Empowering Data-Driven Pipeline Management

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Front Cover: With proactive, data-driven management, utilities can greatly extend the life of transmission mains and force mains. Photo from Maha Heang, Shutterstock.com.

This guide, part of AWWA's Essential Knowledge Series, was prepared in partnership by AWWA and Xylem. AWWA contributors include John R. Hughes, editor; Dawn Flancher, senior manager technical and research programs; Daniel Feldman, designer; and Karen Pacyga, production manager. Xylem contributors include Eric Toffin, global product manager; Ashan McNealy, manager of condition assessment engineering; Cameron White, senior manager of national and strategic accounts; Evan Biedenbach, business development manager; Jeffrey Zdrojewski, business development manager; Dustin Park, senior condition assessment engineer; and Kristina Twigg, demand generation manager.

INTRODUCTION

Water transmission mains and wastewater force mains provide critical services for communities across North America. Leaks, breaks, and age can undermine confidence in these valuable assets. However, factors like age or previous failures aren't necessarily good indicators of a pipeline's current condition.

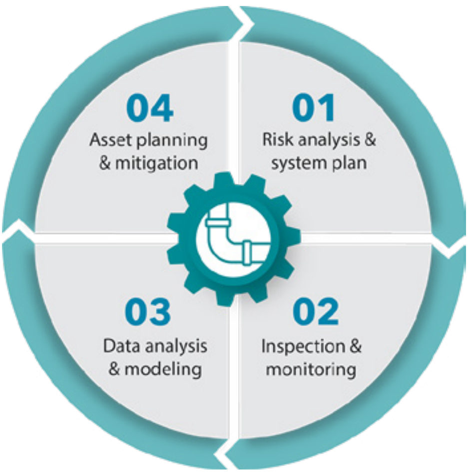

Figure 1. Effective pipeline management is a process that helps water and wastewater utilities better manage buried infrastructure.

The water industry is increasingly adopting proactive management strategies for buried infrastructure. This shift is possible due to assessment technology and data analytics that deliver short- and long-term insights into asset performance. Critical pipelines have long service lives that can be greatly extended with data-driven management. This guide, part of the AWWA Essential Knowledge Series, examines how pipeline owners can collect and leverage data to reduce risk, manage costs, and maintain reliability across their asset life cycles using the framework shown in Figure 1.

INFRASTRUCTURE CHALLENGES

Since 2004, AWWA has conducted its annual State of the Water Industry survey (www.awwa.org/sotwi), which allows water professionals from North America and beyond to share their insights on key water industry challenges and activities. Aging infrastructure and financing capital improvement have ranked in the top five challenges since the survey's inception, and aging infrastructure has maintained the top position for more than 10 years. For the 2023 survey, when asked about the importance of specific issues related to renewal and replacement of existing infrastructure, 48% of respondents rated maintaining infrastructure reliability as a critically important concern.

Utilities are increasingly adopting proactive asset management strategies to help them meet a wide range of infrastructure challenges, including the following:

- **Managing Buried Infrastructure.** Utilities can use inspection and monitoring data to identify and address at-risk pipes in the short term and model future pipe condition to inform defensible long-term plans.
- **Renewing Aging Infrastructure.** Utilities can increase network reliability and extend asset life using condition data to determine which pipes and valves can continue operating and which require repair or replacement.
- **Financing Capital Improvements.** Pipeline owners can more effectively prioritize projects and direct resources with precise data on asset condition and risk. Utilities can

also reduce overall life-cycle costs by making planned repairs, preventing failures, and maximizing asset life.

- **Minimizing Water Scarcity and Ensuring Sustainability.** Leveraging pipeline and valve condition data, utilities can reduce water loss, lower the carbon footprint of renewal and replacement projects, and improve network control and resilience.
- **Improving Community Relations.** Utilities can foster better community engagement and trust with data to validate and improve asset reliability and service levels, limit disruptions, and empower fiscally responsible decisions.

Over the next decade, communities will invest billions of dollars into renewing aging pipeline assets. A proactive condition assessment program can help utilities prioritize where to spend their capital improvement dollars. In addition, advanced technologies can help water and wastewater utilities realize enormous benefits, as shown in Figure 2, by determining the health of buried infrastructure for data-driven asset management decisions.

RISK ANALYSIS AND SYSTEM PLANNING

A condition assessment program gives utilities increased network visibility, enabling pipeline owners to understand what assets they have, their location, and their condition. Assessments

Figure 2. Data-driven pipeline management delivers a wide range of benefits.

also provide the necessary data to develop reliable estimates of asset deterioration over time, so utilities gain a long-range view of system integrity.

Before this work is done, however, an effective condition assessment program requires funding. As detailed in AWWA's Manual of Water Supply Practices M77, *Condition Assessment of Water Mains* (www.awwa.org/M77), such support is built by making a business case for condition assessment; developing effective methods of accounting for condition assessment costs; creating an appropriate budget; and gaining support from city leaders, the public, and other stakeholders through effective communications.

Investment in condition assessment can be justified by reducing risk costs. Utilities can better understand the value of risk-reduction efforts by measuring the social, economic, and environmental consequences of leaks, failures, and resulting emergency repairs. A large-diameter pipe failure can cost a community well over $1 million in direct and societal costs. In fact, societal impacts, such as service interruptions and property damage, can double the cost of failure.

Condition assessment also helps utilities better prioritize or even defer otherwise planned capital investments. In many cases, utilities can extend the life of large-diameter pipelines and reduce asset life-cycle costs by making incremental, data-driven investments in maintenance. According to M77, several utilities have documented returns on investment of 400–800% when implementing an approach in which condition assessment is used to find and target specific pipe defects rather than replacing an entire main.

Traditional pipeline replacement decisions have been primarily reactive—in response to failure or based on limited information such as pipeline age and failure history, qualitative visual inspection data, and asset criticality. However, data show that pipeline failures are usually the result of localized deterioration, with the rest of the pipeline still in serviceable condition. Thus, it's difficult to justify the cost and disruption of full-scale replacement in response to failure or based solely on age.

North American utilities operate thousands of miles of buried transmission mains and force mains. The reality is that funding hasn't kept pace with water infrastructure needs, and pipelines are aging faster than utilities can replace them. This further reinforces the need to understand asset condition and risk.

A proactive condition assessment program starts by identifying which pipes warrant the most attention. Risk evaluation plays a key role in prioritizing assets for inspection and determining the appropriate level of assessment. Gaining an initial understanding of system risk is key to developing a condition assessment program that balances level of service, life-cycle costs, and acceptable risk. A systematic approach looks at all pipe included in the program rather than view each individual asset or assessment on its own. The challenge is to determine the right level of investment for each asset in the program based on risk.

Risk evaluation considers both the probability and consequence of an asset's failure, as shown in Figure 3. Probability of failure estimates the likelihood an asset will not meet defined levels of service. Consequence of failure estimates the social, economic, and environmental impacts should an asset fail.

