

# Calibrated Hydraulic and Water Quality Model Predictions Merge with Break History for an Innovative Approach to Prioritizing Water Main Replacement

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A new approach to prioritizing water main replacements that goes beyond conventional statistical age-based economic analyses merges utility-specific water main break history records with results from a calibrated hydraulic and water quality model that not only prioritizes replacements to reduce maintenance costs associated with failures, but also improves hydraulic capacity and water quality as well.

The new approach is based on the pipe replacement program developed for the City of Bradenton water distribution system. The City relies on water mains installed as early as 1939 to convey water to customers. Over 70 miles (about 30 percent) of the City's water mains are made from unlined cast-iron and asbestos-cement materials, mostly installed before 1970.

A statistical analysis of the City's water system indicated that all cast-iron and asbestos-cement water mains should be replaced immediately. However, this is not economically feasible and is not likely to be the optimum approach. Statistical predictions based on age, economics, and standard material failure probabilities do not always reflect the actual condition of water mains.

The City sought a more innovative approach to water main replacement prioritization that considers more parameters. The new approach includes analyzing historical break records and merging this with results from a calibrated hydraulic and water quality model of all water mains in the City's water distribution system. The amount by which each water main in the system is reducing hydraulic capacity and water quality is determined and an associated score is assigned. The combined score allows for a prioritization to be established. As an extension to this approach, costs associated with the reduced hydraulic capacity and water quality can be determined. The annualized replacement costs based on break history analysis can be combined with these costs to

develop an optimized water main replacement prioritization that maximizes maintenance, energy, and chemical cost savings.

The City of Bradenton authorized Jones Edmunds & Associates Inc. to conduct a data and model study for the Bradenton public water system (PWS) distribution network. As part of this study a hydraulic and water quality model of the Bradenton PWS network was updated and calibrated. In the Bradenton PWS network, breaks are occurring frequently, hydraulic capacity is reduced in some areas, and water quality is impaired in older parts of the system. The calibrated 2012 Bradenton PWS network hydraulic and water quality model was used to recommend and strategize the priority of improvements for the water system.

As water mains age, natural processes result in water main degradation. The Federation of Canadian Municipalities and National Research Council (NRC, 2003, p.3) noted the following manifestations as evidence of deterioration in water systems:

- ◆ Frequent breaks due to corrosion, material degradation, poor installation practices, manufacturing defects, and operating conditions.



Figure 1. Cross Section Cut of Ring Sample No. 16 (Lewis, 2001)

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- ◆ Reduced hydraulic capacity due to internal corrosion (i.e., tuberculation) of unlined metallic components.
- ◆ Impaired water quality due to internal corrosion of unlined metallic components and/or poor maintenance practices.
- ◆ High leakage rate due to corrosion and/or deteriorating joints.

To recommend and prioritize improvements, 18 years of break history data were assessed and used to performed hydraulic and water quality model simulations. The following steady-state and extended period simulations (EPS) were performed to assess hydraulic capacity and water quality conditions that would affect improvement recommendations:

- ◆ 2011 maximum daily demand (MDD) and fire-flow steady-state simulation
- ◆ 2030 MDD EPS
- ◆ 10-day average August 2011 demand water quality EPS

## Objective

This article discusses the perceived water system deficiencies, introduces the water main scoring methodology used to prioritize replacements, and presents an improvement plan.

## Water System Deficiencies

Through the break history data assessment and modeling effort, the following

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were observed: water system deficiencies in the Bradenton PWS network, including water mains with high break rates; hydraulic capacity reductions; and high rates of total residual chlorine (TRC) consumption. All of these issues are related in part to corrosion in unlined cast-iron water mains that make up about 28 percent of the Bradenton PWS network. Figure 1 shows significant corrosion in a cross section view of a ring sample of unlined cast-iron water main taken from the Bradenton PWS network in 2001. Internal corrosion can become apparent in different ways, such as:

- ◆ Water main degradation (e.g., pitting corrosion) that can lead to leakage or vulnerability to mechanical failure.
- ◆ Scale formation and tuberculation that can lower hydraulic capacity and degrade water quality.
- ◆ Corrosion byproduct release (e.g., rusty or red water) that can impair water quality.

