Utah Water Research Laboratory
UtahStateUniversity

Professor Steven L. Barfuss, P.E.

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

December 2023

A Resource to Support Asset Management, Pipeline Renewal, and Replacement

MORE THAN **800** *WATER UTILITIES* **SURVEYED**

260,000 *PIPE FAILURES ANNUALLY*
11.1 BREAKS PER 100 MILES

20% OF PIPES NEED TO BE REPLACED
A $452 BILLION SHORTFALL

Utah Water Research Laboratory
UtahStateUniversity

Executive Summary

Deteriorating Infrastructure

Municipalities and the people they serve depend on pipe networks that provide safe drinking water. This piping is underground, out of sight, and often neglected.

Overall assessment of water infrastructure condition is not good. Using the US as an example:

- In 2009, the American Society of Civil Engineers (ASCE) issued a US report card and gave a D- to drinking water infrastructure.
- In 2017, the grade improved to a D.
- In 2021, the grade was raised to a C-, better but still not good.
- Utilities are currently losing 11% of their water to leakage.
- Pipe life estimates of 75 to 100 years contrast with an average replacement schedule of about 200 years (ASCE, 2017).

The American Water Works Association (AWWA) has also reported on water main replacements in the US. In the annual AWWA State of the Water Industry Report, renewal and replacement of aging water and wastewater infrastructure was listed as the top concern (AWWA, 2017). This has remained a primary issue for utilities nationwide for the last five years (AWWA, 2023).

Deteriorating water mains are threats to the physical integrity of distribution systems, causing adverse effects on flow capacity, system pressure, and water quality (Grigg, et al., 2017). In addition to maintenance requirements and economic impacts, consequences of a broken water main include local flooding, interruption of water delivery, and damage to roads and private property. These outcomes also negatively affect a utility's customer satisfaction.

Utility data clearly indicate that the integrity of water pipelines in the US and Canada continues to deteriorate as the infrastructure ages. Among the many indicators of aging pipes, break rates are the most significant.

Asset Management

Utilities can use asset management to facilitate water infrastructure planning and pipe replacement decision-making. The goals are to control operating costs, reduce service level impacts, and minimize health risks to customers.

Water main break rates are the most important indicator for quantifying failing underground pipelines. For this reason, break rates are a critical factor in asset management decision-making.

Break rates for each utility can vary from year to year and even seasonally. Over time, however, break rates for specific pipe materials are consistent. This consistency is one reason why break-rate information is so important.

This comprehensive study of water main break rates uses input from 802 utilities to compile an accurate data set for making pipe-replacement decisions. This data set is large enough to be valid for asset management decision-making by providing information on the characteristics of aging pipe infrastructure.

2023 Report

The water main break rates presented in this report are based on pipe characteristics and failures reported by the utilities that responded. Utilities were given the opportunity to respond to either a basic or detailed survey which gathered information on water pipe materials, pipe diameters, pipe age, system operating characteristics, and water main failures. The report discusses the importance of water main break data in the context of asset management planning.

Utah State University (USU) has published two similar studies (Folkman, 2012; 2018). This 2023 report references the previous studies to analyze changes over time.

Highlights of the study:

- Break rates of all pipe materials remain consistent when compared to previous USU studies.
- The current study received a wide distribution of responses across utility sizes.
- In the past five years, total miles of asbestos cement and cast iron pipes have been reduced, most likely being replaced with materials such as ductile iron and PVC.
- The replacement of asbestos cement and cast iron pipe is creating a shift in predominant pipe materials in several regions.
- Pipe performance is impacted by soil corrosivity.
- There is a significant correlation between water main breaks and pipe material as well as diameter.

Major Findings

The following section provides key metrics and a summary of the major findings that are listed in chronological order in the report. More details of each finding can be found in the respective sections.

1. Data for Almost 400,000 Miles of Pipe

The 802 basic survey respondents included 399,812 miles of water main pipe, which represents 17.1% of the estimated total length in the US and Canada. Water main break information came from 778 participants who provided data over a 12-month period covering 363,412 miles of pipe; additionally, 690 participants provided main break data over a 5-year period covering 317,889 miles of pipe. Utilities providing break data serve 30.1% of the total population of the US and Canada, providing a significant basis for analysis.

2. Large Data Set Provides Increased Accuracy

The sample size for this study is almost three times larger than the previous 2018 USU water main break study. In terms of pipe mileage, this is the largest study in the US and Canada of its kind. Previous studies have been based on much smaller sample sizes and consequently may have reduced accuracy in data reporting.

3. An Increased Number of Small Utilities (Less than 500 Miles of Water Mains) Responded to the Current Survey

The proportion of small utilities in the study has increased from 68% in 2018 to 75% in 2023. This provides a better representation of installed piping in all utility sizes across the 2.33 million miles of pipe in the US and Canada.

4. Average Population Served per Mile of Pipe is 287 People

The water industry has assumed 325 people are served per mile of water distribution pipe in urban areas. This survey finds a new metric of 287 people served per mile of pipe.

5. Four Types of Pipe Materials Make Up 90% of Water Mains

In the US and Canada, 90% of installed or in-service water mains are a combination of PVC at 29%, ductile iron at 27%, cast iron at 23%, and asbestos cement at 11%. The remaining materials each represent less than 3%.

6. Cast Iron and Asbestos Cement Pipe Inventory Reduced by Almost 8%

In 2018, cast iron and asbestos cement pipe together represented 41.1% of all installed pipes in the US and Canada. In 2023, the combined length for these materials is 33.3%, a reduction of 7.8% in the reported pipe inventory. During the same period, reported PVC pipe length increased by 7.0% and ductile iron remained approximately the same.

7. Pipe Material Inventory Differs by Region

Material usage varies significantly across geographic regions, suggesting that selection of pipe materials is often based on preference. For example, the upper northwest and eastern half of the US (Regions 1, 6, and 8 in Figure 3) is predominantly comprised of either cast iron or ductile iron pipe, while PVC pipe is the most used in Regions 3, 4, 5, 7, and 9. The most common pipe material in Region 2 is asbestos cement.

8. Study Shows Significant Pipe Material Trends over Time

Comparisons of predominant pipe materials from the 2012, 2018 and 2023 USU studies showed significant trends. Regions 3, 4, 5, 7, and 9 are clearly trending toward the use of PVC and Regions 1 and 6 are trending toward the use of ductile iron. Asbestos cement remains the most common pipe material in Region 2 and cast iron in Region 8.

9. Study Illustrates the Advanced Age of Cast Iron and Asbestos Cement Pipes

Of the reported cast iron pipe, 86% is over 50 years old. Similarly, 41% of asbestos cement pipe is over 50 years in age. Interestingly, break rates for both materials have decreased since 2018 (cast iron by 18% and asbestos cement by 1%). It appears that since cast iron and asbestos cement pipes are no longer manufactured and are reaching the end of their expected lives, these legacy pipe materials are being proactively replaced.

10. Approximately 86% of the Water Main Inventory is 12-Inch Diameter or Smaller

This study found that 68% of water mains are 8-inch diameter or smaller and that 10- to 12-inch sizes add another 18%. Based on EPA's estimate of 2.2 million miles of water pipe in the US, these sizes equate to roughly 1.9 million miles of pipe. Similarly, using Statistics Canada's estimate of 133,000 miles of water pipe, it is estimated that roughly 115,000 miles of pipe in Canada is between 3 inches and 12 inches in diameter.

11. Utilities Reported Operating Pressures

The basic survey reported an average operating pressure of 71 psi and an average maximum pressure of 120 psi. Similar pressures were reported for the 2018 USU study.

12. Average per Person Usage is 143 GPD with Peak Demand Factor of 1.6

From the detailed survey, average water demand was 143 gallons per day per person, with a peak demand of 247 gallons per day per person. In the 2018 survey, average demand was 137 and peak was 251.

13. Estimated Average Water Loss to Leakage is 11%

A total of 530 utilities provided estimates of water loss due to leakage. The average value was 11%, compared to 10% in 2018.

14. Overall Break Rates Have Decreased 20% in the Past Five Years

While break rates have remained consistent for most pipe materials over the last decade, overall water main failures between 2018 and 2023 decreased by 20% from 14.0 to 11.1 breaks/(100 mi-yr). This decrease seems to correlate with reduced inventory of cast iron and asbestos cement pipe (both of which have the highest failure rates).

15. About 260,000 Water Main Breaks Occur Annually

The US and Canada experience about 260,000 water main breaks annually, which represent approximately $2.6 billion per year in maintenance and repair costs.

16. PVC Pipe Has the Lowest Failure Rate Among Common Distribution Pipe Materials

When the most common pipe materials (cast iron, ductile iron, PVC, and asbestos cement) were compared, PVC had the lowest overall failure rate and cast iron had the highest, at 2.9 and 28.6 breaks/(100 mi-yr), respectively.

17. Break Rates Do not Correlate to Utility Size

Similar failure rates occurred for utilities of varying sizes (by miles of pipe). These rates range from 9.4 to 12.3 breaks/(100 mi-yr).

18. Distribution Pipes Fail Five Times More Often than Transmission Mains

Distribution pipes (12 inches and smaller), which represent 86% of all water mains in the US and Canada, have overall failure rates of 13.3 breaks/(100 mi-yr) compared to transmission mains at 2.2 breaks/(100 mi-yr). Some materials have significantly large differences in break rates between transmission and distribution mains.

19. Target Break Rate for Pipe Replacement is 21 Breaks/(100 mi-yr)

The average target break rate for pipe replacement was reported at 21 breaks/(100 mi-yr). However, most respondents indicated that they do not have a specific target.

20. Utilities Consistently Report Having Corrosive Soils

A total of 75% of utilities surveyed reported one or more areas with corrosive soil conditions. This is consistent with the 2012 and 2018 USU reports and USDA's soil corrosivity map. The average utility has a moderate to high corrosion risk, demonstrating the importance of corrosion mitigation for water pipelines.

21. Most Utilities Employ Methods of Corrosion Protection

A total of 73% of survey respondents reported using some form of corrosion protection, with polyethylene encasement (polywrap) the predominant method. Other methods reported were zinc coating, bonded coatings, and cathodic protection.

22. Ductile Iron Pipe Has Over Six Times More Breaks in Highly Corrosive Soils

Analysis of soil corrosivity shows that ductile iron pipe in highly corrosive soil has over six times the break rate of ductile iron in low corrosive soil.

23. Construction-Related Failures Are the Same for Both Ductile Iron and PVC Pipes

Due to their predominant use, ductile iron and PVC pipe experience the most construction-related pipe failures, with both being similarly affected.

24. Average Expected Life of Installed Pipe is 78 Years

Average expected life of currently installed pipe is 78 years, compared to 84 years in 2018 and 79 years in 2012. Given the qualitative nature of this survey question, the typical age of a failing water main and expected pipe life have not changed significantly in the last decade.

25. Average Age of Failing Water Mains is Approximately 53 Years

In 2012 and 2018, the average ages of failing water mains were reported as 47 and 50 years, respectively. In this study, the average age of failing water mains is 53 years. Notably, 33% of water mains are over 50 years old, representing approximately 770,000 miles in the US and Canada.

26. Approximately 20% of Installed Water Mains Have Not Been Replaced Due to Lack of Funds

A total of 19.4% of installed water mains are beyond their useful lives, representing approximately 452,000 miles of pipe. In 2012 and 2018, the percentages were 8% and 16%, respectively. This indicates a lack of funding for critical water infrastructure estimated at $452 billion.

27. Almost 70% of Utilities Have a Pipe Replacement Program

The survey showed that 69.9% of utilities have a pipe replacement program. This confirms that utilities are making a concerted effort to actively replace aging infrastructure and failing water mains.

28. Acceptance of Ductile Iron Pipe Has Decreased and Steel Has Increased

The percentage of utilities approving ductile iron has decreased from 86% in 2018 to 78% in 2023, a reduction of 8% in reported acceptance. During the same period, steel pipe has shown a 6% increase in percentage of acceptance from 38% to 44%. Approval rates for other pipe materials have remained approximately the same.

29. Open-Cut Remains the Primary Pipe Installation Method

Survey results indicate that 93% of utilities use open-cut pipe installation/replacement methods. Approximately 65% of utilities use directional drilling. Pipe relining and pipe bursting are used at 32% and 18%, respectively.

30. Approximately 44% of Utilities Conduct Condition Assessment of Water Mains

Condition assessment is typically part of an asset management program. A total of 43.5% of utilities perform some form of regular condition assessment.

> Over 800 utilities participated in the study, representing 30.1% of the population and 17.1% of the estimated total length of water mains in the US and Canada.

1.0 Introduction

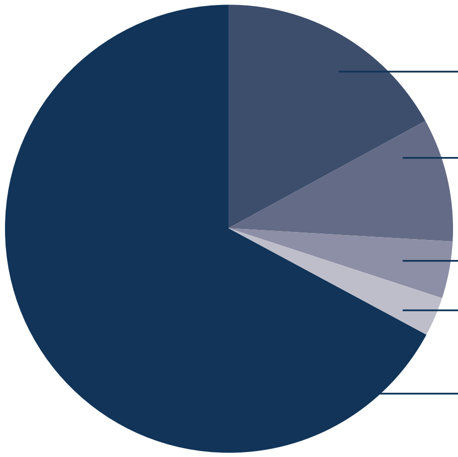
According to the EPA's Drinking Water Infrastructure Needs Survey and Assessment (DWINSA), the estimated 20-year national drinking water need is $625 billion (EPA, 2023). Figure 1 clearly shows that the total anticipated cost to maintain underground distribution and transmission pipelines, at $420.8 billion, represent more than 60% of the water industry's total funding requirements. Similar proportional costs are anticipated for Canada. This funding requirement for the next 20 years is necessary to provide safe drinking water to the public and includes installation of new drinking water pipelines, rehabilitation, and replacement of existing buried pipe infrastructure.

This report directly addresses AWWA's primary concern, which is aging infrastructure and funding. The results of the survey and its findings will provide utility and asset managers with the necessary information to make better financial and performance decisions with their piping materials to improve the sustainability and affordability of their water systems.

1.1 Using Break Rates to Establish Replacement Cycles

According to a Water Research Foundation study, 75% of water utilities cited pipe breaks or leaks as a key criterion in pipe replacement decisions (Grigg, 2007). Due to financial challenges facing water utilities, break rate data from this study are essential in making decisions about pipe maintenance and replacement. *Decades old drinking water infrastructure systems, declining water use, costs of regulatory compliance, and stagnant federal funding* [except for the recent infrastructure funding programs] *has resulted in many water utilities struggling to fund the cost of operations and maintenance of these systems* (ASCE, 2021). Repairing and replacing aging infrastructure, financing capital improvements, and ensuring cost recovery are regularly identified as key issues in AWWA's State of the Water Industry surveys. *These issues continue to be important because many water and wastewater systems built and financed by previous generations are approaching or have exceeded their useful lives [and] are now facing a critical need for renewal and replacement* (AWWA, 2023).

FIGURE 1: TOTAL 20-YEAR NEED BY INFRASTRUCTURE PROJECT CATEGORY (2021 DOLLARS)



Source: EPA, 2023

The lowest life cycle cost, which includes pipe performance, maintenance, monitoring, repairs, and replacement, should be considered. According to a US Conference of Mayors report, pipe materials with low main breaks have lower cost of ownership and address both affordability and sustainability concerns associated with aging water infrastructure. *Spending on pipes can vary widely, and there is an expectation that a large replacement cost is imminent as existing pipes, especially cast iron* [and asbestos cement] *pipe, approaches the end of its design life.... Water and sewer system managers regularly consider whether to repair or replace pipes. If repair, how, where, and for what linear measure? If doing a replacement, also consider what pipe material has the best value* (Anderson, 2018).

The same report pointed out that pipe main failures can be a health concern, stating: *potential for health impacts increases when pipes fail, and sometimes when treatment and/or biofilm protocols are changed or modified. Pipe failure can result in the introduction of waterborne parasites and inorganic elements to the tap* (Anderson, 2018).

The mayors' report lists other factors that should be considered when replacing pipe in addition to complying with required standards. It states: *Why are pipes failing despite established standards for performance? Standards describe the mechanical performance necessary for an application, or in the case of the ANSI/NSF 61 standard, that the pipe complies with all health regulations for materials that contact drinking water. But pipe standards do not specify what pipe to procure or the environmental factors that may cause a pipe to fail prematurely such as the local soil corrosivity, seismic conditions, or use. For existing pipe, age is also an important factor.* (Anderson, 2018).

This report can help utility managers make decisions about pipe materials, the installation environment, and pipe performance. As older pipe systems are replaced, it is important to consider break rates as part of asset management.

2.0 The Survey Instrument

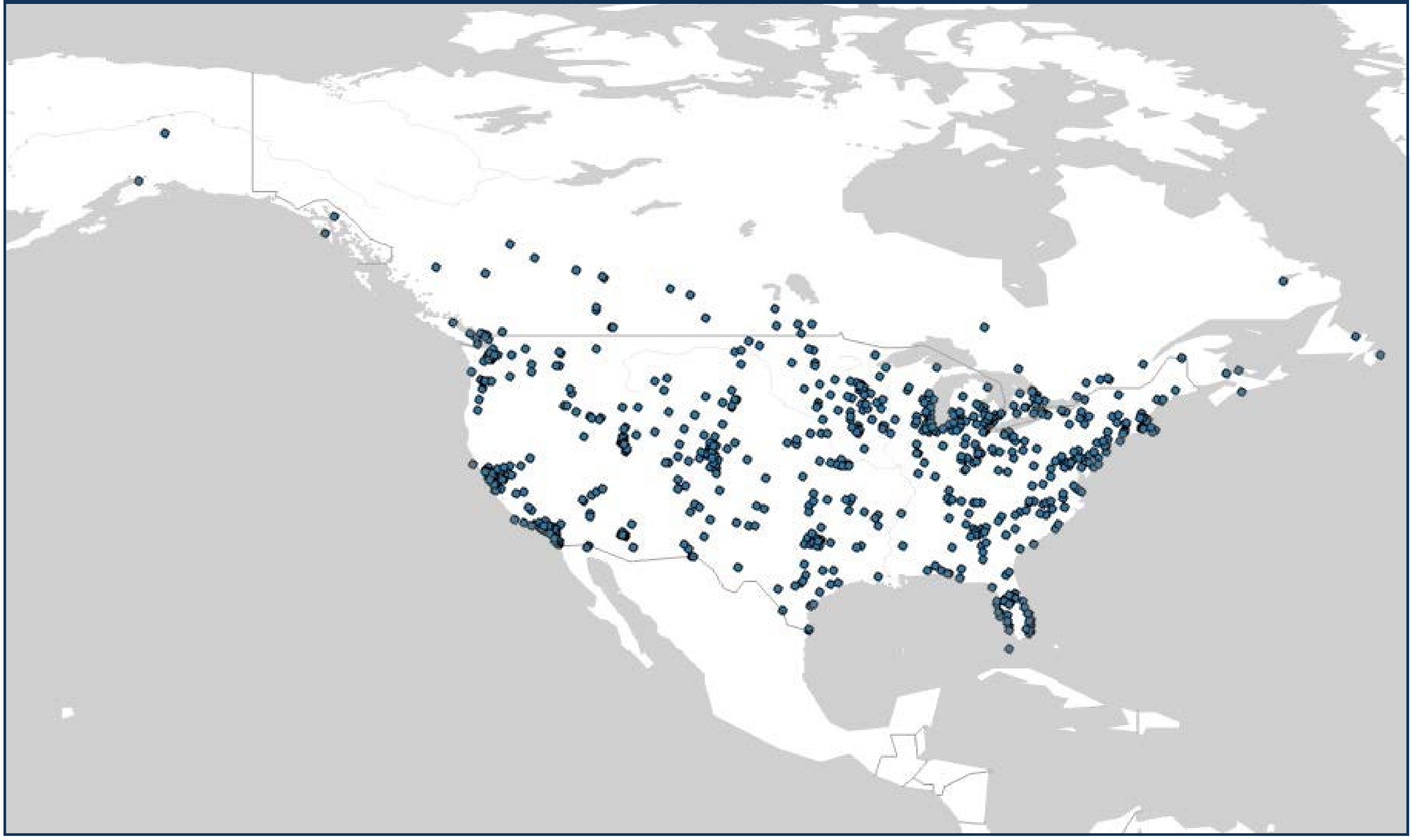
2.1 Methodology

During 2022, Utah State University conducted a survey of utilities across the US and Canada to obtain data on water main failures of water supply systems. The study comprised two parts: a basic survey and a detailed survey. The primary 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. This effort focused on water supply mains that excluded pipes with diameters less than 3 inches. Gravity and force main sewers were also excluded. One of the goals of both the basic and detailed surveys was to look at pipe material performance at a snapshot in time and to track how various factors affect failure rates. The focus of the detailed survey was to obtain additional information such as: expected service pipe life, size and age distribution of the different pipe materials, and corrosion protection methods.

Although the surveys were collected in 2022, this report refers to the results as the "2023 study" to correspond to when the data were tabulated and analyzed. This included data quality control, follow-up phone calls, and data validation. The basic survey participants were asked for data from the previous 12-month period (2021 – 2022) as well as a previous 5-year period (2017 – 2022). A total of 802 basic survey responses were received from 49 of the 50 US states and all 10 Canadian provinces (Figure 2). Of the 802 utilities:

- 791 provided pipe distribution data.
- 778 submitted failure data over 12 months.
- 690 included failure data over 5 years.
- 172 responded to the detailed survey.

FIGURE 2: GIS MAP SHOWING UTILITY RESPONDENTS THAT PROVIDED GEOREFERENCED DATA



For this study, the US and Canada were divided into nine regions (Figure 3). Basic survey respondents were categorized according to region and utility size based on total pipe miles. The study represents 399,812 miles of pipe as shown in Table 1. This report provides results from both basic and detailed surveys and draws from other relevant industry sources.

2.2 Objectives of the Data Analysis

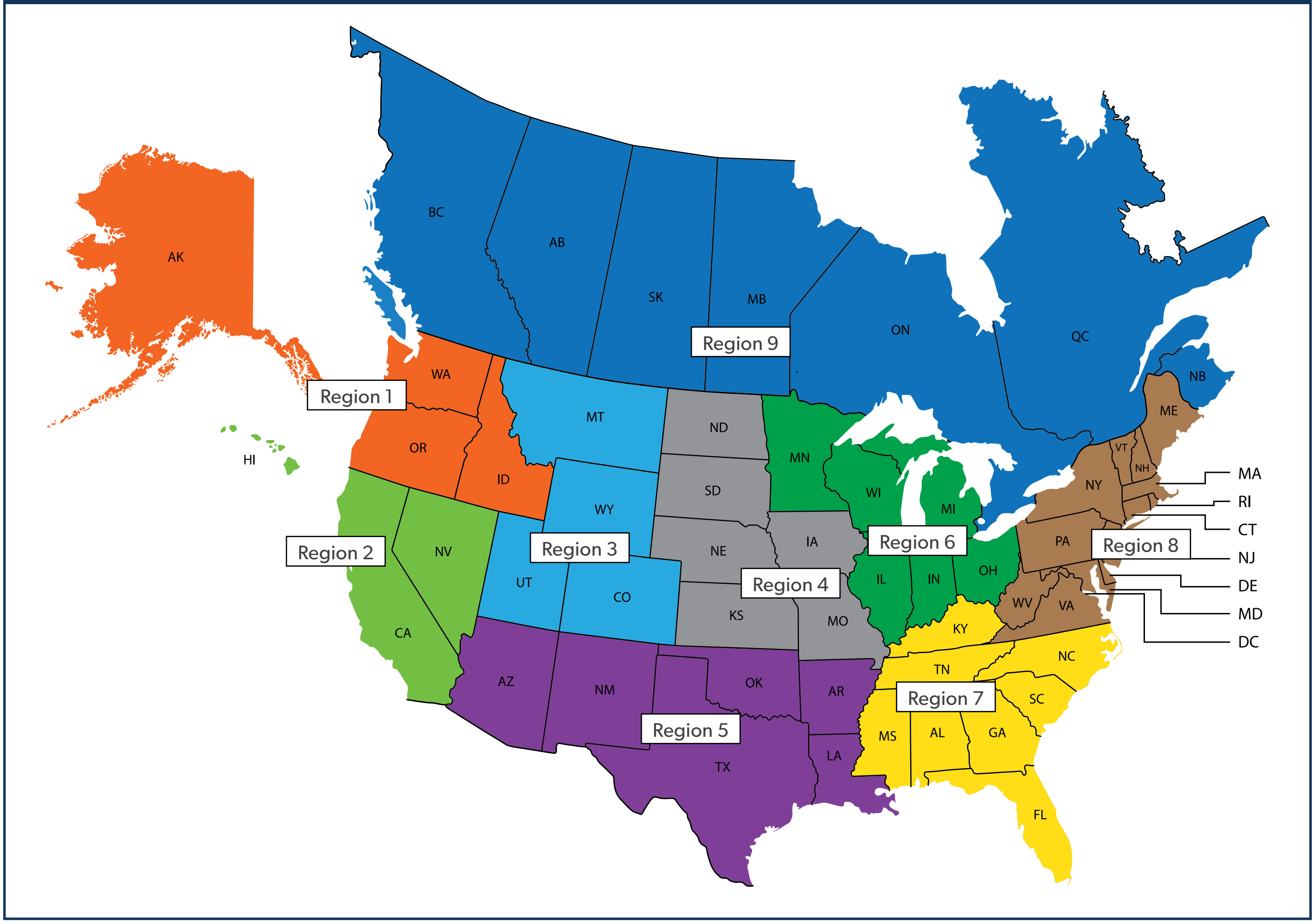
The large data set from the survey respondents allowed the researchers to develop a comprehensive understanding of the following:

- Pipe material trends and break rates between the 2012, 2018, and 2023 Utah State University studies
- Age and size distribution of pipe in water utilities
- Pipe failures over time by material type and diameter
- Most common pipe failure modes
- The extent of corrosive soils
- The influence of corrosive soils on break rates
- Corrosion prevention methods used
- Expected life of new pipe
- Condition assessment methods
- Allowed pipe materials
- How break rates are affected by pipe diameter
- Typical and maximum water pressure in water mains
- Average and maximum daily water demand

TABLE 1: SURVEY RESPONDENTS WITH WATER MAIN DISTRIBUTION DATA BY REGION

	Basic Survey			Detailed Survey		
Region	**Respondents**	**Miles**	**Population**	**Respondents**	**Miles**	**Population**
1	55	18,324	6,338,698	12	4,993	1,240,780
2	96	58,962	21,108,534	17	15,795	6,072,746
3	82	21,001	6,519,209	17	7,912	3,287,568
4	64	34,812	4,559,307	19	11,224	1,887,156
5	83	65,000	16,142,968	25	35,962	8,880,595
6	160	51,789	11,291,816	29	13,153	3,745,325
7	96	67,813	15,270,961	16	21,990	6,646,445
8	80	50,057	14,021,005	18	11,378	3,480,980
9	75	32,054	17,353,584	19	11,216	9,691,901
Total	791	399,812	112,606,082	172	133,623	44,933,496

FIGURE 3: REGIONS USED TO REPORT SURVEY RESULTS



2.3 Survey Regions

To facilitate direct comparisons with previous USU surveys, nine survey regions in the US and Canada were utilized (Figure 3). The regions are used to indicate geographical variations. In total, 791 utilities provided pipe distribution data. Table 1 lists the number of respondents with pipe material distribution data, the miles of pipe, and the population served in the basic and detailed surveys from each region.

