Boca Raton's Proactive Pressure Pipe Renewal Program

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Overview: Developing the Risk-Ranking Analysis Approach

The City of Boca Raton Utility Services Department (city) recently developed an advanced desktop pipeline asset-ranking approach for its water distribution mains and wastewater force main pipeline assets citywide. The city is fortunate to currently experience below-average rates of infrastructure failure when compared with utilities across the United States. The city determined that investing in a detailed analysis of its existing infrastructure would help maintain that below-average rate and methodically project and plan for future capital improvement program (CIP) projects.

The city engaged CDM Smith to assist in performing a risk-ranking evaluation and provided existing geographic information system (GIS) data to assist with the analysis. The firm processed and analyzed the available information using desktop computer software to identify the most appropriate pipeline assets for the city to focus its renewal efforts using two types of methodologies:

1. Long-range planning of capital renewal needs by analyzing service life estimates for specific pipe materials based on estimated asset age to project renewal rates for the system over the next 100 years.
2. Risk-based water pipeline asset ranking using Esri GIS software that leverages the city's previous GIS investment.

A step-by-step decision framework was developed to supplement these two methodologies to screen and prioritize the results of the analyses mentioned and sort the studied pipeline segments into action groups for rehabilitation and/or replacement (renewal). This information will assist the city with incorporating proactive renewal efforts into its multiyear CIP.

Overall, this project provided the city with a holistic, systemwide evaluation of its pressurized water and sewer pipeline infrastructure and an action plan to minimize the risk of future infrastructure failure. The city will also have a new framework to use in the CIP decision-making process that is based on specific system information and recommended engineering approaches.

Forecasting Methodology: Long-Term Renewal Needs by Material

The results of this part of the project's analysis provided the city with a customized renewal-needs curve for its pipeline assets over the next 100 years showing graphically, by type, how much rehabilitation and/or replacement is recommended annually to maintain the system's integrity.

The renewal-needs analysis is driven by the specific pipe materials installed over time and the estimated service life curves for those pipe materials. To begin the evaluation, the primary pipe attributes needed are pipe material types and dates of installation.

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Installed Pipeline Inventory

Table 1 lists the city's large-diameter water and sewer pipe asset groupings used in the analysis and the total miles of pipe installed as extracted from the city's GIS. It is important to note that the cast iron material makes up the majority of the water and force main systems (68 and 46 percent, respectively), with ductile iron mains representing the majority of the remaining material for each system.

Within the city's water distribution GIS layer, there are 7,821 segments, with a total pipeline length of 650.2 mi. Approximately 5 percent of the city's service area includes private water distribution systems. Only city-owned pipeline segments were included in the analysis, for a total pipeline length of 618.1 mi.

Within the city's force main GIS layer, there are 1,315 segments, with a total pipeline length of 126.1 mi. Approximately 10 percent of the city's service area includes private and/or inactive force mains. Only city-owned pipeline segments were included in the analysis, for a total pipeline length of 112.5 mi.

Table 1. City-Owned Pipeline Materials and Lengths

Pipe Material	Material Code	Length (mi)	Percentage of Total System
Water Distribution Pipeline			
Cast Iron	CAS	424	68 percent
Ductile Iron	DIP	140.2	23 percent
Asbestos Cement	AC	56	9 percent
Cured in Place Lined Cast Iron	CIPP	0.5	0.08 percent
Total		621.5 mi	
Sewer Force Main Pipeline			
Cast Iron	CAS	51.4	46 percent
Ductile Iron	DIP	50	44 percent
Polyvinyl Chloride	PVC	5.8	5.0 percent
Reinforced Concrete	RC	5.3	4.7 percent
Total		112.5 mi	

Service Life Curve Development

The long-term renewal model calculates the estimated pipe service life values to develop service life curves, indicating how the pipe assets will "survive" over time 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 are 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 final point on the curve is the date at which only 10 percent of the pipes 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 a very old age.

The software utilizes a Herz distribution function to randomly select pipeline segments of each material type based on these 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.

The pipe service life values shown in Table 2 were used in the city's long-term renewal needs analysis. These service life values are based on guidance from the American Water Works Association (AWWA), as well as other industry standards, that pipe materials, such as ductile iron and polyvinyl chloride, have an approximate service life of 100 years.

