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Water System Condition and Asset Replacement Prioritization

Frederick Bloetscher[1], Zachary Farmer[1], James Barton[2], Teresa Chapman[2], Paula Fonseca[2], Monica Shaner[2]

[1]Civil, Environmental and Geomatics Engineering, Florida Atlantic University, Boca Raton, Florida, USA
[2]Boynton Beach, FL, USA
Email: h2o_man@bellsouth.net

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Abstract

The goal of asset management is to identify and track the maintenance and 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. Such data gathering includes physical and operational properties of the assets as well as collecting and tracking important events during the lifespan of the asset (*i.e.*, pipe breaks, replacement year, maintenance performed, etc.). Critical factors in the asset management plan may be overlooked when there is no data or poor quality data. However, many utilities lack the resources for examining buried infrastructure and lack good quality work order data, so other methods of data collection are needed. The concept for this paper was to develop a means to acquire data on the assets for a condition assessment to identify pipes that were most likely to break and those with the highest consequences for same. Three utilities were used as examples. It was found that for buried infrastructure, much more information was known than anticipated but the actual predictions relied on only a few factors related to pipe type. However, there is a need to track the consequences, in this case breaks, which would indicate a failure. The latter would be useful for predicting future maintenance needs and the most at-risk assets, but is often missing in utility systems as many utilities do not adequately track breaks sufficiently. In this case two utilities were analyzed and predication on a third was developed.

Keywords

Water Main, Predicted Failure, Asset Management, Pipe Failure, Water Distributions

1. Introduction

Public infrastructure has been poorly rated by the American Society of Civil Engineers for over 20 years [1]-[6] and most public officials acknowledge the deterioration of the infrastructure we rely on daily. At present state and local governments spend about 1.8% of the GNP on infrastructure, as compared to 3.1% in 1970 [7]. A large portion of those current expenses are slated for growth as opposed to repair and replacement, hence the need for better tools to manage these existing assets.

Asset management is a process of integrating design, construction, maintenance, rehabilitation, and renovation to maximize benefits and minimize cost. Asset management is used as a tool to help municipalities gauge the health of its infrastructure [8] and create a plan for managing the organization's infrastructure through a decision-making process driven by a defined standard level of service. The term asset management refers to business principles aimed at balancing risk and minimizing life-cycle costs of the physical assets of a utility such as pipes, roads, structures and equipment [9]. It is a continuously reviewed and revised strategy that implements the acquisition, use and disposal of assets to optimize service and minimize costs over the life of the assets. An asset management plan (AMP) considers financial, economic, operational, and engineering goals in an effort to balance risk and benefits as they relate to potential improvement to the overall operation of the system.

Organizations that practice asset management experience prolonged asset life by aiding in rehabilitation and repair decisions while meeting customer demands, service expectation and regulatory requirements. 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 importance and the potential consequences associated with the failure of the individual assets are determined by this evaluation. Managers and operators can then prioritize what infrastructure is most critical to the operation of the system and furthermore which assets to consider for repair, rehabilitation or replacement. This strategy allows for funding, in terms of both repair and replacement (R & R) and operation and maintenance (O & M) dollars, to be distributed accordingly amongst the vulnerable and most likely to fail and/or critical assets. Of utmost importance is to define the acceptability of "failure" of the infrastructure. For example, for a storm water system, "failure" might mean that the community has areas that flood as a result of tidal impacts, sea level, or groundwater elevation. Each community can define it differently, but the expectations of the public must be kept in mind when defining the level of service.

An asset management program for water systems should be developed accordingly to the utility's goals and objectives. It consists of determining the selected area of study, type of system and the quality of data used for evaluation (see **Figure 1**, [9]). The reliability of the assets within the area of interest starts with the design process in the asset management plan. Decision-making dictates how

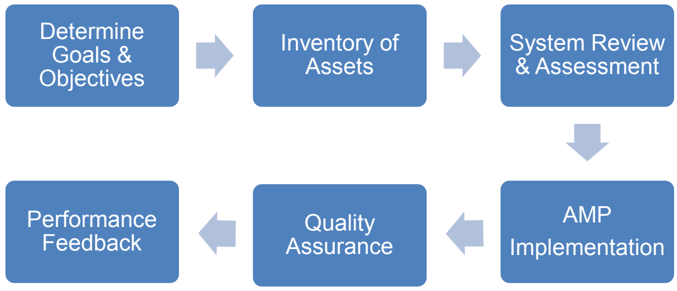

Figure 1. Asset management development chart (from Bloetscher, 2019).

the assets will be maintained and effective means to assure the maximum return on investments. Through condition assessment, the probability of failure can be estimated. Assets can also fail due to exceeding its maximum capacity. Operation and maintenance of the assets are important in reassuring a longer life span as well as getting the most out of the money to be spent. Prioritizing the assets by a defined system will allow for the community to see what areas are most susceptible to vulnerability/failure, which assets need the most attention due to their condition, and where the critical assets are located in relation to major public areas (hospitals, schools, etc.) with a high population.

