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Are Failure Rates on All Water Distribution Systems the Same? (Comparing Predictions among Nine Utilities in Southeast Florida)

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Abstract

The goal of asset management is to identify and track the maintenance and identify the need for replacement of assets that have reached their useful life. For that reason, gathering data and collecting information is a critical step when developing an asset management plan. However, for buried infrastructure, information is often missing and due to its location, observing actual condition is not possible. Many entities lack the resources for examining buried infrastructure without destructive testing, so other methods of data collection are needed. The concept for this paper was to determine if utilities located in the same geographical vicinity could contribute data to develop regional scale predictive means to assess the likelihood of failure of buried potable water mains (failure defined as breaks). Such an effort would be more accessible to utilities and result in an easier means of assessment. The findings indicate that utilities located in the same area may differentiate themselves by pipe material, and the lack of data collection inhibits the ability to use predictive means with confidence.

Keywords

Infrastructure, Water Main Condition, Failure Assessment, Asset Management

1. Introduction

To meet the regulatory requirements to protect the public health, safety and welfare, a water utility must continually construct new pipelines, pump stations and other infrastructure, whether that infrastructure is for growth, to improve existing service, or to replace infrastructure that has reached the end of its useful, economic, and/or physical life. Since the benefits of infrastructure systems are broad-based, within the public interest, and have huge initial costs and long payback periods, they are generally constructed with public funds. However, in many jurisdictions, the ability to keep up with replacement needs along with growth needs may be strained, requiring the entity to make decisions on which to prioritize. Almost always, they will choose growth as that adds to the regional tax base and economic activity. If no growth occurs, the utility may lack the means to perform replacement upgrades.

Over 40 studies have demonstrated that infrastructure drives local economic development (Bloetscher et al., 2017, Bloetscher, 2019). Grimsey and Lewis (2002) noted that since World War II, governments have been the primary constructors of infrastructure projects due to high cost and long payback periods. Arrow and Kurz (1970) were the first to develop theoretical work on the contribution of infrastructure to output, finding a correlation between infrastructure development and economic growth. Borcherding and Deacon (1972) showed statistically significant income growth as a result of highway and water-sewer investment. Aschauer (1989) advanced the concept of using elasticity to show that public investment will induce an increase in the rate of return to private capital and, thereby, stimulate private investment expenditure, suggesting that infrastructure expenditures may have been a key ingredient to the robust economy in the 1950s and 1960s (Aschauer, 1989), and suggested that public infrastructure investments are the primary factors in fostering economic growth and productivity improvement (Aschauer, 1990). Aschauer (1989) and Munnell (1992) also found a strong positive relationship between infrastructure and growth.

However, the robust investments throughout much of the 20th century have slowed. The Congressional Budget Office (CBO, 2015) reports a decline in real public spending on transportation and water infrastructure since 2003, and that both construction and rehabilitation of highways have declined since 1959. At present, state and local governments spend about 1.8% of the GNP on infrastructure, as compared to 3.1 % in 1970 (McNichol, 2016). A large portion of that is for growth as opposed to repair and replacement. The result is deteriorating infrastructure condition. The National Council on Public Works concluded its first assessment grade for infrastructure in the 1980s—piping was not discussed in this report. Public infrastructure has been poorly rated by the American Society of Civil Engineers for over 20 years (ASCE, 2001, 2005, 2009, 2013, 2017, 2021) and most public officials acknowledge the deterioration of the infrastructure relied on daily to support economic growth.

Asset management is a tool used to help municipalities gauge the health of their infrastructure. Asset management systems were developed because no one wants to spend money on stranded infrastructure (Goldwater, 2010). Bloetscher *et al.* (2023)

noted that the general framework of asset management programs involves collecting and organizing data on the physical components of a system and evaluating the condition of these components. The system of assets should be reviewed continuously and adjustments made to the overall asset management strategy based on new or better information as it arises. Ultimately, the goal is to be able to identify infrastructure that is at risk so that managers and operators can then prioritize what infrastructure is most critical to the operation of the system and therefore which assets to consider for repair, rehabilitation or replacement. But the problem still is where and when to invest given that Bloetscher (2019) noted that for most utilities, over half the total investment in infrastructure is subsurface piping.

The major challenge with buried infrastructure is that it is not visible from the surface. Staff at many utilities will tell you they have no idea about the piping systems. Worse, they often have little or no data on main breaks, no photos of piping that was uncovered or when installed, limited knowledge of as-builts and little information about prior conditions. Yet, many for many critical variables staff may have a pretty good idea about their piping materials and size even if little else is known. Hence, at before any asset management system can be developed, an inventory of assets needs to be established. This is most easily done with GIS-based asset management systems. Once the GIS inventory and mapping have been developed, added data can be entered.

A lot of missing data may be available to help the analysis. More as built drawings may be available in some locales that staff realizes. As-builts are a major source of data. Employee memory of prior excavations, repair or tie-ins can be very useful, even if not completely accurate. In most cases, the depth of pipe is fairly similar and any deviations may be known. Soil conditions may be useful—if there is an indication that aggressive soil causes more corrosion in cast, galvanized or ductile iron pipe, it may be useful to include this parameter. Most soil information is readily available from government websites in GIS format. Groundwater is usually known, and if a saltwater interface or a pollution plume exists, it can be mapped and evaluated for impact on pipe in GIS format. Roads with heavy truck traffic create more vibrations in the soil, causing rocks to move toward the pipe and joints to flex, especially older piping. These roads are also visible GIS format or available from local transportation agencies in GIS format. Likewise, tree roots will wrap around water and sewer pipes, so their presence is in the right-of-way or easements detrimental. Trees are easily noted from aerial photographs. Trees in rear yards are also easily seen. Thus, with a little research there are at least 6 variables known with some confidence.