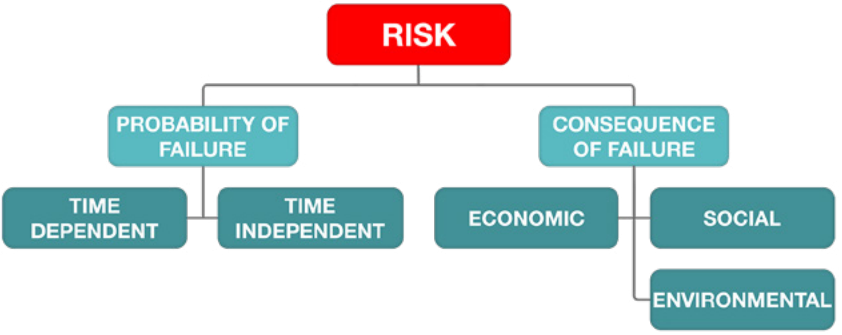

Figure 3. A utility's overall risk framework should consider the probability and consequence of an asset's failure.

Xylem starts a condition assessment project by collecting and reviewing information specific to a utility's assets, such as past failures and soil corrosivity. Combining this information with condition data from similar pipelines around the world offers a valuable benchmarking tool, enabling the utility to see how pipes of the same material, size, age, and design responded to similar operational and environmental conditions.

This initial risk analysis provides insight into suspected pipe condition before utilities invest in an assessment approach. However, probability of failure is still relatively unknown until the actual assessment is conducted. This is why consequence of failure is beneficial in guiding early decisions about the condition assessment plan.

Layering the estimated probability of failure with pipeline criticality and consequence of failure provides a broad measure of risk. As risk increases, so does the value of gathering more detailed information using high-resolution inspection methods and engineering analyses.

For example, a higher-consequence main warrants higher-resolution assessment approaches such as an in-line electromagnetic survey and continuous structural monitoring. A utility that can't tolerate any failures on a critical pipeline will need to invest more in condition assessment and ongoing maintenance. Advanced analytics using high-resolution inspection and monitoring data can predict future pipe performance and inform long-term asset management strategies.

Conversely, utilities could effectively manage a lower-consequence main with screening-level tools, such as leak detection and transient pressure monitoring, which can guide short-term operational and repair decisions that improve infrastructure reliability. Such an approach directs more resources toward higher-consequence pipelines and enables utilities to mitigate risk and allocate resources in the most cost-effective way.

Advances in technology and data analytics are changing the game for buried infrastructure. Pipeline owners can identify distressed pipe segments, make targeted repairs, and return pipelines to like-new status for a fraction of the cost of holistic replacement, using a combination of the approaches shown in Figure 4. By adopting proactive asset management strategies based on condition data, utilities are better positioned to control risks and costs, justify decisions, direct resources where they are needed most, inform short- and long-term plans, and optimize life-cycle costs.

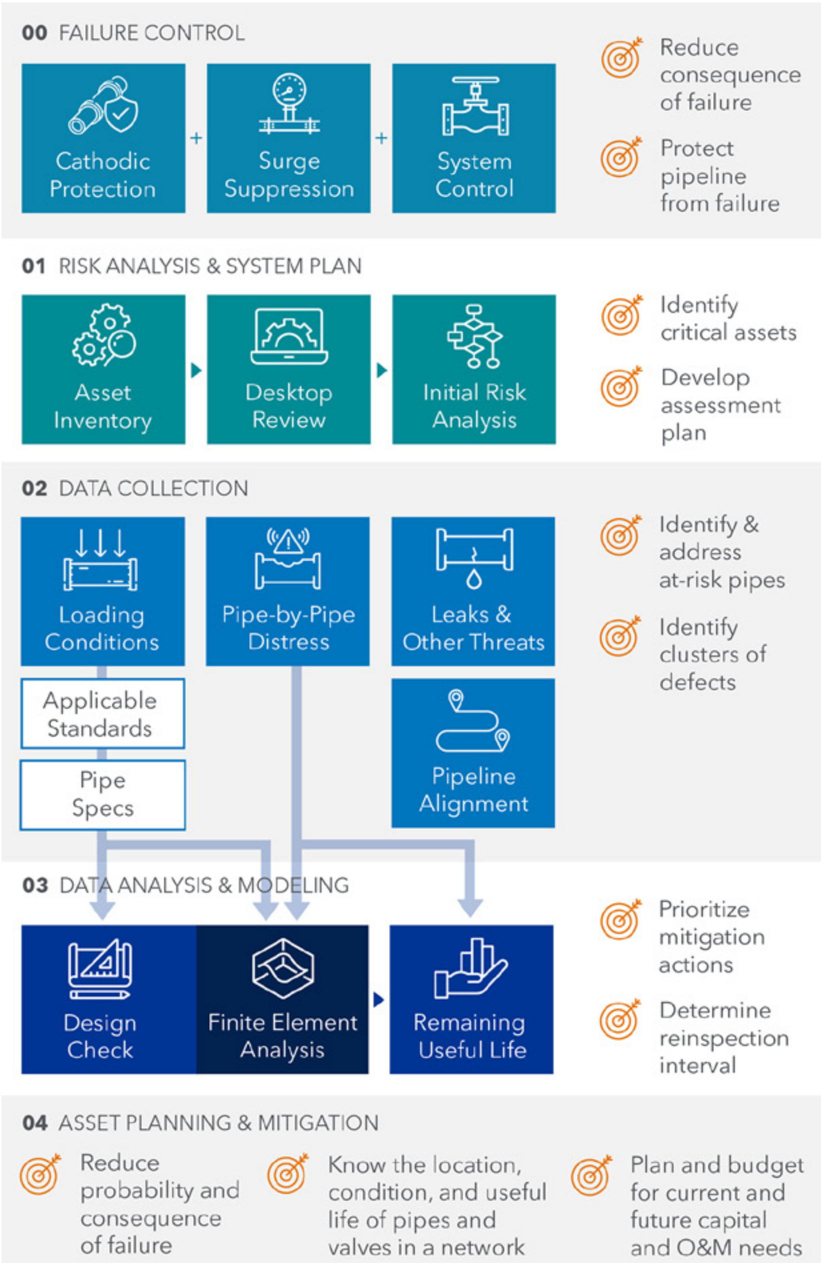

Figure 4. A condition-assessment approach should be based on a utility's goals, budget, and risk tolerance.

SYSTEM CONTROL

Water system control valves, such as gate valves and butterfly valves, help control flow in water networks. Valves are essential for isolating sections of the network to limit the duration and impact of a pipe failure. A proactive system control program ensures that utilities can locate, access, and operate critical valves during an emergency, routine maintenance, or a pipeline inspection.

As distribution systems age, the probability of all forms of failure increases. As shown in Figure 5, the risk of failure is compounded when valves haven't been proactively maintained and don't work when needed. When valves are inoperable, pipe failures can last longer and affect a broader area with service disruptions, water quality and pressure issues, fire flow challenges, flooding, and other problems. As shown in Figure 6, steps to optimize system control include the need to identify and inventory valves, inspect valves, rehabilitate and repair valves, and deliver actionable field data to benefit ongoing operation and maintenance.

Identify and Inventory Valves. Searching for valves wastes critical time, increasing the collateral damage, impact area, and lost water in the event of a main break. Utilities should confirm physical access to valves and verify their exact location.