### Water Main Break History

For the study, Bradenton provided 18 years of water main break documentation, including the address and water main size information; figures 2 through 6 show yearly and monthly statistics for the break history records. The data show that in 2010 water main breaks were far above average. This can be attributed to a temporary increase in the discharge pressure from Bradenton's high-service pump station. At the Bradenton Fire Department's request, discharge pressure was apparently increased to about 80 pounds per sq in. (psig) for a short duration, which led to a high number of breaks in January 2010.

Generally, it was observed that most water main breaks occur in the colder months—December and January. Figure 4 shows that most water main breaks occur in water mains made of cast iron. The water main material with the next most frequent break occurrence is polyvinyl chloride (PVC). In addition, according to Figure 6, the 6-in.-diameter water mains break most

frequently.

Eighteen years of historical data were combined with the model water main material information, and failure curves were developed for each water main based on material and size. These failure curves are unique to break history data that was set for the Bradenton PWS network water mains. Figures 7 through 9 show the failure curves; dashed lines are for water main sizes where sufficient data were available to calculate a failure curve, and solid lines are for water main sizes with extrapolated failure curves based on standard assumptions that break frequency decreases with increasing water main diameter. As shown, the ductile-iron water mains are predicted to have the longest useful life. According to the failure curves, PVC and cast-iron water mains are predicted to have similar useful lives, with PVC having a higher failure rate for water main diameters less than 8 in. and a slightly lower failure rate for water main diameters 8 in. and greater compared to cast-iron water mains.

These failure curves do not consider what is known as the burn-in phase (Berardi et al., 2008), which is a period when water mains usually fail due to poor installation practices or significant material defects, but it does not influence the economic life calculations.

Statistical predictions based on age, economics, and standard material failure probabilities do not always reflect the actual condition of water mains. At times, more detailed inspection of water mains classified as being beyond their economic life (the age after which annual maintenance costs exceed annualized replacement costs) reveals that these water mains are actually in adequate condition. At other times the opposite is true, and water mains are in poorer condition than statistical analyses predict.

The statistical approach is usually only economically viable for predicting failure in smaller-diameter water mains (Berardi et al., 2008); therefore, before a larger-diameter (greater than 10 in.) water main is considered deficient based on a predicted failure

rate, a physical inspection to assess its actual condition may be warranted.

### Fire Department Fire-Flow Goals

Jones Edmunds met with the Bradenton water department and fire department staff to determine the fire-flow goals for flows from Bradenton fire hydrants. Although Bradenton does not have formal fire-flow requirements in its ordinances, the fire department has its own goals. For fire hydrants that contribute to available fire flow (AFF) to a commercial building, the goal is to provide 2,000 gal per minute (gpm) of AFF. For hydrants that contribute to AFF to a commercial building that has a sprinkler system or to a residential building, the goal is to provide 1,000 gpm of AFF.

Fire hydrants in Bradenton that serve commercial buildings and residential buildings were identified. The fire department reported whether the commercial buildings were sprinklered or nonsprinklered. This allowed a determination of fire-flow goals throughout the Bradenton PWS network. The difference between model-predicted AFF and fire department fire-flow goals was used to establish areas where fire flows do not achieve the fire department goals.

### Hydraulic Capacity and Water Quality

The hydraulic capacity and water quality in the Bradenton PWS network appear to be adversely affected by corrosion. In the unlined cast-iron water mains, metal oxides result from pitting corrosion and form tubercles over the pits. These tubercles gradually grow and restrict the hydraulic capacity of the water main (NRC, 2003). The existence of tubercles has been observed by Bradenton staff in the PWS network in numerous locations. Additionally, the rate of internal corrosion in water mains not only affects, but is influenced by, the water quality (NRC, 2003).

In the Bradenton PWS network, a significant amount of water is flushed to maintain acceptable TRC concentrations at the ends of the water system. The Florida Department of Environmental Protection requires the TRC concentration to be maintained at 0.6 mg/L throughout the Bradenton PWS network at all times. Based on water quality modeling, the predicted TRC decay rates are orders of magnitude higher in older water mains of the water system than in newer water mains.