This paper outlines efforts by university faculty and students to develop a means to quickly, efficiently and cost effectively collect data and assess the conditions, and therefore the risk of failure of public infrastructure using simple, readily available means without the need for significant training and expertise. The idea was to coalesce a common evaluation without the need for destructive testing. There are three projects used for demonstration purposes.

2. Methodology

Before a condition assessment can be determined, an inventory of assets and associated information needs to be established. Depending on the accuracy 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 as-built maps, using maps while verifying the assets using aerial photography and video, or field investigations. The goal is to provide strategic continuous maintenance to the infrastructure before total failure occurs. Costs should be well distributed over the life of the asset to help avoid emergency repairs. Emergency repairs can cost multiple times the cost of a planned repair. Therefore, the ultimate goal of asset management is to provide quality economic infrastructure by identifying the system's needs and addressing the needs appropriately.

An asset management program also consists of determining the selected area of study, type of system and the quality of data used for evaluation. The question is how to collect data that might be useful to a utility that does not involve a lot of destructive testing on buried infrastructure is costly and inconvenient. The reality is that one has more data than one thinks. For one thing, most utilities have a pretty good idea about the pipe materials. Employee memory can be very useful, even if not completely accurate. In most cases the depth of pipe is fairly similar, the deviations may be known. Soil conditions may be useful, there is an indication that aggressive soil causes more corrosion in ductile iron pipe, and most soil information is readily available. Groundwater is usually known, and if a saltwater interface or a pollution plume exists, it can be mapped and evaluated for impact on pipe. Likewise, tree roots will wrap around water and sewer pipes, so their presence is detrimental. Trees are easily noted from aerial photographs. Roads with heavy truck traffic create more vibrations in the soil, causing rocks to move toward the pipe and joints to flex. So, with a little research there are at least 6 variables known. If the break history for water system is known, (or for that matter flood records for a stormwater system or sewer pipe condition from televising), the impact of these factors can be developed via a linear regression algorithm. The linear regression algorithm can then be used as a predictive tool to help identify assets that are mostly likely to become a problem. 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 factors may be unproductive.

The following are the steps required to obtain a condition assessment with limited data, utilizing a series of assets gleaned from utility records for a water system for example purposes:

- Step 1: Create a table of 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 variable 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.
- Step 5: Identify correlations between variables.
- Step 6: Develop a linear regression 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.

XLStat® was used for the statistical analysis. Conducting an exercise to develop the methodology was useful, but the next step was to do something with the results. Note the method had previously been applied to a sewer system [9], with promising results.

For this project, three south Florida water distribution systems were analyzed.

All serve at least 50,000 people and have origins at least 60 years ago (*i.e.*, long history of pipe installation and experience with operation). All 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 that is trying to be predicted is 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 3 utilities (the other two had 1 year and 6 months of break data respectively). The third utility community was used for predictive purposes.

3. Results

The first community is primarily residential and inland, so does not experience the tourism issue associated with a beach community, nor the seasonal demands of such communities. The community was incorporated in the early 1960s and the first piping was installed at that time. For this community, the system has over 60 miles of pipe, that is divided into 10,000 pipe segments in their GIS system. **Table 1** is a portion of the overall GIS table for Utility #1 (10,000 lines long). The piping materials were as noted in **Table 2**. Note that AC pipe was commonly used in the 1960s and early 1970s, when this utility experienced is greatest development. Most of the piping is relatively small (see **Figure 2**). An example of the data gathered for each utility is shown in **Table 3**.

Conducting the statistics for the utility, **Figure 3** shows that AC pipe and age were correlated which makes sense because all AC pipe was installed in a 15-year period and has a useful life of 50 years. The linear regression function for XLStat was used to create and equation to identify the factors associated with each variable and the amount of influence that each exerts. In this case the equation is:

$$\text{Breaks} = -3.54426262606869\text{E-}03 - 6.5180516770882\text{E-}03 * \text{DIA} + 2.60152643232182\text{E-}03 * \text{Age}$$

Table 1. Table of assets (part of a larger table).