Note age is not one of the common variables, and actually may not be important given that piping is typically installed in a given area in "eras." For example, in southeast Florida, piping before the mid-1960s was primarily cast iron and galvanized iron with a little AC pipe mixed in. The 1960s and early 1970s were ductile, galvanized and AC pipe. AC pipe was discontinued in the 1970s and replaced with PVC with plastic services. The galvanized pipe was also phased out, leaving PVC and ductile iron as the predominant pipes since that time. Thus, knowing the material then can give the utility an idea of installation date. Houses connected to the pipe can confirm the pipe era. If more accuracy is wanted, the data can be gathered in many ways ranging from on-site field investigation which could take a lot of time, to using existing maps, using maps while verifying the assets using aerial photography and video, or field investigations.

Building upon the prior efforts in Bloetscher (2021) and Bloetscher *et al.* (2023), this paper outlines efforts to develop a means to effectively collect data and assess the condition, and therefore the risk of failure of public infrastructure using simple, readily available means without the need for significant training and expertise using a more regional model to overcome the fact that too many utilities lack useful break data which compromises the ability to predict localized failures. If there is limited break data, the question investigated here was whether data from neighboring jurisdictions could be used to predict breaks in communities with a paucity of data.

The concept should apply to any utility, although the results and factors of concern will be slightly different for each utility. Also, in smaller communities, many variables (ductile iron pipe, PVC pipe, soil condition…) may be so similar that attempts to differentiate the assets within the community may be unproductive. The use of neighboring community data would appear to be useful given that pipe installation and material practices are often similar as the same engineers and contractors are often used, which removes a potential variable that can be a confounding condition when trying to compare widely disparate areas.

2. Methodology

In Bloetscher (2019, 2021) and Bloetscher *et al.* (2023), GIS based data was used in a regression process to analyze water distribution systems in multiple communities. The process was as follows:

- Step 1: Create a table of all buried assets.
- Step 2: Create columns for the variables for which you have data. Note that where there are categorical variables (type of pipe for example), these need to be converted to separate yes/no questions as mixing. Categorical and numerical variables do not provide appropriate comparisons; hence the need to alter the categorical variables to absence/presence variables. So descriptive variables like pipe material need to be converted to binary form—i.e. create a column for each material and insert a 1 or 0 for “yes” and “no”.
- Step 3: Summarize the statistics for the variables. Note missing data is not permitted and known conditions should be entered directly.
- Step 4: Identify break frequency in records that should be kept by the utility. Note for many utilities this data may be limited or completely absent.
- Step 5: Identify correlations between variables.
- Step 6: Develop a regression equation to determine factors associated with each and the amount of influence that each exerts.
- Step 7: The equation can then be used to predict the number of breaks going

forward based on the information about breaks going back in time.

- Step 8: Finally the data can be used to predict where the breaks might occur in the future based on the past.

These factors were used in a linear regression algorithm to evaluate the potential for breaks, identified herein as the "consequence." The better the break history for water system is, the more accurate the prediction should be.

3. Results

Table 1 outlines the basic information for each of the nine utilities surveyed.

Table 1. Basic information on utility systems used for analysis.

Utility	Miles of pipe	Is city located on the coast?	Population served	Incorp.
1	546	yes	153K	1921
2	130	no	134K	1963
3	212	no	58K	1955
4	488	no	171K	1959
5	74	yes	6K	1957
6	140	no	34K	1959
7	601	yes	180	1927
8	61	yes	37	1922
9	91	yes	20	1904

The utilities have a mix of pipe, including galvanized and asbestos concrete. All are primarily residential, with small commercial areas along major roadways. None are intensive "destination" communities. All utilities have a GIS system of pipe containing at least a portion of the data required for this analysis; the rest was gathered by the investigators. The consequence to predict was the likelihood of breaks, so break data was needed. One utility had over 5 years of data so development of information was thought to be the most robust of the utilities (the others had less than 18 months of break data). XLStat®, an Excel based statistical upgrade, was used for the statistical analysis. An equation was developed for each of the nine utilities (see Appendix A). Given the variation in age of the communities, and development patterns in southeast Florida, certain pipes (cast iron and asbestos pipe) may not have been present. Two systems were primarily PVC, so the monolithic nature revealed little useful information. Others had a wide variety of pipe, so each utility had a different equation specific to that mix of pipe and circumstances (like the presence of rail roads and saltwater intrusion).

When trying to create the regional model, Table 2 shows the summary statistics when data for all systems are put together. The challenge is that putting all systems together yields a regression equation that is not enlightening because the data sets are so different with respect to size. Of the 137,000 pipe segments in GIS among the 9 systems, less than 3000 actually include breaks and only two utilities exceed 1 percent of the pipe segments having a break. One pipe had 28 breaks. As a result, the extensive non-break pipe segments exert undue influence on the overall results, especially since only one utility had more than 1 year of data.

To resolve this problem, a process to create similar sets of data was designed. All pipe segments with breaks were removed. For the remaining 134,000 segments, a random number generator was created and a series of pipe segments extracted and added to the break segments making a total dataset of approximately 6000 segments—half with break and half without. Table 3 shows the correlation table when data for all systems are put together. Table 4 shows the reduced data correlation matrix.