Results Summary: Long-Term Renewal Needs by Material

Using the pipe groupings and service life values in Table 2, 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 miles) that reach their end of service life in future years.

Figures 1 and 2 illustrate the renewal needs for the city's water main and force main pipeline networks for the next 100 years. The horizontal axis is the projected years 2016 through 2116; the vertical axis is miles of pipe renewal needed by material per year. The total renewal need is shown in the "top" portion of the stacked bands, with 2016 showing approximately 0.4 mi, or 0.06 percent of the total 618 mi analyzed.

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

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Table 2. City-Owned Pipe Service Life Values Used

Pipe Material	Material Code	90 Percent Pipe Length Remaining	50 Percent Pipe Length Remaining	10 Percent Pipe Length Remaining
Water Distribution Pipeline				
Cast Iron	CAS	75	95	130
Ductile Iron	DIP	70	95	120
Asbestos Cement	AC	55	70	80
Cured in Place Lined Cast Iron	CIPP	85	105	130
Sewer Force Main Pipeline				
Cast Iron	CAS	55	70	90
Ductile Iron	DIP	80	90	100
Polyvinyl Chloride	PVC	45	70	90
Reinforced Concrete	RC	65	80	95

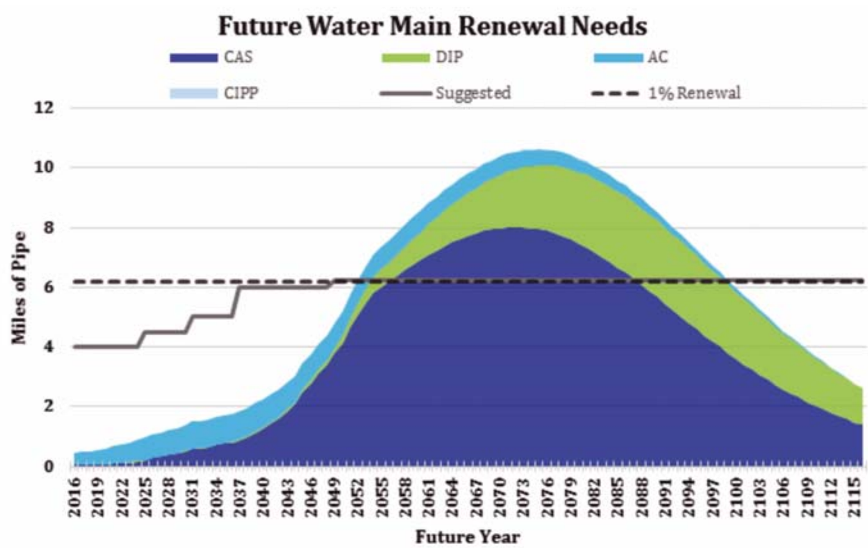

Figure 1. Projected Water Main Pipeline Renewal Needs Through 2116 (in miles)

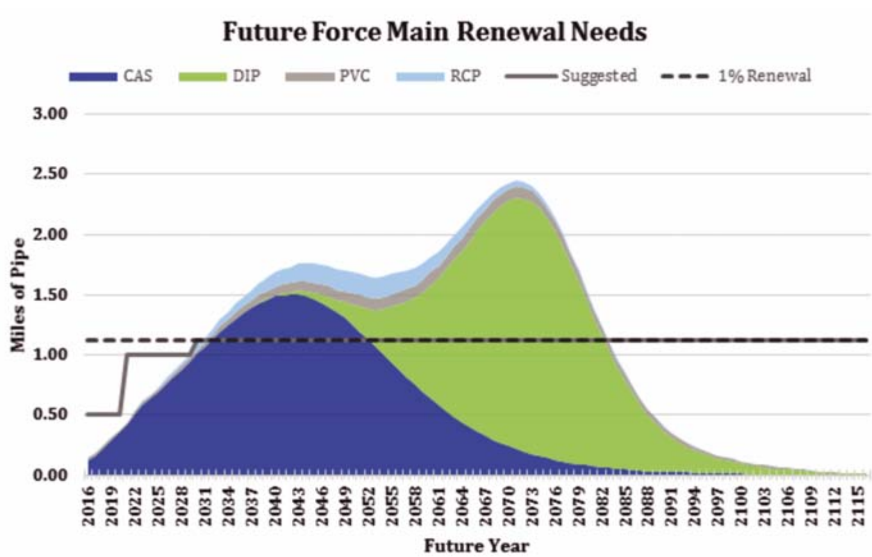

Figure 2. Projected Force Main Pipeline Renewal Needs Through 2116 (in miles)

