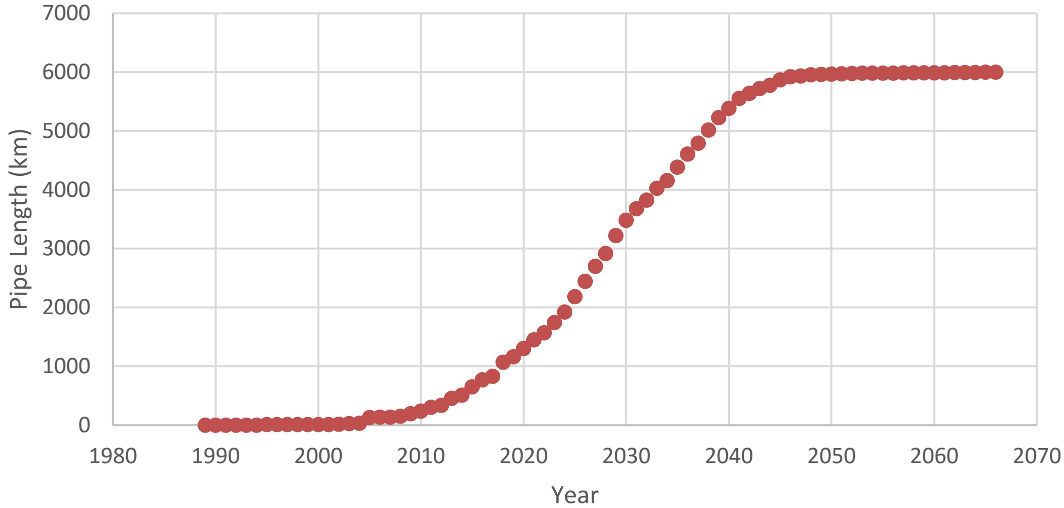

Figure 9: Length of 100 mm AC water mains subject to corrosion failure in coming years based on their age using the NZ corrosion model (NZWWA, 2017).

An interesting comparison can be drawn between the predictions of the corrosion model and the degradation rate projected by the Weibull model for 100 mm water pipes. The Weilbull model projects the length of mains that will 'fail' each year based on an expected lifetime. A Weibull distribution with an expected life of 60 years aligns closely to that of the corrosion model for 100 mm pipe (Fig. 10). A 60-year life span represents the lower end of the range of average life times assumed by most Queensland service providers (Appendix 4).

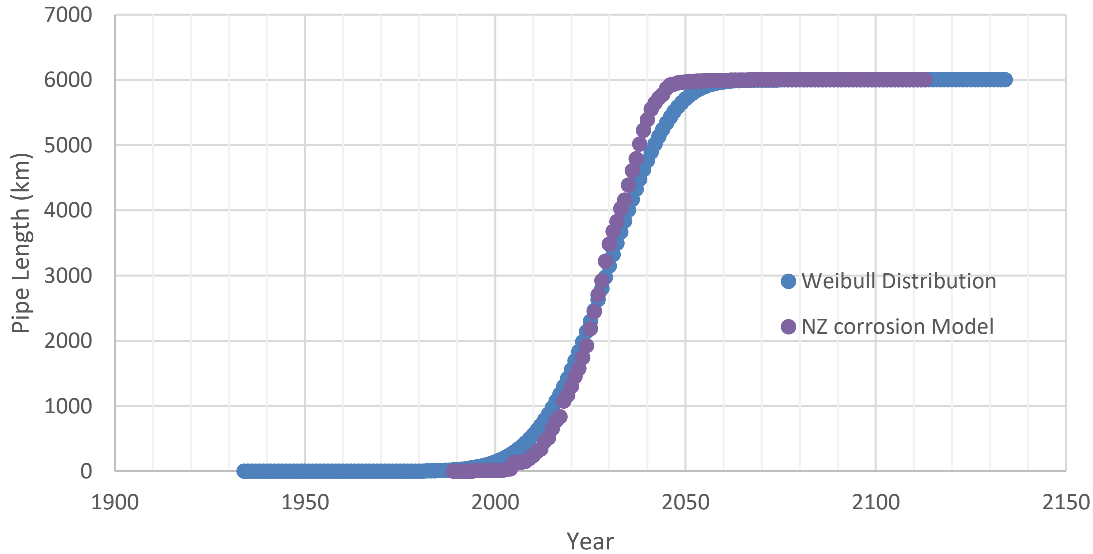

Figure 10: Comparison of the lengths of 100 mm AC water mains projected to have corrosion damage (as in Fig. 9) or to fail as projected by the Weibull model assuming a 60-year lifetime and the NZ corrosion model.

Larger pipes resist corrosion longer as they have thicker walls and applying the corrosion model to the 150 mm size class shows the failure of the pipe is 10-20 years later than that projected for 100 mm pipe (Fig. 11). Around 50% of failures are projected to occur by 2050 with the majority of pipes failing after 2060. There is a rapid increase from the year 2040 as the pipes installed from the 1970s reach a point where average remaining wall thickness (due to corrosion) means that breaks become more common. However, this increase is not as rapid as for the 100 mm pipes.