Table 2. Summary statistics for all piping in one dataset for all utilities.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
BREAKS	136,285	0	136,285	0.000	28.000	0.023	0.175
DIAMETER	136,285	0	136,285	0.000	48.000	7.599	4.029
AC	136,285	0	136,285	0.000	1.000	0.199	0.400
DIP	136,285	0	136,285	0.000	1.000	0.281	0.449
CI	136,285	0	136,285	0.000	1.000	0.054	0.226
GI	136,285	0	136,285	0.000	1.000	0.109	0.312
PVC	136,285	0	136,285	0.000	1.000	0.320	0.466
ROADWAY	136,285	0	136,285	0.000	1.000	0.062	0.240
SOILS	136,285	0	136,285	0.000	1.000	0.122	0.327
TREES	136,285	0	136,285	0.000	1.000	0.017	0.130

Table 3. Summary statistics for all piping in the reduced dataset for all utilities.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
BREAKS	6004	0	6004	0.000	28.000	0.516	0.662
DIAMETER	6004	0	6004	0.000	48.000	7.089	3.759
AC	6004	0	6004	0.000	1.000	0.204	0.403
DIP	6004	0	6004	0.000	1.000	0.202	0.401
CI	6004	0	6004	0.000	1.000	0.033	0.179
GI	6004	0	6004	0.000	1.000	0.130	0.337
PVC	6004	0	6004	0.000	1.000	0.379	0.485
ROADWAY	6004	0	6004	0.000	1.000	0.054	0.226
SOILS	6004	0	6004	0.000	1.000	0.133	0.339
TREES	6004	0	6004	0.000	1.000	0.038	0.191

The linear regression function for XLStat was used to create an equation to identify the factors associated with each variable and the amount of influence that each exerts:

RegBREAKS = 0.856172657991883 − 9.61588410438364E-03 * DIAMETER-0.230270190050999 * AC-0.486686074967913 * DIP-0.560756907702356 * CI-0.265832515418115 * GI-0.220384335206692 * PVC-1.95206859281174E-02 * ROADWAY + 0.034301224750918 * SOILS + 0.168445504356965 * TREES

Figure 1 shows the standardized coefficients—trees and soils were the only positive coefficients. All others were negative. Note that tree roots were associated with small, galvanized lines in rear yards. Figure 2 shows a comparison of prediction

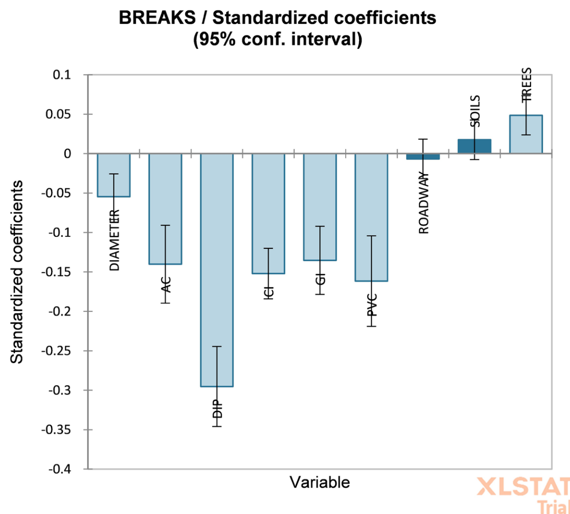


Figure 1. BREAKS/Standardized coefficients (95% conf. interval).

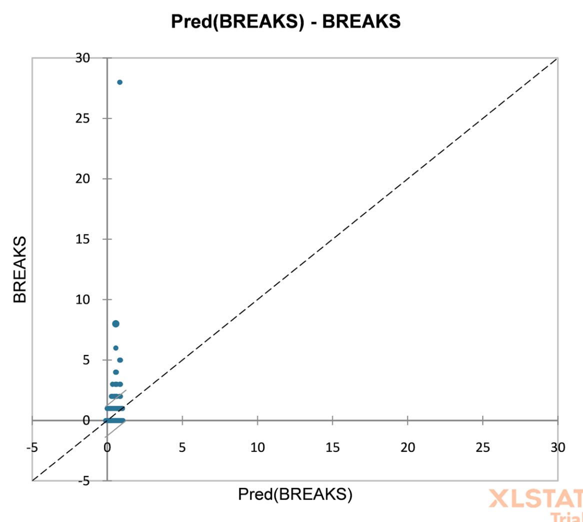


Figure 2. Comparison of prediction based on local vs regional model. Most of the values were within the 95% confidence level although a few extreme number of leaks on a pipe (one had 28) were clear outliers.

a figure with 6000 datapoints located near the origin, most of the values were versus actual breaks based on the local vs regional model. While hard to read within the 95% confidence level although a few extreme number of leaks on a pipe (one had 28) were clear outliers.

Table 5 shows the correlation between the regional model and the utility specific breaks. This was far more informative because the larger systems which tended to have more data, had much higher correlation with the regional model than the utilities with little or no data. Utility 2 had no breaks, and the other two had very limited data.

Table 4. Correlation matrix for reduced data set.