ID_Num	Breaks	DIA	INSTALL_YE	Soil Basinger-Urban Land-Immokalee-Pompano	Soil Hallandale-Margate-Boca	Low Traffic	High Traffic	Trees Y	No Trees	AC	DI	Conc	DI	GS	HDPE	PE	PVC	Shallow	Deep	pressure	Age	Breaks /ft
1	0	8	1987	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	55	34	0
2	0	12	1990	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	55	31	0
3	0	4	1988	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	55	33	0
4	0	4	1988	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	55	33	0
5	0	6	1980	1	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	55	41	0
6	0	6	1974	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	55	47	0
7	1	6	1973	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	55	48	0.016
8	0	2	1971	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	55	50	0
9	0	2	1971	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	55	50	0
10	0	2	1974	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	55	47	0
11	0	2	1974	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	55	47	0
12	0	2	1974	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	55	47	0
13	0	2	1974	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	55	47	0

Table 2. Summary of piping in Utility #1.

Pipe Size	Amt	
2 in Water Main	34,605	LF
4 in Water Main	81,477	LF
6 in Water Main	367,272	LF
8 in Water Main	388,800	LF
10 in Water Main	80,735	LF
12 in Water Main	125,556	LF
14 in Water Main	2777	LF
16 in Water Main	9320	LF
18 in Water Main	7233	LF
20 in Water Main	73	LF
24 in Water Main	3582	LF

Table 3. Piping materials in Utility #1.

Material	Pipe Segments	Percentage
AC	2514	25.5%
DI	717	7.3%
PVC	2623	26.6%
Galvanized	3787	38.4%
HDPE	37	0.4%

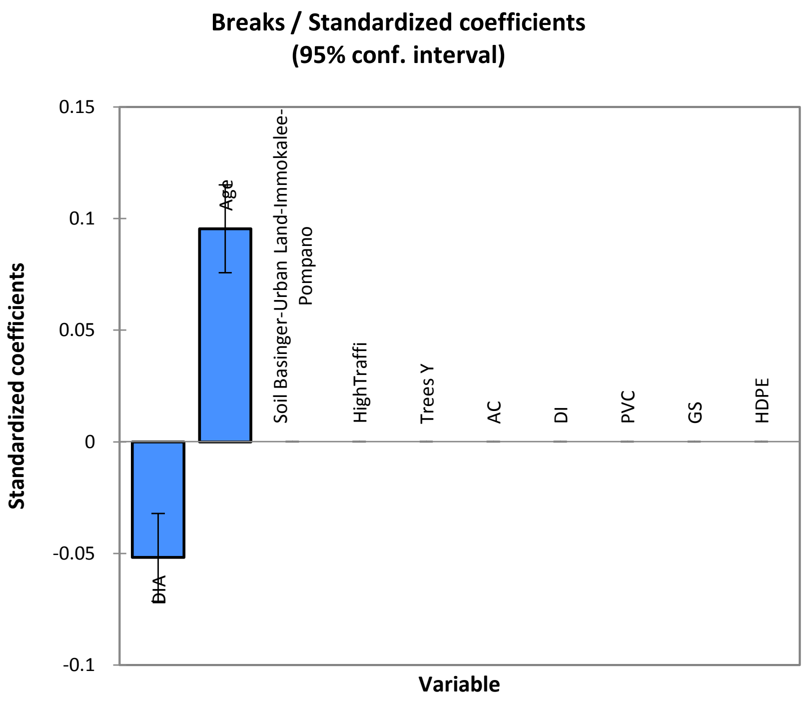

Figure 2. Impact of factors on leaks.