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In Figures 1 and 2, the dashed line represents the 1 percent renewal rate for the system, with the solid line depicting the level of work needed for the city to increase the 1 percent renewal rate. Since the city's break/failure rates are below industry averages, it can gradually increase the renewal rates, while also monitoring break rates in future years to confirm that the renewal efforts are effective.

Table 3 lists the projected pipeline renewal needs between 2016 and 2116 for each material type. The total renewal needs for the water distribution system is 573 mi, or approximately 93 percent of the total 618 mi of pipe analyzed. The total renewal needs for the force main system is 112 mi, or approximately 99 percent of the total 112 mi of pipe analyzed.

These results indicate that not all of the studied pipelines will require renewal over the next 100 years, and that the majority of the existing pipelines, with remaining useful life in 2116, are the newest cast iron pipelines in the water system. Cast iron pipelines are identified in the pipeline ranking process as the lowest risk.

While there is still a need to address these assets, city staff can monitor the cast iron infrastructure to verify that it is not deteriorating at a faster rate than estimated. As expected, due to their harsh operating conditions, nearly all of the force main pipeline assets will need to be renewed or replaced over the next 100 years, with over 50 percent of the pipelines reaching their useful lives by 2070.

Based on these results, the city can attempt to increase the renewal rates within the water distribution and force main pipe networks to meet the anticipated 1 percent system renewal rate. This level of renewal should result in keeping up with the predicted pipeline degradation within the system when coupled with the risk-based pipeline selection process (discussed in the next section).

By addressing the highest-ranked pipelines by risk and by pipeline material, as well as increasing the renewal rate gradually, the city can address its long-term renewal needs and maintain the current low pipeline failure rate.

Table 3. City-Owned System Renewal Needs by Pipeline Group

Pipe Material	Material Code	Total Miles of Renewal Needs	Miles of System Pipe Analyzed	Percentage of Material Within the System Recommended for Renewal
Water Distribution Pipeline				
Cast Iron	CAS	399.8	422.0	95 percent
Ductile Iron	DIP	120.4	140.1	86 percent
Asbestos Cement	AC	52.5	55.5	95 percent
Cured in Place Lined Cast Iron	CIPP	0.5	0.5	100 percent
Total		573.2	618.1	93 percent
Sewer Force Main Pipeline				
Cast Iron	CAS	50.8	51.4	99 percent
Ductile Iron	DIP	49.9	50.0	100 percent
Polyvinyl Chloride	PVC	5.5	5.6	97 percent
Reinforced Concrete	RC	5.3	5.3	100 percent
	Total	111.5	112.5	99 percent

Table 4. Probability of Failure Factors

Factor ID	Criteria	Factor Description
P1	Major Roadways	Larger, more traveled roadways generally have more traffic load, causing potential pipe damage.
P2	Railway Crossings	Railway vibration causing pipe joint failure.
P3	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.
P4	Pipe Age or Vintage	Age of pipeline contributes, in general, to condition of the pipe. Older pipe generally is in a worse condition than newer pipe, with exceptions for known vintages of poor quality.
P5	Material	Different pipe materials or classes have different wall thicknesses, strength, and corrosion resistance.
P6	Number of Connections	More services or pipe connections on a given pipe may weaken the pipe or undermine the pipe due to service leaks.
P7	Proximity to Saltwater/ Swamp/Groundwater	Pipes in salt, groundwater, or swampland corrode more quickly.
P8	Pipe Diameter	Larger-diameter pipelines are less likely to fail than smaller-diameter pipelines due to wall thickness and installation practices.
P9	Water Table Versus Design Depth	Pipelines that are within the potentially changing water table (i.e., right at the water table depth) are subject to soil wetting and drying, causing bedding issues as well as corrosion.