	DIAMETER	AC-0	AC-1	DIP-0	DIP-1	CI-0	CI-1	GI-0	GI-1	PVC-0	PVC-1	ROADWAY-0	ROADWAY-1	SOILS-0	SOILS-1	TREES-0	TREES-1
DIAMETER	1	0.036	−0.036	−0.248	0.248	−0.129	0.129	0.421	−0.421	−0.148	0.148	−0.126	0.126	0.012	−0.012	0.020	−0.020
AC-0	0.036	1	−1.000	−0.254	0.254	−0.094	0.094	−0.196	0.196	−0.395	0.395	−0.037	0.037	−0.041	0.041	−0.059	0.059
AC-1	−0.036	−1.000	1	0.254	−0.254	0.094	−0.094	0.196	−0.196	0.395	−0.395	0.037	−0.037	0.041	−0.041	0.059	−0.059
DIP-0	−0.248	−0.254	0.254	1	−1.000	−0.093	0.093	−0.195	0.195	−0.392	0.392	0.020	−0.020	−0.090	0.090	−0.084	0.084
DIP-1	0.248	0.254	−0.254	−1.000	1	0.093	−0.093	0.195	−0.195	0.392	−0.392	−0.020	0.020	0.090	−0.090	0.084	−0.084
CI-0	−0.129	−0.094	0.094	−0.093	0.093	1	−1.000	−0.072	0.072	−0.145	0.145	0.104	−0.104	−0.051	0.051	−0.037	0.037
CI-1	0.129	0.094	−0.094	0.093	−0.093	−1.000	1	0.072	−0.072	0.145	−0.145	−0.104	0.104	0.051	−0.051	0.037	−0.037
GI-0	0.421	−0.196	0.196	−0.195	0.195	−0.072	0.072	1	−1.000	−0.302	0.302	0.004	−0.004	−0.033	0.033	0.053	−0.053
GI-1	−0.421	0.196	−0.196	0.195	−0.195	0.072	−0.072	−1.000	1	0.302	−0.302	−0.004	0.004	0.033	−0.033	−0.053	0.053
PVC-0	−0.148	−0.395	0.395	−0.392	0.392	−0.145	0.145	−0.302	0.302	1	−1.000	−0.010	0.010	0.158	−0.158	0.085	−0.085
PVC-1	0.148	0.395	−0.395	0.392	−0.392	0.145	−0.145	0.302	−0.302	−1.000	1	0.010	−0.010	−0.158	0.158	−0.085	0.085
ROADWAY-0	−0.126	−0.037	0.037	0.020	−0.020	0.104	−0.104	0.004	−0.004	−0.010	0.010	1	−1.000	0.056	−0.056	−0.005	0.005
ROADWAY-1	0.126	0.037	−0.037	−0.020	0.020	−0.104	0.104	−0.004	0.004	0.010	−0.010	−1.000	1	−0.056	0.056	0.005	−0.005
SOILS-0	0.012	−0.041	0.041	−0.090	0.090	−0.051	0.051	−0.033	0.033	0.158	−0.158	0.056	−0.056	1	−1.000	0.046	−0.046
SOILS-1	−0.012	0.041	−0.041	0.090	−0.090	0.051	−0.051	0.033	−0.033	−0.158	0.158	−0.056	0.056	−1.000	1	−0.046	0.046
TREES-0	0.020	−0.059	0.059	−0.084	0.084	−0.037	0.037	0.053	−0.053	0.085	−0.085	−0.005	0.005	0.046	−0.046	1	−1.000
TREES-1	−0.020	0.059	−0.059	0.084	−0.084	0.037	−0.037	−0.053	0.053	−0.085	0.085	0.005	−0.005	−0.046	0.046	−1.000	1

Table 5. Correlation between the utility's breaks and the regional model.

Utility	Miles of pipe	Corr W Regional	Breaks
1	546	0.43	84
2	130	0	0
3	212	0.22	395
4	488	0.54	87
5	74	−0.28	12

Continued

6	140	0.24	539
7	601	0.66	585
8	61	0.03	70
9	91	0.18	13

Figure 3 is a confusion plot developed from a logistic regression protocol. The goal of a confusion plot is to provide an estimate of the number of correct predictions (breaks) there are in the data. For this dataset, plotting the number of breaks versus the correlation, the results are not informative. There is too little data to separate the breaks. Based on correlations with the individual utility