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Table 1. Break History Scoring and Replacement Need

Score	Water Main Material	Total Linear Feet in Water System	% of Total Water System Piping	Replacement Need Classification
5	Cast-Iron and Asbestos-Cement	200000	15	A
4	Cast-Iron and Asbestos-Cement	193000	14	B
3	Other Water Main Materials	295000	22	C
2	Other Water Main Materials	310000	23	D
1	Other Water Main Materials	345000	26	E

## Water Main Scoring System

Individual water main scores were developed relating to break history, fire-flow goals, hydraulic capacity, and water quality.

### Break History Score

The break history scoring for each water main is based on the relative economic life of

each water main. Table 1 shows the scoring system based on the failure rates, which indicates a replacement need classification for each score. Figure 10 shows the spatial distribution of water main breaks based on the scoring system.

Replacement needs classifications indicate the annual maintenance risk cost for the water main is as follows:

- ◆ A: Immediate-Term – has exceeded the annualized replacement cost.
- ◆ B: Near-Term – has equaled or exceeded the annualized replacement cost.
- ◆ C: Intermediate-Term – has equaled or not

exceeded the annualized replacement cost.

- ◆ D: Long-Term – has not exceeded the annualized replacement cost.
- ◆ E: Distant-Term – will not exceed the annualized replacement cost for some time.

### Fire-Flow Goals Score

Fire-flow simulations were performed using the calibrated hydraulic model. Comparisons of model-predicted AFFs with the fire department AFF goals revealed areas that could be improved. Figure 11 highlights these improvement areas by showing water mains that may be replaced to improve the system and better meet the fire department goals.

These improvement areas received a fire-flow score as shown in Table 2 corresponding to the relative percent difference between the model-predicted AFFs and fire department AFF goals in the area.

The scores reflect the consensus that no PVC, high-density polyethylene (HDPE), or ductile-iron water mains need to be replaced to improve AFF.

### Hydraulic Capacity and Water Quality Score

A combination of hydraulic and water quality parameters were used to attribute a third score to the water system water mains based on the calibrated model prediction for time-weighted mean consumption of chlorine chemical per water main using Equation 1:

$$\bar{m} = \sum_{T_i} \dot{m}_i \frac{T_i}{T_{final}} = \sum_{T_i} \left[ (C_{Calibrated} - C_{Ideal}) \times 0.264Q_i \frac{T_i}{T_{final}} \right]$$

Equation 1

Where:

$m$  = Rate of chlorine mass consumption (mg/min)

$T$  = Time (minutes)

$C_{Calibrated}$  = Predicted change in chlorine concentration (mg/L) across calibrated model water main

$C_{Ideal}$  = Calculated change in chlorine concentration (mg/L) across water main with no wall decay

$Q$  = Flow Rate (gpm)

Scores that were per-water-main-based were established on each water main's relative as shown in Table 3.

Figure 12 shows water quality scores throughout the system.