Forecasting Methodology: Risk-Based Pipeline Asset Ranking

The results of this part of the project's analysis provided the city with a customized CIP for inspection and replacement of pipelines ranked by highest risk, showing graphically by location which pipeline assets require rehabilitation and/or replacement to maintain the system's integrity, and an accounting of the drivers supporting each of the rankings.

Failure Risk Factor Data, Weights, and Analysis

There are multiple factors that can result in a pipeline failure. This project considered 20 common probable and consequent factors that locally affect water and wastewater pipeline repairs. The development and use of 20 total risk factors provides a clear differentiation among the 8,400 or more individual pipe segments within the city's GIS databases for the two pipe networks. This is key when ranking the pipeline assets for renewal.

Generally, it is relatively straightforward for system operators to identify the small percentage of pipelines that are in the worst condition, and those that have higher consequences of failure within a system; however, once those assets are addressed, it is often difficult for utility system managers to accurately determine the next set of critical pipelines for renewal to mitigate future pipeline degradation and failure.

Table 4 provides brief descriptions of the failure probability factors used in this analysis. Each factor was given a unique identifier number (P1 through P9) for easy reference and use in the final ranking database table, as well as in all other documentation developed for this project. Each probability factor utilized a scoring range for various internal factors, as well as an overall weight. For example, the probability based on the previous failures (factor P3), requires a range of internal scores based on the total amount of pipeline breaks the system has experienced.

The individual pipelines were then scored

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based on the number of breaks each has experienced. The scores were multiplied by the factor weight (highest = 5; lowest = 1) to arrive at a final score for the failure probability factor of each pipe. These weighted values provide city staff with the ability to assign importance and/or to rank to each of the factors against one another.

Table 5 provides a brief description of each of the failure consequence of factors used in this analysis. The same process, as with the probability of failure factors, was used to calculate the scoring for each of the factors for all pipelines within the system.

Classification: Risk-Based Pipeline Asset Ranking

The Jenks natural breaks classification method was used to classify the results for the total consequence, probability, and normalized total risk into manageable results. These results can be used to drive renewal activities within the system. This method identifies ideal break points within a range of values by utilizing data clustering techniques to sort values into different classes, which attempts to minimize each class's average deviation from the class mean while maximizing each class's deviation from the means of the other groups. This then reduces the variance within each class and maximizes the variance among classes.

The total risk-ranking values were separated into five classifications and utilized values normalized to 1,000, with the maximum score set to 1,000 and all others divided by this value to create a consistent, comparable range of values. Figures 3 and 4 provide graphs of the normalized systemwide risk-ranking results in total miles of water distribution and wastewater force main pipeline systems.

Table 5. Consequence of Failure Factors

Factor ID	Criteria	Factor Description
C1	Damage or Disruption to Sensitive Locations	Some locations are more sensitive to flooding damage/disruption, with potential for loss of life or disruption to important areas, such as hospitals, schools, police, fire, government buildings, and hotels. Force mains include sensitive water bodies.
C2	Damage or Disruption to Roadways	Disruption to all types of roadways during a pipeline failure. Used scoring ranges based on different levels of roadway traffic/importance.
C3	Service Outage - Priority Customers	Some locations are more sensitive to disruption, with potential for loss of life or disruption to important areas, such as hospitals, schools, police, fire, government buildings, and hotels.
C4	Service Outage - Number of Customers/Demand	Number of customers out of service due to a pipe failure/the amount of user demand is affected by a pipe outage and isolation.
C5	Duration of Outage due to Hard-to-Repair Locations	The pipelines within backyard easements are difficult to repair and were scored by this factor.
C6	Flooding Potential - Diameter	Larger mains or mains with more pressure will release more volume during a failure.
C7	General Disruption to Life - Special Economic Zones	The redevelop area was identified as an area of special concern for pipeline failures.
C8	General Disruption to Life - Zoning	General ranking for all pipelines based on different zoning classifications.
C9	Tank Feeds	Pipes that feed into and out of storage, or pumping features, were scored higher for their criticality to the system.
C10	Hydraulic Criticality	Pipes that are extremely critical to the hydraulics of the system were scored higher for their criticality to the system.
C11	Population Density	The population density from the census data was used to rank areas for disruption due to a pipeline failure.