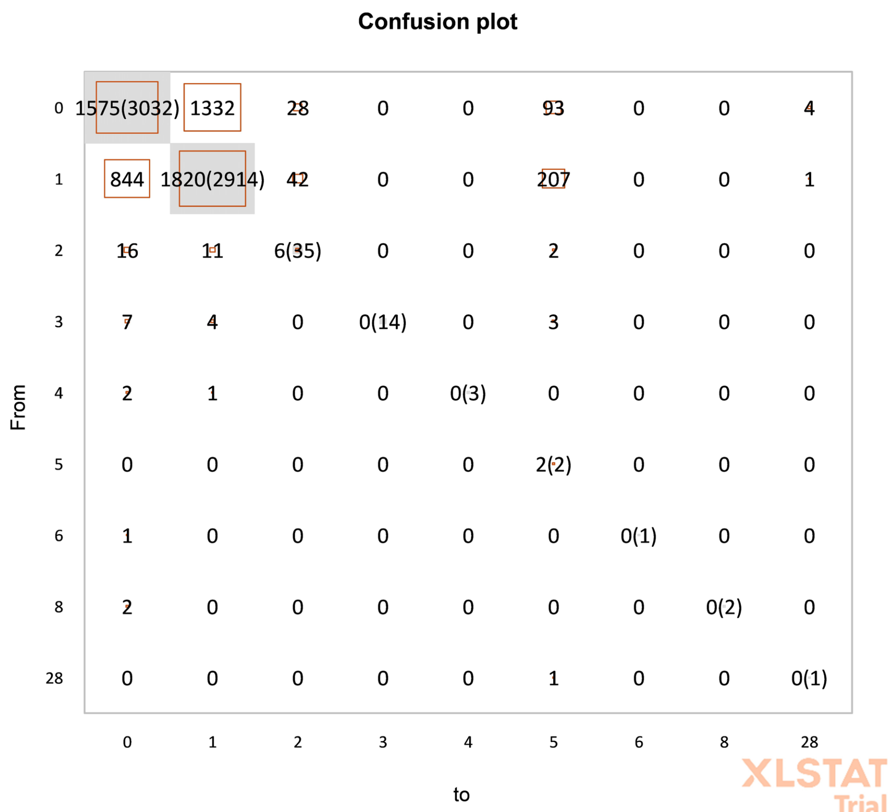


Figure 3. Confusion plot—the data plot shows limited predictive ability of the current data.

datasets, and realizing that many have very little data, the prediction may be better with more breaks. Looking at each utility, Figure 4 shows that unlike the regional model, asbestos pipe and galvanized pipe were frequently factors, but the regional model identified trees and roads as more likely contributors. However, it should be noted that many galvanized lines are in rear years, in easements that have not been maintained so perhaps the model is picking up this issue. For comparison purposes, Figure 5 shows each of the standardized coefficients (95% conf. interval) for each utility, compared to the regional model.

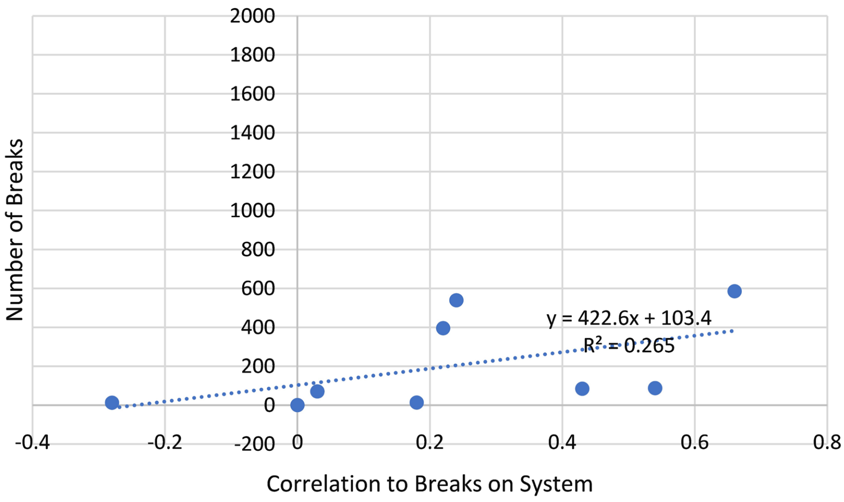
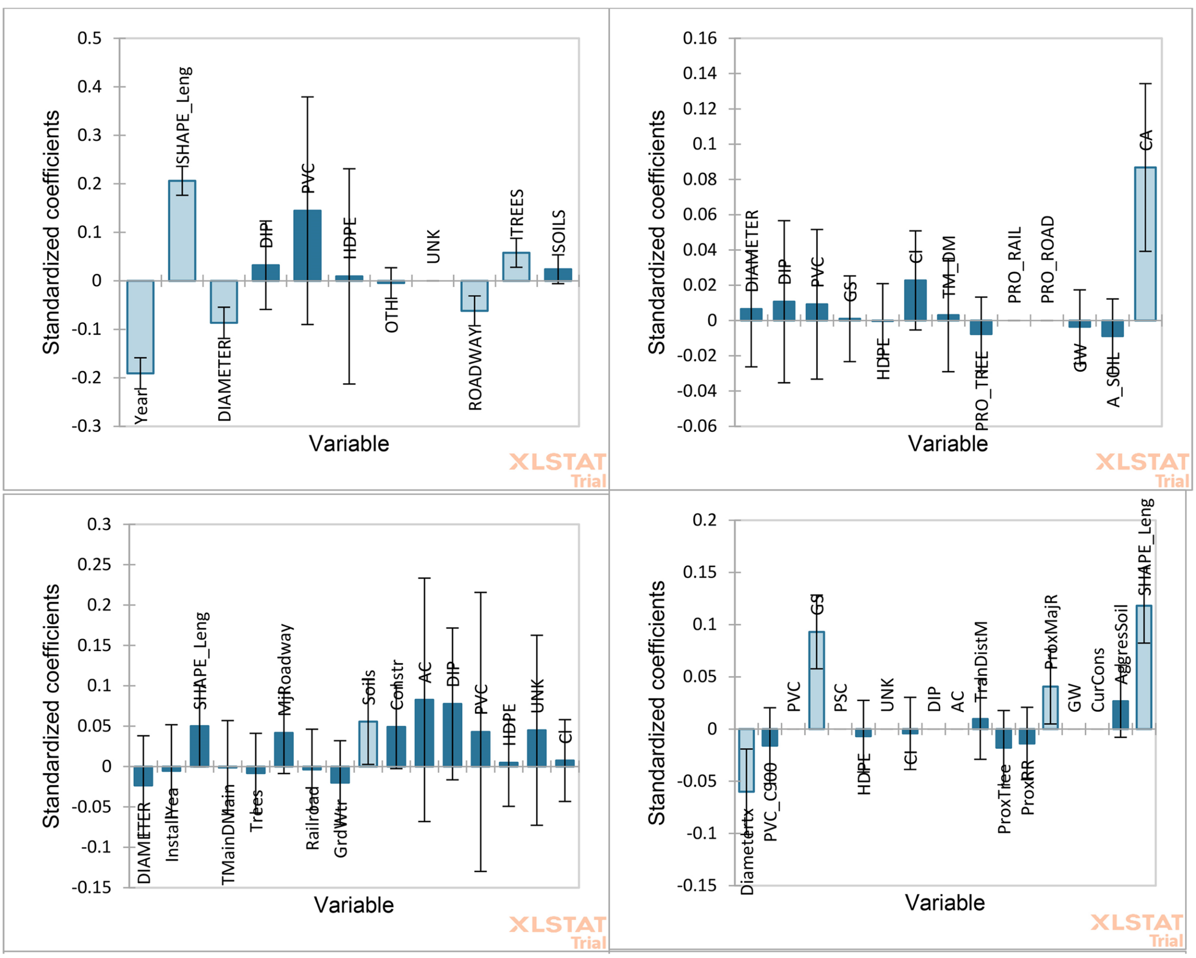