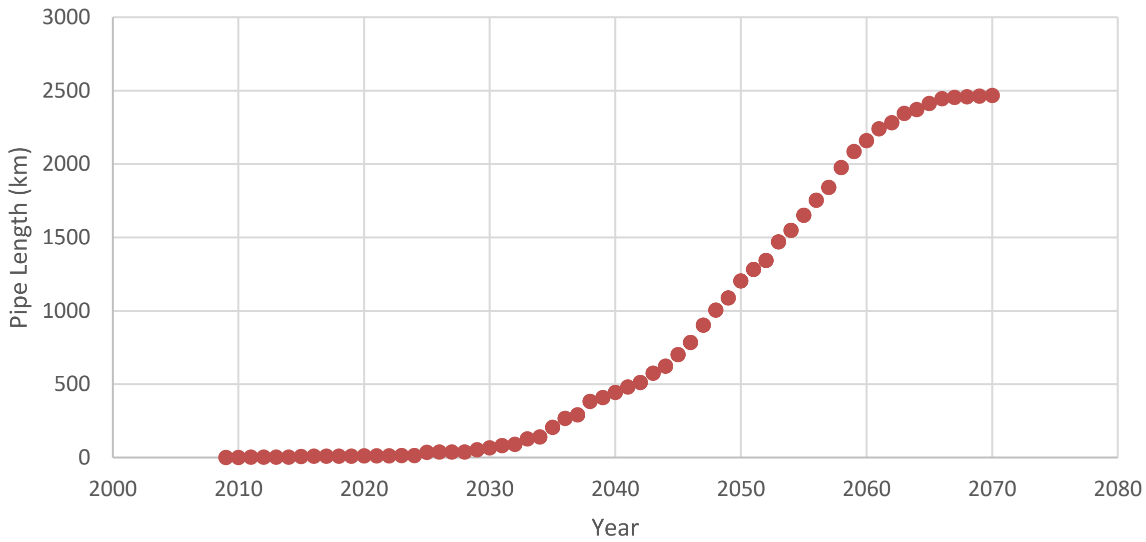

Figure 11: Length of current 150 mm AC water mains predicted to be impacted by corrosion based on their age using the NZ corrosion model.

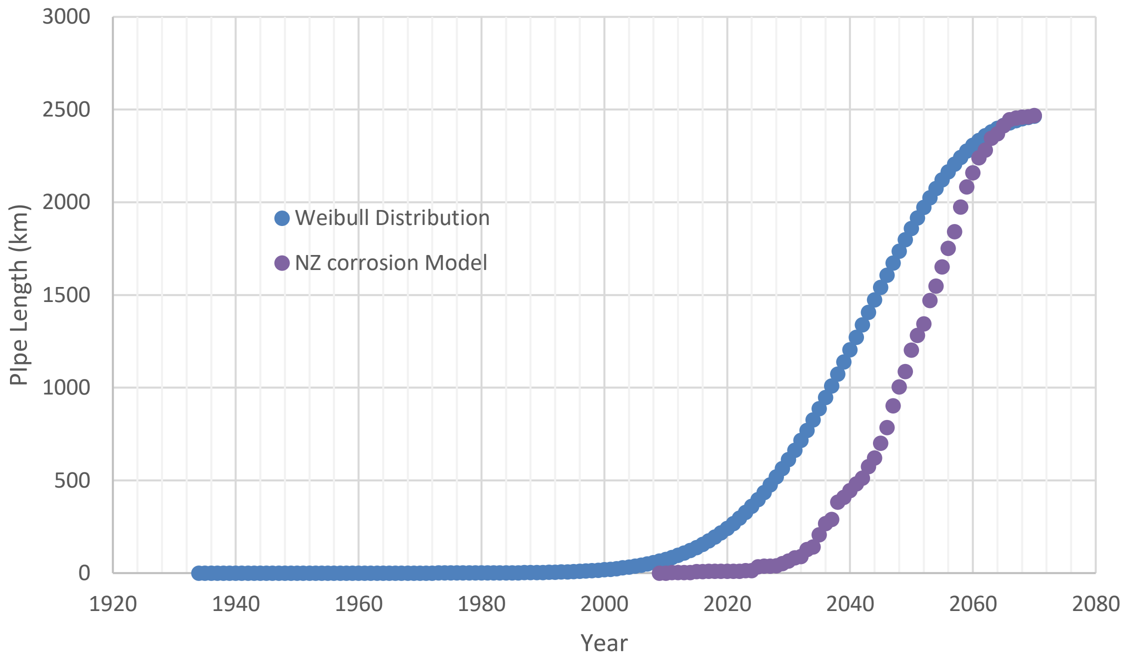

Figure 12: Comparison of the length of 150 mm AC water mains predicted to have corrosion damage or to fail according to the Weibull model using a 70-year lifetime and the NZ corrosion model.

Similar to the comparison made for 100 mm pipes the corrosion model can be aligned with the slope and end failure rates projected by Weibull distribution. However, for these slightly larger pipes a 70-year expected life must be assumed to align the end point of the two predicted curves (Fig. 12). A 70-year lifetime represents the median expected life for AC pipes across the Queensland Service Providers (Appendix 4), possibly reflecting an allowance for the slower corrosion rate for thicker pipes in some councils. Although the Weibull curve matches the predictions of the corrosion model in the final years, it predicts failure will increase earlier but grow more gradually than the corrosion model. This may be because the corrosion model accounts for only a single failure mode whereas the Weibull is a basic stochastic function anticipating many potential failure modes before corrosion has an impact.

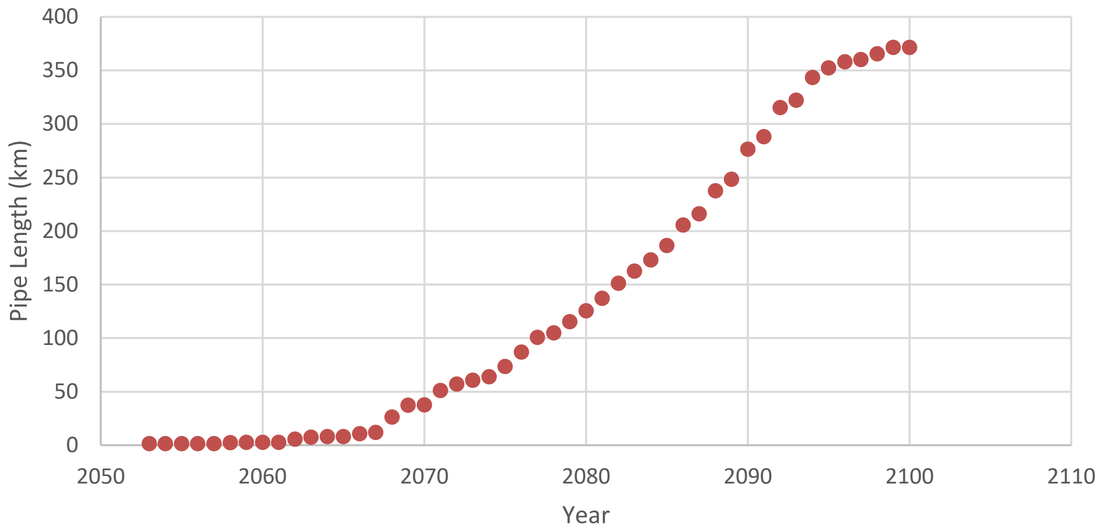

Figure 13: Predicted length of current 300 mm AC water mains corroded based on their age using the NZ corrosion model.