Respondents were asked to report the length of water mains in their system but to not include gravity sewer pipe, sewer force mains, or water pipes less than 3 inches in diameter. Figure 4 illustrates the miles of water mains reported in the basic and detailed surveys on a regional basis. A total of 399,812 miles and 133,623 miles of pipe was reported in the basic and detailed surveys, respectively. Figure 5 illustrates the number of respondents from each region. Due to the large number of utility responses and the widespread representation and distribution from all regions shown in Figure 2, this is the most comprehensive water main break study to date.

FIGURE 4: MILES OF PIPE FROM EACH REGION FOR THE BASIC AND DETAILED SURVEYS

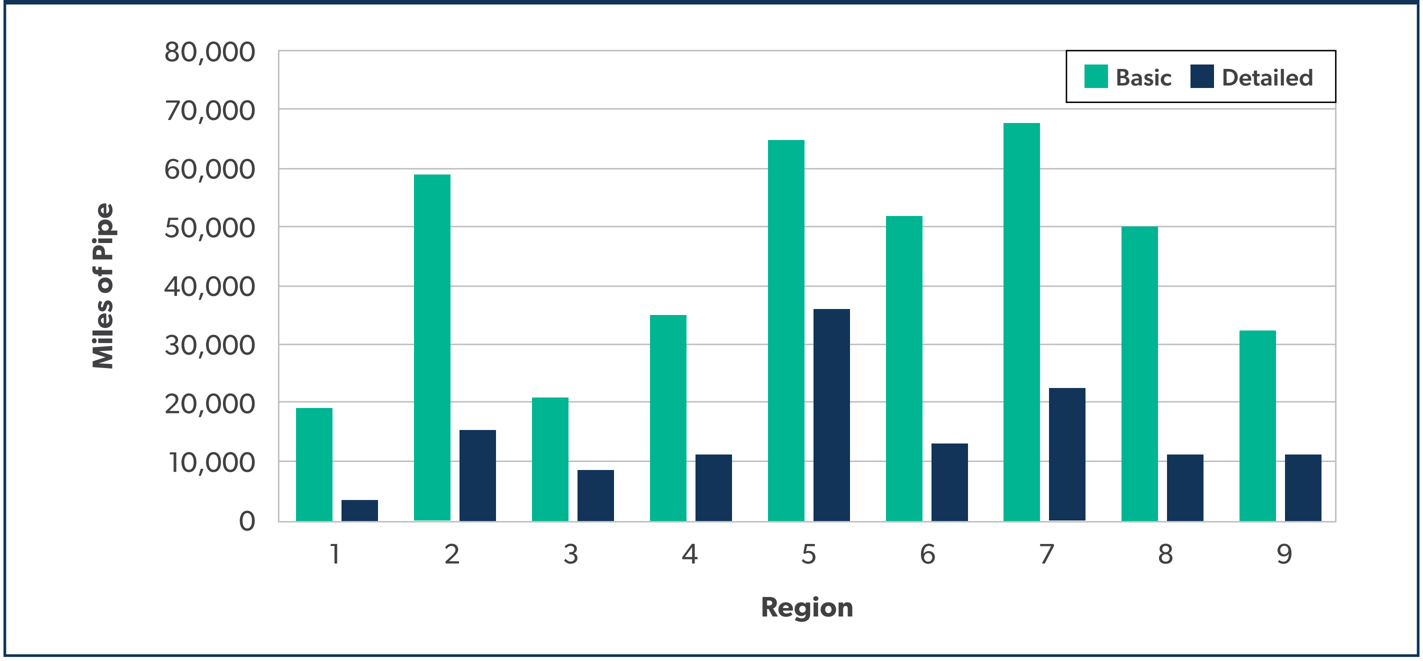
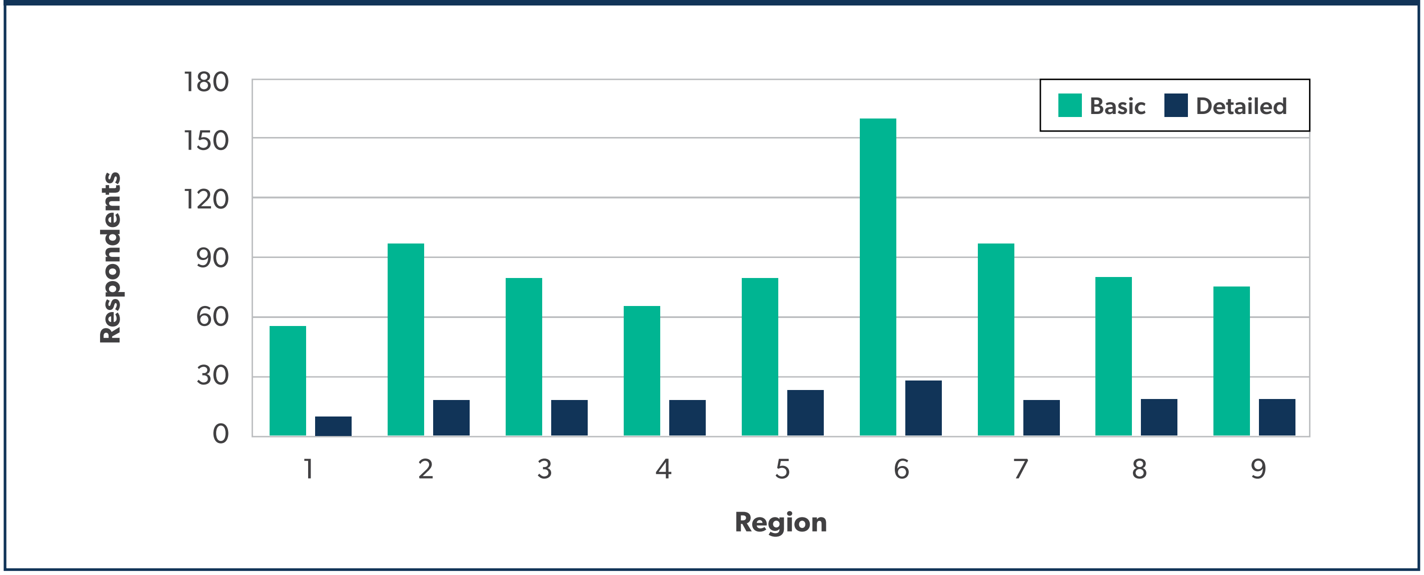
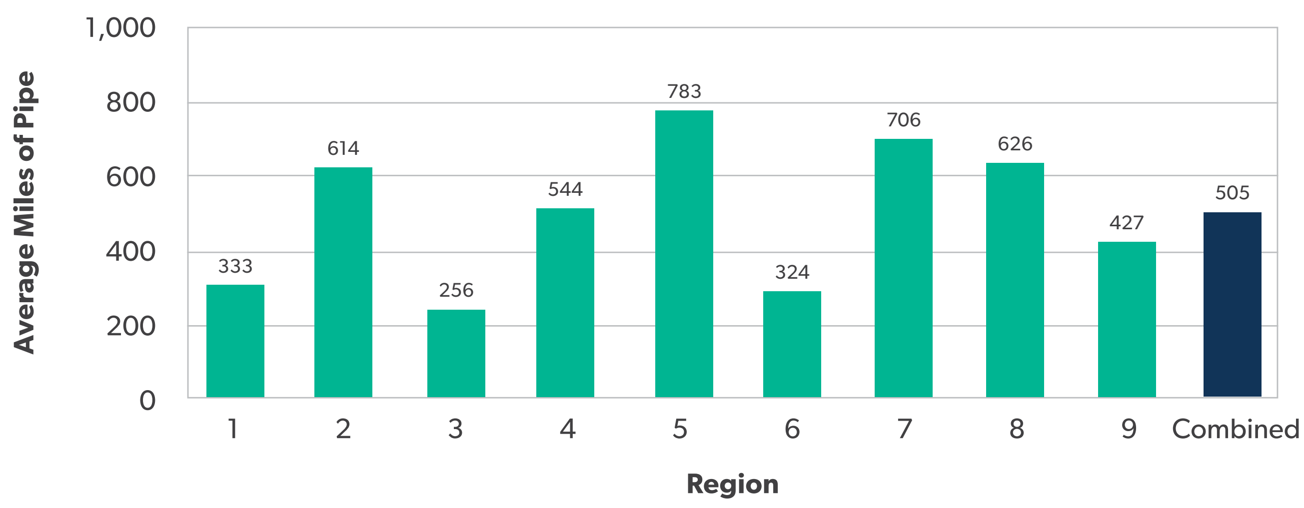


FIGURE 5: RESPONDENTS BY REGION FOR BASIC AND DETAILED SURVEYS



As illustrated in Figure 4, Regions 5 and 7 reported the most miles of pipe from the basic survey. Figure 5 shows that the greatest number of respondents came from Region 6. Figure 6 shows the average miles of pipe per utility from the basic survey by region. Region 5 had the highest average pipe length at 783 miles and Region 3 had the lowest with 256 miles. The average miles of pipe represented per utility respondent is 505 miles (Figure 6) serving an average population of 146,432 (Figure 7). For comparison, the 2012 and 2018 surveys reported an average utility had 626 and 607 miles of pipe serving 164,325 and 186,752 people, respectively. The decrease in both average miles of pipe per utility and average population serviced seems to indicate a greater participation from smaller utilities for this study. The 2023 basic survey had 2.8 times more respondents and 2.34 times more miles of pipe than in 2018, increasing the statistical validity of this study.

FIGURE 6: UTILITY'S AVERAGE MILES OF PIPE BY REGION (BASIC SURVEY)



2.4 Size of Survey Participants

Figure 7 shows the average population served per utility for each region. The average population served per utility for the basic survey was 146,432.

Utilities have been grouped into four categories in this report based on miles of installed water mains as shown in Table 2. Figure 8 shows the distribution of total miles of pipe from the basic survey based on these categories (bar graph with left axis) along with the number of respondents (line graph with right axis). The total miles of pipe are evenly distributed in terms of pipe length within each utility size (from small to very large). Figure 9 shows how the proportion of small utilities in the study have increased from 68% in 2018 to 75% in 2023. The number of utilities reporting from all four size groups increased significantly between 2018 and 2023.

TABLE 2: GROUPING OF UTILITY SIZE

Description	Miles of Pipe Installed
Small Utility/City	0 to 500 miles
Medium Utility/City	500 to 1,500 miles
Large Utility/City	1,500 to 3,000 miles
Very Large Utility/City	Over 3,000 miles

FIGURE 7: AVERAGE UTILITY POPULATION SERVED BY REGION (BASIC SURVEY)

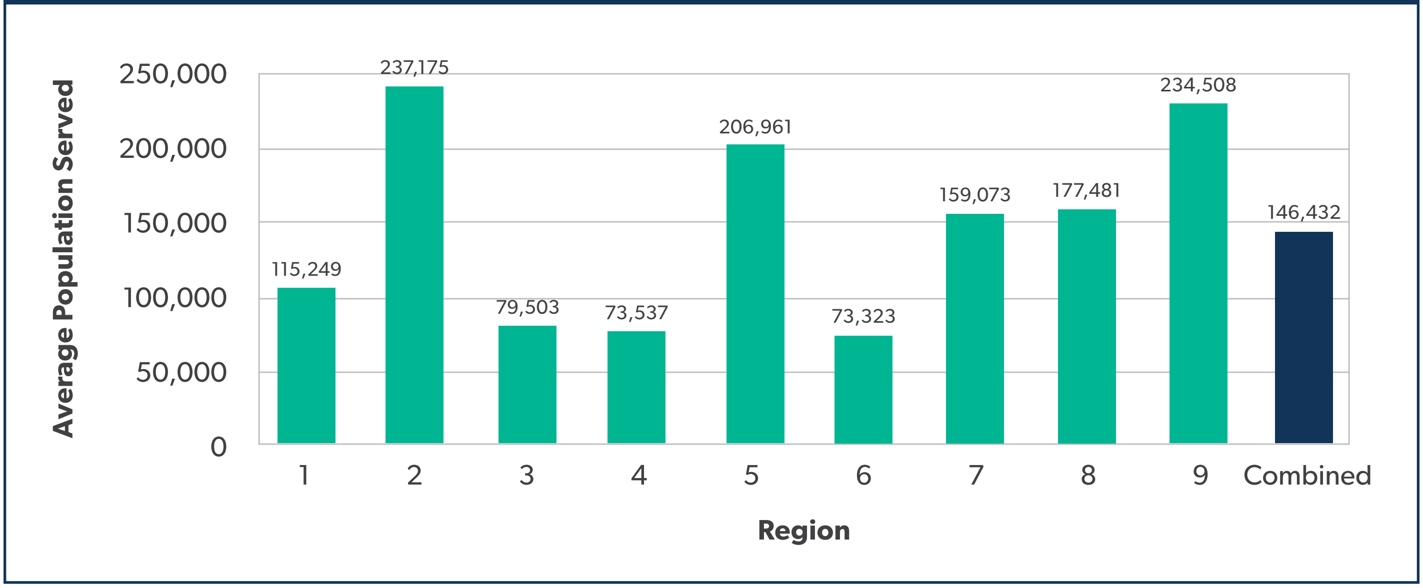


FIGURE 8: TOTAL MILES OF PIPE IN EACH SIZE GROUP AND THE NUMBER OF RESPONDENTS (BASIC SURVEY)

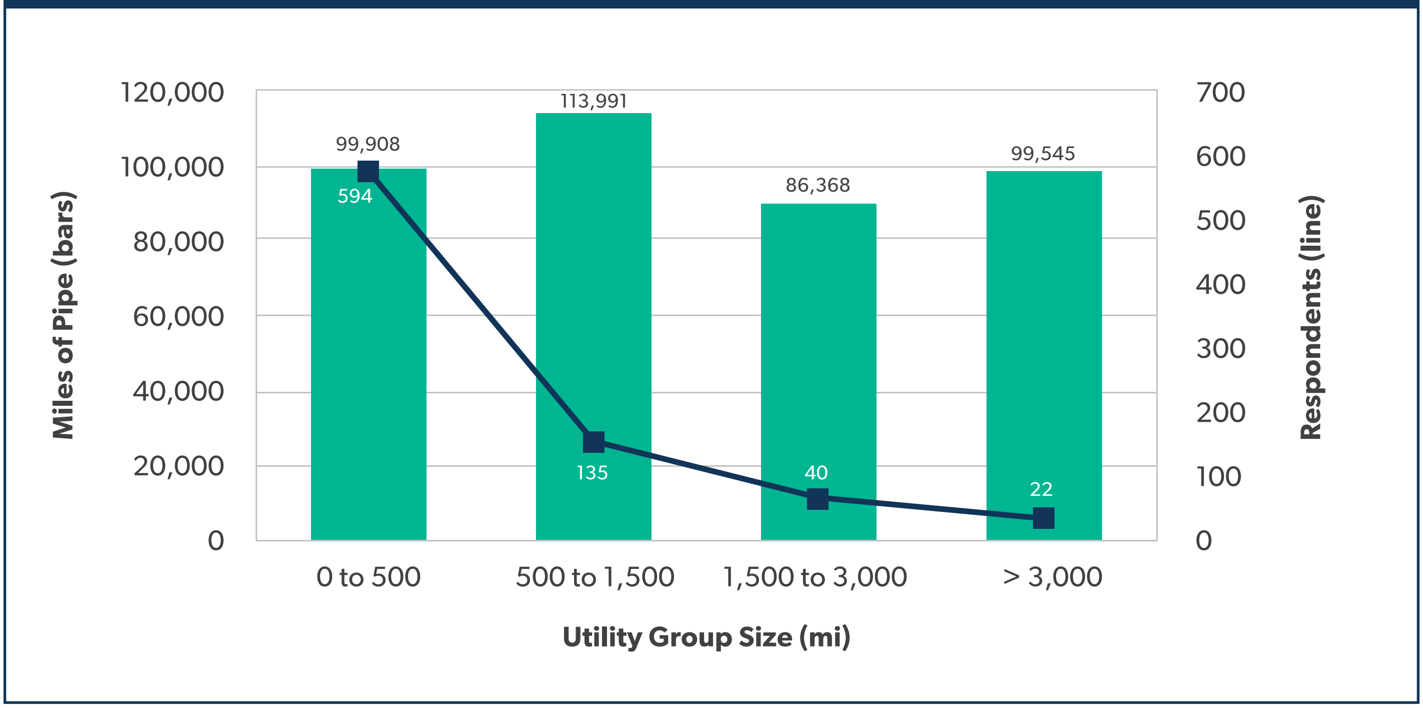
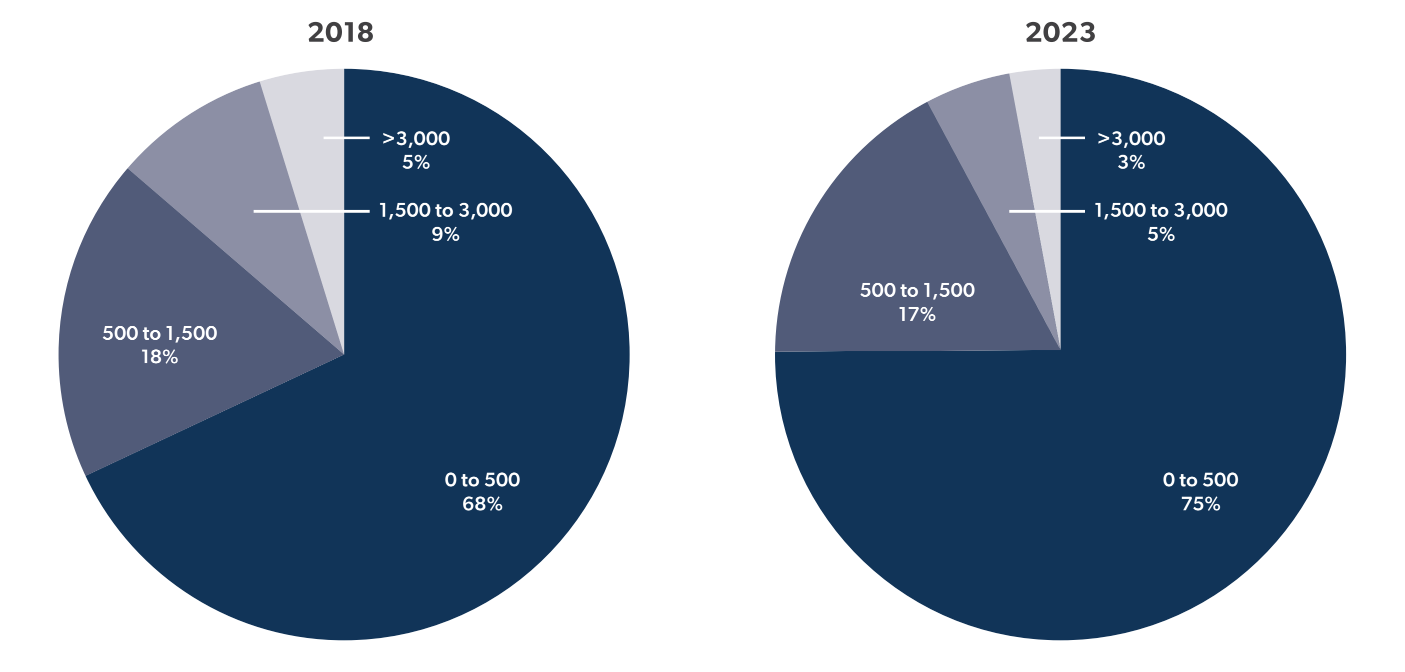


FIGURE 9: DISTRIBUTION ACROSS UTILITY GROUP SIZE (IN MILES OF PIPE) FOR BOTH 2018 AND 2023



2.5 Miles of Pipe vs. Population

Figure 10 illustrates the distribution of population served by the utilities participating in the basic survey against the number of miles of water mains. Figure 11 shows average population served per mile of pipe for each region, producing an overall average of 287 people served per mile. The 2018 survey reported this value as 308 while the 2012 survey reported 264 people served per mile. Utilities that provided transmission pipe data exclusively were not included (typically wholesale water providers). Water systems with a higher density of people served per mile have an increased consequence of failure and may require a higher level of asset oversight.