Figure 4. Comparison of the number of breaks reported versus regional model correlation with actual data.



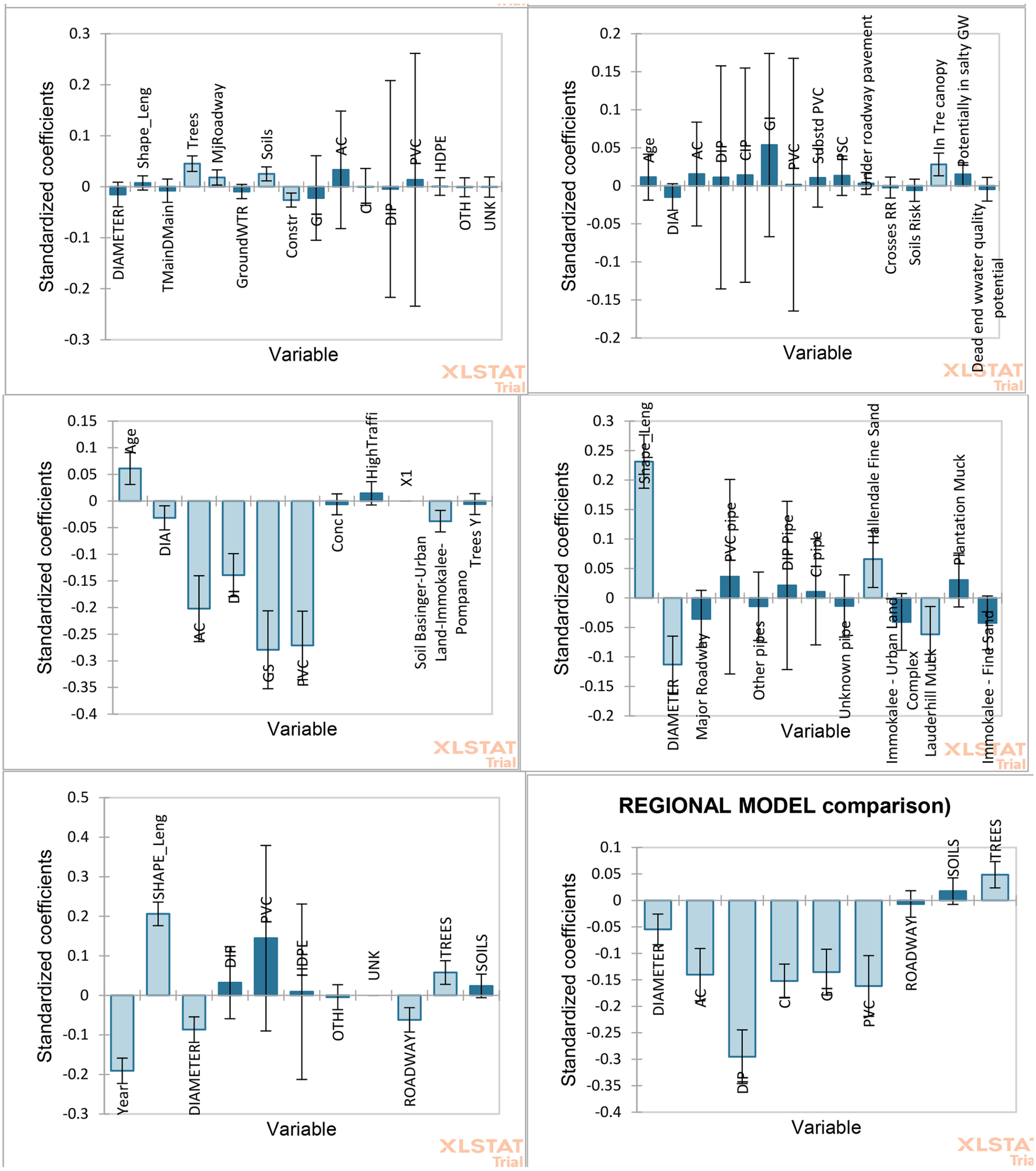


Figure 5. BREAKS/Standardized coefficients (95% conf. interval) for each utility and the regional model.