The corrosion model suggests the majority of 300 mm diameter pipes will survive the impacts of corrosion for several decades with 50% failure occurring in the mid-2080s (Fig. 13). In contrast, the Weibull projections for 300 mm AC water mains (using a 70-year expected life) show a similar failure rate to that of the 150 mm pipes albeit with a slightly slower degradation rate. It projects under 50% of pipes failed by 2042 and total failure in the late 2070s (Fig. 14).

These comparisons highlight the strengths and weaknesses of these two models. The corrosion model predicts failure based on only a single failure mode which although critical, does not represent all the degradation impacts particularly for larger diameter pipes. This means the failure rate may be underestimated. In contrast the Weibull function predicts general failure rates (regardless of cause) but the approximation is not underpinned by actual data and is similar for all pipes (regardless of size or material). The two models independently agree on the expected failure rate for the most common sizes of water pipes (100 and 150 mm) suggesting that ageing AC pipes are suffering increased failure rates that will accelerate rapidly in the next two decades and peak sometime in the 2040s.

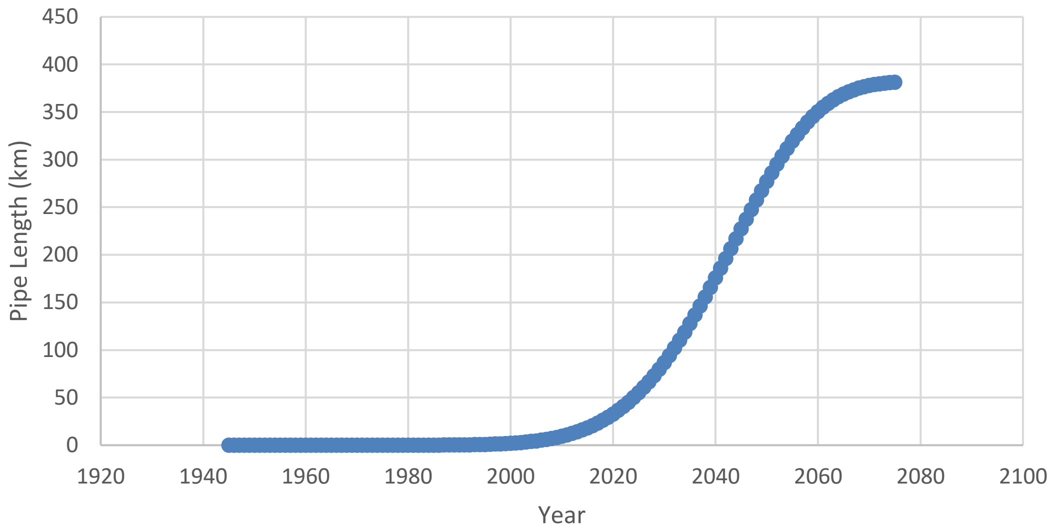

Figure 14: Projected length of current 300 mm water mains failing using the Weibull model with a 70-year lifetime.

4.2 Empirical Model for Water Main Breaks

The physical corrosion and Weibull distribution models provided comparable projections for the expected life of AC water pipes of different sizes. While these models provide a prediction of failure based on age and life expectancies, the third model uses an empirical approach to predict breaks. An exponential function for each pipe size and material estimates the number of breaks that will occur over time in a 100 km length of pipe based on its age (Fig. 15). These curves are based on historical failure data under Queensland conditions.

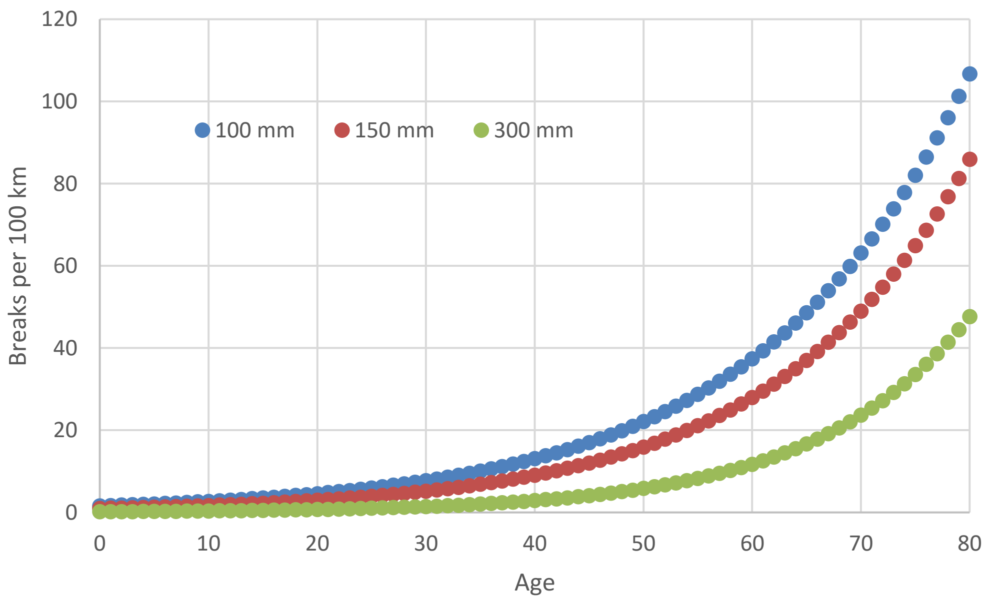

Figure 15: The exponential functions for three common sizes of AC water pipes (prior to application to data).

These functions were used to model total breaks across the three largest size classes of AC water mains for all of the data collected (Fig. 16)[2]. A rapid increase is predicted for coming years, doubling current rates by 2030 and quadrupling by the mid-2040's. The model aligns well with the reported breaks in recent years. Using the breaks model, the number of breaks prior to 2017 were extrapolated back to 2010 assuming that the pipes present in 2017 were of similar length in the previous seven years (i.e. minimal growth or replacement). This extrapolation becomes less accurate with each year and so has been undertaken for seven years (2010 to 2017) to allow comparison of projected breaks with actual data collected since 2010 (SWIM, 2017).