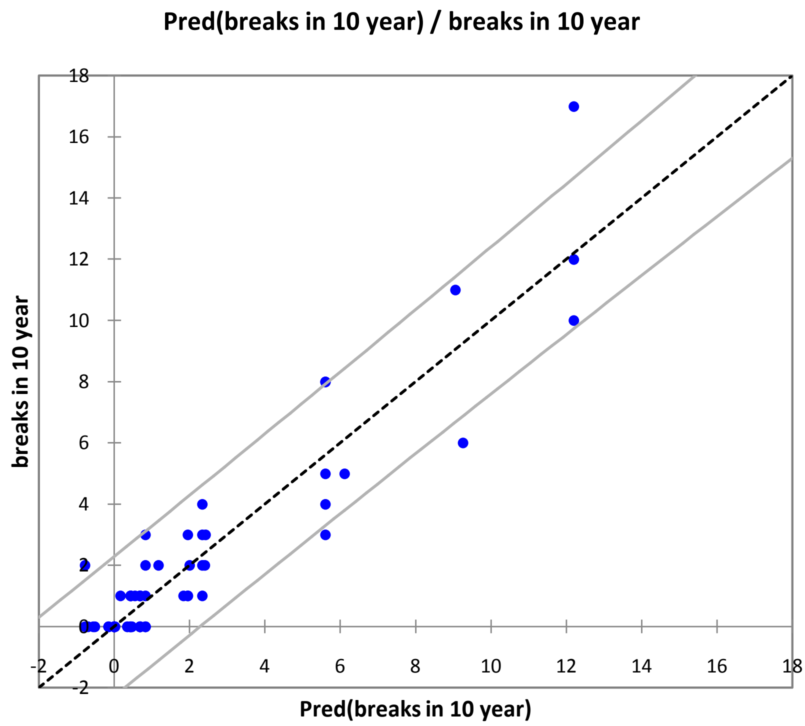

Figure 3. Comparison of predictive and actual breaks over 10 years (correlation desirable).

Applied to Utility #1, the predictive capability of breaks was strong (see **Figure 4**). Older AC pipe was a factor. Note that because this correlation was high, other factors that might impact leaks in other communities were not obvious so other communities would need to recreate this analysis for their situation. Hence the data for this utility may only apply to this utility of one just like it. **Figure 4** is a GIS map of pipe vulnerability. Red pipe is the highest priority to schedule for replacement.

The second community is primarily residential but because it is coastal, experiences a degree of seasonal demands of beach communities. The community was incorporated in the early 1920s and the first piping was installed at that time. For this community, the system has over 500 miles of pipe, that is divided into 20,000 pipe segments in their GIS system (see **Table 4**). The piping materials were as noted in **Figure 5**. Note that cast iron (CI) pipe was common in the early years, with PVC and ductile iron later. Over 200 miles of galvanized pipe was installed in the 1960s and early 1970s, when this utility experienced is greatest development on its western edge. Much of the galvanized has been replaced given less than 100 miles exist today due to chronic leakage. However, the data on pipe breaks was limited.

For utility #2 the same procedure was used. Given the limited amount of data on breaks (less than 18 months), the correlations were small except as it relates to AC and galvanized pipe (**Figure 6**). A linear regression function using XLStat was used to create and equation to identify the factors associated with each variable and the amount of influence that each exerts. In this case, the equation is:

$$\text{Number of Breaks} = 9.72941853770875\text{E-}03 + 5.21803401191647\text{E-}02 * \text{AC} + 0.127707343688261 * \text{GI}$$