4. Conclusion

The goal of this project was to determine if it might be feasible to use data across a region to assess the most likely places for pipe breaks in a water distribution system. The regression model developed here for a regional scale appears to have a use given that many utilities cannot properly assess certain assets like buried pipe because assessment of the assets is too expensive or yields data of limited value. Far too few collect the necessary data over long periods of time to create a useful utility-specific assessment. This is a critical question because as noted in Bloetscher *et al.* (2017) and Bloetscher (2019), for many water utilities, over half their total asset value is in buried infrastructure. The failure of these assets can be minor ongoing irritations, a catastrophic failure or something in between. In any case, they are poor public relations events that can create public health challenges.

Many utilities ignore pipe condition until there is a break, or a repetitive series of breaks on the same pipeline before replacing it. The challenge is that by ignoring these assets, one ignores the fact that they continue to deteriorate with time and the costs for maintenance will increase as well. However, being able to predict the lines more likely to fail and having a plan ahead of time to replace them is a positive public relations tool and saves significant maintenance dollars in the short term. The key is to prioritize pipe repair and replacement costs to control operations and maintenance costs, while increasing system reliability to protect the public health, safety and welfare.

In this paper, an effort was made to develop a regional model as a means to address the paucity of data that may exist in certain locales, using neighboring data to supplement the data. The approach used for developing a model that can be used with minimal field investigation relies on break records. However, because 3 of the systems had very little data on breaks, and at least one was monolithic (all PVC), the regional model, while useful for the larger utilities with more breaks, was less useful for utilities with limited data due to a paucity of data.

The result indicates that the most important issue is the need to collect data on consequences—leaks and breaks. Unfortunately, this is not a priority for many utilities which limits the ability to truly assess asset condition. The lack of information makes predictive efforts far more difficult. Work orders, construction and repair photographs, tracking information on breaks, costs, and materials, and the accompanying GIS updates are critical to improving future information.

The solutions to these challenges involve the following:

1) Implementing work order system to verify all piping materials when excavation and repairs occur;

2) Creating scans or all as-built maps so they are not lost;

3) Using Lead copper rule information to improve information about piping materials and age;

4) Using the property appraiser data to help with age;

5) Developing AI tools to help predict breaks and material consequences;

6) Updating models and asset management plans based on new data.

Ultimately, all of these things should be standard practice for utilities but are often not priority issues for management of field staff. To improve asset management and reduce the risk of breaks, these priorities should be elevated. For some utilities, the ability to track and analyze the data is overwhelming, but there are universities and consultants that can help maintain these databases and provide useful reports to the utility on an annual basis in time for budgeting. These options should be explored.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Arrow, K., & Kurz, M. (1970). *Public Investment, the Rate of Return and Optimal Fiscal Policy*. Johns Hopkins.

ASCE (2001). *2001 Report Card for America's Infrastructure*.

ASCE (2005). *2005 Report Card for America's Infrastructure*.

ASCE (2009). *2009 Report Card for America's Infrastructure*. http://www.infrastructurereportcard.org/making-the-grade/report-card-history/2001-report-card/

ASCE (2013). *2013 Report Card for America's Infrastructure*. http://www.infrastructurereportcard.org/

ASCE (2017). *2017 Report Card for America's Infrastructure*. http://www.infrastructurereportcard.org/making-the-grade/report-card-history/2001-report-card/

ASCE (2021). *Report Card on America's Infrastructure*. https://infrastructurereportcard.org/

Aschauer, D. (1989). Is Public Expenditure Productive? *Journal of Monetary Economics, 23,* 177-200. https://doi.org/10.1016/0304-3932(89)90047-0

Aschauer, D. A. (1990). *Why Is Infrastructure Important*? Conference Series; [Proceedings], Federal Reserve Bank of Boston, vol. 34, pages 21-68. https://ideas.repec.org/a/fip/fedbcp/y1990p21-68n34.html

Bloetscher, F. (2019). *Public Infrastructure Management: Tracking Inevitable Asset Challenges and Increasing System Resiliency*. J Ross.

Bloetscher, F., Farmer, Z., Barton, J., Chapman, T., Fonseca, P., & Shaner, M. (2023). Water System Condition and Asset Replacement Prioritization. *Journal of Water Resource and Protection, 15,* 165-178. https://doi.org/10.4236/jwarp.2023.155010

Bloetscher, F., Wander, L., Smith, G., & Dogon, N. (2017). Public Infrastructure Asset Assessment with Limited Data. *Open Journal of Civil Engineering, 7,* Article No. 79326. https://doi.org/10.4236/ojce.2017.73032

Borcherding, T. E., & Deacon, R. T. (1972). The Demand for the Services of Non-Federal Governments. *American Economic Review, 62,* 842-853.

Congressional Budget Office (CBO) (2015). *Public Spending on Transportation and Water Infrastructure, 1956 to 2014*.