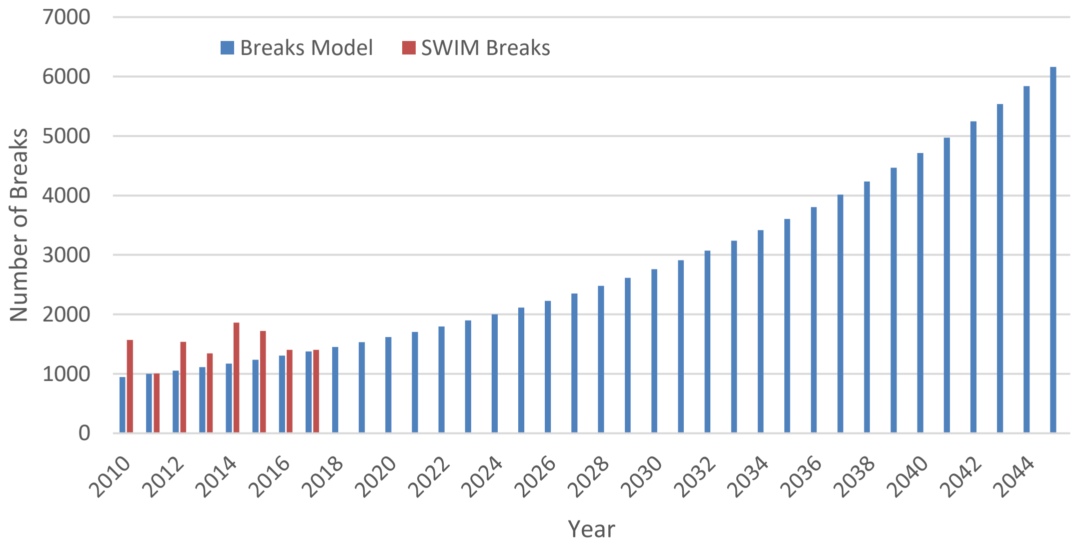

Figure 16: Total breaks predicted for 100, 150 and 300 mm AC pipes in the survey dataset compared to the actual number of AC breaks reported in recent years (SWIM, 2017) (estimated as the fraction of total breaks reported by the same entities based on the proportion of AC pipes).

The predicted breaks shown in Figure 16 represent only the three main size classes of AC water main (covering roughly 82% of all AC pipes in use) so will be a conservative estimate of total breaks. The number of breaks estimated from SWIM reporting is also likely to be underestimated because it is a simple proportion of the three AC mains sizes to the total network length. In reality, AC pipes would form a greater proportion of total reported breaks because they are much older[3]. In effect, both estimates are conservative but there is good agreement between the predicted and reported number of breaks. Although the model output cannot be compared directly with that of the two other models, the predicted patterns all suggest modest increases in degradation due to age by 2020 followed by a rapid increase over the following two decades.

[2] The increase in breaks each year assumes there has been repair, but no replacement of pipes in previous years.

[3] Moreover, older SWIM data is more prone to errors and likely under represents real breaks for the reasons presented in Appendix 3.

4.3 Degradation modelling of sewer mains

AC sewer pipes are not as abundant as water mains and the majority of sewers (76%) are of 150 mm diameter. The three models were used to analyse a range of sewer sizes but a meaningful amount of data was available only for the 150 mm pipes. The corrosion model provides more aggressive rates of degradation for sewers (due in part to the more chemically corrosive potential of sewage) and this is reflected in the steeper degradation projections in Figure 17. It should be noted the corrosion model is designed for pressure sewers so will not be as accurate for gravity sewers which are common in Queensland.

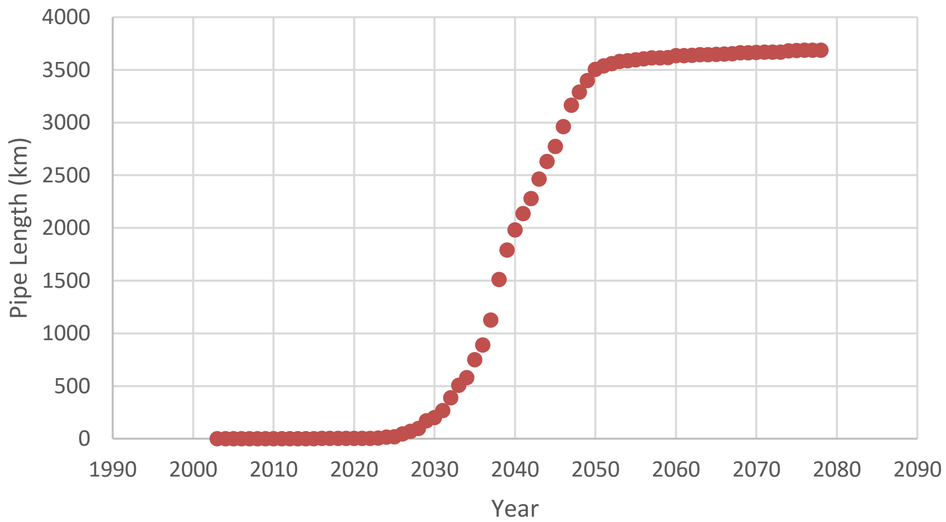

Figure 17: Length of 150 mm AC sewer mains subject to corrosion failure in coming years based on their age using the NZ corrosion model (NZWWA, 2017).

As for water mains, the Weibull model (using a 70-year expected life) predicted an earlier and more rapid decay rate for 150 mm sewer mains than that predicted by the corrosion model despite the increased internal corrosivity allowed for sewage (Fig. 18). The shape of the curves produced by both models were similar but the corrosion model predicted rapid increase in degradation commencing in 2030 and peaking in 2040 whereas in the Weibull modelling these milestones occur 20 years earlier (i.e. similar in timing to the water mains). It is likely that, as for the water mains, the corrosion model underestimates degradation rate because it focusses on a single failure mode, while the Weibull model represents a generic pattern that needs further validation.

