Water Main Break Rates In the USA and Canada: A Comprehensive Study

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An Asset Management Planning Tool for Water Utilities

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Executive Summary

The economic prosperity of modern cities is based on a complex infrastructure network located both above and below ground. A critical component to public health and economic well-being is our drinking water which is brought to the tap through an elaborate network of underground pipe distribution systems. Since most of this infrastructure is underground, it is out of sight and often neglected. Empirical data on water main breaks helps utilities in their repair and replacement decision making processes in order to deliver clean drinking water to their customers at an affordable price. This report documents the survey results of water main breaks and operating characteristics at utilities located in the US and Canada. A similar survey was conducted by Utah State University approximately six years ago and published in 2012 (Folkman, 2012). This 2018 report references this previous study to compare and examine changes over time and discuss the importance of water main break data in the context of water asset management planning.

Evidence of Decline

North America's water infrastructure is in decline. The signs of distress surface daily as water mains break creating floods and service disruptions. The loss of service is more than an inconvenience, causing significant social and economic disruptions. Economic impacts include loss of treated water, increased maintenance budgets, overtime hours for service personnel, traffic and business disruptions, and damage to private property. "Aging and deteriorated water mains are threats to the physical integrity of distribution systems, causing adverse effects on flow capacity, pressure, and water quality in drinking water services" (Grigg, et al., 2017). Disruptions due to water main failures are now a common occurrence. The overall assessment of our infrastructure is not good. In 2009, the American Society of Civil Engineers issued a USA Infrastructure Report Card and gave a D- to drinking water and wastewater infrastructure (ASCE, 2009). In a small sign of improvement, the 2017 ASCE Infrastructure Report Card (ASCE, 2017) grade was raised to a D. In the 1990s, a comprehensive American Water Works Association (AWWA) study also indicated that water main replacement was inadequate (Kirmeyer et al., 1994). The AWWA has formally tracked issues and trends in the US. The top concern in the AWWA surveys for both 2016 and 2017 is "renewal and replacement (R&R) of aging water and wastewater infrastructure" (AWWA, 2017).

The Measurement

The most important and critical factor used to quantify the condition and occurrences of failing underground pipe networks is **water main break rates**. Water main break rates are calculated for all pipe materials used in the transport of water to create a measurement to judge pipe performance and durability. Water main break rates for each utility can vary year to year and even seasonally. However, in aggregate, break rates produce a compelling story which can aid in asset management decision making as it relates to defining pipe criticality and costs of repairing and replacing our underground water pipes.

Purpose and Highlights

This comprehensive water main break rate study for the USA and Canada compiles the collective experience of 308 utilities which should be used for making future pipe replacement decisions. It is the desire of the researchers and participants to offer data and analysis that utility managers, engineers and elected officials can apply to the circumstances of their own operations to facilitate water infrastructure asset management planning and pipe replacement decision making. The objective is to reduce operating costs, service level impacts and health risks to their customers. Highlights of the water main break study include aggregate data on pipe material break rates, the analysis of age and corrosion in failure modes, related observations on pressure, delivery demands, effects of soil corrosivity, and new national metrics for pipe replacement rates and population served per mile of pipe.

The Primary Researcher

Dr. Steven Folkman is a registered Professional Engineer, a member of AWWA and a member of the Transportation Research Board Committee on Culverts and Hydraulic Structures, and has oversight of Utah State University's (USU) Buried Structures Laboratory. The Buried Structures Laboratory at USU has been involved in analysis and testing of all kinds of pipe and associated structures for over 50 years. Previous directors include Dr. Reynold Watkins and Dr. Al Moser who are internationally recognized experts. Dr. Moser and Dr. Folkman are coauthors of the widely used text, *Buried Pipe Design* (McGraw Hill, 3rd Edition). Dr. Folkman's expertise includes structural dynamics, linear and nonlinear finite element analysis utilizing soil/structure interaction, and testing. The USU Buried Structures Laboratory is recognized as one of two laboratories in the United States for performing large scale tests on buried pipes. It is from this expertise and background that the surveys of water main breaks were developed and analyzed to complete this comprehensive study.

Major Findings

The comprehensive nature of this study has provided a national water infrastructure condition assessment and review comparing pipe material performance. Additionally, several national-level metrics which utilities can use for asset management benchmarking purposes are included.

1. Nearly 200,000 Miles of Pipe Condition and Operation Surveyed

A total of 197,866 miles of pipe were reported by the 308 basic survey participants. Of those, 281 participants were able to provide water main break data covering 170,569 miles of pipe. This represents 12.9% of the total length of water mains in the USA and Canada. Equally significant, the utilities providing break data serve a total population of 52,477,346 people. This represents 14.5% of the total population of the US and Canada. The survey recorded 23,803 failures that needed repairs which is a significant basis for break data. It is one of the largest surveys conducted on water main failures and the results give an accurate representation of water main performance and operating conditions in North America. This report can be used to update "average estimated service life" assumptions for pipe materials when considering asset management pipe renewal and replacement decision-making.

2. Break Rates Have Increased 27% in the Past Six Years

Between 2012 and this 2018 report, overall water main break rates increased by 27% from 11.0 to 14.0 breaks/(100 miles)/year. Even more concerning is that break rates of cast iron and asbestos cement pipe, which make up 41% of the installed water mains in the US and Canada, have increased by more than 40% over a 6-year period.

3. 82% of Cast Iron Pipes are Over 50 Years Old and Experiencing a 46% Increase in Break Rates

Cast iron (CI) pipes represent the largest pipe material inventory in North America. 82% of all CI pipe is over 50 years old and their break rates have increased significantly by 46% since 2012 and are expected to continue to increase. 27% of asbestos cement (AC) pipe is also over 50 years in age and AC pipe breaks have increased by 43% in that same 6-year period. CI and AC pipe together are mostly responsible for the spike in overall break rates since 2012. Utilities with large amounts of cast iron and/or asbestos cement pipes may need to accelerate their replacement rates. CI and AC pipes are no longer manufactured and many are reaching the end of their expected lives.

4. Nationwide One Mile of Installed Water Main Serves 308 People

While the industry has assumed 325 people are served for 1 mile of distribution system pipe in urban areas, this survey finds a new national metric of 308 people served per mile of pipe regardless of utility size (or 191 people/km). The data indicates that an average utility has 607 miles of pipe and serves a population of 186,752 people.

5. 85% of Water Main Inventory is Less Than 12" in Diameter

67% of all water mains are 8" (200 mm) or less in diameter and the range of 10" to 12" (250 to 300 mm) sizes make up another 18% of all installed water mains.

6. Smaller Utilities Have Two Times More Main Breaks Than Large Utilities

The survey results show that smaller utilities can have break rates more than twice as high as larger ones. This may be attributable to the fact that larger utilities are better funded which results in improved data, engineering design, installation procedures, and asset management practices. A small or rural utility would typically have more pipe miles per customer. This can result in greater financial burdens in maintaining their water systems compared to larger or urban utilities.

7. Pipe Material Use Differs by Region

Water main pipe material usage varies significantly over geographic regions (see Figure 11). This suggests that the selection and use of pipe materials are based on historical preference versus comparative cost analysis or environmental conditions. The upper northwest and eastern half of the USA (Regions 1, 4, 6, 7, and 8 as illustrated in Figure 1) have either cast iron or ductile iron pipe for much of the installed pipe length. Regions 3, 5, and 9 have more PVC pipe than any other material. The most common pipe material in Region 2 is asbestos cement and it is unique in that respect.

8. A Large Data Set Provides Increased Accuracy

The water main break experiences of one utility may not represent another. Factors such as climate, pipe material, installation practices, and soil corrosivity can greatly affect failure rates. Design and installation practices are very important. Every utility should properly design and install pipe - regardless of material. Many previous studies have been based on a small subset of large utilities. This study provides an increase in accuracy due to the extensive participation of utilities.

9. Four Types of Pipe Materials Make Up 91% of Water Mains

91% of the installed water mains utilize a combination of cast iron (CI) at 28%, ductile iron (DI) at 28%, polyvinyl chloride (PVC) pipe at 22%, and asbestos cement (AC) at 13%. The remaining 9% of pipes used are represented by polyethylene (HDPE), steel, molecularly oriented PVC (PVCO), concrete steel cylinder (CSC), and other materials.

10. PVC Pipe Has the Lowest Overall Failure Rate

When failure rates of cast iron, ductile iron, PVC, concrete, steel, and asbestos cement pipes were compared, PVC had the lowest overall failure rate. This was also the case in the 2012 survey and is confirmed by other industry sources. A lower failure rate contributes to a lower total cost of ownership and helps confirm the performance and longevity of PVC pipes. PVC is not subject to corrosion, unlike ferrous and concrete steel cylinder pipes.

11. Corrosion is a Major Cause of Water Main Breaks

75% of all utilities surveyed reported one or more areas with corrosive soil conditions. Utilities with a higher percentage of iron pipe may experience a higher percentage of corrosion related breaks. This would especially apply to pipe installed without an increased investment in condition assessment, pipe monitoring and corrosion control measures. Corrosive soils and other environmental risks drive up the total cost of ownership. The most common failure mode reported in the detailed survey is a circumferential crack which is the most common failure mode of cast iron (CI) and asbestos cement (AC) pipes. Corrosion issues can be a contributor to many failure modes.

12. Cast Iron Pipe Has 20 Times More Breaks in Highly Corrosive Soils Than in Low Corrosive Soils

Analyses of soil corrosivity completed in this study shows that a cast iron (CI) pipe in highly corrosive soil is expected to have over 20 times the break rate of a CI pipe in low corrosive soil. Traditionally, the thickness of the iron pipe wall provided the additional corrosion protection. CI pipes manufactured after World War II have significantly higher failure rates due to thinner walls. The resulting higher main breaks with iron pipes due to corrosive soils is consistent with other research and studies.

13. Newer and Thinner-Wall Ductile Iron Pipe Has 10 Times More Breaks in Highly Corrosive Soils Than in Low Corrosive Soils

Ductile iron (DI) pipe in highly corrosive soil has over 10 times the break rate than a DI pipe in low corrosive soil. Cast iron (CI) and DI pipe corrode at about the same rate. Corrosion is an important failure mode for CI pipe and is the predominant failure mode for DI pipe. The many types of corrosion can also be combined with other environmental and operating conditions, all contributing to water main failures. Because the wall thickness of DI pipe has decreased over time, internal and external corrosion are a bigger concern for this pipe product.

14. 80% of Utilities Use Some Form of Corrosion Protection for Ductile Iron Pipe

80% of respondents to the detailed survey indicated they utilized some form of corrosion protection for ductile iron pipe with polywrap being the predominate method.

15. The Average Age of Failing Water Mains is Approximately 50 Years Old

When asked for the typical age of a failing water main, the detailed survey participants reported an average value of 50 years. 43% of water mains are between 20 and 50 years old and 28% of all mains are over 50 years old. In 2012 the average age of failing water mains was reported as 47 years. Based on the detailed survey, the average expected life of installed pipe today is 84 years, up from 79 years in the 2012 study. Given the qualitative nature of these questions, the typical age of a failing water main and expected pipe life have not changed significantly over the past 6 years. While pipe life can be estimated at over 100 years, actual life is affected by soil corrosivity, installation practices, and other factors.

16. 45% of Utilities Conduct Condition Assessment of Water Mains

45% of utilities use some form of regular condition assessment of their water mains. Condition assessment is considered a basic part or early step in the development of an asset management program.

17. Over 16% of Installed Water Mains are Beyond Their Useful Life

A total of 16% of installed water mains are beyond their useful lives (up from 8% reported in the 2012 study) and utilities do not have the funds to replace them. For utilities to survive this trend, and considering 28% of all mains are over 50 years old, improved asset management will be essential. These figures correspond well with an EPA study (EPA, 2002) that shows the amount of pipe needing immediate replacement is growing rapidly.

18. The National Rate of Pipe Replacement is 125 Years

According to the survey, an average of 0.8% of installed pipe is replaced each year. This equates to a 125-year replacement schedule. Pipe replacement rates should be between 1% and 1.6%, equivalent to 100-year and 60-year depreciation and/or replacement schedules, respectively. In general, pipe replacement rates need to increase. Asset management and life cycle costing practices can help a utility optimize its pipe renewal and replacement activities. The report finds that on average, utilities have a 125-year replacement rate on water main pipes as the new national average.

19. Construction Related Failures are the Same for Both Ductile Iron and PVC Pipes

The detailed survey asked utilities to report the number of failures related to construction activities and identify the pipe material that failed. The vast majority of construction related failures involved either ductile iron (DI) or PVC pipe and the number of failures for each material was essentially identical. Therefore, DI and PVC pipe have an equivalent rate of construction related failures. This points to the need to improve construction practices for underground infrastructure regarding installation, location services and inspection.

20. Acceptance of PVC Pipe for Use in Water Systems Has Increased by 23% Since 2012

PVC pipe approval has increased from 60% of water utilities allowing its use in 2012 to 74% of utilities allowing its use in 2018. The number of utilities approving of ductile iron, concrete steel cylinder, and steel pipes for use in water systems remains essentially the same.

21. Open Cut Remains the Primary Pipe Installation Method

Open cut pipe installation/replacement remains the primary method used. Where open cut is difficult, other installation methods are used. 62% of utilities have used directional drilling and it is highly recommended in locations where open cut replacement is difficult.

22. The Average Supply Pressure is 69 psi With the Average Maximum at 119 psi

Pressure is an important component in pipe design and material selection. A well-controlled system operated below design limits will lead to extended pipe life. The basic survey provided an average operating pressure of water mains as 69 psi, which is well below the pressure rating of most water mains. The reported maximum operating pressure in the basic survey had an average value of 119 psi.

23. The Average Daily Gallons Per Day Per Person is 137 With a Peak Demand Factor of 1.8

The average daily water demand for utilities which participated in the detailed survey was 137 gallons per day per person with a peak demand of 251 gallons per day per person. This suggests successful water conservation efforts and “value of water” campaigns nation-wide.

24. Estimated Average Water Loss to Leakage is 10%

A total of 200 utilities provided an estimate of their water loss due to leakage and the average reported value was 10%. This statistically significant number suggests that pressure reduction, leak detection and pipe replacement has contributed to the overall reduction of water loss in water distribution systems.

25. Most Utilities Have a Moderate to High Soil Corrosion Risk

Using soil analysis data, corrosion index values were computed for 281 of the cities that participated in the survey. The study found a direct correlation between soil corrosiveness and break rates of metallic pipes. A typical city has a corrosion risk rating somewhere between moderate and high, demonstrating the importance of corrosion mitigation for water systems.

1.0 Introduction

In the United States and Canada, population growth during three main time periods – 1800s, 1900–1945, and post 1945 – led to the installation of underground water infrastructure. Pipes constructed in each of these three eras could all start to fail at nearly the same time over the next couple of decades for a number of reasons ranging from age and corrosion to inadequate design and poor installation. Additionally, the life span of the materials used has become shorter with each new investment cycle (WIN, 2002).

There are approximately 155,693 public water systems in the United States with 52,110 community water systems providing year-round water services for residents. Over 286 million Americans get their tap water from a community water system (CDC, 2017). These community water systems across the US face the inevitable cost of pipe repair and replacement while dealing with decreasing water quality and increasing water loss. It is believed that at many utilities, pipe replacement levels are inadequate to keep up with the rate of deterioration. Maintaining an obsolete system can cause severe financial hardship for cities as well as increase public health risks. Infrastructure asset management is an approach which can help utilities bring together the concepts, tools, and techniques to manage assets at an acceptable service level at the lowest life-cycle cost. Life-cycle costing and assessment analysis can help utility management select pipe materials with a long-expected life that also contributes to a low cost over the expected life of the pipe, while also considering environmental impacts and risks (see Sustainable Solutions, 2017 or Khurana, 2017).

This study provides key inputs to water asset management's life-cycle cost analysis through a comparison of break-rates of commonly used pipe materials. Also, utility operating characteristics given in this report can provide the pipeline designers and system operators with reference values to plan for system replacement and expansion.

1.1. Aging Water Infrastructure

In 2007, the Conference of Mayors conducted a survey of over 300 cities representing over 55 million citizens and over 186,149 miles of water distribution mains (US Conference of Mayors, 2007). A high majority (86.2%) of cities use the number of water main breaks per unit length to evaluate drinking water pipe performance. The survey results concluded that water main breaks continue to be a major concern with 45% of cities experiencing more than 50 breaks annually. Cities also stated that repair and replacement cycles require a long-term view: 43% of city drinking water pipe system repair and replacement cycles extend beyond 50 years; and, 65% of city sewer pipe system repair and replacement cycles extend beyond 200 years. Water operation and maintenance managers recognize that older pipe systems may be constructed with multiple materials such as concrete, cast iron, wood, and some of these pipes may be over 125 years old. Asset inventory, condition assessment and asset management planning practices provide valuable information to enable utilities to more efficiently replace older pipes constructed with underperforming materials.

The EPA's Aging Water Infrastructure research program (EPA, 2010) is working toward the goal of making our nation's water infrastructure sustainable by supporting research and by promoting strategic asset management. The current efforts of the American Society of Civil Engineers Grand Challenge (ASCE, 2017) also helps engineers focus on improving the nation's infrastructure report card grade. ASCE's Grand Challenge aims to enhance the performance and value of water infrastructure by 2025 with a focus on innovation, life cycle costing and transformational change from design to delivery.

The water industry has seen many types of academic surveys and studies on water main replacement programs and the benefits of asset management, condition assessment and prioritization. However, many utilities have not historically tracked all of the elements of water main break data. Over the past 20 years, most utilities have come to realize the importance of tracking all aspects of their infrastructure in a GIS-centric platform and have collected records on the types, sizes, and repair histories of their pipes. As this trend continues, more data and analysis will be available to the industry to improve water distribution system repair and replacement decision making. This comprehensive report based on statistically significant experiences from 308 utilities also draws from other relevant studies to be the most complete and authoritative study on water main break data based on pipe material. Many water utilities consider pipe breaks to be a crucial factor when deciding which pipes to replace. According to a Water Research Foundation (WaterRF) study, 75% of water utilities cited pipe breaks as a key criterion in pipe replacement decisions. Other common factors noted were pipe age (45%), low flows (40%), condition or material type (30%), and need for pipe size changes (30%). In addition, pipe breaks in a water distribution system are one of three critical metrics that can be used to measure the degree of optimization in the system. The other two metrics are chlorine residual (measuring water quality integrity) and pressure management (measuring hydraulic integrity). Breaks reflect the physical condition of a distribution system (WaterRF, Asset Management, 2017).

According to another WaterRF publication, the average pipe break rate (regardless of cause) for water utilities is between 21 to 27 breaks per 100 miles of pipeline per year. An additional WaterRF study cited an average of 25 breaks per 100 miles per year. Although water utilities typically take action to manage and reduce pipe breaks through monitoring, preventing all pipe failures is impossible (WaterRF, Knowledge Portals, 2017).

2.0 The Survey

2.1. Methodology

During 2017, Utah State University conducted a survey of utilities across the USA and Canada to obtain data on water main failures of water supply systems. The study was comprised of two parts: a basic survey and a detailed survey. The focus of the basic survey was to examine the number of failures utilities were experiencing and how those failures related to the pipe materials used and the age of the failing pipes. This effort focused on water supply mains (sewer and force main pipes were excluded) and excluded pipes with diameters under 3 inches. A variety of pipe materials are used in water supply systems and over the past 100 years the materials have evolved with different manufacturing technologies. As a result, pipe performance has changed. A goal of both the basic and detailed surveys was to look at which materials were performing best at a snapshot in time and to track how pipe age affects failure rates. The focus of the detailed survey was to obtain additional utility operational characteristics, pipe age and size, multi-year failure data, and applications of trenchless technologies.

The primary method used to distribute the surveys was email. A subcontractor experienced at mass emailing was utilized along with multiple email lists. Initial emails were sent to personnel at water utilities during April through June of 2017. This report will refer to the survey results herein as the 2018 study to correspond with its date of publication. Participants were given links to both the basic and detailed surveys and requested to complete both, or at a minimum, complete the basic survey. Follow up phone calls were also used to encourage participation. The basic survey participants were asked for data from a previous 12-month time period and thus the results represent a time period that mostly coincides with the year 2016. A total of 308 utilities responded to the basic survey. Of those, 281 utilities were able to provide water main break data in the basic survey and 98 responded to the detailed survey. This comprehensive study covers 170,569 miles of pipe with water main break data. An additional 27 utilities responded with partial data but are not included in the 170,569 mile total to simplify this report. The USA and Canada were divided into nine regions and the 281 basic survey respondents were categorized according to the region and the size of the utility based on amount of pipe. This comprehensive study documents the results from both the basic and detailed surveys and draws from other relevant industry sources.