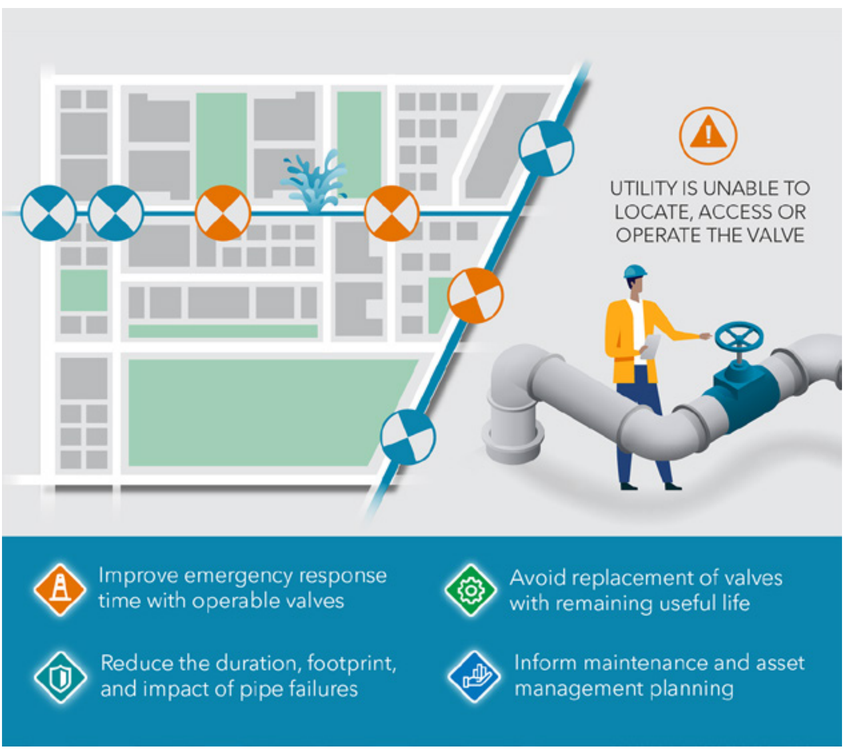

Figure 5. When valves are operational and locatable, utilities can respond faster and minimize the consequences of pipe failure.

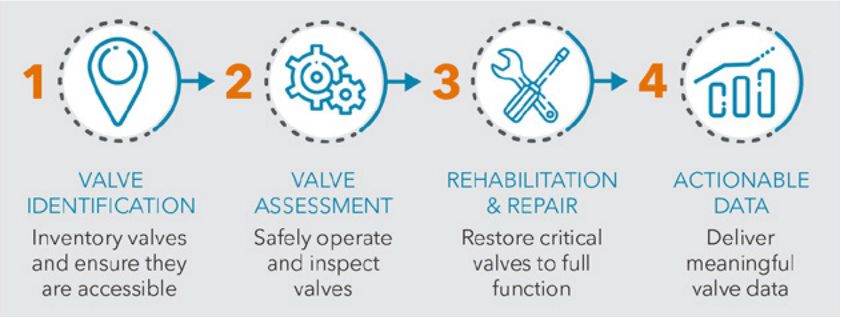

Figure 6. A four-step process can be used to optimize system control.

Inspect Valves. According to Wachs Water Services, a Xylem brand, approximately 40% of all valves the company has serviced are inoperable because of their physical condition (misalignment, tuberculation, debris, etc.) or because they can't be located, are inaccessible, or they are in the wrong position. Once valves are located, it's important to confirm they're operable and free from leaks. If a valve isn't operational, it can't be used for system control and shutdowns.

Rehabilitate and Repair Valves. Most inoperable valves can be rehabilitated, and many can even be repaired in the field during condition assessment and data documentation. On average, only 2% of valves must be replaced to restore usability. Valve rehabilitation can include raising the valve box to grade, replacing operating nuts so the valve can be operated from the street level, re-gearing damaged external gears, and many other repairs that can restore a valve to full function and extend its useful life.

Deliver Actionable Field Data. After assessing valves in the field, utilities will have an inventory of assets and information on their physical condition. The next step is to ensure that accurate, meaningful information is available to all stakeholders. An accessible, well-designed asset information system can be used to generate reports, schedule maintenance, and manage work orders. Data from the field can be uploaded directly into the system to keep it current. Information systems can generate maps of trouble areas and reports that facilitate data analysis and empower informed decisions both proactively and in an emergency.

Significant efficiencies can be gained by integrating valve and pipeline assessment. Valves and appurtenances can be inspected and repaired opportunistically during planned pipeline assessments. For inspections requiring physical entry, utilities must shut down and dewater the pipeline. This is a good opportunity to conduct more extensive in-line assessments on butterfly and gate valve discs as well as the seat rings, gaskets, and seals. Significant cost synergies are typically realized by integrating these types of programs. Integrating valve and pipeline assessment also ensures inspections aren't compromised by inoperable valves.

Additional cost savings can be achieved by avoiding the wasteful practice of replacing valves that can be restored to full function. On pages 10 and 11, see how the City of Grand Rapids saved money by repairing, rather than replacing, its large valves. Nearly every utility in the world faces this choice, and hundreds of thousands—if not millions—of dollars are at stake. By adopting the habit of asking whether an asset needs to be replaced or if it can be restored to full operability at a fraction of the cost, utility leaders can save their communities substantial amounts of money, reduce the need for unaffordable rate increases or financing arrangements, and improve the environmental sustainability of their operations—all while maintaining and enhancing system control.

DATA COLLECTION: INSPECTION AND MONITORING

Inspection and monitoring are the only ways to truly understand the condition of buried infrastructure. Gathering such data may be more costly and time consuming up front, but it typically leads to more focused and efficient repair and replacement decisions. Experience shows that this approach is effective at reducing risk and optimizing capital expenditures over time.

Concrete and metallic pipes are commonly used in large-diameter transmission mains and force mains, which convey flows under pressure. Both materials offer cost-effective options for high pressures and high external loads, but each type of pipe has unique characteristics and failure mechanisms that should be considered when evaluating inspection techniques.

Concrete Pipe. Concrete pipe materials commonly used for large pressure pipe applications include prestressed concrete cylinder pipe (PCCP), reinforced concrete pipe (RCP), and bar-wrapped pipe (BWP). BWP is a composite pipe material in which both the reinforcing bars and steel cylinder provide strength. Metallic inspection methods generally apply to the cylinder, and concrete pipe inspection methods apply to the reinforcing bars.

PCCP is the most common concrete material used for large transmission mains and force mains. PCCP is a reliable pipe material with overall low distress rates. Pure Technologies data show that only about 4% of inspected pipes show signs of distress, and even fewer require repair or replacement. However, PCCP failures are usually catastrophic and come at a high social and economic cost.