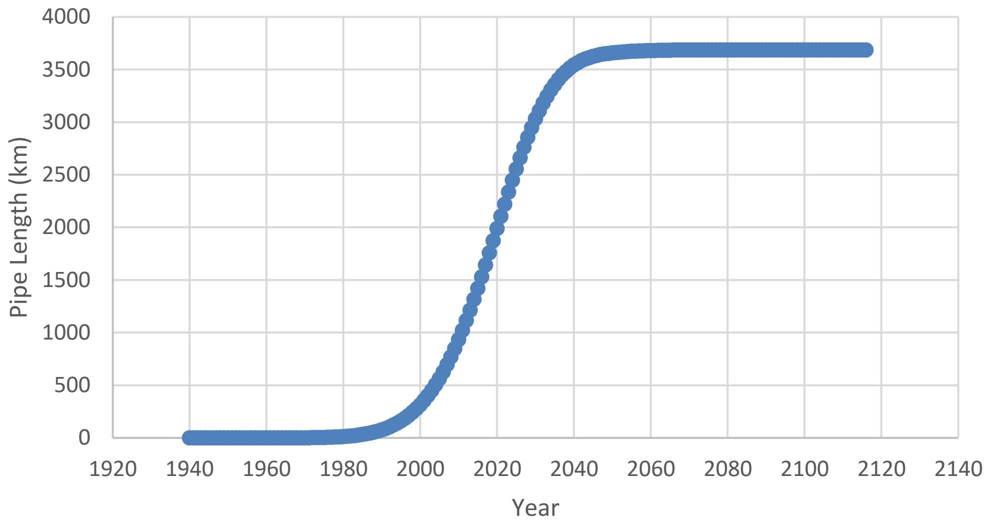

Figure 18: Predicted length of 150 mm AC sewer mains failing based on their age according to a Weibull distribution with a 70-year life time.

The exponential breaks model was calculated in the same manner as for the water mains showing that an increase in breaks will commence later but then increase at a faster rate (Fig. 19). Again, the three models independently confirm an increasing rate of failure over the coming decades. Queensland AC sewers are younger on average than their corresponding water networks meaning that failures will commence at a later date, but the more rapid acceleration of degradation for sewers means that regardless of the model used, sewer failures will have increased dramatically by 2040. This pattern also reflects that predicted for the sewer network of Wannon Water in Victoria (Gant, McLay, Muir & Woodhouse 2017).

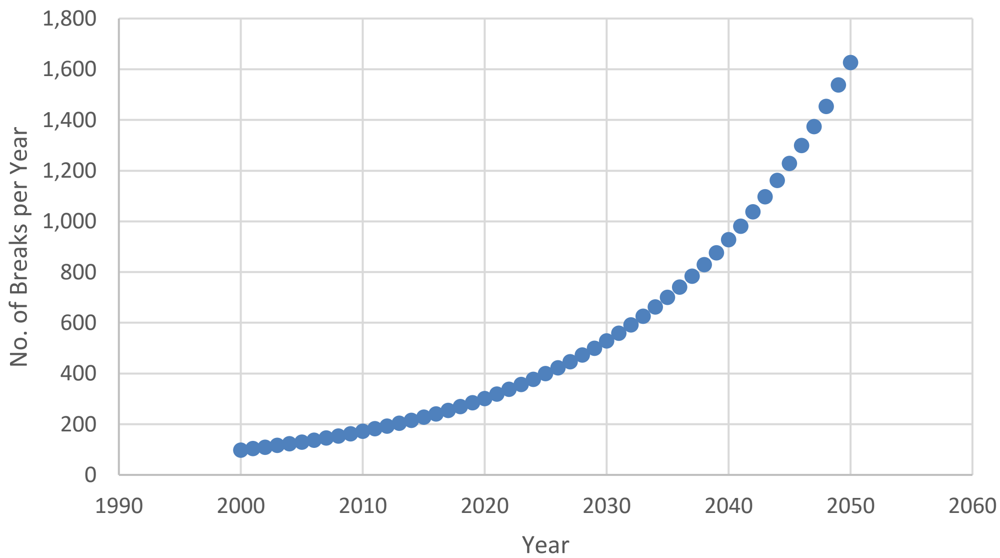

Figure 19: Number of breaks per year predicted for 150 mm AC sewer pipes using the empirical exponential function based on data from a large Queensland utility.

5 Discussion and Conclusions

It is clear from the data collected that a large cohort of asbestos cement (AC) mains across Queensland are close to reaching the end of their useful life. The three independent modelling approaches agreed that AC pipes increasingly fail in the 2020s, reflecting the 20-year period of peak installation. There is likely to be significant variation in individual lives of mains resulting from a range of local variable. However, the incidence of pipes outliving their predicted lifespan and those succumbing early will not change the rapid increase in average failure rates which will peak in the 2040s. The exponential breaks model is likely to provide the most accurate assessment of the timing and indicates that breaks will at least quadruple in this period.

This increase must be placed into perspective. AC pipes form only a proportion of the total Queensland network (38% for water and 22% for sewers) meaning that a large percentage of network not as old. The majority of younger pipes are PVC and PE-based materials subject to different impacts and failure modes. Like AC pipes, these products have expected lives of 70-80 years, as do the CI and DI pipes (that form much of the remainder of modern water mains) and the uPVC pipes representing most modern sewers (Appendices 4 and 5). This has two implications. First, this cohort of assets will reach the end of its expected life commencing during the peak of AC mains replacement. Second, many asset owners have experienced only recent network growth using materials expected to last into the second half of the current century and may be less aware of the implications of the older networks.

The AC network alone comprises over 22,000 km of AC pipes, or 29% of all water and sewer mains. The rapid increase in failures in this cohort predicted by the models adds to the background failure rates across all materials and ages. Moreover, because most pipes are attributed expected lives of 70-80 years (see Appendices 4 and 5) other aged mains, notably CI and DI water pipes, and VC and cement sewers, will concurrently be suffering increasing failures. At the current replacement rate of 0.3% estimated for Australian utilities (WSAA, 2013), it would take over 170 years to replace the AC mains alone. The current low rate of replacement along with the length of pipe at risk means the emerging acceleration in network failures represents a potential infrastructure cliff that requires a significant shift in the way in-ground assets are managed over the entire State.