2.2. Objectives and Goals of the Study

There were many objectives of the surveys. These objectives include:

- Understanding the age and size distribution of pipe in water utilities
- Providing utilities with data they can use such as typical and maximum water pressure in water mains, average and maximum daily demands of water, and leakage rates
- Itemizing pipe failures over a time period with the data broken down by material type and age
- Identifying the most common pipe failure modes and materials as identified by the utility
- Determining whether corrosive soils are present, analyzing the influence of corrosive soils on break rates, and identifying corrosion prevention methods being used
- Highlighting pipe replacement plans, expected pipe life of new pipe and condition assessment methods
- Determining which pipe materials are allowed

FIGURE 1: REGIONS USED TO REPORT SURVEY RESULTS

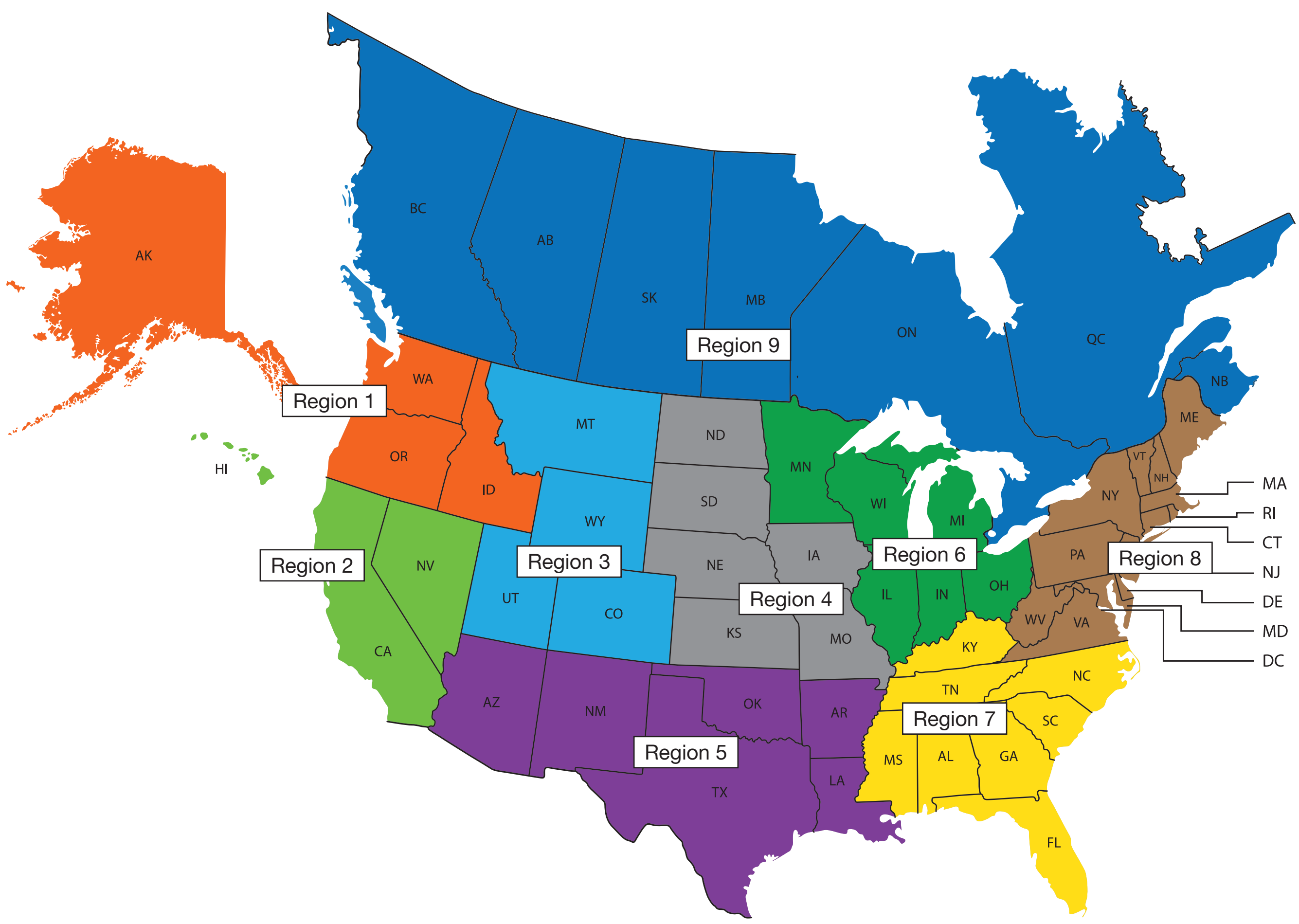


TABLE 1: NUMBER OF SURVEY RESPONDENTS WITH WATER MAIN BREAK DATA BY REGION

	Basic Survey			Detailed Survey		
Region	Number of Respondents	Miles of Pipe	Population Served	Number of Respondents	Miles of Pipe	Population Served
1	18	10,395	3,790,992	9	5,361	2,142,784
2	33	28,096	13,047,139	10	14,781	7,768,396
3	14	9,676	2,611,838	6	7,237	1,729,838
4	24	11,039	1,965,740	7	5,041	960,148
5	44	28,649	5,779,390	18	23,080	3,522,330
6	64	24,220	6,922,536	21	13,312	3,896,092
7	28	20,291	5,508,899	8	8,632	1,020,243
8	35	21,064	5,584,389	9	9,345	1,996,568
9	21	17,138	7,266,423	10	11,307	4,112,900
Total	281	170,569	52,477,346	98	98,097	27,149,299

FIGURE 2: LENGTH OF PIPE FROM EACH REGION THAT RESPONDED TO THE BASIC AND DETAILED SURVEYS

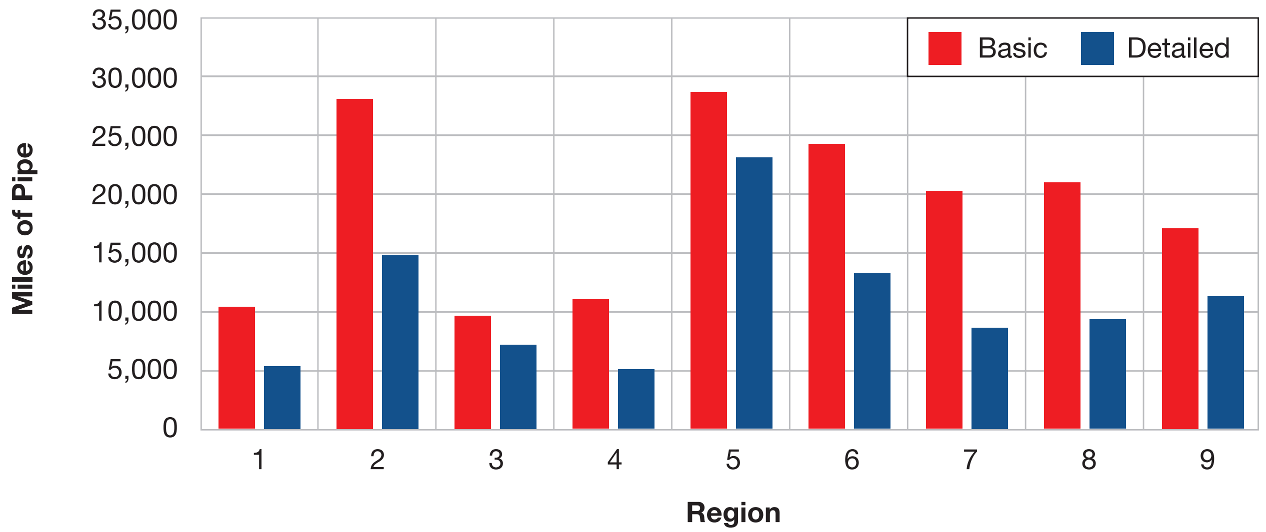
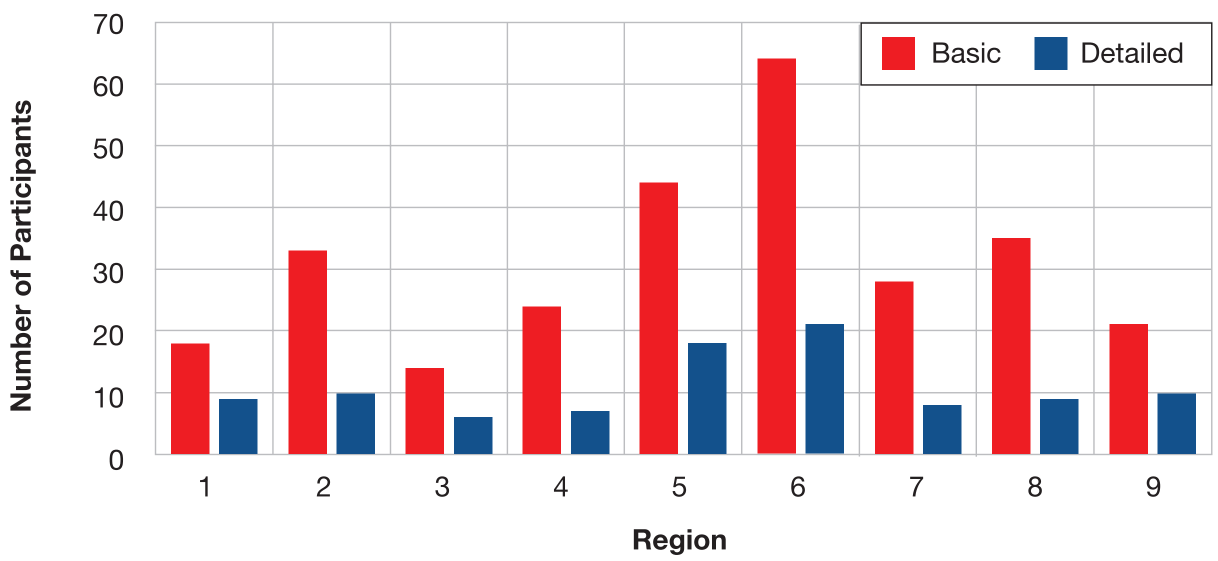


FIGURE 3: NUMBER OF RESPONDENTS FROM EACH REGION THAT RESPONDED TO THE BASIC AND DETAILED SURVEYS



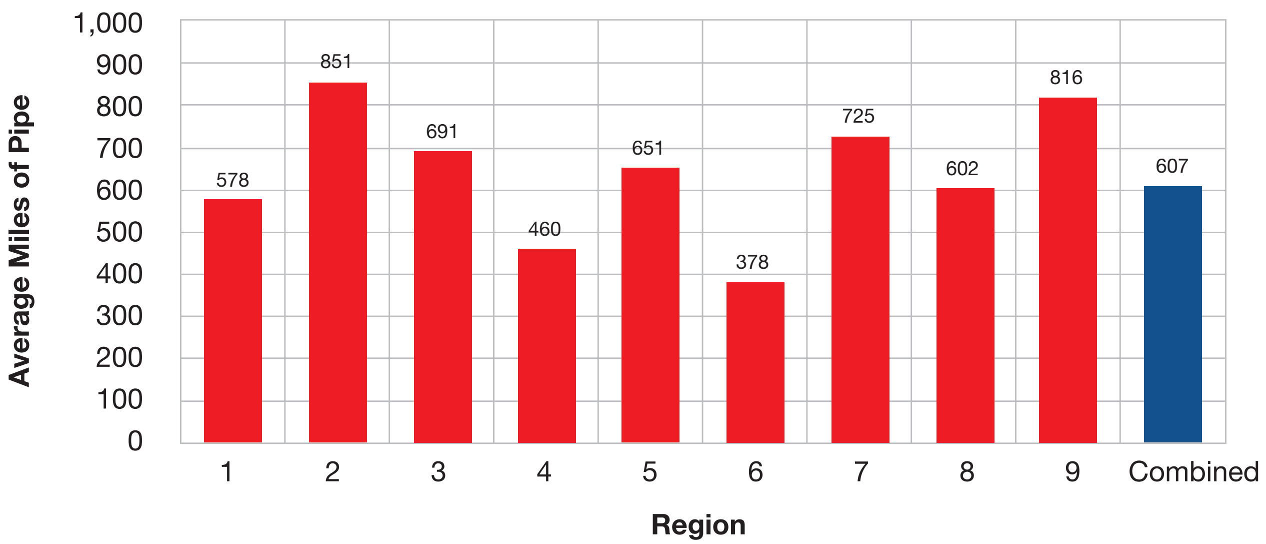
2.3. Survey Regions

In total, 281 utilities participated in the surveys and provided failure data. To examine regional variations, nine survey regions in the United States and Canada were selected. The regions defined in the study are used here to indicate the wide geographical distribution of the respondents. Table 1 lists the number of respondents with failure data, the miles of pipe, and the population served in the basic and detailed surveys from each region. Figure 1 illustrates the locations of the nine different regions used in this report. Respondents were asked to report the length of water supply mains in their system but not to include sewer or force mains or lines with a diameter less than 3 inches. Figure 2 illustrates the miles of water main pipe that were reported in the basic and detailed surveys on a regional basis. A total of 170,569 miles and 98,097 miles of pipe was reported by respondents in the basic and detailed surveys, respectively. Figure 3 illustrates the number of respondents from each region. There were 26 additional respondents to the basic survey that could not provide failure data and these are not included in the miles of pipe or populations served in Table 1. The respondents are distributed across a large survey area. The basic survey was able to get respondents from 48 of the 50 states in the US and 7 out of 10 provinces in Canada. This study is more comprehensive than other studies to date.

Based on miles of pipe shown in Figure 2, the basic survey got the most miles of pipe from Regions 2 and 5. Figure 3 shows that the peak number of respondents came from Region 6.

Figure 4 shows the average miles of pipe per utility for the basic survey by region. Region 2 had the highest average pipe length of 851 miles and Region 6 had the smallest with 378 miles. Overall, based on the basic survey, an average utility participant had 607 miles of pipe and served 186,752 people. For comparison, the 2012 survey results reported an average utility had 626 miles of pipe and served 164,325 people, which are similar results. The 2012 survey had 188 respondents covering 117,603 miles of pipe with failure data and thus the 2018 basic survey had a 49% increase in respondents and 45% more miles of pipe. This increase in survey coverage increases the statistical validity of this study.

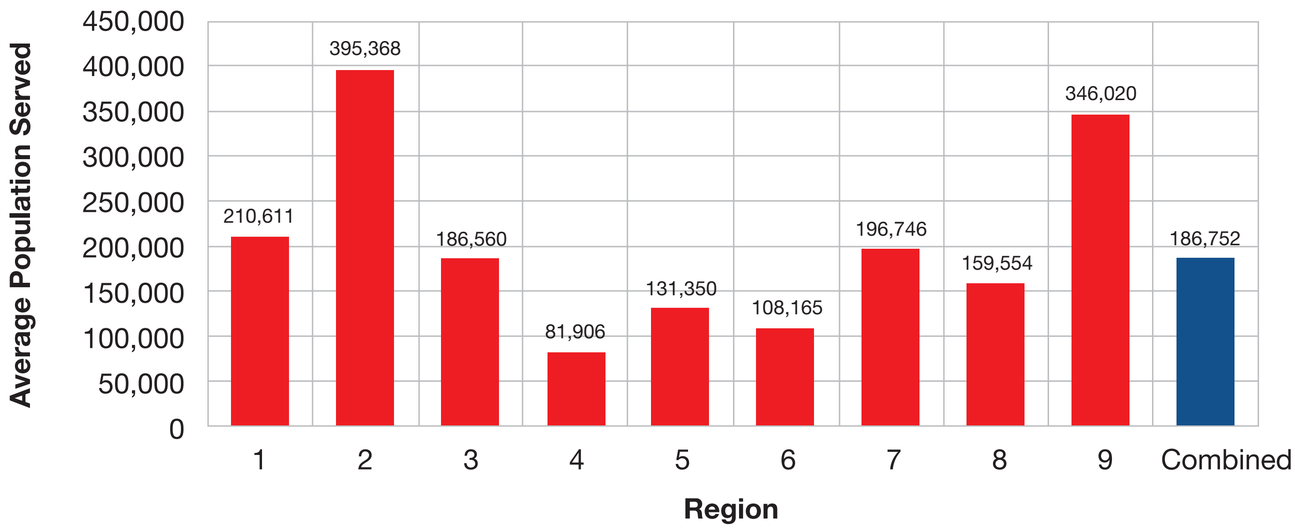
FIGURE 4: AVERAGE MILES OF PIPE FROM EACH REGION RESPONDING TO THE BASIC SURVEY



2.4. Size of Survey Participants

Figure 5 shows the average population served per utility for each region in Figure 1. The average population served per utility for the entire basic survey was 186,752.

FIGURE 5: AVERAGE POPULATION SERVED FROM EACH REGION RESPONDING TO THE BASIC SURVEY

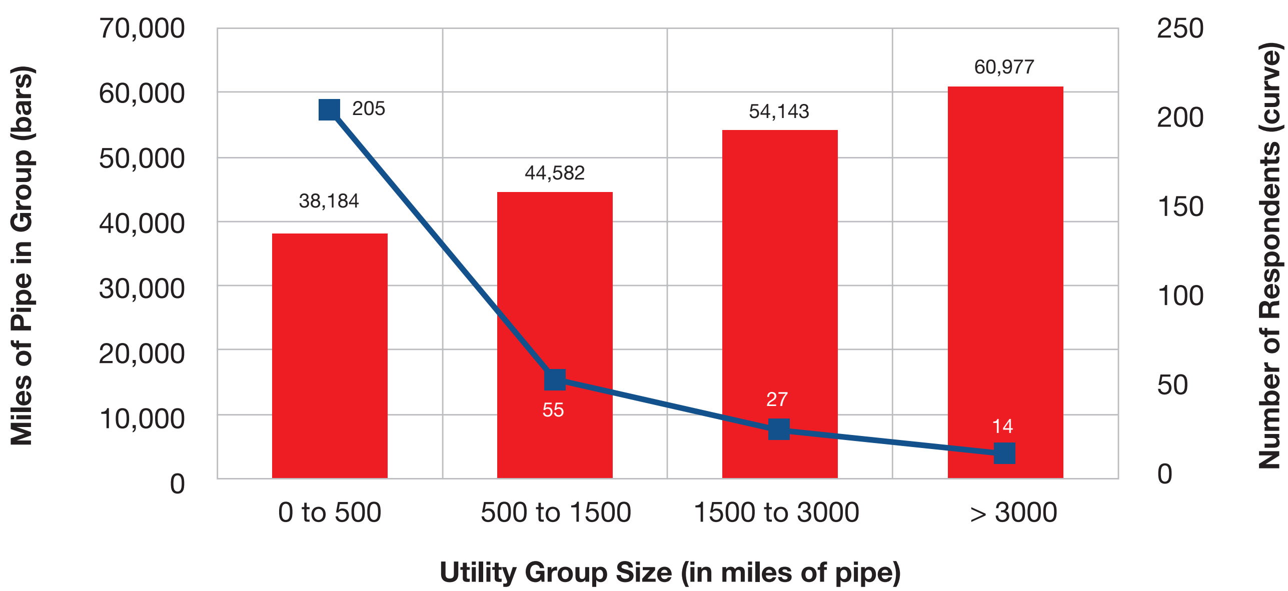


Four categories of utility size were used as shown in Table 2 and each survey participant was allocated to one of the categories based on the miles of installed water mains. Figure 6 shows the distribution of total miles of pipe from the basic survey based on these categories (bar graph) along with the number of respondents (line graph with right axis). Respondents covered the range from very small to very large with each group from Table 2 well represented. In terms of total length of pipe from each of the size groups in Table 2, this survey has reasonable uniform distribution of pipe length from small to large utilities.

TABLE 2: GROUPING OF UTILITY SIZE

Description	Miles of Pipe Installed
Small Utility/City	0 to 500 miles
Medium Utility/City	500 to 1500 miles
Large Utility/City	1500 to 3000 miles
Very Large Utility/City	Over 3000 miles

FIGURE 6: TOTAL MILES OF PIPE IN THE BASIC SURVEY IN EACH SIZE GROUP DEFINED IN TABLE 2 AND THE NUMBER OF RESPONDENTS (CURVE AND RIGHT AXIS)



2.5. Miles of Pipe vs. Population

Figure 7 illustrates the relationship between the population served by the utilities participating in the basic survey and the number of miles of water main pipe. The trend line and equation are a best fit to the data. The slope of this line indicates that there are on average 322 people served for each mile of water main installed. Figure 7 tends to be biased by the points most distant from the origin. Figure 8 utilizes the data in Table 1 to compute average population served per mile of pipe for each region. We see that this produces an overall average of 308 people served per mile. More rural areas such as Regions 3, 4, and 5 have lower population to miles of pipe ratios as expected. Utilities that were exclusively transmission systems were excluded. This compares with a commonly used estimate of 325 people per mile (Eidinger, 2001). The 2012 survey reported this value as 264 people served per mile. Pipe breaks in utilities with a higher count of people per mile would have a greater impact on the community.

