Globally, aging water and wastewater infrastructure is rapidly deteriorating and sometimes failing, with potentially dire human, environmental, and financial consequences. As this aging process continues, utilities are faced with costs they can no longer afford. Recent advances in smart water network (SWN) modeling technology have played a crucial and growing role in addressing this challenge. SWN technology has equipped utilities with a comprehensive set of decision-making tools designed to help them effectively manage these critical assets while maintaining the desired level of service at the lowest life-cycle cost. By seeking the lowest life-cycle cost and reinvesting the savings in their infrastructures, utilities are able to help close the infrastructure gap and place their assets on the road to efficiency and sustainability. These advances have the capacity to transform how infrastructure is conceived, designed, and delivered to enable a sustainable future and continue to promote economic development and quality of life.
ASSET MANAGEMENT OVERVIEW

Water and wastewater infrastructure in the United States is continuously aging, and current capital spending is not expected to keep pace with needs. More than one million miles of water pipes are nearing the end of their useful lives, meaning they need to be replaced sooner rather than later (AWWA 2012). Assuming every water pipe is replaced, the cost could reach more than $1 trillion over the next couple of decades (Boulos & Wiley 2013). Total capital investment needs for US wastewater systems are estimated at $298 billion over the same period.

With between 700,000 and 800,000 mi of public sewer mains, pipes represent the largest capital need, making up three-quarters of total needs (Boulos & Walker 2015). Yet this critical infrastructure is projected to see the largest investment gap, falling 73% short of needs. Because of insufficient investment, this gap will only widen with time as more pipes reach the end of their effective service lives. Compounding this problem is the need to address stricter regulatory requirements, growing populations, increased service demands, limited water supplies, increased potential for flooding and drought, and decreased state and federal funding. This does little to assuage the public’s health and economic needs or maintain its confidence in the safety of our drinking water and the ecological health of the nation’s waterways.

A key objective in managing aging assets is to balance system performance and cost (USEPA 2013, Shamir & Howard 1979). Selection of main segments for replacement should be based on a comparison of two alternatives: (1) replacing the pipes and incurring the replacement (capital) costs and future marginal (operations plus maintenance plus risk) costs associated with the new lines or (2) keeping them for the time being, saving the replacement costs but incurring future marginal costs. The conventional end-of-design life (e.g., 50-, 75-, or 100-year) main replacement cycle, while easy to communicate to the public and policymakers, can lead to replacing mains that have years of remaining useful life and does not take into account the risk of not replacing the mains (Flynn 2014). It is therefore essential to base any replacement strategy on a risk-based economic life cycle rather than short-term benefits such as the pipe’s initial capital cost, end-of-service life when the asset can no longer serve its intended purpose, or end-of-physical life when the asset becomes physically non-functioning. Managing water and wastewater pipes to the lowest life-cycle cost and accounting for failure risk (i.e., the product of failure likelihood and failure consequence) is the best basis for creating an optimal replacement strategy and reducing the infrastructure gap (Figure 1).

The cost of owning any asset (in this case, pipe) warrants its replacement when it exceeds the new asset’s (pipe’s) ownership cost (Figure 2). This serves as the basis for strategic asset management. Strategic asset management is aimed at maintaining the desired level of service at the lowest life-cycle cost—the best appropriate cost for rehabilitating or replacing an asset. The goal is to find the point in the asset’s life cycle or...
economic life where the cost of replacement is balanced against the expected cost (or consequences) of failure, the accelerating cost to maintain it, and the declining level of service. To find this point, a utility must know which pipes are most critical to sustain desired system performance and service level and then gauge their remaining useful lives. Critical pipes are those that have a high failure risk and major consequences if they fail. Consequence of failure can depend on a number of pipe attributes, including buried depth, number of connected customers, and proximity to critical facilities (e.g., rivers, wetlands, hospitals, schools, manufacturing, high-density housing, airports, military facilities). The remaining useful life of these pipes is estimated using probabilistic pipe-deterioration-condition curves. This helps utilities make risk-based decisions by choosing the right mains for replacement at the right time. This process will help reduce pipeline failures and their adverse effects, minimize life-cycle costs, and give stakeholders the assurance of long-term system sustainability and security.

If the goal is to minimize the present value of the total cost of ownership, the optimum period for replacing mains represents the end of the economic life for an existing pipe, determined as the point in time when the present value of the future total ownership cost is no longer the lowest life-cycle cost alternative (i.e., when it is cheaper to buy a new pipe). This enables utilities to ensure the smartest distribution of dollars spent on replacement and renewal of their assets. It also helps them create reliable, cost-effective, risk-based capital improvement plans that enhance operational efficiency and quality of service.