FIGURE 10: POPULATION SERVED RELATIVE TO TOTAL MILES OF PIPE (BASIC SURVEY)

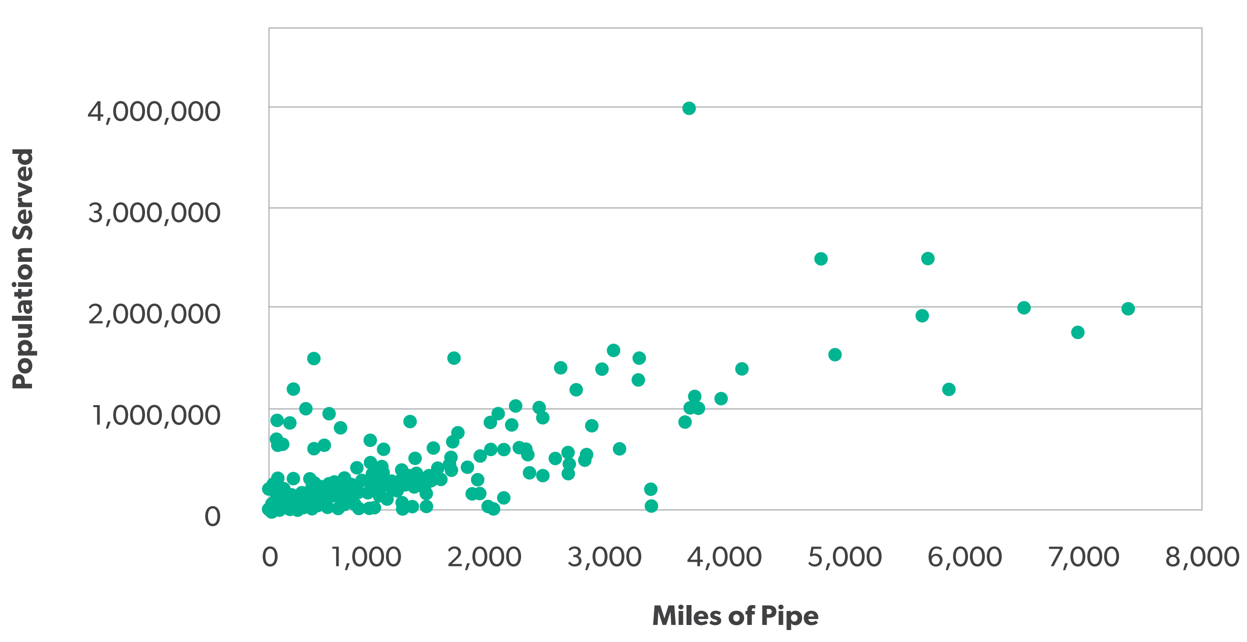
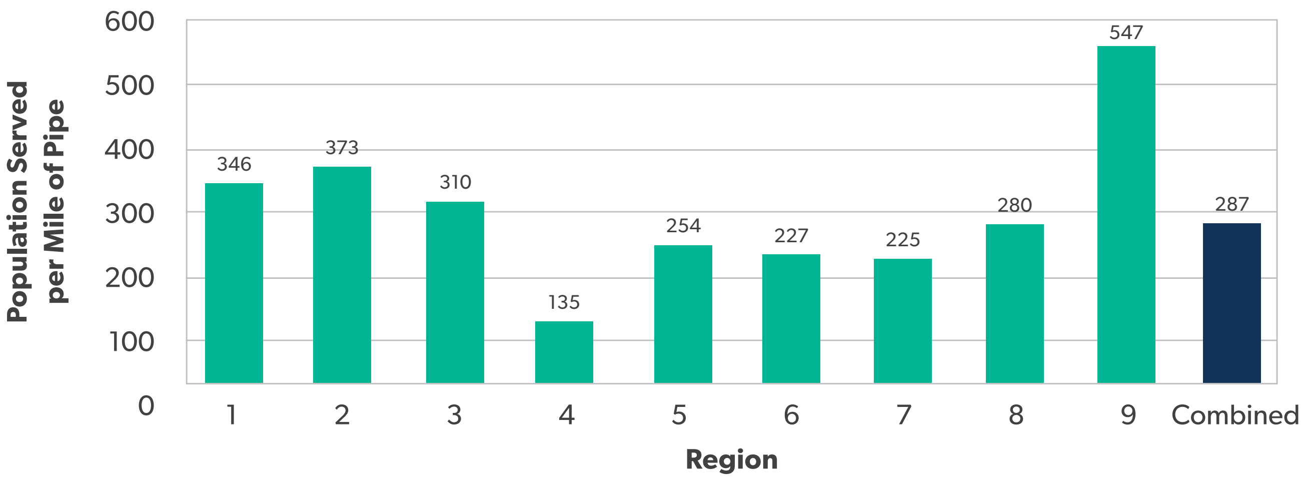


FIGURE 11: POPULATION SERVED PER MILE OF PIPE BY REGION (BASIC SURVEY)



2.6 Total Pipe Mileage and Population in the US and Canada

The survey's total length of water pipe in the US and Canada is 399,812 miles. The latest EPA estimate is 2.2 million miles of water mains in the US (EPA, 2018; ASCE, 2021). Dividing the population of the US, which is 334.2 million (US Census Bureau, 2023), by 287 people/mile of pipe as shown in Figure 11 results in 1.16 million miles of pipe (in contrast to the EPA figure of 2.2 million miles). The difference between these two values is believed to be due to the number of small community water systems with 500 or fewer customers, which total approximately 29,000 utilities (EPA, 2011). This report has a much larger representation of these smaller utilities than previous studies. The population of Canada is estimated at 39.5 million (Statistics Canada, 2023). Dividing 39.5 million by 287 people/mile of pipe amounts to 137,000 miles of pipe. This closely matches the 133,000 miles of pipe estimated by Statistics Canada in 2020 and shown in Table 3. Table 3 also shows that this survey covers approximately 30.1% of the population and 17.1% of the water mains, providing a survey sample size that is both comprehensive and reliable.

Small water utilities may find it challenging to renew their water infrastructure in the coming years. They have lower populations with fewer customers per mile of pipe, which has the effect of increasing the financial burden of maintaining these systems.

TABLE 3: ESTIMATED COVERAGE OF THE BASIC SURVEY

	Population	Miles of Pipe
US*	334,200,000	2,200,000
Canada*	39,500,000	133,000
Total	373,700,000	2,333,000
US Survey Response	95,252,498	367,758
Canada Survey Response	17,353,584	32,054
Total Survey Response (with pipe data)	112,606,082	399,812
Survey Coverage of US (%)	28.5%	16.7%
Survey Coverage of Canada (%)	43.9%	24.1%
Total Survey Coverage (%)	30.1%	17.1%

*Population and miles of pipe numbers from EPA, US Census Bureau, and Statistics Canada

3.0 Pipe Materials and Their Distribution

The purpose of this study was to determine accurate break rates for each pipe material. Achieving this required a significant sampling of each material in all pipe sizes (3-inch and larger), including both distribution and transmission mains. Table 4 lists the pipe materials and their abbreviations as they are utilized in this report. Water main pipe characteristics include pipe diameter, wall thickness, corrosion protection methods, etc. These factors, along with installation practices and environmental conditions, affect the life expectancy of a pipe. Both the basic and detailed surveys were simple to complete and, thus, encouraged participation of the water utilities. However, most utilities have limited records as to which specific pipe materials were installed decades ago and what corrosion protection measures were used historically. The primary focus of this study is on pipe material and diameter.

Figure 12 illustrates the length of pipe by material type reported in the basic survey. The "Other" category in Figure 12 includes materials such as wood and fiberglass. The "Unknown" category includes reported mileage for unidentified pipe material. When only small amounts of pipe mileage are available for analysis, calculated break rates become unreliable. There was very little high density polyethylene (HDPE) pipe and molecularly oriented polyvinyl chloride (PVCO) reported in this survey, so these two materials along with the materials in the "Other" category were excluded from the failure rate analysis. Concrete steel cylinder (CSC) pipe was also omitted from the analysis because the data included only transmission pipe in larger diameters and did not include smaller pipe sizes.

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 12: MILES OF PIPE BY MATERIAL TYPE (BASIC SURVEY)

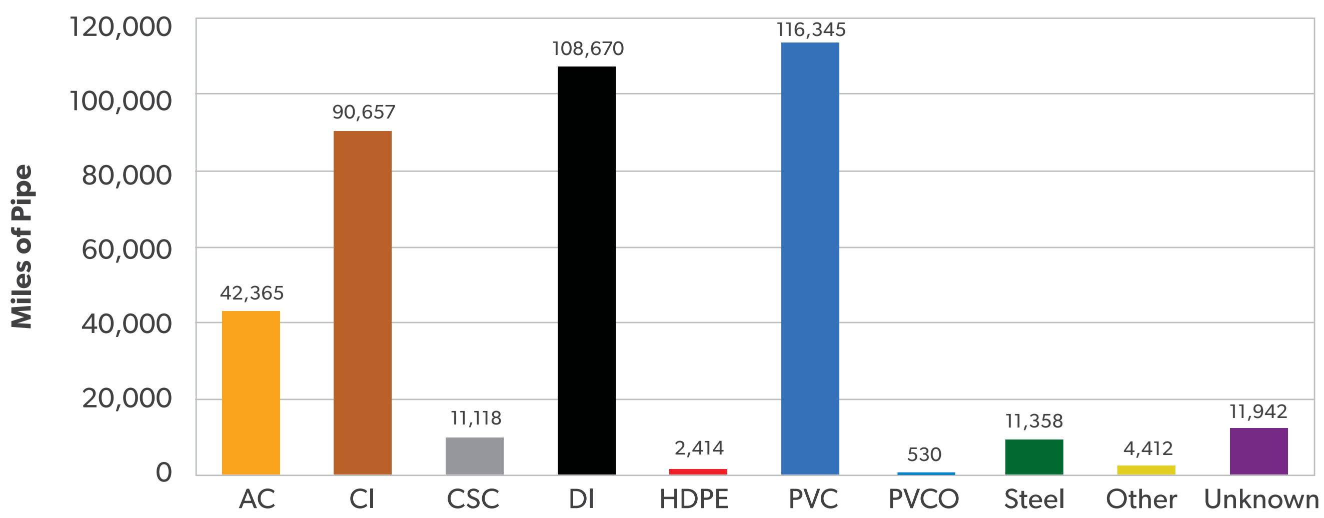


Figure 13 illustrates the percentage of total length of water mains by pipe material. It is significant to consider that nearly 90% of the water mains reported are made from cast iron (CI), asbestos cement (AC), ductile iron (DI), and polyvinyl chloride (PVC) materials. This is consistent with earlier USU studies (Folkman, 2012; 2018). The EPA provides a summary of the timelines of when these materials have been in use: *The majority of distribution piping installed in the United States, beginning in the late 1800's up until the late 1960's, was manufactured from cast iron... referred to today as "pit" cast iron pipe. ...In 1920, the process of centrifugally casting pipe in a sand mold was introduced... referred to as "spun" or "centrifugally" cast iron pipe* (which was commonly installed until the 1970's). Asbestos cement became commercially available in the 1930's and was commonly installed during the 1950's and 1960's. Following this was *the introduction of ductile iron pipe in the late 1960's*. Shortly after the introduction of ductile iron, *the use of ... polyvinyl chloride (PVC) ... in this country began to emerge in the 1970's* (EPA, 2002).

As shown in Figure 13, the percentages for the installed CI and AC pipe in 2023 are 22.7% and 10.6%, respectively. Figure 13 also illustrates that PVC has the highest percentage of all pipe materials at 29.1%, with DI pipe at 27.2%. As shown in Figure 14, in 2018 CI and AC pipe accounted for 28.4% and 12.7% of all pipe miles, respectively. The combined inventory for these two materials in 2018 was 41.1%, and 33.3% in 2023. This represents a reduction of 7.8% in the reported pipe inventory. During the same 5-year period, reported PVC pipe length increased by 7.0% and DI remained approximately the same. It is noteworthy that the reduction in CI and AC is similar to the increase in the installed length of PVC pipe.

FIGURE 13: PERCENTAGE OF PIPE LENGTH BY MATERIAL TYPES (BASIC SURVEY)

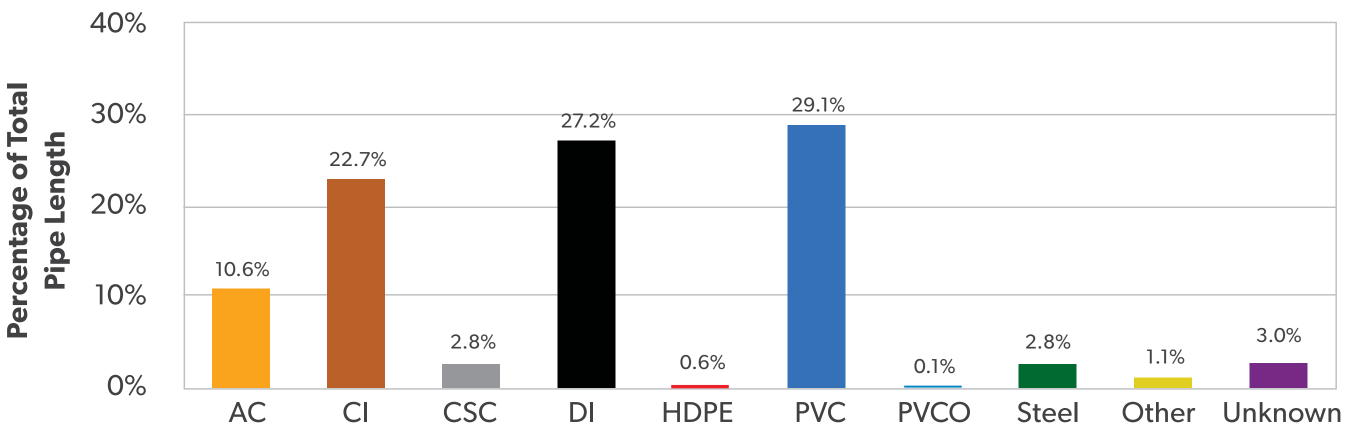


FIGURE 14: PERCENTAGE OF PIPE LENGTH OF THE MOST COMMON MATERIALS (2018 AND 2023)

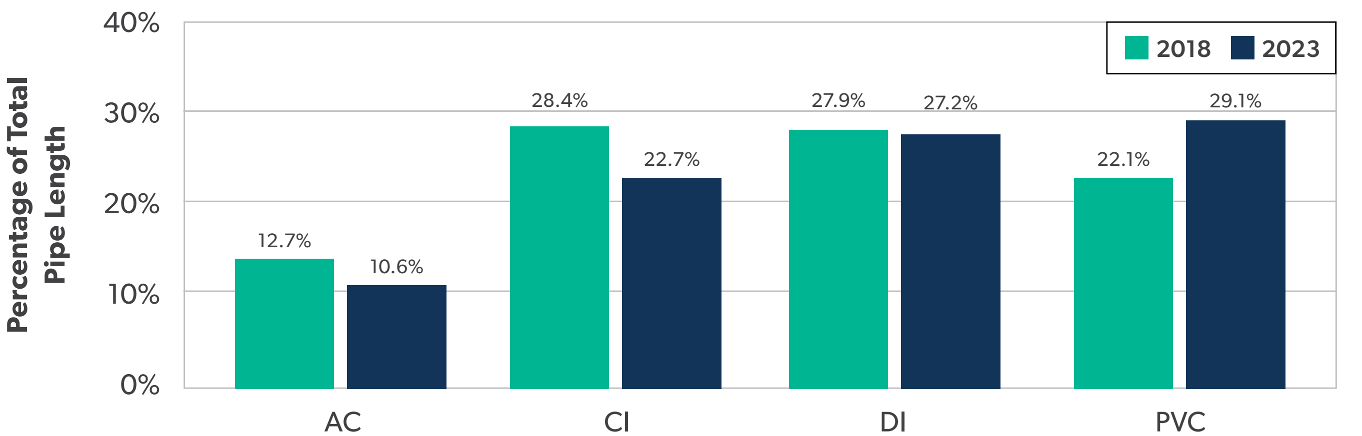


Figure 15 illustrates again the regions represented in the report. Figure 16 shows the regional distribution of pipe material usage as a percentage of the total length in that region. It is interesting to note the significant differences in regional pipe material utilization. CI is predominant in Region 8, while DI pipe is predominant in Regions 1 and 6. PVC has a leading role in Regions 3, 4, 5, 7 and 9. AC pipe has a significant presence in Region 2.

FIGURE 15: REGIONS USED TO REPORT SURVEY RESULTS

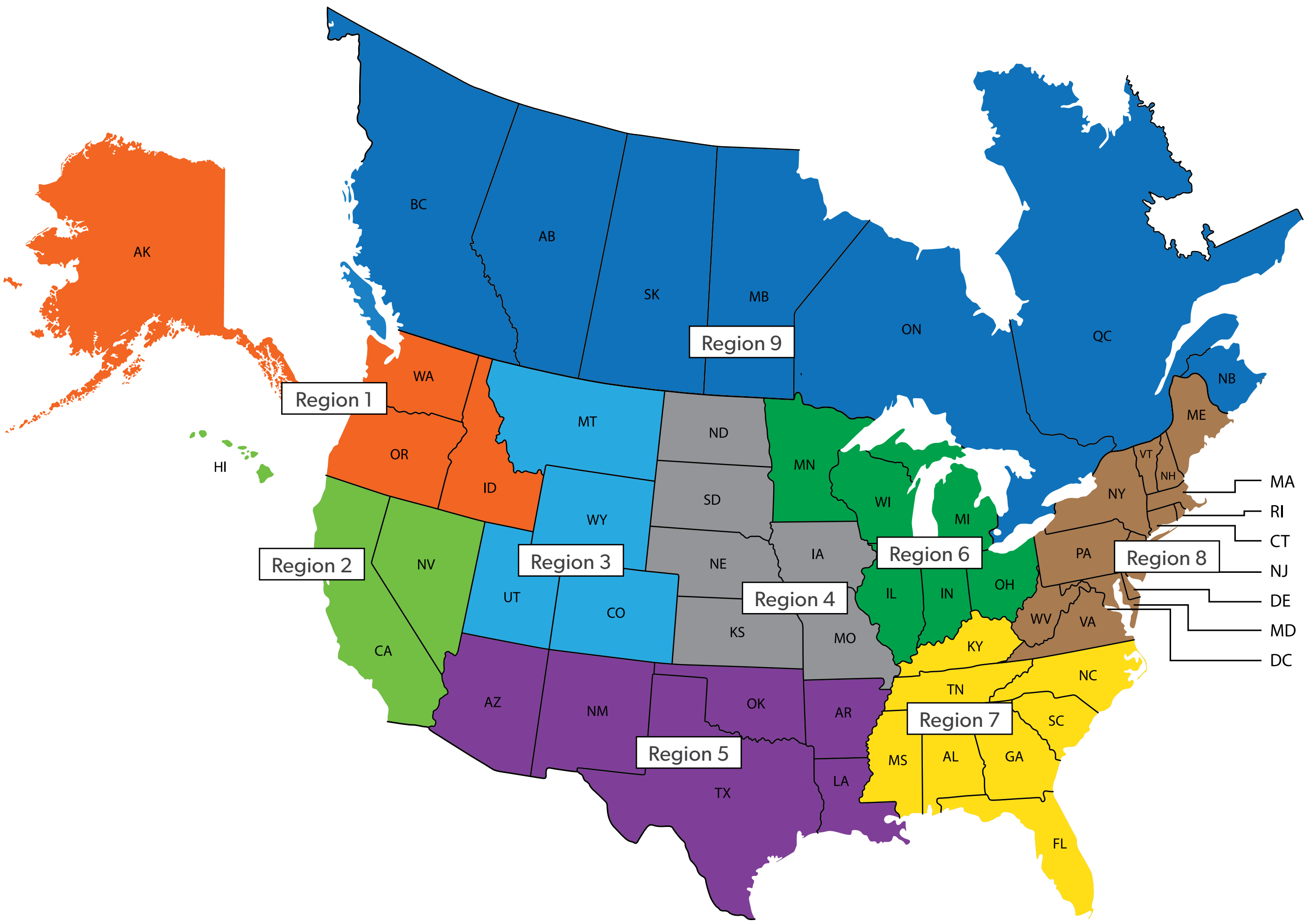
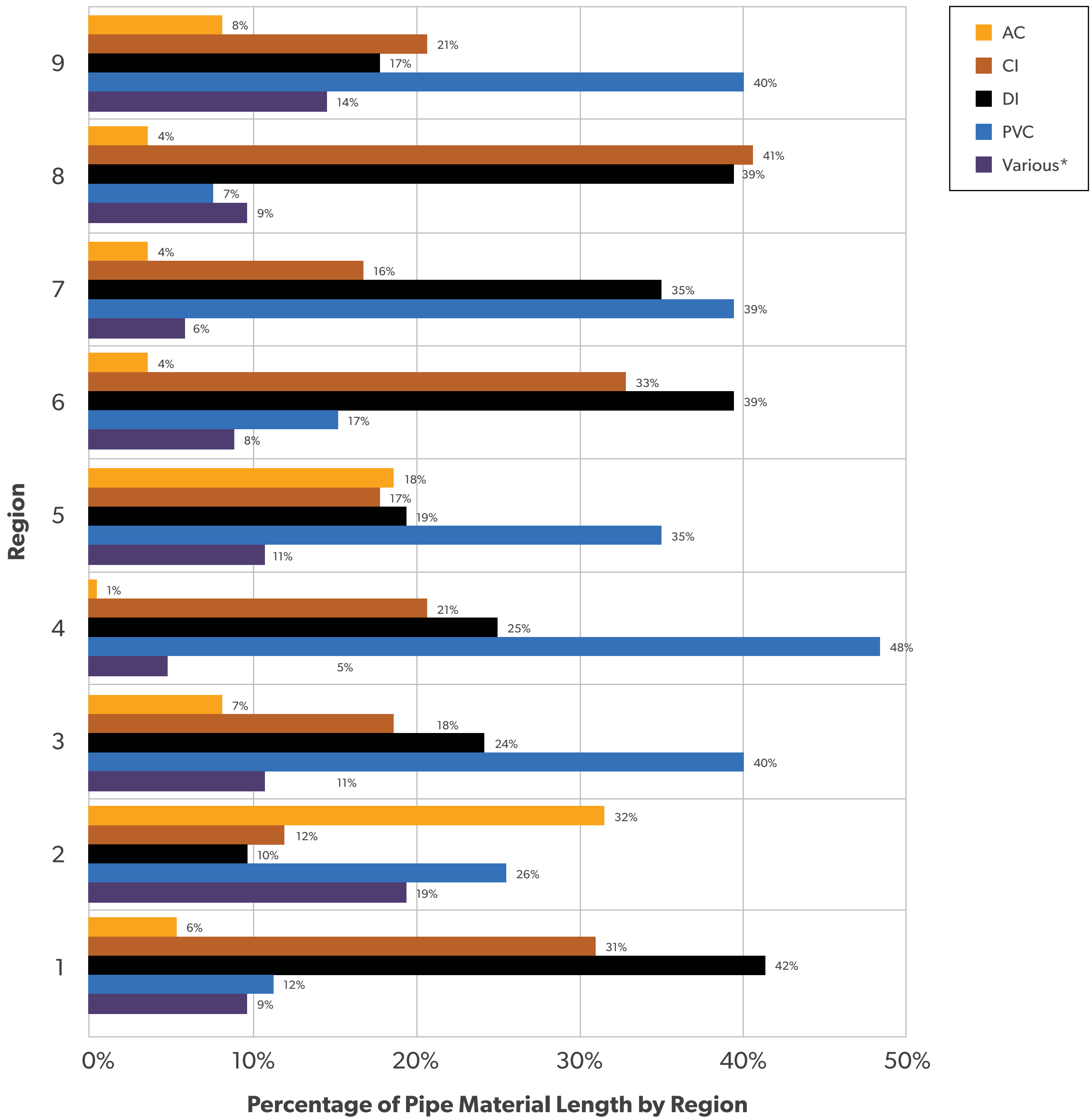


FIGURE 16: PIPE MATERIAL USAGE AS A PERCENTAGE OF TOTAL LENGTH BY REGION (BASIC SURVEY)



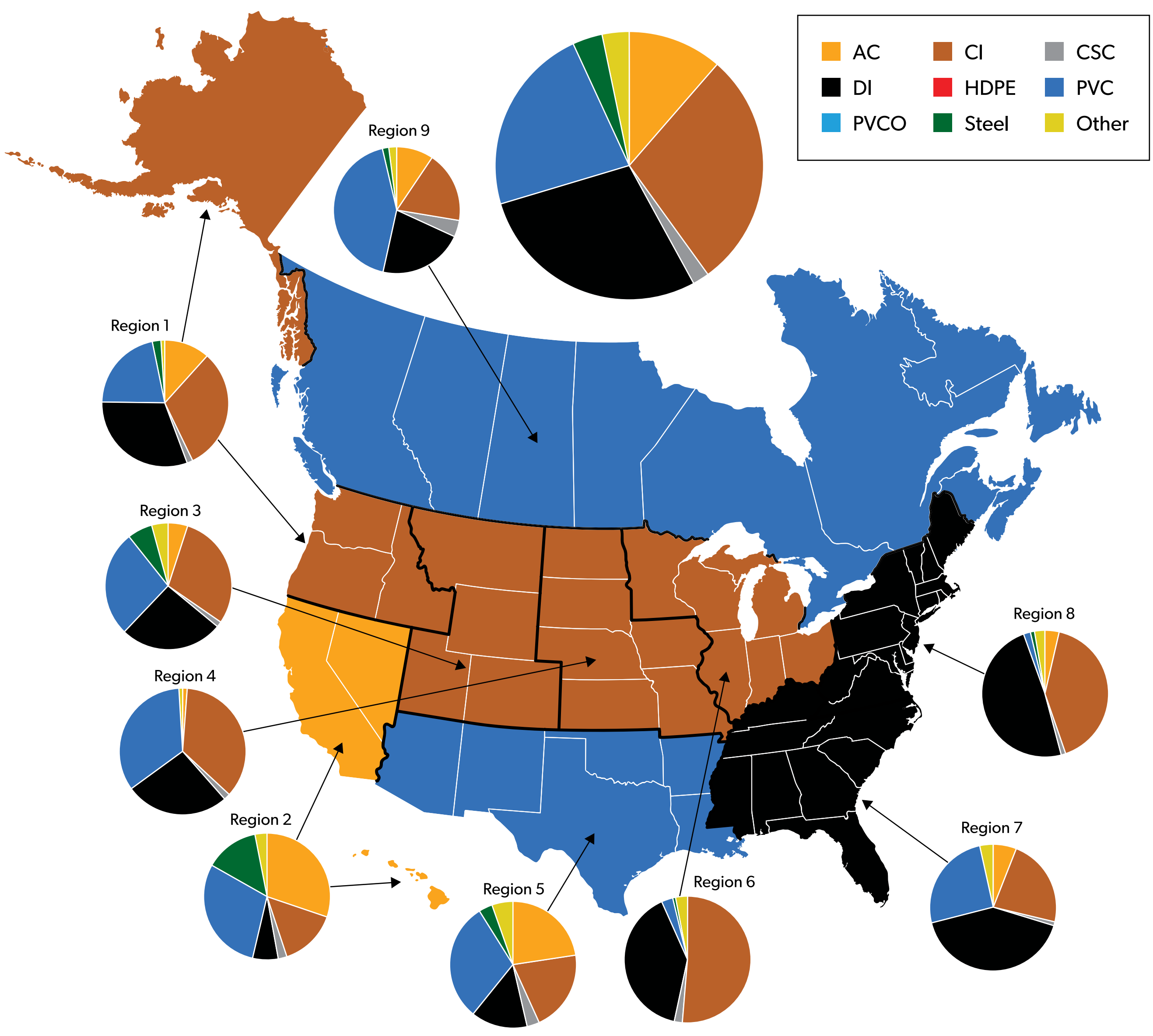
*The "Various" category combines all pipe materials that are at 3% and below of the total pipe length, which includes: CSC (2.8%), HDPE (0.6%), PVCO (0.1%), Steel (2.8%), Other (1.1 %), and Unknown (3.0%).