Goldwater, D. (2010). An Important Tool for Asset Management. *Utility Infrastructure Management: Journal of Finance and Management for Water and Wastewater Professional*. http://mail.uimonline.com/index/webapp-stories-action/id.378/archive.yes/Issue.2010-04-01/title.rehabilitation

Grimsey, D., & Lewis, M. K. (2002). Evaluating the Risks of Public Private Partnerships for Infrastructure Projects. *International Journal of Project Management, 20,* 107-118. https://doi.org/10.1016/S0263-7863(00)00040-5

McNichol, E. (2016). *It's Time for States to Invest in Infrastructure*. Center on Budget and Policy Priorities. http://www.cbpp.org/research/state-budget-and-tax/its-time-for-states-to-invest-in-infrastructure

Munnell, A. H. (1992). Infrastructure Investment and Economic Growth. *Journal of Economic Perspectives, 6,* 189-198. https://doi.org/10.1257/jep.6.4.189

Bloetscher, F. (2021). Analysis of Inflow Solutions among Eleven Sewer Systems. *Journal of Geoscience and Environment Protection, 9*, 64-86. https://doi.org/10.4236/gep.2021.99005

Appendix A: Regression Equations Developed for Each Utility

1 Number of Breaks = 0.001617163734317 + 2.93520582458788E-05 * Ae2-2.28874210338945E-04 * af2 + 5.15786169166412E-03 * ag2 + 1.66341853798395E-03 * ah2 + 2.22933362887419E-03 * ai2 + 1.00156151198285E-02 * aj2 + 2.04919298519084E-04 * ak2 + 6.46308145749591E-03 * al2 + 1.35407013100996E-02 * am2 + 5.01918280885909E-04 * an2-3.57517432551364E-03 * ao2-1.09618924516312E-03 * ap2 + 1.17552498531525E-02 * aq2 + 2.60435278746286E-03 * ar2-1.56264944876879E-03 * as2

2 BRK_1_2 = 7.34633687188947E-02 + 1.93982422177599E-04 * z2-1.01674448024179E-02 * aa2-2.84774500894531E-02 * ab2 + 4.02837210278206E-02 * ac2-6.91069645988855E-02 * ad2 + 2.89949189106736E-02 * ae2 + 2.47609709735044E-02 * af2-8.79901202806858E-02 * ag2 + 4.61963530832518E-02 * ah2-4.39978190384273E-02 * ai2-5.68887541854132E-02 * aj2 + 4.88180515666322E-02 * ak2-6.97211838435718E-02 * al2

3 Breaks = 0.232627500704334 + 1.66421235440179E-03 * e2-3.98152231194033E-03 * f2-0.181232982962693 * g2-0.209458010309068 * h2-0.224498684512934 * i2-0.239838243402453 * j2-0.241306579624421 * k2 + 1.70311010525222E-02 * l2-3.01512547585288E-02 * n2-2.18460249448524E-02 * o2

4 Breaks = 4.24550803269627E-03-3.25720695513302E-04 * D2 + 2.29356059775998E-06 * e2-1.41256476573415E-03 * f2 + 3.39254117894683E-02 * g2 + 3.64572301907794E-03 * h2-1.57908888991901E-03 * i2 + 4.0688436601383E-03 * j2-4.4838369723949E-03 * k2-1.21373536183144E-02 * l2 + 1.29234592009304E-02 * m2-7.01669387434051E-04 * n2-9.17862298310472E-04 * o2 + 2.45562034377267E-03 * P2 + 1.76632772701294E-03 * q2-3.66570949019766E-03 * r2-1.93534443797973E-03 * s2

5 Breaks = 5.48004019123281E-02-1.17088792092359E-03 * z2-2.96807387707452E-05 * aa2 + 1.21042415586724E-05 * ab2-6.33126646195216E-04 * ac2-7.04922599363746E-03 * ad2 + 9.07747911205107E-03 * ae2-5.48005599116335E-03 * af2-3.56086106405211E-03 * ag2 + 9.66106893503274E-03 * ah2 + 2.11640964367759E-02 * ai2r + 1.74406571628529E-02 * Aj2 + 2.92221316808937E-02 * ak2 + 7.58961387066232E-03 * al2 + 6.61946529269021E-03 * am2 + 1.26902159821406E-02 * an2 + 2.56625238607795E-02 * ao2

6 BREAKS =10.8848211319982-5.44125670164173E-03 * r2 + 2.67412567400692E-04 * s2-1.29501663520665E-02 * t2 + 9.02278716431921E-02 * u2 + 0.148978754674617 * v2 + 1.00899441327534E-02 * w2-9.80638258797033E-02 * x2-7.14166453237781E-02 * z2 + 7.69175261817414E-02 * aa2 + 2.10517337082513E-02 * ab2

7 Breaks = 5.40363922869012E-02-8.16437702130421E-04 * j2-2.33725372343019E-02 * k2-3.80306182123697E-02 * n2-4.11383862629096E-02 * m2-2.29079684351363E-02 * o2-1.83628863294663E-02 * r2-1.34715011837828E-03 * w2 + 1.08540901256518E-03 * x2 + 4.53759174687401E-02 * u2

Continued

8 BREAKS = 5.40363922869012E-02-8.16437702130421E-04 * l2-2.33725372343019E-02 * x2-3.80306182123697E-02 * m2-4.11383862629096E-02 * q2-2.29079684351363E-02 * o2-1.83628863294663E-02 * n2-1.34715011837828E-03 * u2 + 1.08540901256518E-03 * w2 + 4.53759174687401E-02 * s2
9 BREAKS = 5.40363922869012E-02-8.16437702130421E-04 * v2-2.33725372343019E-02 * s2-3.80306182123697E-02 * aa2-4.11383862629096E-02 * z2-2.29079684351363E-02 * x2-1.83628863294663E-02 * w2-1.34715011837828E-03 * ae2 + 1.08540901256518E-03 * af2 + 4.53759174687401E-02 * ac2