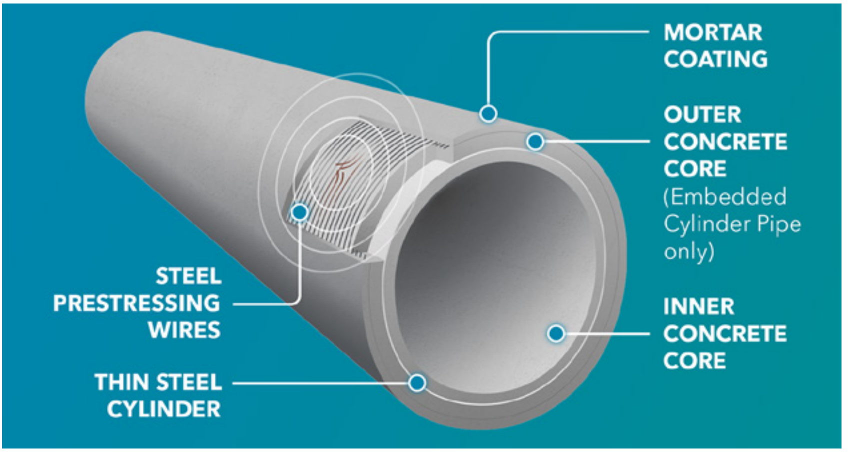

Figure 7. Wire break damage is the principal failure mechanism for PCCP.

Operating conditions, environmental factors, third-party damage, and other variables can contribute to localized PCCP deterioration. As shown in Figure 7, PCCP's inner concrete core and thin steel cylinder act as a water barrier. Steel prestressing wires are wrapped under tension either directly around the cylinder (lined cylinder pipe) or around the outer concrete core (embedded cylinder pipe). The wires are the pipe's primary structural component. They place the pipe in compression to offset expected internal loads. An outer mortar coating protects the steel components from corrosion.

Over time, the prestressing wires can corrode and snap, primarily due to corrosion or hydrogen embrittlement. Corrosion of the prestressing wires most often occurs when the pipe's protective mortar coating is damaged. Hydrogen embrittlement is the result of past poor manufacturing practices and improperly designed or operated cathodic protection systems. Although the damage mechanism differs between corrosion and hydrogen embrittlement, the outcome is the same: breakage of the pipe's primary structural component. As broken wire wraps accumulate, the pipe's structural integrity weakens, and the likelihood of failure increases.

Grand Rapids Saves Money Through Large Valve Assessment

The City of Grand Rapids is the second largest water system in Michigan and delivers clean drinking water to the Grand Rapids area using Lake Michigan as its water source. The city operates about 1,250 miles of pipelines, 31,000 system valves, and more than 1,300 large valves (16 inches and greater). Many of these valves were inoperable due to a lack of routine maintenance, so the city began to seek funding for valve replacements.

Grand Rapids was aware of a long segment of transmission line that couldn't be isolated due to inoperable valves. To regain control of the line, the city replaced five large valves at an average cost of $125,000 per valve, each taking an average of one week to replace. This amount of work and cost was a wake-up call that compelled the city to find alternate methods of rehabilitating its valve assets.

"Rehabilitating valves as opposed to replacing valves is a no-brainer when you look at the cost in addition to the time and operational capability benefits," explains Alex Fleet, assistant water system manager with the City of Grand Rapids.

With limited information on which valves required attention and a limited capital budget for asset replacement, the city needed more information to make decisions. In accordance with the city's asset management plan, the first step was to determine the status of these valves. Based on age (80+ years), the city doubted that any of the valves selected for assessment would work properly.

In October 2017, Grand Rapids partnered with Xylem to assess and evaluate 20 large valves in the city's transmission system as part of a pilot maintenance, operation, and rehabilitation program. The results would help the city determine next steps to improve performance across the system.

The results defied expectations. In conducting its evaluation, Xylem found that 12 of the 20 valves worked well. These numbers were consistent with the company's experience that, on average, 40% of valves in water systems across the United States are either inoperable, not locatable, or in the wrong position.

Xylem repaired and restored the eight remaining valves assessed, bringing them

Although PCCP isn't the most common material in water networks, it dominates in large water transmission mains or force mains over 14 inches in diameter. As a result of their size and the catastrophic nature of PCCP failures, these pipelines typically have the highest consequence of failure in a transmission network. This is why PCCP pipelines usually call for a high-resolution assessment approach that yields precise probability of failure and accurately forecasts future asset condition.

Metallic Pipe. Metallic pipe, including cast iron, ductile iron, and steel, makes up the majority of water networks. Metallic pipe failure mechanisms fall into three categories: corrosion, leakage, and mechanical failures. Although pipe failures present as distinct events, factors leading to failure can be complex and are often a result of multiple damage mechanisms.

In metallic pipelines, any wall loss due to corrosion affects the pipe's structural integrity. Corrosion occurs when pipelines are exposed to stray electrical currents or corrosive substances in the soil or product flow. Corrosion can lead to pitting and leaking; it can also weaken the pipe and increase the likelihood of cracking from external loading and internal pressure.

For less than the cost of replacing just one valve, the City of Grand Rapids, Mich., restored eight critical valves to full operability, including a critical 36-inch valve (inset) that was inoperable for more than 30 years.

back to full operability for less than the cost of replacing just one—a total savings to the city of more than $800,000. This included designing and manufacturing the necessary replacement parts for each valve as well as rehabilitating one inoperable 36-inch gate valve by fabricating and replacing a disintegrated bull gear.

Grand Rapids updated its asset information, allowing the city to identify which control valves to operate in the event of an emergency. This rehabilitation work took approximately one to two days per valve, and only one main had to be taken out of service. Overall, the city improved its operational resilience and obtained critical information (physical, locational, and operational data) for its asset inventory while avoiding the cost and inconvenience associated with valve replacements.

Typical Assessment Technologies. Table 1 highlights common inspection and monitoring techniques for critical pressurized pipelines. Although this isn't a comprehensive list, it provides guidance on the types of inspection techniques typically used for transmission mains and force mains. Techniques vary significantly with regard to cost and level of effort. Many can be used while the pipeline remains in service and don't require extensive civil work or a significant interruption to standard operations. Some methods, usually high-resolution tools, require modifications to the pipeline for access or could require full isolation and dewatering of the main.

Utilities can manage many lower-consequence pipelines safely using lower-resolution techniques, such as transient pressure monitoring, leak and gas pocket detection, or above-ground surveys. These approaches can identify red flags and justify further action. Leak and gas pocket inspections, for example, can identify problem areas such as potential corrosion, deteriorated joints, and cracking. Internal hydrogen sulfide corrosion is a leading cause of force main failure and starts when a gas pocket forms inside the pipeline. Leaks are often a precursor to failure, especially in metallic pipes. By proactively identifying and repairing leaks, utilities can prevent failures, reduce real water loss, and prioritize mains for more detailed inspection.

In-line leak detection technologies are an effective option for pipelines eight inches and above. These tethered or free-swimming tools can travel inside the pipeline without disrupting service. By bringing an acoustic sensor directly to the leak, in-line tools can pinpoint small leaks, discern between multiple leaks along a section of pipeline, and work effectively in pipes of all materials. Some leak detection tools have other on-board sensors to improve data accuracy, enable mapping of pipeline alignment, and capture video inside the pipeline.

For higher-consequence pipelines, utilities can use higher-resolution techniques to gather more detailed information and improve confidence in their decisions. Nondestructive electromagnetic and ultrasonic technology can locate and quantify pipe wall deterioration. Electromagnetic inspection allows utilities to understand the condition of each pipe by detecting existing broken wire wraps in PCCP and areas of cylinder wall loss in metallic mains. Ultrasonic technology is also available for water and raw water metallic pipelines. Ultrasonic sensors collect high-resolution data on internal and external wall loss, pitting, and pipe out-of-roundness. On page 14, see how Green Bay Water leveraged in-line leak detection and pipe wall inspection technology to direct repairs and extend the life of two critical transmission mains.

