As water distribution systems age, utilities are faced with the need to rehabilitate water mains to minimize leaks and restore capacity lost from tuberculation. Due to high costs and limited funds, utilities must prioritize rehabilitation projects to provide the best return on investment. Prioritizing pipe improvements can be done by conducting desktop evaluations or using specialized software packages. The end result is a scoring system that allows the utility to address the most critical needs first.

Several criteria should be considered to prioritize pipes for rehabilitation. The importance of each factor varies among utilities. Input to the analysis may include: main break history, pipe age, pipe material, valve status, soil pH, pressure, flow velocity, and proximity to critical facilities, such as hospitals. A scoring and weighing system is assigned for each input, and each pipe is then assigned a weighted sum. The higher the score, the more critical the pipe is to the system and the higher the priority for rehabilitation.

For example, pipe material can have an impact on water quality. Unlined cast-iron pipes are known to become tuberculated and harbor biofilms that decrease disinfectant concentrations. Water quality is a high priority for all utilities, and, thus, pipe material may be weighted more heavily than another factor.

After prioritizing, the pipes can be tabulated and mapped, with rehabilitation costs estimated for each. Pipes can be grouped into annual projects that conform to budget constraints. The best methods of rehabilitation for each pipe (e.g., pipe replacement vs. pipe lining) can then be evaluated based on factors such as constructability and site conditions.

This article will describe a case study in Roanoke Rapids, NC. Methods of prioritizing pipes, assigning scoring values, making repair or replacement decisions, and estimating costs will be discussed.
Hazen-Williams C factor of 34. Lined pipe installed in the 1950s through 1990s had an average C factor of 120.

Aging infrastructure has caused a variety of problems in the RRSD distribution system. Leaks have become more numerous over time as pipes deteriorate. A water audit determined that leaks accounted for a significant portion of non-metered and unbilled water, making water losses a financial problem. Breaks not only result in water loss, but cause interruption of service and public safety concerns. Older pipes are tuberculated, causing more head loss and reduced fire flows.

Prioritization Method: Because such a large portion of the distribution system is unlined cast iron, RRSD needed a method to prioritize renewal efforts. Prioritizing was a challenging task because it involved making many decisions about which pipes to renew and when. This process required integrating all relevant available information about each pipe.

A scoring system was established using InfoWater CapPlan software (MWH Soft, Version 2.0). Creating a pipe renewal plan with this software involved four general steps:

1. Estimate Likelihood of Failure of each pipe (LOF).
2. Estimate Consequence of Failure of each pipe (COF).
3. Estimate Risk: Use consequence and likelihood of failure to estimate the overall level of risk for each pipe.
4. Produce Pipe Rehabilitation Plan: Prioritize based on risk and use unit cost data and budget information to create a pipe rehabilitation plan.

We estimated the likelihood of failure for each pipe by considering:

- **Failure History Data:** Two sets of data were used to indicate the failure history of each pipe. One was the number of repairs for each pipe, and the other was the status of valves on each pipe. Pipes with a larger number of repairs and more valves in poor condition were considered higher risks.

- **Pipe Attributes:** The two pipe attributes used to indicate risk were pipe material and type of joints. The pipe age was used to estimate the pipe material and the type of joints.

- **Hydraulics:** The hydraulic model was used to predict pressures. Higher pressures increase the relative likelihood of failure.

A score from 0 to 20 was given to each pipe based on those definitions. Unlined cast iron pipe, for example, was given the highest score of 20 for pipe material, whereas ductile iron was given a score of zero. Each parameter was then weighted on a scale of 1 to 10. An adjusted score was then calculated for each pipe using the following equation:

\[
\text{Adjusted Score} = \text{Weight} \times (\text{Parameter Score})^{\text{Exponent}} \tag{Equation 1}
\]

Pipe material was given an exponent of 2 to ensure that unlined cast-iron pipes would be the highest priority for rehabilitation. All other parameters were given exponents of 1.

We analyzed the consequence of failure for each pipe by considering:

- **Critical Facilities:** Critical facilities identified in RRSD were schools, hospitals, natural gas and power facilities, state-owned facilities, and critical manufacturing customers. Pipe failures near such facilities have higher consequences.

- **Isolation:** Isolation analysis determined how much of the network would be out of water if a pipe was shut off for repair. This was done by tracing the network in all directions until valves were identified that would isolate the subject pipe. Pipes that affect numerous customers when shut off would receive a higher risk score.

- **Hydraulics:** Flow (as calculated by the hydraulic model) also was
used to assign a score for consequence of failure to each pipe. Pipes with high flow rates are carrying water from one part of the system to another, not just the local area. Using flow instead of velocity helped reduce the risk of over-weighting smaller pipes that may be overloaded but do not transport much water.

- **Fire Flow Improvements:** Another important consideration for this infrastructure renewal plan was to improve fire flows. Pipes that would eliminate an existing fire flow deficiency if the C factor is restored were assigned a top priority for rehabilitation. Pipes in areas where fire flows would be deficient even after cleaning and lining were candidates for replacement with larger pipes. A score from 0 to 20 was given to each consequence definition. Pipes associated with a high flow, for example, were given the highest score of 20, whereas low flow pipes were given a score of 1. Each parameter was then weighted on a scale of 1 to 10 with one exception. A weight of 20 was given to each pipe with deficient fire flows in order to assign highest priority for those pipes. An adjusted score was calculated for each pipe by adding all the individual parameter scores according to Equation 1. All consequence scores were given exponents of 1.

