Capital Improvement Program Forecasting to Analytically Target Distressed Infrastructure

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Palm Beach County Water Utility Department (PBCWUD) owns and operates a wastewater collection system consisting of 1,250 mi of gravity sewer pipe, ranging in size from 4 to 30 in. in diameter, and 600 mi of wastewater force main that has been in operation for over 50 years, A program was recently initiated by PBCWUD to develop a desktop analysis approach to access these systems, and it determined that the analysis would help to best allocate inspection, maintenance, and replacement projects and project future capital improvement programs (CIPs).

The PBCWUD contracted with CDM Smith to assist in the development of the analysis tool using existing geographic information system (GIS) data, determine infiltration within the systems, evaluate the systems, identify pipes for inspection, perform pipeline assessment certification program (PACP) inspections, rank inspected pipes, and develop design packages for identified pipes renewal. Renewal efforts by PBCWUD focused on combining four decision levels:

- Long-range planning or capital renewal needs estimating pipe-specific life expectancy for the next 100 years.
- Risk-based pipe ranking using GIS software.
- PACP inspection of gravity sewer systems and ranking of pipes from inspection.
- Decision framework to optimize and schedule the pipe renewal cured-in-place pipe (CIPP).

Installed Pipeline Inventory

Table 1 lists the gravity and force main pipeline asset groupings used in the analysis, and the total mi of pipe installed as extracted from the GIS at PBCWUD. The polyvinyl chloride (PVC) material makes up the majority of the gravity and force main systems (92 and 65 percent, respectively), with ductile iron mains representing the majority of the remaining material for each system. It's important to note this, as the assumptions regarding the service lives of these major materials will have the greatest impact on the results of the analysis. Figure 1 geographically locates vintage pipes by age.

Table 1. Palm Beach County Water Utility Department Pipeline Materials and Lengths

Pipe Material	Material Code	Length (mi)	Percentage of Total System
Gravity Main Pipeline			
Polyvinyl Chloride	PVC	1165.52	92.19%
Lined Ductile Iron	LINED	44.01	3.48%
Vitrified Clay	VCP	28.85	2.28%
Mixed PVD and Ductile Iron	P_D	11.28	0.89%
Ductile Iron	DIP	8.26	0.65%
Unknown	UNK	4.37	0.35%
Asbestos Cement/Transite	AC	1.52	0.12%
Mixed Vitrified Clay and	V_D	0.20	0.02%
Cast Iron	CAS	0.18	0.01%
Total		1,264.20 mi	
Force Main Pipeline			
Polyvinyl Chloride	PVC	388.67	65.1%
Ductile Iron	DIP	157.26	26.3%
Cast Iron	CAS	19.34	3.2%
Prestressed Concrete	CNC	13.06	2.2%
Unknown	UNK	8.20	1.4%
Asbestos Cement/Transite	AC	6.42	1.1%
Polyvinyl Chloride	HDPE	3.97	0.7%
Mixed PVD and Ductile Iron	P_D	0.41	0.1%
Total		597.34 mi	

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Service Life Curve Development

The renewal modeling calculations used estimated pipe service life values to develop service life curves, indicating how the pipe assets will "survive" over time. These curves are developed using a three-point method:

- The first point on the curve indicates the date at which the majority (i.e., 90 percent) of the pipes within that group is expected to be in service (before they have the potential to "fail").
- The second point on the curve is the point at which 50 percent of the pipes in that category are expected to be in service (assuming half also fail).
- The third point on the curve is the date at which only 10 percent of the pipes are expected to remain in service, on average.

This can similarly be related to human life expectancy curves, with the majority of people statistically surviving to middle age, some infant mortality, and some people living to very old age. The analysis utilizes an industry standard pipeline aging distribution function developed by R.K Herz in 1996 and used throughout a number of pipeline asset analysis software packages. The Herz distribution function is used to randomly select pipeline segments of each material type based on the service life curve values. The software then models the potential failure of each pipeline type over time, based on its installation year. By doing this, the software model generates a random distribution of potential pipeline failures to mimic real-world asset degradation.