Results Summary: Risk-Based Pipeline Asset Ranking

As seen in Figure 3, the quantity of water distribution pipeline in the high- and extreme-risk categories is relatively small when compared to the medium-risk group. The extreme- and high-risk pipeline groups comprise only 10 and 12 percent, respectively, of the overall system, for a total of 138 mi. If the city increases pipeline renewal rates following the levels shown on the solid line on Figure 1, it will represent approximately 95 mi of pipeline renewal over the next 20 years. It will also allow the city to address all extreme-risk pipelines and over 50 percent of the high-risk pipelines.

The amount of high- and extreme-risk force main pipelines shown in Figure 4 represent larger overall percentages of the total force main system risk, at 22 and 13 percent, respectively. If the city increases pipeline renewal rates following the levels shown on the solid line on Figure 2, this will represent approximately 19 mi of pipeline renewal over the next 20 years. While this amount is less than the 25 mi of extreme-risk pipeline in the force main system, it is an-

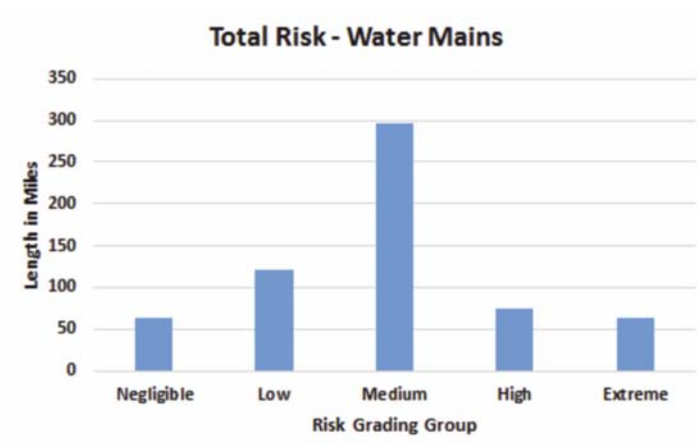

Figure 3. Normalized Total Risk-Ranking Groups for Water Distribution Pipe (in miles)

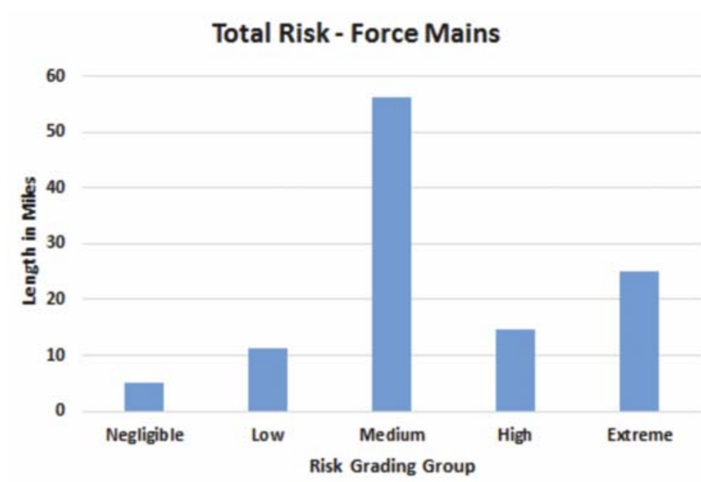

Figure 4. Normalized Total Risk-Ranking Groups for Force Main Pipes (in miles)

ticipated that current and future advanced pipeline inspection technologies can be used to determine the actual condition of the force main assets. This can reduce the total risk for some of the high- and extreme-risk assets if they are found to be in acceptable condition and can be operated with longer service lives with continued monitoring.

Capital Improvement Program Integration

The long-term renewal needs and risk-based ranking analysis developed in this project have provided city staff with detailed information regarding the amounts, locations, and drivers for future pipeline renewal projects. Moving forward, projects will need to balance available funding and group assets with mixed-risk cohesive projects. In addition, specific extreme-risk pipelines with high-risk pipeline assets have also been identified to allow the city to develop a cohesive, efficient long-term program, while providing the flexibility to address individual extreme high-risk assets where needed at the same time.