FIGURE 7: POPULATION SERVED RELATIVE TO TOTAL MILES OF PIPE FROM THE BASIC SURVEY

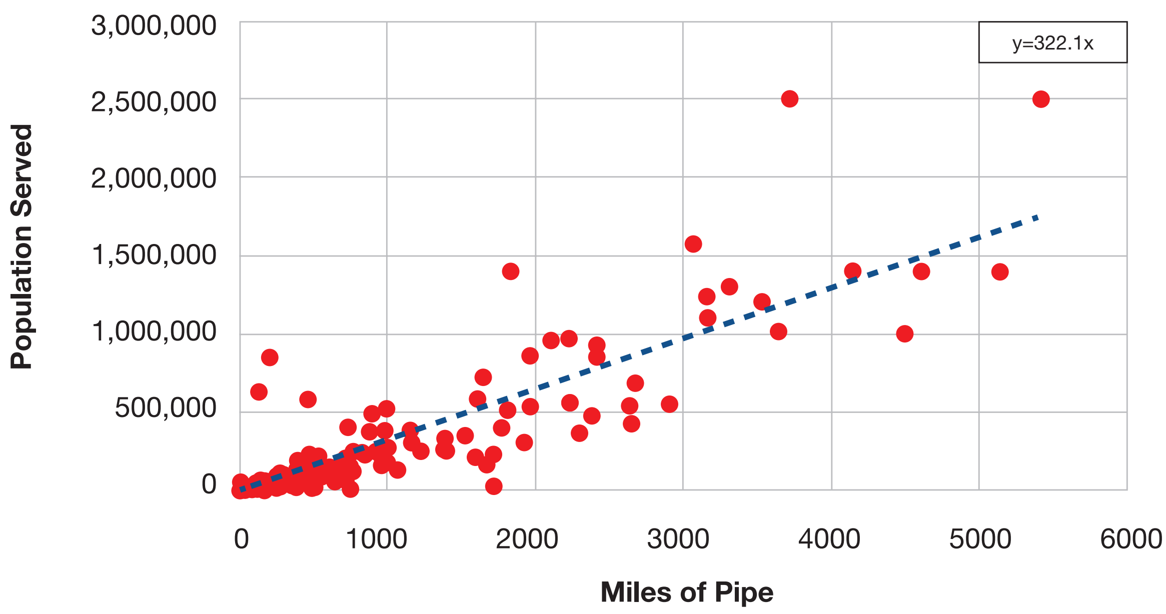
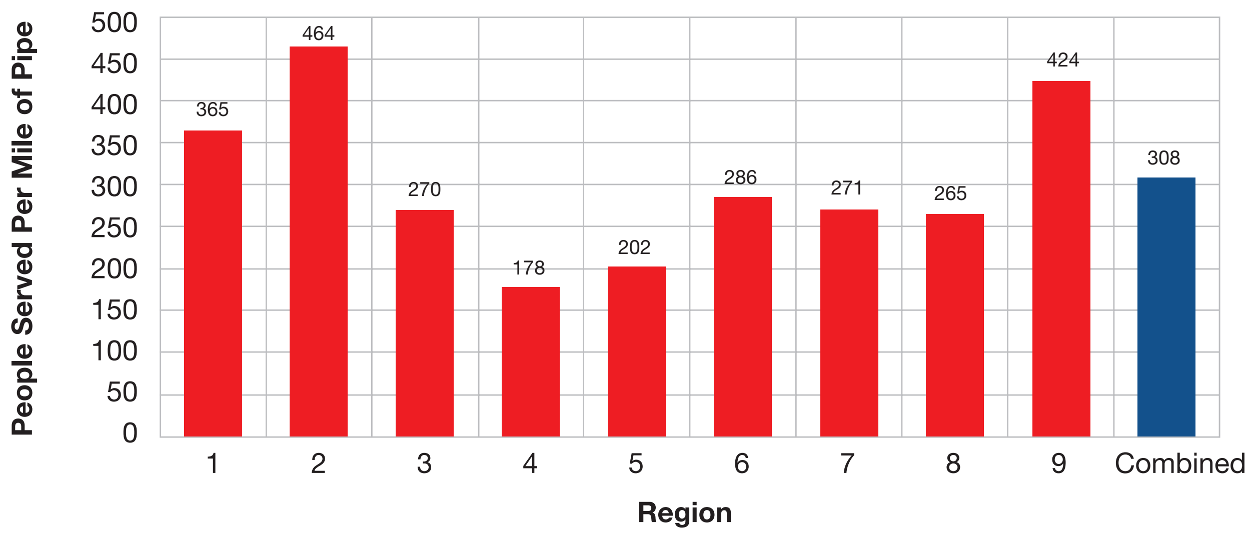


FIGURE 8: POPULATION SERVED PER MILE BY REGION



2.6. Survey Sample Size

The total length of water main pipe reported by the 281 basic survey participants with break data was 170,569 miles (the survey did not include sewer or force mains). Based on an EPA report, there are approximately 880,000 miles of distribution pipe in the USA (EPA, 2007). Other EPA reports (EPA, 2002 and EPA, 2013) estimate the amount of installed water main pipe in the USA at over 1 million miles and 1.5 million miles. Using the above result of 308 people/mile of water main and the current US population of 326.0 million, this produces an estimate of 1.06 million miles of pipe. Currently, a commonly cited value for the length of water mains in the US is 1.2 million miles (Walton, 2016). The population of Canada is estimated at 36.7 million. Assuming there are 308 people served per mile of pipe in Canada, then an estimate of the miles of pipe in Canada is 119,156 miles. Table 3 summarizes this data along with survey results from Table 1 to show that this survey covered approximately 14.5% of the population and 12.9% of the miles of water mains in both the US and Canada. Thus, survey sample size is significant and therefore can provide reliable results.

Small and rural communities may find it challenging to renew their water infrastructure in the coming years. Small utilities have fewer people, and those people are often more spread out, requiring more pipe "miles per customer" than urban systems (AWWA, 2012). This has the effect of increasing the financial burden of maintaining these systems.

TABLE 3: SUMMARY CALCULATIONS OF THE COVERAGE OF THE BASIC SURVEY

	Population	Miles of Pipe
US	326,000,000[1]	1,200,000[3]
Canada	36,700,000[2]	119,156[4]
Total	362,700,000	1,319,156
Survey Response (with break data)	52,477,346	170,569
Survey Coverage (%)	14.5%	12.9%

1- Source: https://www.census.gov/popclock/
2- Source: http://www.worldometers.info/world-population/canada-population/
3- Source: (Walton, 2016)
4- From: the population of Canada 36,700,000 and there are 308 people/mile of pipe.

3.0 Pipe Materials

Table 4 lists the pipe materials and their abbreviation used in this report. Many pipe products have evolved over the years of use, and most pipe products could be broken down into subcategories based on pipe manufacturing and surface treatments. These changes along with new installation techniques should affect life expectancy of the pipe. Both the basic and detailed surveys were intended to be relatively simple to complete and, thus, encourage wide scale participation of the water utilities. Most utilities have limited records as to which specific pipe materials were installed decades ago and what corrosion protection measures were used. Therefore, tracking subcategories of material types was not part of this study.

Figure 9 illustrates the length of pipe reported in the basic survey broken down by pipe material. The "Other" category in Figure 9 includes materials such as copper, fiberglass (FRP), and some galvanized steel. It is noted that galvanized steel was reported in both the steel and other categories by participants, which was unfortunate. Figure 10 illustrates the percentage of total length of water mains separated by pipe material. There is so little HDPE pipe (859 miles) and PVCO pipe (83 miles) in this survey, that these two pipe materials will be added to the of the "Other" category in the remainder of this report. If there are only small amounts of a pipe material utilized, break rates can be highly inaccurate because of large scatter in the data. It is significant to consider that over 91% of the water mains are made from asbestos cement, cast iron, ductile iron, and PVC materials. This is consistent with earlier studies (Stone et al., 2002).

TABLE 4: MATERIAL TYPES AND THEIR ABBREVIATIONS

Abbreviation	Description
AC	Asbestos Cement
CI	Cast Iron
CSC	Concrete Steel Cylinder
DI	Ductile Iron
HDPE	High Density Polyethylene
PVC	Polyvinyl Chloride
PVCO	Molecularly Oriented PVC
Steel	Steel

FIGURE 9: LENGTH OF PIPE SEPARATED BY MATERIAL TYPE FROM THE BASIC SURVEY

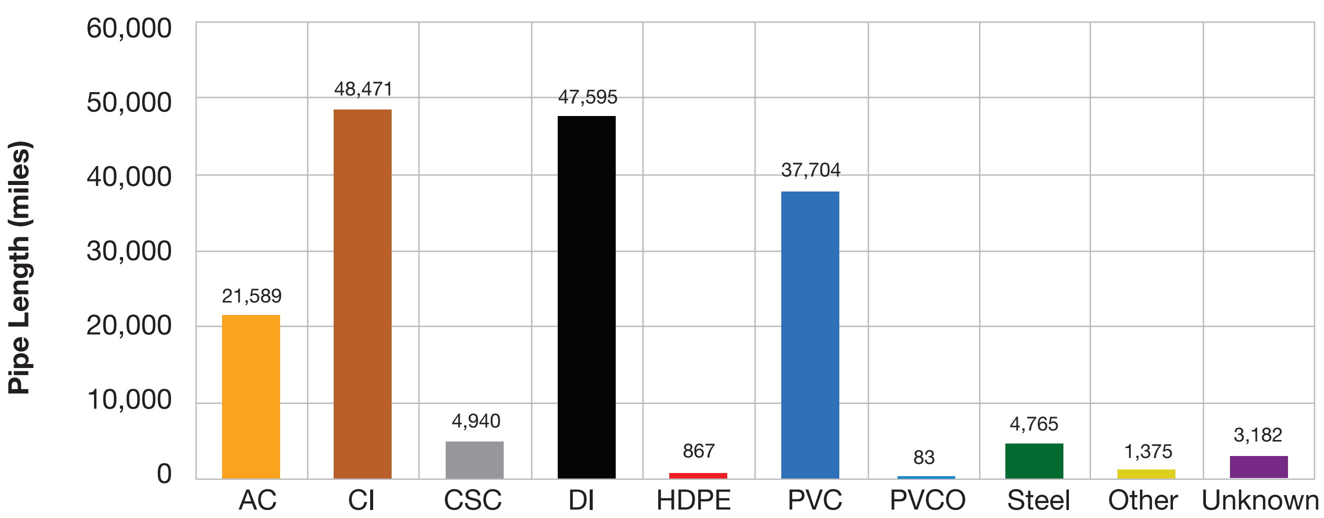


FIGURE 10: PERCENT OF TOTAL LENGTH OF PIPE SEPARATED BY MATERIAL TYPE

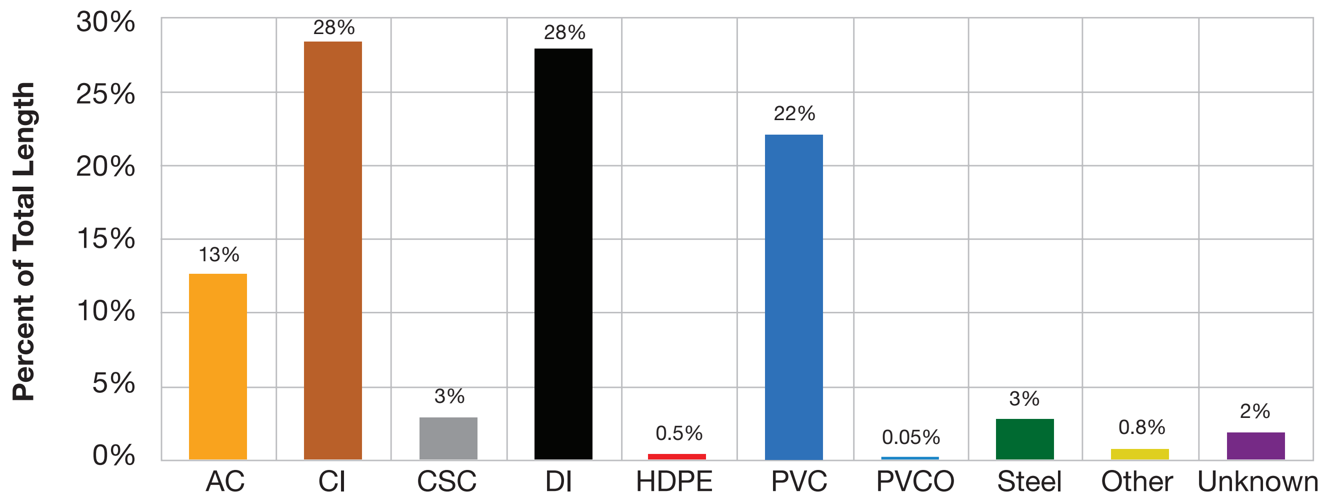


Figure 11 illustrates the regional distribution of pipe material usage as a percentage of the total length in that region. It is interesting to note the significant differences in regional pipe material utilization. Cast iron (CI) and ductile iron (DI) pipe represent approximately 86% of the water mains in Region 6 and over 75% in Regions 4, 7, and 8. PVC has a leading role in Regions 3, 5 and 9 and is slightly behind asbestos cement (AC) pipe in Region 2. AC pipe has a significant presence in Regions 2 and 5. Region 2 is unique in that it is the only region where AC pipe is the most common material. This suggests that the selection and use of pipe materials are based on historical preference versus comparative cost analysis or environmental conditions. Since CI and AC pipes are no longer manufactured in the US and Canada, the use of these materials in water systems should be decreasing with time as they are replaced. By applying asset management best practices, life cycle cost analysis should be used to do a comparative total cost of ownership evaluation of what pipe material should replace the CI and AC pipes.

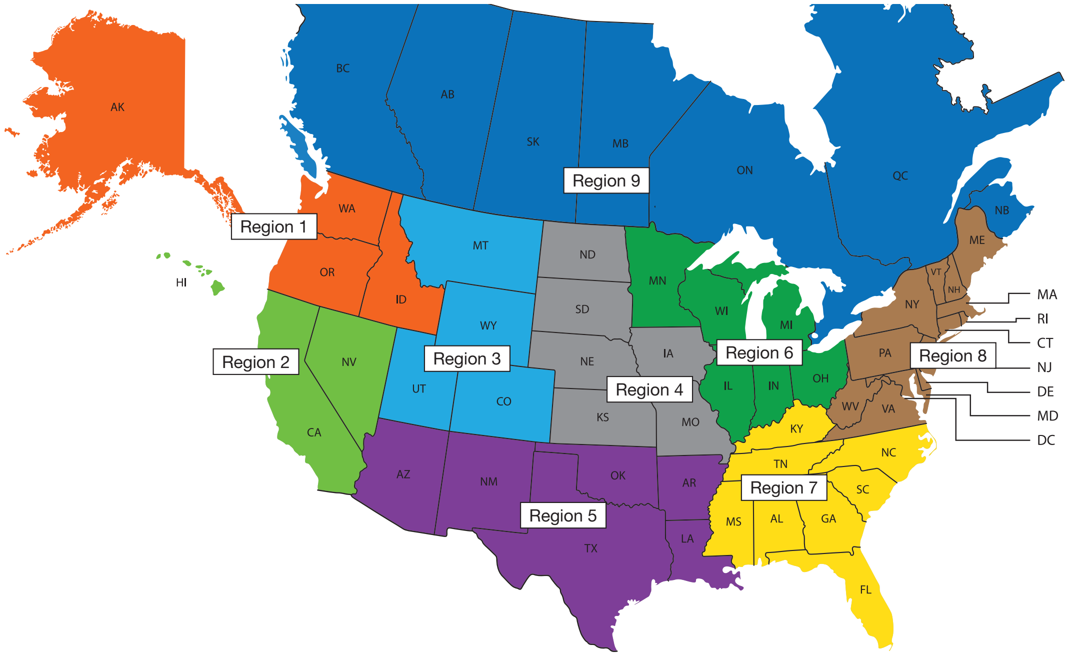
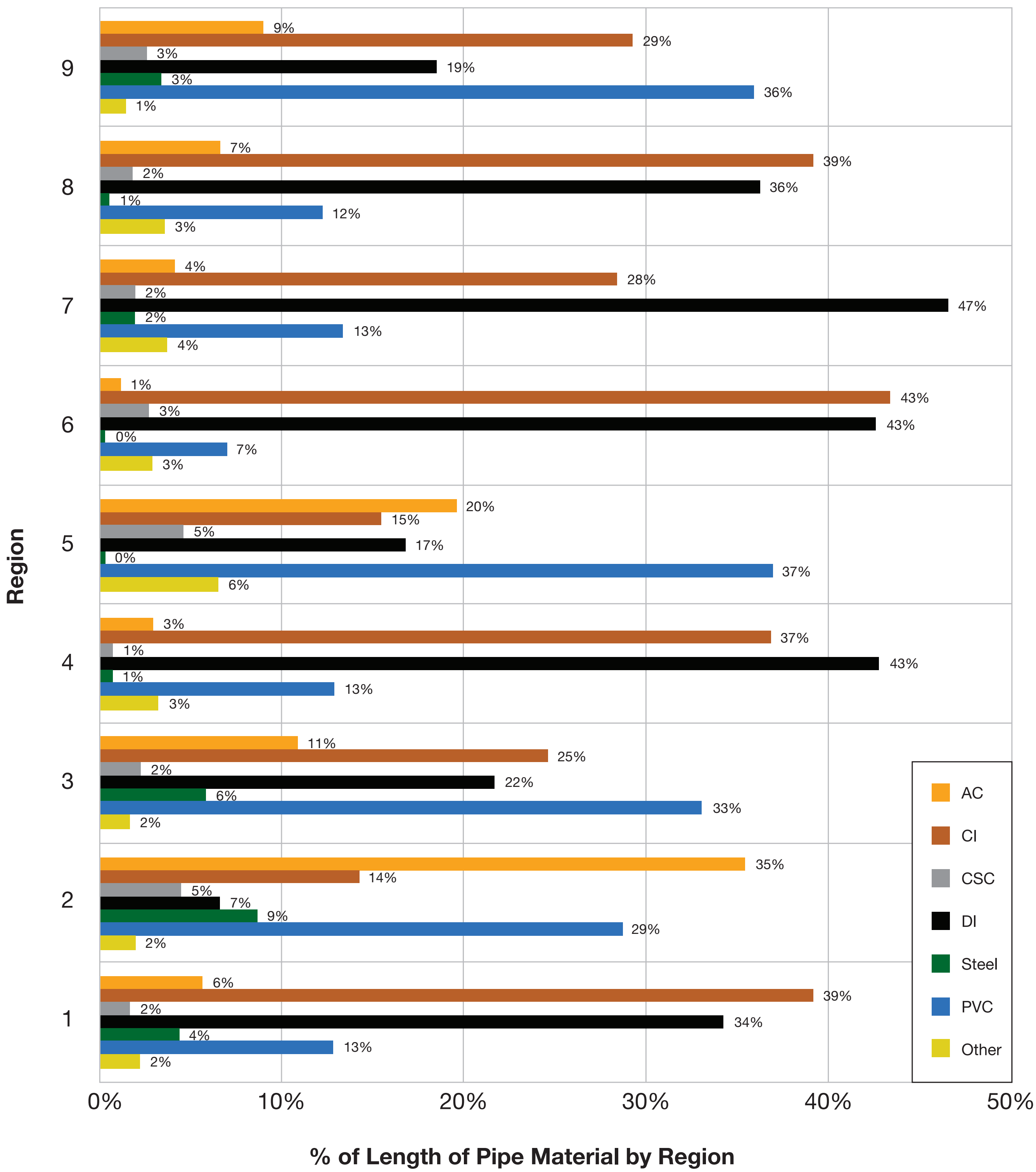


FIGURE 11: REGIONAL PERCENTAGE OF LENGTH OF PIPE BY MATERIAL TYPE (BASIC SURVEY)



3.1. Pipe Age and Diameter

The detailed survey asked respondents to provide the distribution of installed pipe by age and by material type. Four age groups were provided; 0 to 10 years, 10 to 20 years, 20 to 50 years, and over 50 years. Figure 12 shows the age distribution for all pipe materials combined and shows 28% of installed pipes are over 50 years old. Figure 13 illustrates the age distribution for each material type by length. For example, essentially all cast iron pipe is over 20 years old and 18% of it is in the 20 to 50 year category while 82% is over 50 years of age.

Figure 14 shows the age distribution as a percentage of total length of all pipe materials. For example, cast iron pipe older than 50 years is 20% of all installed pipe. For ages between 0 to 10 years, ductile iron (DI) and PVC both have about 5% of the total installed length. The most common pipe materials installed during the last 10 years are DI and PVC.