In order to develop the service life values for the PBCWUD systems, information gathered during previous nearby projects in Miami, Boca Raton, and Seminole County; Raleigh, N.C.; and from discussions with other utilities was used. The latest guidance from American Water Works Association (AWWA) regarding water main service lives was also utilized. Table 2 lists the sewer main service lives by material type recommended by AWWA for utilities in the United States.

Based on discussions with PBCWUD staff, it was determined that the AWWA service life value estimates might represent service lives that are too long for use in the more caustic wastewater pipeline environments. The agreed-upon pipe service life values shown in Table 3 were used in PBCWUD's long-term renewal needs analysis.

Long-Term Renewal Needs Results

Using the pipe groupings and service life values in Table 3, the renewal needs model provided a year-by-year pipeline quantity (by material type) that should be targeted for replacement between 2016 and 2116 (100-year study period). The model output is a list of pipeline quantities by material (in mi) that reach their end-of-service life in a given future year.

Figures 2 and 3 illustrate the renewal needs for PBCWUD's gravity sewer and force main pipeline networks for the next 100 years. The horizontal axis is the projected years 2016 through 2116; the vertical axis is the mi of pipe renewal needed by material per year based on the service life. The total renewal needs for the gravity main system is shown in Figure 2 in the "top" portion of the stacked bands, with the peak need of 29.5 mi of pipeline occurring in 2054, or 2.25 percent of the total 1,313 mi analyzed. The total renewal needs for the force main system is shown in Figure 2 in the "top" portion of the stacked bands, with the peak need of 16 mi of pipeline occurring in the Year 2052, or 2.4 percent of the total 668.7 mi analyzed.

The width of each colored band indicates the estimated amount (in mi) of each material type that needs to be considered for renewal in each future year. The general industry guidance is to reach a "sustainable" renewal level per year. If 1 percent of the system were renewed each year, the entire system would be completed over 100 years and remain consistent with the average material service life (assumed to be 100 years).

The dashed black line shown in Figures 2 and 3 represents the average renewal needs for each system over the 100-year analysis period, or 12.5 mi of renewal for the gravity system and 5.9 mi for the force main system. Each of those values is approximately 1 percent of the system per year. The solid grey line represents a recommended approach to stepping up the renewal amounts over the next 15 years for each system. These renewal rates and amounts were used in conjunction with the pipe-by-pipe risk ranking analysis to develop final recommendations for a multiyear capital plan.

Risk-Based Pipeline Asset Ranking

The ranking approach used for the PBCWUD analysis assesses the gravity and force main pipeline assets involved in the use of GIS-based software in calculating the probability and

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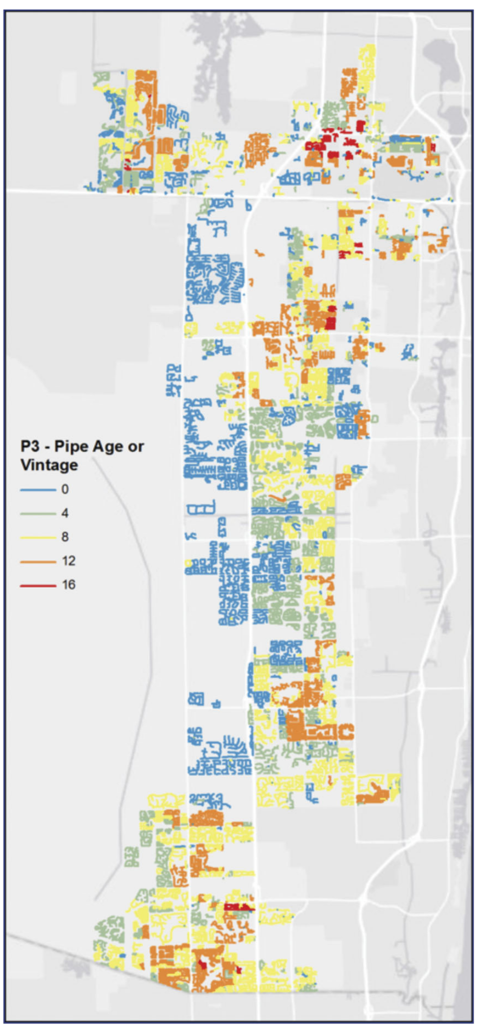