The impact of ageing AC assets will not be uniform across Queensland. As the majority of AC pipes are 100 to 150 mm in diameter, the need for renewal will be felt most where these pipes are common, namely spread throughout the reticulation network and connecting directly to customers. While impacts will be felt most strongly in networks with older pipes and where current rates of replacement are low[4], the density of schemes will also be a key factor. Rehabilitation costs are higher where assets are difficult to access and even modern trenchless techniques (e.g. boring and relining) have limitations in dense urban areas. Utilities locate services outside property boundaries wherever possible, but this has not always been standard practice. Consequently, the need for increased repair, relining and replacement will exceed current 'business as usual' practices to different extents across all service providers.

[4] A number of councils have active replacement, relining or research programs seeking to mitigate the impact of ageing networks.

Sub-optimal capital decision-making is the biggest long-term risk to the sector because up to 90% of the cost to provide services is driven by capital investment driving ongoing operational costs, depreciation and debt. In other words, the greatest potential to improve the safety, security, sustainability of regional services in the long term is to improve infrastructure planning and avoid investments that unnecessarily inflate the future 'cost-to-serve.' A considered approach to the need for increased monitoring, maintenance and rehabilitation of Queensland's ageing in-ground assets can provide significant savings in coming years. "Postponing the investment steepens the slope of the investment curve that must ultimately be met…[and]… increases the odds of facing the high costs associated with water main breaks and other infrastructure failures." (AWWA, 2013, p. 13). However, because "it is not cost-effective to replace a pipe before, or even after, the first break […] a proactive approach to pipe asset management is crucial in determining the optimal time to replace a pipe" (Punurai and Davis, 2017).

Optimal renewal of in-ground assets prioritises methods and timing for repair, relining and replacement based on maintaining agreed levels of service at the lowest cost. All methods seek to balance the need to maintain services and optimise the trade-off between replacement and repair. "Ideally, pipe replacement occurs at the end of a pipe's 'useful life'; that is, the point in time when replacement or rehabilitation becomes less expensive going forward than the costs of numerous unscheduled breaks and associated emergency repairs" (WSAA, 2013, p. 8). This is a nuanced trade-off which varies from town-to-town and even from pipe-to-pipe and must be based on appropriate data.

To provide input to the decision-making and trade-offs among repair, relining and replacement at a State level, the second stage of this research analyses the costs of renewal of in-ground assets in the survey dataset. The cost to renew all the pipes expected to expire in the next 25 years depends on the sizes and lengths to be replaced, complexity of the network and (sometimes contentious) unit rates for repair and replacement. The report will provide estimated costs and an examination of some of the current approaches of Queensland service providers to shed light on options to deal with the potential infrastructure cliff.

6 Glossary

AC:	asbestos cement
CI:	cast iron (CICL – cast iron cement lined)
DI:	ductile iron (DICL – ductile iron cement lined)
LGAQ:	Local Government Association of Queensland
NPR:	National Performance Report
PE:	polyethylene (HDPE – high density polyethylene)
PVC:	polyvinyl chloride
SWIM:	State-wide Water Information Management system
TOTEX:	Total expenditure incorporating OPEX and CAPEX across an entire life cycle.
uPVC:	unplasticised polyvinyl chloride
VC:	vitreous cement
WSAA:	Water Services Association of Australia

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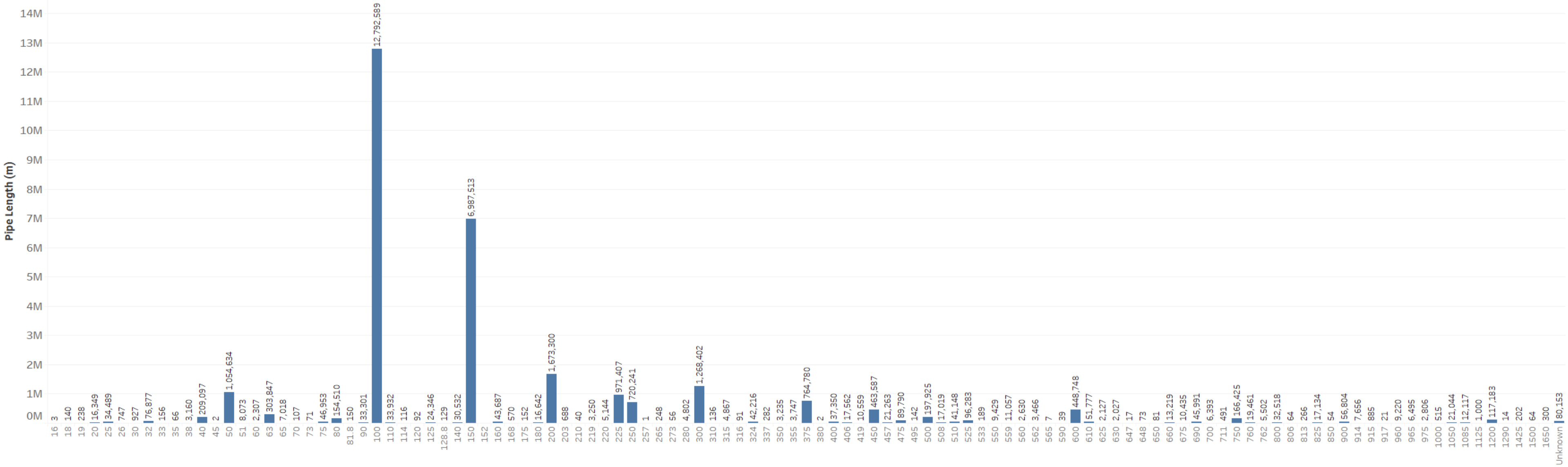
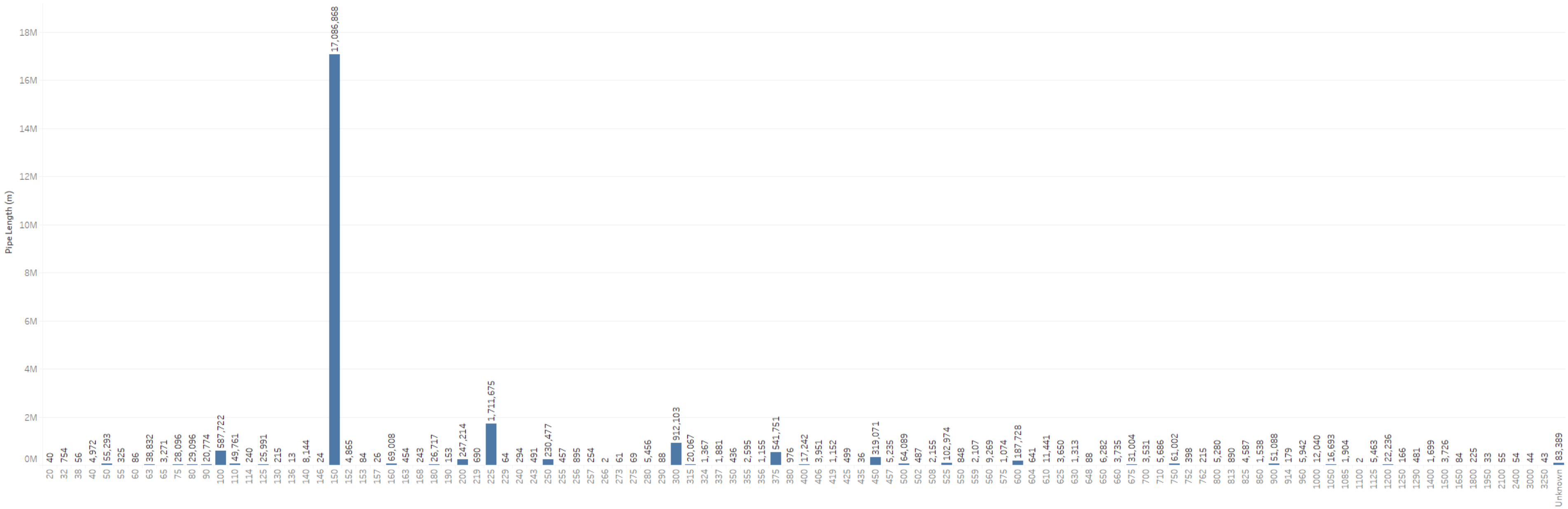
Appendix 1. Length of AC Water Pipes of All Diameters showing the preponderance of 100 and 150 mm pipes.