FIGURE 12: PIPE AGE DISTRIBUTION FOR ALL MATERIAL TYPES FROM THE DETAILED SURVEY

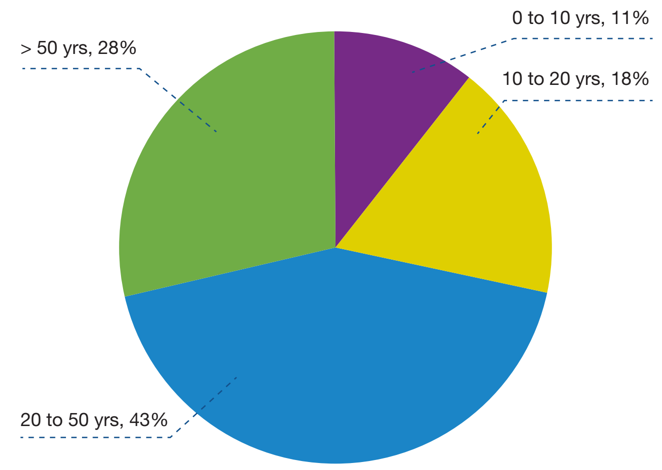


FIGURE 13: PIPE AGE DISTRIBUTION FOR EACH MATERIAL TYPE FROM THE DETAILED SURVEY

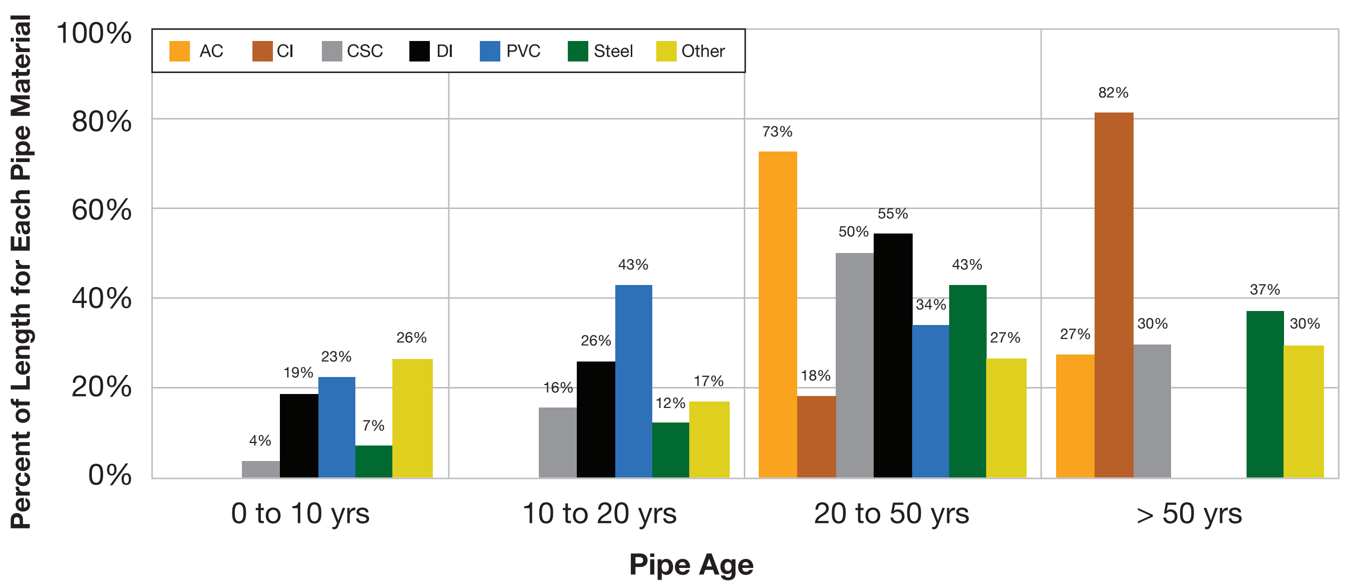
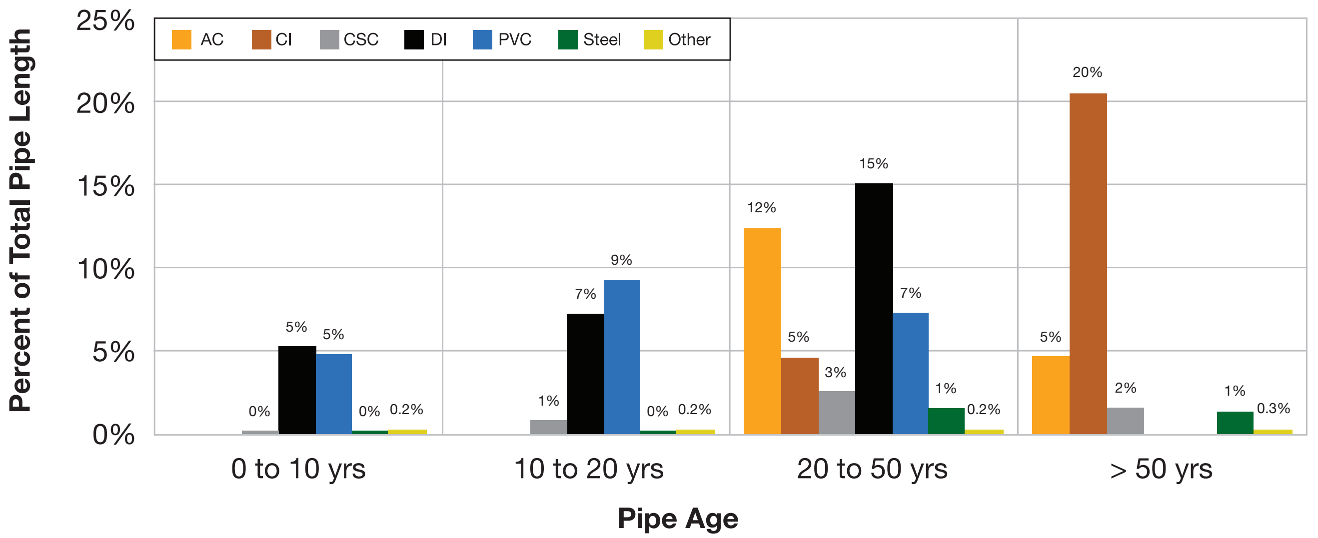


FIGURE 14: PERCENT OF TOTAL LENGTH OF PIPE BY AGE FROM THE DETAILED SURVEY



The detailed survey respondents were also asked to break down the fraction of total installed pipe length by six pipe diameter categories. Figure 15 illustrates the percentage of water main that fit into each size range. Figure 15 indicates that approximately 67% of the installed pipe is 8 inches or less in diameter. The 2012 survey found that 66% of the pipe was 8 inches or less in diameter showing good agreement. Earlier studies assumed 73% of water pipes were 10 inches or less in diameter (Stone et al., 2002). Figure 16 illustrates the diameter distribution for each material type. Figure 16 shows that large diameter transmission pipes are dominated by steel and concrete pipe materials with 18% of all concrete pipe and 14% of all steel pipe having a diameter greater than 48-inches. Figure 17 illustrates the percent of total length of all pipe materials broken down by material type and diameter. Figure 17 illustrates that cast iron pipe from 3 to 8 inches in diameter represents over 19% of the installed pipe.

FIGURE 15: PERCENT OF TOTAL LENGTH OF PIPE BY AGE FROM THE DETAILED SURVEY

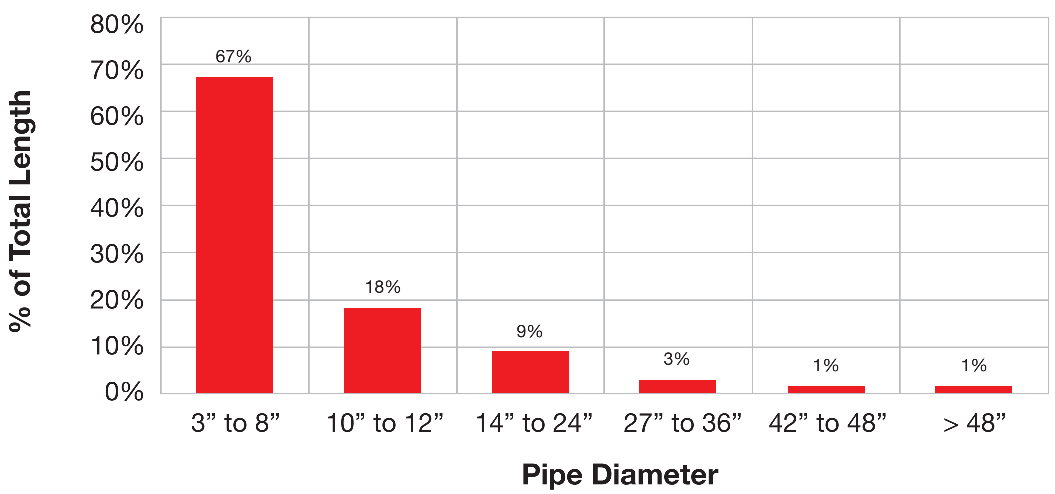


FIGURE 16: PIPE DIAMETER DISTRIBUTION BY MATERIAL TYPE FROM THE DETAILED SURVEY

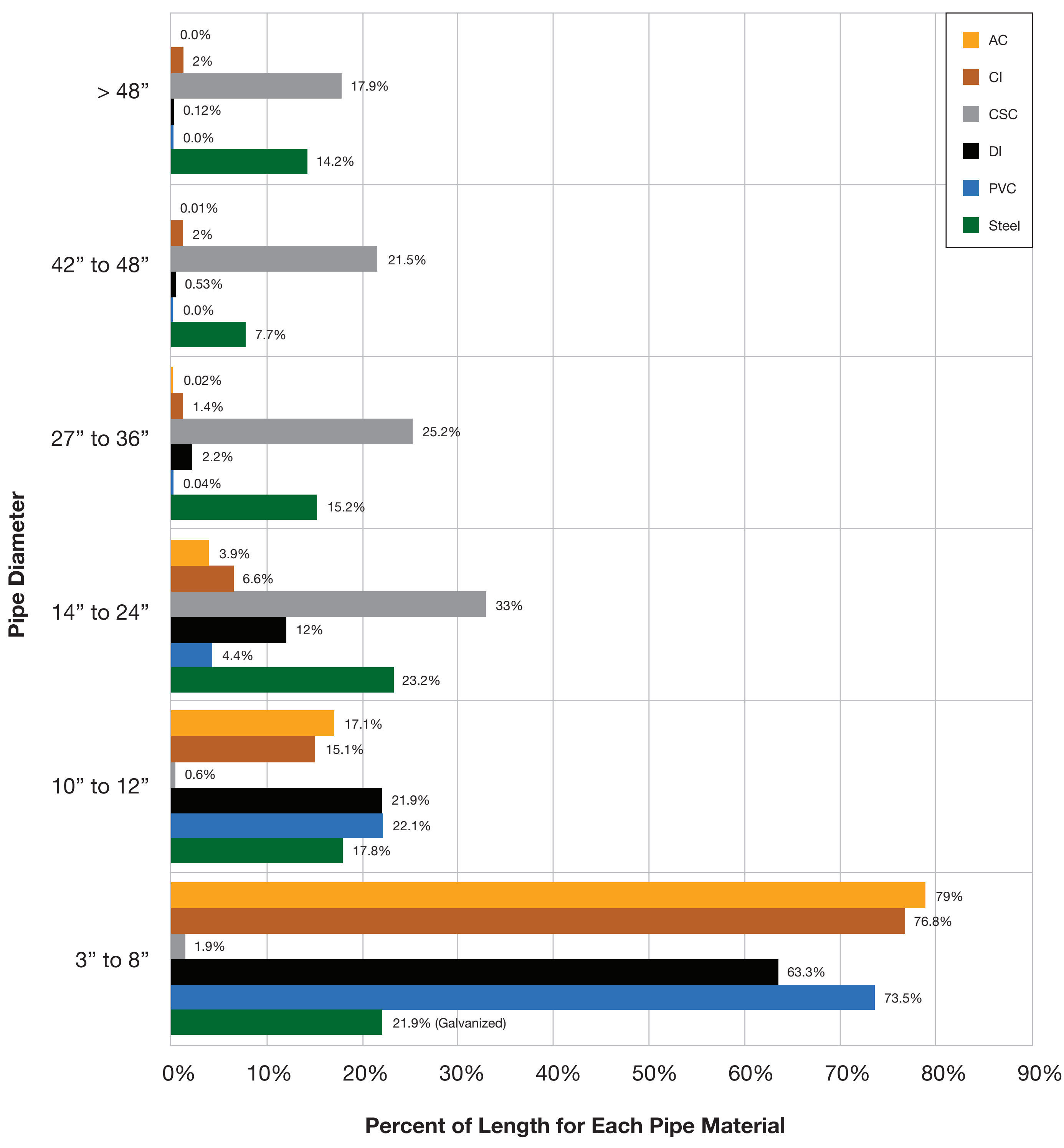
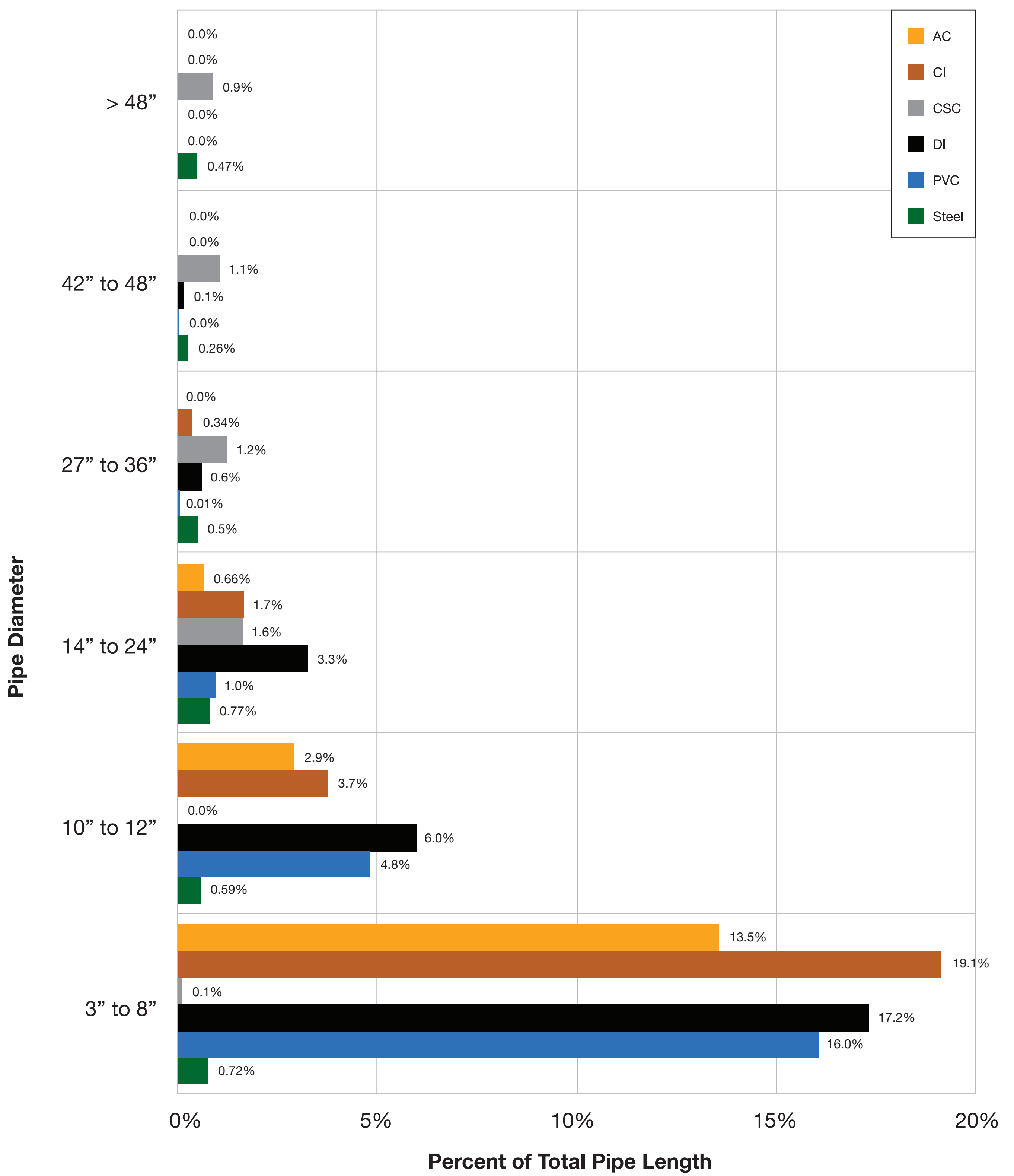


FIGURE 17: PERCENT OF TOTAL PIPE LENGTH BROKEN DOWN BY PIPE DIAMETER AND MATERIAL TYPE FROM THE DETAILED SURVEY



4.0 Delivery Pressure and Volume

The basic survey asked for the average and maximum water supply pressures. The mean values are 69 and 119 psi. The average of the reported values is illustrated in Figure 18. In the 2012 survey, the average pressure was 77 psi which has good agreement with this survey result but also indicates a possible downward trend. It is noted that some utilities have reduced operating pressures to reduce leakage rates. Pressure control and reduction is a common methodology to both reduce water leaks and reduce water main breaks.

The detailed survey asked for the average and maximum daily water demand. The reported values were divided by the population served and averaged. Utilities that were only transmission systems were excluded. The average water demand is 137 gallons per day for each person. The maximum water demand is 251 gallons per day for each person. Water demands are related to the population served. Figure 19 plots each utility's average and maximum demand values in units of MGD (millions of gallons per day) versus the population served in millions. Also provided are linear fit equations to the data (the dotted lines) and their equations. For example, a utility with a population of one million people would have a maximum water demand of 215 MGD and an average demand of 131 MGD.

FIGURE 18: AVERAGE AND MAXIMUM WATER SUPPLY PRESSURES

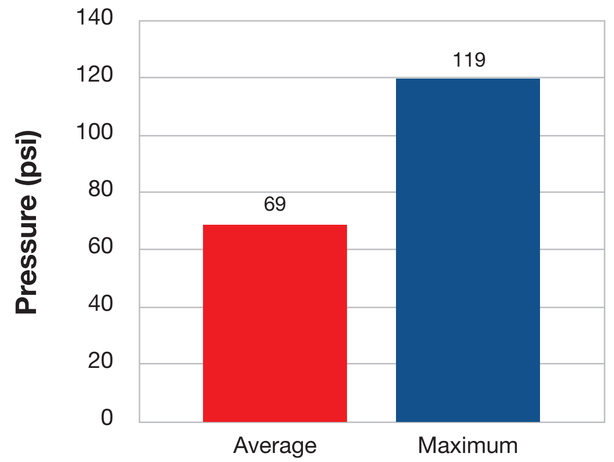
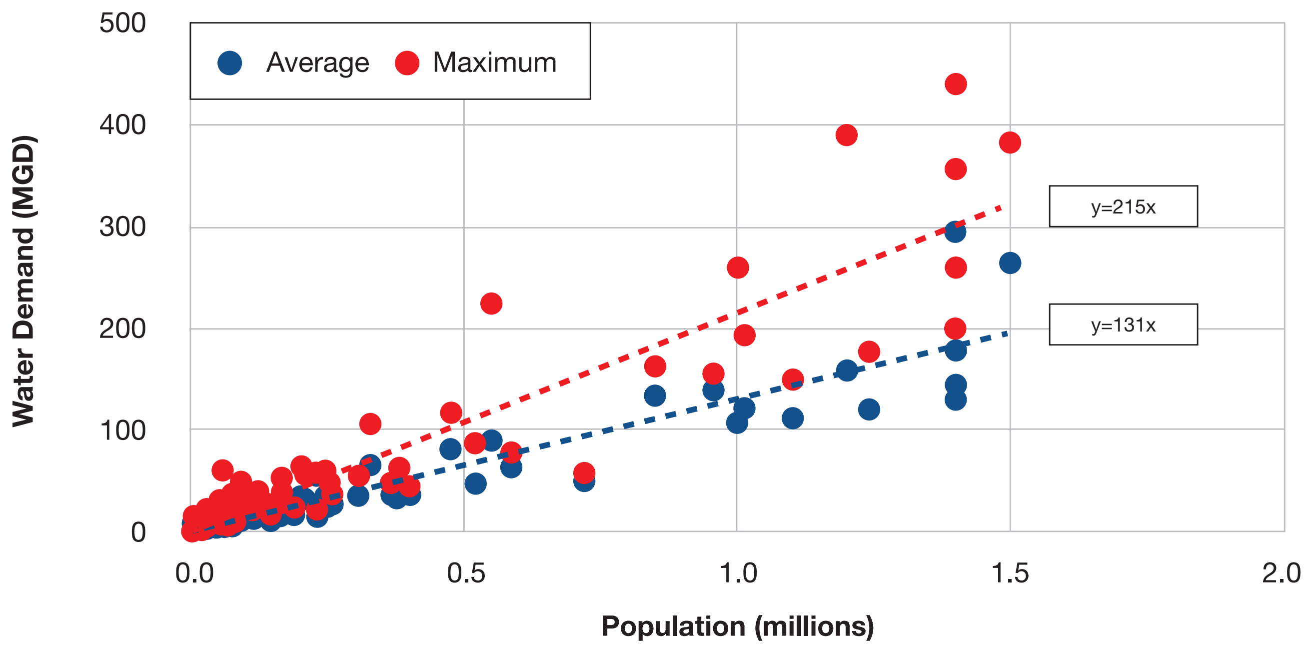


FIGURE 19: AVERAGE AND MAXIMUM WATER DEMAND VERSUS POPULATION



5.0 Computing Water Main Failure Rates

Both the basic and detailed surveys asked respondents to consider a water main failure as one where leakage was detected, and repairs were made. However, they were requested to not report failures due to joint leakage, construction damage, or tapping of service lines because these failures are not indicative of pipe degradation and are often identified early in the first year of operation. The goal was to examine pipe longevity.