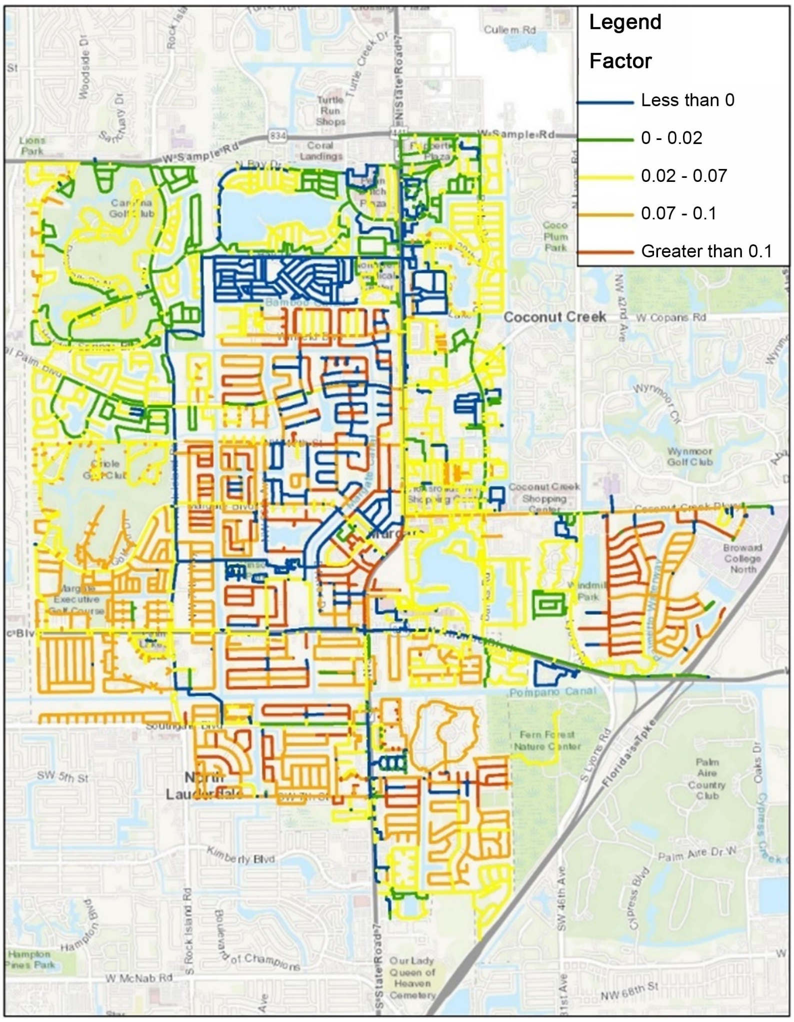

Figure 4. Pipes most likely to fail for Utility #1, red pipe is highest risk.

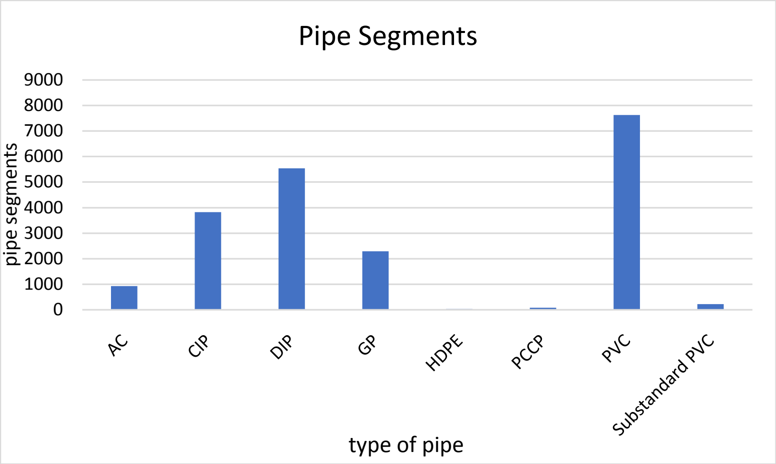

Figure 5. Pipe Segments by material.

Table 4. Piping sizes in Utility #2.

Pipe Size	Pipe Length	Units
1 in Water Main	383	LF
1.5 in Water Main	3513	LF
2 in Water Main	422,530	LF
3 in Water Main	23,148	LF
4 in Water Main	391,438	LF
6 in Water Main	473,425	LF
8 in Water Main	388,800	LF
10 in Water Main	15,330	LF
12 in Water Main	977,374	LF
14 in Water Main	1697	LF
16 in Water Main	84,944	LF
18 in Water Main	4654	LF
20 in Water Main	1044	LF
24 in Water Main	88,776	LF
30 in Water Main	8280	LF
36 in Water Main	36	LF
42 in Water Main	322	LF

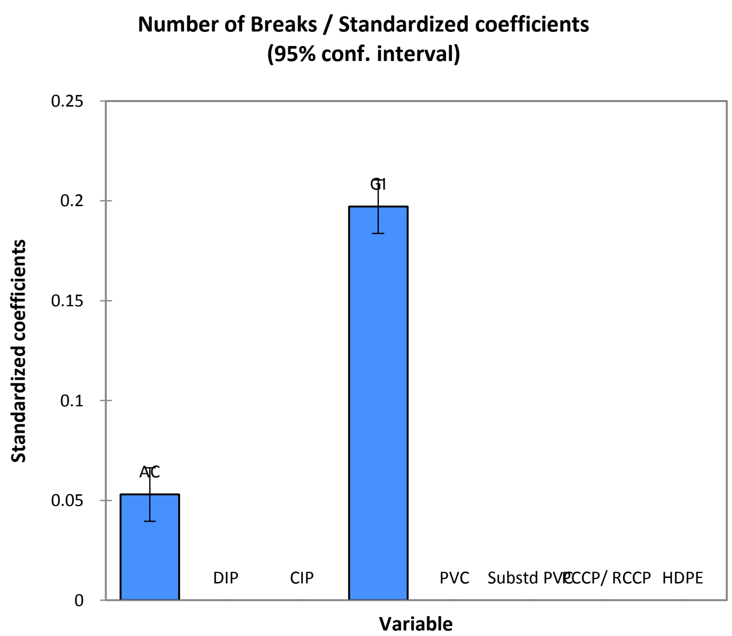

Figure 6. Primary influences on pipe failure in Utility #2.