Adding up all values for each region equals 100%.

Figures 17, 18, and 19 display the use of pipe materials as reported in the 2012, 2018, and 2023 USU studies, respectively. Each region on the map is colored according to the predominant pipe material installed there. Comparing these figures provide an understanding of the significant pipe usage trends occurring in the US and Canada in the last decade, which are as follows:

- Regions 1 and 6 are trending toward DI.
- Regions 3, 4 and 7 are shifting towards PVC.
- PVC remains predominant in Regions 5 and 9.
- CI and DI remain the most common pipe materials in Region 8.
- AC is still the most common pipe material in Region 2.
- CI has been replaced by other materials in Regions 1, 3, 4 and 6.

FIGURE 17: PIPE DISTRIBUTION AND MOST COMMON PIPE MATERIAL BY REGION (2012 BASIC SURVEY)



Note: HDPE and PVCO data were not individually reported.

FIGURE 18: PIPE DISTRIBUTION AND MOST COMMON MATERIAL BY REGION (2018 BASIC SURVEY)

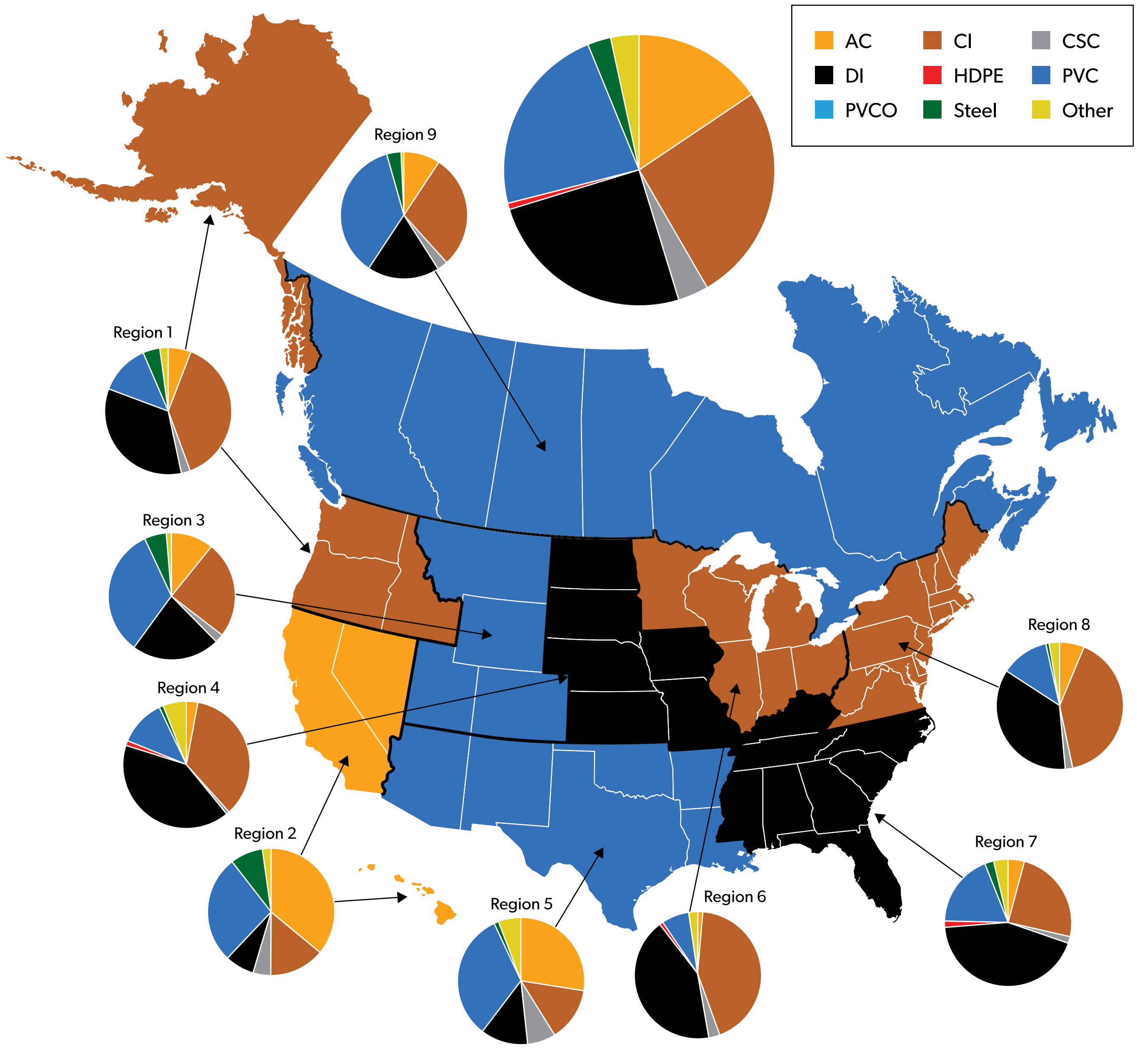
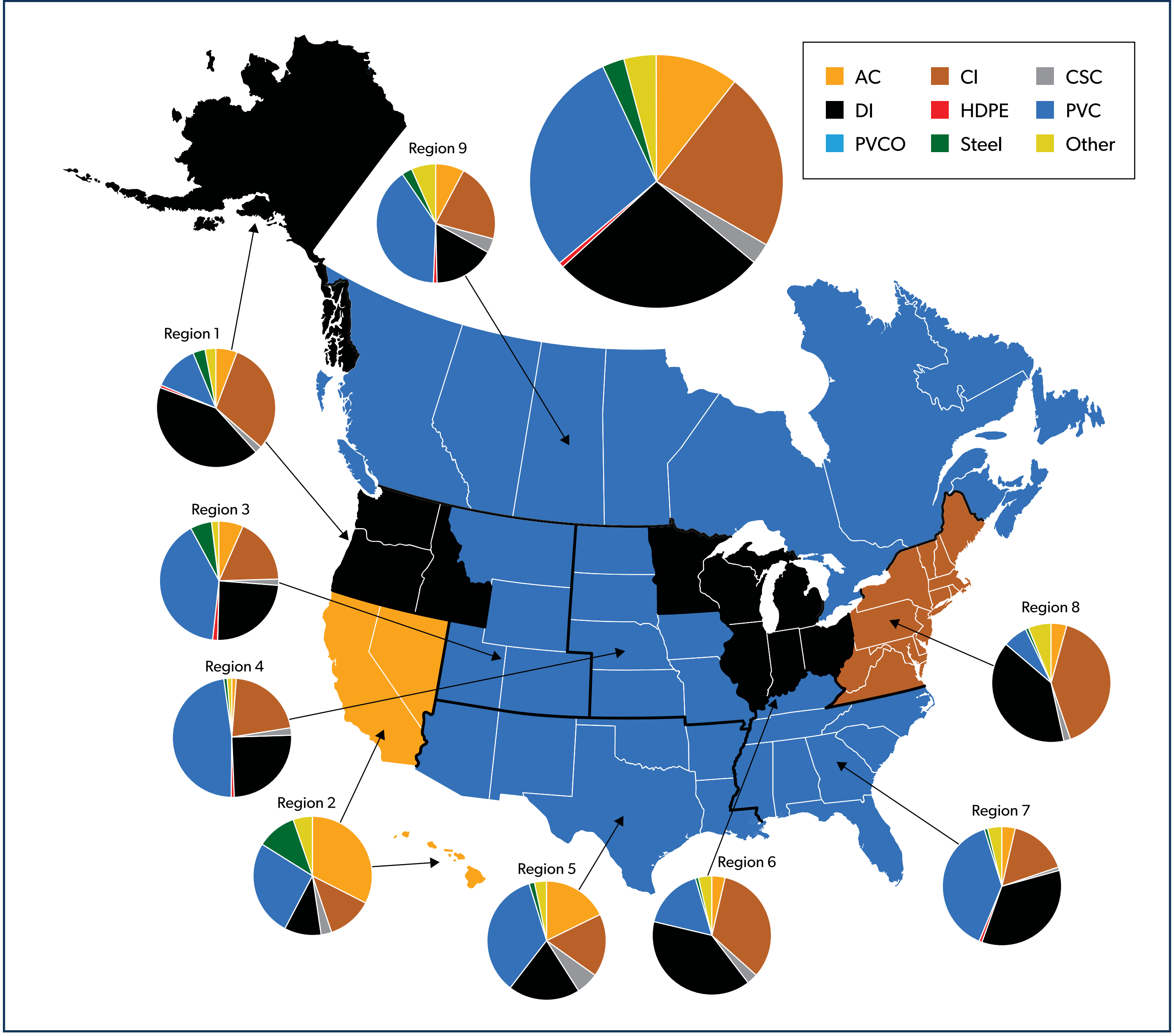


FIGURE 19: PIPE DISTRIBUTION AND MOST COMMON PIPE MATERIAL BY REGION (2023 BASIC SURVEY)



3.1 Pipe Age and Diameter

Data for pipe age and diameter came from the detailed survey. The focus of the detailed survey was to complement the data collected from the basic survey and look more specifically at topics such as pipe age, water demand, pipe size distribution, target break rates for pipe replacement, expected pipe service life, condition assessment methods, and pipe material acceptance. Note: the proportions of each pipe material differ between the basic and detailed survey due to differences in sample size.

PIPE AGE. The detailed survey asked respondents to provide the distribution of installed pipe by material type and age, grouped as follows: 0 to 10 years, 10 to 20 years, 20 to 30 years, 30 to 40 years, 40 to 50 years, and over 50 years. Figure 20 shows the age distribution for all pipe materials combined, indicating that 33% of all installed pipes are over 50 years old.

The bar graph in Figure 21 illustrates the age distribution for each pipe material by length. For example, survey results indicate that the majority of CI pipes are over 40 years old with 11% in the 40- to 50-year category and 86% over 50 years of age. Conversely, HDPE and PVCO are relatively new pipe materials with most being installed in the last 20 years.

The pie chart in Figure 21 summarizes the significance of each pipe material in terms of reported total pipe mileage in the detailed survey. For example, DI is at 33.8%, CI shows 24.4%, while HDPE represents 0.5%, and PVCO is 0.1% of all pipe miles.

FIGURE 20: PIPE AGE DISTRIBUTION FOR ALL MATERIAL TYPES (DETAILED SURVEY)

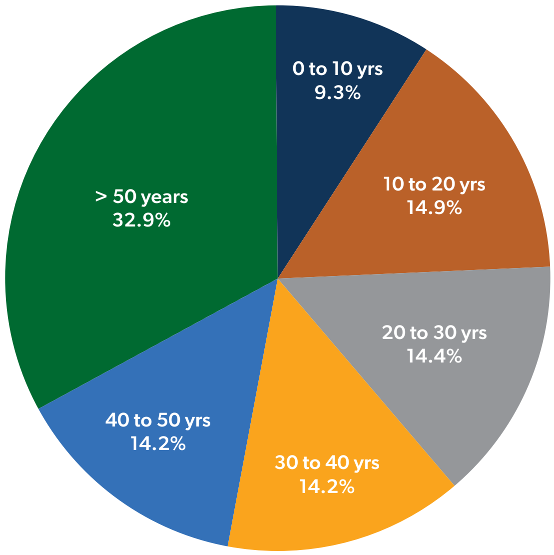


FIGURE 21: PIPE AGE DISTRIBUTION FOR EACH MATERIAL TYPE (DETAILED SURVEY)

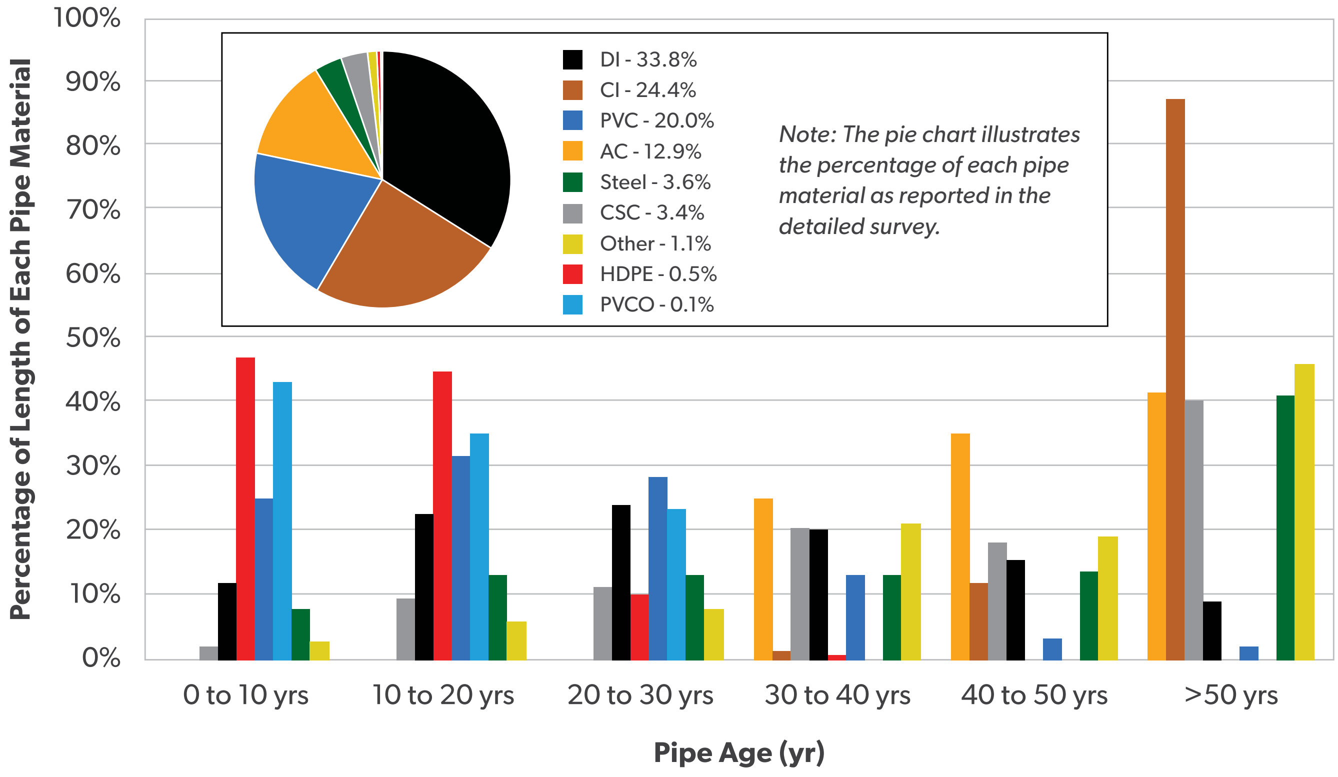
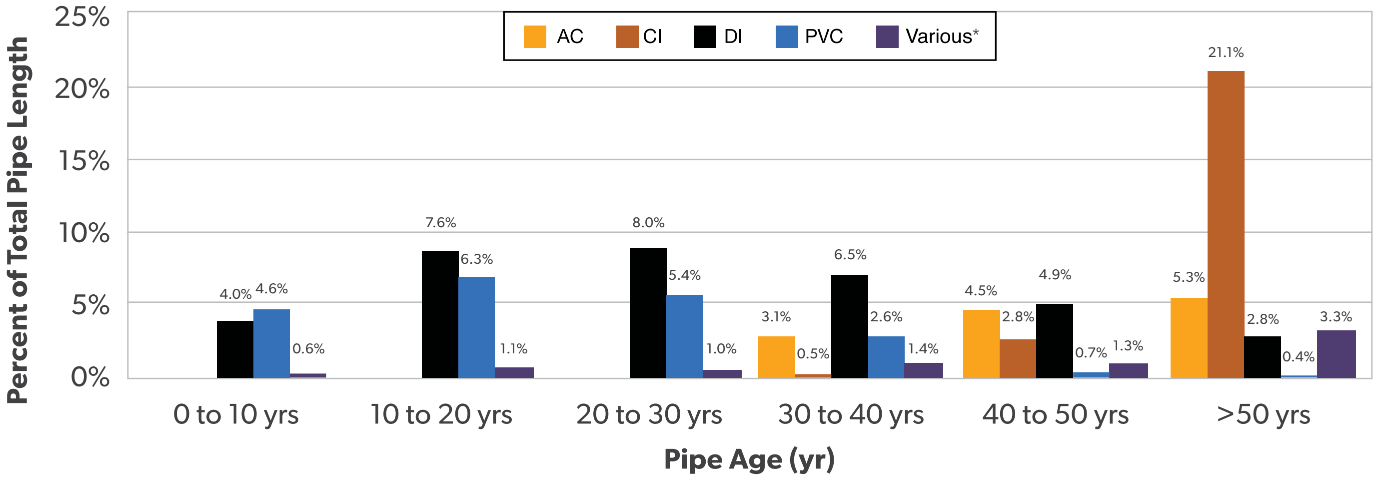


Figure 22 shows the age distribution as a percentage of the total length of all pipe materials from the detailed survey. For example, CI older than 50 years is 21% of all installed pipe. For ages between 0 to 10 years, DI and PVC both have about 4 to 5% of the total installed length. This means that the most common pipe materials installed over the last 10 years are DI and PVC.

FIGURE 22: PERCENTAGE OF TOTAL PIPE LENGTH BY AGE (DETAILED SURVEY)



*The "Various" category combines all pipe materials that are at 3% and below of the total pipe length in the basic survey, which includes: CSC (2.8%), HDPE (0.6%), PVCO (0.1%), Steel (2.8%), Other (1.1 %), and Unknown (3.0%).

Adding up all values equals 100%.

PIPE DIAMETER. The detailed survey respondents were also asked to break down the total installed pipe length by six pipe diameter categories. Figure 23 illustrates the percentage of pipe divided into each size range. Figure 23 indicates that approximately 68% of installed pipe is 8-inch or smaller, and 86% is 12-inch or smaller. In comparison, the 2012 and 2018 USU surveys found that 66% and 67% of the pipes were 8-inch or smaller, respectively. This demonstrates consistent pipe size usage and validation of data accuracy (Folkman, 2012; 2018).

Based on EPA's estimate of 2.2 million miles of water pipe in the US, these sizes equate to roughly 1.9 million miles of pipe in the US. Similarly, using Statistics Canada's estimate of 133,000 miles of water pipe, it is estimated that roughly 115,000 miles of pipe in Canada is between 3- and 12-inch in diameter.

FIGURE 23: PERCENTAGE OF TOTAL PIPE LENGTH BY SIZE (DETAILED SURVEY)

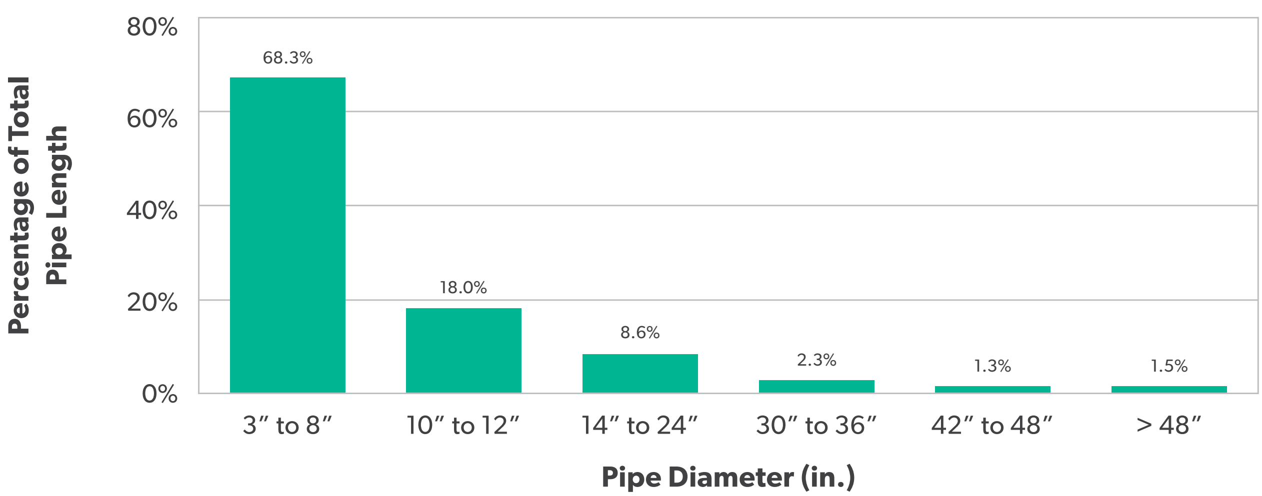
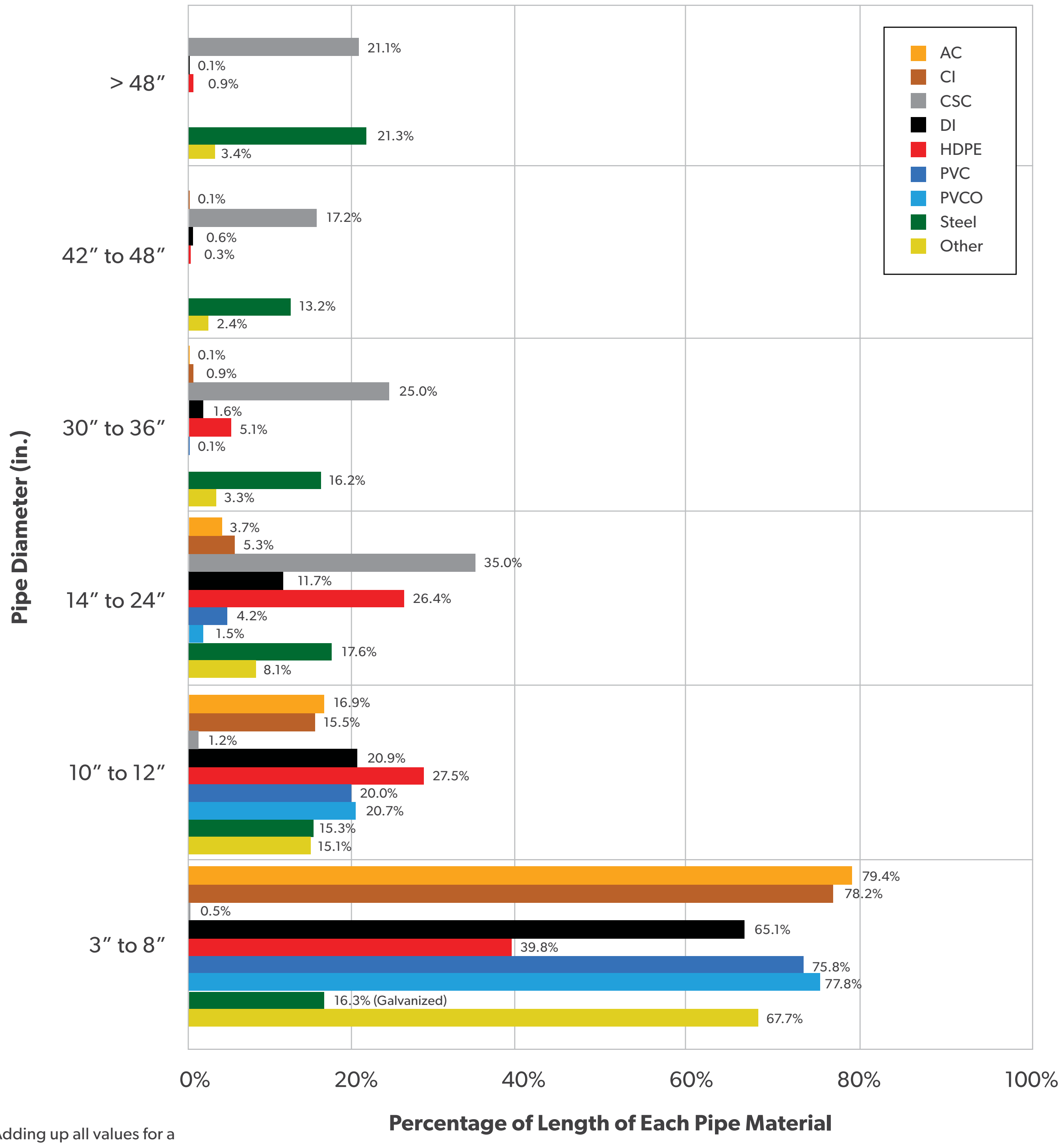


Figure 24 illustrates the diameter distribution for each material type as reported from the detailed survey. The figure shows that most large diameter pipes (14-inch and larger) are predominantly steel and CSC, with each material having more than 21% of their length in sizes larger than 48-inch. More than 98% of the CSC pipe was in sizes 14-inch and larger. The figure also shows that over 75% of all AC, CI, PVC and PVCO pipe, respectively, is 8-inch or smaller.