Quick Guide to Pipeline Inspection Methods

There are a growing number of assessment technologies available to evaluate critical pressure pipelines, including the following:

In-line Leak Detection. Identify and quantify leaks in the joint, barrel, and features with acoustic technology.

Pipe Wall Inspection. Locate and quantify structural defects in the pipe wall using electromagnetic or ultrasonic sensors or visual and sounding techniques.

Pipeline Monitoring. Measure operating and transient pressure and continuously detect wire breaks in PCCP.

Corrosivity Surveys. Test external conditions around the pipe, including soil, groundwater, and stray currents.

Table 1. Established Inspection and Monitoring Technologies for Critical Pressure Pipelines

Technologies	Description	Deliverable
All Pipe Materials		
Corrosivity Survey	Soil samples and above-ground inspections are used to determine soil chemistry and identify stray currents.	Characterizes soil corrosivity, measures corrosion activity, and assesses the effectiveness of coatings and cathodic protection systems.
In-line Acoustic Leak Detection	Free-swimming or tethered technology detects the distinct acoustic signature of water escaping a pressurized system and entrained air.	Identifies small leaks and gas pockets in addition to mapping pipeline alignment.**
Visual Inspection	Collected internally via physical entry or using video inspection technologies.	Identifies cracks, lining spalls, internal corrosion, excessive deformation, joint separation, or other visual signs of distress.
Transient Pressure Monitoring	Pressure sensors with high sampling rates are used to continuously monitor internal pipeline pressure.	Measures pipeline operating pressure and transient events, including water hammer.
Metallic Pipe (DIP, CIP, and Steel)*		
Ultrasonic Inspection	Pipe wall thickness is determined using the time-of-flight of high-frequency ultrasonic pulses. Can be deployed in-line via free-swimming technology or externally via spot assessments.	Identifies pipe wall loss and can provide pipeline out-of-roundness.**
Remote Field Testing (RFT) Electromagnetic Inspection	Pipe wall thickness is determined from electromagnetic signal changes. Can be deployed via internal piloted, robotic, and free-swimming technology or external spot assessments.	Identifies pipe wall loss.
Broadband Electromagnetic/ Pulsed Eddy Current	Pipe wall thickness is determined from electromagnetic signal changes. Can be deployed through internal piloted inspection technology or external spot assessments.	Identifies pipe wall loss.
Magnetic Flux Leakage	Detects magnetic flux leakage caused by abnormalities in the pipe wall. Sensors must be in close proximity to the pipe wall. Can be deployed through internal piloted technology or external spot assessments.	Identifies pipe wall loss.
Concrete Pipe (PCCP, BWP, RCP)*		
Electromagnetic Inspection	Detects electromagnetic signal disruptions caused by discontinuities in reinforcing wire or bar wraps. Can be deployed through internal or external piloted technology as well as internal robotic or free-swimming tools.	Identifies broken prestressing wire wraps (PCCP), broken bars (BWP), and broken reinforcing wires (RCP).
Acoustic Fiber Optic Monitoring	Detects the distinct acoustic signature of reinforcing wires breaking. Permanently installed near or within the pipeline.	Actively monitors, identifies, and locates individual wire breaks (PCCP).

*DIP—Ductile Iron Pipe; CIP—Cast Iron Pipe; PCCP—Prestressed Concrete Cylinder Pipe; BWP—Bar-Wrapped Pipe; RCP—Reinforced Concrete Pipe

**Dependent on technology platform

Based on information available in AWWA's Manual of Water Supply Practices M77, *Condition Assessment of Water Mains* (www.awwa.org/M77).

Green Bay Benefits from Data-Driven Asset Management

Green Bay Water is Wisconsin's third largest drinking water supplier, providing water to more than 107,000 residents and four wholesale customers. The utility treats and transports water from Lake Michigan to meet the needs of its growing community. Critical to the network are two twinned prestressed concrete cylinder pipelines that convey potable water over 12 miles from three reservoirs into the city's distribution network.

Green Bay Water first inspected these critical, 36-inch pipelines in 2010 with Xylem's PipeDiver technology. This free-swimming tool travels through the pipeline using electromagnetic sensors to quantify broken wire wraps on a pipe-by-pipe basis.

The team assessed a total of 25 miles of pipeline. The tool identified 20 pipes with broken wire wraps. The wire break damage was minimal, and the utility decided no action was justified at the time of the inspection.

Then, in 2012, just before New Year's Day, one of the damaged pipes failed catastrophically. Green Bay Water made emergency repairs on the failed pipe and planned repairs on 17 other distressed pipes identified in the 2010 inspection. The utility also added three interconnections between the twinned pipelines to reduce pressure loss when performing future maintenance.

Green Bay Water reinspected the lines in 2021 with Xylem's in-line leak detection tool, SmartBall. The tool identified three leaks with acoustic sensing technology. Armed with dig sheets showing the leak locations, the utility excavated and confirmed the problematic pipes. One pipe had a small, intermittent leak from a rolled gasket during its original installation in 1967. The other two leaks were significant and presented serious structural concerns.

Green Bay Water was an early adopter of pipeline condition assessment technology.

Photo from Jacob Boomsma, Shutterstock.com.

Xylem also planned to reinspect the mains with the PipeDiver platform. However, the tool lodged on a butterfly valve—a new brand of valve installed in 2016 with an unexpected disc type and orientation. The team had to tap the pipe and isolate, depressurize, and dewater the line to remove the tool. The utility communicated early and often with the public about the operation. Public conservation efforts were key to maintaining an adequate water supply for the area's essential users.

Two months later, Xylem remobilized with an innovation that enabled PipeDiver to pass over the modified butterfly valves. The tool inspected all 25 miles of pipeline and passed 12 valves without issue. In total, the inspection covered 8,204 pipes, and of those, fewer than 1% had broken wire wraps. Nine pipes were newly distressed since the 2010 inspection. However, no pipes showed signs of increasing deterioration since the previous assessment.

Green Bay Water plans to repair the nine distressed pipes within its capital program. Condition data help the utility safely extend the life of its transmission mains while providing reliable, affordable service.

Utilities can better understand the value of risk-reduction efforts by measuring the social, economic, and environmental consequences of leaks, failures, and resulting emergency repairs.