The analysis indicated that galvanized and AC pipe drive breaks as expected. The pipes most likely to fail are shown in a map in **Figure 7**. Note older cast iron pipe is not part of the highest risk of failure piping.

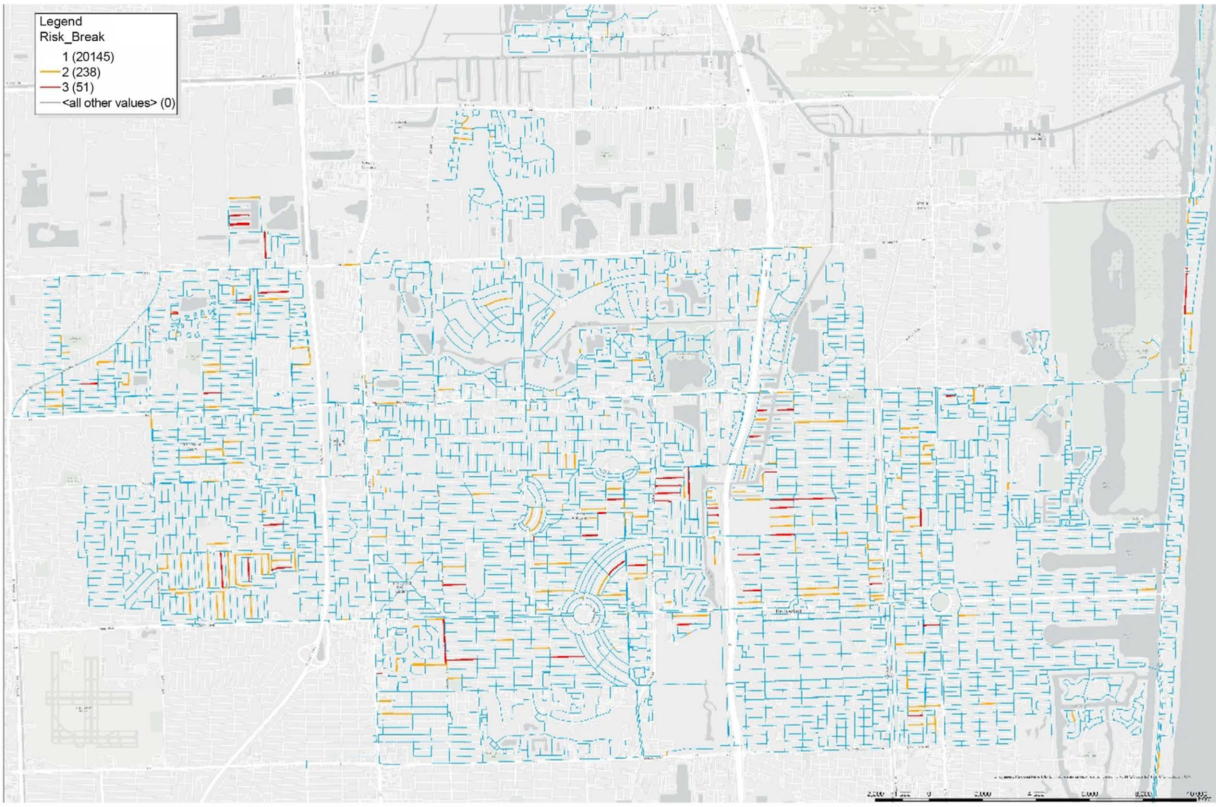

Figure 7. Pipes most likely to fail for Utility #2.