Utilities reported the number of failures over a recent 12-month period for each pipe material and the installed length of each pipe material. The failure rate was computed by dividing the total number of failures from all utilities for a particular pipe material by the total length of that pipe material.

For example, the survey reported a total of 23,803 failures of water mains during a recent 12-month period for all pipe materials. The total installed water main length from the survey was 170,569 miles (or 1705.69 hundreds of miles). Thus, the overall failure rate is 23,803/1705.69 = 14.0 failures/(100 miles)/year. This represents a 27% increase from the 2012 survey which had a rate of 11 failures/(100 miles)/year.

This simple method for computing failure rates was used because it discourages biases toward large or small utilities. It is noted that utilities experience widely different failure rates for the same pipe material. Indeed, this should not be surprising. Several significant variables affect the results including pipe age, soil types (corrosive or noncorrosive), different corrosion prevention techniques, different installation practices, and climate such as extreme cold and drought events.

Literature reviews indicate that between 250,000 and 300,000 breaks occur every year in the U.S., which corresponds to a rate of 25 to 30 breaks/(100 miles)/year (Grigg, 2007; Deb et al., 2002). The AWWA Partnership for Safe Water Distribution System Optimization Program goal for a fully-optimized distribution system is 15 breaks per 100 miles of pipe annually (AWWA Partnership for Safe Water, 2011). Pipe material performance and selection is an important component of optimizing distribution systems.

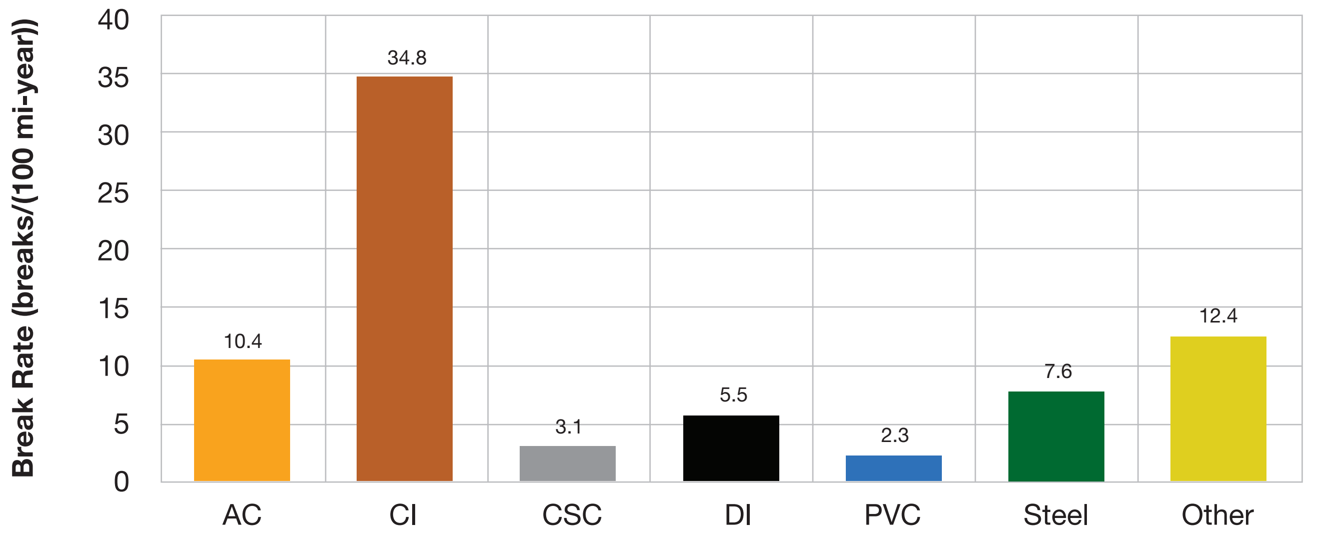
5.1. Failure Rates for Each Pipe Material

The survey measured pipe failures over a recent 12-month period and was broken down by material type. Table 5 lists the total length of pipe by material type, the number of failures (breaks) over a recent 12-month period, the break rate for each pipe material, the 2012 survey break rates, and the percent change in break rates. Figure 20 illustrates the failure rates as a function of material type. In both the 2012 and 2018 surveys, PVC was the pipe material with the lowest break rate.

TABLE 5: SUMMARY OF FAILURE DATA FROM THE BASIC SURVEY OVER A 12-MONTH PERIOD

	Length	Failures	2018 Break Rate	2012 Break Rate	% Change
AC	21,589	2,240	10.4	7.1	46%
CI	48,471	16,864	34.8	24.4	43%
CSC	4,940	152	3.1	5.4	-43%
DI	47,595	2,627	5.5	4.9	13%
PVC	37,704	878	2.3	2.6	-10%
Steel	4,765	362	7.6	13.5	-44%
Other	5,506	680	12.4	21	-41%
Total	170,569	23,803	14.0	11	27%

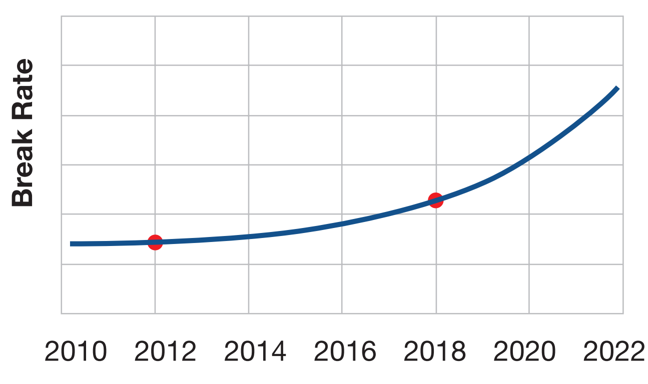
FIGURE 20: BREAK RATES OF EACH PIPE MATERIAL FROM THE BASIC SURVEY



Comparing this 2018 survey with the 2012 survey in Table 5 shows that overall, break rates increased by 27%. The change is primarily due to failures in asbestos cement (AC) and cast iron (CI) pipes with increases of break rates by over 40%. As Figure 14 shows, AC and CI pipe represent the largest percentage of oldest pipe currently installed and thus are nearing the end of their useful lives. Many studies show that water-main failure rates generally increase exponentially over time (Kleiner, 2002). One could envision a rapid increase in break rates in the future as illustrated in Figure 21. Certain utilities could experience the need to rapidly accelerate the rate at which they are replacing CI and AC water mains. If a break rate doubles, the economic impact is significant; one would need to double the number personnel repairing the breaks along with supplies while loss of treated water increases, and societal impacts could be devastating.

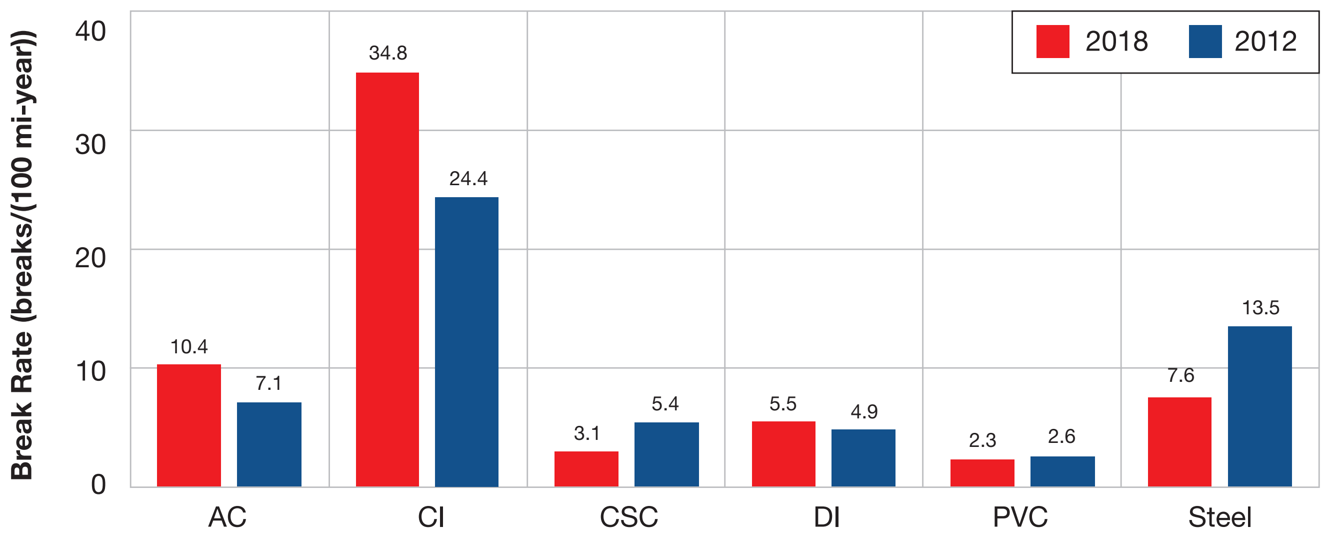
Figure 22 compares the break rates of the 2012 and 2018 surveys. Since over 90% of installed pipe consists of AC, CI, DI, and PVC, the break rates for those material types will be most accurate. From 2012 to 2018, Figure 22 shows a small decrease in break rates for PVC and a small increase for DI pipe. The overall consistency of those values demonstrates they are accurate. Again, the increase in break rates for AC and CI pipes is a very significant observation.

FIGURE 21: EXPONENTIAL CHANGE IN BREAK RATES



The amount of concrete and steel pipe in this survey is less than 6% of the total installed pipe length. When only a small amount of pipe break data is available, the accuracy of the break rates from survey data will be decreased. The 42% decrease in break rate for concrete pipe was likely due to the fact that over twice as much concrete pipe is in this 2018 survey and should be more accurate. Steel pipe also saw a large decrease in break rates. The break rate for steel pipes are largely attributed to smaller diameter galvanized steel pipes that are rapidly being replaced. Large diameter steel pipes used in transmission lines have a very low break rate.

FIGURE 22: COMPARISON OF BREAK RATES OF THE 2018 AND 2012 SURVEYS



The size of a utility can affect break rates. Three sizes of utilities are considered here based on the length of pipe; small with less than 200 miles, intermediate with 200 to 1000 miles, and large with over 1000 miles. Figure 23 illustrates the overall break rate (for all pipe materials) and then separated by the four most common pipe materials in these three utility sizes. The large utilities consistently had lower break rates than intermediate and smaller utilities. This is likely due to better funding and larger staffs for engineering design, monitoring and information gathering, installation oversight, and repair of water mains. It is very significant that small utilities consistently have break rates at least double that of a large utility.

FIGURE 23: BREAK RATES BY UTILITY SIZE FROM THE BASIC SURVEY

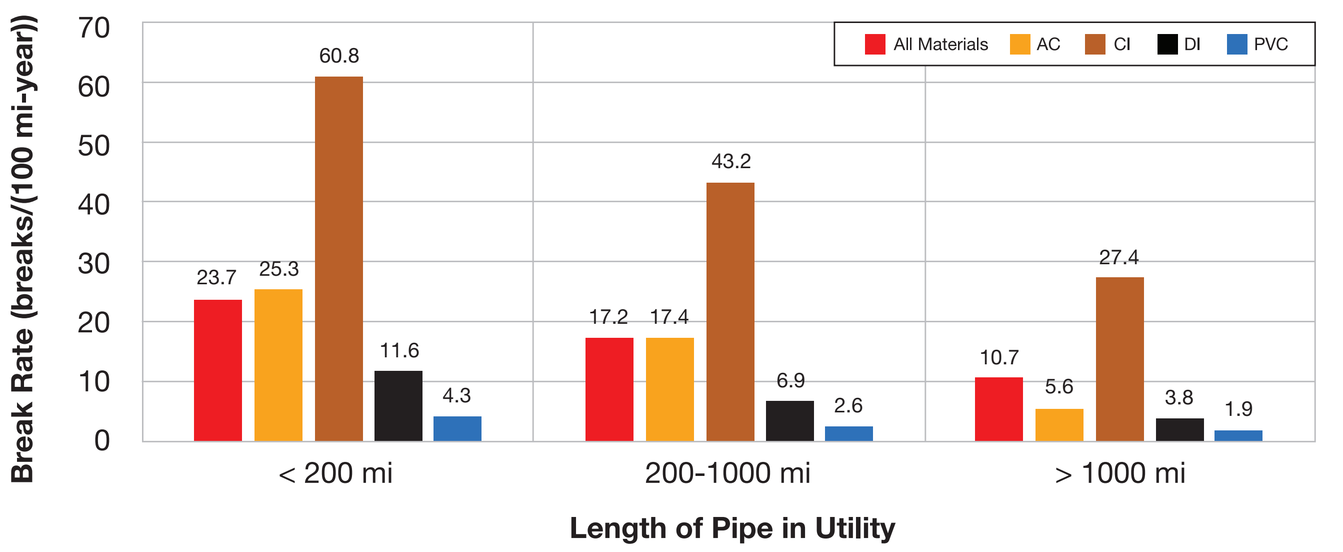


Figure 24 illustrates the overall break rate broken down by region. Clearly not all regions are experiencing the same failure rate. In Table 1, the number of respondents for each region is reported. It was desired to separate US and Canadian break rate data. This is illustrated in Figure 25. Canada can have very corrosive soils (Seargeant, 2013) and this is reflected in the high break rates of cast and ductile iron pipes in Figure 25. Seargeant reported that the highly corrosive soil in Edmonton necessitated a transition from cast iron to asbestos cement pipes in 1966 and then to PVC starting in 1977. The transition to PVC has produced a dramatic reduction in water main break rates for the city.

FIGURE 24: OVERALL BREAK RATES BY REGION FROM THE BASIC SURVEY

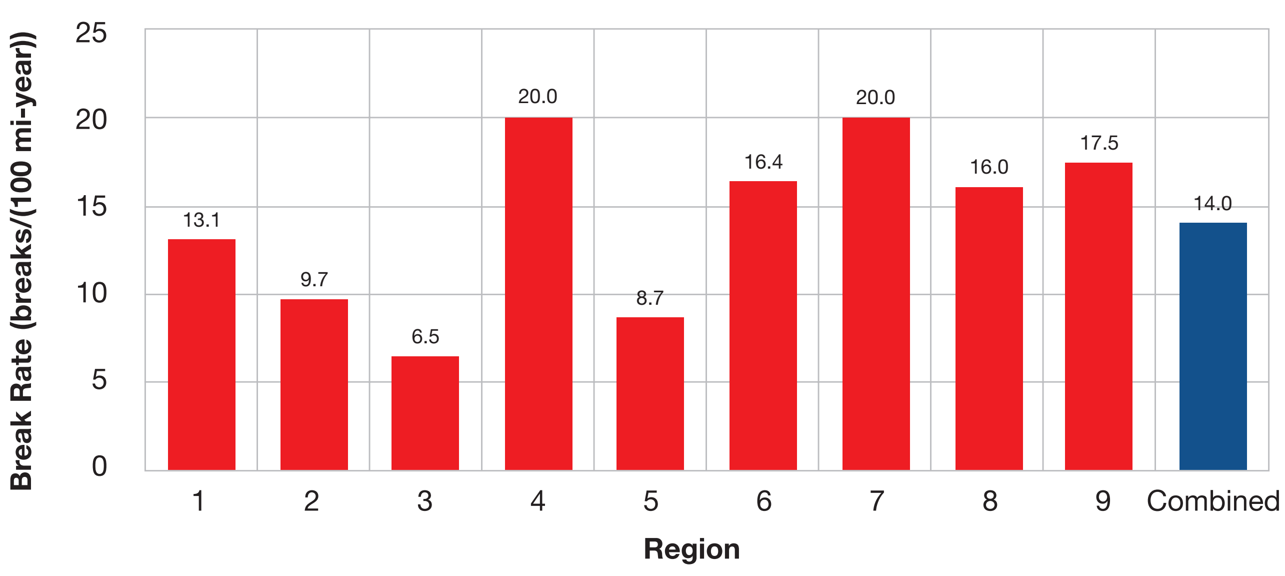
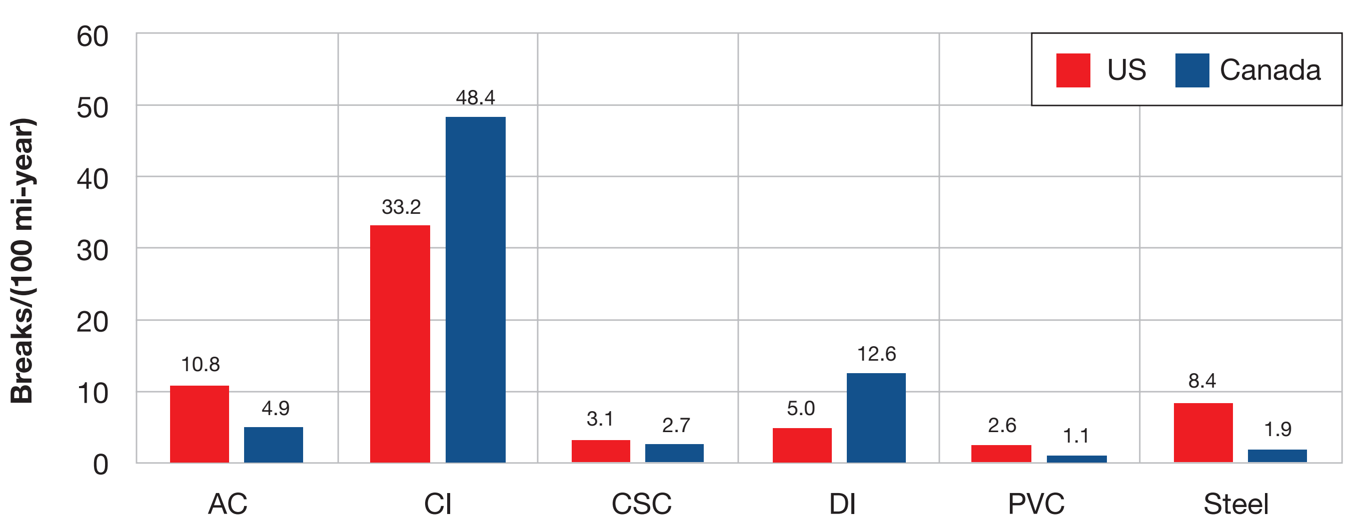


FIGURE 25: BREAK RATES FROM THE US AND CANADA FOR SELECTED MATERIAL TYPES



5.2. Effects of Age

The basic survey asked respondents to break down the failures into the decade when they were installed. Some of the respondents did not know the age of the failed pipes and they were not included in the results. Figure 26 illustrates the percentage of failures of each pipe material based on the decade of installation. For example, asbestos cement (AC) pipe had 60% of the breaks from pipe installed in the 1960's, 28% in the 1970's, and 12% of the breaks in pipes installed in the 1980's. Note that the largest percentage of failures is usually not in the oldest pipes (AC being an exception), which has several possible causes. One important cause is the amount of pipe present in a given age range. As the older pipe is replaced there is less available to fail. Also, cast iron and ductile pipe wall thickness has decreased over the years which can affect time to failure. The results in Figure 26 are also related to when a pipe material was introduced or removed from the market. AC pipe has not been installed in the USA and Canada in the past 25 years, and thus, all AC pipe failures date from the 1980's and earlier. Little cast iron pipe has been installed since the 1980's and that is reflected in Figure 26. Widespread ductile iron and PVC pipe production in the USA did not start until about 1970, so we should expect to see a small failure percentage for both DI and PVC installed in the 1960's and none in the 1950's and earlier.

Most of the failure versus age distributions in Figure 26 seem to be quasi bell-shaped (again, asbestos cement pipe failures are an exception). It would appear the AC pipe installed in the 1960's may be near its end of life and utilities may want to consider planning for rapid replacement of that pipe. Cast iron pipe shows the most uniform failure distribution and does not give much guidance on which pipe age needs replacement first.

5.3. Target Replacement Break Rate

The detailed survey asked participants if they utilized a target break rate at which pipe replacement was implemented. Only 28% of the respondents said that they had a specific value. The average response was a target rate of 11 breaks/(100 miles)/year. Most respondents commented that they do not have a specific target break rate. However, break rates are a very important factor when locations for critical services are considered and when roads are being reconstructed. Although Figure 26 provides some insight to when pipe needs to be replaced, the most appropriate metric to making this decision should come from looking at break rates at sections of pipe with a similar age and material.

5.4. Most Common Failure Age and Mode

The detailed survey asked the participants the typical pipe age of most water main failures. The average response was 50 years with a range from 10 to 100 years. In 2012 the average age of failing water mains was reported as 47 years. Given the qualitative nature of this question, the typical age of a failing water main has not changed significantly over the past six years.

The detailed survey requested participants to select the most common failure mode from the following: corrosion, bell split, circumferential crack, longitudinal crack, leakage at joints, fatigue, or other. Figure 27 illustrates that 56% of the respondents identified a circumferential crack as the most common followed by corrosion at 28%. These are the typical failure modes of CI and AC pipe.