Figure 1. Age of Gravity Mains

Table 2. American Water Works Association Service Life Values

AWWA Material Type	Derived Service Lives (Years)
Pit Cast Iron	130
Spun Cast Iron	120
Ductile Iron	110
PVC	100
Steel	100
Concrete and PCCP	100

(source: "Buried No Longer: Confronting America's Water Infrastructure Challenge," AWWA, February 2012)

Table 3. Palm Beach County Water Utility Department Pipe Service Life Values Used

Pipe Material	Material Code	90% Pipe Length Remaining	50% Pipe Length Remaining	10% Pipe Length Remaining
Gravity Main Pipeline				
Polyvinyl Chloride	P VC	45	65	85
Lined Ductile Iron	LI NED	35	45	50
Vitrified Clay	V CP	60	70	80
Mixed PVD and Ductile Iron	P _D	35	55	75
Ductile Iron	DI P	60	75	90
Unknown	U NK	45	70	85
Asbestos Cement/Transite	A C	45	55	60
Mixed Vitrified Clay and	V	40	50	60

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consequences of failure for each pipeline. These factors are separated into groups by probability factors and by consequence of failure factors, which together represent the predicted risk of failure of the asset.

Failure Risk Factor Data, Weights, and Analysis

While there are multiple factors that can result in pipeline failure, this project considered 31 total risk factors that provided a clear difference between individual pipe segments within the two PBCWUD networks. Ensuring a clear difference between pipe segments is the key to ranking pipe assets for renewal. Most utilities can identify the small percentage of pipelines that are in poor condition and those that have higher consequences of failure within a system; however, once those assets are addressed, it's often hard to logically determine the next set of critical pipelines for renewal to mitigate future pipeline degradation and failure.

Probability of Failure Risk Factor

Table 4 provides brief descriptions of each of the probability of failure factors used in the analysis. Each factor has been given a unique identifier number (P1 through P11) for easy reference and use within the final-ranking database table and all documentation developed for the project (note that not all factors apply to both the force main and gravity main systems). The table indicates the systems involved for each factor.

Each factor utilized a scoring range to account for different factors, or ranges, of variation in the scoring, as well as an overall weight for each factor. For example, the probability of failure for pipelines based on the previous failures, or breaks (P2 factor), requires a range of scores based on the number of total breaks that the pipelines within the system have experienced; the individual pipelines were then scored based on the number of breaks each experienced. Each of the scores was then multiplied by the factor weight (5 being the highest weight and 1 being the lowest weight) to arrive at a final score for the P2 factor for each pipe. The weighting values provided PBCWUD staff with the ability to assign the importance (or rank) to each of the factors against one another.

For each of the probability factors, a description of the factor's intent in assigning a probability of failure, as well as the process and data used in calculating each factor, are discussed. In addition, a table and map illustrating the overall results for the corresponding pipelines within the system for that factor are shown (Table 4 and Figure 4). Each table describing the results includes the input value, the score value for each, the total score (score multiplied by the weight), the total mileage of pipeline for that input value, and the overall percentage of the collection system pipelines for that input value.

Consequence of Failure Risk Factors

The consequence of failure measures how disruptive or damaging a pipe failure can be. Risk factors associated with the consequence of pipe failure were developed and applied to the analysis as described.

The consequence of failure factors have been given a unique identifier number (C1 through C20) for easy reference and use within the final-ranking database table and all documentation, user manuals, and tools for the project.