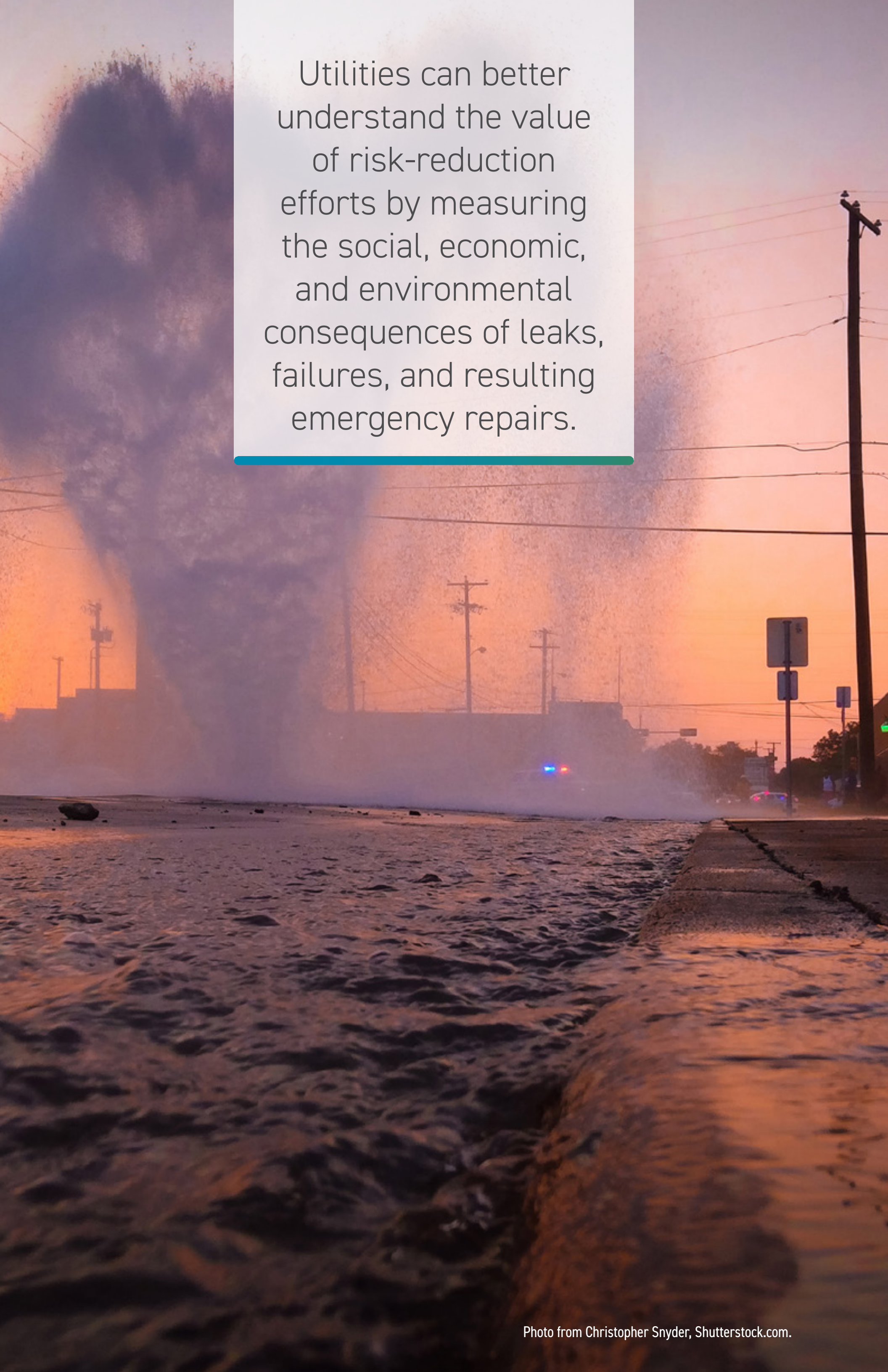

Photo from Christopher Snyder, Shutterstock.com.

There are a variety of pipe wall inspection tools available, including Xylem's PipeDiver platform shown in the photo below. Technician-operated tools, free-swimming platforms, and robotic crawlers are available to meet utilities' unique operational needs. For critical PCCP pipelines, acoustic fiber optic monitoring is also available to detect, locate, and alert utilities to wire breaks in near real time.

Inspection and monitoring tools collect the data to help pipeline owners prioritize investment in the pipes that need it most. However, there is no one-size-fits-all approach to condition assessment. A successful approach uses the right mix of methods to cost-effectively reduce risk. High-consequence pipelines typically require multisensor inspections that can compensate for technology limitations or blind spots to deliver a comprehensive understanding of pipe threats. A screening-level investigation may be more appropriate for lower-consequence mains. Utilities can use a phased approach in which progressively higher-resolution techniques are used to collect the necessary information. Typically, the cost and complexity of a condition assessment project increases with increasing resolution and data reliability. As a result, the condition assessment technologies used should be guided by the initial risk assessment completed during the planning process.

DATA ANALYSIS AND ASSET PERFORMANCE MODELING

Collecting pipeline condition data is a critical step in the overall asset management process. However, having the analysis techniques to make decisions with that data is just as important. Deterioration doesn't necessarily indicate a pipe requires immediate or short-term renewal. There are a series of techniques and models that can be used to help make the data actionable.

Innovations in inspection and monitoring tools make condition data more accessible to utilities. Free-swimming tools like PipeDiver operate while pipelines remain in service and limit the civil work needed to access the mains.

Quick Guide to Pipeline Data Analytics

Analysis can unlock new insights from inspection and monitoring data. There are various levels of analyses utilities can use to inform decisions, including the following:

- *Design checks* verify that pipeline specifications are adequate for the anticipated loads in the pipeline.
- *Finite element analysis* models the pipe under pressure and external loading to determine the amount of distress that will cause the pipe to reach a performance limit related to failure.
- *Remaining useful life analysis* predicts how long the pipeline can operate before a failure is expected based on different deterioration simulations.

Engineering recommendations based on data analyses help utilities determine whether pipelines can continue operating safely or if individual pipes require repair.

Consider the following steps for a comprehensive condition assessment:

Data Quality Control Checks. Inspection data are reviewed on-site before the field team demobilizes. This step is essential to ensure the data collected can be analyzed and to avoid remobilizations.

Data Analysis. The raw inspection data are then backed up and loaded into specialized analysis and interpretation software. Data analysts use the software to process, annotate, transpose, and georeference the raw data. At this stage, raw inspection or monitoring data are transformed into actionable information, such as leak location and magnitude, number and location of broken wire wraps in PCCP, or percent depth and area of wall loss on metallic pipes.

Utilities can use this information to make immediate and short-term decisions. For example, a critical PCCP with a barrel leak and a large number of broken wire wraps adjacent to a hospital may be a good candidate for an immediate repair or replacement. For cases where the next steps are less clear, further analysis can determine the structural consequence of deterioration.

Structural Analyses. Once the raw data have been interpreted, in many cases a structural analysis is needed to determine the pipeline's safety factor. This typically begins with a basic design check to determine whether the pipe specifications are adequate for the actual current loads in the pipeline.

Design Check. Analysts compare the as-built specifications of the pipe, in its undamaged condition (wall thickness, pressure rating, bury depth, etc.), to design standards in place when it was constructed as well as current design standards. The design check assumes the pipe doesn't have any damage. A more detailed analysis may then be used to confirm the structural integrity of pipes based on known distress levels.

Finite Element Analysis. This structural analysis is currently the most accurate method for understanding how a defect affects a pipe's structural capacity. The computational model considers the actual geometry and position of a defect, interaction of multiple defects, internal pressure, external loading, and soil interactions for each analyzed pipe. Defect areas are modeled and manipulated to simulate the growth of the corroded area (metallic pipe) or number of broken wire wraps (PCCP). The resulting stress developed in the pipe wall is then compared with the minimum yield strength of the pipe to determine the internal pressure required to reach yield. The result is a pipe performance curve that shows the amount of deterioration that will result in the pipe reaching its yield limit, the point at which utilities should consider prioritizing pipe rehabilitation. As shown in Figure 8, the accuracy provided by this structural analysis enables confident and defensible repair/replacement decisions.