An alternate approach to examine the failure modes is by using those reported in the basic survey. Participants were asked to provide a cause of failure from the following list; circumferential crack, longitudinal crack, corrosion (internal or external), bell splitting, rock impingement, other, or unknown. Where multiple failures occurred, multiple causes were given, and each was given equal weight. Figure 28 illustrates the percentage of each failure mode with unknown responses ignored. Again, the top two failure modes are circumferential cracks followed by corrosion.

FIGURE 26: PERCENT OF FAILURES PER DECADE OF INSTALLED PIPE MATERIAL

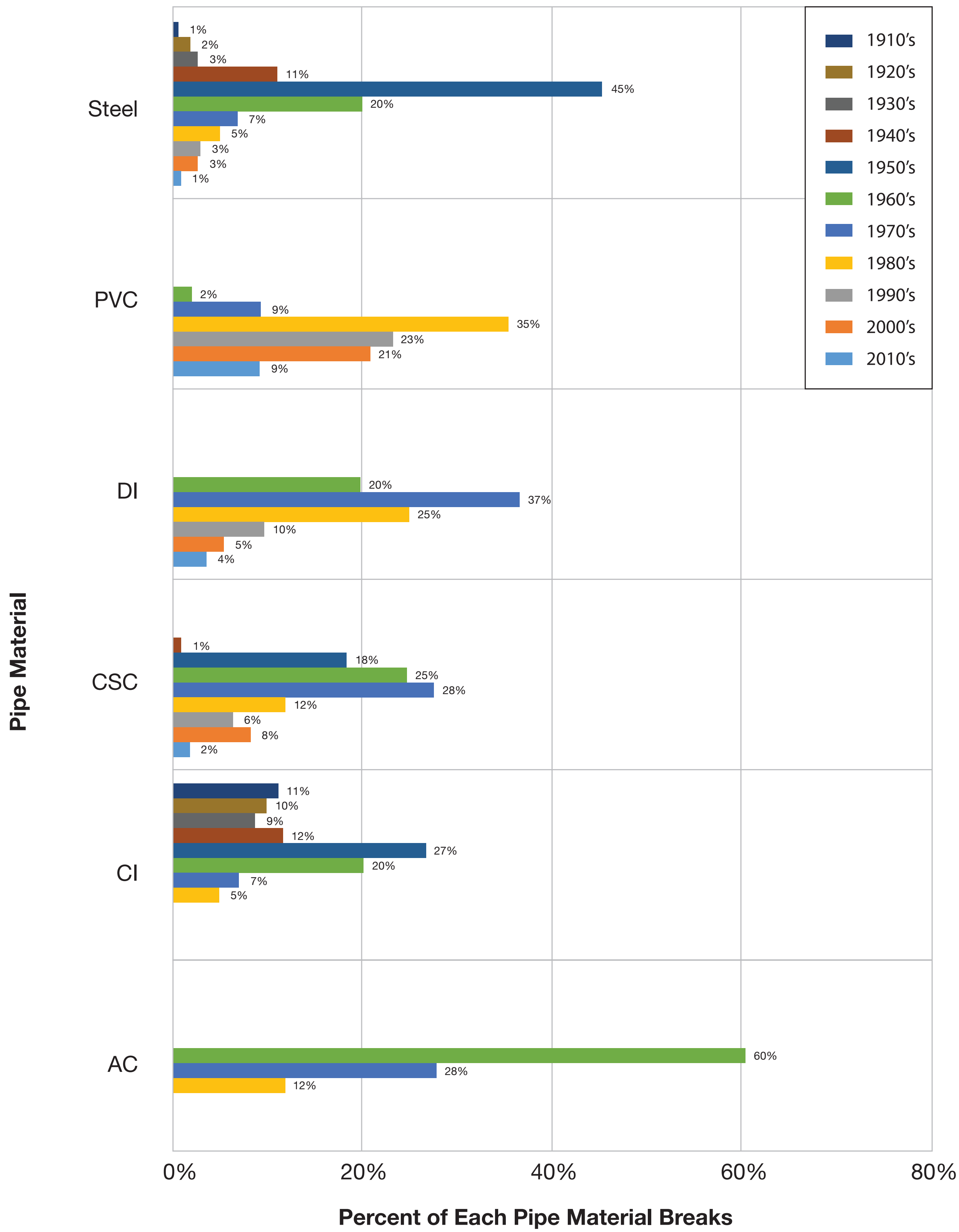


FIGURE 27: PERCENT OF RESPONDENTS SELECTING A MOST COMMON FAILURE

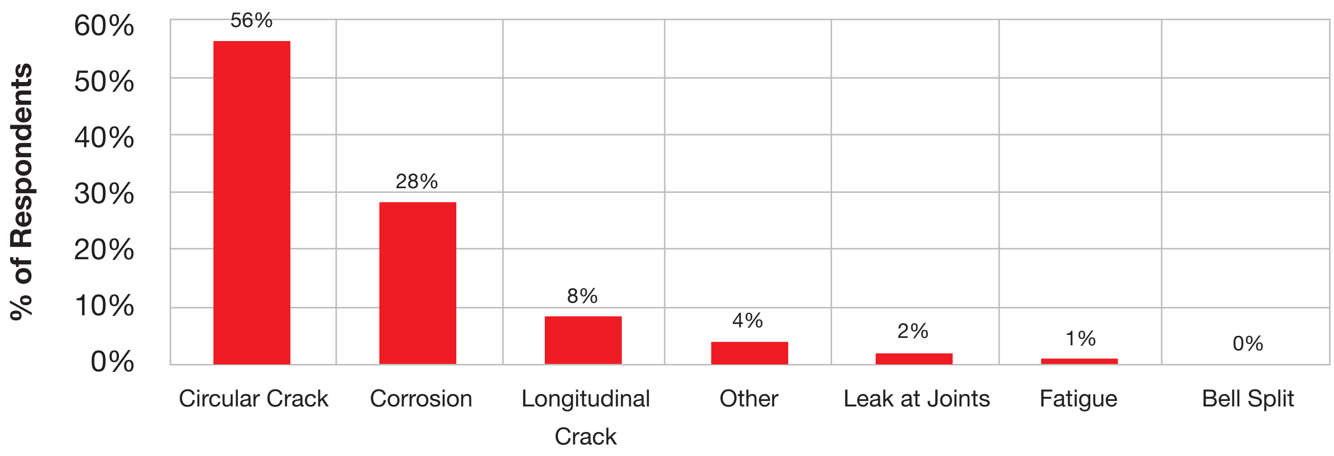
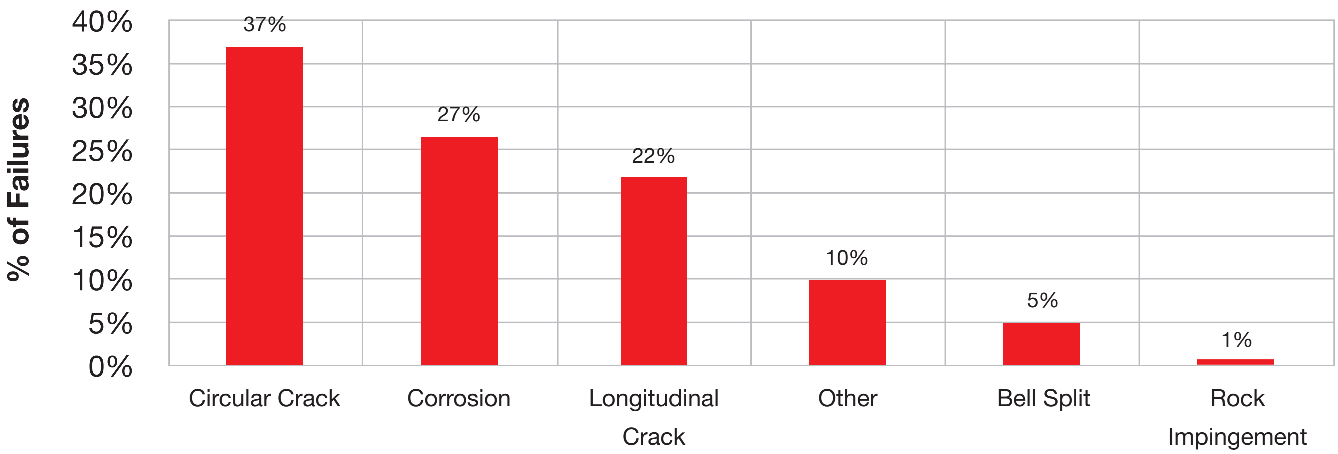


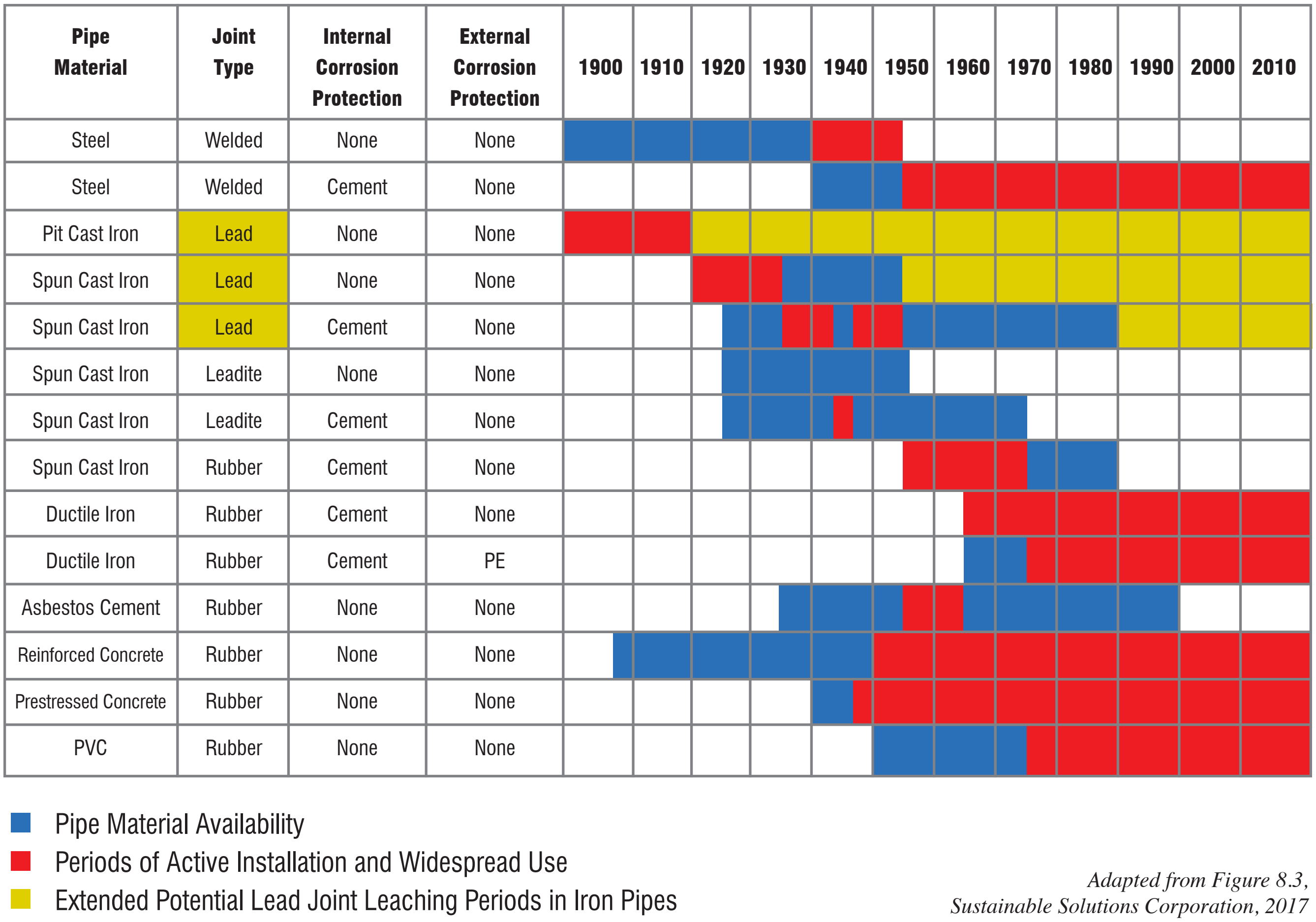
FIGURE 28: DISTRIBUTION OF FAILURE MODES FROM THE BASIC SURVEY



5.5. Pipe Cohorts and Vintage

As mentioned in section 3.0, the survey did not track the many subclasses of pipe that have been installed because many utilities do not have that information. Individual utilities should try to add to their database as much as they can about what is referred to as a pipe cohort and other details about their installation. Copeland, et al. (2015) provides a good example of data to record. A pipe cohort is a group of pipes with similar characteristics. This concept is useful in pipe management because defining different pipe cohorts can be helpful in identifying pipes that have different risk characteristics (see Figure 29).

FIGURE 29: TIMELINE OF PIPE TECHNOLOGY IN THE US IN THE 20TH CENTURY



Adapted from Figure 8.3, Sustainable Solutions Corporation, 2017

Changes in pipe manufacturing, such as the introduction of new pipe-making technologies, are a major criterion when identifying pipe cohort concerns (e.g., longevity of a pipe and risk of breakage). For instance, pit cast gray iron pipe and centrifugally cast gray iron pipe of the same diameter should likely be considered in different pipe cohorts, because the significant differences in manufacturing cause the pipes to behave differently. Other factors that can affect pipe longevity and breakage include transportation and installation methods (WaterRF, 2013).

Another pipe cohort is cast iron with leadite joints. There are at least two reasons for high failure rates associated with leadite joints: “First, leadite has a different coefficient of thermal expansion than cast iron and results in additional internal stresses that can ultimately lead to longitudinal splits in the pipe bell. Secondly, the sulfur in the leadite can facilitate pitting corrosion resulting in circumferential breaks on the spigot end of the pipe near the leadite joint. The failure rate in the industry for leadite joint pipe is significantly higher than for lead joint pipe even though the pipe may not be as old.” (EPA, 2002, p3)

6.0 Corrosive Soils and Corrosion Prevention Methods

The detailed survey asked respondents if they have one or more regions in their service area with soils that tend to be corrosive. A total of 75% of the respondents reported that they do have at least one area with corrosive soils. This corresponds to the results found in the 2012 survey. The survey also asked if they utilized any kind of corrosion protection methods. A total of 80% of the respondents reported that they do utilize some kind of corrosion protection. The respondents were also asked to describe the method(s) they used. The most common answer was polywrap installation. Table 6 lists most of the methods mentioned ordered from most common (rank 1) to least common (rank 5).

TABLE 6: TYPICAL CORROSION PREVENTION METHODS

Rank	Corrosion Prevention Methods
1	Polywrap
2	Anodes or cathodic protection
3	V-bio polywrap
4	Impressed current
5	Dielectric coatings

Water utilities often do not know the specific cause of external corrosion observed on their water mains, and consequently, the chosen preventative measure may not work effectively. Historically, these choices are based on data from other industries (e.g., gas and oil) and may not be suitable for the water industry. Corrosion of metallic pipes can be caused by a variety of mechanisms, each of which requires a different solution. Determining which corrosion mechanism is at work is not a simple matter, because the resulting pipe damage looks similar for all of them. The failure to properly identify corrosion sources may produce prevention systems that are ineffective or do not last. For example, it is not effective to install an anode on a main that has a bacteriological corrosion problem. Similarly, an anode bag installed to reduce corrosion caused by a stray impressed current would be quickly used up and would provide only short-term protection. Also, polywrap does not protect a pipe from all corrosion types and may get damaged during the installation (Romer, 2005).

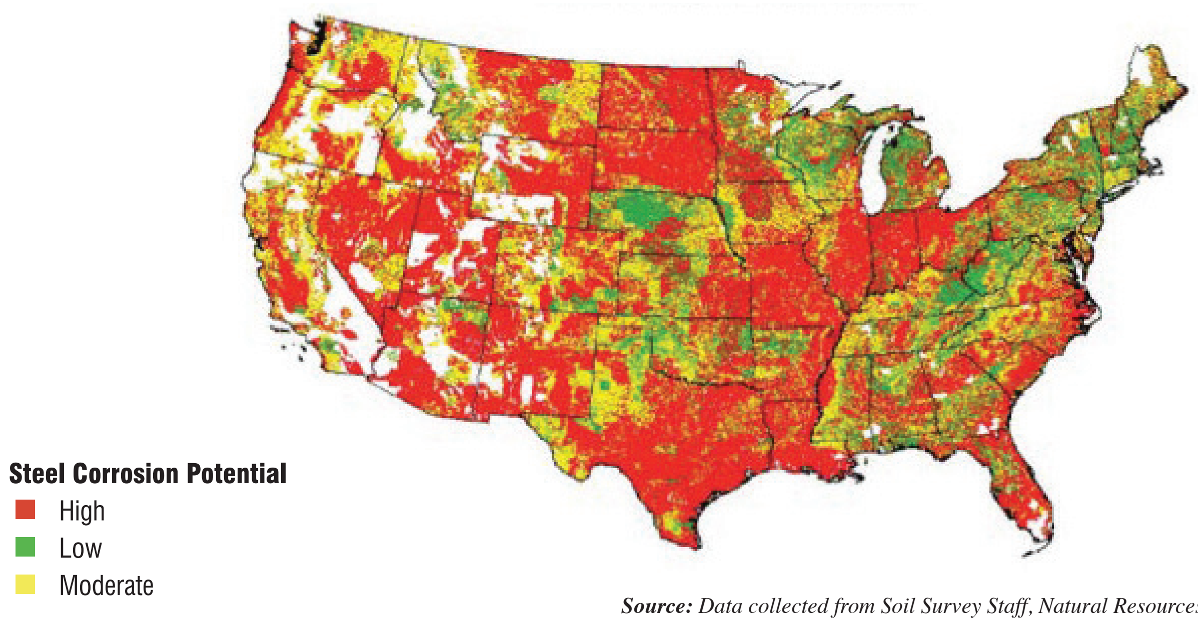
6.1. Effect of Corrosive Soils on Break Rate

The USDA Natural Resources Conservation Service provides results of soil surveys across the US. One of the aspects of the soil surveys is a "risk of corrosion" analysis that pertains to potential soil-induced electrochemical or chemical action that corrodes or weakens uncoated steel. The soil is rated as either "low," "moderate," or "high" based on measurements of moisture, particle size, acidity, and electrical conductivity. This is not a precise analysis and additional factors may be neglected. Nevertheless, it is a reasonable estimate of soil corrosiveness in lieu of better data. The USDA soil survey website (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx) allows the user to select an area of interest (AOI) and then produces a plot coloring low risk areas in green, moderate risk areas in yellow, and high risk areas in red. An overview of soil across the US is given in Figure 30.

Soil risk can change over a distance of a few blocks. This is illustrated in Figure 31 which shows a screen capture of soil risk colors inside the boundaries of a town in California. This town has all three regions present; low (green), moderate (yellow), and high (red). Soil analysis data is not available in regions with a light gray color.

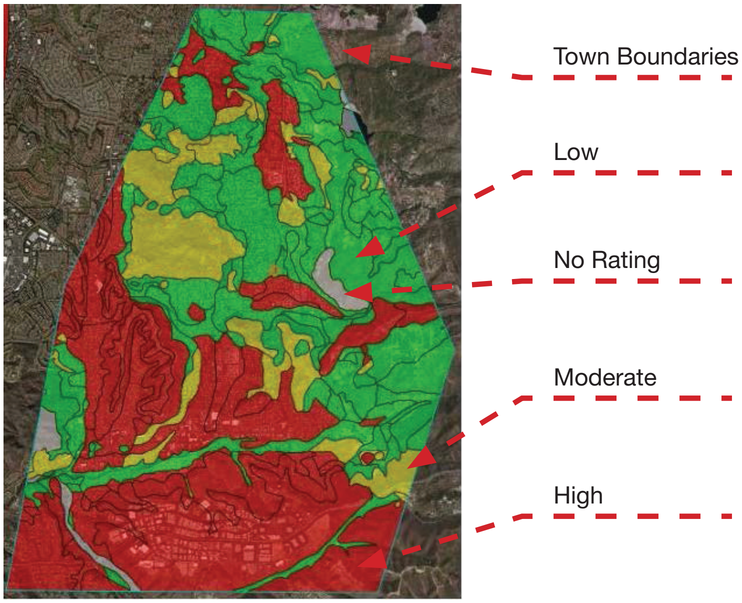
It was desired to relate water main break rates to soil corrosivity. Since most cities have a combination of low, moderate, and high regions, a numerical ranking was developed that provided an overall level of soil corrosiveness. To do that, pictures of each area served by the utilities in the basic survey were created. Next a program was developed that counted the number of reddish, greenish, and yellowish pixels in each photo. To provide a numerical ranking, pixels that were low risk were given a value of 1, moderate pixels were given the value 2, and high risk pixels were given the value 3. The pixel values were summed and then divided by the total number of red, yellow, and green pixels. The computed value is called a corrosion index. Cities with a corrosion index near 1 have low corrosion risk while those close to 3 have high corrosion risk. For the area in Figure 31, the computed corrosion risk was 2.1 or slightly above a moderate level.