Utility #3 also has over 500 miles of pipe with sizes ranging from 2 inches to 36 inches (see **Table 5**). The oldest pipe in this service area is galvanized pipe in rear yards and AC pipe. While the earliest pipes in this service area were installed in the late 1960s, the community really expanded in the 1990s and 2000s. As a result, the vast majority of water mains on the system are PVC C900 pipe, creating somewhat of a monolithic system (see **Table 6**). Utility #3 only had 10 total breaks recorded, so a combination of utility #1 and #2 equations were used to create **Figure 8**, predicted utility breaks. One of the challenges with Utility #3 is that the few breaks were on PVC, the utility recorded only three small breaks on the galvanized and AC pipes. Using the predictive analysis models from prior utilities, the pipes expected to fail are located at older areas where galvanized and AC pipe material exist. However, these small predicted pipe failures are unlikely to be catastrophic to the system.

As a result, a means to define the consequence of critical pipe failures was developed as outlined in **Table 7**. These factors were added and the total multiplied by the pipe failure results from the regression model. The concept was that larger, critical and single feed systems would have more impact from breaks than small looped lines. The resulting factors can be applied to the linear regression predictive model, is a simple algebraic formula that can be run by multiplying the summation of the risk factors by the summation of the criticality factors for all pipes which makes some minor changes in priority for both utilities #2 and #3 (see **Figure 9** and **Figure 10**).

Table 5. Pipe sizes in Utility #3.

Pipe Size	Length (ft)
2	128,595
4	53,878
6	276,068
8	1,738,889
10	62,536
12	311,207
14	2849
16	255,738
18	4038
20	20,349
24	51,409
30	13,764
36	139
42	14,081

Table 6. Pipe materials in Utility #3.

Pipe Material	Length (ft)
AC	113,188
CI	7952
DI	336,069
GP	78,533
PVC	2,392,425
HDPE	1040
UNK	4308

Figure 8. Predicted water distribution system failure risk for Utility 3.

Table 7. Water distribution system risk analysis data collection criteria.

Criteria	Priority Rating		
	1: Low	2: Medium	3: High
Risk Data - Pipe Properties			
Pipe Properties Material	HDPE, PVC C-900	DI, RCP, PCCP	GS, Thin PVC, AC, CIP, HDPVC
Number of Breaks	0	1	>1
Risk Data - Proximity To			
Major Roadway	Not in Right of Way	In Right of Way	Under Pavement
Residential Backward	Not in Backyard	N/A	Within Backyard
Criticality Data			
Diameter	<12"	12" to <16"	16" and greater
Large User	No	N/A	≥4" meter
Critical Customer	No	N/A	Yes
WTP Transmission	No	N/A	Yes
Storage Tank Transmission	No	N/A	Yes