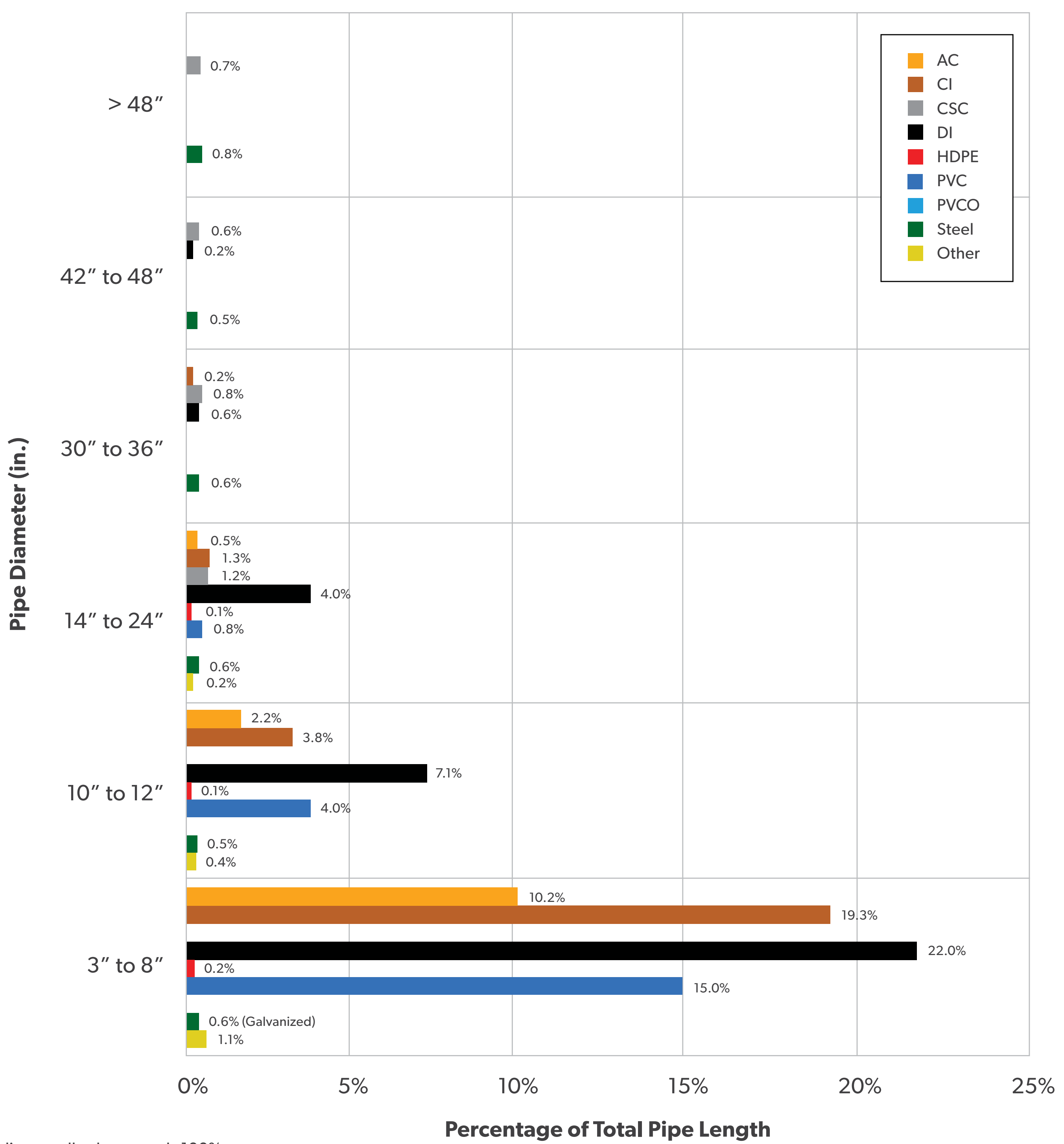
FIGURE 24: PIPE DIAMETER DISTRIBUTION BY MATERIAL TYPE (DETAILED SURVEY)



Adding up all values for a given material equals 100%.

Figure 25 illustrates for each pipe material the percent of total length by material type and diameter. It shows that DI and PVC pipe from 3 to 8 inches in diameter represent over 22% and 15%, respectively, of all installed pipe as reported from the detailed survey. Steel pipe less than 14-inch in diameter is most likely galvanized steel, while larger diameter steel is typically carbon steel. As discussed previously, the pipe mileage data from the detailed survey differs from the data collected in the basic survey due to the difference in sample size.

FIGURE 25: PERCENTAGE OF TOTAL PIPE LENGTH BY DIAMETER AND MATERIAL TYPE (DETAILED SURVEY)



Adding up all values equals 100%.

4.0 Delivery Pressure and Volume

The basic survey asked for the average and maximum water supply pressures. As shown in Figure 26, the mean average and maximum water supply pressures are 71 and 120 psi, respectively. In the 2018 survey, the mean and maximum pressures were 69 and 119 psi, respectively, which is consistent with this survey result.

The detailed survey also asked for the average and maximum daily water demand. The reported values were divided by the population served and averaged. To prevent potential overcounting, utilities that were only transmission systems were excluded since they are typically wholesale water providers and do not service end users. The average water demand is 143 gallons per day for each person. The maximum water demand is 247 gallons per day for each person. The values for 2018 were 137 and 251, respectively. Figure 27 shows each utility's average and maximum demand values in units of MGD (millions of gallons per day) versus the population served in millions.

The survey also asked about water loss due to leakage. A total of 530 utilities provided an estimate of their water loss due to leakage and the average reported value was 11% as compared to 10% reported in 2018.

FIGURE 26: AVERAGE AND MAXIMUM WATER SUPPLY PRESSURES (BASIC SURVEY)

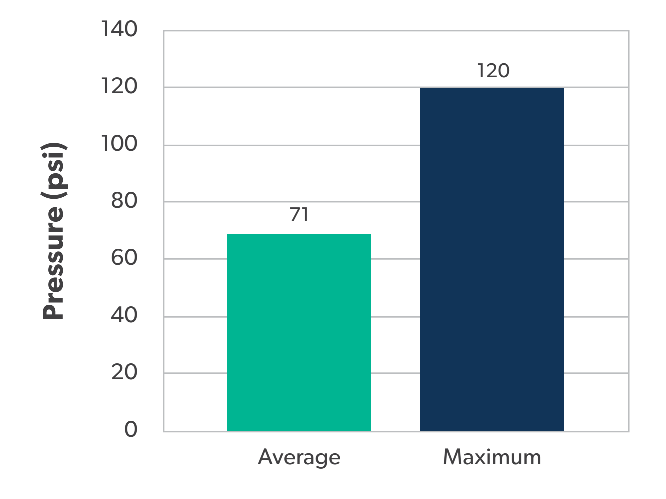
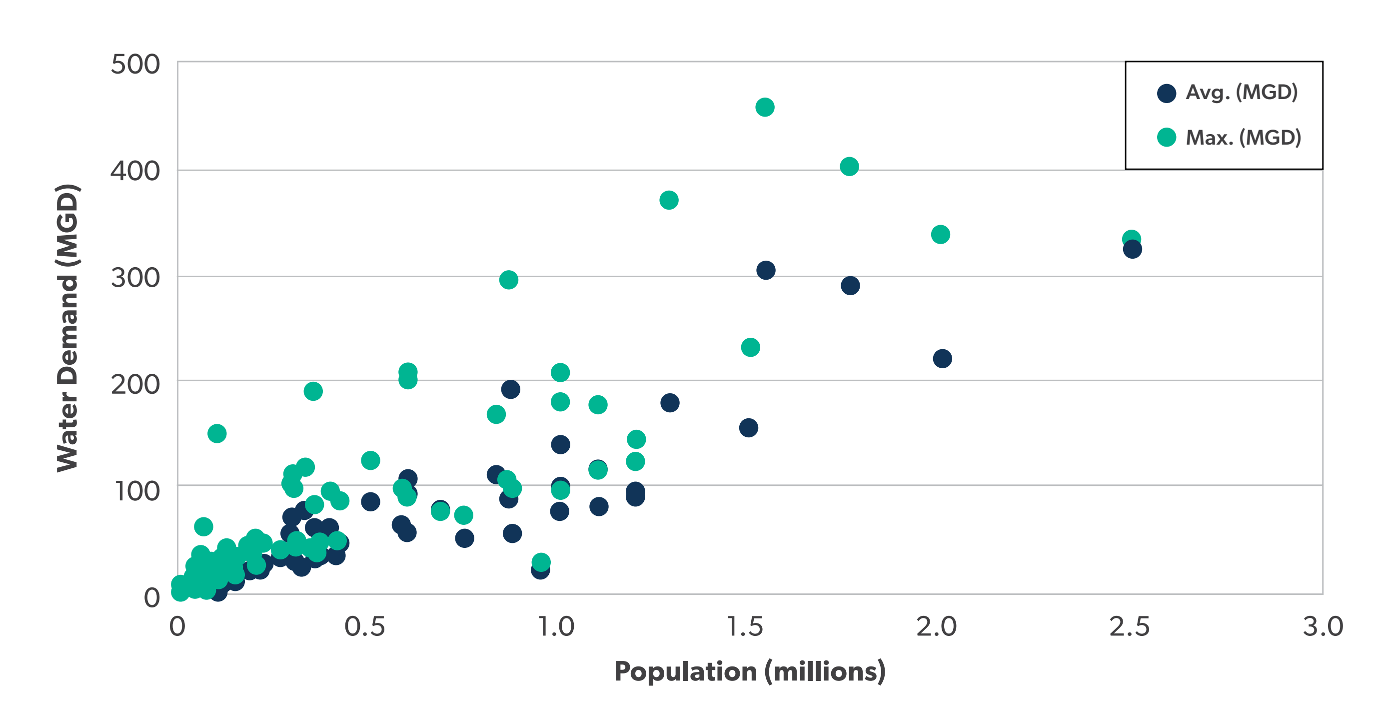


FIGURE 27: AVERAGE AND MAXIMUM WATER DEMAND BY POPULATION (DETAILED SURVEY)



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. One of the primary objectives of this study was to examine pipe material performance.

Utilities provided the number of water main failures over recent 12-month and 5-year periods. The installed length of each pipe material was also included. The break rate was computed by dividing the total number of failures for a particular pipe material by its total reported length.

For example, the basic survey reported a total of 40,489 failures during a recent 12-month period for all pipe materials. The total installed water main length with sufficient break data was 363,412 miles (or 3,634.12 hundred miles). Thus, the overall failure rate is calculated as follows:

$$\frac{40{,}489}{3{,}634.12} = 11.1 \text{ breaks/(100 mi-yr)}$$

Applying 11.1 breaks/(100 mi-yr) to 2.33 million miles of pipe, it is estimated that the US and Canada experience roughly 260,000 water main breaks annually. This finding provides a new metric for the US and Canada. If it is assumed that a single water main break repair costs an estimated $10,000 (direct and indirect costs), this represents $2.6 billion annually. As a point of reference, the EPA reports 240,000 water main failures per year in the US (EPA, 2023).

This simple method for computing failure rates was used because it discourages biases toward large or small utilities. Utilities experience widely different break rates for the same pipe material. Indeed, this should not be surprising. Several significant variables affect break rates including pipe age, soil corrosivity, corrosion prevention methods, installation practices, and climate. These factors demonstrate why pipe material performance and selection are an important component of optimizing distribution systems.

5.1 Failure Rates for Each Pipe Material

Table 5 lists the 2012, 2018 and 2023 USU survey break rates by material type. Break rates were determined for a 12-month period shortly prior to each report. Additionally, it shows the pipe length and the number of failures for each material for 2023. The 2023 failure rate of 11.1 breaks/(100 mi-yr) represents a 20% decrease compared to the 2018 USU study, which reported 14.0 breaks/(100 mi-yr). The relative break rates between pipe materials in the 2012, 2018 and 2023 survey remain consistent.

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

	2012 Break Rate (breaks/(100 mi-yr))	2018 Break Rate (breaks/(100 mi-yr))	2023 Length (miles)	2023 Failures	2023 Break Rate (breaks/(100 mi-yr))
AC	7.1	10.4	37,909	3,896	10.3
CI	24.4	34.8	84,691	24,251	28.6
DI	4.9	5.5	100,999	5,175	5.1
PVC	2.6	2.3	96,471	2,807	2.9
Steel	13.5	7.6	10,904	1,003	9.2
Other	15.0	8.0	32,438	3,357	10.3
Total	11.0	14.0	363,412	40,489	11.1

Figure 28 illustrates the failure rates by pipe material for the 12-month period used in the current study. PVC has the lowest break rate of the materials shown, while CI has the highest. In both 2012 and 2018 USU surveys, PVC also had the lowest break rate. Figure 29 shows the failure rates over 12-month and 5-year periods. In both cases, the relative break rates remain the same for all materials, and therefore, it is anticipated that future break rates will continue to remain consistent. Pipe materials that did not have a significant presence in the survey results (in terms of pipe miles represented) are not included in subsequent tables and figures. This decision was made to avoid calculating unrealistic break rates due to low reported miles of pipe.

FIGURE 28: BREAK RATES BY PIPE MATERIAL FOR A 12-MONTH PERIOD (BASIC SURVEY)

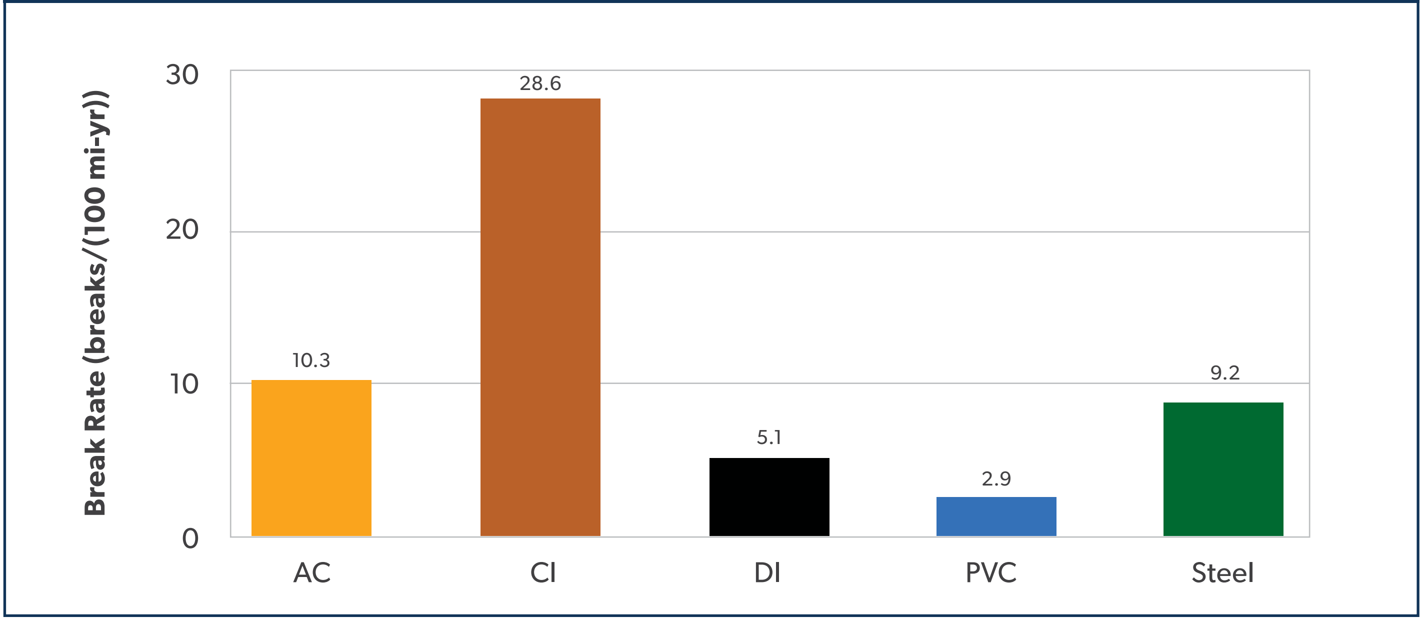


FIGURE 29: BREAK RATES BY PIPE MATERIAL FOR A 12-MONTH AND 5-YEAR PERIOD (BASIC SURVEY)

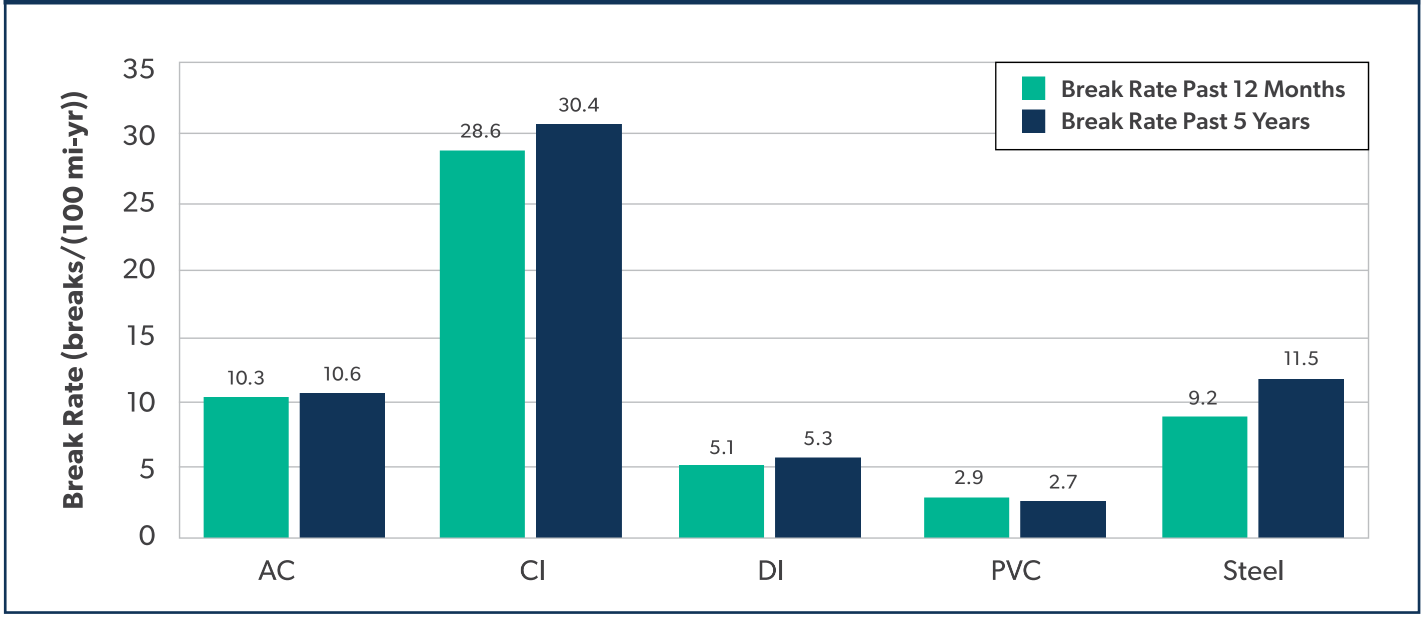


Figure 30 illustrates the overall reported break rates from this survey and the two previous reports (Folkman, 2012; 2018). It is apparent from the figure that the current survey represents a significant number of pipe miles. Even with this large sample size, the overall break rates are relatively consistent with only a slight reduction in failure rates in the last five years. This decrease may indicate that more utilities are applying asset management techniques and replacing pipe with the highest break frequency.

FIGURE 30: CHANGE IN OVERALL BREAK RATE BETWEEN SURVEYS (BASIC SURVEY)

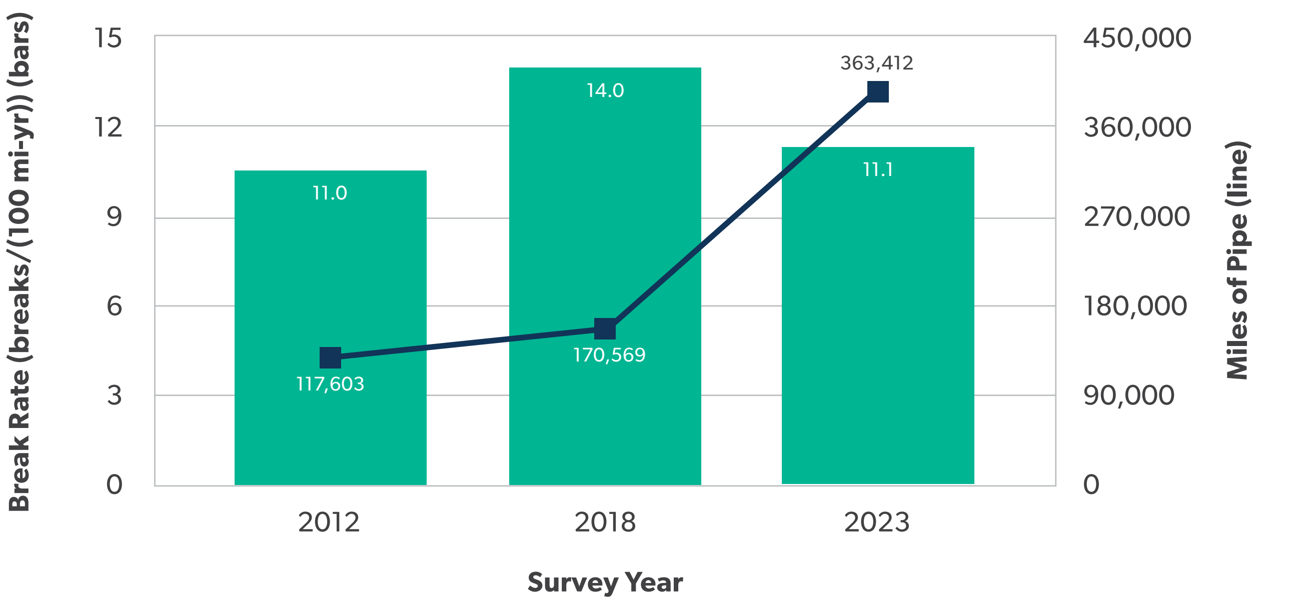


Figure 31 compares the break rates of common water pipe materials from the 2012, 2018, and 2023 USU surveys. The consistent break rates across the three studies help to validate the accuracy of the data. Small variations can be assumed to be data scatter. Since about 90% of installed pipe consists of AC, CI, DI, and PVC, the break rates for these materials are the most accurate, which avoids inaccurate calculations for pipe materials with low reported mileage. Figure 31 shows an insignificant break rate change over time for PVC and DI pipe.

Figure 32 also confirms the accuracy and consistency of the break rate data for this study by comparing the responses from the same 151 utilities that reported break rates for both 2018 and 2023 USU studies.

FIGURE 31: COMPARISON OF BREAK RATES FROM THE 2012, 2018, AND 2023 BASIC SURVEYS

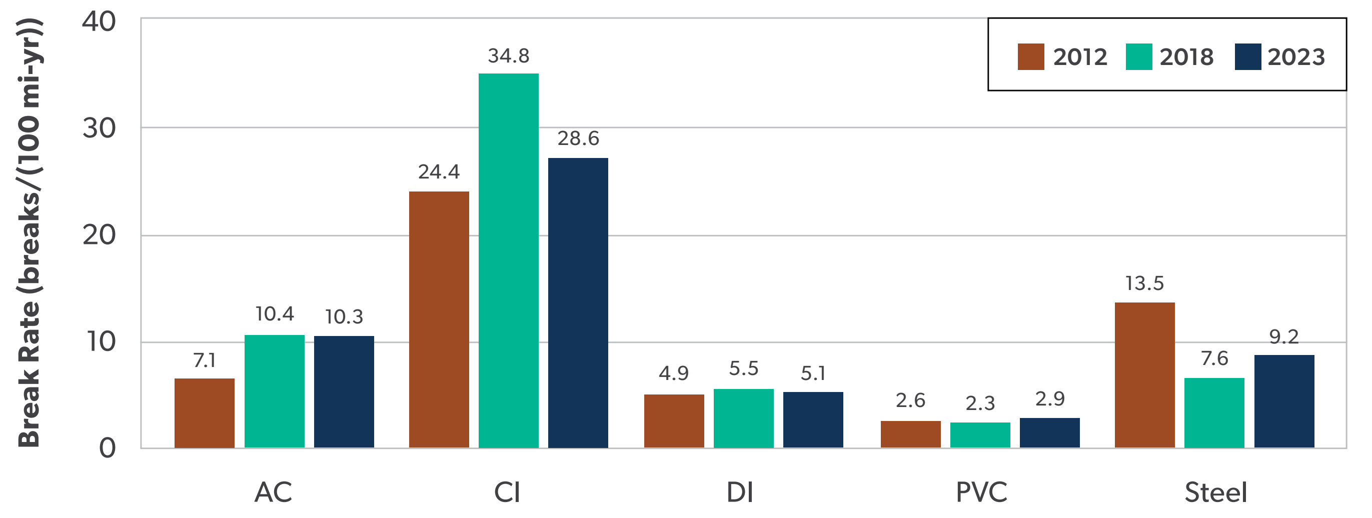
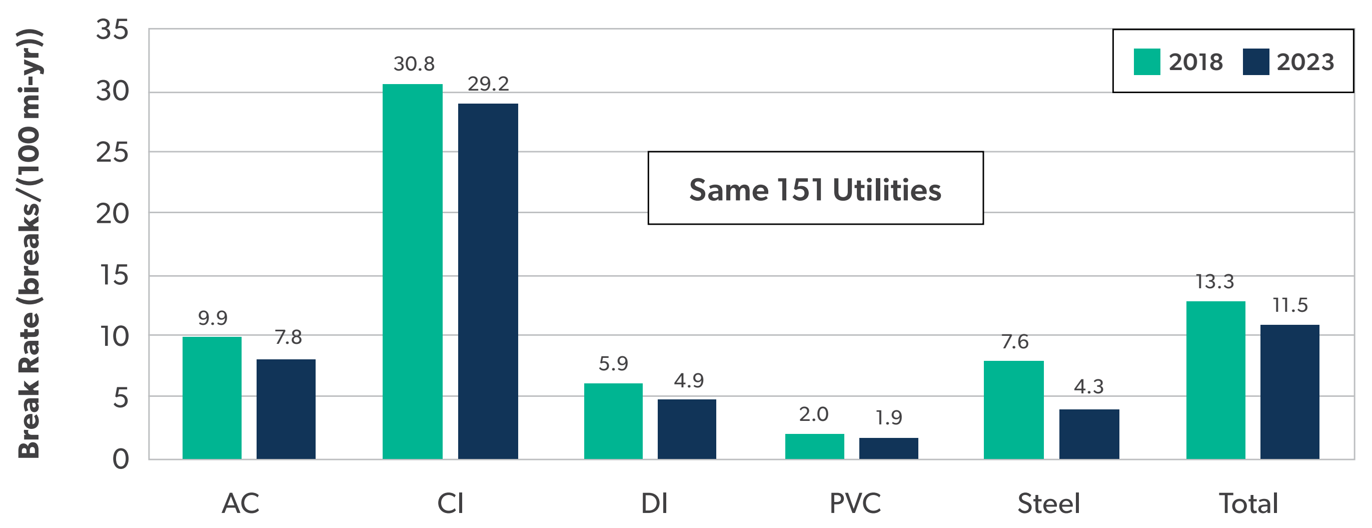


FIGURE 32: COMPARISON OF BREAK RATES FROM THE 2018 AND 2023 BASIC SURVEYS FROM THE SAME 151 UTILITIES



Survey results were also evaluated by correlating the size of a utility and its resulting break rates. Four sizes of utilities were considered based on the length of pipe in their systems:

- Small — 500 miles of pipe
- Medium — 500 to 1,500 miles of pipe
- Large — 1,500 to 3,000 miles of pipe
- Very Large — over 3,000 miles of pipe

Figures 33 and 34 show overall break rates by pipe material and utility size over 12-month and 5-year periods, respectively. It is noteworthy that both graphs show little correlation between break rates and utility size. Additionally, the break rates between the two figures are consistent.