FIGURE 30: US CORROSIVE SOILS MAP (CONUS POTENTIAL FOR STEEL CORROSION)



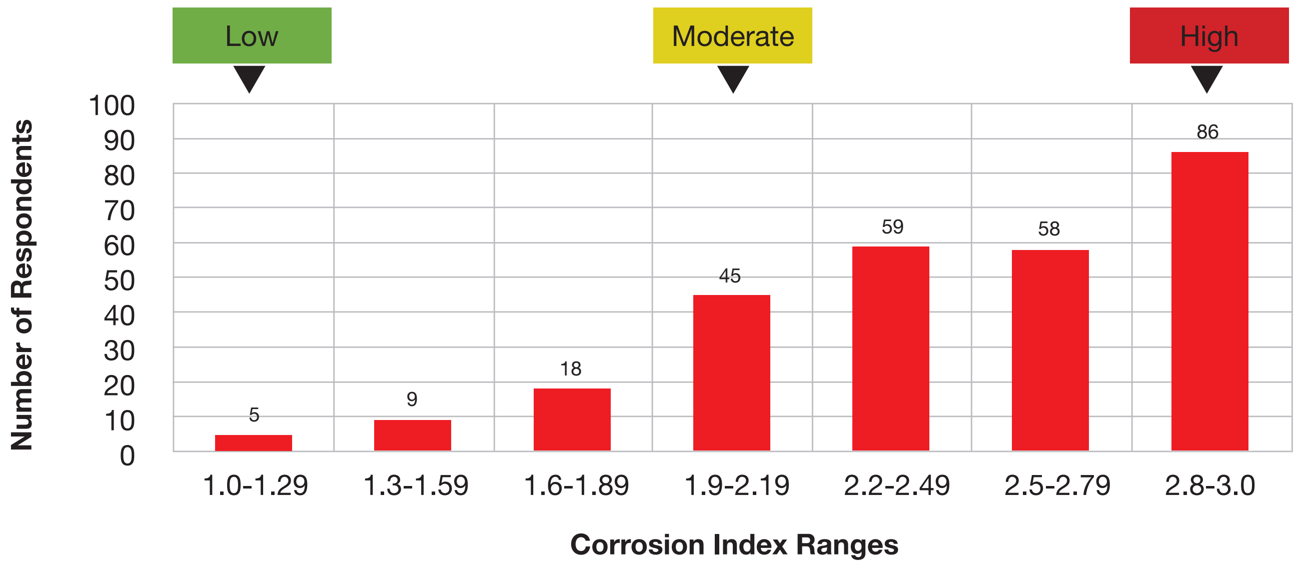
Source: *Data collected from Soil Survey Staff, Natural Resources Conservation Service, U.S. Department of Agriculture Soil Survey Geographic Database.*

FIGURE 31: CORROSIVE SOIL RISK PLOT



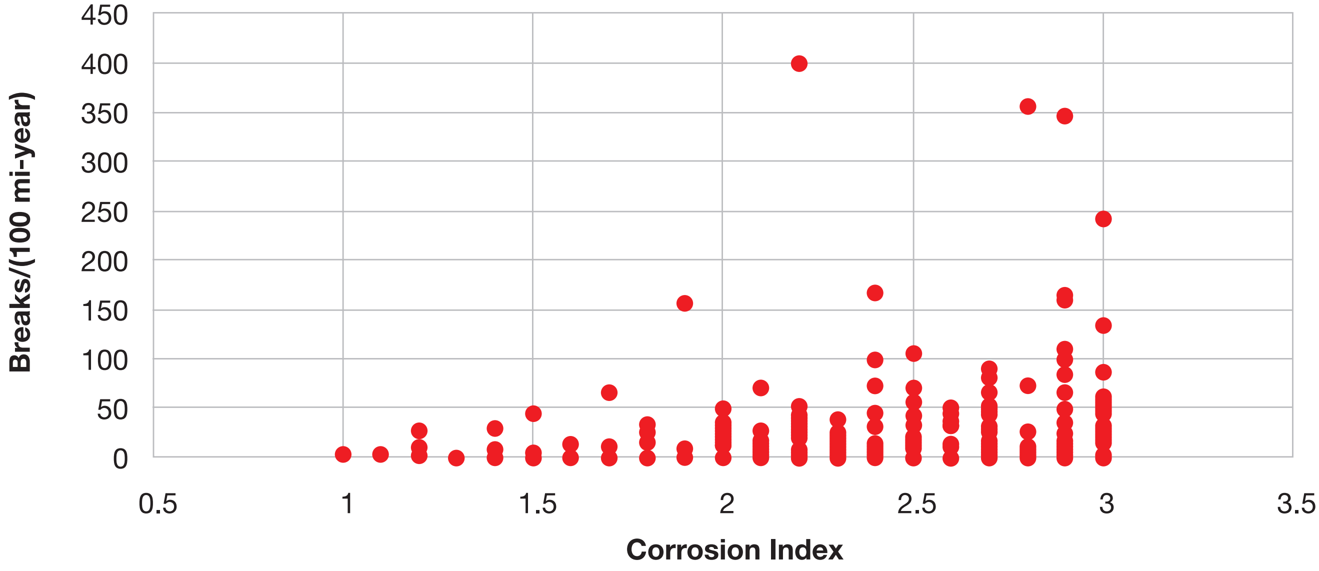
Corrosion index values were computed for 281 cities in the US. Some US cities had little or no data for the soil inside their boundaries preventing computation of a corrosion index. For analysis, the corrosion index values were broken down into seven ranges and the number of utilities in each range is plotted in Figure 32. The average corrosion index for all the US utilities in the basic survey was 2.4 or close to midway between moderate and high corrosion risk. That is, most utilities in the US have a moderate to high soil corrosion risk which is consistent with the detailed survey report that showed 75% of utilities have one or more areas with corrosive soils.

FIGURE 32: NUMBER OF UTILITIES VERSUS THEIR CORROSION INDEX



It is reasonable to expect break rates would increase when pipe is installed in corrosive soils. To examine this, plots were made of a utility's corrosion index versus break rate. Figure 33 illustrates this for cast iron pipe. There is a trend of higher break rates with increasing corrosion index, but the wide scatter in the data makes analysis difficult. The high break rates in Figure 33 are associated with small utilities that have a small amount of pipe. Consider a utility with 1 mile of cast iron pipe with 2 breaks during the past year. That would translate to a break rate of 200 breaks/(100 miles)/year. If that utility had no breaks the following year, the break rates drop to zero.

FIGURE 33: INDIVIDUAL UTILITY BREAK RATES FOR CAST IRON PIPE VERSUS THEIR CORROSION INDEX

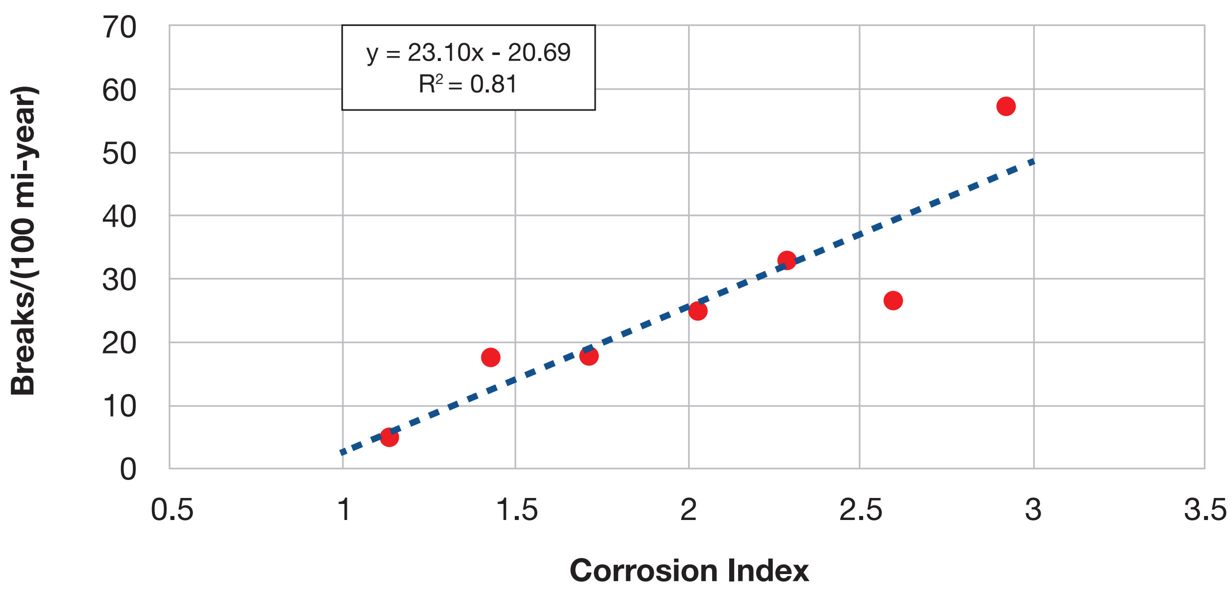


To get a realistic estimate of break rates, we need to add the number of breaks of a pipe type from several utilities and divide by the sum of the length of that pipe type to compute break rates. The corrosion index data was broken down into the same seven categories used in Figure 32. The results are listed in Table 7. The break rates versus corrosion index data are plotted in Figure 34 for cast iron pipe and Figure 35 for ductile iron pipe. The figures also contain a regression equation fit and a correlation coefficient. Correlation coefficients close to 1.0 indicates an excellent correlation and zero indicate no correlation. Both cast and ductile iron results in reasonably good fits to the data.

TABLE 7: BREAKDOWN OF CORROSION INDEX VALUES INTO SEVEN CATEGORIES

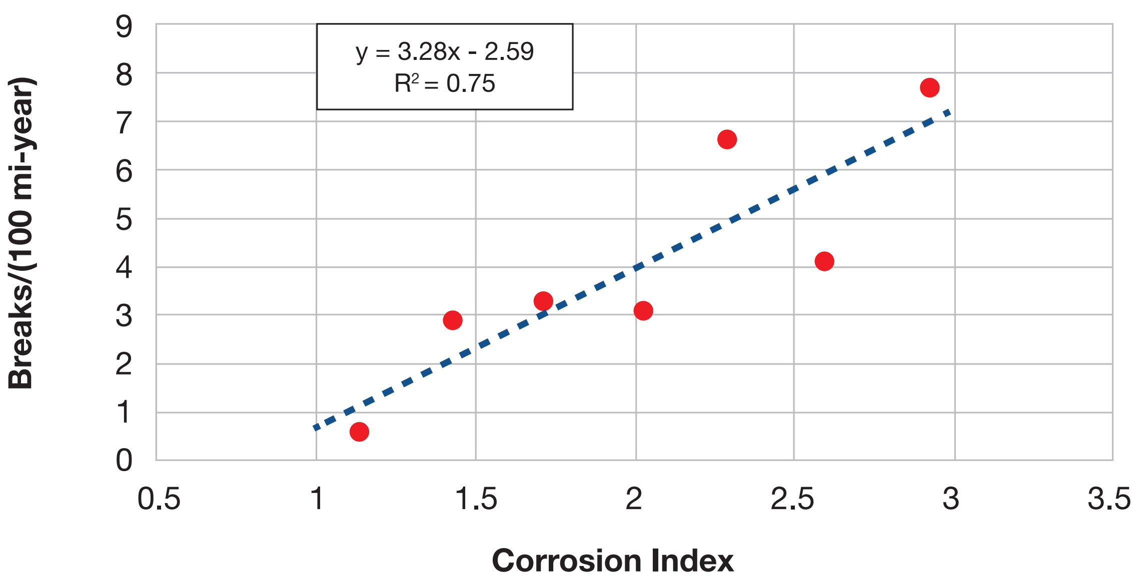
Category	Corrosion Index Range	# of Utilities	Average Corrosion Index	Break Rates (breaks/(100 mi-year))	
				Cast Iron	Ductile Iron
1	1.0 - 1.29	5	1.14	4.93	0.57
2	1.3 - 1.59	9	1.43	17.59	2.89
3	1.6 - 1.89	18	1.72	17.76	3.27
4	1.9 - 2.19	45	2.03	24.96	3.09
5	2.2 - 2.49	59	2.29	32.79	6.63
6	2.5 - 2.79	58	2.60	26.39	4.09
7	2.8 - 3.0	86	2.93	57.20	7.69

FIGURE 34: CAST IRON PIPE BREAK RATE VERSUS CORROSION INDEX



Using the equations in Figure 34 with x=1 for a low corrosion risk and x=3 for a high corrosion risk, one can show that a cast iron pipe in a high corrosion soil is expected to have over 20 times the break rate of one in a low corrosion soil. Similarly, ductile iron pipe in a high corrosion soil has over 10 times the break rate than one in a low corrosion soil. Very poor correlations were found for the other material types in this survey.

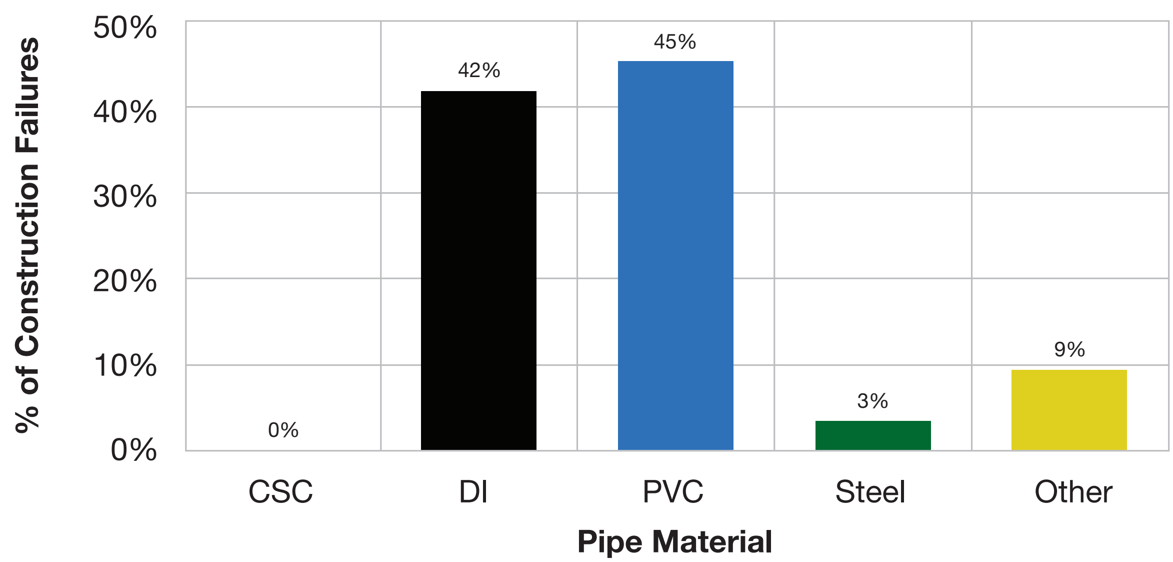
FIGURE 35: DUCTILE IRON PIPE BREAK RATE VERSUS CORROSION INDEX



7.0 Construction Related Failures

The detailed survey asked respondents to report failures related to construction activities. Figure 36 illustrates the percentage of total construction failure related to a particular pipe material. Ductile iron and PVC pipes have the majority of construction related failures at a nearly equal frequency. Figure 14 shows that DI and PVC are the two pipe materials that are also most commonly being installed today. This points to the need to improve construction practices for underground infrastructure regarding installation, location services and inspection.

FIGURE 36: PERCENT OF TOTAL REPORTED CONSTRUCTION RELATED FAILURES FROM THE DETAILED SURVEY



8.0 Condition Assessment Methods

The detailed survey asked if utilities utilize condition assessment methods to monitor the condition of their water mains. 45% of the respondents reported that they do use some kind of condition assessment process but normally limited this effort to larger diameter transmission system pipes. A large percentage of those reported using some visual assessment along with electromagnetic, acoustic, tapping coupons, and other means.

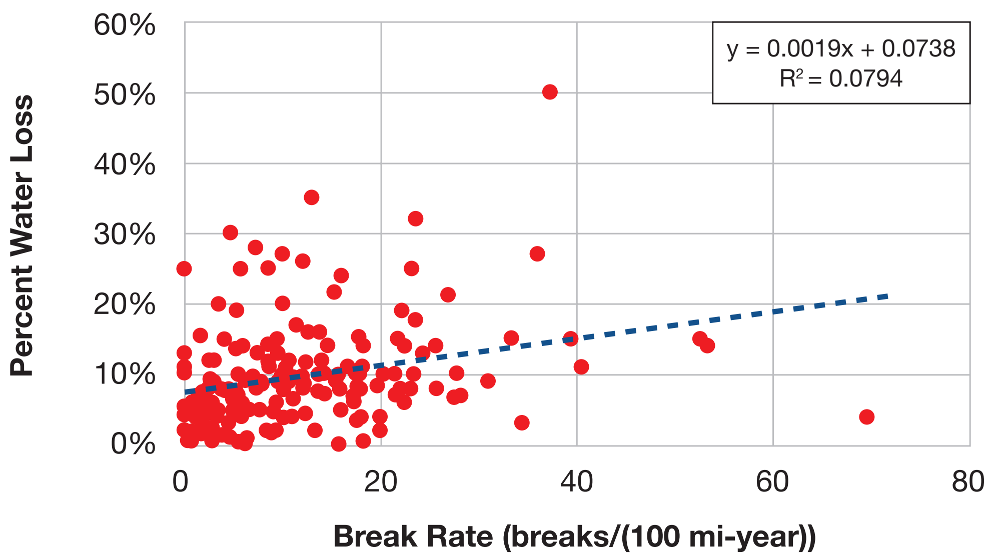
9.0 Water Loss Due to Leakage

Water loss due to leakage is reaching critical levels where in some cases 20% to 30% of water is leaking from water mains (New Jersey 101.5, 2017). The basic survey asked what percentage of water volume input to the system is water loss (due to leakage). A total of 201 utilities were able to provide a water loss value. The reported average leakage from the basic survey was 10% with a standard deviation of 7.7%. It is recognized that there are multiple ways to express and account for water loss (see Taylor, 2008). Water loss can be due to unbilled authorized consumption such as flushing water mains and fire-fighting, unauthorized consumption, and real losses due to leakage. The term non-revenue water comprises all of those losses. It was not anticipated that most of our respondents would have a recent detailed water audit that would provide just the water leakage amount. Thus, the 10% value may include authorized losses. For example, a recent analysis of utilities in Indiana which had a 100% participation rate showed that non-revenue water averaged 19% to 24% of the potable water supplied. The study also noted that a significant number of the state's water pipes are reaching the end of their useful lives (Indiana Finance Authority, 2017). More accurate audits of water utilization would be beneficial to understanding water losses and their cause.

It was postulated that there may be a correlation between water main break rates and water losses. Figure 37 plots individual overall break rates (breaks/(100 miles)/year) versus the reported utility loss rate. A linear regression to the data yields the equation in the figure which is illustrated in the dotted line in Figure 37. This plot omits a few small utilities with failure rates greater than 100 that skew the equation fit considerably. There is considerable scatter in the data and the correlation coefficient is very small indicating essentially no correlation. However, the trend of high leakage values with increasing break rates might be inferred. Perhaps if more accurate leakage values were used, a better correlation might be obtained.

Leaks can occur from pipe damage caused by third parties or corrosion in the pipes, as well as from joints in the distribution system. There are two ways in which water utilities can assess leakage. One way is through conducting a system-wide water audit, which estimates water consumption and water loss. The process enables water utilities to develop performance indicators to assess water loss, benchmark themselves with other water utilities, and set performance metrics. Another way in which water utilities can assess leakage is through conducting leakage investigations on all or part of the water system, using technologies to find the leaks. Many of these technologies can track the sound of a leak, allowing the utility to identify the exact point of the leakage and make needed repairs. There is also increasing use of various "smart technologies," typically tied to newer "smart meters," that can also aid in leak identification" (WaterRF, 2013).

FIGURE 37: PERCENT WATER LOSS VERSUS UTILITY BREAK RATES



10.0 Plans for Replacing Water Mains

The detailed survey respondents were asked questions about expected pipe life and pipe replacement and the answers are summarized in Table 8. The typical age of failing water mains had an average response of 50 years (up from 47 years in 2012) which is well below what most manufacturers say should be expected. The average expected life of a newly installed pipe is 84 years (up from 79 years in 2012). Given the quantitative nature of these questions, the typical age of failing water mains and expected pipe life have not changed significantly over the last six years. The basic survey asked if utilities have a pipe replacement program and 77% said they did. However, the detailed survey asked utilities if they had a regular pipe replacement program and only 58% of the respondents stated they did and of those that did, the average amount replaced each year was 0.8% of their total installed length. Respondents were asked for the percentage of their water mains that are beyond their useful life but lacked funds to replace them. The average response was 16% of water mains are beyond their useful life. In the 2012 survey the same question was asked and the response was 8.4%. This would indicate that the backlog of needed pipe replacement is growing.