**SWN MODELS**

Recent advances in SWN modeling technology can assist utilities in addressing the challenges related to aging water and wastewater infrastructure. SWN models can be divided into four general categories: geographic information system (GIS), network, asset integrity, and finance models. Used together, these highly complementary models constitute a decision support and strategic asset management tool for utility managers (Figure 3). By using them to conduct a wide-ranging risk-based economic life-cycle cost analysis, they can estimate the lifetime performance of each individual pipe in their water and wastewater networks, including their expected failures, repairs, and eventual replacement, as well as associated costs of optimizing the management of those high-risk assets. This knowledge can help utilities preserve structural, hydraulic, and water quality integrity and ensure that their pipe networks operate well into the future at maximum cost savings.

**GIS.** A GIS model acts as the central storehouse for all water and wastewater network asset data (e.g., pipe length, diameter, material type, location, age, surrounding soil condition, leakage/break/defect history). From
this spatial database, inputs to all models are generated and model results are associated for query, analysis, and display on the network map. Over time—as pipes are rehabilitated, repaired, or replaced—asset maintenance, break history, and inspection data are updated. This allows utilities to develop a condition assessment and rating system for all pipes. The data can also be used to predict the future rate of deterioration and estimate when a pipe will fail. The ability to view this asset analysis data on a map is a powerful tool for recognizing spatial trends and hot spots.

**Network.** Network models represent the most effective way to predict network behavior of water and wastewater systems under a range of loading and operating conditions. They make use of continuity, energy and momentum principles, and reaction kinetics to track actual system hydraulic and water quality performance over time in meeting desired levels of service. The expected levels of service help characterize the importance of each asset and its criticality. These assets include fire-fighting and storage capacity, disinfectant residual concentration, system losses, inflow and infiltration, extent of flooding and overflows, frictional losses, and operating pressures. They are shaped by minimum performance requirements such as regulations, permit conditions, water quality standards, and discharge limits. Through their criticality analysis capabilities, these models can also carry out vulnerability assessments to determine the consequence of failure of each pipe.

**Asset integrity.** Asset integrity models estimate the failure potential for all network pipes. As a pipe ages and deteriorates, the likelihood of failure increases, thereby increasing risk. The objective is not necessarily to determine the cause of pipe failures, but rather when they might be expected to fail in the future. Because it is not feasible to directly observe buried (underground) infrastructure, condition assessments for water and wastewater mains are normally based on their estimated remaining useful lives. Using existing pipe condition inspection and historical failure rate data, condition curves of future failure or survival probability can be determined. The most widely used models to forecast pipe failure include the non-homogeneous Markov chain, non-homogeneous Poisson process, linear extended Yule process, Cox proportional hazards model, and time-based probabilistic Weibull and Herz models. The accuracy of the models is determined by how well pipe cohorts are grouped in terms of common factors. Critical pipes (i.e., those with the highest risk of failing) are identified, and those with the greatest negative impact are given the most attention.

**Finance.** Finance models balance capital (replacement) expenditure against marginal cost to minimize the overall cost of asset ownership (Figure 4). Marginal cost can be expressed as the present value of the expected risk cost (or consequences) of pipe failure, the accelerating cost to maintain it (maintenance cost), and declining level of service (operational cost). These costs can also include internal resources and overheads; leakage, additional pumping, and traffic and disruption costs; and costs related to sustainability, resiliency, greenhouse gas emissions, and health and safety. At the same time, the discounted (or present value) replacement cost declines as pipe renewal is deferred. The total ownership cost, or expected life-cycle cost,

![FIGURE 4](image)
typically forms a convex shape, whereas the minimum point (i.e., when the gradient is zero) depicts the optimal time of replacement. This optimal replacement time represents the pipe’s economic life. Knowing the full costs and revenues generated by the water and wastewater systems enables utilities to determine a long-term funding strategy and allocate utility resources in the most efficient way.

CONCLUSIONS

Water and wastewater utilities worldwide face the constant challenge of sustaining and improving the performance and extending the life of their assets with limited resources. SWN models can play a growing role in meeting this challenge because of their inherent ability to optimize scheduling of pipe replacement while maintaining desired levels of service. These models allow utilities to proactively rehabilitate or replace their pipes on a continual basis rather than wait to repair failing or damaged ones when the move is considerably more expensive and disruptive to system operations. They can also serve as a logical framework for making functional industry procurement changes from a low-bid first costs procurement strategy (i.e., lowest design and construction costs) to a life-cycle costing that will result in the most cost-effective, efficient, and resilient infrastructure. This framework is aligned with the American Public Works Association’s call for establishing life-cycle costing of public infrastructure as a replacement for low-bid procurement (Ross 2001).

A critical part of any capital improvement plan is gaining the support of administrators, elected officials, ratepayers, and other nontechnical stakeholders. Implementing such recommendations is expensive, and decision-makers demand transparency and supporting documentation. With a sound SWN framework, utilities are better positioned to receive the support they need to maintain their financial and operational sustainability well into the future. Knowing the full costs and revenues generated by water and wastewater systems enables utilities to determine a long-term funding strategy and allocate utility resources in the most efficient way.

EDITOR’S NOTE

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REFERENCES