Each factor utilized a scoring range for the different types of factors, or ranges, of variation in the scoring, as well as an overall weight for the factor. The weighting values (5 being the highest weight and 1 being the lowest weight) provide PBCWUD with the ability to assign importance, or rank, to each of the factors against one another.

As with the probability of failure factors, each of the consequence of failure factor descriptions in this section provides the factor's intent in assigning consequence of failure, as well as the process and data used in calculating each factor. A map and table illustrating the overall results for the pipelines within the collection system are then developed.

System-Wide Risk Ranking Results

In order to classify the results for the total consequence, probability, and normalized total risk into the best groups to use the results to drive renewal activities within the system, the use of the Jenks Natural Breaks classification method was recommended. This method of identifying the best breakpoints within a range of values utilizes data-clustering methodology to determine the best arrangement of values into different classes by seeking to minimize each class's average deviation from the class mean, while maximizing each class's deviation

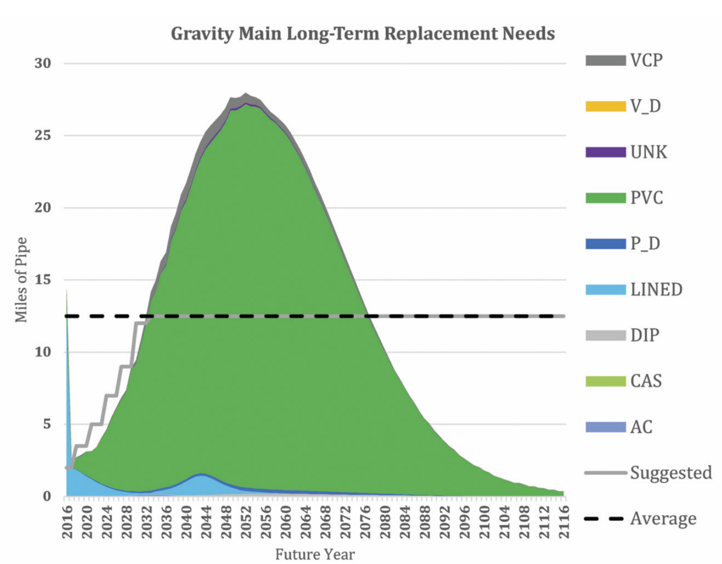

Figure 2. Projected Gravity Sewer Main Pipeline Renewal Needs Through 2116 (in mi)

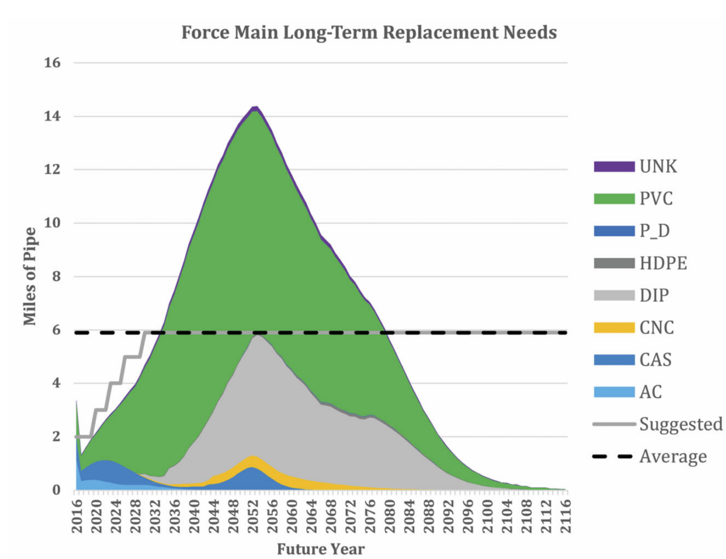

Figure 3. Projected Force Main Pipeline Renewal Needs Through 2116 (in mi)

from the means of the other groups. This thereby reduces the variance within each class and maximizes the variance between classes.