Statistical Analyses. Statistical analyses leverage engineering principles and mathematical models to draw broader conclusions about the pipe's condition. Such analyses are used to provide short- and long-term pipeline management recommendations. Statistical analyses can be used to evaluate the pipe's current condition or estimate the pipe's deterioration rate and forecast its future condition.

Evaluate Current Condition. Some inspection techniques only sample a small percentage of the pipeline. Statistical analyses can infer the general level of a pipeline's distress. The intent is to use the statistical analyses to make recommendations on a broader scale despite the limited data sets inherent with some inspection techniques.

Calculate Deterioration Rate. Statistical analyses are also used to forecast the future condition of a pipeline or determine recommended inspection intervals. This type of analysis offers a long-range view of pipeline integrity and is useful for developing long-term pipeline management strategies. This information can benefit capital planning and any associated business case evaluations.

Analysts can predict a pipe's remaining service life using a statistical simulation that estimates future degradation based on the pipe's past and current condition, structural analyses, and other available records. The simulation uses a distribution of possible deterioration rates to better imitate the random nature of pipeline degradation. The expected number of broken wire wraps (PCCP) or the change in wall thickness (metallic) is projected for each year. The model simulates the deterioration of all pipes in the pipeline until an "intervention limit" is identified for each pipe in each year. Pipeline owners define the intervention limit based on their risk tolerance and mitigation plan preference. The intervention limit could be the structural yield identified with finite element analysis.

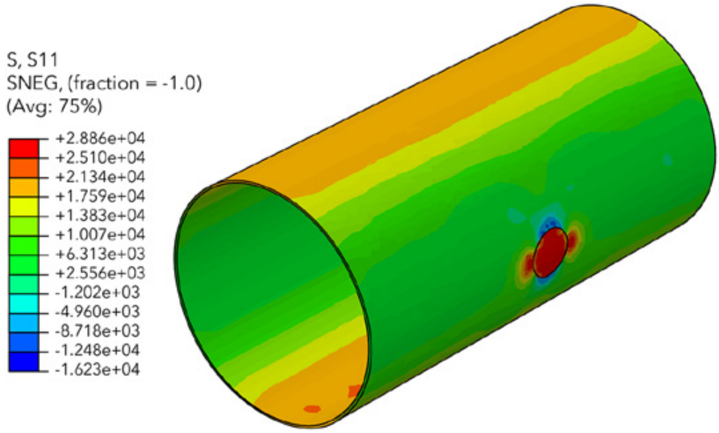

Figure 8. Finite element analysis models how a pipe responds to degradation with increasing pressure and defect size.

Inspection and monitoring tools collect the data to help pipeline owners prioritize investment in the pipes that need it most.

Remaining useful life estimates based on first-time inspection data are less reliable. Inspection offers a snapshot of pipeline condition in time, and degradation patterns from installation to the time of first assessment are uncertain. Remaining useful life estimates become more reliable as the degradation rate comes into focus with multiple pipeline inspections over shorter intervals. This gives utilities a greater degree of confidence that the pipe's predicted and actual condition are more closely aligned. Analysts can also supplement and tighten

Utility Harnesses Data for Better Planning, More Savings

Lake Huron and Elgin Area Primary Water Supply Systems provide water services for about 500,000 residents across 15 municipalities in southwestern Ontario. The Lake Huron Primary Transmission Main is critical to these services, transporting up to 90 mgd over 37 miles from Lake Huron.

The original pipeline was constructed of prestressed concrete cylinder pipe (PCCP) in 1965. The 48-inch pipeline experienced failures in 1983 and 1988. Because of these failures, Lake Huron Primary Water Supply System (LHPWSS) undertook a major capital project to create redundancy along the pipeline, twinning it in three high-pressure areas. Then, in 2010 and 2012, the transmission main failed again in sections that weren't twinned.

The 2012 failure cost approximately CA$1.9 million (in 2023 dollars). These failures disrupted the supply of drinking water to a significant portion of southwestern Ontario. The failures also caused serious flooding. Soil erosion and deposition across multiple farms affected approximately 173 acres of prime agricultural lands.

LHPWSS decided it needed to assess the condition of the Lake Huron Primary Transmission Main. However, inspections were complicated by the fact that shutdowns can't last longer than 24 hours, and there are long distances between access points.

In 2012, LHPWSS partnered with Xylem to conduct an acoustic leak detection inspection with the SmartBall platform and an electromagnetic inspection of the pipe wall with the Pipe-Diver platform. These in-line, free-swimming tools can inspect pipelines while they remain in service and cover long distances in a single deployment.

Despite previous failures, only a small fraction (0.5%) of the nearly 10,000 pipes inspected showed signs of deterioration. Most of the distressed pipes identified had low-level damage. However, the inspection revealed some sections with signs of significant pipe wall deterioration.

Xylem evaluated the likelihood of failure for each distressed pipe using finite element analysis, which helped to determine the point at which a distressed pipe should be replaced. Based on the inspection data and structural analysis, LHPWSS proactively replaced six pipe sections. Each proactive repair represents a 5:1 return on investment in cost avoidance compared to a failure.

In 2015, LHPWSS began monitoring the Lake Huron Primary Transmission Main with Xylem's SoundPrint AFO. This acoustic fiber optic monitoring platform detects and locates wire breaks in near real time, providing an advanced warning system to avert potential failures.

The baseline electromagnetic assessment provided a snapshot of the Lake Huron Primary Transmission Main's condition at the time of inspection. Ongoing monitoring provides continuous information on the condition of each pipe and a better understanding of pipe deterioration rate.

deterioration estimates using a database of inspection and monitoring information from similar pipelines. High-resolution inspection data are ideal for remaining useful life analysis, as they are generally more accurate and take thousands of discrete measurements from each individual pipe. The case study below details how Lake Huron and Elgin Area Primary Water Supply Systems used such analyses to identify urgent repair needs and plan future maintenance and capital projects.

An acoustic fiber optic monitoring platform provided data that allowed Lake Huron and Elgin Area Primary Water Supply Systems to proactively repair damaged PCCP.

In 2018, Xylem developed a model for predicting future pipeline degradation using inspection and monitoring data and a large database of comparable results. The model estimated with a probability greater than 75% that five pipes would exceed their yield limit in the next five years, and in 20 years, 68 pipes were likely to exceed their yield limit. Since the original model was developed, LHPWSS has proactively replaced four distressed pipe sections in response to increasing wire break activity detected by the continuous monitoring platform.

Xylem updated the model in 2023 with five more years of structural performance data. Based on new transient pressure monitoring information, Xylem also lowered the pressure in its structural analysis by 30%, meaning pipes could sustain more distress before reaching their yield limit.

With the four pipe replacements and new data, the updated model predicts that one pipe will exceed its yield limit by 2034, and seven pipes will exceed their yield limit by 2045. This means 50% fewer future interventions than predicted in 2018 and only one intervention over the next 12 years.