The city plans to integrate this information into its existing CIP and work toward the goal of meeting the needs identified by the long-term analysis. This will be accomplished by replacing, rehabilitating, or inspecting pipeline assets (as appropriate) and utilizing the digital results for total risk, total consequence, and total probability. The digital results are linked to the city's GIS pipeline asset layers and can be displayed and queried with ease. Since the results are digital, the city can narrow in on specific project locations and boundaries to facilitate the planning of future CIP projects.

Clusters of high-risk or linear runs of high consequences are being analyzed based on the rankings to determine appropriate projects and actions to take for each project. Figures 5 and 6 show the water distribution and wastewater force main system pipelines mapped by total risk ranking.

Conclusion

The City of Boca Raton capital planning staff members have always been proactive regarding the management of their critical water and wastewater assets. The results of the long-term renewal needs and risk-based ranking analysis developed in this project have provided them with additional tools to more accurately pinpoint the pipeline assets that require action or monitoring today, while also allowing them to look into the future to best identify future funding needs.

Figure 5. Water Distribution System Mapped by Total Risk Value

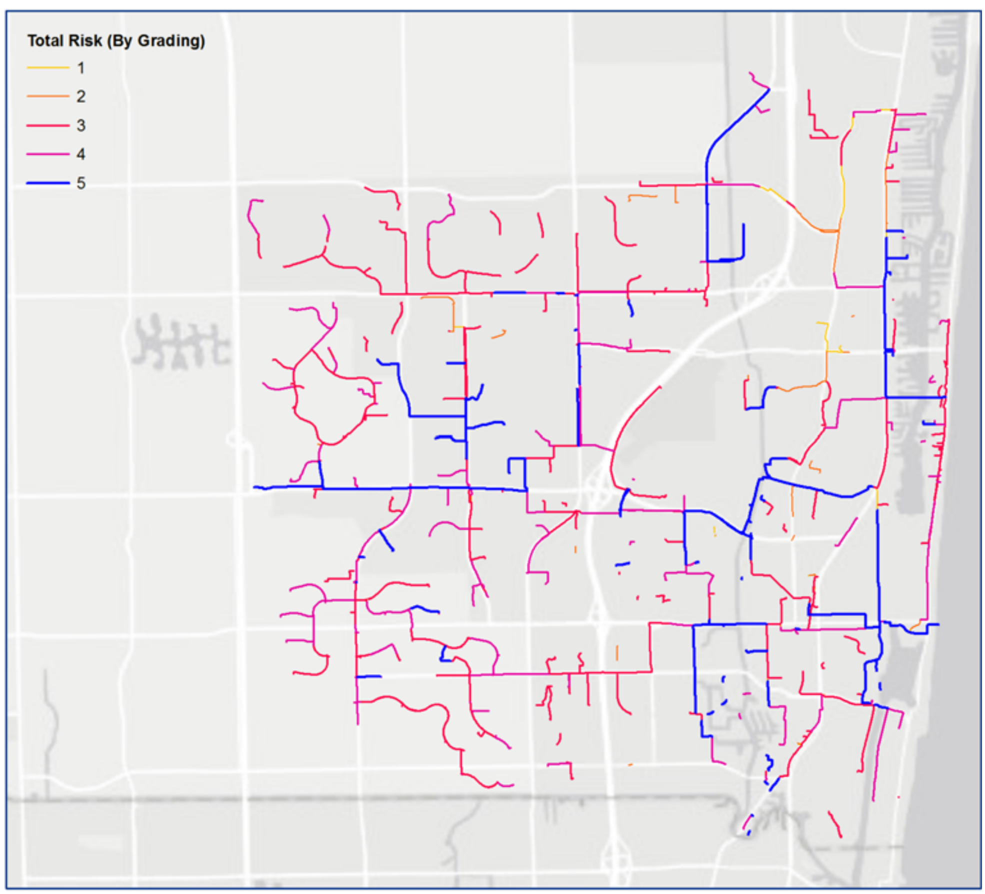

Figure 6. Force Main System Mapped by Total Risk Value