Ten scoring ranges were used in ranking pipeline assets (Figure 4), and the Esri ArcGIS software includes tools to categorize the results of the risk-ranking tools into scoring ranges using the Jenks methodology. The risk-ranking values are normalized to 1,000, where the maximum score is set to 1,000 and all others are divided by this value to create a consistent and comparable range of values.

Sanitary Sewer Evaluation Survey Plan and Sanitary Sewer System Analysis

The highest-risk pipeline areas forming the analysis were prioritized into three areas of immediate need for field inspection. Closed-circuit television (CCTV) data were gathered and inspected using the GraniteNet™ inspection software platform. All located defects were coded in accordance with PACP standards, and all digital records were stored in both GraniteNet and PACP exchange formats for redundant record keeping (GraniteNet is the native inspection file specified by PBCWUD). Videos were reviewed in detail for each pipe, pipe segment coding, and scoring using PACP defect descriptions, which included:

- *Structural Defect Coding* – This group includes the type of defects where the pipe is considered to be damaged, ranging from a minor case defect to a more severe case, depicted as pipe failure. This group includes defects described as cracks, fractures, broken pipe, holes, deformities, collapsed pipe, joint defects, surface damage defects, weld failures, point repair codes, brickwork defects, and lining failures.
- *Operation and Maintenance (O&M) Coding* – This group includes the various codes that involve the spectrum of defects that may impede the O&M of the sewer piping system, and is comprised of defects such as roots, infiltration, deposits and encrustations, obstacles/obstructions, and vermin.
- *Construction Features Coding* – This group includes the various codes associated with the typical construction of the sewer piping system and is comprised of defects associated with taps, intruding seal material, pipe alignment codes, and access points.
- *Miscellaneous Features Coding* – This group includes observation codes, such as water levels, detection of sags, pipe material changes, and dye testing notes.

The PACP standard condition grading system was then applied to define inspected pipe segments with defects. The PACP system assigns a distinct code (1-5) for each structural defect and O&M defects observed during the CCTV inspection. The interface software used during CCTV inspections assigned the PACP codes and recorded them in an information database.

The PACP system, however, does not account for factors like pipe material, depth, soil, or surface condition. The developed algorithm included pipe material, which PBCWUD identified as important due to specific maintenance problems associated with pipe types in the system. The pipe material algorithm ensures that all clay pipes will receive, at a minimum, a structural score of 3.

Defects Identification

The National Association of Sewer Service Companies (NASSCO) PACP version 6.0.1 classifies defects as either a structural or O&M type, with coding of 1 through 5 (1 being a minor defect and 5 being the most severe). Table 5 summarizes the found structural and O&M defects

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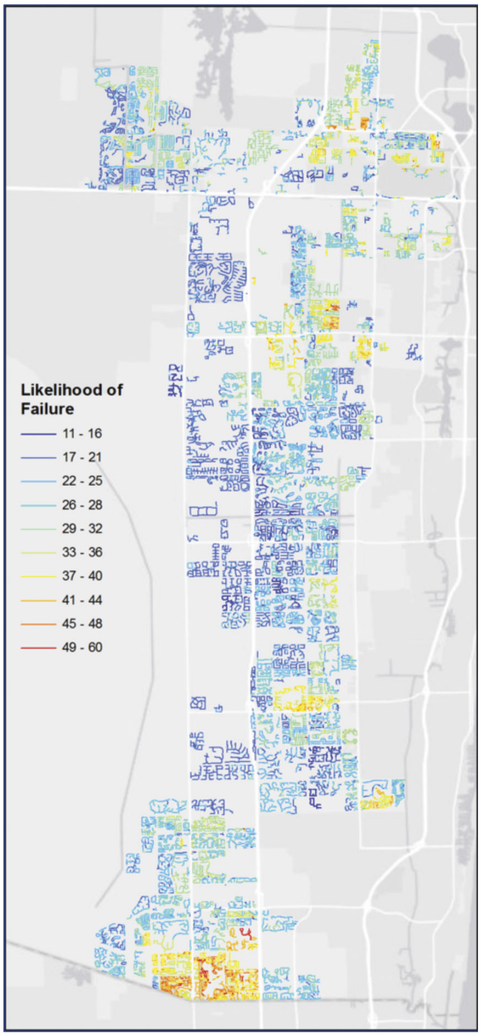