Appendix 2. Length of AC sewers of all diameters showing the preponderance of 150 mm pipes.



Appendix 3: Water main breaks reported since 2010

Currently Queensland water and sewerage entities report the total number of breaks for various reporting purposes (e.g. National Performance Report (NPR), Queensland Government Key Performance Indicator Report, Bureau of Meteorology (BoM) Reporting, Australian Bureau of Statistics (ABS)) via the State-wide Water Information Management System (SWIM). SWIM first started recording data in 2006 and the total number of breaks has been reported for a number of years with the data quality and coverage improving over time. Data from SWIM is provided by Water Service Providers but ***qldwater*** and the WSP(s) involved offer no warranty as to its accuracy and are not liable for any loss or damage however caused, suffered or incurred by other parties in connection with the Data.

Table A3.1 summarises the data on breaks for water mains reported by the subset of entities that also provided data for the current research. Data since 2010-11 was used and reflects the increasing breadth and accuracy of reporting over this period. It is important to note that the 'breaks' indicator data also includes breaks caused by third parties, such as excavations, which do not reflect a pipe's natural integrity.

Table A3.1: Summary of break data reported (SWIM, 2017).

	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17
number of entities reporting	22	23	29	28	35	37	34
% mains represented*	60.4	71.1	92.9	96.9	99.5	99.6	99.1
total breaks reported	2512	3848	3365	4654	4305	3508	3507
total breaks/100km	614.4	561.1	614.2	714.5	830.1	999.6	1217.5
average breaks/100km	27.9	24.4	21.2	25.5	23.7	27.0	35.8

* the proportion of mains represented increases as more of the 41 reporting entities include breaks data.

From 2014/15 reporting covers over 99% of the mains despite some very small entities not reporting breaks but there is considerable variation (Fig. A3.2). The number of breaks correlates with size of service provider but some variation results from entities interpreting the indicator in different ways. A stricter NPR definition is needed but even then, "number of breaks per 100 km" will over-represent breaks in communities with small networks.