Cast iron continues to have the highest break rate for utilities of all sizes. It can be assumed that the resulting high break rate for steel in small utilities is most likely due to it being galvanized steel.

FIGURE 33: BREAK RATES BY UTILITY SIZE FOR 12-MONTH PERIOD (BASIC SURVEY)

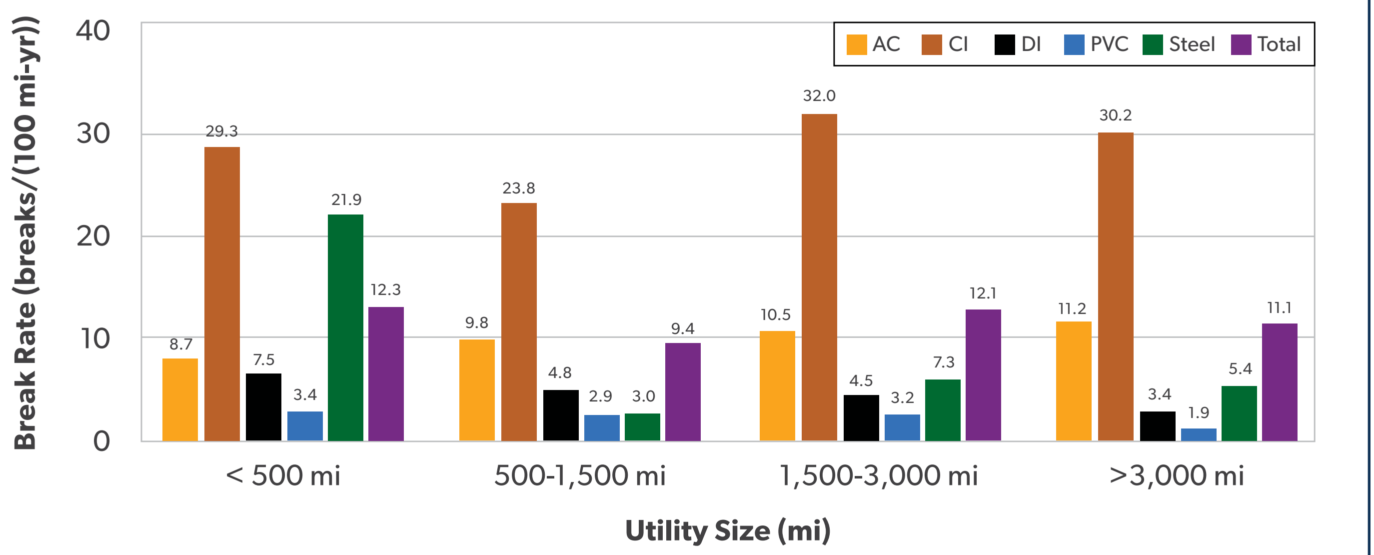


FIGURE 34: BREAK RATES BY UTILITY SIZE FOR 5-YEAR PERIOD (BASIC SURVEY)

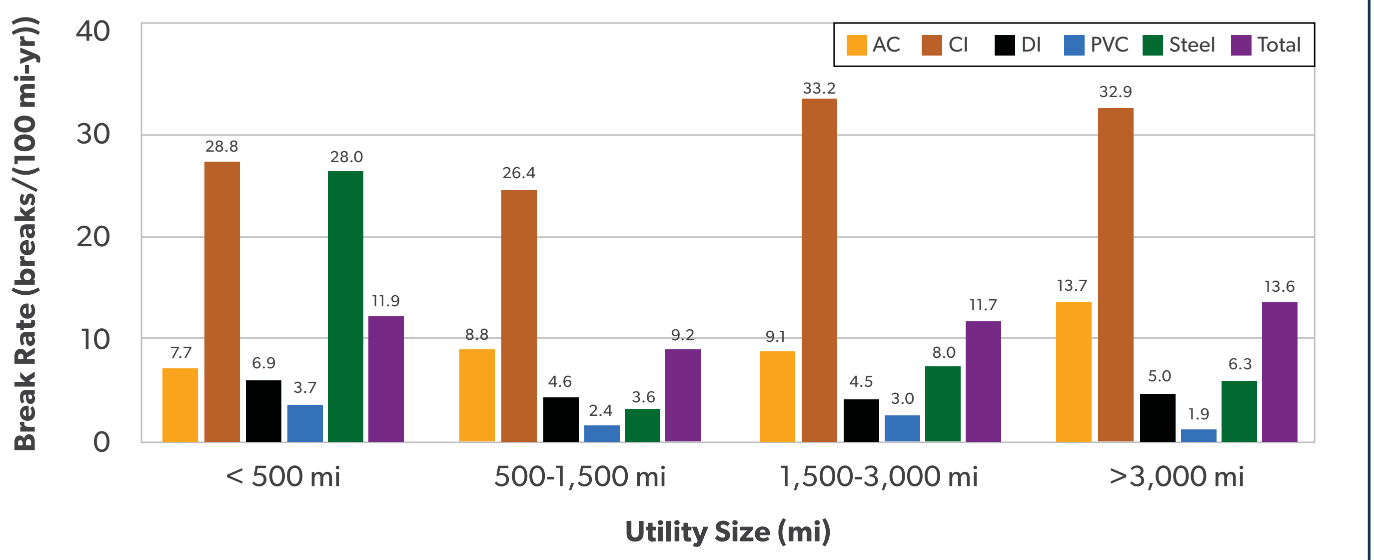


Figure 35 illustrates the reported overall break rates by region (Figure 15). In Table 1, the number of respondents for each region is summarized. Not all regions are experiencing the same failure rate. Five of the regions (4, 5, 6, 8, and 9) are above the overall average break rate.

FIGURE 35: OVERALL BREAK RATES BY REGION (BASIC SURVEY)

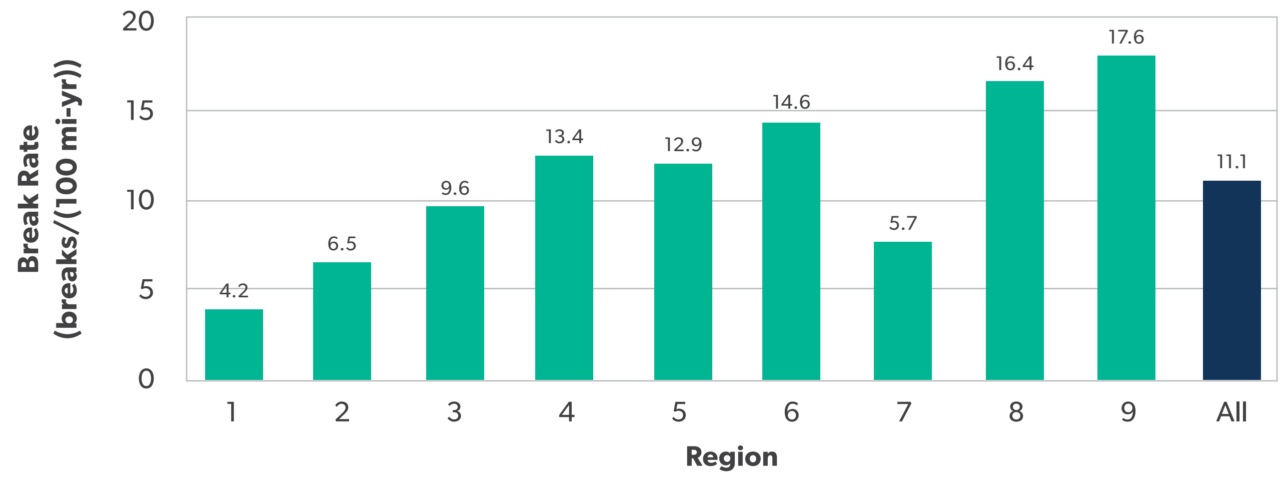
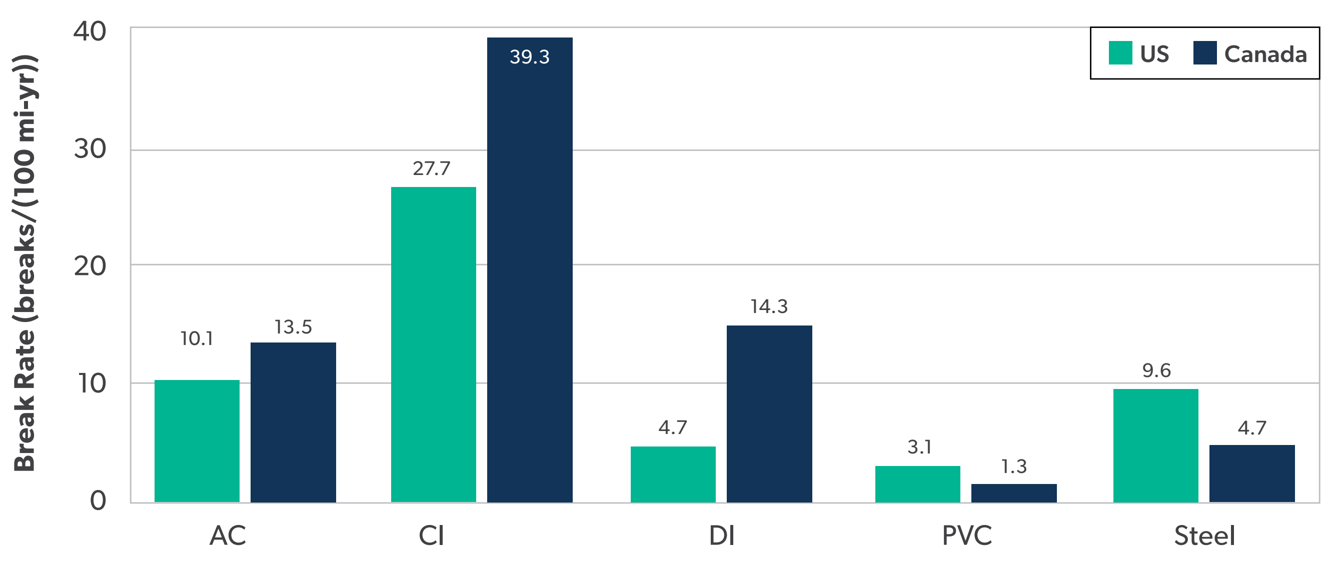


Figure 36 shows the break rates between US and Canada for the most common water pipe materials. It should be noted that portions of Canada have very corrosive soils and can have extremely cold weather. These factors could potentially explain the high Canadian break rates for CI and DI pipes (Seargeant, 2018).

FIGURE 36: BREAK RATES FROM THE US AND CANADA FOR COMMON PIPE MATERIALS (BASIC SURVEY)



5.2 Effects of Pipe Size

The detailed survey asked utilities for information on the size of different pipe materials in their water systems and their corresponding break rates. Figure 37 illustrates how the break rate changes as a function of pipe diameter. It is noteworthy that the break rate for all materials decreases as pipe diameter is increased. This is likely because of the greater effort put into installing, maintaining, and monitoring larger diameter pipes due to a higher consequence of failure. The higher break rates in larger diameters for AC and CI pipe are likely due to the low number of miles for these materials in this survey.

FIGURE 37: BREAK RATE BY DIAMETER OF PIPE MATERIAL (DETAILED SURVEY)

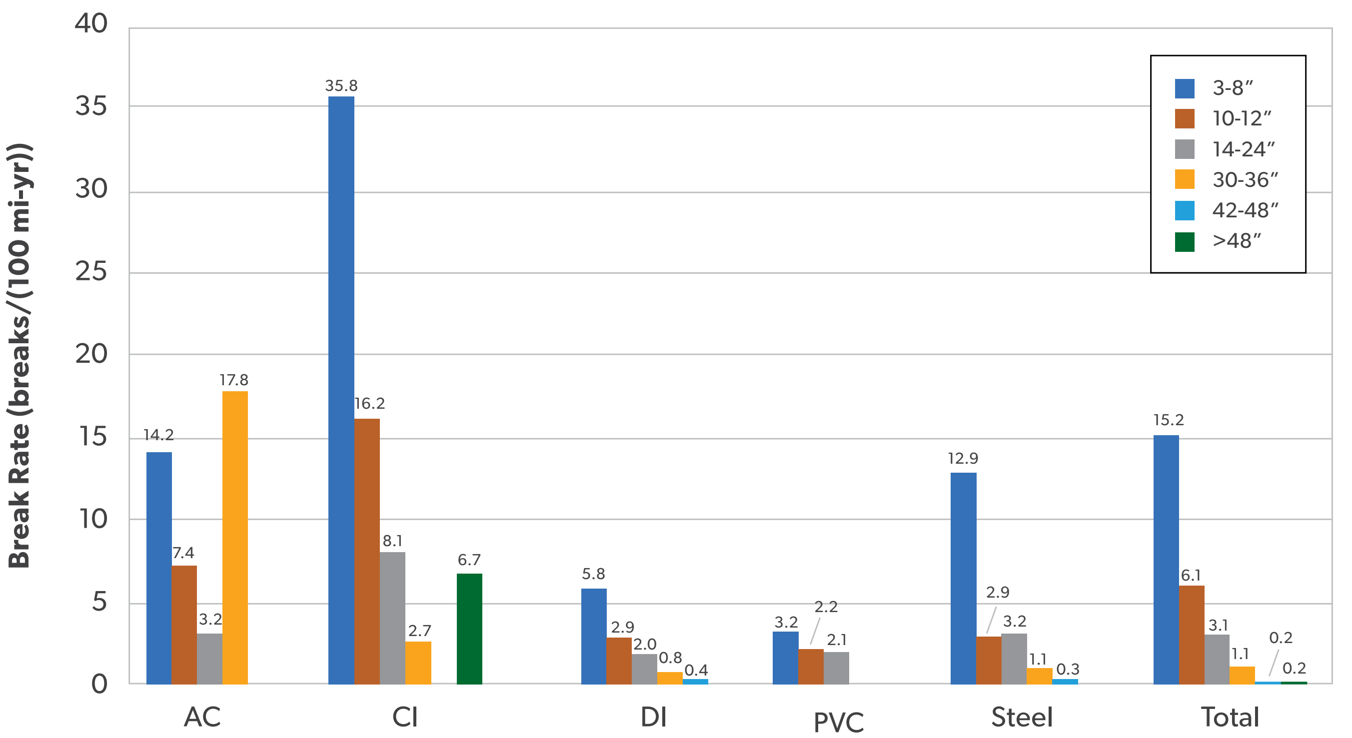


Figure 38 displays the break rates for the following size ranges: 3- to 8-inch, 10- to 12-inch, and 14- to 24-inch pipe. The objective is to focus more on the most used pipe diameters. The 14- to 24-inch sizes are commonly considered transmission mains, while 12-inch pipe and smaller is usually categorized as distribution pipe. Figure 23 indicates that 86% of all miles of water pipes are 3- to 12-inch in diameter, and a total of 68% are 3- to 8-inch in size.

FIGURE 38: BREAK RATES FOR 3- TO 8-INCH, 10- TO 12-INCH, AND 14- TO 24-INCH PIPE BY MATERIAL (DETAILED SURVEY)

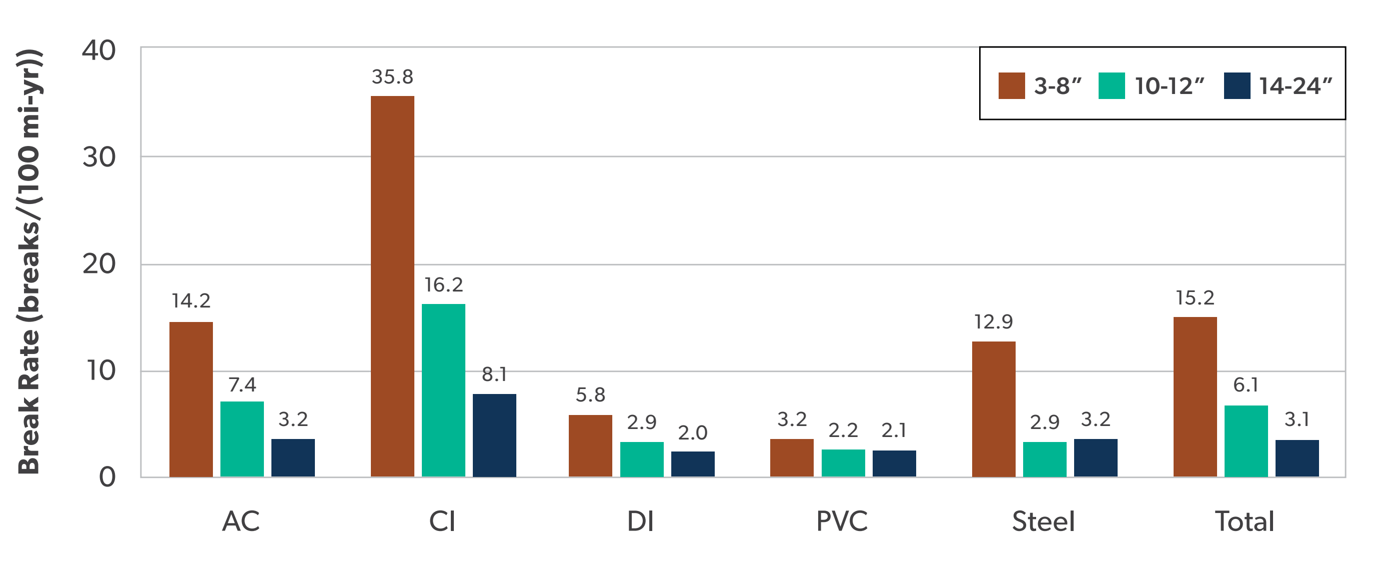


Figure 39 illustrates the break rate of 3- to 12-inch pipe, while Figure 40 indicates the break rates of 3- to 8-inch pipe. Comparing these two figures shows a small difference in break rates. The 3- to 12-inch diameter range represents 86% of all pipe materials.

FIGURE 39: BREAK RATES OF 3- TO 12-INCH PIPE BY MATERIAL (DETAILED SURVEY)

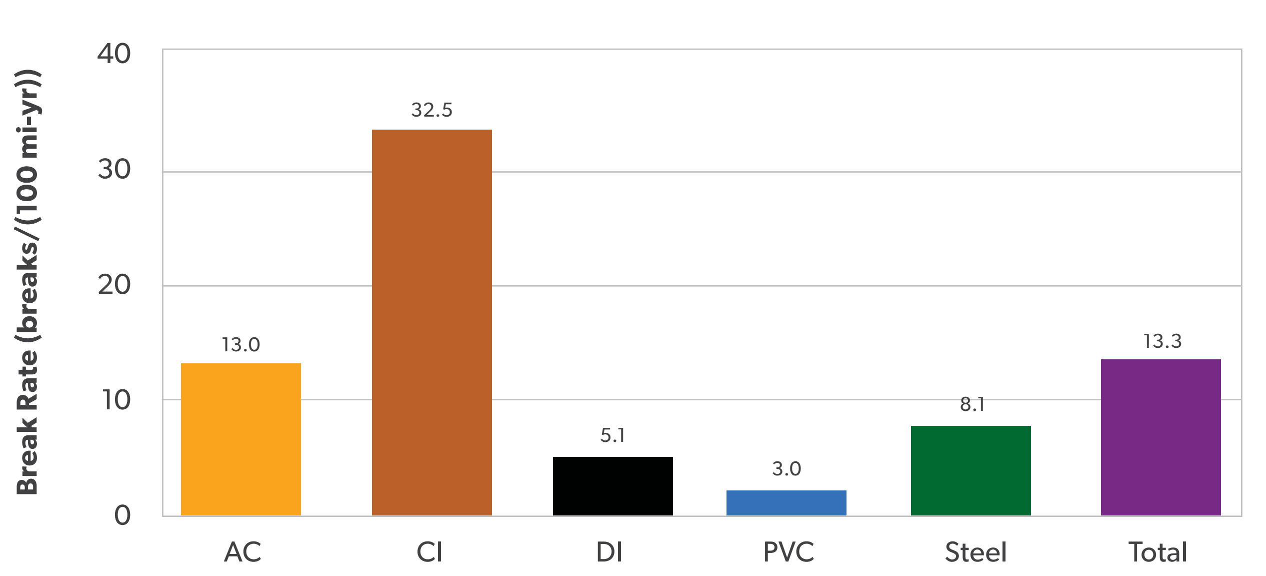
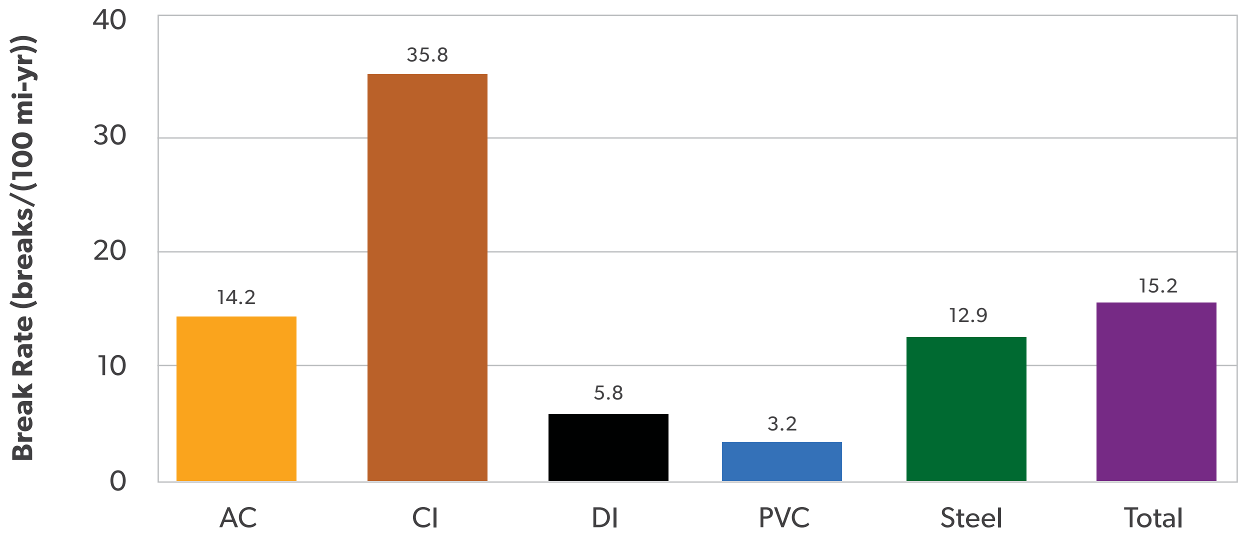


FIGURE 40: BREAK RATES OF 3- TO 8-INCH PIPE BY MATERIAL (DETAILED SURVEY)



5.3 Pipe Reliability Across Size Ranges

Table 6 summarizes the break rates by pipe material when comparing transmission (14-inch and larger) to distribution (3- to 12-inch diameter) pipe sizes and calculates the percent increase from transmission to distribution. Overall distribution main failure rates at 13.3 breaks/(100 mi-yr) are 505% higher than for transmission mains at 2.2 breaks/(100 mi-yr). The table shows that some materials have significantly large differences in break rates across size ranges.