Figure 4. Map of Total Probability Failure Results: Gravity Mains

Table 4. Probability of Failure Factors

ID	Criteria	Factor Description	Weight	System
P1	Paved vs. Unpaved Roadways	Pipelines under unpaved roadways suffer from greater amounts of vibration than those under paved roads.	2	Both
P2	Past Breaks/ Leaks/Service History Issues	Previous breaks in a pipe section and/or known sections of poor pipe conditions provide physical indications of weaker pipe, including sections of pipe that are immediately downstream and upstream of previous breaks.	5	Both
P3	Pipe Age or Vintage	Age of main contributes, in general, to the condition of the pipe. Older pipe generally is in a worse condition than newer pipe, with exceptions for known vintages of poor quality.	4	Both
P4	Pipe Coating or Material Change	Pipelines with external coatings have a better chance of remaining in good condition and pipelines, with different materials installed along their length having a greater potential for issues.	3	Both
P5	Material	Different pipe classes have a different wall thickness.	3	Both
P6	Bury Depth	Pipelines that are buried more deeply suffer from greater amounts of infiltration.	3	Both
P7	Soil Resistivity and Type	Different soils have different rates of corrosion on metallic mains.	4	Force Main
P8	Pressure	Higher pressure on mains may contribute to shorter lifespans or joint failure.	4	Force Main
P9	Number of Connection	More laterals or pipeline connections on a given pipeline may weaken the pipe (connections/1000 ft).	2	Gravity
P10	Pipe Crossing Large Water Mains or Conduits	Pipelines crossing over or under other utilities or conduit casements can be damaged by those other pipelines.	3	Both
P11	Infill Areas	Pipelines infill areas may fail due to poor structural support.	3	Both

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that occur in each level for the inspected pipes. Structural defects are grouped into seven categories: broken, deformed, cracked, fractured, hole, sag, and joint. Fractures, sags, and cracked pipe are the three most prevalent defects observed in the inspected system. The O&M defects are grouped into four categories: infiltration, roots, tap, and deposits/obstructions. The most common O&M defect observed in the inspected pipes was infiltration, and the majority of infiltration was coded as level 4 and 5.

Table 5. Structural and Operation and Maintenance Defects in Gravity Sewer

		PACP Level					Total # of Defects
		1	2	3	4	5	
Design Structural	**Broken**	0	0	2	0	10	12
	Deformed	0	0	0	0	2	2
	Cracked	2	57	12	0	0	71
	Fractured	0	125	250	229	0	604
	Hole	0	0	1	0	1	2
	Sag	0	0	117	1	6	124
	Joint	11	1	0	0	0	12
O&M	**Infiltration**	0	1	9	213	72	295
	Roots	55	1	17	0	0	73
	Tap	0	46	0	0	0	46
	Deposits/Obstructions	0	156	28	2	5	191

Results

The goal of the PBCWUD 2017 collection system rehabilitation project was to prioritize lift station basins for rehabilitation, field-inspect the highest-priority lift station basins using standardized NASSCO methods, and identify pipes for rehabilitation. Sanitary sewer renewal and rehabilitation design packages are being developed from the pipes identified during this analysis.

By using the GIS-based statistical desktop analysis, PBCWUD evolved from using a basic reactive method to proactive rehabilitation planning. The desktop analysis first reduced the areas to be inspected in the field, reducing mobilization and inspection costs incurred when the lift station basins in good condition are inspected. Field inspections, combined with the standardized pipe scoring, pinpointed the pipes for rehabilitation. Pinpointing individual pipes reduced the cost from the previous method of rehabbing the entire basin.