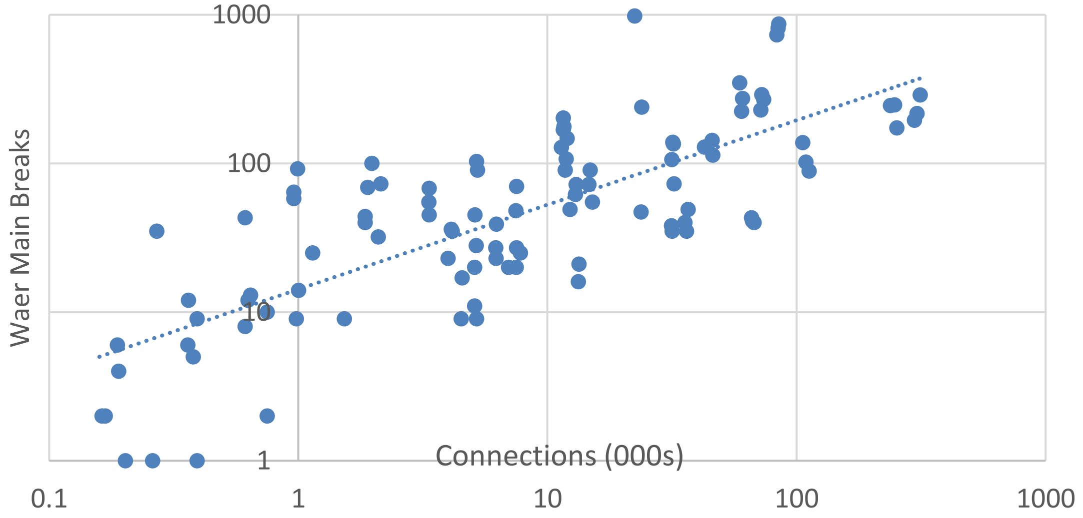
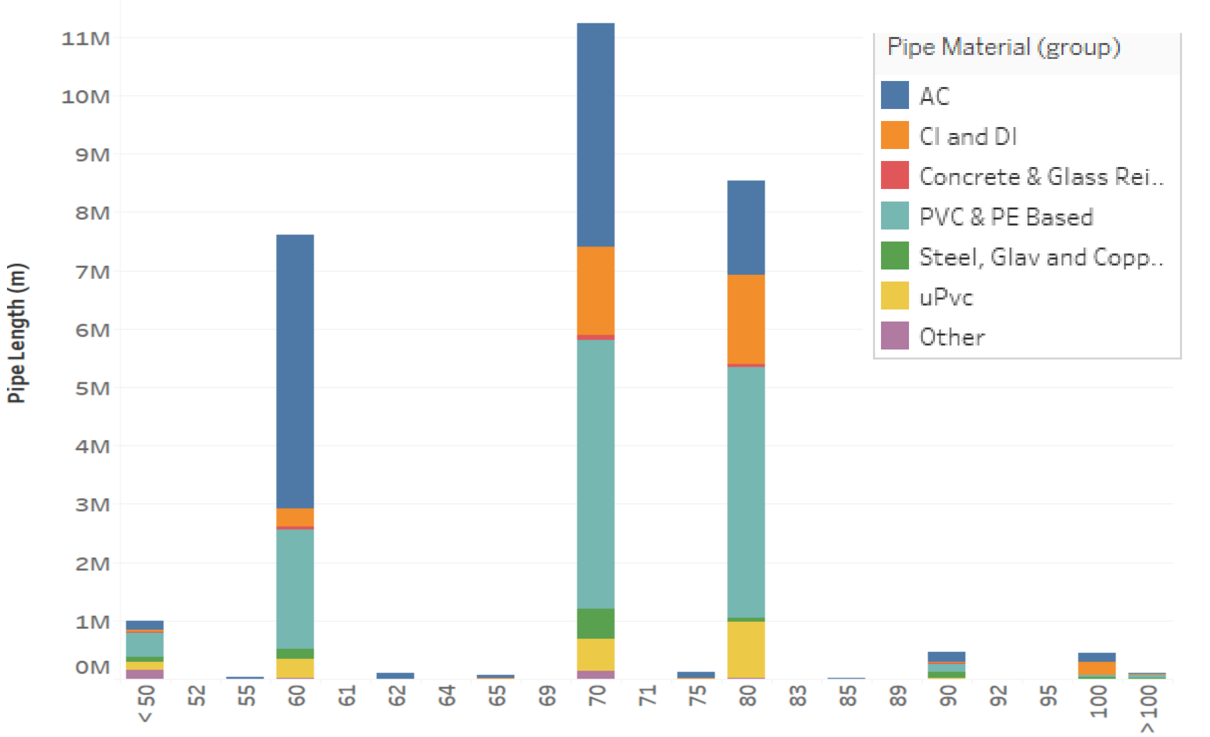


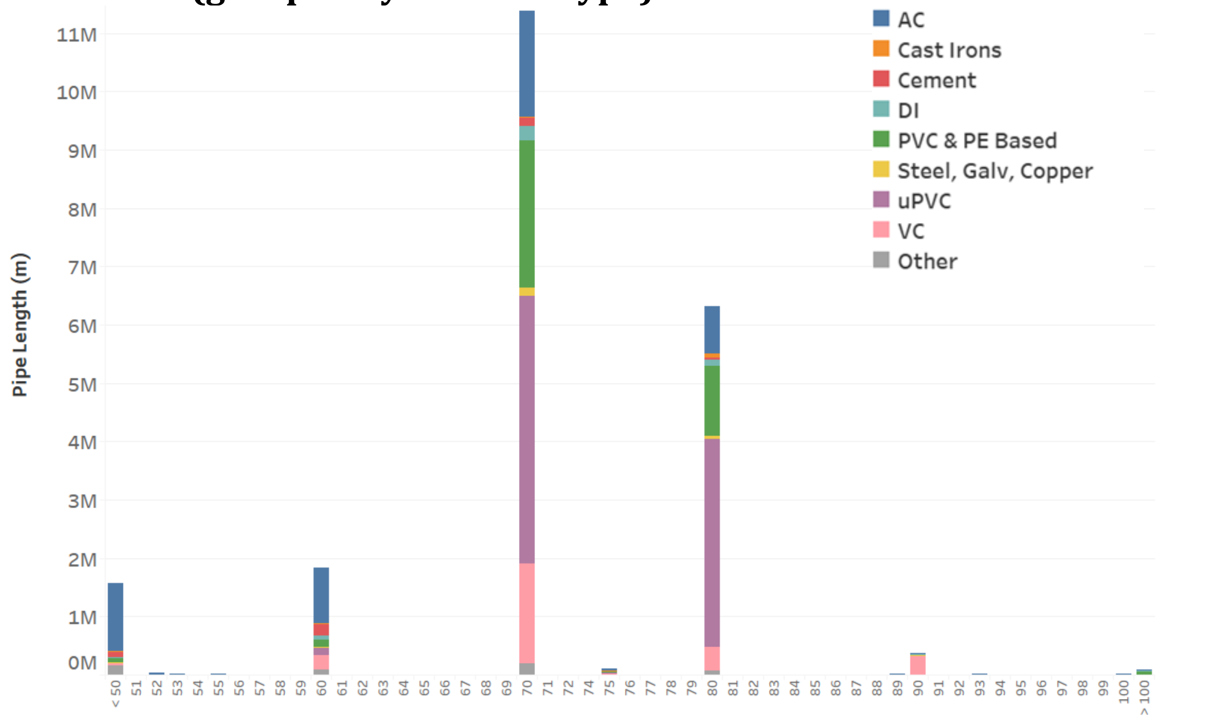
Figure A3.2: Number of water main breaks reported by 34 Queensland service providers between 2013/14 and 2016/17 versus connections (trend line shown is a power function, note logarithmic axes).

Appendix 4: Summary of reported expected lives for different water main diameters (grouped by material type).



The graph above depicts the length of pipe (Y axis) in millions of metres and Expected Useful Life (X axis) reported in the asset registers.

Appendix 5: Summary of reported expected lives for different sewer diameters (grouped by material type).



The graph above depicts the length of pipe (Y axis) in millions of metres and Expected Useful Life (X axis) reported in the asset registers.