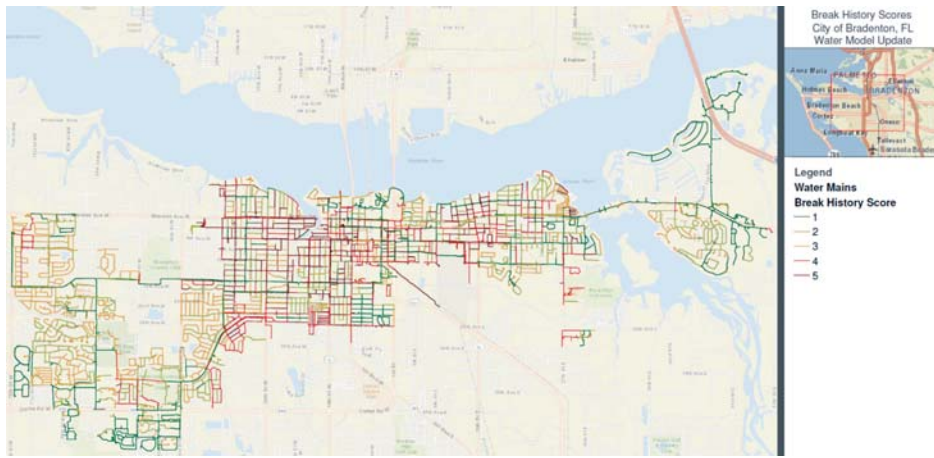


Figure 10. Break History Scores

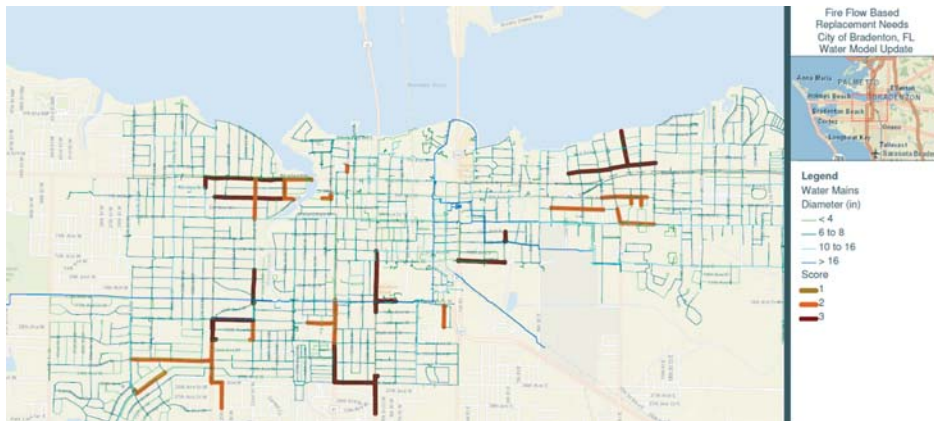


Figure 11. Fire-Flow-Based Replacement Needs

Table 2. Fire-Flow Scores

Score	Difference	Total Linear Feet
3	>50% Difference	21,000
2	25 to 50%	19,000
1	<25% Difference	150
0	Goal is Met	N/A

Table 3. Chlorine Consumption Scores

Score	Chlorine Consumption Ratio Classification
3	Highest
2	Middle
1	Lowest



## Score Definitions and Hotspot Analysis

A three-digit scoring system was developed: the first digit corresponds to the break history score, the second corresponds to the fire-flow score, and the third to the hydraulic capacity and water quality score. Based on the scoring methodology, a water main could have a score as high as 533 or as low as 101.

A score of 533 indicates a cast-iron or asbestos-cement water main that:

- ◆ Is in immediate need of replacing based on its failure risk.
- ◆ Is near a hydrant that provides only 50 percent of the fire department AFF goal and would improve the AFF if replaced.
- ◆ Consumes chlorine at the highest bracketed consumption rate.

Conversely, a score of 101 indicates a PVC, HDPE, or ductile-iron water main that:

- ◆ Does not need to be replaced, based on its failure risk.
- ◆ Does not need to be replaced to improve flow from a hydrant to meet the fire department AFF goal.
- ◆ Consumes chlorine at the lowest bracketed rate.

The resulting scores are provided in descending order to establish a replacement prioritization on an individual water main level:

533	511	422	203
532	501	421	202
531	433	401	201
523	432	303	103
522	431	302	102
521	423	301	101

These scores reflect the consensus that no PVC, HDPE, or ductile-iron water mains need to be replaced to improve AFF.

After each water main was assigned a water-main score, a hotspot analysis was performed. The hotspot analysis allows a spatial assessment of the relative density of high-scoring water mains and further defines the priority for replacement based on areas in the water system. Using this method will allow replacement work to begin and end in each area of the water system without a location being revisited, thereby reducing the associated engineering, survey, and contractor mobilization costs.