TABLE 6: PERCENT INCREASE OF BREAK RATES FROM TRANSMISSION TO DISTRIBUTION MAINS BY MATERIAL (DETAILED SURVEY)

	Transmission Main Break Rates (≥14”)	Distribution Main Break Rates (3”-12”)	Percent Increase
AC	3.5	13.0	271%
CI	7.2	32.5	351%
DI	1.8	5.1	183%
PVC	2.1	3.0	43%
Steel	1.1	8.1	636%
Other	1.0	14.3	1,330%
Total	2.2	13.3	505%

5.4 Target Replacement Break Rate

According to AWWA, water mains should be replaced to improve water quality, hydraulics, and structural integrity, which reduces leakage, repairs and maintenance costs and improves system reliability (AWWA, 2014). For small diameter pipes, replacement may be more cost-effective than making structural improvements. The AWWA Partnership for Safe Water (PSW) performance improvement program states *the optimization goal for main break frequency annually is a maximum of 15 for each 100 miles of distribution pipelines…A reduction in the main break frequency (rolling 5-year trend) is an indication of progress toward optimized performance* (AWWA, 2011).

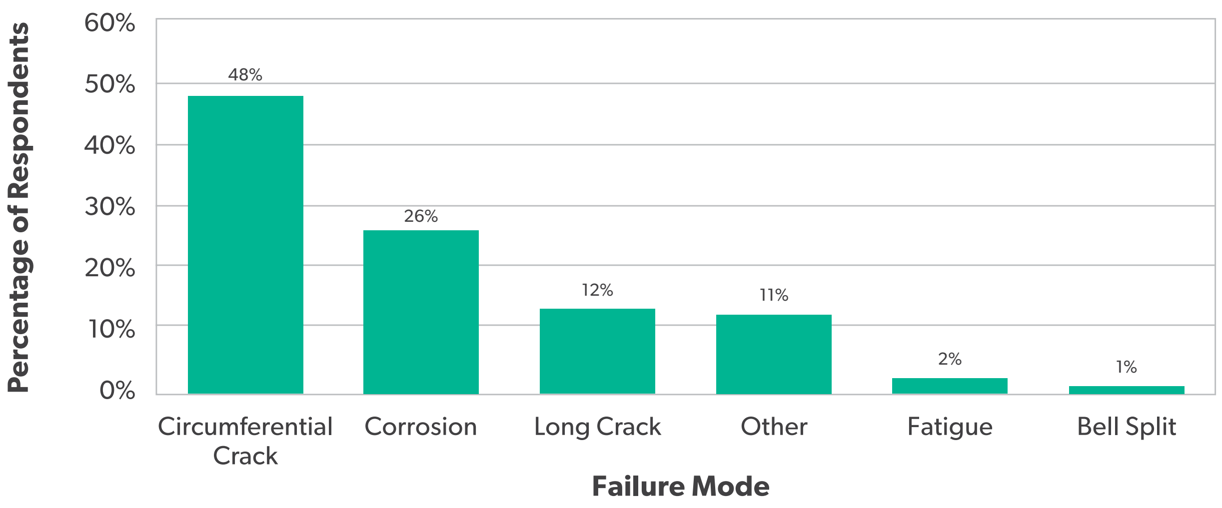
The detailed survey asked participants if they had a target break rate at which pipe replacement was implemented. Only 20% of the respondents replied, providing an average target rate of 21 breaks/(100 mi-yr). The low number of responses may indicate a need for a greater focus on using failure rate targets for water main replacement decisions. A 2017 study confirms the importance of system rehabilitation plans and the societal costs of water main breaks. Indirect costs such as customer outages, travel delays, health effects, and property damage account for more than 59% of the average failure cost (Yerri, 2017).

5.5 Most Common Failure Age and Mode

The detailed survey asked participants the typical pipe age of water main failures. The average response was 53 years with a range of 10 to 130 years. In 2012 and 2018 the average age of failing water mains was reported as 47 years and 50 years, respectively. This value has not changed significantly over the past decade.

Pipe breaks are complex and can be caused by multiple factors. Accordingly, the detailed survey requested participants to select the most common failure mode from the following: corrosion, bell split, circumferential crack, longitudinal crack, fatigue, or other. Figure 41 illustrates that a circumferential crack is the most common at 48%, followed by corrosion at 26%.

FIGURE 41: MOST COMMON FAILURE MODES (DETAILED SURVEY)



6.0 Corrosive Soils and Corrosion Prevention Methods

The detailed survey asked utilities if they have one or more locations in their service area with soils that are corrosive. A total of 75% reported having at least one area with corrosive soils. This corresponds to the results found in the 2012 and 2018 surveys. The survey also asked about their use of corrosion protection methods. A total of 73% answered that some kind of corrosion protection technology is utilized. They were also asked to list the most common method(s) used. Polyethylene encasement (polywrap) was the most approved followed by cathodic protection. See Table 7 for the complete list, ranked by 1 being the most common to 5 being the least. Without corrosion protection, it is assumed that break rates for metallic piping (CI, DI, and steel) will be significantly higher.

TABLE 7: 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

6.1 Additional Corrosion Studies

A 2018 Water Research Foundation (WRF) study titled, "Water Main Break Findings: Practical Condition Assessment and Failure Probability Analysis of Small Diameter Ductile Iron Pipe," states that *[S]mall diameter DIPs (pipes with diameter less than or equal to 12 inches) have thinner walls as compared to large diameter DIPs (pipes with diameter greater than 24 inches). As a result, wall penetrations due to corrosion can occur in a shorter period of time* (Kumar, 2018). The study surveyed utilities and found that *the average total number of failures per year per 100 miles of small diameter DI pipe* [less than 12-inch] *was 15.1 breaks/year/100 miles* (Kumar, 2018).

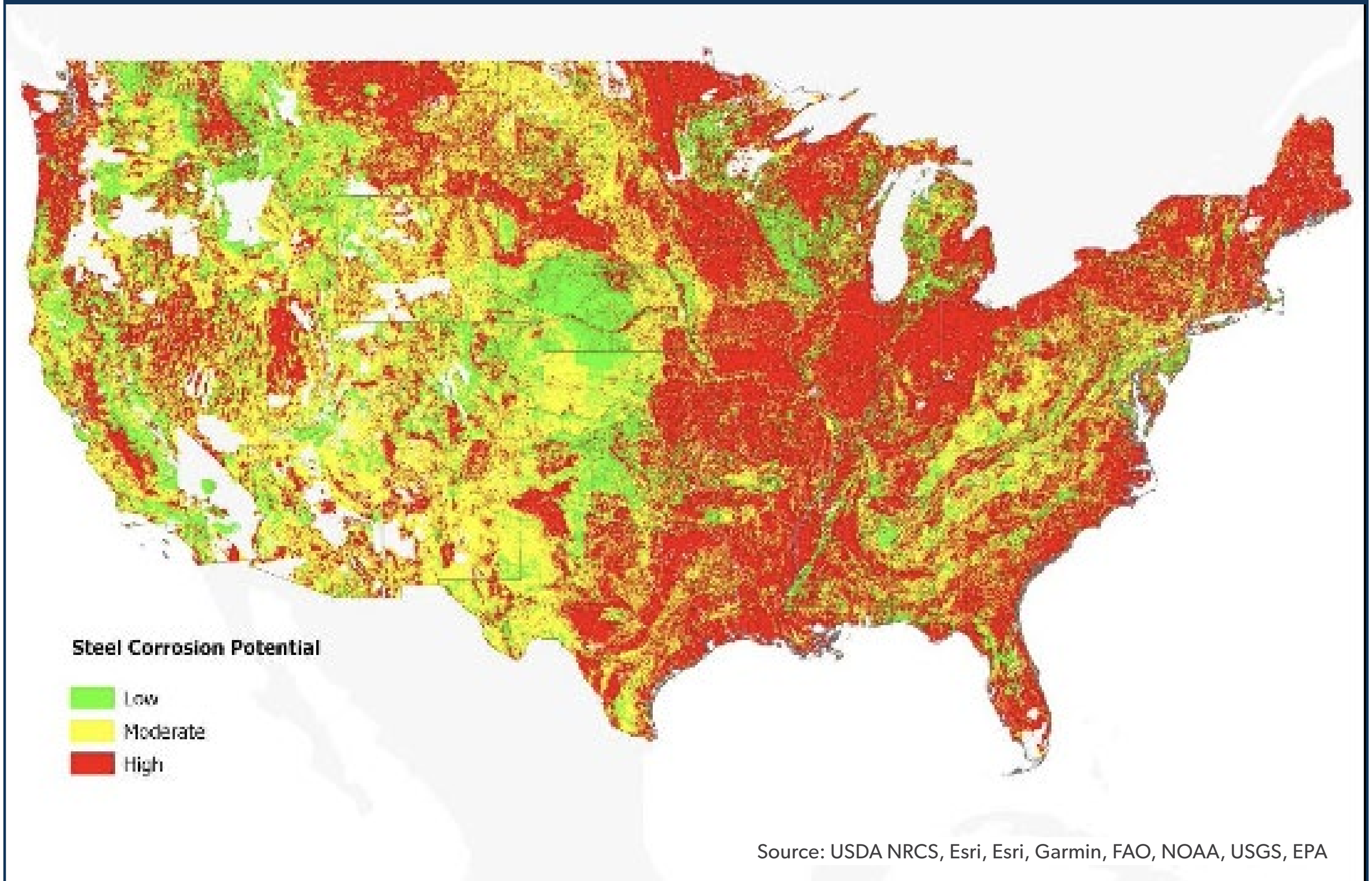
This 2023 USU study also found the same correlation between higher break rates and smaller diameter DI pipe. However, this current study, which has a much larger data set, reports a DI break rate of 5.1 for diameters 12-inch and less. Regarding pipe wall thickness, another WRF study found that *thinner pipe wall will be perforated* [due to corrosion] *faster than thicker wall* (Rajani, 2011). These research reports indicate that thicker class DI pipes may be considered by utilities as a corrosion protection method. The 2023 USU study did not account for the performance of varying corrosion mitigation methods for metallic pipes nor DI pipe wall thicknesses as they relate to water main break frequency.

6.2 Effect of Corrosive Soils on Break Rate

The USDA Natural Resources Conservation Service has developed a soil survey map showing areas where there is a "risk of corrosion" potential from soil-induced electrochemical or chemical action that corrodes or weakens uncoated steel. Soils are rated as either "low," "moderate," or "high" risk based on moisture, particle size, acidity, and electrical conductivity measurements. This can be found on USDA's Soil Survey Geographic Database (SSURGO) which can be viewed on ArcGIS to produce plots, showing low-risk areas in green, moderate-risk areas in yellow, and high-risk areas in red.

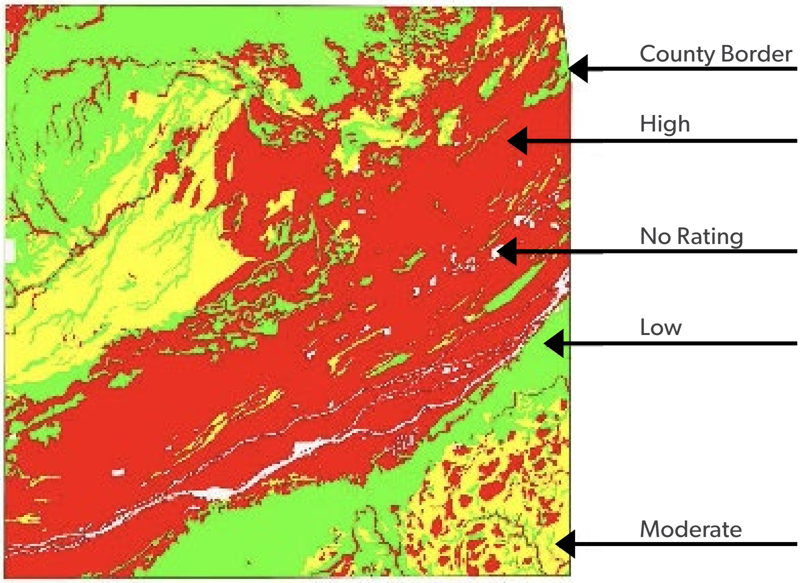
An overview of soils across the US is illustrated in Figure 42. Soil risk can change over very short distances as demonstrated in Figure 43, which shows a screen capture of soil risk conditions inside the boundaries of a county in Nebraska. This county provides an example of all three levels of soil corrosivity: low (green), moderate (yellow), and high (red). Soil analysis data are not available in areas colored light gray. For the 2023 report, each color was assigned an index number, with green = 1, yellow = 2, red = 3. ArcGIS computed the corrosion indices for each US county where one or more utilities were located by weighting the percentage of each color within the area.

FIGURE 42: US CORROSIVE SOILS MAP (POTENTIAL FOR STEEL CORROSION)



Source: USDA NRCS, Esri, Esri, Garmin, FAO, NOAA, USGS, EPA

FIGURE 43: COUNTY MAP SHOWING CORROSIVE SOIL RISK

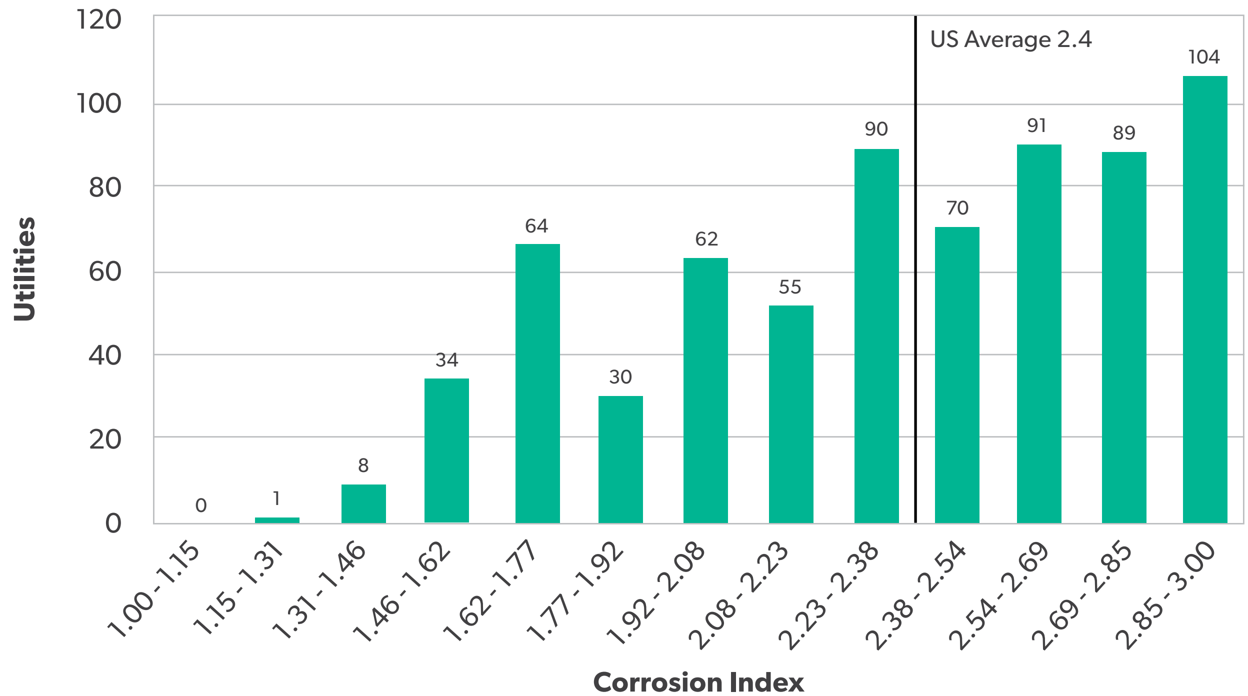


Source: USDA NRCS, Esri, Nebraska Gake & Parks Commission, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS

Corrosion index values were computed for 458 counties in the US. For example, the county shown in Figure 43 generated a corrosion index of 2.2, which is slightly above a moderate level. Some US counties had little or no data for the soils inside their boundaries, preventing determination of a corrosion index.

The corrosion index value calculated for each county was placed into one of thirteen range categories, shown in Figure 44.

FIGURE 44: NUMBER OF UTILITIES FOR EACH CORROSION INDEX GROUP



The average corrosion index for all the US utilities in the basic survey was found to be 2.37 or close to midway between moderate and high corrosion risk. Notably, the overall corrosion index of the US from Figure 44 is 2.4. 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 soil.

It is reasonable to expect that break rates will increase when metallic pipe is installed in corrosive soils. Plots were made to examine a utility's corrosion index versus break rate. Table 8 distributes the break rates of CI and DI pipe into thirteen corrosion index ranges where the number of utilities represented in each range is approximately equal. The results are listed in Table 8. These data are then plotted in Figure 45 for CI and Figure 46 for DI pipe. The figures also contain a regression equation fit and a correlation coefficient. Correlation coefficients close to 1.0 indicate an excellent statistical relationship and a zero suggests no correlation. The DI regression produced a reasonably good correlation. It should be noted that a low correlation exists between soil corrosivity and CI break rates. This may be due to CI pipe's thicker walls and material properties making failure rates for CI more a factor of pipe age than soil corrosivity.

TABLE 8: BREAKDOWN OF CORROSION INDEX VALUES (BASIC SURVEY)

Category	Corrosion Index Range	No. of Utilities	Average Corrosion Index		Break Rates (breaks/(100 mi-yr))	
			Cast Iron	Ductile Iron	Cast Iron	Ductile Iron
1	1.00 – 1.66	48	1.46	1.49	22.1	2.2
2	1.66 – 1.78	60	1.71	1.70	13.6	3.5
3	1.78 – 1.99	53	1.90	1.90	27.7	2.5
4	1.99 – 2.12	54	2.07	2.05	27.4	3.4
5	2.12 – 2.25	54	2.21	2.20	14.1	3.2
6	2.25 – 2.32	53	2.30	2.30	26.2	4.2
7	2.32 – 2.45	53	2.39	2.40	19.1	3.6
8	2.45 – 2.57	52	2.51	2.51	34.9	4.4
9	2.57 – 2.66	54	2.60	2.60	29.9	5.3
10	2.66 – 2.75	54	2.70	2.69	27.1	5.7
11	2.75 – 2.84	55	2.80	2.80	27.1	5.2
12	2.84 – 2.92	65	2.86	2.86	35.8	4.5
13	2.92 – 3.00	58	2.96	2.97	28.5	6.7

FIGURE 45: CAST IRON PIPE BREAK RATE BY CORROSION INDEX (BASIC SURVEY)

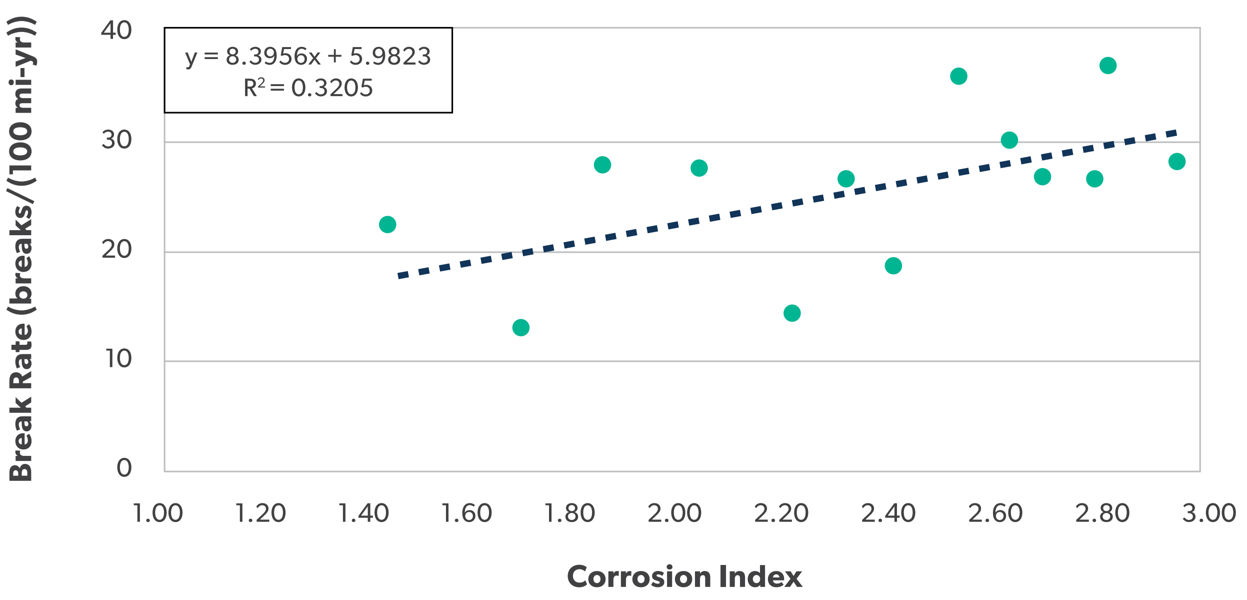
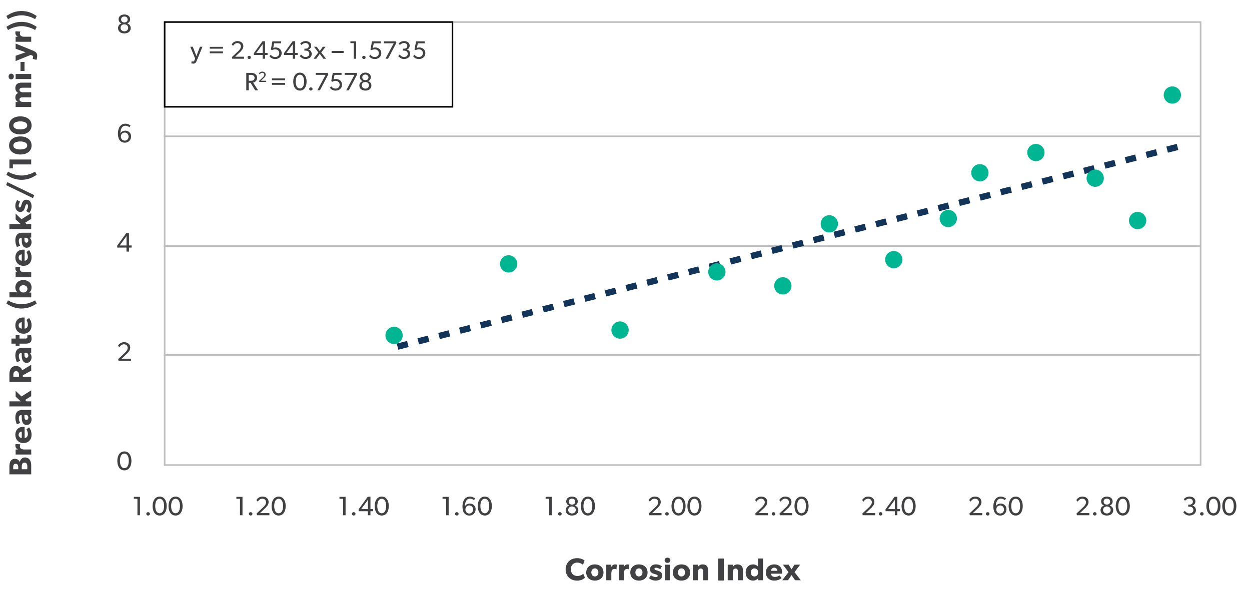


FIGURE 46: DUCTILE IRON PIPE BREAK RATE BY CORROSION INDEX (BASIC SURVEY)



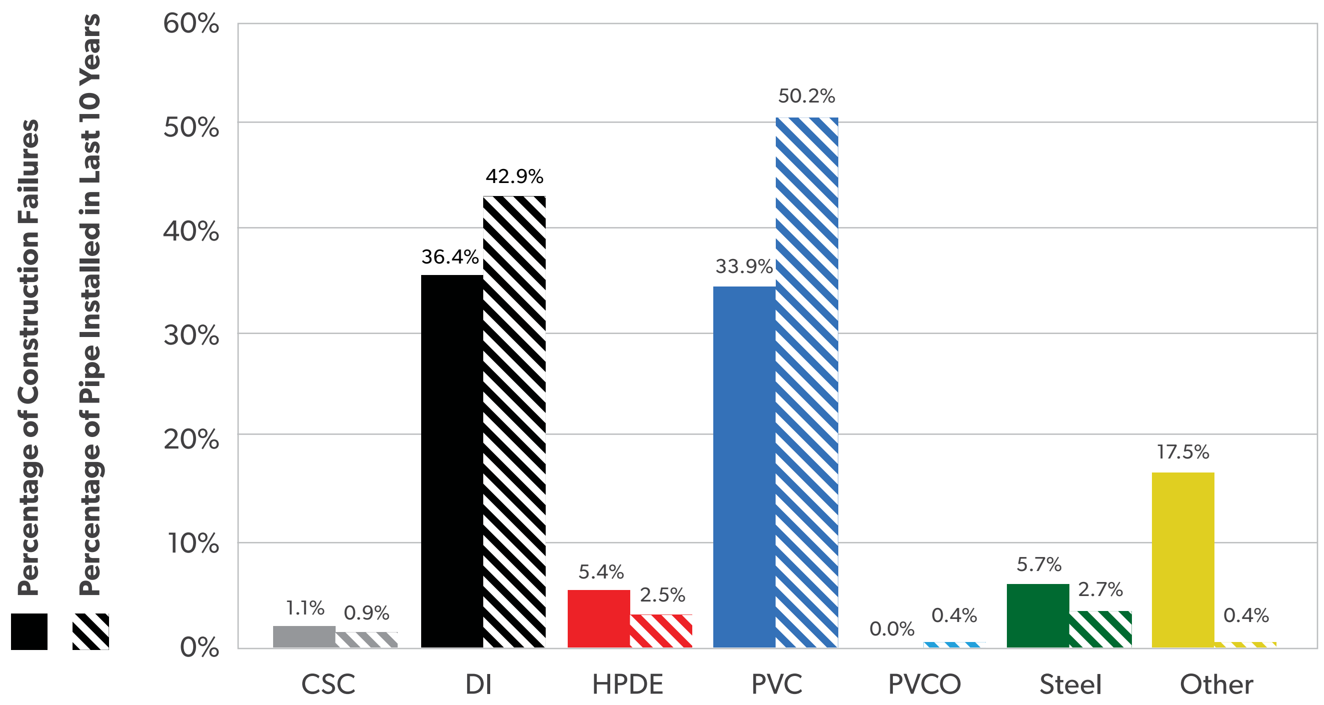
The slope of the line in Figure 45 demonstrates that CI pipe in highly corrosive soil (corrosion index of 3.0) is expected to have more than twice the break rate of one in low corrosive soil (corrosion index of 1.0). Similarly, Figure 46 shows that DI pipe in highly corrosive soil (corrosion index of 3.0) will have a break rate approximately six times greater than one in low corrosive soil (corrosion index of 1.0). Very poor correlations were found for all other pipe materials in this survey. It is understood that other factors not included in the survey may contribute to DI and CI pipe's failure rates.