It is of interest to compare these results with a study done by the EPA (EPA, 2002). The report classified water main pipe condition into six categories: “Excellent,” “Good,” “Fair,” “Poor,” “Very Poor,” and “Life Elapsed.” The study examined data for the years 1980 and 2000 and provided forecasted data for 2020. Figure 38 below is reproduced from the EPA report and estimates that the condition of 9% of pipes will be categorized as “Life Elapsed” and 23% as “Very Poor” by the year 2020. Of note is the projected growth in the “Very Poor” category during this period as shown in Figure 38. This is consistent with the results of this survey. The rapid rate of growth of pipes in the “Very Poor” category will make it very difficult for utilities to keep pace and replace them before they reach end of life or their “Life Elapsed” condition. An AWWA study (AWWA, 2012) echoes this trend as illustrated in Table 9. Table 9 shows aggregate costs to cover both replacement and growth in water mains in the USA.

TABLE 8: QUESTIONS ABOUT REPLACEMENT OF FAILING WATER MAINS

Questions	Average or Response
Typical age of failing water main	50 years
Expected life of new water mains	84 years
Percentage with plan to replacing water mains	77%
Percentage regularly replacing water mains	58%
Percentage of total water main length replaced annually	0.8%
Percentage of water mains beyond useful life but lack funds to replace (overall response)	16%

FIGURE 38: ASSESSMENT OF PIPE CONDITION WITH TIME (FROM EPA, 2002)

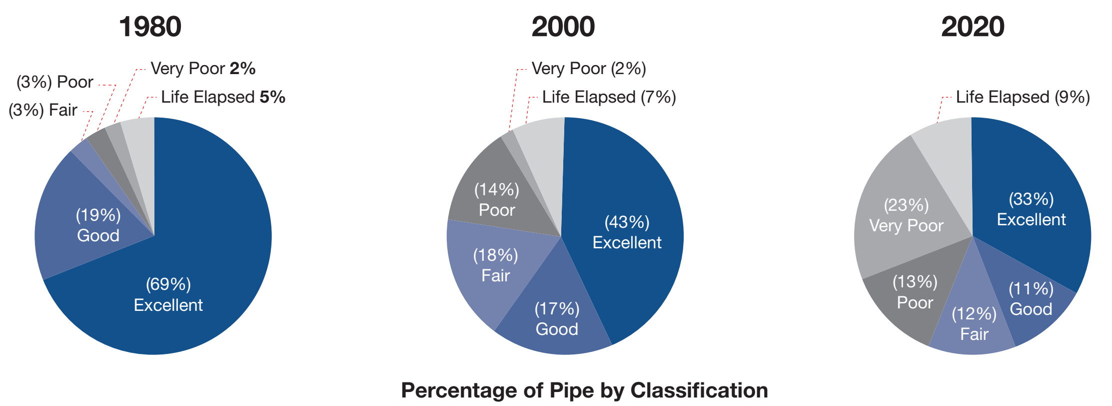


TABLE 9: AGGREGATE NEEDS FOR INVESTMENT IN WATER MAINS THROUGH 2035 AND 2050 BY REGION OF THE UNITED STATES (AWWA, 2012)*

	2011 - 2035 Totals			2011 - 2050 Totals		
Region	Replacement	Growth	Total	Replacement	Growth	Total
Northeast	$92,218	$16,525	$108,744	$155,101	$23,200	$178,301
Midwest	$146,997	$25,222	$172,219	$242,487	$36,755	$279,242
South	$204,357	$302,782	$507,139	$394,219	$492,493	$886,712
West	$82,866	$153,756	$236,622	$159,476	$249,794	$409,270
Total	$526,438	$498,285	$1,024,724	$951,283	$802,242	$1,753,525

** (2010 $M)*

Table 9 represents an estimate of pipe material investment (in millions of dollars) which is needed in each region based on an AWWA report (AWWA 2012). Investment is needed in two areas - replacement (where existing users pay for the pipe at the end of its useful life) and growth (where system expansion needs to occur due to population growth). These two drivers impact each region differently. Over the coming 40-year period, through 2050, these needs exceed $1.7 trillion. Replacement needs account for about 54% of the national total, with about 46% attributable to population growth and migration over that period.

America's water main investment needs impact the nation's regions in different ways. The South and West will face the steepest investment challenges but this will be paid for through growth, unlike the Northeast and other parts of the country facing population decline or only modest growth, which means it will be difficult for them to pay for the needed upgrades (AWWA, 2012).

The US Conference of Mayors 2013 report, "Municipal Procurement: Procurement Process Improvements Yield Cost-Effective Public Benefits," provides expert advice on developing a business case for pipe material selection when evaluating pipe replacement strategies. It reads:

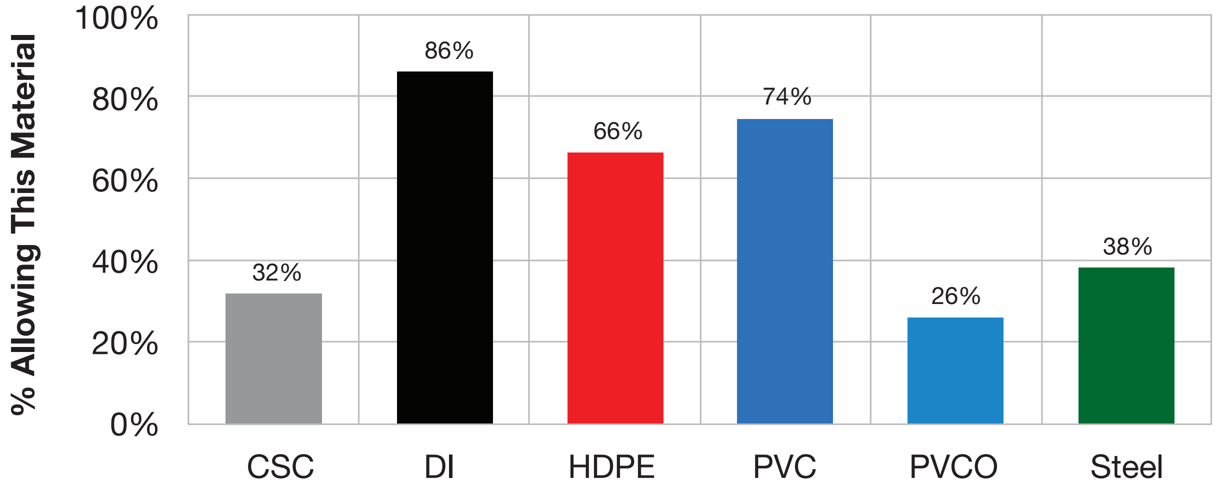
"The conventional approach to water pipe replacement decision making has been to merely replace the pipe with roughly the same product regardless of price, and based on manufacturer's recommendations. In fact, this replacement ideology and tradition is still heavily imprinted upon the thinking of even modern engineers. Communities in the United States, a century ago, used thick cast iron pipes that are now failing. The majority of these pipes are failing for one basic reason – corrosion. Failure to recognize this systemic performance problem in metallic pipes has allowed traditional procurement practice to make suboptimal materials procurement decisions…"

"An important step in effectively managing assets is to create an open procurement and selection process which allows for all appropriate materials to be considered and accurately and fairly compared. Any improvement in this area can represent a huge cost savings for rate payers considering the perpetual high cost of underground infrastructure replacement. Procurement habituation in pipe material consideration combined with a failure to take advantage of the open bidding process impedes competitive cost savings. Closed procurement processes lead to unnecessary costs, and may diminish public confidence in a local government's ability to provide cost effective services."

Source: US Conference of Mayors, 2013

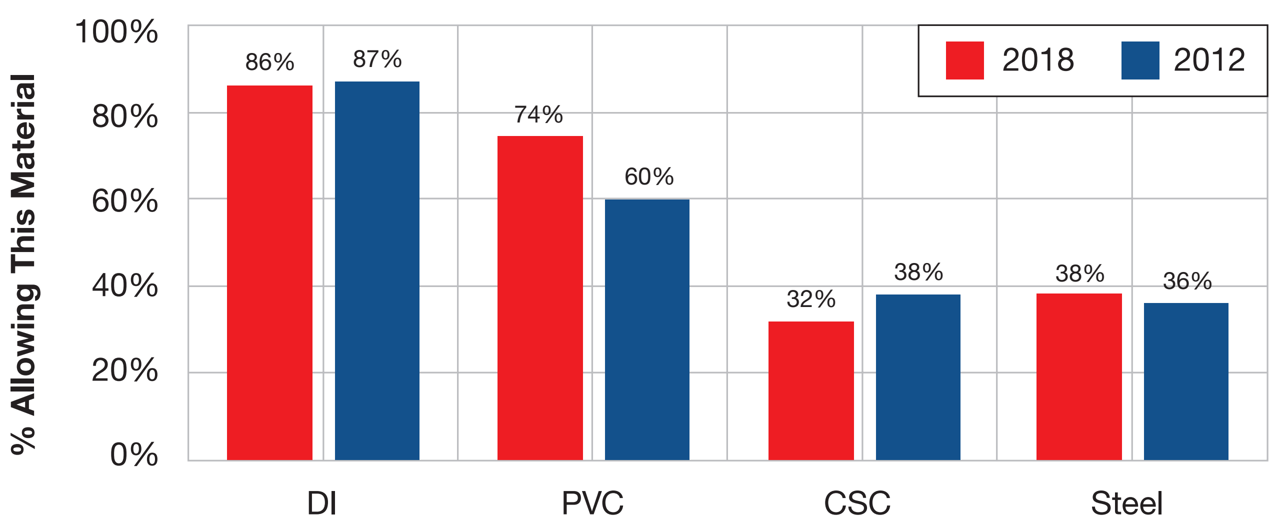
11.0 Approved Pipe Materials

FIGURE 39: RESPONDENTS ALLOWING INSTALLATION OF THESE WATER MAIN MATERIALS



The detailed survey also asked respondents what water main pipe materials are currently approved for use at their utility. Figure 39 illustrates the percentage of respondents that allow a particular pipe material to be installed. HDPE pipe at 66% allowance for use in water systems represents a high degree of acceptance for trenchless applications such as pipe bursting and directional drilling, whereas for open cut installations PVC and ductile iron pipe are the predominantly accepted materials (see Table 10). Figure 40 compares the pipe materials approved for use by utilities in the 2018 survey with the data obtained in the 2012 survey. Figure 40 shows a 23% increase in the acceptance of PVC water pipe by North American utilities since 2012. Specifically, PVC pipe approval among survey respondents increased from 60% of water utilities allowing its use in 2012 to 74% of utilities allowing its use in 2018. The number of utilities approving of ductile iron, concrete steel cylinder, and steel pipes for use in water systems remains essentially the same.

FIGURE 40: COMPARISON WITH 2012 SURVEY FOR ALLOWED MATERIALS



12.0 Preferences for Pipe Installation

The detailed survey asked respondents about experiences with three techniques of repairing, replacing, and installing water main pipes. They were relining deteriorated pipes, replacing pipes with a pipe bursting technique, and installation of new pipes using directional drilling. Table 10 summarizes their responses. The rating scale in Table 10 is from 1 to 5 with 1 being "Not Satisfied" to 5 being "Very Satisfied." Not many respondents have utilized pipe bursting, but an increasing number are looking at using both pipe relining and pipe bursting techniques. A majority of respondents have utilized directional drilling and are very happy with the results, but it is usually only used where open cut replacement is problematic. Open cut replacement remains the most commonly used method of pipe replacement.

TABLE 10: QUESTIONS ABOUT REPLACEMENT OF FAILING WATER MAINS

	Pipe Relining	Pipe Bursting	Directional Drilling	Open Cut
% of respondents that have used this technique	35%	10%	62%	100%
Most common materials installed	HDPE, CIPP, cement lining, epoxy	PVC, HDPE, DI	HDPE, PVC, DI	PVC, DI, CSC, Steel
Average Rating 1 to 5	3.8	3.8	4.4	4.7
% of respondents that will use this technique in the future	58%	44%	93%	100%
Comments	High cost, used when open cut not feasible, only for large diameter pipe, many not happy with it	High cost, useful in some situations, need to excavate for service lines	Worked well particularly for river and street crossings, more expensive	Standard installation method

13.0 Infrastructure Asset Management

Infrastructure asset management is an approach which can help utilities bring together the concepts, tools, and techniques to manage assets at an acceptable service level at the lowest life-cycle cost. Asset management practices applied to underground infrastructure help utilities understand the timing and costs associated with replacement activities. The knowledge gained from these efforts also helps in the development of effective pipe material selection through comparative financial analysis called "life cycle costing" as part of replacement strategies and funding plans. Understanding the longevity of a pipe improves the ability for management to make better infrastructure investment decisions with improved affordability results for customers.

Traditionally, there has been a lack of analysis which would combine both underground pipe performance and affordability. Existing practices tended to ignore the effect of environmental conditions on different pipe materials. Yet, every engineer understands how the complexity of underground infrastructure has increased along with the array of choices. The ability to change old habits and consider new materials requires additional analysis, and improved design and installation practices. This enhanced analysis of pipe design, selection and installation sets forth the longevity and life-cycle costs critically influencing water service affordability and sustainability for the next 100-200 years.

There have been many studies on water main failure rates in the US, Canada, Australia, and Europe over the last three decades. These studies mainly compared the number of pipe breaks by general pipe type and by length. While these studies have been very helpful to the water industry, the new driver has been the need to take into consideration the reduction of repair and replacement costs and improvement of water service affordability in underground pipe decisions. This new level of fiscal accountability and demand for transparent utility management back to their owners and stakeholders has increased the need for additional evidence to demonstrate the improved decision-making. Dig-up reports and pipe performance and longevity studies form the next body of evidence needed to corroborate water main break surveys and studies. The simple formula in a life cycle cost framework is essentially that "a pipe which has a long life at a low cost is the most affordable." Engineers are to make available every alternative that can answer the simple question of longevity and cost at each relevant point within the underground network providing service. A key issue in the life cycle cost framework is the expected life of a pipe.

Accurate pipe service and performance life estimates are critical to the effective management of underground infrastructure. This study provides accurate break data which can be used to improve life cycle costing analysis of water pipelines. Pipe break rate data is fact-based quantitative information which can help to precisely assess the durability, performance and longevity of pipe networks. Water main break rates are a critical decision making metric used in infrastructure asset management repair and replacement planning. Some of the data provided in this study, however, such as the average age of failing water mains and average expected pipe life, is qualitative in nature, i.e., subjective since it is based on perception rather than on quantitative data like break rates. While this can be helpful to utility officials, it lacks needed precision. A similar problem exists with the AWWA 2012 *Buried No Longer* report, which provides estimated service lives of different pipe materials based on a mixture of data which includes perceptions of service life versus quantitative data; and therefore is only of limited value for use in pipe material comparisons, asset management replacement planning, life cycle cost projections, and pipe service life estimates.

There is a large body of information on the importance of asset management and particularly as it relates to water systems. The reader is encouraged to refer to the following excellent documents that are available:

- *Asset Management for Water and Wastewater Utilities* https://www.epa.gov/sustainable-water-infrastructure/asset-management-water-and-wastewater-utilities
- *What is Asset Management?* https://www.michigan.gov/documents/deq/deq-ess-mfs-formsguidance-DWassetmngmntguide_426744_7.pdf
- *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials* http://www.sustainablesolutionscorporation.com/paper-unibell.html

13.1. Life Cycle Cost Analysis and Life Cycle Assessment

According to Dr. Sunil Sinha, Professor of Civil and Environmental Engineering and Director of the Sustainable Water Infrastructure Management (SWIM) Center at Virginia Tech, “In order to meet the important challenges of the 21st century, a new paradigm for the planning, design, construction, and management of water pipeline infrastructure is required, one that addresses the conflicting goals of diverse economic, environmental, and societal interests.” (Sinha, 2018) The new paradigm must include life cycle costs analysis (LCCA). LCCA helps in justifying the selection process of a particular system, product or activity based on the total life cycle cost rather than the initial design and installation cost. It enables a transparent selection process. Life cycle cost analysis helps in the identification of high cost areas during the life cycle of the asset and helps in minimizing the costs. Attributing costs to each phase in an asset’s life cycle and understanding the full cost to deliver services is important for determining costs for various service levels, maintenance and renewal decision making and rate setting. For example, in a model utilizing utility cost data, PVC was found to have an overall lower total cost of ownership because each cost element (initial pipe cost, installation cost, condition assessment cost, pipe repair cost, rehabilitation cost, replacement cost, indirect and recurring costs and disposal costs) for PVC pipe was lower than ductile iron pipe (Khurana, 2017).

Life cycle assessment (LCA) is a tool used to measure the environmental impacts of different products or systems during their life cycle. By measuring the environmental impacts throughout the life cycle, life cycle assessment provides a complete picture related to sustainability and helps in providing true environmental tradeoffs in the product selection. For example, in a 2017 study following an ISO framework, PVC was found to have a lower carbon footprint than ductile iron pipe (Sustainable Solutions, 2017).

Life cycle cost analysis provides justification from the economic point of view to make better investment decisions, whereas life cycle assessment provides justification related to sustainability issues. It is important to integrate both life cycle cost analysis and life cycle assessment to provide a holistic picture to the decision maker.

14.0 Conclusion

This comprehensive water main break report for 2018 surveyed a statistically significant number of utilities that have collected data on underground infrastructure. The study was focused on material usage in water mains across the USA and Canada and was successful in getting 281 participants to respond to a basic survey and 98 utilities to respond to a detailed survey. The central focus was to obtain average values for water main break rates across North America. These results were presented in Figure 20, but are repeated in Figure 41. PVC has the lowest break rate of all the pipe materials considered. Lower break rates mean lower costs and improved longevity. Compared with the 2012 survey results, break rates for asbestos cement and cast iron pipes have increased significantly and should therefore be cause for concern for policy makers and utility officials alike.

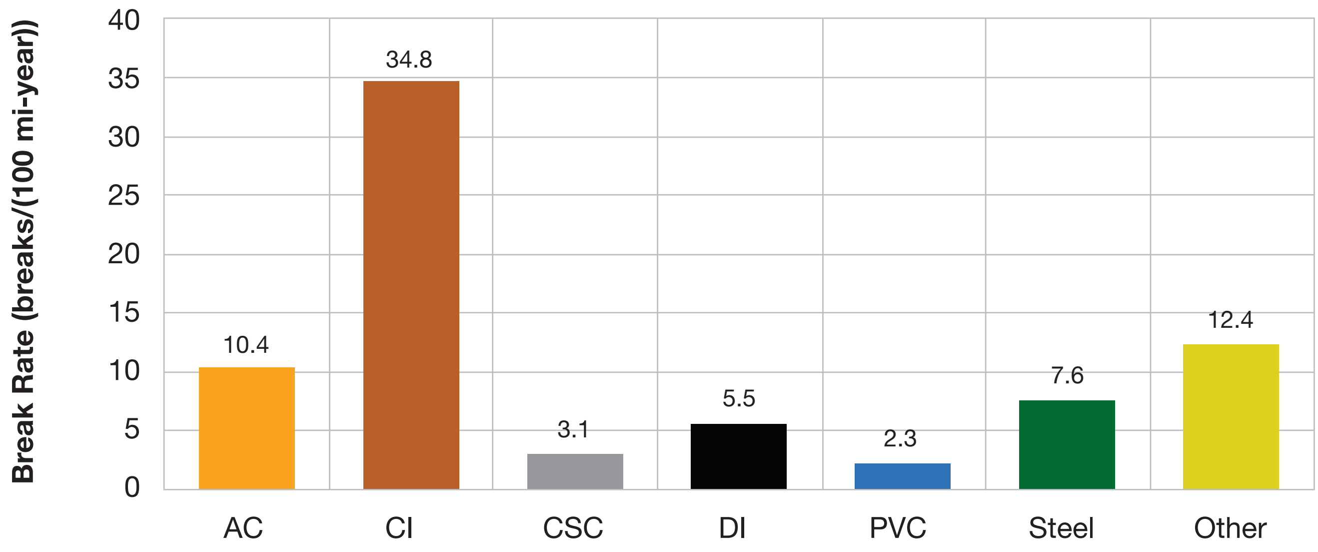
It is hoped that this study will be helpful to utility managers in comparing their experiences with the survey results and thereby make better decisions regarding possible changes in their asset management and procurement practices. Through greater understanding of the risks and issues surrounding the performance of our underground water infrastructure, utilities will be better able to manage our pipe networks and ensure their cost-effectiveness and sustainability.

14.1. Significant Results From This Study

Highlights of the water main break report also include:

- Pipe failure rate data for seven commonly used pipe materials
- Pipe break rates as a function of utility size
- Data on the distribution of pipe failures with pipe age for each material
- Data on the distribution of pipe failure modes for each material
- Analysis of the impact of soil corrosiveness on break rates
- The computation of a national corrosion index value for utilities
- A revised correlation of people served per mile of installed water main
- Average and maximum daily water demand correlations
- Current pipe material usage with a regional breakdown
- Pipe age and size distribution
- Average and maximum operation pressure data
- Most common pipe failure age and modes
- Percentage of utilities that allow installation of certain pipe materials
- Data on water main replacement rates and condition assessment
- Average water loss rate and correlation with break rates
- Preferences about pipe replacement methods

FIGURE 41: BREAK RATES OF EACH PIPE MATERIAL FROM THE BASIC SURVEY



14.2. Acknowledgements

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