The CapPlan software estimated the overall risk level of each pipe using the consequence and likelihood scores and applying a bi-directional distribution risk assessment.

The bi-direction distribution classified the range of scores into low, medium, and high risk levels, for both consequence and likelihood of failure. Scores in the lowest 10% of the score range were classified as ‘Low.’ Scores in the 10-60% range were classified as ‘Medium,’ and scores in the top 40% of the range were classified as ‘High.’ A matrix was defined for overall risk assessment as shown in Table 1.

### Results and Discussion
A color-coded map was generated showing the relative priority of all distribution system pipes (Figure 2). After prioritizing each pipe, we also addressed the following questions:

1. How should each pipe be rehabilitated?
2. What will be the annual cost of rehabilitation?

How a pipe should be rehabilitated means deciding whether a pipe should be cleaned and lined, replaced, or otherwise repaired. This depends on several factors:

- **Joint type:** Lead and leadite joints were commonly used in pipes installed before 1956. These types of joints sometimes cause leakage, even after a pipe has been cleaned and lined. However, there are relatively new lining materials and methods that offer structural integrity at joints and may be cost effective (polyester reinforced polyethylene pipe or Class III structural polyurea coating, for example).

- **Available Fire Flow:** If a pipe with a low C-factor is located in an area with a deficient fire flow, two solutions are possible. The pipe could be rehabilitated (cleaned and lined or replaced with a new pipe of the same diameter), which would decrease head loss, thus improving the available fire flow. However, if rehabilitation does not eliminate the fire flow deficiency, the pipe should be replaced with a larger diameter pipe. In RRSD, approximately half of all the deficient fire flow locations would be improved by rehabilitation (assuming C factor of 120), and those that are not were addressed as part of a capital improvement plan.

- **Site Restrictions:** Replacing pipes in most cases requires digging a trench and installing new laterals (or service lines from each residence). Logistically, with respect to construction, this can be difficult at some locations. Downtown areas with busy streets, for example, are typically problematic due to other utilities, pedestrians and traffic. Cleaning and lining avoids many site constraints, as would pipe bursting and replacement methods, however, temporary service to each residence must be installed above-ground while the pipes are cleaned and lined. Above-ground temporary connections may be a problem at some locations. There are some technologies that limit service disruption to one day, eliminating the need for temporary service.

### Table 1: Bi-Directional Distribution Matrix of Overall Risk

<table>
<thead>
<tr>
<th>Scores</th>
<th>Likelihood of Failure – Low</th>
<th>Likelihood of Failure – Medium</th>
<th>Likelihood of Failure – High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consequence – High</td>
<td>Medium</td>
<td>High</td>
<td>Extreme</td>
</tr>
<tr>
<td>Consequence – Medium</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Consequence – Low</td>
<td>Negligible</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>
• Cost: The unit cost estimate for cleaning and lining for the RRSD project was about $6.50 per inch of diameter per linear foot (inch-foot) of pipe. This was an average based on recent cleaning and epoxy lining projects in North Carolina and includes labor and other relevant expenses. Average replacement costs were approximately $5.80 per inch-foot for PVC and $7.25 for ductile iron. These costs also include labor and other relevant expenses. According to RRSD staff, recent repairs, on average, cost approximately $600 per break or more depending on the local conditions. On a unit cost basis, there is little cost difference between replacing pipes or cleaning and lining. On an annual basis, repairing pipes that leak or break may be less expensive in the short term. However, as pipes continue to age, more and more repairs will be necessary and, therefore, consume more of the annual budget. Other costs that are difficult to quantify with respect to pipe breaks include water loss (unbilled water), public safety, and staff exposure to hazardous conditions.

Other factors to consider are water quality and public relations. Repairing breaks does not improve water quality, but cleaning and lining or replacing a tuberculated pipe greatly improves water quality. Making numerous repairs on a recently paved street is guaranteed to create a public relations problem.

For RRSD, a detailed rehabilitation plan was outlined. The order of rehabilitation was based on the pipe prioritization as described above. RRSD will consult with local contractors when starting the rehabilitation plan. There could be cost savings based on specific site conditions for rehabilitating certain pipes as part of one project in a localized area, even if those pipes are not high on the priority list. Because unit costs were very close for RRSD, estimates will be obtained on a site by site basis to determine the cost difference between cleaning and lining or replacement.

The annual budget required to rehabilitate all the unlined cast iron pipes for RRSD within the next 20 years was estimated to be approximately $375,000 (in 2010 dollars). RRSD used this estimate for planning an adequate annual budget for infrastructure renewal. The rehabilitation schedule can be adjusted depending on available funding.

By using a systematic approach to prioritize pipes for rehabilitation, a utility can make efficient use of its funds. Planning for pipe rehabilitation or renewal is an important step toward maintaining a safe and functional distribution system as infrastructure ages.

About the Authors
Megan G. Roberts, P.E., is a senior principal engineer in Hazen and Sawyer’s Greensboro office. Ms. Roberts has more than eight years of experience in water distribution studies including hydraulic modeling, GIS analysis, hydraulic design, master planning, and water quality analysis and modeling.

Crystal M. Broadbent, P.E., is a senior principal engineer in Hazen & Sawyer’s Charlotte office. Mrs. Broadbent has 10 years of experience in hydraulic and surge modeling. Her other areas of expertise include hydraulic design, erosion control, sewer inspection, and environmental assessment.

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