LHPWSS now has a better understanding of when individual pipes may fail. The analysis also showed a higher density of predicted deterioration around a pump station.

LHPWSS uses inspection and monitoring data combined with engineering analyses to identify urgent repair needs and plan future maintenance and capital projects. With this information, the utility has reduced the risk of service failure at a fraction of the capital cost of building further redundancy into the system.

Risk Mitigation Steps and Reinspection Intervals. Understanding pipe deterioration and remaining useful life estimates provides guidance for reinspection interval planning. Reinspection timing depends on how quickly pipes are degrading, the utility's risk tolerance, and any risk-reduction measures taken following the initial condition assessment.

Regular reinspection identifies new distress areas and determines whether problem areas are worsening. With each reinspection, utilities gain more data on pipe deterioration rate to decrease the uncertainty of forecasts and refine remaining useful life predictions. Once another inspection is completed, the data collected in that inspection should be analyzed in conjunction with the data presented in the initial report to provide a more accurate and robust remaining useful life evaluation.

ASSET PLANNING AND MITIGATION

Pipeline inspections and structural performance evaluations help utilities understand current pipeline condition and address short-term risk. Advanced degradation analyses provide insight

In-line Inspection Informs Pipeline Renewal

WaterOne, an independent public water utility serving the Johnson County, Kan., area since 1957, was an early adopter of pipeline condition assessment practices. WaterOne historically focused inspection efforts on older, prestressed concrete pipelines. However, annual risk analyses and the threat of corrosion led the utility to shift its approach and inspect more metallic mains.

In October 2019, the Quivira Road water main rose to the top of WaterOne's priority list following a pipeline break. Most of the 30-inch ductile iron transmission main is located under a major arterial road that passes through three cities. It includes a highway and railroad crossing along its 3.6-mile route. Additionally, two of the cities were planning roadway capital improvement projects along the corridor, further increasing the importance of assessing the main.

Through a competitive procurement process, WaterOne partnered with Xylem to deploy PipeDiver Ultra, an in-line condition assessment tool that directly measures the wall thickness of metallic water pipelines using high-resolution ultrasonic sensors. The tool provides utilities with data on wall loss and pipe out-of-roundness. Its high-definition cameras can also capture visual defects such as air pockets and cracking. Like other PipeDiver models, the free-swimming tool collects data over long distances while the pipeline remains in service. The alternative option would have required the utility to fully dewater the pipeline and provide multiple access points along the inspection route.

The Quivira Road pipeline consists of two parts: the original unwrapped main installed in 1966 and a polywrapped section relocated and installed in 1992. Results showed that 13% of pipes had moderate to significant wall loss, most of which was on the older, unwrapped main. Design checks and finite element modeling performed by Xylem showed that no pipes were expected to have exceeded their yield limit—the threshold where repair is recommended. However, the team did elevate several pipes for further consideration.

into when pipes are likely to reach the end of their useful life. This empowers defensible long-term planning and budgeting for reinspection and repairs.

Depending on the pipeline's reported condition and physical location, as well as the owner's tolerance for risk, it can be more cost effective to rehabilitate a pipeline as opposed to replacing it or leaving it in its current state. AWWA's Manual of Water Supply Practices M28, *Rehabilitation of Water Mains* (www.awwa.org/M28), details rehabilitation methods appropriate to extend the life of high-consequence water mains. The case study below details how WaterOne used pipe wall assessment data to mitigate risk for a critical ductile iron main. For additional details, see the May 2023 *Opflow* article on the project at https://doi.org/10.1002/opfl.1815.

Replacement of damaged pipe segments either through open-trench removal methods or trenchless options, such as pipe bursting and sliplining, can restore the pipeline's structural integrity. External options for rehabilitation include post-tensioning repair systems for PCCP and external repair sleeves for other pipe materials. Utilities may also consider internal structural

To assess a critical 30-inch ductile-iron main, WaterOne selected an in-line condition assessment tool.

Armed with condition assessment data, WaterOne carried out near-term rehabilitation actions to mitigate risk at the most vulnerable points along the pipeline and made long-term management plans. On the 1966 main, WaterOne performed nine spot repairs on pipes where wall loss was 60% or greater. The utility placed three anode retrofits in a bonded joint area to help slow corrosion and mitigate risk over the short term. It also replaced a 280-foot section of the pipeline through an intersection ahead of one of the city road improvement projects. As part of its Master Plan, WaterOne will replace the 1966 pipeline in two phases in coordination with city capital improvement projects.

On the 1992 section, WaterOne conducted four spot repairs on pipes with defects at and exceeding 50% wall loss. Given these repairs and the current inspection results, the utility isn't planning to replace the pipeline for at least 40 years.

rehabilitation options, including cured-in-place pipe lining techniques, carbon fiber-reinforced polymer, and internal joint seals. Although cement-mortar lining and spray-on polymer lining aren't generally considered structural options, they may be appropriate for pipelines with minimal deterioration. M28 provides decision-flow diagrams to help guide the types of rehabilitation appropriate for given pipeline conditions.

Each rehabilitation method has advantages and limitations that affect its applicability to a project. At a minimum, the following factors should be evaluated to determine feasibility and preference:

- Pipe condition to determine whether a full-length or spot repair is needed as well as the amount of structural improvement needed (nonstructural, semistructural, or structural)
- Pipe attributes such as diameter, material, length of repair, pressure and flow requirements as well as number and location of connections
- Site conditions and available access to excavate or physically enter and work inside the pipeline (e.g., depth of cover, number of and degree of bends, number of and location of access points)
- Life expectancy of the repair and long-term plans for the pipeline
- Availability and performance of pipeline rehabilitation contractors
- Costs and benefits of the various rehabilitation options

In general, the more structural improvement afforded by the repair, the higher the costs. In addition to the direct project costs, utilities should consider the effects on water service, traffic patterns, sensitive areas, adjacent property and infrastructure, competing projects in the right of way, and general community disruption.

Another means of reducing the risk of pipeline failure is to manage pressure in the main. This can be done by lowering the operating pressure of the main and by mitigating surge pressures. Surge mitigation may involve installing one or more of the following: surge relief valves, variable frequency drives on pumps to better control pump startup and shutdown, proper pump startup and shutdown operating logic, and slow-closing and -opening pump operation valves.

Cathodic protection is a simple and cost-effective method used to control external corrosion of underground metallic pipelines. The basic premise is to cathodically polarize the pipeline by installing and connecting counter electrodes (anodes) to significantly reduce the oxidation rate of the metal. Cathodic protection has been used effectively for decades by numerous utilities to control external corrosion of metallic water lines.

Galvanic/sacrificial anodes and impressed current systems are the two primary types of cathodic protection systems. The choice between these two general options depends on several factors, including the pipeline's configuration and whether the pipeline's electrical continuity can be confirmed or established. Soil characteristics, such as observed pipe-to-soil potential and soil resistivity, are also critical to cathodic protection design. More information can be found in AWWA's Manual of Water Supply Practices M27, *External Corrosion Control for Infrastructure Sustainability*.

It isn't always feasible to extend pipeline life through rehabilitation or other mitigation actions. In these cases, condition data are still valuable for managing risk while planning for replacement within a favorable window, such as in coordination with larger municipal capital improvement plans or during periods of lower system demand.

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