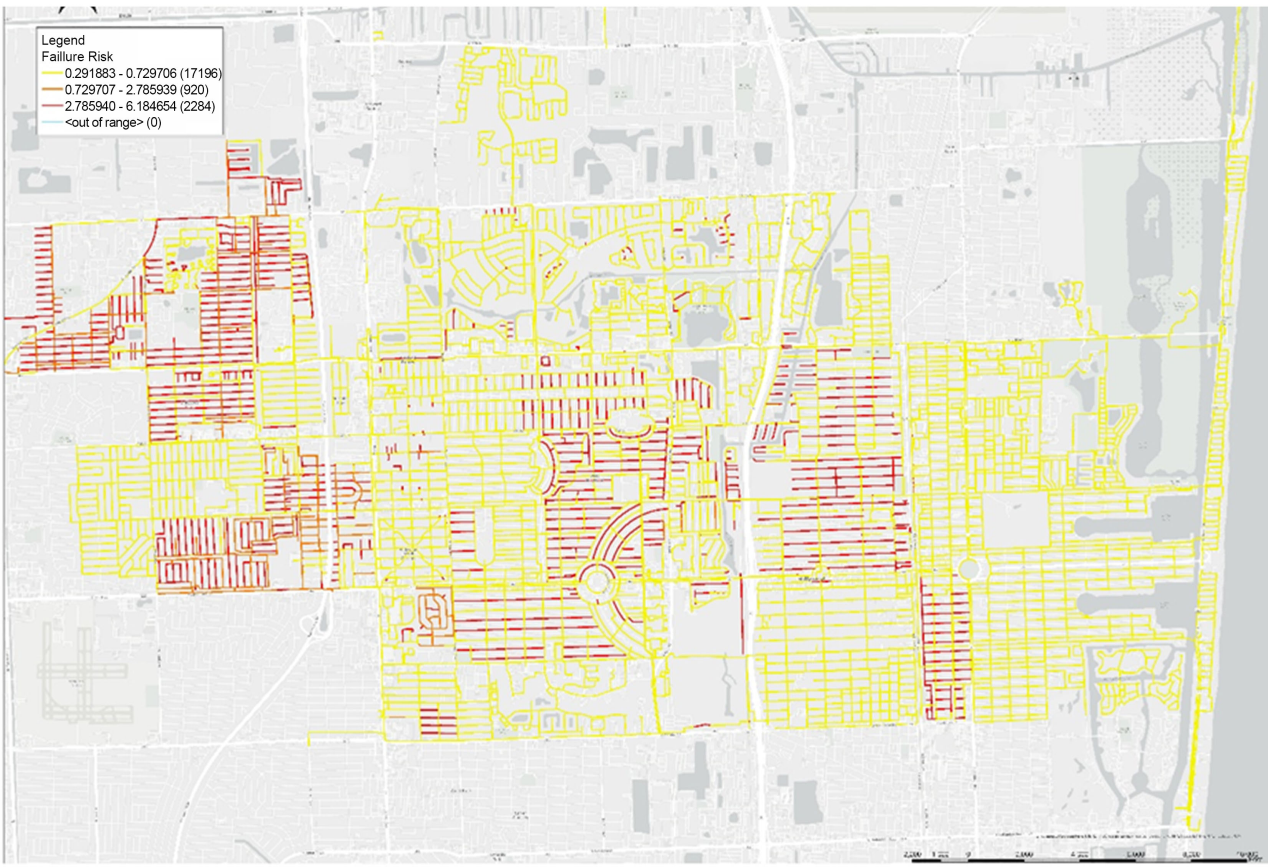

Figure 9. Water distribution system criticality failure risk for Utility #2.

Figure 10. Water distribution system criticality failure risk for Utility #3.

4. Conclusions

Many utilities have not implemented comprehensive asset management plans for their assets. In part this is due to the belief that they cannot properly assess certain assets like buried pipe because assessment of the assets is too expensive or yields data of limited value. As noted in Bloetscher *et al.* [9] [10], for many water utilities, over half their total asset value is in buried infrastructure. The failure of these assets can be minor ongoing irritations, catastrophic failure or something in between. However, these assets will deteriorate with time and the costs for maintenance will increase as well. The key is to prioritize pipe replacements to control operations and maintenance costs and increase system reliability to protect the public health, safety and welfare. One of the most important issues is that utilities need to collect data, in this case pipe breaks. The lack of information makes predictive efforts far more difficult. Work orders, tracking information on breaks, costs, and materials, and the accompanying GIS updates are critical. It means a GIS system is necessary although complete data is not needed to begin the effort.

Under the evaluation of this water system condition and asset replacement prioritization, approximately 500 miles of pipes, ranging in size from 2 inches to 36 inches were evaluated for Utility #3. The materials for the water main system included galvanized, AC and PVC C900; being this last one most of the pipe materials in the system. Due to poor water main break records, a combination of adjacent utility data was used to develop the predictive utility break model. The predictive analysis model concluded that pipe expected to fail is mainly located at older areas where the galvanized and AC pipe material exist.

Conflicts of Interest

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

References

[1] ASCE (2001) 2001 Report Card for America's Infrastructure. http://ascelibrary.org/doi/book/10.1061/9780784478882

[2] ASCE (2005) 2005 Report Card for America's Infrastructure. http://ascelibrary.org/doi/book/10.1061/9780784478851

[3] ASCE (2009) 2009 Report Card for America's Infrastructure, ASCE, Alexandria. https://www.infrastructurereportcard.org/2009/

[4] ASCE (2013) 2013 Report Card for America's Infrastructure, ASCE, Alexandria. http://www.infrastructurereportcard.org/

[5] ASCE (2017) 2017 Report Card for America's Infrastructure, ASCE, Alexandria. https://2017.infrastructurereportcard.org/

[6] ASCE (2021) Report Card on America's Infrastructure, ASCE. https://infrastructurereportcard.org/

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

[8] Goldman, D.G. (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

[9] Bloetscher, F. (2019) Public Infrastructure Management: Tracking Inevitable Asset Challenges and Increasing System Resiliency, JRoss, Plantation, FL.

[10] Bloetscher, F., Wander, L., Smith, G. and Dogon, N. (2017) Public Infrastructure Asset Assessment with Limited Data. *Open Journal of Civil Engineering*, **7**, Article ID: 79326. https://doi.org/10.4236/ojce.2017.73032