7.0 Construction-Related Failures

The detailed survey asked respondents to report failures related to construction activities. Figure 47 illustrates the percentage of total construction failures related to a particular pipe material (indicated by the solid bar). Ductile iron and PVC pipes have the most construction-related failures, with DI reporting a slightly higher number at 36.4% compared to PVC at 33.9%. As previously shown in Figure 12, DI and PVC are the two most installed pipe materials today, and accordingly, it is expected that these two would experience the highest number of failures during or after installation. Because AC and CI pipe are no longer installed, they were not included. The "Other" category in Figure 47 includes outlier materials such as wood and fiberglass, as well as "Unknown" pipe materials.

For each pipe material, the hashed bar represents the percent of total installed length over the last 10 years. While DI and PVC have a high number of construction-related failures, they also have the most installed length. In contrast, HDPE and steel have a low number of construction-related failures and a low installed length compared to DI and PVC. Whenever the hashed bar is higher than the solid bar, it indicates that the material has comparatively lower construction-related damage.

FIGURE 47: PERCENTAGE OF TOTAL REPORTED CONSTRUCTION-RELATED FAILURES (DETAILED SURVEY)



8.0 Water Main Replacement Planning

The detailed survey asked respondents about expected pipe life and pipe replacement. The answers are summarized in Table 9. The average age of failing water mains was 53 years (up from 50 in 2018 and 47 years in 2012), which is well below what most manufacturers claim. In contrast, the average reported expected life for all pipe is 78.4 years (this value was 84 years in 2018 and 79 years in 2012). The typical age of failing water mains and expected pipe life have not changed significantly over the last eleven years.

Both the basic and detailed surveys showed that approximately 70% of utilities have a pipe replacement program. 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 19.4%. The response in the 2012 and 2018 surveys was 8.4% and 16%, respectively. These trending responses indicate that the need for pipe replacement is growing.

TABLE 9: QUESTIONS ABOUT REPLACEMENT OF FAILING WATER MAINS

Question Topics	Average or Response
Average age of failing water mains	53 years
Average expected life of new water mains	78 years
Percentage with a pipe replacement program (basic survey)	70%
Percentage with a pipe replacement program (detailed survey)	69%
Average percentage of water mains beyond useful life but lack funds to replace	19.4%

In 2018, the detailed survey determined that the average replacement rate for water mains was 125 years. The 2023 survey did not repeat this question. However, when asked what length of pipe is planned as part of a replacement program, the average response was 4.4 miles. Generally, most utilities target a 1% annual replacement rate, representing a 100-year replacement cycle. The percentage of water utilities regularly replacing water mains increased from 58% in 2018 to 69% in 2023, which aligns with the recorded reduction of CI and AC pipe in this study.

The average age of a failing water main is 53 years old. In addition, 33% of installed pipe in the US and Canada is over 50 years old, representing approximately 770,000 miles of piping. Furthermore, a total of 19.4% of installed water mains, representing 452,000 miles of the total estimated 2.33 million miles of pipe in the US and Canada, were reported to be beyond their useful lives but have yet to be repaired or replaced due to lack of funds. These figures highlight the need for replacement programs.

In order to cover the costs of these replacement needs, significant funding will be required. Applying an example replacement cost of $1 million per mile ($189 per linear foot), the total funding shortfall needed to replace the 452,000 miles would be approximately $452 billion. Study results indicate that 43.5% of utilities do use some form of regular condition assessment of their water mains. This highlights the need for pipe performance data and pipe condition assessment as part of a cost-effective asset management program.

9.0 Approved Pipe Materials

The detailed survey asked respondents what water main pipe materials are currently approved for use at their utility. Accepted pipe materials do not necessarily represent what is actually installed by a utility (Figure 12). Figure 48 illustrates the percentage of respondents that allow a particular pipe material to be installed (indicated by a solid bar).

For each material, the hashed bar represents the percent of total installed length over the last 10 years. For example, DI and PVC have a high acceptance rate and the most installed length. In contrast, HDPE is also commonly approved but only a small amount has been installed. Steel, CSC, and PVCO have both low acceptance rates and installed length. Pipe materials that have the largest difference between solid and hashed bars indicate that, although they may be accepted, they may only be used in specific applications.

FIGURE 48: PERCENTAGE OF UTILITIES ALLOWING USE OF WATER MAIN MATERIALS (DETAILED SURVEY)

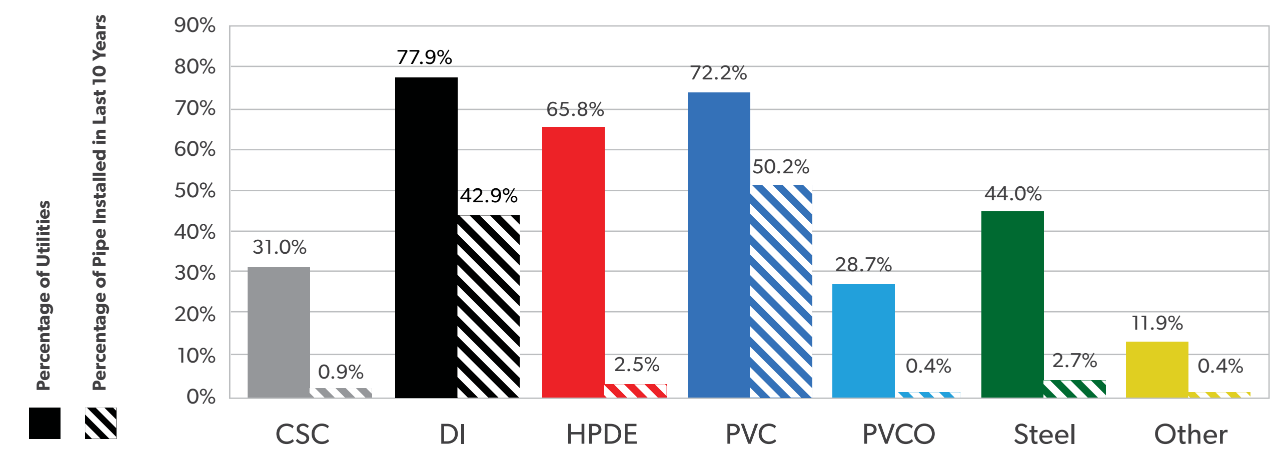
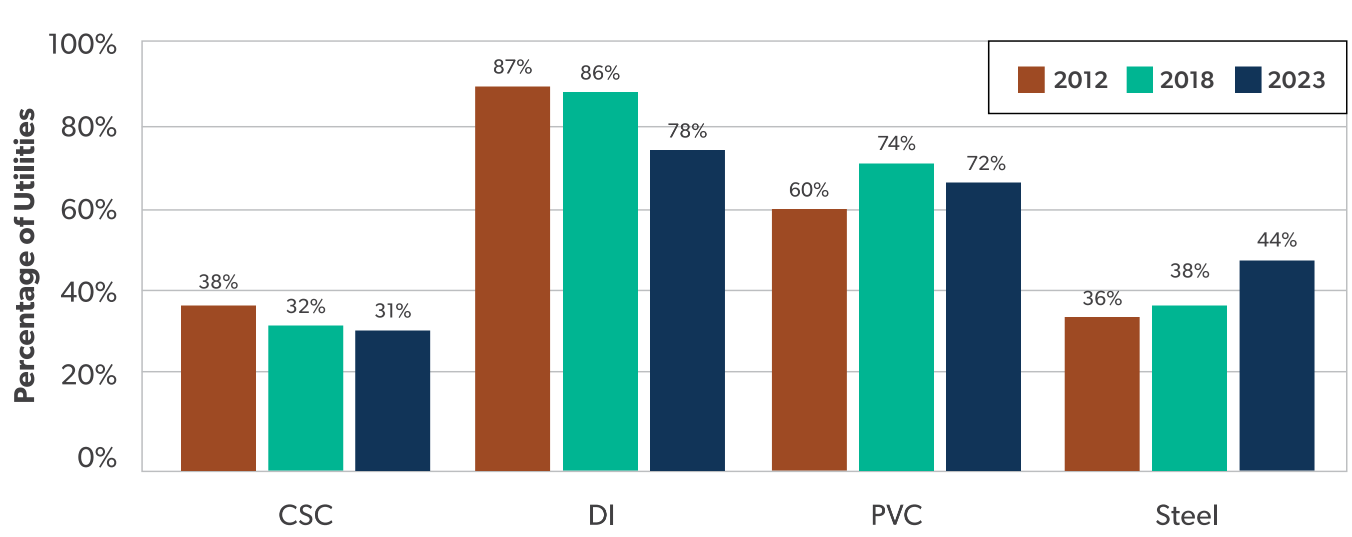


Figure 49 compares the pipe materials approved for use by utilities in the 2023 survey along with the data obtained in the 2012 and 2018 surveys; CI and AC are not listed because these materials are no longer manufactured. The number of utilities approving CSC and PVC pipes for use in water systems remained essentially the same as in 2018. The largest change is the 8% reported reduction in the acceptance of DI water pipe. The next largest change is the 6% increase in percentage of acceptance of steel pipe. It is important to note that HDPE and PVCO were not included in Figure 49 due to limited usage and data from the 2012 USU report. However, between 2018 and 2023, the percentage of acceptance for HDPE and PVCO did not significantly change. For comparison, Figures 17 through 19 illustrate actual pipe use across the three study periods by region.

FIGURE 49: COMPARISON WITH PREVIOUS SURVEYS FOR ALLOWED MATERIALS (DETAILED SURVEY)



10.0 Preferences for Pipe Installation

The detailed survey asked respondents about their experiences with installing, rehabilitating, and replacing water main pipes. This includes installation of new pipe using open-cut or directional drilling, relining deteriorating pipes, and replacing pipes utilizing pipe bursting. Table 10 summarizes the responses. The table uses a scale from 1 to 5, with 1 being "Not Satisfied" to 5 being "Very Satisfied." Not many utilities use pipe bursting, but an increasing number are considering this technique along with pipe relining and directional drilling. Open-cut is the most widely accepted method of pipe installation.

TABLE 10: PIPE INSTALLATION METHODS (DETAILED SURVEY)

	Open-Cut	Directional Drilling	Pipe Relining	Pipe Bursting
Percentage of respondents who have used this technique	93%	65%	32%	18%
Reported materials used	DI, PVC, HDPE*	HDPE, PVC, DI, Steel	Epoxy, CIPP**	PVC, HDPE
Average Rating 1 to 5	4.6	4.5	4.0	3.5
Percentage of respondents who will use this technique in the future	98%	85%	68%	55%
Comments	This installation method is standard but can be slower.	This installation method works well for river, railroad, and street crossings.	This installation method has higher cost but causes minimal disruptions and is used when open-cut is not feasible, primarily for large diameter pipe.	This installation method has higher costs and is useful when other methods are not feasible.

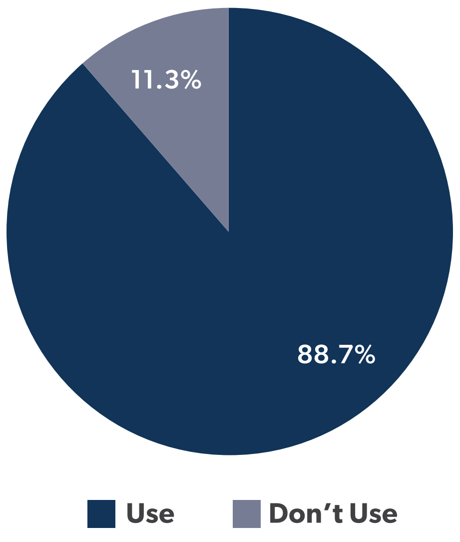
*Very few responses submitted (less than 5%).
**CIPP stands for Cured-In-Place-Pipe.

11.0 Infrastructure Asset Management

An overall objective of the 2023 USU study is to provide water utilities and asset managers with additional insight to support improved water pipe asset management. The comprehensive nature of the 2023 survey and the participation of over 800 water utilities in the US and Canada alone suggests that since 2012 more water utilities have been collecting data on their water pipes. To accomplish this, water utilities have been populating underground water infrastructure data (linear assets) in a geographic information system (GIS). GIS is a core technology component of asset management and can be integrated as part of a larger work order computer maintenance management system (CMMS) or asset management system. When survey respondents were asked about their use of GIS, 88.7% confirmed GIS capabilities. Figure 50 illustrates the reported GIS users and nonusers.

Accurate pipe performance metrics and service life estimates are critical to the effective management of underground infrastructure. This study provides accurate infrastructure data which can be used to improve life cycle costing analysis of water pipelines. Pipe break rate information can help to precisely assess the performance and longevity of pipe networks.

FIGURE 50: SURVEY QUESTION ON USE OF GIS (BASIC SURVEY)

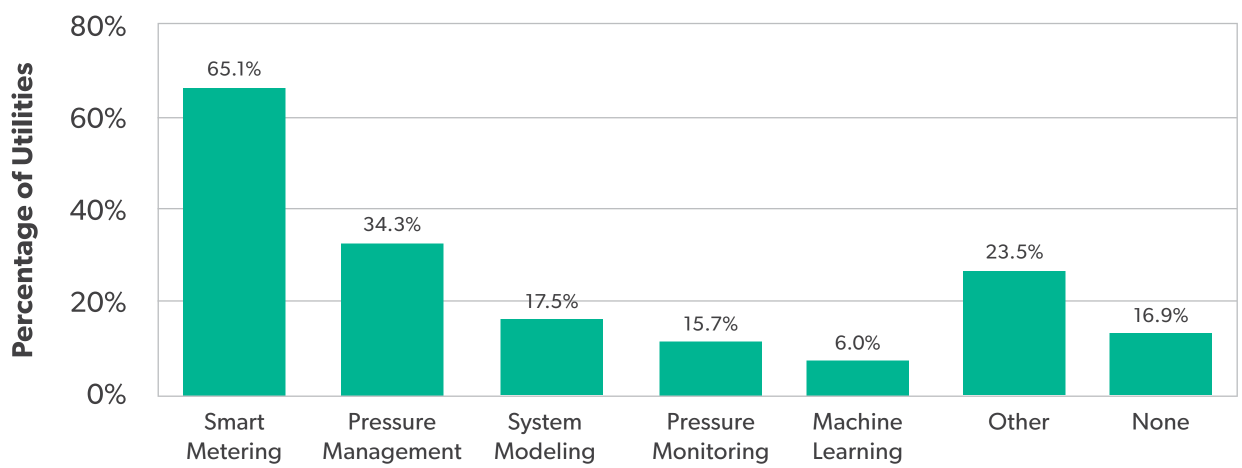


11.1 Digital Asset Management

Digital technologies are increasingly being used by utilities as an asset management tool. These technologies help provide insight into which assets are critical to sustain an acceptable level of service and assist with operations and maintenance, saving staff time and avoiding water service disruptions.

The detailed survey asked respondents about their usage of five different digital technologies: smart metering/advanced metering, system-wide pressure management, real-time system modeling, high-frequency pressure monitoring, and artificial intelligence/machine learning for condition assessment. The "Other" category includes technologies such as: leak detection, supervisory control and data acquisition (SCADA) software, risk modeling, etc. Figure 51 shows the percentage of utilities that use the listed technologies.

FIGURE 51: UTILITIES USING DIGITAL TECHNOLOGY IN ASSET MANAGEMENT (DETAILED SURVEY)



12.0 Conclusion

This report summarizes one of the most comprehensive and statistically significant water main break studies ever accomplished on underground infrastructure. This study focused on water main material, pipe diameter usage, age, trends in material use, break rates, effects of soil corrosion, and utility size characteristics in the US and Canada. The study was successful in getting 802 participants to respond to a basic survey and 172 utilities to respond to a detailed survey. The primary goal of the study was to obtain average values for water main break rates by pipe material and diameter. These results are presented in Section 5, and summarized in Figure 52. Study results indicate that PVC has the lowest break rate of the most commonly used water pipe materials.

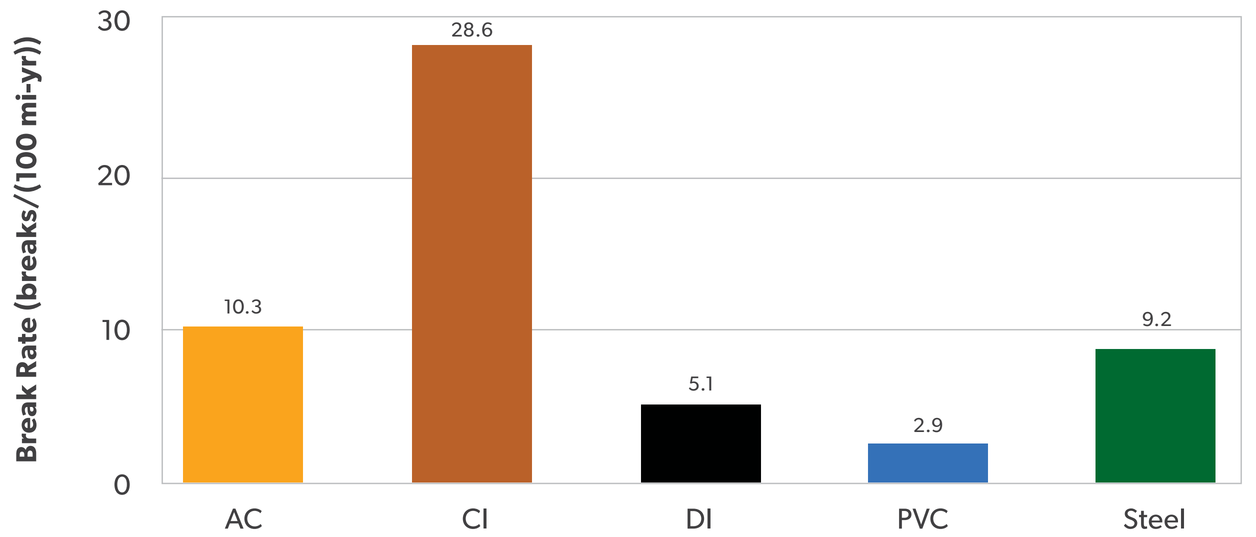
The data generated from this study enables utility managers to compare the performance of their pipe systems with the survey results to improve asset management and procurement practices. Through greater understanding of the risks and issues regarding the performance of water infrastructure, utilities can better manage their pipe systems.

12.1 Significant Results from This Study

Highlights of this water main break report include:

- Much larger sample size (utility response) compared to previous reports: Sections 2.1, 2.6 (Table 3)
- Population and pipe mileage data across the US and Canada: Section 2.5 (Figures 10 – 11)
- Trends in use of pipe materials when comparing 2012, 2018, and 2023 surveys: Section 3.0 (Figures 17 – 19)
- Pipe age and size distribution: Section 3.1 (Figures 20 – 25)
- PVC break rates are the lowest of the most common pipe materials: Section 5.1 (Table 5 and Figure 28)
- Failure rate data for five commonly used pipe materials: Section 5.1 (Table 5 and Figure 28)
- Pipe break rates as a function of utility size: Section 5.1 (Figures 33 – 34)
- Break rate comparisons by pipe diameters: Sections 5.2, 5.3 (Figure 37 and Table 6)
- Analysis of the impact of soil corrosiveness on break rates: Section 6.2 (Table 8 and Figures 45 – 46)
- Data on water main replacement programs: Section 8.0 (Table 9)
- Percentage of utilities that allow use of different pipe materials: Section 9.0 (Figures 48 – 49)

FIGURE 52: OVERALL BREAK RATES OF PIPE MATERIAL (BASIC SURVEY)



12.2 The Primary Researcher

Steven L. Barfuss is a professor in the Department of Civil and Environmental Engineering at Utah State University in Logan, Utah. He is the Associate Director of the Utah Water Research Laboratory (UWRL), where he has performed research on hydraulic structures and appurtenances for more than 37 years.

The UWRL is a world-renowned water research laboratory where environmental, water resource, hydrologic, and hydraulic water problems are studied. The hydraulics laboratory at the UWRL has one of the largest flow capacities in North America, with testing capability up to 72-inch diameter pipe.

Professor Barfuss has considerable experience in the hydraulics of pipelines and pipe failures. He is a registered Professional Engineer, a member of AWWA, and has published more than 75 peer-reviewed journal articles and major research reports as well as more than 1,500 minor test reports. Professor Barfuss has performed many pipe-roughness coefficient and pipe-burst tests on most pipe materials and pipe sizes.

As the principal researcher for this study, Professor Barfuss performed the collection, analysis, and reporting of all data provided by the 802 utility respondents.

12.3 Acknowledgements

Utah State University is solely responsible for the content of this report. However, it would not have been possible without the more than 800 water utilities that participated in this survey. Also appreciated are the invaluable efforts of USU Research Assistants Matthew Fugal and Reilly Hendrix during this project. USU would like to thank the Uni-Bell PVC Pipe Association for their partial financial support, as well as the Water Finance Research Foundation for their technical advice.

13.0 References

Anderson, R., "Municipal Procurement: Competitive Bidding for Pipes Demonstrates Significant Local Cost-Savings," US Conference of Mayors, 2018.

ASCE, "2009 Report Card for America's Infrastructure," 2009.

ASCE, "2017 Infrastructure Report Card: A Comprehensive Assessment of America's Infrastructure," 2017.

ASCE, "2021 Report Card for America's Infrastructure," 2021.

AWWA, "2017 State of the Water Industry Report," 2017.

AWWA, "2023 State of the Water Industry Report," 2023.

AWWA, "M28 Rehabilitation of Water Mains, Third Edition," Manual of Water Supply Practices, 2014.

AWWA, "Partnership for Safe Water Distribution Program," 2011.

Burn, S., et. al., "Long-term Performance Prediction for PVC Pipes," Water Research Foundation, 2005.

EPA, "Deteriorating Buried Infrastructure Management Challenges and Strategies," 2002.

EPA, "Drinking Water Infrastructure Needs Survey and Assessment, Sixth Report to Congress," 2018.

EPA, "Drinking Water Infrastructure Needs Survey and Assessment, Seventh Report to Congress," 2023.

EPA, "National Characteristics of Drinking Water Systems Serving 10,000 or Fewer People," 2011.

EPA, "Water Infrastructure and Resiliency Finance Center," 2023.

Folkman, S., "Water Main Break Rates in the USA and Canada: A Comprehensive Study," Utah State University, 2012.

Folkman, S., "Water Main Break Rates in the USA and Canada: A Comprehensive Study," Utah State University, 2018.

Grigg, N.S., "Main Break Prediction, Prevention, and Control," Water Research Foundation, 2007.

Grigg, N. S., and Hess, J., "Collecting Failure Data to Improve Asset Management," Water Research Foundation, 2017.

Kumar, S., et. al., "Practical Condition Assessment and Failure Probability Analysis of Small Diameter Ductile Iron Pipe," Water Research Foundation, 2018.

Rajani, B., et. al., "Long-Term Performance Prediction of Ductile Iron Pipes," Water Research Foundation, 2011.

Seargeant, D., "PVC Watermain Pipe – 40 Years of Successful Service," AWWA ACE, 2018.

Statistics Canada, "New Construction of Water Infrastructure Accelerated in 2017 and 2018," 2020.

Statistics Canada, "Population Estimates, Quarterly," 2023.

US Census Bureau, "National Population Totals and Components of Change: 2020-2023," 2023.

Yerri, S., "Empirical Analysis of Large Diameter Water Main Break Consequences," Clemson University, 2016.

Utah Water Research Laboratory
UtahStateUniversity

8200 Old Main Hill
Logan, UT 84322-8200