The total number of priority replacement areas is not constrained by the total

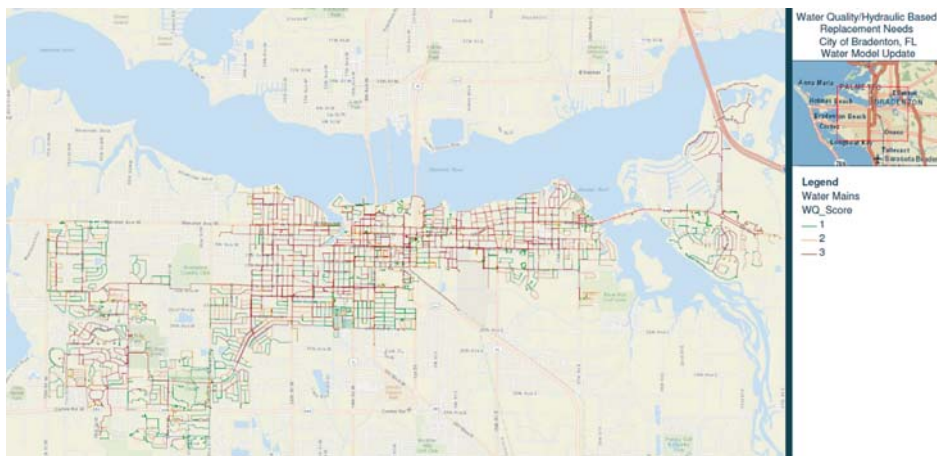


Figure 12. Water Quality/Hydraulic Based Replacement Needs

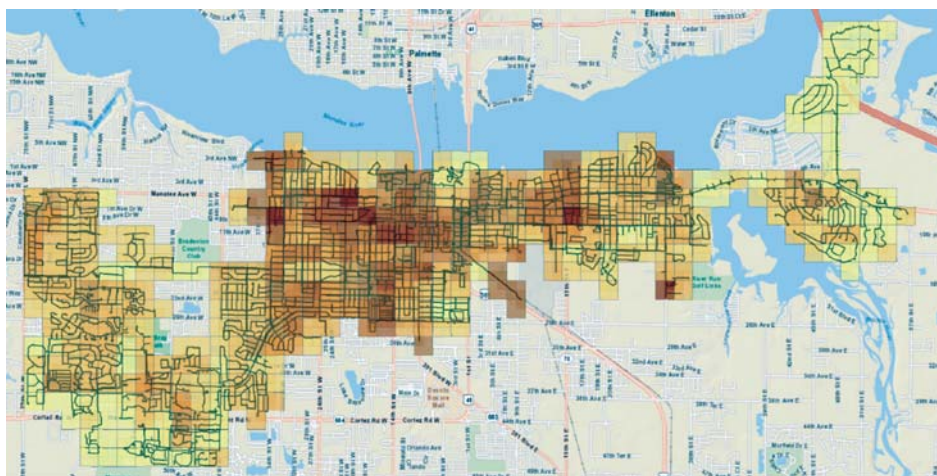


Figure 13. Hotspot Analysis Map

possible number of water-main scores because priorities are ordered based on the relative density of high-scoring water mains.

Figure 13 shows the resulting hotspot analysis map (the darker the area, the more hotspots) for the limits of the Bradenton PWS network, which allowed a spatial assessment of the relative density of high-scoring water mains based on the scoring methodology established earlier.

### Future Work

In an extension to this work, a method was developed to account for each water main's contribution to chemical and electrical costs. Using the calibrated hydraulic and water quality model, the chlorine consumption and friction loss in each water main can be calculated. Then, each modeled water main can be replaced with a modeled replacement water main. This main would have appropriate wall decay coefficients (the parameter that influ-

ences how much chlorine is consumed in the simulated water main) and friction coefficients (the parameter that influences the amount of friction loss that occurs in the simulated water main) for a water main in new condition.

After model simulations with the replacement water mains were performed, the results could be compared to the calibrated model results. It's expected that, in each case, the chemical consumption and friction loss will reduce by a specific amount. This specific amount would be attributed to the water main under consideration and could be used to establish how much chemical is consumed and how much energy is lost through that water main over time. Annual chemical and energy costs to keep the aged water main in service could be calculated and used in a replacement prioritization. Combined with the economic life calculations, annualized chemical and energy costs would result in a replacement prioritization that maximizes cost savings.

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## Recommendations

It was concluded that the aged cast-iron and asbestos-cement water mains should be replaced because they are past their useful life. Bradenton already had a replacement program in place; however, the schedule and prioritization of replacements were adjusted to incorporate the water-main-scoring methodology outlined to allow Bradenton to target improvements in the most problematic areas first.

## Budgeting and Priorities

The oldest water mains installed in the Bradenton PWS network have reached the end of their expected useful life or will do so

during the next 30 years. This study estimated that \$35 million should be invested over the next 30 years to replace existing (deteriorated) water mains in the network.

The current rate of water main replacement is largely influenced by the annual water main replacement budget. Figure 14 shows the historical range of water system infrastructure replacement cycles and rates for the City based on a high- and low-cost per-ft assumption.

Based on the construction materials and water main sizes in the network, a realistic average water main replacement cost is about \$100 per ft. This means that at the 2012 budgeted water main replacement dollar amount, Bradenton is on an approximately 426-year replacement cycle, which is unsustainable. A more sustainable approach is to replace the water system at a rate con-

sistent with its useful life. To begin moving toward sustainability and decrease water main repairs, Bradenton used the water main scoring and hotspot analysis to prioritize water main replacements and justify increasing the water main replacement budget. The result is the water main replacement cycle time has decreased to less than half what it was in 2012.

Figure 15 shows the prioritized water main replacement groups for the first 10 years, based on the hotspot analysis.

## Conclusions

As Bradenton implements the recommendations from this study, the City will reduce the water main break frequency and improve hydraulic capacity and water quality. The water main scoring methodology presented allows Bradenton to prioritize water main replacements based on relative water main condition and each water main's relative influence on hydraulic capacity and water quality. Targeting water main replacement using this method should result in the lowest overall cost for improvements. Extending this approach to an assessment of each water main's effect on chemical and energy costs could result in the development of a purely cost-based replacement prioritization that minimizes operation and maintenance costs.

## Acknowledgements

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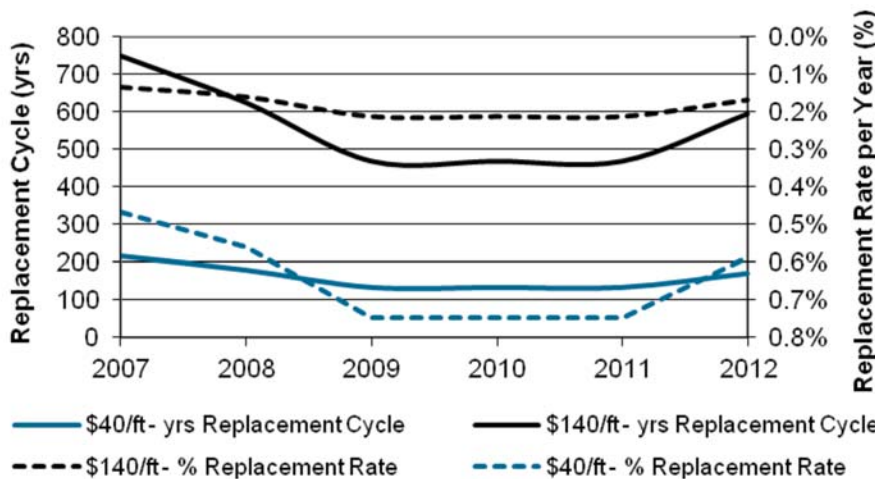


Figure 14. Water Main Replacement Cycles and Rates

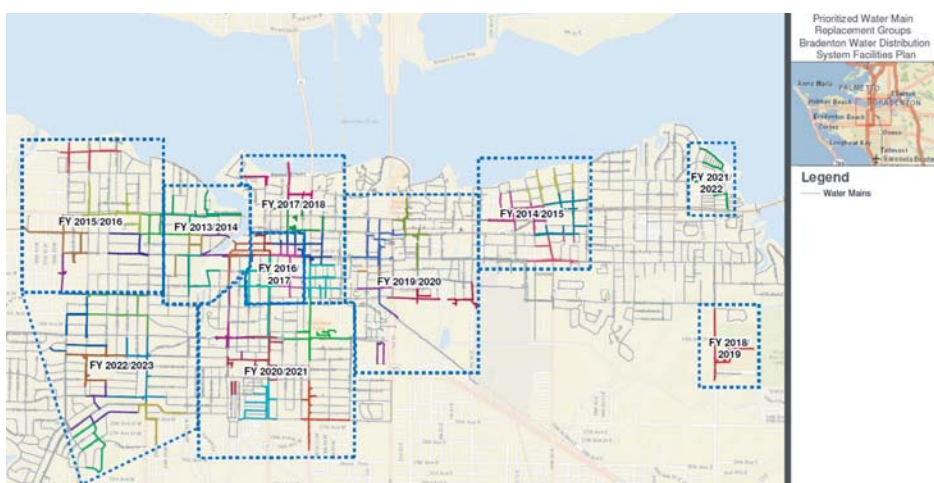


Figure 15. Prioritized Water Main Replacement Groups